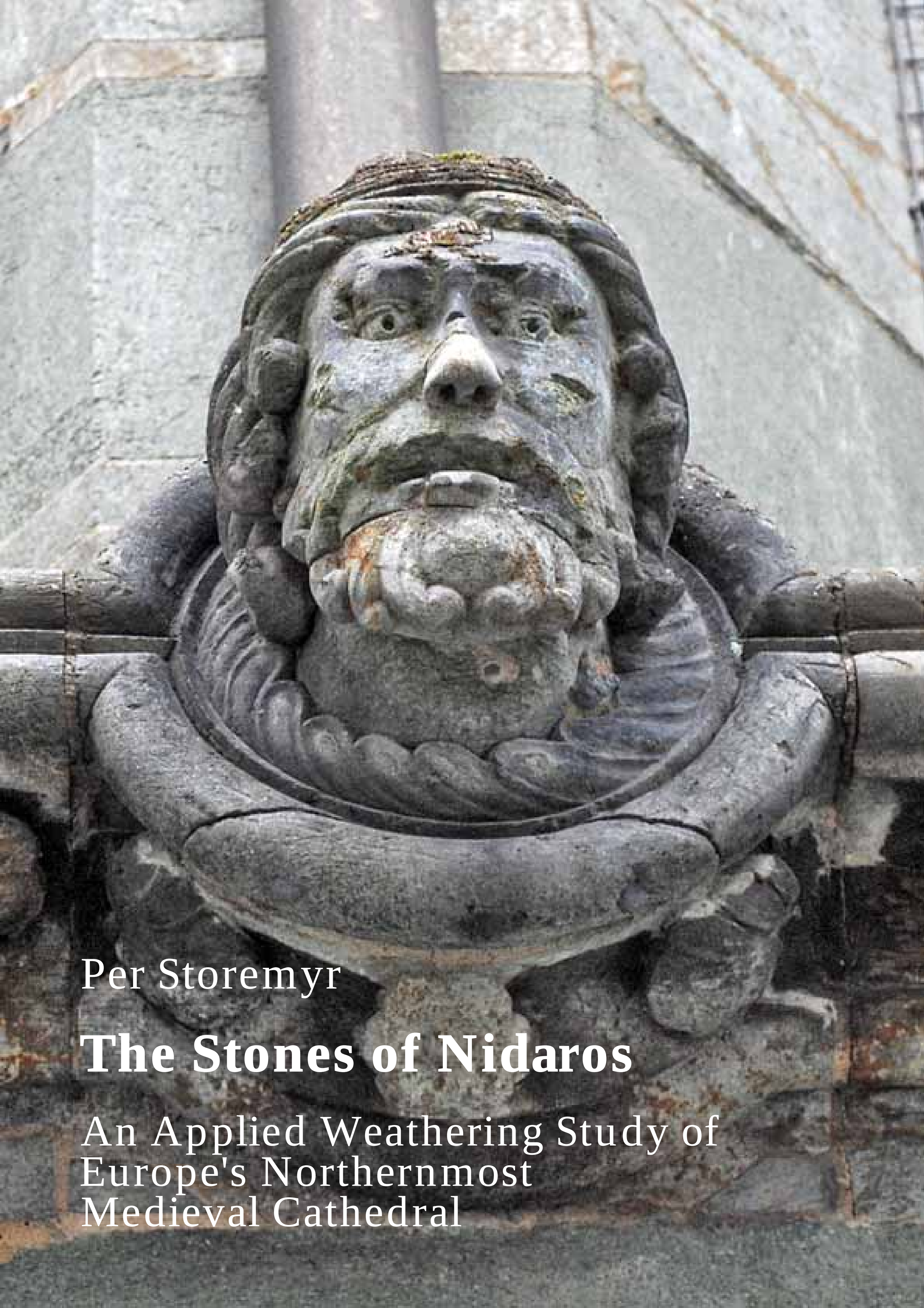

Per Storemyr

The Stones of Nidaros

An Applied Weathering Study of Europe's Northernmost Medieval Cathedral

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Original printed edition 1997
Layout by Per Storemyr
ISBN 82-471-0128
ISSN 0802-3271

This edition:
Slightly edited and prepared for PDF
2010 Per Storemyr

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An Applied Weathering Study of
Europe's Northernmost Medieval Cathedral

Thesis submitted in partial fulfillment of
the requirements for the degree Doktor Ingeniør

by

Per Storemyr
Department of Architectural History
Norwegian University of Science and Technology
Trondheim, Norway

1997

For Fränzi

But we cannot avoid remaking our heritage,
for every act of recognition alters what survives.

David Lowenthal
"The Past is a Foreign Country"

Preface

When I was introduced to the field of stone weathering and stone conservation as a geologist in 1990, I saw black gypsum crusts formed as a result of air pollution everywhere. This was in my happy days as a politically correct environmentalist and represented the “one-dimensional phase” of my career as a stone weathering scientist. Two dimensions appeared somewhat later as I realised that various stone types behaved differently and that black crusts were very unevenly distributed on the walls of Nidaros cathedral (Trondheim, Norway) which is the building used as a case study in this thesis. Realisation that a cathedral, like any building, is a three-dimensional or *spatial* system, new perspectives became apparent. It also became clear that this spatial system heavily interacted with the climatic conditions in the Trondheim region. The weathering of the cathedral became much more complex than first thought.

However, the great qualitative leap forward occurred on realising that the cathedral had a history back to the Middle Ages and that thousands of skilled and unskilled people had built, restored and rebuilt the church. When *time* and *people* entered my scientific world, I became so interested in weathering studies that I started to work on this thesis. It was fascinating that there were a great many relationships between weathering phenomena, history and how people interact with a cathedral. My aim was to explore such interactions in order to make a scientific contribution to the field of conservation of historic stone buildings. I also wanted to give the cultural heritage authorities, particularly those responsible for the condition of Nidaros cathedral, a better and broader basis for strategic planning, risk analysis and conservation measures.

It would have been impossible to explore these relationships without considerable co-operation and help. Prof. **Knut Einar Larsen** at the Department of Architectural History, Norwegian University of Science and Technology (NTNU), Trondheim, offered in 1991 to be my main supervisor and kindly helped me establish the formal framework. Since the content of the thesis gradually moved away from his area of expertise, Dr. **Andreas Arnold** at the Institute for Preservation of Historical Monuments and Sites (*Institut für Denkmalpflege*), at The Swiss Federal Institute of Technology, (ETH), Zurich, has in practice, although not formally, been my supervisor over the last five years. I am most grateful for his intellectual guidance and friendship, and that I could work, whenever I wanted, in his laboratory. My sincere thanks also go to the head of *Institut für Denkmalpflege*, Prof. **Georg Mörsch**, for receiving me as a student and scientist at ETH.

The Restoration Workshop of Nidaros Cathedral (RWNC) under the leadership of Cathedral Architect **Arne Gunnarsjaa** and later Director **Øivind Lunde** has also made a significant contribution to this thesis. Firstly, by allowing complete access to every corner of the building; secondly, by letting me search all archives; and finally, by offering me a position as a conservation scientist at the workshop. Thus, I have become rather familiar with the cathedral, which was a prerequisite for this thesis.

The work was carried out at the three institutions mentioned above. Department of Architectural History and *Institut für Denkmalpflege* were my bases in 1992/1994 and 1993, respectively, and since 1995 I have been fully employed at The Restoration Workshop. In addition to the people mentioned above, I have received qualified scientific and personal help from several others at these institutions:

At the Department of Architectural History, **Staale Sinding-Larsen** and **Dag Nilsen** have commented upon earlier drafts of parts the thesis, especially related to theory and method. **Ellen Woldseth** and **Astrid Presthus** have provided a safe haven at the institute and generously helped me with all practical details.

At the *Institut für Denkmalpflege*, **Konrad Zehnder** shared his wonderful way of observing and describing weathering phenomena during extensive illuminating visits to monuments in Switzerland. He and **Andreas Küng** also patiently tried to answer all my many questions concerning soluble salt analysis, which was carried out at the institute. I would also like to thank the people at the laboratory for conservation research and technology at the Swiss National Museum, located with *Institut für Denkmalpflege*, for their help.

At The Restoration Workshop, several individuals have been directly and indirectly involved in my work, many of whom have given me invaluable practical help and insight into craftsmanship and traditions at this 130 year old institution. I am particularly indebted to **Erling Refseth** who helped so much in the early phases of the work, **Øystein Ekroll** who taught me about building archaeology and history and also commented upon the historical part of this thesis, as well as **Geir Magnussen** who widened my knowledge about mortars and commented upon the mortar chapter. **Atle Elverum** helped with surveying and mapping the chapter house, while former restoration architect **Torgeir Suul** copied several old photos from the rich archive of The Restoration Workshop (ARW).

Observation and explanation of weathering phenomena in the old soapstone and greenschist quarries of the cathedral constitute an important part of this work. I have had many fine field trips with **Tom Heldal** at the Norwegian Geological Survey; he has also commented upon the stone weathering section of this thesis. **Lisbeth Alnæs** at my former employee, the Foundation for Scientific and Industrial Research (SINTEF) in Trondheim, also gave significant help as we worked together with dimension stone and stone weathering in the early phases of this thesis. The x-ray laboratory at the Department of Geology and Mineral Resources Engineering (NTNU) provided many stone analyses, while the Norwegian Building Research Institute (NBI) in Trondheim generously undertook specific accelerated weathering tests.

Although this thesis primarily deals with Nidaros cathedral, I have travelled extensively throughout Norway and the rest of Europe in order to observe old stone buildings and gain experience about how they weather, and participate at conferences. I have met colleagues and friends who were ready to share their knowledge with me through discussion and practical work.

In Sweden, **Runo Löfvendahl** at the Central Board of National Antiquities followed my work and commented upon drafts and final parts of the thesis over the last 5-6 years. We also undertook several field trips and I especially wish to highlight some weeks on the island of Gotland in 1992. At Gotland I was also for the first time introduced to practical stone conservation by Swedish conservators.

In Germany, **Esther von Plehwe-Leisen** (Cologne) and **Eberhard Wendler** (Munich) realised that we had common interests as they were involved in conservation of soapstone monuments in Brazil. They helped with specific material analysis and skilled interpretation of weathering phenomena. *Bayerisches Landesamt für Denkmalpflege* in Munich should also be mentioned as I spent some useful weeks with its staff studying conservation projects in Bavaria in 1992.

During my work I have also been lucky to have been supervisor for two candidates, **Margrethe Moe** and **Sander Solnes**, at the School of Conservation at The Royal Danish Academy of Fine Arts in Copenhagen. They have made extremely good partners for discussion over the last few years.

Towards the completion of this thesis I had a serious problem finding someone to correct my relatively poor English. **Francis Witkowski** at the Department of Geology, Royal Holloway, University of London came to my aid. This thesis would have been unreadable without his careful corrections. To him, all those mentioned above (as well as those too numerous to mention): Thank you!

A thesis cannot be written without funding. The Norwegian Research Council, with its three years scholarship (1992-94) and funding for one year at ETH, carried the heavy financial burden. The Restoration Workshop also contributed a great deal, especially as I could use much of my time at work to write. In addition, NTNU and the Directorate for Cultural Heritage (Oslo) contributed. I am most grateful.

This thesis is dedicated to **Franziska Rüttimann** who entered my life just before this work began. She has inspired me and helped significantly with ideas, suggestions and corrections. More importantly, she has kept up with me during these, at times, turbulent years. Needless to say, I am happy to be with you.

Trondheim in July 1997
Per Storemyr

Abstract

The deterioration of Nidaros cathedral, Trondheim, Norway has been studied to obtain a basis for adapting conservation measures to be concentrated on zones at risk. Subdivided into six parts, this thesis focuses especially on weathering of masonry and stone decoration, as well as on the historical aspect of weathering, which is embedded and highlighted in a more general weathering context. This so-called “soapstone cathedral” is studied from the original building period in the Middle Ages, via decay and neglect in the post-Reformation period and the gigantic restoration works between 1869 and 1969, to the present condition. The thesis may not only interest cathedral conservators, but also scientists working with weathering and conservation of historic stone buildings.

The thesis begins with a comprehensive introduction to the weathering problems of the cathedral. *Part I* contains methodology guidelines and a brief summary of current theories of weathering processes related to soluble salts and air pollution. The methodology guidelines highlighting the context-dependent nature of weathering are derived from the work of Andreas Arnold and supplemented by a brief summary of the structural aspects of stone buildings, as well as illustrative case studies of Molasse sandstone, a medieval church in Germany and 3500 year old Egyptian obelisks.

Part II gives an overview of the cathedral’s history, building construction and significant structural problems. Soapstone, greenschist, marble, sandstone, various hard stone and slate from 60 different quarries are briefly described, as are medieval lime mortars and mortars based on Portland cement which were introduced in 1869. Attention is also paid to specific conservation methods used during the restoration. This section ends with a comprehensive overview of Trondheim’s cold temperate maritime climate, the history of air pollution in this relatively “clean” city and the warm and dry indoor climate of the cathedral.

Part III deals with description and interpretation of observed weathering phenomena on the most important types of soapstone and greenschist at the cathedral. Weathering phenomena in eight quarries are presented and compared to the behaviour of the respective stone types at the cathedral and other monuments. The study shows that there are significant differences between soapstone and greenschist used in the Middle Ages and soapstones introduced during the restoration. Such differences are interpreted on the basis of analyses of material properties and experiments. The study also shows that several stone types produce sulphate salts due to their content of iron sulphides.

Part IV contains three case studies of selected large sections of the cathedral; the choir, nave and north transept. These case studies give an overview of their associated weathering problems and explain the findings in terms of building construction, stability problems, materials, exposure conditions and recorded water leaks. The last issue is extremely important.

Part V contains four case studies of selected parts of the cathedral severely affected by salt weathering and one case study of Romanesque corbel heads. The evolution of the salt systems are followed from the original building period to the present. Generally, salt weathering was a minor problem prior to the restoration and it was the introduction of highly alkaline Portland cement as well as gypsum derived from stone and air pollution that greatly increased the salt load. It is also shown that the alteration of roof design in the 1880s can explain the rapid weathering of Romanesque corbel heads.

Part VI summarises and discusses the results obtained and gives comprehensive suggestions for conservation measures. The most urgent problems are: 1) Structural instability occasionally resulting in stonework detaching inside the cathedral; 2) Rapid weathering of certain stone types frequently leading to loss of large pieces from elevated exterior areas; 3) Extremely poor water discharge systems and unsatisfactory insulation of exterior gangways and platforms, giving rise to leaks, salt weathering and unwanted run-off along sensitive stonework; 4) Joint fissures in stone capped towers, gables and large sills, resulting in salt weathering below; 5) Rapid weathering of poorly protected medieval sculpture as well as new sculpture made from stone of poor durability.

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Fig. 1.1*: The Nidaros cathedral as it currently appears after a century of restoration (photo: ARW = Archive of the Restoration Workshop of Nidaros Cathedral)*

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Chapter 1

Introduction

This thesis deals with the deterioration and conservation of Nidaros cathedral, the northernmost of Europe's great medieval cathedrals. Situated in Trondheim, the regional capital of Central Norway, the cathedral represents a highlight in Scandinavian architecture, of a size only surpassed by Sweden's Uppsala cathedral.

Being the main symbol of Norwegian history and independence, the cathedral rose to prosperity during the 12th and 13th centuries, only to fall into partial ruin in the late Middle Ages. From then on, the remains of the cathedral went through numerous fires and subsequent rebuilding and beautification phases. It was not until 1869 that plans for a thorough restoration could be realised. The new rise of the cathedral was completed a hundred years later, in 1969.

Despite its relative “youth”, Nidaros suffers - like most European cathedrals - from severe deterioration of old and new stonework. This stonework is in many senses unique. Although diverse “normal” building stone like marble, sandstone and granitic stone has been used, the cathedral is mainly built from soapstone and greenschist. These soft building stones are easy to carve and dress, but rarely to be found as structural and decorative materials outside Norway.

1.1 The cathedral as a case study

Since the late 1980s, there has been considerable public concern about the condition of the cathedral. This is certainly the main reason for choosing the building for a thorough case study. A more personal reason is that I find the cathedral's history and - as a geologist - its stonework fascinating. The cathedral also offers, due to rich archive material, a superb opportunity of investigating a much overlooked dimension in deterioration studies: the dimension of time - in other words: how the deterioration has evolved throughout history. Keeping this perspective in mind, I soon realised that the popular version blaming acid rain and recent emissions of air pollutants for the deterioration was very superficial - and that further or other explanations of the deterioration had to be sought.

When studying deterioration of historic buildings, it is easy to fall for beautiful signs of ageing and patina, for intriguing weathering phenomena and for the complexity of the structural behaviour of Romanesque and Gothic masonry. However, the rather problematic condition of the cathedral calls for something more than admiring its fabric. It calls for a wide range of conservation measures.

In summary: Using a combined historical and scientific approach, the main objectives of this thesis are *to investigate, understand and show how, why and how fast the cathedral deteriorates,* in the hope that answers may lead to a well-founded basis for future conservation measures. I especially hope that the work will show the necessity of concentrating adapted measures to parts of the cathedral which really are at risk.

1.2 The cathedral after a century of restoration

As it appears today, the cathedral includes seven main architectural bodies. It is 100 m long, 50 m wide and strongly influenced by Norman and English medieval architecture, as well as Neogothic architecture of the last century and later. The main bodies are (from east to west):[1]

- The Late Romanesque (Transitional) chapter house by the north side of the choir.
- The superbly decorated Early Gothic (partly Early English style) octagon with three chapels, ambulatory and an internal, Gothic (partly English Decorated style) screen wall bordering the choir.
- The Gothic (Early English) choir with two aisles, two turrets in the eastern straight end towards the octagon and a large porch on the south wall. The quadripartite vaults of the choir are 19 m high.
- The mixed Romanesque (Norman, Transitional) and Gothic (Early English) transept with chapels and a main porch in the north transept.
- The 49 m high mixed Romanesque, Gothic and Neogothic central tower above the crossing. When including the Neogothic spire the tower is 97,8 m high.
- The Early Gothic and High Gothic (Decorated) nave with aisles. The tierceron vaults of the nave are 21 m high.
- The Gothic and Neogothic west front (English screen front) with 75 full size sculptures and two massive west towers flanking the front.

Fig. 1.2*: Nidaros cathedral and the neighbouring Archbishop's palace situated in the southern part of Trondheim, the regional capital of Central Norway (photo: Aune kunstforlag).*

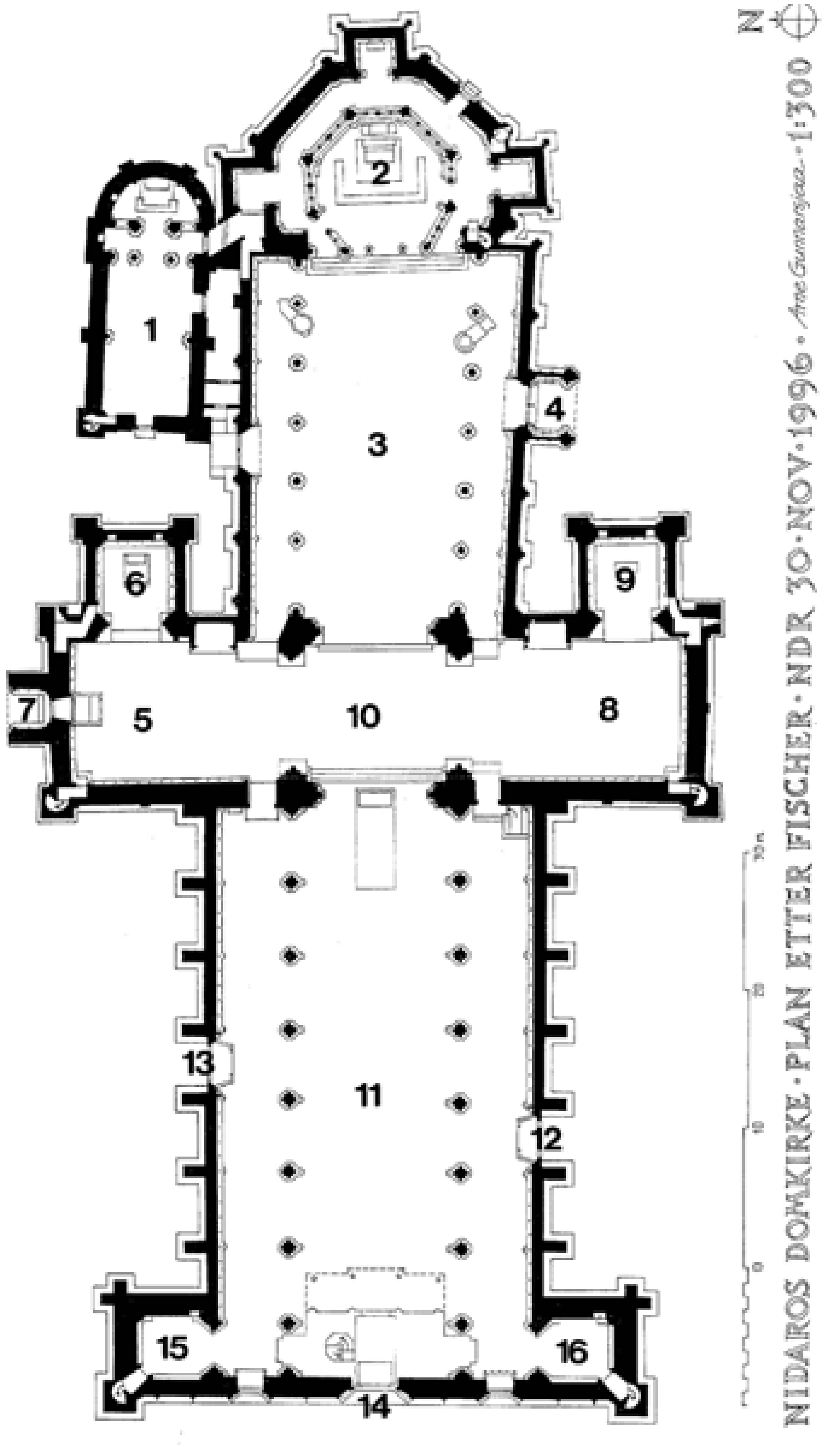


Fig. 1.3*: Plan of the cathedral surveyed by Gerhard Fischer 1942-43 and redrawn by Arne Gunnarsjaa 1996. 1) chapter house; 2) octagon; 3) choir; 4) King's porch; 5) north transept; 6) Lectorium and St. Mary's chapel; 7) north porch and St. Michael's chapel; 8) south transept; 9) St. John's and St. Olav's chapels; 10) central tower; 11) nave; 12) St. Mary's portal; 13) St. Olav's portal; 14) west front; 15) northern west tower; 16) southern west tower.*

An extensive cellar which was largely excavated in this century occupies most of the area under the cathedral. In the cellar there are a few burial crypts, museal collections, archives and a central heating plant (below the chapter house).

As mentioned above, and like most medieval stone churches, the Nidaros cathedral was heavily restored during the last century. It has also been subjected to massive reconstruction works, and several new building parts have been added in this century. The works were undertaken by The Restoration Workshop of Nidaros Cathedral (RWNC) between 1869 and 1969.[2] The Restoration Workshop is still highly active. At present it engages 35 people involved in management, maintenance, repair and "re-restoration" of the cathedral as well as of the nearby Archbishop's palace and other stone buildings in Norway.

The restoration followed mainly stylistic ideals, aimed at bringing the cathedral back to how it may have looked when it was finished around 1300.[3] In 1869, the church was partly a ruin - what remained from the Middle Ages included the chapter house, the octagon and the transept, as well as the lower parts of the choir, central tower, nave and west front. All the rest had disappeard, largely due to the effect of as many as five fires.[4]

The eastern part of the building - including the chapter house, the octagon, the choir, the transept and the central tower - had, however, been kept in usable condition since the Middle Ages by constant repairs following the styles of the different periods and the economy of the parish.[5]

In summary, the cathedral was subjected to gigantic restoration and reconstruction works between 1869 and 1969. These works also stripped the cathedral of all post-Reformation[6] elements, including the Baroque interior of the choir.[7]

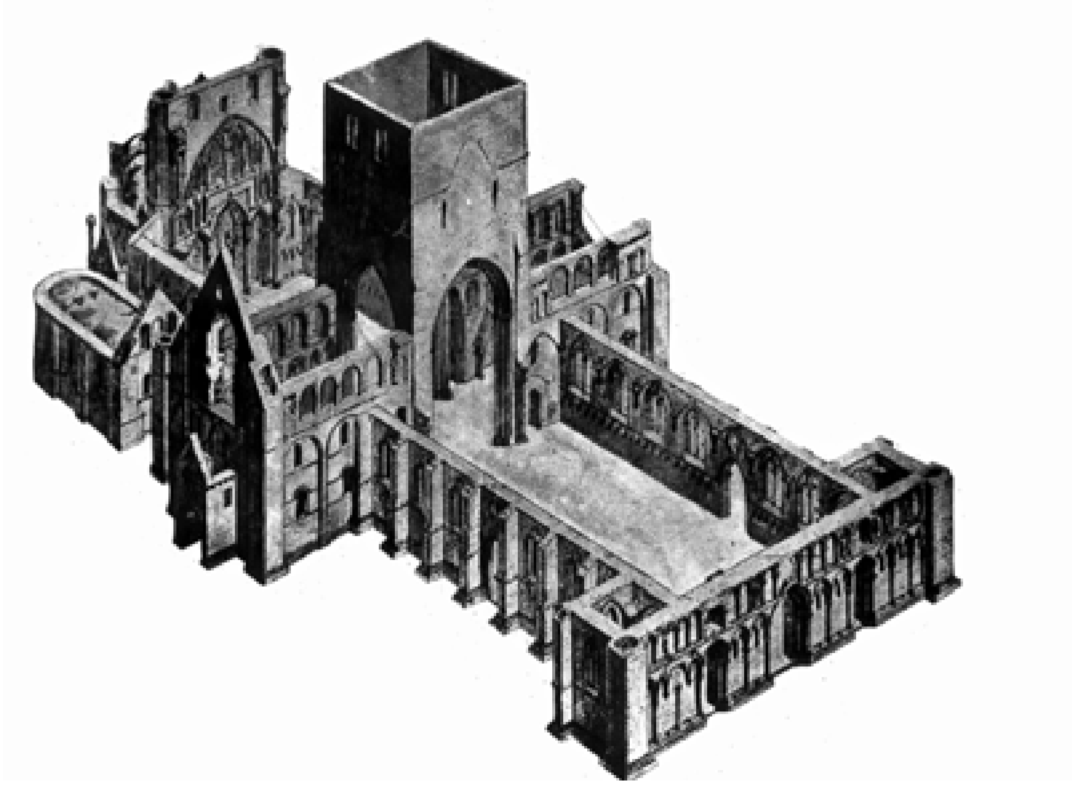


Fig. 1.4*: Remaining medieval masonry before the restoration started in 1869. Drawing by J. Mathisen (photo: ARW, no. 5042).*

***Fig. 1.5**: The interior of the restored nave, looking east toward the choir and octagon (photo: ARW).*

1.3 Concern about the deterioration of the cathedral

Deterioration of the cathedral has, from different perspectives, "always" been of great public concern.[8] From 1869 the deterioration of old and new parts has certainly been of vital interest for The Restoration Workshop. However, except for investigation of structural problems, scientists have only rarely been greatly involved in assessing the condition of the cathedral and finding particular causes of its deterioration. In fact, it was not until the late 1980s that The Restoration Workshop felt the need to involve scientists in more profound research on the condition of the cathedral. Below, I describe some aspects of the history leading to this situation, but first relevant Norwegian, scientific studies of stone weathering are presented.

Two scientific weathering studies a hundred years apart

Norway is a country of wooden architecture and has, unlike the rest of Europe, few stone buildings. Records show some 150 remaining medieval buildings (mostly small churches), about 50 medieval ruins, some post-Reformation castles, fortresses and dwellings, as well as diverse churches and public buildings erected in the period between 1880 and 1914.[9] Perhaps as a consequence of the limited number of stone buildings, very few Norwegian researchers have been interested in how and why building stone weathers. In fact, the only comprehensive, published investigations were undertaken already in the 1890s and as recently as 100 years later, in the early 1990s.

100 years ago, during the vogue for natural stone in Norwegian architecture, the geologist J.H.L. Vogt studied the behaviour of marbles and limestones - including those which had been used on the Nidaros cathedral. Vogt based his investigations on observations of buildings, and did not use various experimental tests of durability to explain his findings, which generally showed that the behaviour of most Norwegian marbles was excellent.[10]

Durability tests were the main point of interest for the geologist Lisbeth Alnæs who made extensive comparative studies of a wide range of modern Norwegian building stone in the early 1990s.[11] Alnæs also studied the general behaviour of soapstone and other stone to be found at Nidaros cathedral. She did not pay specific attention to the contextual behaviour of the stone, but concentrated on petrographical and other "primary" properties in order to explain why some stone weathered rapidly and why others behaved excellently after as much as 800 years of exposure. A major reason for the investigations was related to public concern about what was thought of as accellerated weathering due to air pollution and "acid rain" - just as elsewhere in Europe.

Fig. 1.6*: Typical appearance of the nave's medieval soapstone ashlars. The green-grey, dense and soft matrix of talc and chlorite is intersected by carbonate mineral veins (photo: PS 8/95).*

Alnæs readily showed that the primary properties of many stone types represented a greater threat than the relatively low concentrations of air pollution in Trondheim. However, she did not thoroughly integrate the behaviour of different stone with the design and structure of the cathedral, its complex history and the extremely diverse exposure conditions - in other words the actual situation. Hence, the investigation did not enable her to understand the real risks at hand or to recommend conservation measures other than very general ones. This thesis aims at a much more specific and fundamental understanding of the actual weathering situations and possibilities of interventions.

Weathering - a main theme at Nidaros since the 1920s

In many ways Alnæs summarised and explained observations made by masons and architects since the 1920s. Prior to 1920 it was well known that a main stone type (Grytdal stone), used for restoring the cathedral since 1869, was literally rusting to pieces due to its high iron content (iron sulphide). Consequently, the masons had to replace enormous numbers of ashlars, mouldings and decorations on parts of the cathedral completely restored only 30-40 years earlier.[12] The masons did not, however, replace all the rusting stones - many of them still represent a great problem.

Likewise, grotesque gargoyles and projecting mouldings made of another main stone type from the restoration (Bjørnå stone) started to fall from elevated areas of the cathedral by the 1940s. The decorations had been carved and put in place only 20-30 years earlier, and by 1955 it was firmly established that this particular stone was especially susceptible to the action of rain and frost - it became “rotten” when exposed to the weather.[13]

Fig. 1.7*: Part of a frieze from the choir, made of Grytdal soapstone in the 1880s. The stone is notorious for its rapid weathering and presents serious conservation problems (photo: ARW 1992).*

Weathered mouldings and decorations have, almost without exception, successively been replaced by copies since the 1950s. In addition to the questionable character of this practice (see below), a main problem has been the difficulty in finding and selecting appropriate stone types for the copies. Thus, possible solutions to this problem will be mentioned in this thesis.

In the 1950s there was also considerable concern regarding the white, unsighty excretions of “salpetre” (efflorescences of soluble salts) on the walls of the cathedral. Although no damage was reported as a result of the efflorescence, the architect-in-chief, Helge Thiis, suggested refraining from using mortars based on Portland cement for the west towers and instead reintroducing traditional lime mortars. Unfortunately, the use of Portland cement was not abandoned, but the incident shows that “salpetre” was considered a result of using it.[14] Everybody with some insight into weathering can today easily observe that soluble salts represent a great problem at the cathedral. It will therefore be given much attention in this thesis.

When the results of decades of elevated concentrations of air pollutants - especially sulphur dioxide and “acid rain” - became evident at an international level in the 1960s and 1970s, local and national newspapers published sensational reports about their possible effects on the cathedral - the “national sanctuary”.[15] In 1973 the first scientific report about effects of air pollution on the stonework of the cathedral was published by the Norwegian Institute for Air Research. The work did not significantly widen knowledge about possible “acid attack”, but effects of oxidizing iron sulphides in the stone was reported.[16]

Fig. 1.8*: Large salt deposit (calcite crust) on a flying buttress, north side of the choir. Salts represent a major problem at the cathedral (photo: PS 1990).*

Structural instability, leaks, fire and air pollution

The 1970s and 1980s represented a problematic period for The Restoration Workshop. Signs of structural instability became increasingly evident, columns cracked and collapsed inside the church,[17] and in 1983 a disastrous fire hit two wings of the nearby Archbishop's palace. The catastrophe was underlined by the fact that the burnt-out buildings had been serving as the cathedral's museal collections. Consequently, many medieval stone decorations and later plaster casts were fully or partially destroyed.[18]

Since the beginning of the restoration (1869), plaster casts were taken of almost every architectural decoration - for instance corbel heads and other sculptures. Their destruction meant that an important source of documentation was lost forever - and that a major programmme making new copies of remaining decorations had to be started. This programme is not yet finished.

A major conservation programme aimed at preserving destroyed stone decorations also began after the fire. Archaeologist Elin Dahlin was engaged by The Restoration Workshop to undertake this work, which resulted in scientific investigations of how the fire had altered the structure and mineralogy of the soapstones in question.[19] Dahlin was not only interested in preserving fire-damaged soapstones, she soon became very concerned about the weathering of the cathedral itself. Hence, she began cooperating with Swedish colleagues who had started a national research programme aimed at investigating the effects of air pollution on the cultural heritage.[20]

Thanks to Dahlin, an international exhibition called “Air attack” (*Luftangrep*) was brought to Trondheim in 1989.[21] From today's perspective this exhibition grossly exaggerated the effects of air pollution on the cathedral - just as “acid rain” had been used as the simple and “politically correct” explanation of most weathering phenomena elsewhere in Europe.[22] However, due to the public success of the exhibition, a foundation was laid for comprehensive, interdisciplinary research on the complex causes of weathering at the cathedral. The work of Lisbeth Alnæs (see above) and several additional scientific publications[23] - as well as this thesis are the results of the efforts in the late 1980s.

1.4 Concern about the “old fashioned” conservation philosophy

The restoration (and rebuilding) of the cathedral was completed in 1969, a century after the work began, although some new sculptures of the west front were put in place as recently as in 1984. The enormous socio-cultural changes which have taken place since the late 19th century are indeed reflected in the ideas which governed the work at the cathedral through the different periods. Such issues are described in chapter 3. However, in order to present the basic conservation philosophy which governs the present work, we have to take a look at recent developments which are unfortunately characterised by a lack of guidelines for practical conservation work.[24]

Rebuilding the central tower vs. historical values

Although The Restoration Workshop has been continuously involved in “re-restoration” of restored parts of the building after 1969, discussion about conservation philosophy has mainly related to the plans for building a new central tower. Since the present tower, designed by architect Chr. Christie, was finished at the turn of the century, the debate about its historical and aesthetic qualities has been ongoing. Until the 1970s it was the Norwegian parliament's view that the tower ought to be given a new, upper storey.[25]

The plans were shelved by the parliament in 1982 after discussions among professionals from all over the country.[26] Hans-Emil Lidén, a leading architectural historian, maintained in 1972 that the plans for rebuilding Christie's tower represented an “old fashioned” conservation philosophy - a philosophy closely related to the stylistic ideas of the last century. His aim was to introduce more objective, scientific views, implying that the cathedral should be looked upon as completed - and that all parts of the building should be treated with equal respect (cf. the principle of historical equivalence).[27]

Art historian Dag Myklebust reached similar conclusions to Lidén in 1984.[28] Myklebust based his view on the relativistic value system elaborated by the Austrian art historian Alois Riegl at the turn of the century,[29] and maintained that one ought to pay attention to the remaining historical value of the cathedral. Myklebust argued that a century of gigantic rebuilding operations had taken place at the expence of the cathedral's value as a historical document and that - as a matter of priority - conserving what was left should be considered more important than building a new central tower.

Although it is clear that these ideas stand in a certain opposition to views which underline that a cathedral is a “living building” and consequently should never be regarded as completed, my own view is very much the same as that of Myklebust. Hence, the fundamental philosophy governing the present work is that top priority should be given to the *historical value* of the cathedral. When planning conservation measures there are, however, many additional value dimensions to be considered (see also chapter 2). The fact that the cathedral constitutes an architectural “wholeness” (cf. *aesthetic value*) and is a living church (cf. *use value*) have to be mentioned - as well as the very significant *age value* (Riegl) which stresses that an old building ought to look old (cf. “graceful ageing”). As argued by the German architectural historian Georg Mörsch, it is today possible to suggest that the historical value and age value of Riegl should be reconciliated.[30] Personally - and on the basis of underlining the importance of preventive maintenance and repair - I believe Mörsch is right.

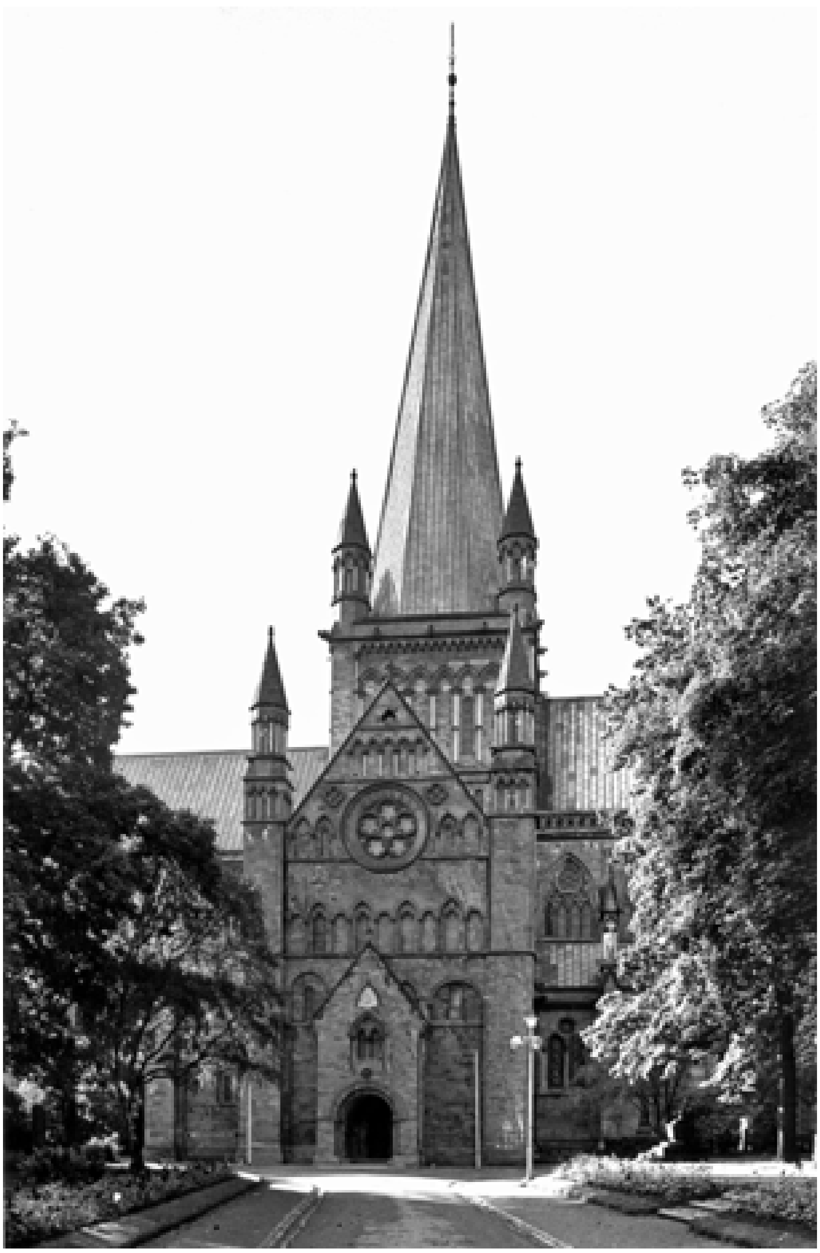


***Fig. 1.9**: The mixed Romanesque and Gothic transept and the Neogothic central tower, looking south (photo: ARW)*

“Creeping reconstruction” vs. historical values

Heated discussion about rebuilding the central tower has recently lost its topicality. Hence, the issue of how intervention in already restored parts of the cathedral ought to be carried out is currently of great interest. Since the rebuilding of the west towers finished in 1969, it seems that The Restoration Workshop has not been able to renew its philosophy and practical methods of conservation. It is probably fair to maintain that the “rebuilding tradition” has been very much alive until recently. The practical results of this tradition have been what William Murtagh describes as “creeping reconstruction”.[31]

“Creeping reconstruction” means large-scale, but - from a weathering and conservation perspective - rather unnecessary stone replacement of ashlars, mouldings and decorations. The octagon, choir, transept and nave have all been subjected to such stone replacement since 1969, meaning that the historical/age values have largely been disregarded.[32] This is not the view taken by the masons of The Restoration Workshop. They do not consider the majority of stone replacement unnecessary, but as an important measure undertaken because the church would otherwise have appeared quite unsightly or mouldings would have fallen down.

At a large cathedral it is extremely difficult to avoid significant stone replacement. Replacing strongly weathered, projecting elements about to fall down from elevated areas is only one example of a necessary and meaningful intervention, even if it disregards historical/age values. However, on the basis of maintaining that material and form constitute an inseparable unity, it could also be argued that stone replacement should be restricted to the parts that really are at risk, especially where other possibilities of securing or preserving seem unreasonable.

Stability and security vs. historical values

Stone replacement within particular zones at risk may sometimes be regarded as part of the security management at a large cathedral. However, security management involves several additional and often more important aspects: control of structural stability and protection against fire, theft and vandalism.[33]

Such issues have been given high priority after the rebuilding of the cathedral was finished in 1969. Securing the structure of the choir (1986) is one example. Others include installation of a modern deluge system (1985-86) as well as an electronic system for preventing theft and vandalism inside the church. Although the actual design of the different systems may be questioned, they are indeed of great importance for the maintenance of historical values.

1.5 Limitations of the work

Deterioration of stone buildings may be looked upon as a consequence of:[34]

- Structural instability - caused by the combined action of gravity and atmospheric agents.
- Material alteration (or weathering) caused by the action of atmospheric agents (including air pollution and indoor climate).
- Direct and indirect human action - for instance related to misguided or poor conservation measures and insufficient maintenance.

How these factors work together can be elucidated by the classical example in which structural instability cause the development of cracks, which again may result in water leaks leading to weathering of stonework. Attempts to prevent the leaks by insufficient methods or inappropriate materials may temporarily reduce the weathering rates, but once the leaks restart, the weathering may proceed even faster than before.

To the extent that they are important for understanding the condition of the cathedral, all the previously mentioned factors will be given due attention in the present work. However, the main point of interest is deterioration of masonry and stone decorations as a consequence of *weathering* as well as recommendations for conservation measures related to such objects.

A cathedral is like a small universe - *a structural environmental spatial system*, as stated by Bernard Feilden.[35] Within the complex system called Nidaros cathedral there are many more factors in addition to those described above. The system includes for instance a range of artistic works other than the architectural and decorative framework, such as stained glass windows, altars, paintings, tombstones - and organs. Nidaros has two large organs - a Steinmeyer organ as well as a recently restored Baroque organ. Managing and maintaining these works of art represents a major challenge for The Restoration Workshop. However, such issues are beyond the scope of this thesis.

1.6 A note on terminology

In textbooks and papers covering the field of historic monuments, value-laden terms like damage, deterioration, degradation, decay, destruction and weathering are frequently used without any further explanation.

According to standard English dictionaries,[36] these terms are defined as meaning “to make things worse, a status or act of decline to the negative”.[37] Weathering represents a special case, not only because it involves specific causes (the action of the atmosphere), but also due to the fact that it is much “weaker” (less value-laden) than other terms. In practice, weathering is also frequently used as a completely value-free term, or even as a term referring to pleasant changes.[38]

When considering only the material or physical context of monuments (not including socio-cultural and psychological dimensions), all the previous terms may be regarded as value free. There exist, however, much better value free terms - also frequently used within the field of monument conservation - namely alteration and transformation, which simply mean change or the act of making things different.

Fig. 1.10 *One of the most difficult problems of the cathedral is rapid weathering of medieval sculpture. The picture shows a Gothic mask on the octagon. Why is the weathering taking such a peculiar form? Only combined historical and scientific investigation may give the answer (photo: PS 1990).*

Since this thesis primarily deals with strongly value laden issues, *deterioration* is used as an overall term. It means the act or status of decline with regard to cultural values (historical, age, use, artistic etc) resulting from any cause whatsoever. As previously mentioned, my main point of interest is deterioration as a consequence of the actions of atmospheric agents. Thus, the term *weathering* is mostly used when describing and interpreting specific situations throughout this thesis.

Since the relationship between deterioration and weathering sometimes may be quite problematic, a further comment may prove useful: All monuments are in one way or another weathered, but it is only in particular situations that we perceive the weathering as a deterioration of cultural values.[39] Thus, as a matter of priority, the main focus should be set at understanding these situations because they ought to define where to concentrate conservation measures.

In many situations it may be extremely difficult to evaluate whether conservation should be undertaken or not. In other cases the severity or the rapid development of the weathering processes make it - in practice - clear that something has to be done in order to 1) prevent or 2) mitigate the evolution of weathering processes - or 3) strengthen the material assemblages against weathering.[40] This pragmatical perspective is maintained throughout this work.

There is often some confusion regarding the differences between the terms conservation and restoration. When using the term *restoration*, I usually mean the generally accepted, strict definition: to bring the building back to a former state or condition, most often the “original” one.[41] However, restoration has also been used as an overall term for any intervention relating to historic buildings, much like the term *conservation* is used today. As overall terms, restoration and conservation encompass interventions like maintenance, repair, preservation, replacement, reconstruction and sometimes even rebuilding and addition of new elements.[42]

Since *restoration* is traditionally used as an overall term at the Nidaros cathedral (cf. The *Restoration* Workshop of Nidaros Cathedral), I have in many cases decided to keep this definition of the term, but only when it seems appropriate.

1.7 Summary of objectives of this thesis

Following the general description of the cathedral's recent history, as well as the discussion about conservation philosophy, ***the main objective of this thesis is to describe and understand where, how, why and at what rate the weathering of the cathedral takes place, in order to evaluate the risks of loosing cultural value.***

This cannot be reached on the basis of studying the weathering alone. Phenomena related to structural instability, the history of conservation measures and any other relevant issue have to be brought in as well. Moreover, unless the historical dimension of weathering is included, it may be impossible to reach satisfactory answers as to how, why and at what rate the weathering progresses. The historical perspective may particularly help to correct many prejudices about the rate of observed weathering - an important aspect with regard to the second objective of this thesis, which is to ***recommend conservation measures aimed primarily at preventing or mitigating the evolution of weathering processes in order to maintain the cultural value - in particular the historical value and age value - of the cathedral.***

Few researchers have developed comprehensive methodologies for reaching the abovementioned aims. There are, moreover, few methodologies which properly account for the historical dimension of weathering. Therefore, the third objective is to ***develop a methodology adapted to achieve the aims of the study.*** Since the work may be regarded as a piece of applied, interdisciplinary science ***it does not aim to seriously question established theories of***

weathering processes. In fact, the aim is to use relevant, well-known theories in order to understand the particular weathering phenomena observed at the cathedral.

This study is yielding results which are specific to the Nidaros cathedral. It is also hoped that it will be of more general interest to those working with weathering and conservation of historic buildings. In this respect, it would have been interesting to compare Nidaros cathedral with other European cathedrals, not least with regard to weathering and evaluation of possible conservation measures. Although I have included observations made at many other churches and cathedrals during months of travelling, a comprehensive comparison was not possible within the practical and economic framework of this investigation.

1.8 Structure and content of this thesis

The title of this thesis, *The Stones of Nidaros*, was selected on the basis of a particular source of inspiration - Alois Kieslinger's *Die Steine von St. Stephan*, which is a comprehensive work on the history, materials, weathering and 1945-fire of the cathedral of St. Stephan, Vienna. Kieslinger, an Austrian geologist, published the work four years after the disastrous shelling of the cathedral during the the Second World War. Kieslinger worked with similar themes as I did, and although I have paid more attention to detailed descriptions of weathering phenomena, my organisation of the material is very much the same as in his book:

- ***Part I: How to study the weathering of a medieval cathedral?*** This section includes a discussion on methodology and particularly important theories of weathering processes.
- ***Part II: Nidaros cathedral and its environmental setting.*** This includes a general building history, a description of the cathedral's building construction and stability problems, as well as a summary of different materials and conservation methods used. It also includes a comprehensive review of the weather in Trondheim, the history of air pollution, as well as the indoor climate and characteristic exposure conditions of the cathedral - in summary a description of issues necessary for reaching an understanding of the weathering phenomena.
- ***Part III: Weathering of stone.*** This section contains a characterisation of typical weathering phenomena clearly related to the properties of the most important stone of the cathedral. Weathering phenomena in stone quarries are compared with phenomena observed at the cathedral and other buildings. Explanations are also based upon material analyses and tests, as well as on current theories of weathering processes.
- ***Part IV: Weathering of large sections of the cathedral.*** This describes the weathering situations or the zones at risk of very large areas of the building, namely the choir, the nave and the north transept. Overall recommendations for conservation measures are also included.
- ***Part V: The historical dimension of salt weathering.*** Salt weathering is clearly of major importance at the cathedral. Therefore, this section describes four smaller building sections as well as Romanesque decorations very much affected by salts. The studies focus on the historical development of salt systems.
- ***Part VI: Discussion, recommendations and conclusions.*** In this section the most significant weathering phenomena are summarised, discussed and explained in general terms, also on the basis of comparison with other relevant buildings. The study ends with recommendations for a possible conservation strategy.

Part I

How to study the weathering of a medieval cathedral ?

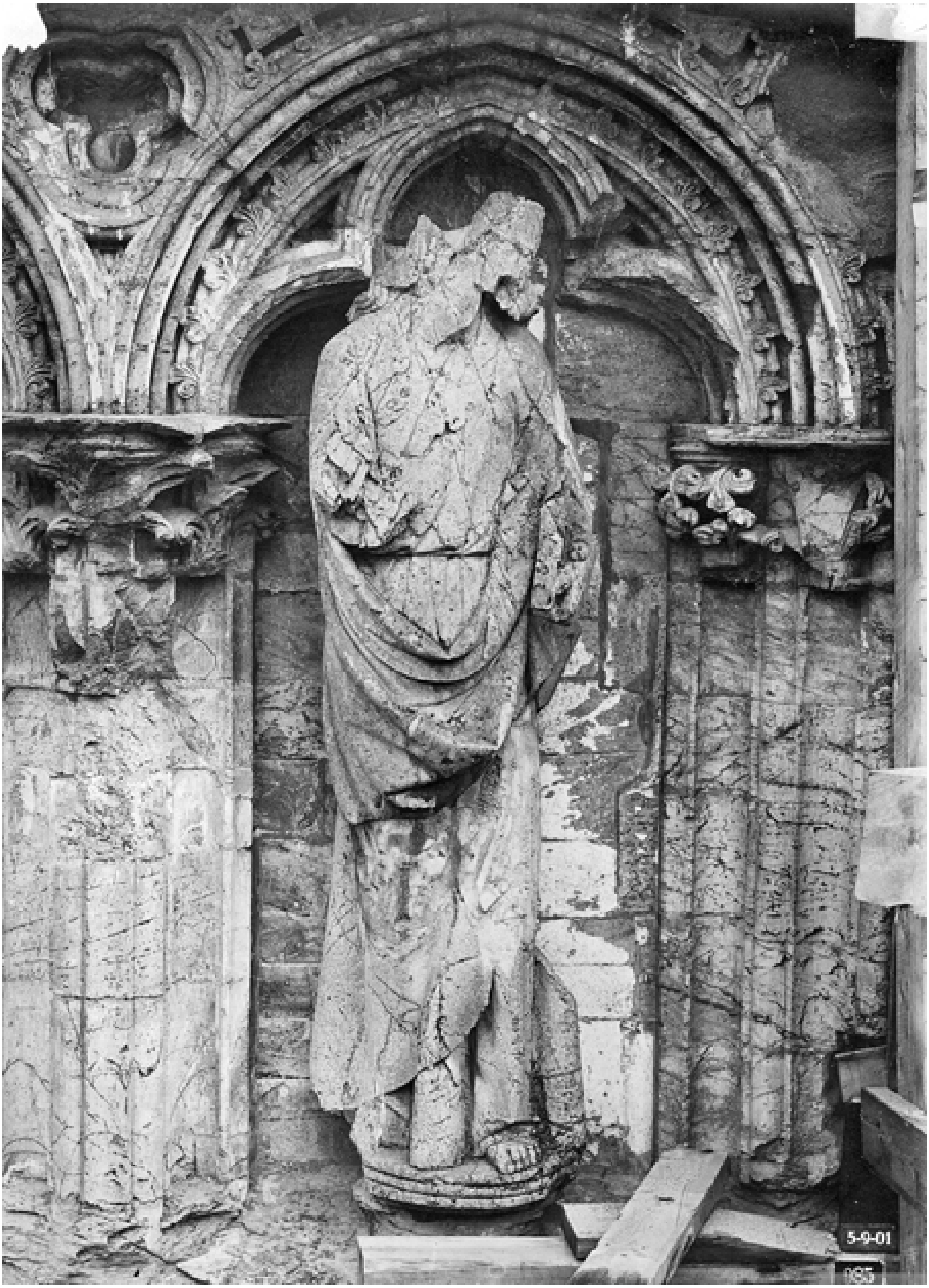


Fig. 2.1: *Medieval sculpture, probably Matthew the Apostle, of the west front of Nidaros Cathedral before the restoration began. Today in the museal collections (photo: ARW, no. 985).*

Chapter 2

Methodology for applied weathering studies

In a practical field such as conservation of historic stone buildings, long-term experience from field work is essential in order to make sound judgements with regard to causes of deterioration and recommendations for intervention. Nonetheless, and particularly since the causes of deterioration have become progressively complex and the number of conservation methods has drastically increased, there is a need for more profound methodological considerations. Currently there is also a wide range of sciences involved in conservation work, meaning that it is very difficult for those responsible for the condition of monuments to evaluate the relevance of different scientific contributions. Thus, in this chapter a proposal for a more general methodology for applied weathering studies will be given. The term applied means that the primary aim is to be able to work out a sound prognosis for the parts of the monument that really are at risk.

A methodology may be conceived as a normative system based on certain values, and including various guidelines, methods and techniques which, when used, are supposed to lead to the best possible understanding of the phenomena at hand.[1] In order to glimpse the complex field of conservation - and simultaneously the basic values that govern the present work, it is necessary to first address the general significance and problems of monuments today.

2.1 A note on the significance and problems of monuments

The modern conservation movement commenced with the European Romanticism and Neogothic trends of the 18th and 19th centuries.[2] From being an elite movement and closely related to the rise of the national state, conservation has during the last 200 years developed into a global phenomenon and - as many professionals maintain - a socio-cultural necessity.[3]

Value dimensions of the cultural heritage

Cultural heritage, once restricted to buildings and artefacts symbolising the great past of a nation, is today attributed universal human values (*Venice Charter* 1964) and ranges from single objects to the physical environment as a "whole". This means that all physical traces of human life are *potential* candidates for being included in the cultural heritage. The term *integrated conservation*, which for the European context was defined in the *Amsterdam Declaration* in 1975, states that conservation has to be seen as an integral part of the general planning and development policy, thus giving conservation of cultural heritage an importance equal to the protection of the natural environment. In some countries, as in Norway, conservation of cultural heritage is today politically governed by national environmental ministries.[4]

Although giving human beings different impulses and associations, cultural heritage and the natural environment are closely connected[5] - not least with regard to how mankind deals with material resources. This perspective is at present very important to maintain, considering the enormous technological and economic growth which has led to world wide ecological crisis,[6] as well as to extremely rapid and profound changes in our built environment, especially since the Second World War.

In this situation cultural heritage represents vital values worth protecting and caring for. From the perspective of cultural identity and historical continuity, conservation often means strengthening the feeling of belonging to a community and preventing the past becoming more foreign than it already is.[7] From the perspective of ecological awareness, protecting and including old buildings and infrastructures in modern development projects means taking seriously the need for fighting resource depletion and wasteful new-building.[8]

There are also other value dimensions of cultural heritage; one is the cultural diversity and richness it represents, helping us to increase tolerance and respect for humans with different lifestyles;[9] another is the importance it has for science and the humanities. Scientific and humanistic investigation help us understand historical events and processes - a value which some professionals regard as the most significant argument for conservation.[10]

This summary has dealt with what could be called “positive” values legitimating conservation of the cultural heritage. In practice these values might represent a false legitimisation of hidden political or other motives. Monuments used in the service of nationalism has been a well known phenomenon ever since the modern conservation movement started. As an example of another problematic motivating factor we could mention the “pure” economic one, e.g. related to aggressive market forces and the modern tourist industry.[11]

Contemporary conservation norms for old stone buildings

Arising from the background of, among other factors, the large number of monuments that were stylistically restored in the 19th century,[12] and the enormous reconstruction works after the Second World War,[13] people of our time have developed restrictive normative theories and guidelines for how to practically conserve old stone buildings.

A comprehensive set of guidelines can be found in the *Venice Charter* (1964), which stresses preservation in favour of restoration. The *Venice Charter* was developed along the lines of the tradition represented by restrictive preservationists like John Ruskin, William Morris, Alois Riegl and Max Dvoràk.[14] As long as the structural integrity of the building is secured, the statement "do as little as possible, but undertake regular maintenance with traditional crafts and materials", neatly sums up the overriding norm in contemporary conservation philosophy in Europe.[15] Moreover, and with regard to the principle of "reversibility", an important aim is that interventions should be undertaken as relatively small, corrigible measures, and not encompass the whole monument.[16]

It is important to remember that the use of traditional crafts and materials is considered a value in itself today (an aim, not only a means). To use modern technology should therefore be regarded as an exception rather than the rule.[17] Another definition of contemporary conservation is "the continuos management of change in order to reduce the rate of decay".[18]

Fig. 2.2: *Extremities of contemporary conservation. Left (opposite page): Rebuilding of Frauenkirche in Dresden 50 years after it was destroyed by allied bombing in the Second World War (photo: PS 1996). Right (this page): Leaves that clog up a downpipe at St. Mary's church in Bergen and cause water infiltration in a valuable Romanesque portal just below (photo: PS 1993)*

The generally restrictive conservation norms have been further elaborated for practical use in books like *Conservation of Historic Buildings* by Bernard Feilden[19] and in *Management Guidelines for World Cultural Heritage Sites*.[20] The latter book includes comments on the *World Heritage Convention*. Further comments on this convention - and with particular reference to the difficulty of maintaining *universal* conservation norms versus the application of *local* conservation traditions can be found in proceedings from the *Conference on authenticity in relation to the World Heritage Convention*.[21]

Why involve science in conservation ?

Since modern conservation of historic buildings commenced - and coincided with the scientific revolution - 200 years ago, natural science and technology, as well as materials, products and instruments based on technological innovations have been important - even vital - companions to the conservation movement. Although present conservation doctrines strongly recommend using traditional knowledge and craft, modern conservation has become unthinkable without highly specialised science and technology.[22]

The most obvious reason for this development is that within western culture science is generally considered one of the most reliable ways of obtaining knowledge. Another reason is that most monuments are severely threatened by the socio-cultural development itself. Man-made factors that threaten the values we attribute to monuments, when excluding wars and other major disasters (e.g. fire), are “hard” rehabilitation and over-restoration, unsatisfactory installation of modern equipment in order to satisfy present usage demands, the “historism” of our time combined with an aggressive tourist industry which increases physical wear and tear, a changing environment with air-pollution as a main ingredient, the fact that an adapted craft-tradition was abandoned by the end of the last century - being replaced by modern technological materials as well as technicians and the modern building industry.[23] The past and present use of numerous chemicals in conservation is, moreover, a factor that might still be underestimated as a main cause of many weathering phenomena.[24] The same can be said about the mere involvement of science and technology when people from such disciplines give unsatisfactory, incomprehensible or otherwise problematic advice for practical conservation work.[25] In addition, poor maintenance of monuments has indeed “always” been a problem.

Studying the record above, the actions of nature might seem of secondary importance with regard to weathering and deterioration. Yet one must remember that the actions of man have to be considered as initial factors that nature nevertheless reacts with one way or another. Generally, when acting within the limits that nature sets, weathering will be slow, when not - monuments might deteriorate faster than we appreciate.

With so many threatening factors, it becomes clear that architects, conservators, craftspeople and other practitioners traditionally involved in conservation, cannot solve the present diverse and complex problems alone. The above record can thus be regarded as justifying the involvement of a self-critical and responsible science in conservation.[26]

Science and applied weathering studies

Science and technology are currently involved in conservation of monuments in basically four ways:[27]

- investigations of monuments in order to determine the *nature, composition, manufacturing, stratigraphy and age of their material assemblages and structures*;
- for the purpose of developing *modern conservation systems* (products, materials), instruments and documentation techniques;

- for the purpose of *basic research* in for instance weathering mechanisms and structural behaviour of old buildings;
- for the purpose of *applied investigations* (case-studies) aiming at understanding the actual and local causes of weathering and deterioration, and giving recommendations for conservation measures. Applied studies may give valuable contributions and feed-back on basic research.

Within most fields various methods have been developed in order to make as safe and objective analyses, statements and conclusions as possible.[28] It comes, however, as no surprise that very few professionals have been occupied by profound methodological considerations with regard to *applied investigations*. This may be regarded as the most difficult field because it confronts the researcher with value-laden issues ("is this damage or not?") and an endless stream of observations and information ranging from historical interpretations via perception of the current situation to chemical formula.

Methodological considerations are often restricted to underlining the importance of undertaking historical investigations and a proper diagnosis of damage (often by stressing laboratory experiments) before conservation interventions (therapy) commence. *Integrale Objekterfassung*, an interdisciplinary method used in Germany has also been popular lately.[29] It aims at bringing all relevant parties and sciences together in order to make as safe a diagnosis of particular objects as possible. The trouble is that until recently contributions from various scientific fields were not properly related to the actual context, often making it very difficult to understand the real risks at hand. In effect, investigations have produced an enormous amount of very interesting scientific results, obtained at high costs with modern instruments and techniques, but they are rarely applicable in practice.

The Swiss geologist and conservation scientist Andreas Arnold seems to have been rather provocated by this development.[30] According to my knowledge, he is the only European scientist who has tried to meet the fundamental challenge of trying to turn the tide, simultaneously acting in a constructive way by developing comprehensive methodological guidelines for applied, scientific investigations of monuments.

Since the main objective of this thesis is applied, it is natural that the thoughts of Arnold will be given a broad presentation. Additional suggestions will be derived from particular case studies undertaken by well known scientists.

2.2 Andreas Arnold on applied weathering studies

The responsibilities of scientists and their ways of working within conservation are major issues treated by Andreas Arnold in his writings.[31] The following studies these issues, as well as his general normative approach to science in conservation.

Interdisciplinary research

Arnold's normative basis can be elucidated by quoting his definition of conservation from a scientific point of view:

> "Preservation of monuments" means: To recognise them as monuments, to establish their state of conservation and decay, to understand their risks of decay, and then to act in order to let them survive authentically as long as possible.[32]

This definition is valid when undertaking applied weathering studies. The terms "preservation" and "authentically"[33] mean that the objective of such studies is to preserve the monuments in their existing state, or better: to reduce the rate of weathering by eliminating or hindering its causes.

There is a logical structure of the definition. First the monuments must be perceived and understood as objects with values that transcend human rationality, then the state of conservation and weathering must be established by interdisciplinary efforts. The task of the scientist is to undertake investigations that can lead to an understanding of the weathering as well as to an assessment of the risks that threaten the monument in the future. Moreover, the scientist must be able to communicate her findings in a way that gives plausible explanations of the causes. Finally, it is the task of the practitioners (architects, restorers, conservators etc.) to react to the causes of weathering - not the symptoms. In practice it is certainly difficult to follow the logical structure of the definition. Arnold stresses this point by showing examples of how the interdisciplinary work between scientists, humanists and practitioners might turn out in reality.[34]

Presumably, Arnold has worked out the definition in reaction to the single minded way he believes science is often involved in modern conservation. He maintains that the main efforts of science and technology "are focused on protective treatment of the materials on monuments"[35] and that scientists are not so interested in understanding the "*evolution of real decay processes* on the objects".[36] This may cause misguided conservation interventions resulting in serious failures.

As can be seen, the interdisciplinary research method has much in common with investigations leading to the "standard" condition report which is always a prerequisite before practical conservation measures commence. Such, often relatively simple reports are normally worked out by architects and conservators. In contrast to the normal ways of working, in which scientists are consulted as "experts" only with regard to single issues, for instance analysis of material properties and investigations of very valuable murals, sculptures etc., Arnold demands that the scientist should take a responsible part in the overall work on assessing the condition and finding the causes of weathering. However, this demands not only a readiness for involvement and a critical stand against technological manipulation, but also that the scientist has particular skills and experience.[37]

Analytical vs. phenomenological ways of working

The skills and experience of scientists - and how scientists actually work - are main themes discussed by Arnold. These themes are of vital importance because practitioners might have the tendency to assume that any kind of scientific investigation will be helpful for finding the causes of weathering. Arnold maintains that in particular chemists and physicists are working in an *analytical* way, which means that they are trying to logically reduce weathering phenomena to mathematically formulated, strongly simplified natural laws of only little practical value.[38]

It is tempting to characterise this way of undertaking research in the following way: The scientists are stuck in the Newtonian paradigm. They are highly specialised scientists, typically doing most of their work in laboratories and often having limited knowledge about the general history and theory of conservation. In addition, they tend to reduce deterioration phenomena to a physico-chemical context, not considering that the causes in many cases may only be found in the combination of physico-chemical, historical and socio-cultural contexts.

Even if scientists working in an analytical way are needed in conservation (e.g. complex material analyses and measurements), Arnold proposes *broad generalism* as a reaction against single minded analytical ways of working. He calls such generalists *phenomenologists*,[39] scientists that might be able to bridge the possible gap that exists between practitioners and scientists working in an analytical way. The abilities of a phenomenologist may be elucidated by mentioning the different fields she should have some insight into. These include: material properties, historical craft and materials, contemporary conservation systems, natural weathering, environmental and climatic processes, history of conservation and contemporary conservation ideology. In summary, a generalist should be able to use knowledge from different fields in order to fulfil the objective of understanding and explaining real weathering processes and their evolution on the monuments.

Typically, a phenomenologist prefers research on the monuments rather than laboratory work. Perhaps phenomenologically oriented scientists have realised that the Newtonian image of “perfect” natural laws does not apply to the weathering of monuments in practice. The phenomenologists rather belong to the ecological paradigm of our time - seeking all relevant relations in order to understand the causes and directions of change.[40]

The value of traditional craft

Arnold respects traditional crafts for two reasons. Firstly, he considers traditional workmanship and materials as well adapted to solve weathering problems of monuments. A general maxim followed by Arnold is to *stay in the system.* That is to use the traditional materials in all the cases where we know by experience that they are working well. This maxim is followed by another one, namely that the responsibility of proving the adaptability of new materials lays in the hands of the people who want to apply them.[41]

Secondly, Arnold sees the practical *experience* of many craftsmen as a kind of a “model” for scientists. Rather than denouncing craft as “subjective”, the scientist should try to see that craft really represents practical inter-subjectivity and that most things we know about nature and monuments are in fact based on experience rather than deductive, scientific conclusions.[42]

We should add that most crafts in our technological world are not traditional anymore - but heavily influenced by the modern building and construction industries. In many cases this might of course make it difficult to really trust the “traditional” craft.[43] The “deterioration” of traditional crafts throughout our century seems in fact greater than the deterioration of the monuments themselves.

2.3 A proposal for methodology guidelines

A reasonable point of departure for discussing how to study the weathering of *old stone buildings* is the perception of damage (or deterioration forms).[44] Ranging from major cracks and crumbling of whole façades to the smallest signs of disintegration and colour change, damage is not easily observed and described. Moreover, the perception of damage is extremely value-laden, implying that people with different backgrounds or within different traditions tend to look very differently upon what damage actually is.[45] In the following the term *weathering form* is mostly used, and may be conceived as signs of material alteration apparently related to the influence of atmospheric agents. The forms may be categorised as particular *weathering types*, like cracking, flaking and granular disintegration.

Using the perception of weathering forms as a starting point, the discussion below touches on the following issues:

- Weathering as a context dependent phenomenon
- Weathering situations
- Weathering as an evolution of processes
- The monument's weathering history
- Predicting future weathering

Derived from the writings of Arnold, and further elaborated below, the issues may be regarded as important ingredients of a general methodology. However, an equally important issue - not considered by Arnold - is the structural behaviour of large masonry buildings. Since to a considerable extent they determine the evolution of weathering phenomena, structural aspects will also be given a brief introduction.

Weathering as a context dependent phenomenon

Weathering forms develop - by definition - as a result of atmospheric agents affecting the material assemblages and structures of monuments.[46] The atmospheric agents may be solely natural (sun, wind, precipitation etc.) or strongly influenced by the actions of man (for instance air pollution, rising damp and indoor climate).

The mechanisms by which the atmospheric agents work are theoretically categorised as physical (or mechanical), chemical and biological (or biogenic) - but it is known that one cannot easily distinguish between these three categories in real contexts. Therefore, when talking about weathering, we often use terms like salt weathering, frost weathering, hygric dilatation, dissolution of carbonate etc. - processes which include simple or complex combinations of the three categories of mechanisms mentioned above, and which seem to have been given names according to traditional theories of the most significant mechanisms involved (for instance pressure developed due to crystallising salts and freezing water).

The study of weathering mechanisms and processes may be undertaken as experiments under controlled conditions in laboratories, completely independent of the real context - which in our case is the monument itself. However, in the real context, we are confronted with atmospheric agents which can only rarely be controlled. We are, moreover, confronted not only with single materials with known properties, but with smaller or larger structures normally consisting of diverse material assemblages having complex histories of production and application. The buildings also have a history, usually a long history of structural problems, known and unknown human interventions and atmospheric influences as well as the effects of catastrophic events (e.g. hurricanes, earthquakes and fires).

Direct and indirect human interventions range from deliberate destruction to alterations, additions, conservation measures and changes in the physical environment. The histories of monuments in a specific region or country may of course show several similarities, but in principle each monument is unique. Moreover, *all human intervention - direct and indirect - may potentially change the course of any weathering process* taking place on the monument, making it clear how important it is to understand the history of the monument before trying to consistently interpret why it is weathering.

As can be seen, the real monument context consists in fact of the *two equally important cultural and natural dimensions* - including their histories. These dimensions are usually so intimately connected that it often becomes meaningless to try and isolate either of them. Hence, the methodological maxim “everything hangs together”, suggested by numerous ecophilosophers, can be used as a guide when undertaking applied investigations.[47] With this maxim in mind, we also understand that meaningful investigation of weathering has to be related to the specific context under study - with regard to both the natural and cultural dimension of the actual monument.

Andreas Arnold states: “Weathering occurs on certain places, at certain times, under distinct conditions, with a certain (rate) velocity and with a certain effect.”[48]

Structural aspects of large masonry buildings

It may be meaningless to study the weathering of a building when signs of large-scale structural faults are not considered. Firstly, structural problems may cause severe safety risks or - in the worst case - collapse of the building. Secondly, many weathering phenomena may be dependent on the structural behaviour of the building, for instance when water leakage occurs as a result of masonry cracks.

Structural behaviour of large masonry buildings erected before the scientific revolution is often difficult to investigate and predict. This is because their construction relied on practical and empirical design experiences rather than on mathematical engineering principles, according to which most modern buildings are constructed. Hence, the structural behaviour of old buildings has become a special field of research, involving engineers as well as architectural historians.[49]

Since the main objective of this thesis is related to weathering and not to structural behaviour, only brief mention is made of some general aspects of the nature and causes of structural failure - in particular with regard to Romanesque and Gothic cathedrals which are the types of buildings relevant to this work. How to practically investigate structural problems can be found in relevant text books.[50]

Any building is “alive”, adjusting and readjusting itself according to the loads with which it is interacting. The *dead loads* (weight) of the building is obviously a major factor to consider, but the “external forces” or the *dynamic loads* of earthquakes, traffic (vibrations) and changes in temperature and moisture may be just as important. Also *active loads* such as the weight of people, furniture and goods may play major roles in some circumstances.[51]

The risk of structural failure is dependent on how the building is able to balance all these loads. Again this is dependent on the soils on which the building rests, its construction (design) and building materials. Put simply, the building may be regarded as being out of balance when failure - be it cracking, crushing, buckling, inclination of walls (or collapse) - occurs. However, due to the fact that most masonry buildings have the ability to readjust themselves when failure occurs at one location (indeterminate structures), signs of major cracks may not necessarily represent a great risk. When cracks open steadily over a prolonged period of time, there is definite cause for concern.[52]

Examples of frequent causes of failure essentially attributable to soils, structure/design and materials are:[53]

- Differential or uneven settlement of the building. This may be caused by varying soil properties, major ground water changes, great differences in dead loads of adjacent building parts etc. A special case of differential settlement is related to addition of heavy towers long after the rest of the building was essentially finished.
- Too fragile piers, buttresses etc. unable to balance dead and dynamic loads of roofs, vaults and winds over prolonged periods of time.
- The use of hard and inelastic Portland cement mortars incompatible with the original “weak” materials (lime mortar and soft stone) of old masonry buildings. Such mortars may not be able to follow the “natural” movements of the building, consequently resulting in varying degrees of cracking.

Regarding Romanesque masonry buildings, it should be noted that they are usually rather bold and massive, almost “hollowed out”. Consequently, the diverse loads are very much dispersed along walls, often resulting in minor risks of structural failure. Differential settlement may nonetheless be a major issue of concern in such buildings.[54]

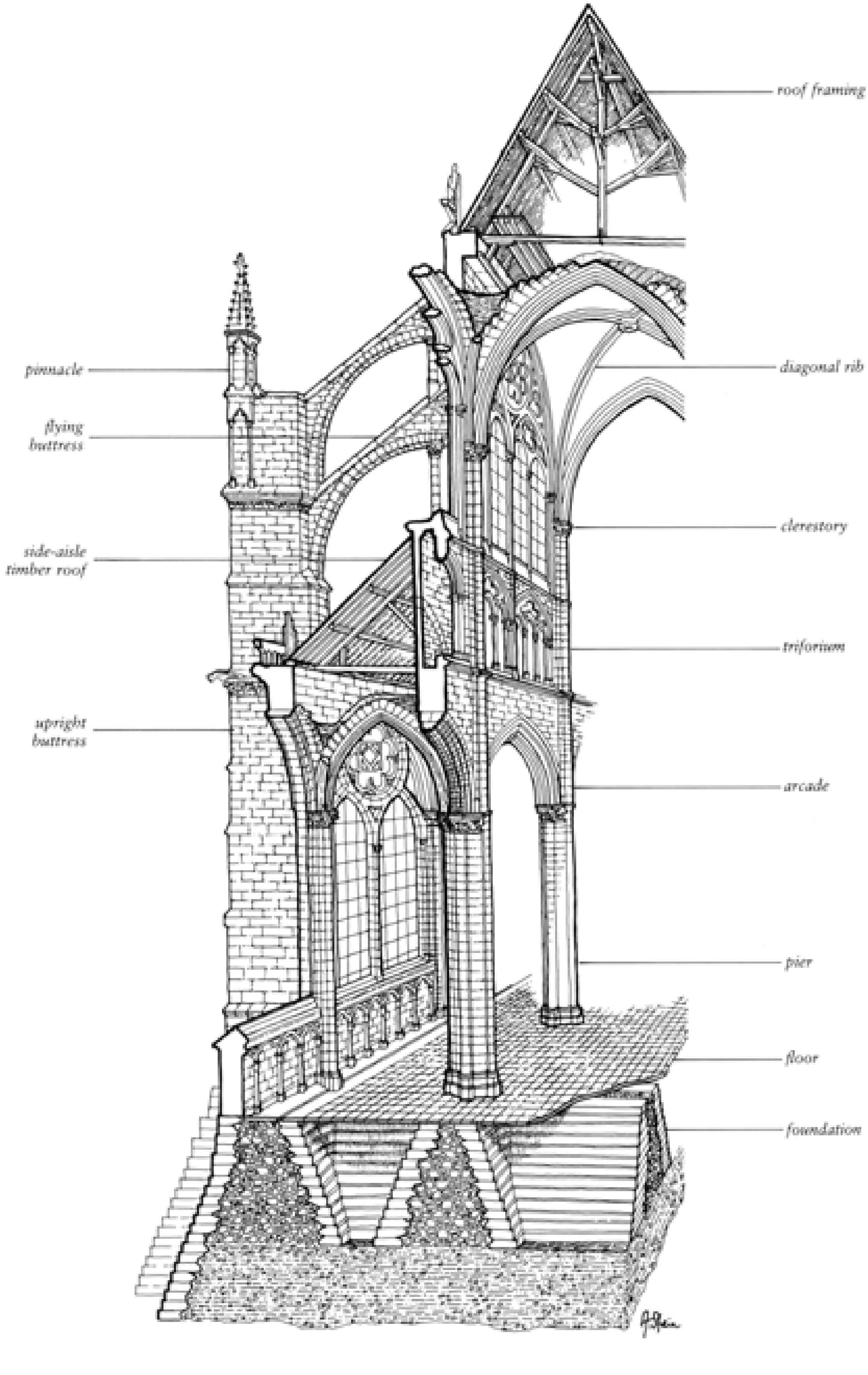


Fig. 2.3: *Amiens cathedral, France, showing typical Gothic design. Redrawn in Mark (ed.)(1993), after Violett-le-Duc and Durand.*

Gothic buildings (cathedrals) represent a very different world from a structural point of view. Being a novelty in the Middle Ages and designed essentially in order to meet the need for light and elevation, the forces from roofs and vaults were concentrated into frames of stone, usually with the help of the flying buttress - probably the greatest innovation of the Gothic builders. Hence, a great risk of structural problems arising from supporting piers and buttresses too weak for the loads were simultaneously introduced.[55]

It should be pointed out that most medieval masonry buildings are neither completely Romanesque, nor completely Gothic, but usually a mixture of styles. Moreover, such buildings generally have a long and complicated history of additions, alterations, rebuilding and restoration - all of which may have changed the structural behaviour throughout time. It is therefore essential to try to view the present structural condition in the light of the historical context when aiming at a real understanding of the risks of structural failure.[56]

How to grasp a weathering situation?

Having established that weathering is a context dependent phenomenon, and that structural aspects must be taken into account, it seems reasonable to try and relate the perceived weathering forms (damage) to the weathering *situation* in which they occur. Andreas Arnold has “defined” the weathering (damage) situation like this:

> Man kann Schadensituation wohl nicht allgemein und einfach definieren. Es sind Verwitterungsbilder mit einzelnen oder mehreren, kombinierten Verwitterungsformen, die aufgrund ihres Aussehens, ihrer Lage (am Bauwerk), ihrer Exposit-ion und anderer Erscheinungen Zusam-menhänge erkennen lassen zu bestimmten Ursachen und Arten des Verwitterungs-geschehens (etwa analog zu einem Krankheitsbild, in der Heilkunde).[57]

Examples of weathering situations are the zone of rising damp, recognisable leaks, run-off courses along façades, areas around

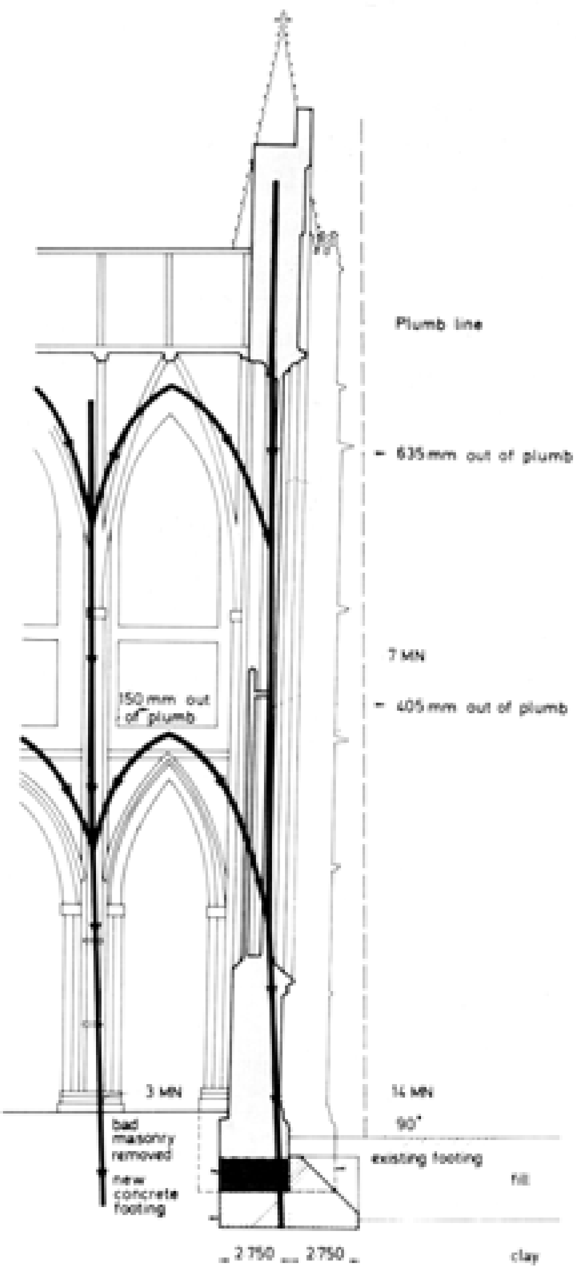


Fig. 2.4: *Diagram of thrusts and movements, east end, York Minster, England. The diagram shows the line of thrust dangerously close to the outside face of the wall and indicates eccentric loading on the foundations. New reinforced concrete foundations were designed to give concentric loading. Diagram from Feilden (1982), after Ove Arup & Partners.*

defective gutters and downpipes, and crumbling stonework on severely exposed elements (e.g. copings). Although such situations may involve very complex weathering processes, the basic causes are often relatively simple and easily perceived, especially if the investigator has experience from analogous situations.

Other weathering situations are much more complex and it may take a lot of experience, measurements and analyses - as well as luck and intuition in order to understand complex situations.[58]

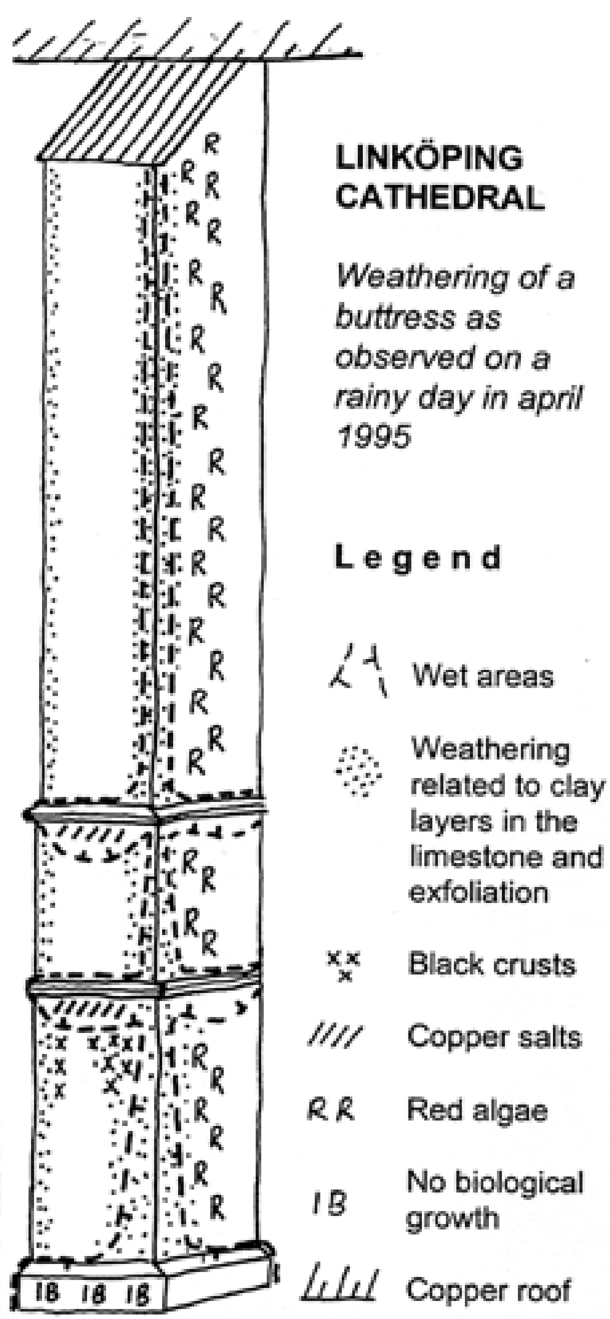
The central elements of a weathering situation are the *exposure conditions*. An exposure condition can be understood as how atmospheric agents locally affect specific parts of the monument. Thus, it is vital to understand the relationship between the local weather and climate, and the orientation and design of the monument. Such relationships may be categorised into four basic types:[59]

- Areas directly affected by precipitation (exposed areas)
- Areas protected from precipitation (sheltered areas)
- Areas affected by run-off along the surface
- Areas affected by water penetrating the structures

Fig. 2.5*: Exposure conditions at Linköping cathedral, Sweden, in the spring of 1995. Above: After several small showers, the corners of the buttresses, as well as projecting string courses were thoroughly soaked (photo: PS). Right (next page): Crumbling of the limestone buttresses takes place mainly on their most exposed parts. The string courses were replaced by hard granite in the last century (diagram: PS).*

This scheme is very simplified. In reality intermediate forms and combinations are the rule rather than the exception. In her thesis on the weathering of *Berner Sandstein* in Berne (Switzerland), Christine Bläuer described eight typical exposure conditions on which the weathering forms of the stone are strongly dependent.[60]

When perceiving a weathering situation we simultaneously observe a momentary condition in the evolution of weathering processes. According to the various influences, the processes evolve at different rates - and they may even reach static states during which the resulting damage ceases further development.[61]



Weathering as an evolution of processes

Weathering processes do not evolve along prescribed linear or exponential functions, but according to atmospheric and other *events* giving rise to complex interactions between the monument and its environment. Mostly with regard to the *natural dimension* of monuments, Andreas Arnold maintains that processes are perceived as individual events or as a continuous progression (rapid sequen-ces of events). He has given the following examples of typical *singular* events and *repeated* events:[62]

- Singular events, often catastrophic (fire due to lightning, extreme events of condensation).
- Repeated accidental events (rain falls, floods, condensation).
- Repeated periodic events - daily cycles (light, frost-dew, thermal expansion, some salt crystallisation).
- Repeated periodic events - weekly cycles (weekend heating in churches).
- Repeated periodic events - seasonal cycles (frost, indoor heating, rainy periods, dry periods)

Several additional examples could be given, for instance connected with daily, weekly and seasonal cycles in emission of air pollutants. Air pollution, as well as indoor heating, however, also belongs to the *cultural dimension* of the monuments. These are also some of the few man-made factors that occur as repeated events. Other events belonging to the cultural dimension, ranging from deliberate destruction to conservation interventions, should be regarded as singular.

In this connection it is important to note that conservation authorities strongly recommend that interventions like maintenance should be carried out on a *periodic* basis.

The rates by which the weathering processes evolve are strongly dependent on the frequency of the events in question. While a disastrous fire caused by lightning may occur once or twice in the life-time of an old building, certain types of salt damage may sometimes take place on almost a daily basis according to differences in relative humidity between day and night.

It is very important to be aware of the fact that the frequencies of many events - and thereby the rates of weathering - cannot be reliably predicted.[63] Moreover, many weathering processes are only active when two or more events coincide, making it even more difficult to predict the rate. An example of this is weathering due to frost. A damaging frost event may only take place when the (susceptible) materials in question have a high (internal) moisture level and when cycles of freeze/thaw occur simultaneously.[64] The process is also complicated by the presence of soluble salts.[65]

Even if it is difficult or impossible to scientifically predict the future path and rate of weathering, it is possible to obtain reasonable indications on the basis of experience and comparison with analogous situations. The simple example is that weathering usually proceeds rapidly as long as an active leak is not repaired. Moreover, many situations involving rising damp develop rather slowly and crusts and lichens on certain stone types may be stable over decades. These examples do not change the fact that in principle it is impossible to state with certainty how complex weathering processes develop. For example, note that even when masses of Portland cement are injected into walls and giving extreme damages immediately afterwards, the situation may stabilise quite quickly - in contrast to what would have been theoretically reasonable to predict.[66]

Since weathering involves complex processes developing at rates that are hard to predict, there are few methods other than to regularly observe what happens in order to make fair predictions about their evolution. In addition, there is a much overlooked source of information in every single case: the historical records.

Interpretation of the monument's weathering history

It is, indeed, impossible to understand many weathering situations without reference to historical events.[67] Which historical perspective is relevant for weathering research? Building history, architectural history, art history, restoration history, environmental history, urban development history, history of air pollution, history of climatic change? It is perhaps correct to state that these histories are not specifically relevant in themselves. Weathering research deals with the monument's *weathering history*, a history that has to be reconstructed and interpreted on the basis of - among many other issues - the histories above.

Reconstructing a weathering history - *a history of the evolution of a weathering situation* - is just as complex and time-consuming as reconstructing any other. This is important to bear in mind because people have a tendency to look upon weathering without considering its historical dimension. Just as an architectural historian has to reconstruct the stylistic development of a building after having investigated and described the present state, a weathering researcher has to do the same with regard to how the weathering of the building has evolved.

The historical sources used by architectural historians and building researchers are also of major importance for weathering research, only a different perspective is used when evaluating the relevance of and interpreting the sources. The sources may be books and articles, restoration reports, photographs, drawings and plans, account books and other relevant published and unpublished material. Such documents can be used for comparing consecutive, former states of preservation with the present condition. This may help not only to estimate weathering rates, but also to locate specific problematic areas of the building that may have been overlooked when investigating the present weathering situations.

How to find and select relevant source material is often a major problem. In a European context and with regard to medieval buildings, it is generally possible to suggest that understanding the significance of the great 19th and 20th century restorations is of prime importance. Not only were the design of many buildings altered - the monuments were also subjected to a great range of modern, technological materials which often changed former courses of weathering completely. When dealing with monuments of antiquity (e.g. ancient Egypt), the task of selecting relevant source material may be completely different. It may for instance be of great importance to understand the significance of how and during which periods the monuments were buried in desert sand.[68]

Comparing consecutive states of weathering and conservation is not the same as interpreting *why* weathering has evolved. In order to undertake such interpretations, it is necessary to gain information about historical design and materials, a reasonable understanding of the historical environment, climate/weather and relevant theories on weathering. Hence, there is a need to reconstruct and interpret the histories of atmospheric influence on the monuments in the light of the relevant theories. Knowing that there is no single, written history of atmospheric phenomena, it is necessary to combine information from several sources, e.g. the history of air pollution, urban development and other types of environmental change.

***Fig 2.6**: Cathedral of St. Vitus in Prague. Note that the entire nave is a modern - or a Neogothic - construction. See Kostílková (1994)(photo: PS 1996).*

Predictions of future weathering

Having established the history, including (if possible) the rate of change, of a specific weathering situation, there may be a sound basis for predicting the future development of the situation. However, as stated above, it is difficult or often impossible to make safe predictions about future weathering rates on the basis of history and theory alone. Thus, in such situations, it is necessary to follow up and periodically observe what actually happens in the course of reasonable period of time.[69]

Observations can be made solely visually, but it is often much more reliable to supplement with photos, video and periodic measurements of weathered material whenever possible. The latter method is in particular applicable to weathering taking place indoors (weighing fallen material). It is essential to try and relate observed weathering to the influence of atmospheric events. This is particularly true with regard to salt weathering which often proceeds rapidly in clearly defined periods of condensation, drying out of walls etc., and which may be completely inactive when the relative humidity and temperature outwith specific levels.

Observations and predictions regarding to the evolution of weathering processes within a weathering situation can be conceived as part of a *risk assessment* before planning relevant interventions. Knowing that atmospheric events govern the evolution of the processes, it is the risks of events such as lightning, condensation, storms, rainfall and snow (leaks, run-off, frost) that are important. Hence, when the *influence* of such events can be controlled, the field of preventive conservation measures is entered.

An assessment of the future risks relating to a specific weathering situation certainly involves structural aspects and the possible actions of man - in this case especially related to various conservation measures. This topic will be a main theme in the case studies of the Nidaros cathedral later in this thesis.

Measurements, material analyses and experiments

Measurements, material analyses and scientific experiments may be helpful, often necessary, during all stages of investigation and interpretation of weathering processes, but only if properly selected and conducted with due reference to the actual context.

There are a large number of destructive, micro-destructive and non-destructive scientific methods and techniques, often involving advanced instruments, available for making diverse measurements and analyses. Indeed, there are so many that in this thesis it is only possible to concentrate on the actual fields within which it may be important to carry out measurements and analyses. The actual, rather simple and inexpensive methods used in the present thesis are described in chapter 2.7.

It should be noted that much necessary information is readily available from existing sources (for instance information on climate, air pollution and stone properties), implying that within a weathering/conservation project it is wise to check them all out before designing new programmes. Common types of measurements and analyses include those which are:

- *Related to structural behaviour:*[70] Soil properties • settlement • crack development • inclination of walls
- *Related to exposure conditions:*[71] Local climate (all relevant types of weather phenomena) • sea salts/aerosols • local air pollution • long-range air pollution (“acid rain”) • deposition of air pollutants and other aerosols
- *Related to indoor climate and thermal/hygric behaviour of a whole building:*[72] Air temperatures • relative humidity • wall (surface) temperatures • moisture within walls • air circulation/ventilation

- *Related to materials (inorganic, esp. stone and mortar):*[73] Petrographic, mineralogical and chemical properties • mechanical properties (strengths) • thermal properties • hygric properties, including pore system
- *Related to specific weathering situations:*[74] Soluble salts • biological growth • "weathering profiles" • "Non-Destructive Tests" (NDT)
- *Common types of laboratory experiments include:*[75] Standard durability tests of materials • specially designed weathering experiments

Note that laboratory experiments may be very important for the understanding of specific weathering processes. They are, however, rather worthless if the results are not confirmed or compared with in-situ observations.[76]

Making priorities and recommending interventions

Having established a thorough diagnosis of the weathering by means of:

- understanding the structural behaviour,
- grasping the weathering situation,
- direct observations over a period of time,
- interpretation of the weathering history,
- understanding the evolution of the weathering processes,
- measurements, material analyses and experiments, and
- general experience from analogous situations,

there is still a vital question to be answered before conservation interventions may commence: How is the prognosis to be related to the attributed values of the monument? It is quite clear that preferring the age value or the historical value may justify completely different interventions than would be the case if artistic values (for instance "architectural wholeness") are preferred. Moreover, an important, but frequently forgotten measure is to refrain from undertaking interventions!

Although every specific situation ought to be treated individually, it is possible to maintain that conservation takes place on the basis of sound judgement in the context defined by:

- Value preferences
- The actual state of the monument
- Prognosis of the future weathering/deterioration
- Available conservation methods

Recalling that contemporary conservation norms underline the importance of undertaking as little as possible (and regular maintenance), and that maintaining age/historical values are considered of great importance in the present work, the suggestion is that principles of a conservation strategy should include - in preferred order:

- Prevent further weathering
- Mitigate the evolution of the weathering processes
- Strengthen the monument/materials against weathering.

The methodology suggested in this chapter will be of help for making reasonable *priorities* with regard to where and by what means interventions should be undertaken. In practice, it is clear that structural instability and zones weathering rapidly deserve special attention, while other parts of the monument may be left for further observation of how the situation develops. However, such considerations may be completely insufficient when issues related to deterioration of moveable works of art and how the monument is to be used occur. According to my experience, the chance of acting wisely in such a complex, practical field depends on - as Aristotle maintained - our readiness to take decisions *pros ton kairon* - as the occasion requires.[77]

It should also be remembered that acting wisely in a practical field like conservation means that *it is not necessary to investigate everything by scientific methods*. Many monuments can and should still be investigated and treated by using experience and traditional craft if available.[78]

2.4 Sources of inspiration I: Swiss Molasse sandstone

Many case studies undertaken by respected scientists have been inspirational for this work. They have also given valuable guidelines for practical methods of investigation. The cases presented in detail include the typical behaviour of a particular stone type (Molasse sandstone), weathering situations at a large Gothic church (Abbey church of Salem) and the weathering history of Egyptian monuments (Cleopatra's Needles).

The two latter cases will be described after the presentation of the weathering of Molasse sandstone, which is a group of stone types originating from erosion of the Alps. It has been widely used for buildings in Switzerland and other parts of Central Europe and is generally known for its record of poor durability due to widespread exfoliation, granular disintegration and other weathering forms.

Methodology considerations

During studies undertaken around 1980 in order to clarify the causes of weathering of Molasse sandstone, Konrad Zehnder made a fundamental contribution to the development of overall methodologies for weathering studies.[79] The basic concept of Zehnder's methodology was observation and description of typical weathering forms as a function of local exposure conditions, both on natural outcrops and old quarries, as well as on monuments (in Zurich and St. Gallen).

Fig. 2.7: *Weathering in a natural outcrop of Molasse sandstone, Martinsbrugg, near St. Gallen, Switzerland. On exposed surfaces (left), scaling is the most important weathering form, grading into granular disintegration in sheltered areas (right). White patches are salt efflorescences (photo: PS 1993).*

Although there are major differences between natural outcrops and monuments, for instance related to the fact that a building is "hollow" while an outcrop is "massive" and that much more intense weathering can be observed in outcrops, Zehnder showed that it is possible to find outcrops resembling complex façades on monuments. Such outcrops are usually vertical or semi-vertical and characterised by exposure conditions ranging from completely sheltered, but influenced by moisture from "within", to strongly exposed to rain and run-off. Zehnder studied selected outcrops, as well as monument examples, on a periodic basis and in all seasons in order to characterise the local exposure conditions and weathering phenomena.

Observations and explanations

The most interesting observation of Zehnder was that the weathering forms on relevant outcrops strongly resembled those found within similar exposure situations on monuments. Contour scaling (or exfoliation/flaking) was the most typical form occurring at places exposed to precipitation, while granular disintegration - followed by salt crusts and efflorescences - could be found in sheltered locations.

Following up the field observations with relevant petrographic, mineralogical and chemical analyses, Zehnder showed that the typical weathering forms develop mainly because of accumulation of gypsum at characteristic depths below the surface. On parts strongly exposed to precipitation, gypsum tends to accumulate in a distinct zone below the surface, leading to disintegration of the stone in this zone and therefore to loosening of larger flakes (contour scaling). Conversely, when an area is sheltered from precipitation and simultaneously strongly influenced by moisture (from "within") evaporating close to the surface, gypsum (and other salts) crystallise on or just below the surface, leading mainly to granular disintegration. Regarding the sources of salts, Zehnder concluded that oxidising aggregates of pyrite was a main factor in the natural outcrops, while anthropogenic emissions of sulphur dioxide (wet and dry deposition) had to be considered an additional important factor on buildings in urban areas.

These explanations are very simplified and they have also been subjected to research campaigns both before and after the investigations of Zehnder.[80] How cycles of wetting/drying affects the accumulation of gypsum (and other salts) in particular zones below the surface has been a major area of investigation, and Zehnder himself underlined that frost and thermal stresses may strongly affect the weathering processes as well.

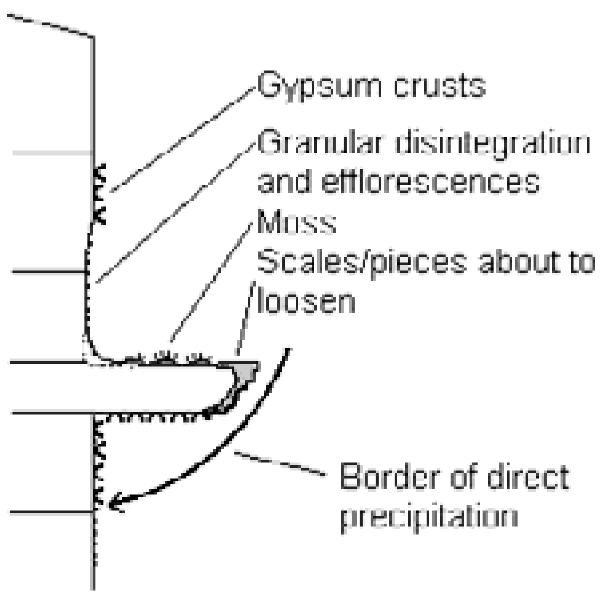


Fig. 2.8: *Principles of the weathering of a cornice made of Molasse sandstone. On the exposed parts weathering takes the form of scaling, while black crusts and granular disintegration are the most common phenomena on sheltered parts. Drawing simplified from Zehnder (1982).*

General relevance of the study

The results obtained are not directly applicable to other stone types, even though the explanation of contour scaling is relevant for most porous materials. However, the actual results are - from the perspective of this thesis - not as interesting as the methodology used. Showing that weathering in *relevant* natural outcrops may strongly resemble weathering on *relevant* parts of monuments, the study may be used as a model for investigations of other stone types in other environments. The aim of such studies would be to determine the typical behaviour of the stone in question and to gain experience in order to readily grasp particular weathering situations on monuments.

Other researchers have used similar methods to Zehnder in order to compare the weathering of natural outcrops with monuments. In the late 1980s, Christine Bläuer studied the *Berner Sandstein* (Berne area, Switzerland) with similar aims, methods and results,[81] and the discourse on the origin of oxalate crusts/films on monuments has been significantly widened by studies of natural outcrops. In the latter case, Del Monte *et al* showed in 1987 that the presence of oxalates on monuments are strongly connected with the growth of lichens and other organisms - just like on natural outcrops.[82]

2.5 Sources of inspiration II: Abbey church of Salem in Germany

The study of Zehnder on Molasse sandstone was based on the perception of weathering situations. Perceiving weathering situations was also the main point of another investigation carried out by Zehnder, now in co-operation with Hans Ettl, namely of the Gothic abbey church of Salem in the countryside in Baden-Württemberg (Germany). The three-aisled church, which has a simple design, had been subjected to numerous "analytical" investigations before Ettl and Zehnder described and documented the weathering situations in 1991.[83]

***Fig. 2.9**: Abbey church of Salem in Baden-Württemberg, Germany. The three-aisled Gothic church was begun in the late 13th century and is made of Molasse sandstone (photo: PS 1992).*

Objectives and general methodology

The aim of the documentation was firstly to obtain a general understanding of the actual state of conservation of the building as a whole, as well as to locate specific zones at risk. In contrast to the usual way of making a condition report, in which only the "damage" is described, the documentation of weathering situations enabled Ettl and Zehnder to interpret the most obvious causes of weathering. In this way it was also possible to interpret the former, isolated, "analytical" results in the context of the real monument. It was, moreover, the hope of the investigators that their specific method would result in future conservation interventions restricted to the actual zones at risk.

A prerequisite for using the "weathering situation"-method was that certain observations had to be undertaken during rainfall, and that the building history, including the type and age of the building materials, was properly known in advance. In the context of this thesis it is only necessary to note that the erection of the present church began in the late 13th century and that large-scale alteration and restoration took place in the 18th and late 19th centuries. During these interventions large parts of the walls were subjected to stone replacement (ashlars, mouldings, copestones). The original local types of Molasse sandstone were usually replaced by other kinds of Molasse sandstone from nearby or from Switzerland. Portland cement mortars were introduced for jointing and repointing around 1890.[84]

Mapping methods

In order to be able to map the whole church, using façade plans, within a reasonable period of time, Ettl and Zehnder used a relatively simple legend of weathering forms. The extremely detailed classification systems which have been developed in Germany, especially by Fitzner and Kownatzki,[85] were considered irrelevant because they are not designed for relating the

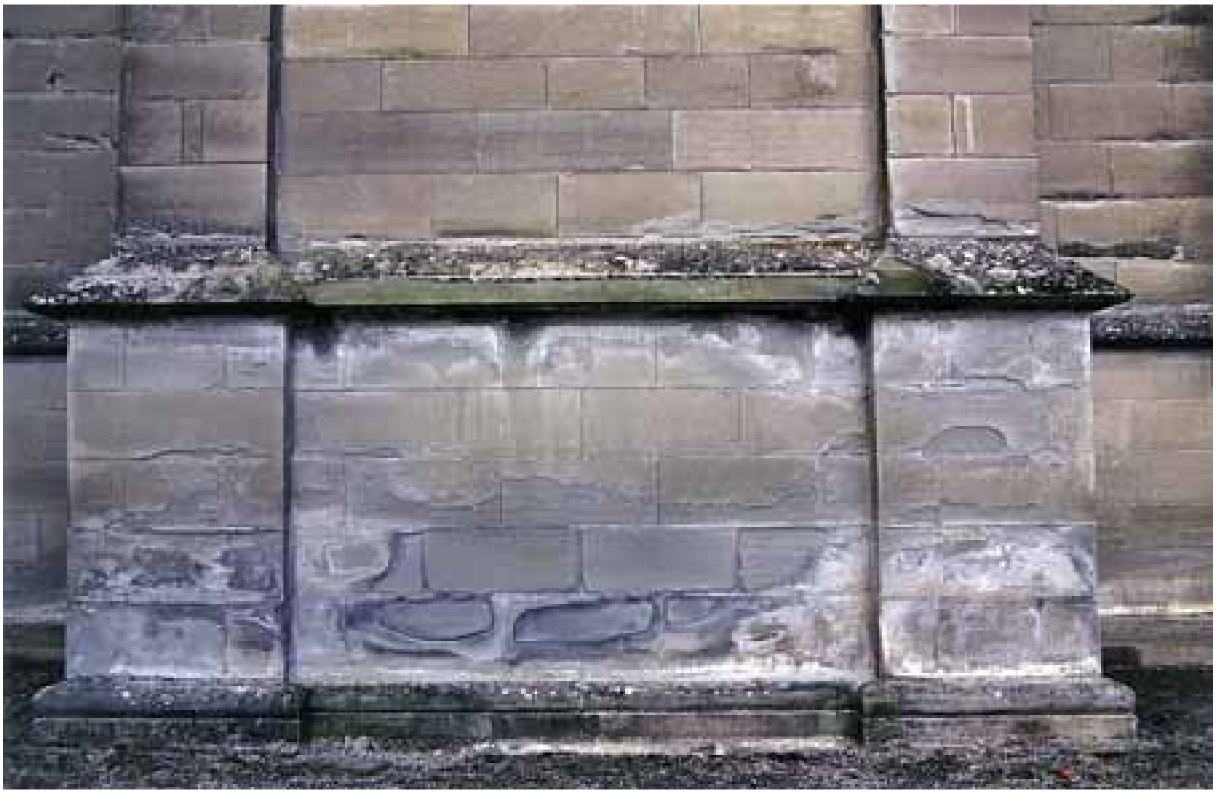


Fig. 2.10: *Typical weathering situation at Abbey church of Salem: Granular disintegration and scaling above the base due to rising saline solutions in a partly sheltered area; organic growth and scaling on and near exposed string course (photo: PS 1992).*

weathering forms to specific weathering situations. It is also extremely time consuming to use such classification systems. The typical weathering forms at Salem church were thus classified according to the following scheme:

- *Organic growth*. Algae, lichens and moss occur on exposed details, especially on projecting and horizontal elements. Stone surfaces are usually intact, but contour scaling may sometimes be found in the border zone between exposed and less exposed parts.
- *Contour scaling* (and multiple contour scaling) forms on rain-exposed walls, especially in the zone bordering sheltered parts of the walls. The surface itself is usually intact, but distinct planes of weakness can be found at certain depths below the surface.
- *Granular disintegration*, flaking and formation of gypsum crusts occur on parts sheltered from rain, but affected by moisture from “within” the masonry, or from adjacent run-off areas.
- *Cracks and joint fissures*. Masonry cracks developed due to structural problems are very unusual. However, open joints and joint fissures frequently occur on the otherwise weathered parts. The joints were formerly repaired by cement mortar.

The typical weathering situations

Recalling that a weathering situation is characterised by the relationship between one or more weathering forms, the exposure conditions and other peculiarities of the object, Ettl and Zehnder were able not only to locate typical situations, but also to show that several situations repeated on various parts of the church. Moreover, several, rather obvious causes of weathering could be deduced from the situations themselves. The typical weathering situations were:

- *Zone of rising damp*. The whole church, *both outside and inside*, is obviously affected by rising damp and salt weathering reaching heights up to two metres. Weathering forms on the partly exposed lower walls include granular disintegration, flaking and contour scaling - always associated with gypsum crusts/efflorescences. The projecting, exposed base is, however, not heavily weathered. Although rising ground water is suspected as the main source of moisture, direct rain and snow affecting the base cannot be excluded as sources.[86]
- *Zones around leaks and run-off*. The typical situations include zones just below open joints in cornices. In the centre of run-off areas, the stones are usually intact (salts are washed away), but often overgrown by algae/lichens. On each side of the run-off areas there are zones of intense weathering in which gypsum prevails. Similar phenomena can be found on wall corners on which one side is severely exposed to while the other is protected from rain.
- *Zones around cornices and string courses*. Exposed cornices, string courses and copings on buttresses are overgrown by algae/lichens, but otherwise intact. Just above the horizontal elements, a situation similar to the zone of rising damp can be found. Sheltered stonework below cornices and string courses are usually severely affected by granular disintegration and flaking - and the weathering is always followed by efflorescences of gypsum.
- *Zones around defective gutters and downpipes*. Leaks from defective gutters and downpipes have resulted in severe weathering restricted to the specific zones affected (outside and inside). At several places the weathering is inactive because the defects have been repaired.
- *Zones related to cement mortar joints*. Plain walls often show severe contour scaling along joints repointed with Portland cement mortars, in particular along the borders between strongly and less exposed areas.

The present zones at risk are located at places which were subjected to large-scale stone replacement around 1890. According to Ettl and Zehnder this feature might be explained by the particular exposure conditions, but also by the possible poor durability of the Molasse sandstones from 1890. Although obvious causes (exposure, salts etc.) of the weathering could be reasonably well explained, Ettl and Zehnder maintained that additional in-depth investigations ought to be conducted in order to reach an understanding sufficient for undertaking conservation measures. This is particularly the case with regard to the origin of rising damp.

2.6 Sources of inspiration III: Cleopatra's Needles

How history is perceived depends largely on the perspective from which investigations are carried out and how available historical sources are interpreted. These basic features of historical research are excellently displayed by the historic implications of the weathering of the Cleopatra's Needles of New York and London - 3500 years old Egyptian granite obelisks shipped to the respective cities in the last century.

Today both obelisks are strongly weathered along their bases, but while the rest of the London obelisk has remained relatively well preserved, the hieroglyphics on the west side of its New York counterpart are completely unreadable. The east side, however, is still in good repair.[87] Due to these differences, geologist and conservation scientist Erhard Winkler did not believe former interpretations which "ascribe the damage flatly to the toxic urban atmosphere of New York City".[88] He therefore challenged himself to explore the historical events for both obelisks in detail.

Fig 2.11: *Left: The Cleopatra's Needles on the shore of the Mediterranean sea in 1798. One obelisk is standing, the other has fallen over. Painting by Cécile, reproduced in Clayton (1987). Right: Cleopatra's Needle of New York City. Situated in Central Park, the granite obelisk weighs more than 200 tons. Source: http://en.wikipedia.org/wiki/File:Obelisk_Central_Park.jpg*

Fig. 2.12: *Cleopatra's Needle of New York City. Different grades of weathering. Sources:* *http://en.wikipedia.org/wiki/File:Obelisk_Central_Park.jpg* *(left);* *http://en.wikipedia.org/wiki/File:Cleopatra%27s_Needle-2.jpg* *(right).*

Winkler's 1980-interpretation of the weathering[89]

According to Winkler the history is largely related to salt crystallisation and simplified like this: Both obelisks were quarried and carved in Aswan around 1500 BC. They were shipped on the Nile downstream and erected in Heliopolis (present day Cairo) where they stood for 1000 years.

Around 500 BC the obelisks were taken off their plinths by order of the Persian king Cambyses who had invaded Egypt. Then the obelisks laid prostrate on the ground, in flood plain silts of the salt-laden Nile river for nearly 500 years. It is reasonable to maintain that salts were introduced in the obelisks during this long period.

Around 16 BC the obelisks were relocated to Alexandria, only 100 feet from the Mediterranean ocean, by the Roman emperor Augustus. During the next 1800 years the bases of the obelisks were buried in drifting sand, from which sea salts were introduced. Sea salts were also introduced to the obelisks by winds.

By the excavation around 1880 AD, scaling and disintegration were observed at the bases of the obelisks, but their condition was still good enough for transportation by boat to New York and London (1880-81). Upon arrival, the London obelisk was immediately treated with hot wax and remained in rather good repair during the following decades. The New York obelisk was not treated with wax before 1884, and before then it had lost nearly 500 kgs of material in the form of scalings, especially during spring time. Since then both obelisks have slowly weathered and been subject to conservative treatment several times. The humid climate in London and New York has also washed out most of the salts in the obelisks.

According to Winkler the interpretation of the weathering is as follows: The obelisks picked up salts in two periods - while laying on the salt-laden Nile delta (500 years) and while standing in Alexandria (1800 years). The salts were concentrated on the upper sides (the present west side of the New York obelisk) while laying on the Nile delta, and in the bases during their time in Alexandria. However, the climate in Egypt was too dry for the salts to act strongly on the stone, and it was not until the obelisks were relocated in humid London and New York that the salts could really start their work. The reason why the London obelisk fared better must be ascribed to the immediate treatment with wax.

Winkler's 1996-interpretation of the weathering[90]

The story of the Cleopatra's Needles does not end with the 1980 account of their weathering. After all, the obelisks are 3500 years old, implying that Winkler might have overlooked or disregarded important events related to their fate. Indeed, that is exactly what happened - and 16 years after his first interpretation, Winkler published a new report about the historical implications.

Especially for the London obelisk, additional historical sources open up more questions about the weathering. Firstly, the obelisk fell over while standing in Alexandria, probably due to earthquake (956 AD, 1303 AD or 1847 AD).[91] Secondly, the ocean voyage from Alexandria to London was not as safe as formerly believed. In fact, during the whole voyage the obelisk was laying in a container in which entrapped sea water (with 3,5% salt) sloshed around. The question remains whether old salts were washed out or new salts added during the short time of exposure to sea water. If old salts were washed out, it is easier to explain why the London obelisk remains in better repair than its New York counterpart.

There might also be another reason why the New York obelisk is more weathered. This is because it was treated with heat after application of molten paraffin in 1884. Winkler suggests that the temperature may have been so high that the granite burst or formed microcracks, but he does not give definite conclusions.

According to Winkler a lesson has been learned from this case: All objects arriving in American museums from desert regions are today routinely stripped of entrapped salts in destilled water to avoid salt weathering problems. The question is if this lesson really is the right one? It would seem that Winkler makes the classical error of generalising too broadly from a case study. It might well be that leaching objects of their salts is a good treatment in many cases, but *the lesson* is that all monuments have their own histories and particular problems.

The case of the weathering of the Cleopatra's Needles should not be looked upon as finished at this stage, especially since Winkler himself has opened up new possibilities. Moreover, the following historical statement, made in 1842 and not mentioned by Winkler, does not really fit his interpretations:

> Die beiden Obelisken, von denen der eine noch stehende die Nadel der Cleopatra genannt wird, sind auf den Wetterseiten sehr verwittert, und zum Theil ganz unleserlich geworden.[92]

Is this description trustworthy, or should it be looked upon as less important than other sources? Recently, other researchers have also made observations which suggest that the London obelisk is today just as weathered as its counterpart in New York.[93] How does this information fit into the interpretation of Winkler? Another question deals with careful *in situ* investigations. In his work, Winkler never made any reference to such investigations, which ought to include mapping of weathering forms and petrographical analyses. Perhaps such investigations could give new insight into the weathering of the needles?

Despite these critical remarks, Winkler in his two interpretations 16 years apart has made an important contribution to the science of weathering of monuments. He has shown that interpretation of historical events should be a vital part of a weathering researcher's competence. However, as “The past is a foreign country”,[94] we cannot expect to achieve definitive answers in these matters.

2.7 Applied methods of investigation in this thesis

In this section practical methods of investigation used in this thesis are presented.

Selected objects

In order to understand the typical behaviour of the cathedral's most important stone types (soapstone and greenschist), eight quarries have been studied (chapter 8-10). These studies were carried out in roughly the same manner as those of Konrad Zehnder on Molasse sandstone, that observations in the quarries were compared with the behaviour of stones used at relevant places on buildings. “Relevant places” are simple architectural features like copings and string courses, as well as sheltered stonework relatively uninfluenced by complex historical events (e.g. fire and restoration measures). In addition to selected features at the Nidaros cathedral, a few regional buildings and monuments made of the same stone were also included for comparison. The objects presented in this thesis were chosen from among a large number of investigated buildings and monuments in the Trondheim region.

In order to understand the zones at risk from very large sections of the cathedral, the choir, the nave and the north transept were selected (chapter 11-13). Weathering situations were observed and mapped in much the same manner as Ettl and Zehnder did on the Abbey church of Salem. In addition to the actual weathering phenomena, both historical records and structural behaviour were considered in order to obtain the knowledge necessary for suggesting appropriate conservation measures.

Winkler's historical study of Cleopatra's Needle was the main source of inspiration for the studies of weathering of smaller building parts and decorations (chapter 14-18). In these thorough case-studies the overall methodology was used in order to gain as complete an understanding of the weathering phenomena as possible.

Historical investigations

A major problem at the beginning of the work was that significant parts of the cathedral's history were not properly known. The standard books about the cathedral, Gerhard Fischer's three comprehensive volumes on the medieval history (1070-1537) and the restoration history (1869-1969), as well as Trygve Lysaker's volume on the post-Reformation history (1537-1869), include detailed information on stylistic issues and matters regarding various building periods and repair projects (and fires). However, the books - with a few exceptions - lack information on subjects which are important from a weathering perspective. Such information can be summarised as:

- Building structure
- Stability problems
- Materials (stone and mortar)
- Stone replacement during the restoration (1869-)
- Record of water leaks
- Interventions after the main restoration phases (1869-)
- Particular conservation methods
- Indoor heating

Therefore, a thorough historical study was undertaken first. The study, presented in part II, is based on observations and available scientific articles and reports, especially written during the restoration of the cathedral (1869-), as well as material found in the chaotic archive of The Restoration Workshop, which covers the period from c. 1860 until today:

- Reports on structural issues elaborated by external consultants
- Annual and semi-annual reports of the restoration architects (especially between 1869 and 1940)
- Diaries of the restoration architects (especially between 1904 and 1975)
- Account books and contracts
- Newspaper articles, letters and other written material

Much of the information was located with the help of cathedral archaeologist Øystein Ekroll and has been collected in special reports written for The Restoration Workshop.[95] Overall historical records for each building part have also been worked out (see also appendix 1).[96]

In addition to the above-mentioned historical material, investigations of historical photos have been extremely important, not least because there are some 8.000 pictures in the archive of The Restoration Workshop. They are often of excellent quality (especially those from the early phases of the restoration) - making it possible to follow the weathering of the cathedral from 1860 until today.

Another important source of information has been discussions with craftspeople. Some of the elder masons have worked with The Restoration Workshop for up to 40 years, meaning that first-hand information, particularly related to the use of materials, has been available.

Geology, material properties and salt analyses

Stone types and stone quarries used for the building and restoration of the cathedral (see appendix 2) were located especially with the help of three excellent, old monographs on Norwegian building stones:

- On soapstone and slate, by A. Helland (1893)
- On marble, by J.H.L. Vogt (1897)
- On granite and other hard stones, by J. Oxaal (1916)

Also old scientific papers, especially by the geologist C.W. Carstens (1920s), archive material and information from the craftspeople were helpful. The quarries selected for weathering studies had, moreover, to be geologically described. In addition to the material mentioned above, reports from the archives of the Norwegian Geological Survey have been used for this purpose with only a few additional observations. Properties of stones (petrography, mineralogy, hygric properties, mechanical properties etc.) were analysed, mostly by standard methods (see chapter 10), in collaboration with Lisbeth Alnæs (Trondheim) and Esther von Plehwe-Leisen (Köln).[97]

Investigating the mortars of the cathedral represented a major challenge, not least because there have been many misconceptions with regard to when and where modern Portland cement mortars were introduced. Therefore, all relevant historical sources (mentioned above) had to be carefully studied and compared with information in early text books on principles of "modern" (c. 1880-1920) masonry construction in Norway, especially the comprehensive work of Bugge (1918). In addition, samples taken from the cathedral were analysed (by external consultants) with regard to their content of lime and cement. Also in-depth observations on all parts of the cathedral had to be carried out.

Soluble salts were at the outset considered a major factor in the complexity of weathering processes at the cathedral. Hence, 500 salt samples were analysed by light microscopy and microchemistry, and when relevant by X-ray diffraction, mostly in the laboratory of *Institut für Denkmalpflege* at ETH in Zürich.[98] Detection of alkaline salts was also simply carried out by the use of pH-paper.

Weather, history of air pollution and indoor climate

The exposure conditions of the cathedral, as well as local weather conditions and air pollution, were part of a study carried out by the Norwegian Institute for Air Research in 1990-91.[99] However, several important issues were not covered in this study, in particular those related to the history of air pollution in Trondheim. Measurements of air concentrations of sulphur dioxide in the city centre are available from 1973, but former concentrations had to be reconstructed on the basis of available literature on the industrial development and use of heating fuels since c. 1820 - when coal and coke were introduced.

Local weather phenomena have been deduced using data from the nearby meteorological stations in Trondheim (Voll, 1926-67) and at Værnes (35 km east of the city, 1946-). They cover the international normal periods 1931-60 and 1961-90, respectively. Also the station at Tyholt in Trondheim (mainly 1965-81) has provided some data. When necessary, data from 1990-96 have been obtained from Værnes via the Norwegian Meteorological Institute (Oslo).

No readily available information about the indoor climate of the cathedral was available before the work started. Therefore, it was necessary to reconstruct the history of the cathedral's heating systems on the basis of the historical sources mentioned above. Thermohygrograph recordings from the last few years have also been helpful. The most helpful study on indoor climate, in particular with regard to large-scale movements of air, was carried out by Sven Nørsett as part of his M.Sc. thesis at the Norwegian University of Science and Technology (1995).

Mapping of weathering forms/situations

The main weathering forms of the whole cathedral were mapped during two months in the summer of 1994 using façade maps provided by The Restoration Workshop. In order to be able to cover the whole cathedral, most observations were undertaken from the ground and from the exterior gangways, often using binoculars. A mobile lift was also used. The weathering forms and other relevant phenomena were classified according to the following simple scheme:

- Pronounced stone weathering on semi-exposed or sheltered parts
- Pronounced stone weathering on exposed parts, often followed by organic growth (algae, lichens, moss) and fissures between stone and mortar (joint fissures).
- Joint fissures, often followed by organic growth
- White crusts (calcite) associated with leaching from mortar joints
- Black crusts (all types, from very thick ones to thin black layers)
- Salt efflorescences
- Larger masonry cracks
- Known or assumed points of water infiltration
- Evidence of fire (brown stone surfaces)

All the maps can be found in appendix 3. As a result of the mapping campaign, a comprehensive condition report was worked out for The Restoration Workshop. The report focuses on weathering situations and specific zones at risk, and includes priorities with regard to necessary/possible interventions and further investigations.[100]

Parts of the cathedral selected for in-depth case studies were subject to more detailed mapping of weathering forms on detailed façade maps provided by The Restoration Workshop (appendix 4). The classification of weathering forms was established on the basis of existing systems and adjusted to the particular stone types of the cathedral (tab. 2.1). Detailed information about how the system was established can be found in earlier publications.[101] It should be stressed that the weathering forms are strongly idealised and that in practice it is much more common to observe combinations and transition forms than the “pure” types. Moreover, the forms described in tab. 2.1 are not meant as a standard, but as a help for practical work, in which one has to adjust the “legend” according to the actual situation at hand.

Tab. 2.1: *Weathering forms on stones*

Type	***Explanation***
Granular disintegration:	Loosening of small grains and mineral aggregates from the surface
Delamination:	Opening of layers along the foliation planes of foliated or schistose stones
Flaking:	Loosening of small, single flakes or multiple flakes parallel to the surface
Exfoliation/scaling:	Loosening of extensive, single flakes or mutiple flakes parallel to the surface
Chipping:	Loss of larger pieces of stone
Pitting:	Small pits in the surface, often as a result of chemical dissolution of soluble minerals (carbonates)
Relief:	Pronounced surface topography on stones, often as a result of selective weathering (e.g. fine-grained matrix vs. large veins and aggregates)
Fissure:	Tiny cracks through stonework
Crack:	Larger masonry cracks
Black crust/black layer:	Deposits of relatively thick, cauliflower-like black (gypsum) crusts and thinner layers with similar composition
White crust:	Deposits of calcite crusts, often in the form of “stalagtites stuck to walls”
Salt efflorescence:	All types of salt efflorescences (powdery, whiskers, needles, cotton-like etc.)
Algae/lichen/moss:	Organic growth on stonework

Regular observation of exposure conditions

Since the work began on this thesis in 1992, regular investigation and observation of the “whole” cathedral, parts of the cathedral and most of the stone quarries in all seasons and under practically all types of weather conditions has been undertaken. The observations were especially aimed at understanding the weathering forms observed as a function of exposure conditions:

- Areas exposed to rain, snow, sleet and icicles
- Areas sheltered from direct precipitation
- Areas influenced by run-off and leaks
- Condensation phenomena, including white frost
- Periods of salt efflorescence

In addition to describing observed phenomena (with the help of diaries), extensive use was made of a Nikon camera. A total of 3000 “working-photos” have been taken. Many observations would not have been possible without the use of the mobile lift of The Restoration Workshop.

From the summary of practical methods of investigation, the reader may have the impression that the whole project was well planned and followed a strict scheme. This is a misconception. The study was often undertaken in a rather chaotic manner and as a rush in and out of blind alleys. Thus, everything written above has to be regarded as an idealised reconstruction.

2.8 Summary of theory and method

The overall guidelines for the present work can be summarised by the definition of conservation elaborated by Andreas Arnold:

> "Preservation of monuments" means: To recognise them as monuments, to establish their state of conservation and decay [weathering], to understand their risks of decay [weathering], and then to act in order to let them survive authentically as long as possible.

From this definition a methodology for applied weathering studies of historic stone buildings, also based on the works of Andreas Arnold, has been developed. It focuses on weathering as a context dependent phenomenon evolving due to the effects of structural actions, atmospheric events and the actions of man. Any man-made intervention - intentional or not, direct or indirect - may in principle change the course of the weathering processes.

The central element of the methodology is to grasp the context in which the weathering processes occur, first by perceiving the actual *weathering situation* at hand. A weathering situation may be defined as the relationship between weathering forms and: 1) exposure conditions, 2) structure or design of the building as well as 3) properties of the building materials and 4) other relevant factors.

In order to understand the evolution (including rate of change) of weathering processes, it is essential to interpret the present weathering situation in the light of *historical events*, both atmospheric and man-made. Such interpretations also have to be undertaken in the light of *available theories on weathering processes*. In this connection it should be stressed that the aim of applied weathering studies is not to develop new theories on particular weathering processes. However, results obtained from applied investigations may give valuable feed-back to basic research.

Having established the history of the weathering situation and the former rate of change of the weathering processes, one may have a good basis for *evaluating the future risks* relating to the situation and elaborate a reasonable *prognosis*. However, principally it is impossible to accurately predict the future course and rate of weathering. Hence, it is important to observe what actually happens by regular inspections, for instance while conservation measures are undertaken in the form of relatively small and corrigible steps.

Undertaking weathering studies according to this methodology may give significant help before recommending conservation measures. However, scientific studies cannot solely be the basis for recommendations. They also have to be given in the light of the values that are attributed to the actual monument, as well as the available crafts and conservation methods. Presuming that the aim is to maintain historical values and age values, the principles of a conservation strategy could be (in preferred order) to: 1) prevent further weathering; 2) mitigate the evolution of weathering processes; 3) strengthen the monument/materials against weathering.

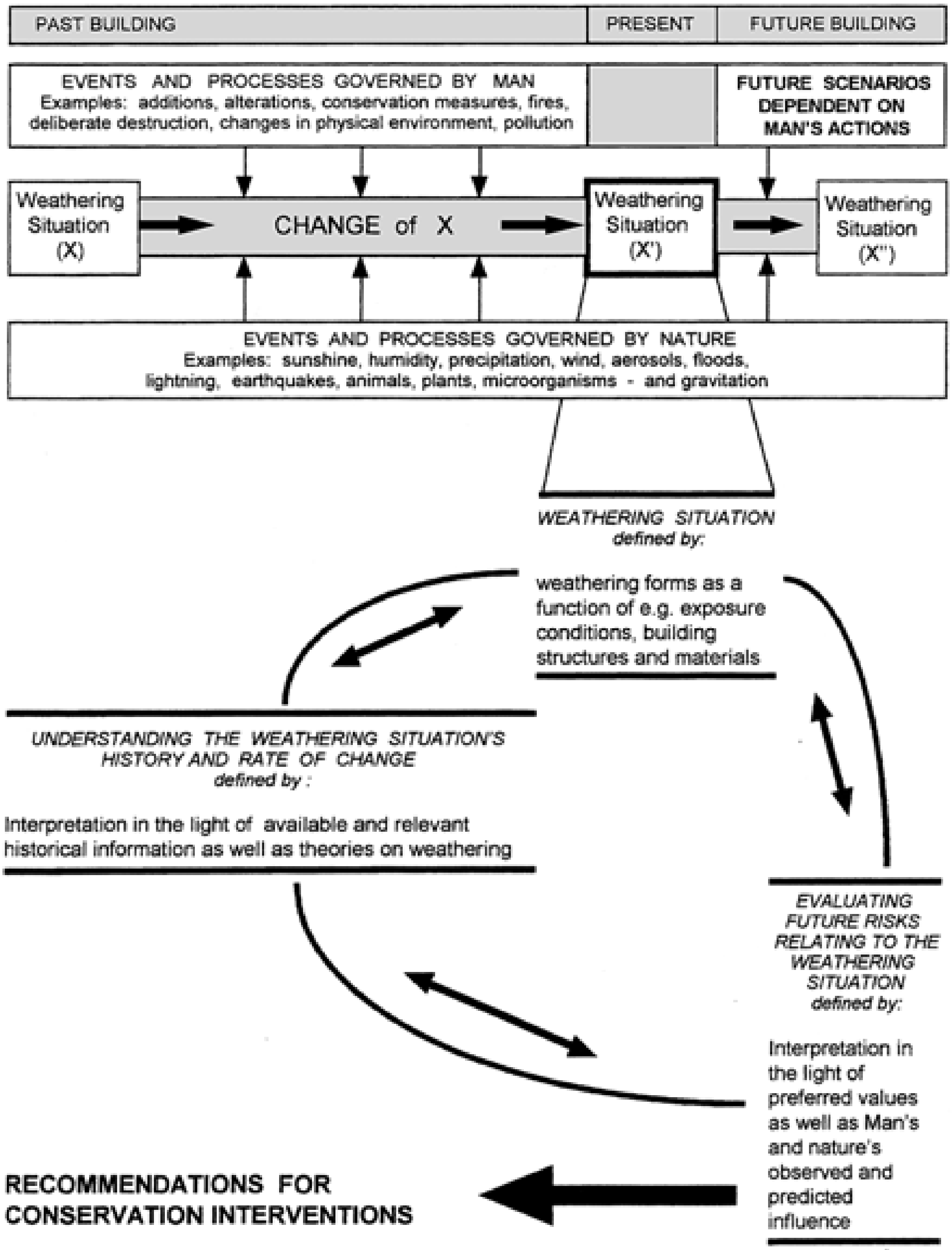


Fig. 2.13: *Weathering situations and their alteration. Summary of research method. Upper part: Phenomena interfering with an old stone building. Lower part: Research strategy.*

Fig. 3.1: *Weathered capital made of Grytdal stone in the choir of Nidaros cathedral (photo: Torgeir Suul).*

Chapter 3

Theories of selected weathering processes

The aim of this thesis is not to seriously question particular theories of weathering processes, nor to modify the general understanding of such processes or to develop new ones. In contrast, well-known theories will be used when interpreting particular weathering situations at the Nidaros cathedral and in the investigated quarries. Several theories, found in the textbooks mentioned below, for instance related to frost action and fire, hygric/thermal expansion, biogenic processes and dissolution mechanisms, are briefly described when relevant in later chapters. Since, however, weathering due to soluble salts, air pollution and the use of Portland cement mortars are of special interest, and are referred to in chapter 1, these processes will be described in detail below. The effect of fire on soapstone has previously been investigated by local researchers.[1]

3.1 Standard texts on weathering theories

Probably as long as stone buildings have existed, there has been interest in why they deteriorate and decay. Vitruvius and Pliny the Elder made observations offering explanations of certain deterioration phenomena almost 2000 years ago, and since the Scientific Revolution many professionals - especially earth scientists - have worked in this field.[2]

Despite the fact that in recent years increasing numbers of specialised scientists have been occupied by observing and explaining deterioration phenomena, and frequently those related to air pollution, it is reasonable to state that most of the common theories *used today in practical conservation work* were elaborated around the turn of the century.

Such theories were collected and presented in some of the early standard text books on weathering and deterioration of stone monuments. These include the famous and comprehensive works of R. J. Schaffer (*The weathering of natural building stones*) and Alois Kieslinger (*Zerstörungen an Steinbauten*), both published in 1932. 40 years later, in 1973, Erhard Winkler followed Schaffer and Kieslinger and published *Stone: Durability in Man's Environment*, which was revised and updated in 1994, with the new title *Stone in Architecture*. Among other recent texts there are *Stone Decay and Conservation* by Amoroso and Fassina (1983) and *Conservation of Building and Decorative stone*, edited by Ashurst and Dimes (1990).

3.2 Salt weathering in general

Despite more than 100 years of scientific investigation, the phenomenon of weathering due to soluble salts is not yet properly understood, but it seems to be related to the pressure developed when salts crystallise or otherwise expand within the pores of stone and other porous

Tab. 3.1: *The most important salts present in walls and their theoretical equilibrium relative humidities. After Arnold & Zehnder (1989).*

Group	Species	Chemical formula	EQRH (20°C)
Carbonates	Calcite	$CaCO_3$	
	Dolomite	$CaMg(CO_3)_2$	
	Magnesite	$MgCO_3$	
	Nesquehonite	$MgCO_3\bullet 3H_2O$	
	Lansfordite	$MgCO_3\bullet 5H_2O$	
	Hydromagnesite	$Mg_5[OH(CO_3)_2]_2\bullet 4H_2O$	
	Natrite (natron)	$Na_2CO_3\bullet 10H_2O$	97,9
	Thermonatrite	$Na_2CO_3\bullet H_2O$	
	Nahcolite	$NaHCO_3$	
	Trona	$Na_3H(CO_3)_2\bullet 2H_2O$	
	Kalicinite	$KHCO_3$	
Sulphates	Gypsum	$CaSO_4\bullet 2H_2O$	
	Bassanite	$CaSO_4\bullet ½H_2O$	
	Epsomite	$MgSO\bullet 7H_2O$	90,1
	Hexahydrite	$MgSO\bullet 6H_2O$	
	Kieserite	$MgSO\bullet H_2O$	
	Mirabilite	$Na_2SO_4\bullet 10H_2O$	93,6
	Thenardite	Na_2SO_4	82
	Arcanite	K_2SO_4	97,6
	Bloedite	$Na_2Mg(SO_4)_2\bullet 4H_2O$	
	Aphthitalite	$K_3Na(SO_4)_2$	
	Picromerite	$K_2Mg(SO_4)_2\bullet 6H_2O$	
	Boussingaultite	$(NH_4)_2Mg(SO_4)_2\bullet 6H_2O$	
	Syngenite	$K_2Ca(SO_4)_2\bullet H_2O$	
	Gorgeyite	$K_2Ca_5(SO_4)_6\bullet H_2O$	
	Darapskite	$Na_3(SO_4)(NO_3)\bullet H_2O$	
	Humberstonite	$K_3Na_7Mg_2(SO_4)_6(NO_3)_2\bullet 6H_2O$	
	Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O$	
	Thaumasite	$Ca_3Si(OH)_6(CO_3)(SO_4)\bullet 12H_2O$	
Chlorides	Bischofite	$MgCl_2\bullet 6H_2O$	33,1
	Antarcticite	$CaCl_2\bullet 6H_2O$	30,8
	Tachyhydrite	$CaMg_2Cl_6\bullet 12H_2O$	
	Halite	$NaCl$	75,5
	Sylvite	KCl	85,1
Nitrates	Nitrocalcite	$Ca(NO_3)_2\bullet 4H_2O$	53,6
	Nitromagnesite	$Mg(NO_3)_2\bullet 6H_2O$	54,4
	Nitratite	$NaNO_3$	75,5
	Niter	KNO_3	94,6
	Ammonium nitrate	NH_4NO_3	60 (c.)
Oxalates	Whewellite	$Ca(C_2O_4)\bullet H_2O$	
	Weddelite	$Ca(C_2O_4)\bullet 2H_2O$	

materials.[3] In our context we need not pay much attention to the actual mechanisms of how stone is disrupted due to salts, but merely state that salts can - and do - produce severe damage. Instead of concentrating only on weathering mechanisms, we discuss the whole process which starts with the origin of the salts.

Hence, we have to consider the *types and sources* of the salts, how they are *transported* in masonry, how they *accumulate* on specific parts of a building, what happens when the salts *crystallise* and finally how they are affected by the *ambient weather/climate*. This process-oriented theory was elaborated mainly by Arnold and Zehnder on the basis of extensive field studies, and most of the information below is based on their work.[4]

Common types and sources of salts

More than 40 different salt species have been found on buildings and monuments (tab. 3.1). Carbonates, sulphates, nitrates and chlorides of sodium, potassium, calcium and magnesium are the most frequent types, but oxalates and other types may also be quite normal in some places.

The sources of salts are diverse and they form due to complex (inorganic) chemical reactions as well as biological metabolism. Regarding buildings and monuments, we may summarise the most common sources as thus:

- Salts derived from the ground and ground water.
- Salts derived from the actions of people and animals (excrements, preservation of food, gun-powder storage, de-icing salts).
- Salts derived from building and conservation materials (mortars, especially Portland cement mortars, stone, cleaning agents like acid and lye, certain consolidants like water-glass).
- Salts derived from the natural atmosphere (especially sea salts, gases formed by volcanic eruptions)
- Salts derived from air pollution (mostly from sulphur dioxide, nitrogen oxides and hydrochloric acid)

When the actual salt species occurring within the complex system of a monument is known, it is sometimes possible to state their source. Sodium and potassium carbonates are for instance usually derived from alkaline building materials and conservation products. Portland cement mortar contains up to 1,3 % soluble alkaline components,[5] which upon reaction with carbon dioxide in the air give species like natrite, thermonatrite and trona. Calcite may also form from Portland cement via dissolution of calcium hydroxide and a reaction with carbon dioxide. The presence of sulphate in Portland cement, may also cause sodium sulphates as well as aphthitalite to form directly from this material.[6]

Gypsum is frequently derived from the reaction between sulphur dioxide and sulphate aerosols (air pollution), and calcium carbonate present in the building materials (stone and mortar). Magnesium sulphates may form in a similar way. However, gypsum and magnesium sulphates are also common components of a wide range of stone types - often formed by the reaction between sulphate derived from oxidising sulphides like pyrite and pyrrhotite, and calcium/magnesium from minerals like calcite, dolomite and magnesite.

Having said that sodium sulphates may form from Portland cement, we also have to mention that they are easily formed by the reaction between sodium carbonates and sulphate from air pollution or stone (tab. 3.2). This is because sodium carbonate is not stable in sulphate rich environments.[7]

Sodium chloride (halite) is another example of a salt which may stem from multiple sources. Heavy winds may bring large amounts of the salt from the coast to the inland, it may stem from reactions between cleaning agents like hydrochloric acid and sodium hydroxide, it may have been introduced in walls when used for conserving food - or brought about as a result of de-icing of roads, pavements and stairs in the winter time.[8]

This short introduction on sources of salts shows that this subject is quite complex, and that one has to be extremely careful with regard to definite conclusions about sources. Hence, interpreting possible sources of salts has to take note of the actual situation at present as well as an investigation of the monument's historical record.

Tab. 3.2: *Reactions of alkaline salts in walls. After Arnold & Zehnder (1989).*

Sources of salts:	Portland cement, water glass products, alkaline cleaning and sealing materials
Saline minerals:	Natrite, thermonatrite, trona, nahcolite, kalicinite (sodium and potassium carbonates, $\mathbf{Na_2CO_3}$ and $\mathbf{K_2CO_3}$)

Reactions with acid atmosphere (air pollution, SO_2) (simplified):

$$\mathbf{Na_2CO_3} + H_2SO_4 \rightarrow Na_2SO_4 + CO_2 + H_2O$$
$$\mathbf{K_2CO_3} + H_2SO_4 \rightarrow K_2SO_4 + CO_2 + H_2O$$

Reactions of alkali carbonates with sulphates, nitrates and chlorides in walls (strongly simplified):

$$\mathbf{Na_2CO_3} + MgSO_4 \rightarrow Na_2SO_4 + MgCO_3$$
$$\mathbf{Na_2CO_3} + CaSO_4 \rightarrow Na_2SO_4 + CaCO_3$$

$$\mathbf{Na_2CO_3} + Mg(NO_3) \rightarrow 2NaNO_3 + MgCO_3$$
$$\mathbf{Na_2CO_3} + Ca(NO_3) \rightarrow 2NaNO_3 + CaCO_3$$

$$\mathbf{Na_2CO_3} + MgCl_2 \rightarrow 2NaCl + MgCO_3$$
$$\mathbf{Na_2CO_3} + CaCl_2 \rightarrow 2NaCl + CaCO_3$$

$$\mathbf{K_2CO_3} + MgSO_4 \rightarrow K_2SO_4 + MgCO_3$$
$$\mathbf{K_2CO_3} + CaSO_4 \rightarrow K_2SO_4 + CaCO_3$$

$$\mathbf{K_2CO_3} + Mg(NO_3) \rightarrow 2KNO_3 + MgCO_3$$
$$\mathbf{K_2CO_3} + Ca(NO_3) \rightarrow 2KNO_3 + CaCO_3$$

$$\mathbf{K_2CO_3} + MgCl_2 \rightarrow 2KCl + MgCO_3$$
$$\mathbf{K_2CO_3} + CaCl_2 \rightarrow 2KCl + CaCO_3$$

Transportation, accumulation and fractionation of salts

Salts are mostly transported in solution on a building. Even though the solution may be very dilute, “water” is in fact always a salt solution. Water sources like rain and melting snow - and sometimes even condensation - give rise to leaks and run-off, while rising damp carrying salts occurs due to the capillary forces of porous building materials.

With regard to leaks and run-off, it is also the capillary forces of building materials that enable the salt solution to actually enter their structure. Generally, if a stone is very porous, salts may potentially penetrate deeply into its interior. Conversely, in a dense stone salts usually only affect its outer areas. In the latter case, salt solutions are mostly transported in relatively porous parts of the walls, e.g. joints and rubble cores - as well as along cracks.

When soluble salts are transported on/in a building structure, they tend to accumulate in particular zones. The most well-known example is rising damp, in which different salt species accumulate in different zones above the ground according to the solubility products of the salts as well as available moisture (fractionated salt systems). A similar phenomenon is likely when salt solutions are carried downwards or sideways along walls: The least soluble salts concentrate close to the water/salt source, while more soluble salt species are transported farther away. In such cases we also have to consider that salts are transported to the interior of materials (often giving rise to contour scaling), and that driving rain affecting exposed walls is going to transport already formed salts further downwards and eventually all the way down to the ground. Hence, highly soluble salts on *old* masonry buildings are usually found at places where rain is not able to wash them away, e.g. underneath or below projecting elements. In contrast, very soluble salts may cover whole exposed façades of *new* masonry buildings. However, after several years they usually disappear as a result of rain washing.

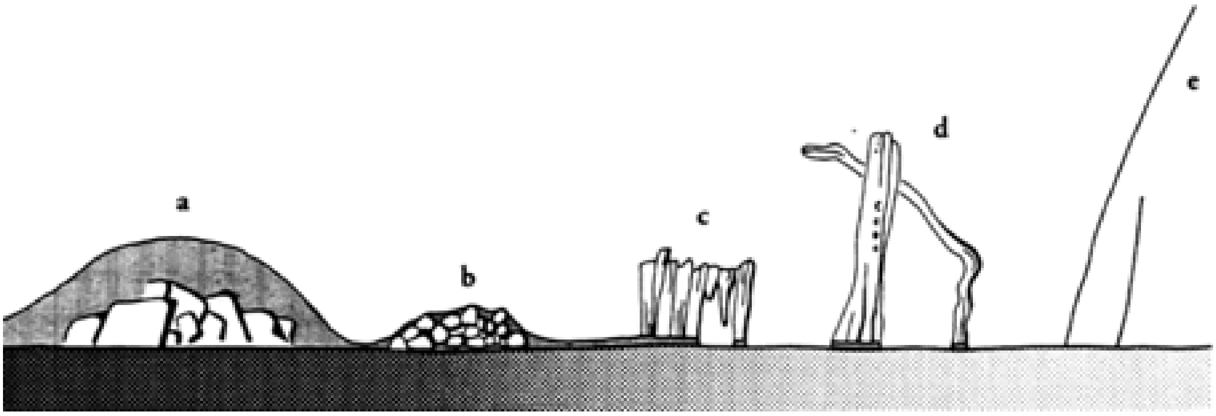


***Fig. 3.2**: Various forms of crystallising soluble salts as a function of available moisture. See explanation in text (after Zehnder & Arnold 1988).*

Precipitation and crystallisation of salts

When solutions are saturated and water evaporates, salts precipitate. Generally, salts may precipitate within the materials (subflorescence) or at their surfaces (efflorescence). The actual location of the precipitation is dependent on numerous factors, of which solution supply, the properties of the materials, available moisture, ambient temperature and relative humidity are the most important ones.

Depending on available moisture and temperature, the salts may crystallise in various forms. Simplified, we may state that when salts crystallise “within” a saturated solution (on a wet substrate), various forms of isometric grains and crusts will form (a and b in fig. 3.2). A little less moisture will give relatively thick whiskers (c), while thin needles and “cotton”-like structures tend to develop when even less moisture is available (d and e).[9] Powdery or “flour-like” efflorescences are also frequently observed. Such forms may form when certain salts dehydrate (see below).[10] It is important to know that the least soluble salts (for instance calcite and often gypsum) usually produce different forms of crusts. More soluble salts may produce a range of forms from isometric crystals to “cotton”-like structures.

Hygroscopic salts and hydrate-forming salts

Apart from the least soluble types, most salts are capable of reacting with the ambient air humidity. Such salts are hygroscopic and often hydrate-forming too.

Hygroscopic salts dissolve when the ambient relative humidity (RH) rises above the *Equilibrium Relative Humidity* (EQRH) of any particular species. Conversely, it recrystallises when RH drops below the EQRH. EQRH is dependent on temperature and has been measured experimentally for a large number of pure salt species. However, these experimental values are usually not valid when the same species is found within a complex salt system. This indicates that it is not possible to directly use the experimental EQRH-values when attempting to reduce indoor salt weathering rates (e.g. by controlling RH and temperature). In such cases, one has to observe under which conditions the salt species actually dissolves/recrystallises in order to design a satisfactory indoor climate.[11]

An important feature of hygroscopic salts is that when dissolved, they tend to make surfaces look relatively dark and wet. Hence, dissolved hygroscopic salts may easily be mistaken for moisture arising from condensation. Only regular observation (including T/RH measurements) and/or chemical analysis can confirm which type of "wetness" is present.

Hydrate-forming salts are able to include a single or several water molecules into their structure (crystal water). Taking sodium sulphate as an example, it occurs either as thenardite (Na_2SO_4) or as mirabilite ($Na_2SO_4 \bullet 10H_2O$). Generally, when RH rises, slow conversion (hydration) from thenardite to mirabilite takes place through complex dissolution and multi-step recrystallisation processes. If RH rises further (above the EQRH of about 90-95% at 20°C) mirabilite dissolves - it is in other words hygroscopic. Conversely, when RH drops, the opposite process (dehydration) takes place. Dehydration is generally a much faster process than hydration.[12]

In rather wet and cold climates, salts like sodium sulphate and sodium carbonate "originally" crystallise from solution as hydrated forms (mirabilite and natrite). This is because their dehydrated equivalent (thenardite and thermonatrite) cannot form directly from solution below some 33-35°C. Considering that salts often dissolve on exterior walls in climates with frequent rainfall (or condensation), it is reasonable to maintain that direct crystallisation of the hydrated salt species tend to produce most damage.[13]

Weathering mechanisms

The process of salt damage is a major field of research. Put very simply there are at least two possible mechanisms of weathering when salts are found within the pores of a material (see also fig. 3.3-4):

- Pressure developed due to direct crystallisation from solution. Hydration may be regarded as a special case of crystallisation.
- Pressure developed due to thermal expansion of already formed salt species (for instance gypsum).

Fig. 3.3: *Scaling (or flaking) of a Molasse sandstone due to salt crystallisation (white). Natural outcrop at Martinsbrugg near St. Gallen in Switzerland (see Zehnder 1982) (photo: PS 10/93).*

It is important to be aware of the great influence the stone's pore structure has on the weathering forms which develop as a result of salt crystallisation. Laue, Bläuer-Böhm and Jeanette have clearly shown this phenomenon in a recent case study of the Crypt of St. Maria im Kapitol (Cologne), where large amounts of halite and other salts are present. Sandstone with interconnected macropores and micropores tend to suffer granular disintegration as the main weathering form because when evaporation (by water vapour diffusion) occurs, salts crystallise within the micropores instead of being brought to the surface of the stone.

Fig. 3.4: *Disintegration of a wall painting due to crystallisation of powdery natrite efflorescences. Lavin church in Graubünden, Switzerland (photo: Konrad Zehnder 1984).*

In contrast, a limestone with a very fine, homogeneous and well-connected pore structure allows all salts to be brought to the surface, leading to the build-up of thick salt crusts, but little harm to the fabric of the stone. A volcanic stone (trachyte) with heterogeneous pores mainly in the form of fissures tends to allow the salts to crystallise within fissures near the surface, thus leading to spalling of relatively large fragments.[14]

In general, salts preferentially crystallise where inhomogenities occur. Thus, when stone and mortar are coated by paint layers, it is common to observe salts just behind the paint, which is then in great danger of flaking off. In stone and mortar containing micas, salts often grow on the mica flakes, leading to small fissures and eventually to flaking or other weathering forms.[15]

Salts and frost

Frost is a major weathering agent in cold temperate climates. Since frost damage mainly occurs on strongly exposed architectural elements made of susceptible stone,[16] it will be described with reference to actual situations in later chapters. However, frost may also be of great importance when salt-laden masonry is concerned, for instance in zones affected by water leaks and when the temperature drops strongly just after major condensation events. Frost action on salt-laden stone has mainly been investigated experimentally. Very few - if any - empirical works have been undertaken. Below, only reference to recent experimental studies undertaken by Wessmann on Swedish building stones is made.[17]

Generally, salts in combination with frost may possibly increase the weathering potential due one or several of the following reasons (modified after Wessmann):

- Frost bursting may increase the porosity and surface area of the stone (especially relatively dense stones), thus facilitating more effective dissolution processes, deposition of air pollutants and salt crystallisation.
- Salt bursting may likewise change the structure of the stone, so that frost will have more effect.
- Salt solutions may cause more damage on freezing than pure water.

Wessmann studied the third hypothesis by dilatation tests and standard freeze-thaw tests, using Swedish sandstones, limestone and granite soaked in sodium chloride and sodium sulphate solutions. Generally, in the standard test, she found that weathering rates (in the form of scaling) drastically increased when sodium chloride was present, but that moderate concentrations (0,5-3%) had a more detrimental effect than high concentrations (greater than 4%). Tests performed with sodium sulphate resulted in much less damage than those using sodium chloride. Regarding the susceptibility of the different stones, the least porous granite (0,6%) was least affected, while the moderately porous limestone (3%) displayed extreme damage. Highly porous sandstone (17-20%) also showed great damage, but much less than the limestone.

Wessmann did not explain the actual weathering mechanisms, but the study clearly shows that one has to consider the combined effect of salts and frost when interpreting real weathering situations.

3.3 Air pollution and weathering

The most significant effect of air pollution in relation to building stone is blackening of walls, salt weathering and dissolution of minerals. The simple, overall scheme, discussed by many researchers, is that deposited sulphur compounds and calcium from building materials react to form gypsum, which may give rise to subflorescence and the well-known "black crusts" observed on stone façades in urban areas (fig. 3.5). Presented briefly below are the generally known processes from emission, transportation and deposition of sulphur compounds, via accumulation of gypsum to weathering mechanisms. Much of the information is obtained from the works of Fassina (1988) as well as Cooke & Gibbs (1993).

Sulphur compounds are not the only air pollutants. Due to ever increasing automobile traffic, nitrogen oxides are far more important - especially with regard to human health - in urban areas at present. The effect of air-borne nitrogen compounds on building stones is, however, rather uncertain and a topic of much debate - but it will not be discussed further in this thesis.[18]

Emission and transportation of sulphur compounds

Although decay of natural sulphide, volcanic eruptions and the oceans (sea spray) are important sources of air-borne sulphur compounds on a global scale, they are insignificant when compared to anthropogenic emissions in Europe. Anthropogenic emissions are caused by several combustion processes and industrial practices, of which the most important are:

- Combustion of fossil fuels (oil, coal - heating, industry, traffic)
- Smelting of sulphur-containing ores (esp. sulphide ores)
- Processes in the wood pulp and paper industry

The gas sulphur dioxide (SO_2) is the main sulphur compound emitted. Sulphur dioxide is unstable in the atmosphere for prolonged periods of time (c. 1 day, dependent on weather conditions), it oxidises to form several new compounds of which sulphate (sulphuric acid) is the most important. Sulphate may stay in the atmosphere for a longer time (typically 5 days), which is enough time for long-distance transportation, e.g. across large parts of Europe. Transportation phenomena are strongly dependent on local weather conditions close to the site of emission, as well as on main wind directions in the actual region.[19]

Emissions of anthropogenic sulphur have been strongly reduced in large parts of Europe since the early 1980s.[20] Environmental awareness and clean air acts have led to the use of less sulphide-rich fuels and cleaning equipment in polluting industries. The picture is, however, entirely different in other parts of the world.[21]

Deposition of sulphur compounds on stonework

Sulphur compounds are deposited on stonework in two main ways:

- As *dry deposition* of sulphur dioxide (gas) and sulphur aerosols ("dust")
- As *wet deposition* of sulphuric acid and sulphate ("acid rain")

Considering that sulphur dioxide is not stable in the atmosphere for prolonged periods of time, we understand that sulphur dioxide emitted from *local sources* is by far the most important source of dry deposited sulphur compounds. Wet deposition of sulphuric acid and sulphate is, in contrast, important in regions affected by *distant sources*. Generally, local sources are today considered much more important than distant ones with regard to weathering phenomena occurring as a result of sulphur dioxide emissions.

Wet deposition takes place on building areas receiving rain (and run-off), while dry deposition may principally occur everywhere on the building. However, dry deposition is relatively more important in sheltered locations because the sulphur compounds are readily washed away at exposed places (depending on properties of the substrate). In addition to the actual concentration of sulphur dioxide in the air and prevailing wind conditions, the amount of *dry deposited* sulphur compounds are strongly dependent on the following factors:[22]

Fig. 3.5: *Black crusts on a limestone sculpture in Lausanne, Switzerland. The black-and-white pattern has developed because of rain washing (run-off) (photo: PS 3/93).*

- The properties of the substrate (esp. porosity). More porous stones tend to “take up” more sulphur dioxide
- The moisture conditions on the substrate (wetness after rain, relative humidity, condensation phenomena, presence of hygroscopic salts, esp. NaCl). Moist stones tend to “take up” more sulphur dioxide.

Formation of gypsum

The formation of gypsum due to dry and wet deposition of sulphur compounds involves complex chemical reactions. The wet deposition of sulphate (sulphuric acid) on stones containing calcium (calcite) may be simplified like this:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$
$$\text{Calcite + Sulphuric acid} \rightarrow \text{Gypsum + Carbon dioxide}$$

Dry deposition involves, in contrast, much more complex multi-step processes, although the end product (gypsum) is the same. The rate of gypsum formation as a result of dry deposition is also highly dependent on several factors other than air concentration and available calcium, including:[23]

- Properties of and moisture conditions on the substrate (see above).
- The presence of catalysing agents, such as metal oxides (esp. iron and manganese), nitrogen oxides and ozone (from air pollution)
- The presence of soot particles (carbon-containing particles)

As can be seen, the process involves two important “end members”: dissolution of calcite and formation of gypsum. In this connection it should be noted that dissolution of calcite also takes place without sulphuric acid present (due to rain water with dissolved carbon dioxide).

The presence of calcium is normally a prerequisite for the formation of gypsum.[24] Hence, calcareous stones (limestone, marble, certain sandstones) are the most susceptible to air pollution. However, several other stone types also contain minor

Fig.3.6: *Cathedral of St. Stephan in Vienna. The rain-washed west side of Stephansturm has less black crusts than the south side of the cathedral (photo: PS 4/94).*

amounts of calcite, dolomite and/or magnesite. When dolomite and magnesite are present, magnesium sulphates are likely to form as well, but this process has not been thoroughly investigated. The reason why gypsum may form due to air pollution on stone containing no calcium whatsoever (e.g. granite) is usually because calcium is supplied from surrounding mortar joints. There are, moreover, often traces of former whitewash on many stone buildings - whitewash not entirely removed by cleaning operations.

Accumulation of gypsum and formation of black crusts

It is easy to understand that in sheltered locations, e.g. beneath projecting elements such as cornices and string courses, an accumulation of gypsum formed as a result of dry deposition will take place. The black or dark grey colour of gypsum crusts is caused by dust and diverse inorganic and organic particles (soot, asphalt dust, metals, biofilms etc.).

At places where lashing rain affects buildings from one main direction only, it is often possible to observe whole façades covered by black crusts. This is the case in Vienna where the overall wind direction is westerly.[25] The cathedral of St. Stephan (fig. 3.6) is consequently "black" on most sides facing north, east and south, as well as on the lower parts of walls facing west (because these walls are protected by nearby buildings). All projecting elements are, however, "white" on their upper surfaces (fig. 3.7), and it is usually possible to observe a few "white" lines on otherwise "black" walls as well. The latter phenomenon is caused by run-off from elements upon which rain water accumulates.

The run-off pattern on façades is a major factor governing the distribution and accumulation of black crusts. Due to the fact that dry deposition may take place on whole façades (when it is not raining), gypsum which is not carried away by run-off tends to become redistributed along the margins between rain-washed and sheltered areas. In this particular zone it is also possible to observe an accumulation of cauliflower-like black crusts - they are usually thicker than in the sheltered areas.[26]

In porous stone - in contrast to dense stone - gypsum formed as a result of air pollution may also accumulate in particular zones below the surface, even at exposed places, and produce weathering forms like contour scaling (fig. 3.8).

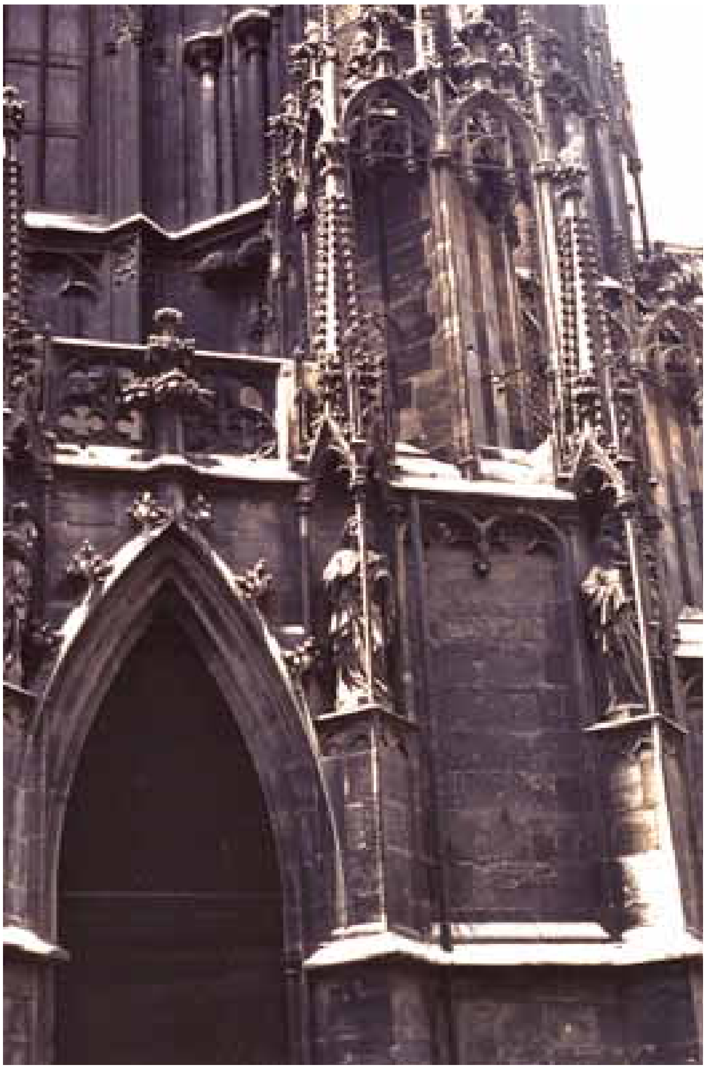


Fig. 3.7: *Cathedral of St. Stephan in Vienna. The snow-white projecting elements of limestone make a great contrast to the walls which are covered by black crusts (photo: PS 4/94).*

Weathering mechanisms

One of the main effects of air pollution (acids) is the increased dissolution of minerals (especially carbonates) on rain-exposed walls. In limestone and marble, this may result in a relatively rapid thinning-out of the stone, but few other problems.

Concerning weathering mechanisms, it is very important to be aware of the difference between dense and porous stone (fig. 3.8). Sulphate/gypsum is not able to penetrate deeply into dense stone, implying that black crusts usually can be observed as mere layers on the surface - rarely doing any specific harm to the fabric of the stone.[27]

In contrast, porous stone, especially calcareous sandstones, allow sulphate to penetrate deeply into their fabric. Such stone typically develop granular disintegration below a layer of partially flaking black crusts in sheltered locations. On exposed places there are no black crusts: the formation of gypsum takes place in particular zones below the surface - giving rise to granular disintegration, flaking and contour scaling depending on where gypsum accumulates. Except for the obvious dissolution of carbonate minerals, granular disintegration, flaking etc. form mainly as a result of crystallisation of gypsum.[28]

These explanations are indeed simplified. In reality this type of weathering is usually complicated by several additional processes. Salts other than gypsum may be present, frost may play a role and the hygric/thermal behaviour of the stone in question may contribute as well. Moreover, the actual source of gypsum itself is frequently difficult to determine - stones and mortars may well be as significant as sulphur dioxide from air pollution in many situations.

It is worthwhile noting that black discoloration of building façades may be caused by completely different processes to those which form black crusts. Dark biofilms (fungi, algae, lichens etc.) are extremely important and may at a distance be mistaken for gypsum crusts. Siliceous crusts on sandstones may also be mistaken for black crusts.

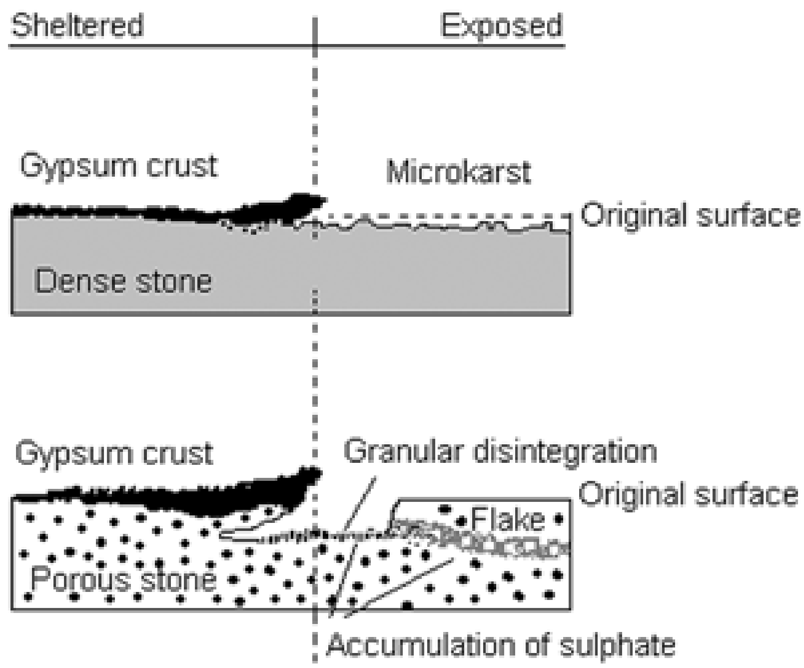


***Fig. 3.8**: Different weathering phenomena observed on porous and dense stones as a result of air pollution (chemical dissolution, black gypsum crusts and accumulation of gypsum) (after Arnold 1984b).*

3.4 The disadvantages of Portland cement

In previous chapters it was established that Portland cement mortars may have a detrimental effect on the large-scale behaviour of masonry buildings (chapter 2.3) and that they often give rise to large amounts of alkaline salts (chapter 3.2). Here follows a summary, worked out by Bernard Feilden, of the most serious disadvantages of Portland cement when used in historic masonry which was built from “weak” lime mortars/plasters:[29]

1. Its use is not reversible. To remove it damages all historic building materials, which cannot then be recycled.
2. It is too strong in compression, adhesion and tension, so that it is not compatible with the weak materials of historic buildings. It is a paradox that such weak materials have the greatest durability.
3. Because of its high strength it lacks elasticity and plasticity when compared with lime mortar, thus throwing greater mechanical stresses on adjacent materials and hastening their decay.
4. It is impermeable and has low porosity, so it traps vapour as well as water and prevents evaporation. Consequently it is no good for curing damp walls. In fact, the reverse is true, for if used it only drives moisture upwards. When used as a mortar its impermeability accelerates frost damage and increases internal condensation.
5. It shrinks on setting, leaving cracks for water to enter, and because it is impermeable such water has difficulty in getting out. Therefore, it increases defects caused by moisture.
6. It produces soluble salts on setting which may dissolve and damage porous materials and valuable decoration.
7. It has high thermal conductivity and may create cold bridges when used for injections to consolidate walls.
8. Its colour is “cold” grey and rather dark. The texture is too often smooth and “steely”. These characteristics are generally judged aesthetically incompatible with traditional materials.

This list of disadvantages is not applicable to modern buildings and constructions made of Portland cement mortars and concrete. It is also important to note that on several occasions concrete has indeed helped in saving large old buildings, for instance when used to strengthen weak foundations.[30]

A topic which has not been seriously discussed by weathering researchers is whether the alkaline components of Portland cement may give rise to an alkali aggregate reaction in stone. Alkali aggregate reaction - a chemical reaction between alkaline components and certain minerals - is a well known cause of severe failure in modern concrete constructions.[31] It has also been reported that bricks soaked in alkaline solutions may chemically break down (when salt crystallisation mechanisms could not have been active).[32] It would be interesting to know if similar phenomena can take place when large amounts of Portland cement mortar or concrete are in contact with moist stonework.

Part II

Nidaros cathedral and its environmental setting

Fig. 4.1: *Construction of the west front in the 1930s (photo: ARW).*

Chapter 4

General building history

The history of a medieval cathedral can be written in numerous ways. Below, I have concentrated on historical events and processes of major importance in order to aid the understanding of currently observed weathering phenomena. I have paid particular attention to the last main restoration phase, begun in 1869 and not finished until 1969. Several conservation measures were also undertaken after the main restoration of each building part. Such measures are described in chapter 11-18 and they are also listed in appendix 1.

4.1 The rise of the cathedral (1030-1328)[1]

Romanesque precursors (1030-1140)

1030: King Olav Haraldson, who is regarded as the main introducer of Christianity to Norway and also as the major unifying force for the country, died in the battle of Stiklestad, some 100 km north of Nidaros. He was made a martyr saint, whose corpse apparently soon began to work miracles. A wooden chapel was later built on his grave at Nidaros, but there are no visible signs of this church today. The death of St. Olav was a primary reason for the establishment of Nidaros as an ecclesiastical centre.

1070-1140: King Olav the Peaceful (1066-93), the son of King Harald the Hardruler (1042-66) who lost the battle of Stanford Bridge in 1066, began building a Christ church to house the shrine of St. Olav. This stone church was probably built in the heavy Anglo Saxon Romanesque style, but whether it was completed is unknown. It seems that the church included a small choir, a nave and a large west tower where the present central tower is situated. The reason why the south wall of the present choir stands at an oblique angle compared with the rest of the church is probably related to the Anglo Saxon church. When the church was successively demolished, giving way to new plans, large numbers of building stones were almost certainly reused.

The Norman and Transitional periods (1140-1180)

1152-1153: The Archbishopric[2] was established at Nidaros, strengthening the town's position as an ecclesiastical centre. The establishment required enlarging the Christ church, as well as building the Archbishop's palace because of the growing number of clerical staff, as well as pilgrims visiting St. Olav's shrine.

1140-1160: The lower part of the present transept, including vaulted eastern chapels and the north porch, was built on each side of the old tower. Easily recognised by chevron arches, the lower part of the transept is typically Norman, a style which had been refined in Normandy and on the British Isles since the late 11th century. Being bold and massive, with

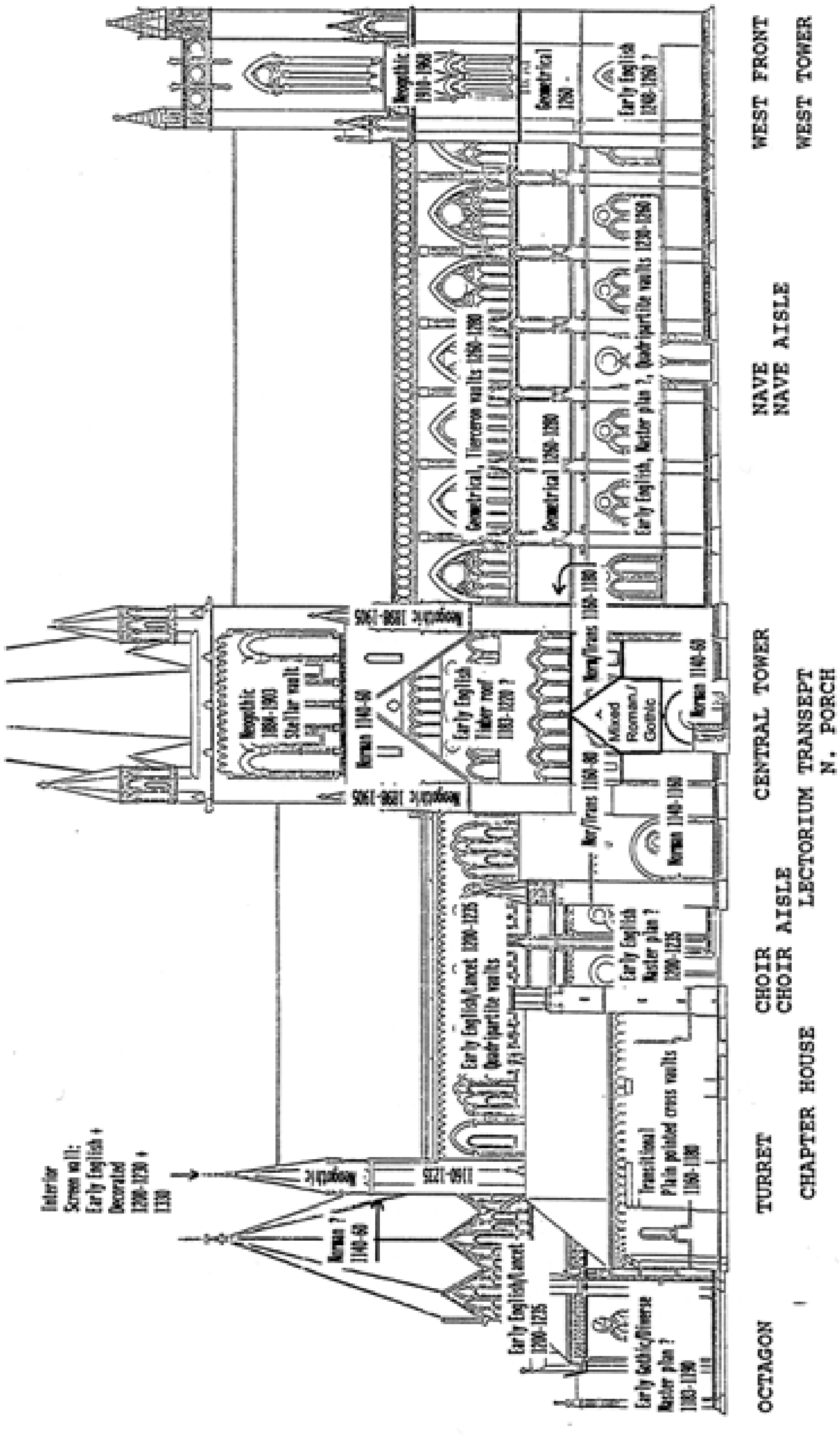


Fig. 4.2: *North façade of the cathedral showing the original building period and architectural style of each part. Reconstructed on the basis of Fischer (1965).*

semicircular arches, rib vaults and decorations like the chevron and scalloped capitals, the style was eventually mixed and replaced by Gothic style in the middle and late 12th century.[3]

1160-1180: As in England, the so-called Transitional style is often used when describing the mixture between Romanesque and Gothic styles in Nidaros cathedral. Possibly the first building in Norway to include pointed arches and plain pointed rib vaults, the chapter house was built in this period. As the Cistercians may have given the lead, Gothic innovation was supplemented by plain Cistercian elements and traditional Norman forms, giving the building an austere, massive appearance. The triforia and clerestories of the transept are also supposed to have been built in this period.

All these works were undertaken by the widely travelled, second Norwegian archbishop, Eystein Erlendsson (1161-1188), who is regarded as the master of the cathedral. He was in charge of building the chapter house and parts of the transept, but first and foremost he was the master of the Gothic cathedral.

The eastern part of the Gothic cathedral (1183-1235)

1180-1183: Due to civil war in Norway, archbishop Eystein had to flee to England where he was fully exposed to the new Gothic style. Eystein probably brought Norwegian craftsmen with him in exile and he is supposed to have visited several cathedrals and monasteries (e.g. Canterbury). The new Gothic structures being built in England, their lightness and contrast to the heavy Norman architecture, must have struck him. Upon returning to Norway he abandoned plans for finishing the Nidaros cathedral in the Norman style. Instead a Gothic cathedral was to arise.

1183-1190: The first consequence of this new course included replacing the old, tiny choir with the magnificent octagon, which was to house the shrine of St. Olav. The octagon is an artistic puzzle - and nowhere else in the world do we find such an east end to a medieval cathedral. It includes five outer walls of the aisle and three small, vaulted chapels to the north, east and south. Inside there is an octagonal ambulatory with arcades rising up to the triforium and the lancet openings of the clerestorium. Everything is crowned by an octagonal, pointed rib vault. Six flying buttresses were included, but as they are semi-circular and extremely slender, they lack structural significance. The decorative richness of the octagon is unique, lacking any kind of single model. Mouldings, capitals, heads, animals, dragons - everything is combined in a manner inspired by the most diverse ideals. However, the freshness is strictly framed by a heavy base, a flower ornamented string course running along the walls and the dog tooth ornamented groups of pointed lights. The only portal in the octagon - “the Bishop's entrance” - can be found in the south-east wall. Archbishop Eystein did not live to see much of the work completed. After his death in 1188 building operations probably ceased for a while due to civil war.

1200-1235: The erection of the central and upper parts of the octagon may have resumed after 1202, but it was not before 1210 that further work became really intensive. Now the erection of the octagon and the new choir continued simultaneously using newly recruited masons, some of whom probably came from England. Having built the outer walls of the choir's aisles in much the same way as the outer walls of the octagon, the masons constructed the arcades and clerestories by applying many elements which can be found in the east transept of Lincoln cathedral. These are typical of the Early English Gothic style; the quadripartite vaults (which were originally intended as sexpartite), the tall and narrow lancet openings, the dog tooth ornaments and the crocket motif. The heavy vaults and the size of the new choir demanded flying buttresses. However, the buttresses are rather slender - a puzzling fact which, as we shall see later, has caused great structural problems during the life of the cathedral. Another part built along with the choir was the elegant south porch ("King's porch"). Further works in the period before 1240 included the gables of the transept, the turrets and the upper part of the central tower.

The western part of the Gothic cathedral (1235-1300)

1235-1250: It is improbable that the eastern part of the cathedral was finished before building operations commenced on the nave. There are in fact striking similarities between the walls of the nave's aisles and the lower parts of the choir and octagon. All have similar window openings - groups of two pointed lights below a circular opening. However, when compared with the octagon and the choir, the lower part of the nave includes but a few decorations, making the whole impression more "academic" and calm.

1250-1300: The interior arcades, the buttressing system, the clerestory and the vaults of the nave all show an architecture quite different from the eastern part of the church. We meet the ripe Gothic style as is found in, for instance, the Angel choir of Lincoln cathedral. There might in fact be a close connection between this choir and "our" nave, but which building inspired the other is hard to say. What is certain is that the decorative richness of the arcades and the bar tracery of the clerestory windows marks the end of the Early English Gothic style and the beginning of the heavily ornamented Decorated style. This is traditionally regarded as the second phase of the development of English Gothic.[4] The vaulting of the nave's aisles is traditional quadripartite, while the nave has tierceron vaults. Even if the size of the nave is limited compared with large English or French cathedrals, it has a fully developed buttressing system which is several times more solid than the frail system of the choir.

If the east end of Nidaros cathedral (the octagon) is a spectacular construction, the west front marks the second highlight of the building. Since it was only the two lower storeys which remained intact when the restoration began in 1869, it is not known what it really looked like towards the end of the 13th century. However, it seems to be clear that the front, in principle, is an English screen front, which may be regarded as a particular way of constructing the west end of a cathedral. A traditional solution to the problem was to build two flanking towers rising from the aisles, while the west front in Trondheim has large towers on each side of the aisles. Towards the end of the 13th century, the building of the flanking west towers may have been well underway, but were probably never completed in the Middle Ages.

4.2 The fall of the cathedral (1328-1869)

The fall of the cathedral began in the 14th century due to several coinciding circumstances, including fires, the Black Death and political and religious struggle.

Catastrophes and rebuilding (1328-1537)[5]

1328: Lightning struck the cathedral on April 4th and a disastrous fire broke out, causing all wooden structures to be destroyed. Piers and arches were affected and large cracks developed in the vaults. There is reason to believe that the interior was completely repaired, most radically with regard to arches and tracery of the octagon. The screen wall between the octagon and the choir was also rebuilt in the Decorated Gothic style.

1349-1350: The Black Death - the great plague sweeping across Europe - undoubtedly ended all building operations for a long time. In the 14th century general decay of Norwegian political power also occurred - from 1319 the country was united with Sweden and from 1380 to 1814 with Denmark.

1432: Lightning struck the cathedral, which once again burnt “to the ground”. This statement may be somewhat exaggerated, but the interior was probably severely affected. However, recently restored parts in the octagon seem to have been little afflicted. After the fire, the rose window of the gable in the north transept was replaced by a Gothic bar tracery window. Moreover, the King's porch was turned into a closed (burial?) chapel. A similar chapel was also built by St. Mary's portal on the south side of the nave.

1453: The cathedral may have been struck by another fire, but this assumption is not based on historical documents. However, the cathedral was described as “decaying” in 1453. The most serious problem for the cathedral during the 15th century and later was the lack of funds for maintenance and repairs.

1510-1521: Archbishop Erik Valkendorf raised necessary funding and undertook a thorough restoration of the octagon. Large areas of the interior as well as the gables of the three radiating chapels were repaired. The restoration was remarkably “modern”, including careful - but lifeless - copying of older forms.

1531: The devastating city fire on May 5th made the cathedral a “pitiful and sorry” sight:

> The roof and the tower helmet had burned, the vaults of the [choir] and nave had collapsed. The walls of the central tower were destroyed down to clerestory level, while the appearance of the upper terminal is unknown. The nave suffered the most. Only the sad remains of the west towers, the west front and the exterior walls of the aisles were left. The octagon and the chapter-house fared the best. Here the vaults held their own [ ]. The Archbishop [Olav Engelbrektsson] mentions that his first goal was to bring the church under roof. How much of this he accomplished before he was forced to flee, is unknown. The eastern parts comprising octagon, [choir] and chapter-house were perhaps brought under roof. But before the [choir] could be roofed, new supporting walls had to be erected. The magnificent [arcades of the choir] had been destroyed and were replaced by thick smooth walls. The material used was rubble, column stumps and mouldings from the destroyed parts of the church. Towards the aisles the walls were pierced by high, pointed arcades [ ] which corresponded with [ ] plain pointed-arched windows in the clerestory. Any form of decoration was renounced. The general principle was to save what could be saved as quickly as possible by getting a roof over the remaining vault and walls.[6]

Today we have to be happy about this strategy - because soon the Archbishop faced more serious trouble...

1537: ...the Reformation! Catholicism was subsequently abolished and the last Norwegian Archbishop, Olav Engelbrektsson, fled to the Netherlands. The cathedral's land holdings and fabrica fund were confiscated by the king.

From cathedral to parish church (1537-1708)[7]

1540-1580: The repair works naturally stopped for a while after 1537, but they resumed in order to close the large arches of the central tower towards the west and south with thick massive walls. The upper storey of the tower was also rebuilt with a high pointed helmet. Materials for the works were obtained from other dilapidated churches in Trondheim. However, rebuilding of the nave was abandoned. It remained in ruins, and was periodically used as a stone quarry, until the 20th century. Until then the congregation had to use the octagon, the choir and the crossing below the central tower for services.

1585-1630: Even if repairs until now were managed with the help of other churches, this situation could not continue - the church needed an income of its own. In 1585 the cathedral was consequently made a parish church for half of Trondheim. The remaining walls of the nave were already roofed by 1590 in order to protect the ruin, and in 1625 burials were permitted within the remains of the church for a very high fee - an important source of income for the poor church. During the subsequent 180 years (until 1805) the floor was dug up and literally filled with graves. The Lectorium and the chapter house were the only parts of the church never used for this purpose.

1633-1650: In this period the new Baroque style was introduced in the church. The choir got enclosed, wooden pews for wealthy families, and much of the interior was plastered/whitewashed and painted with bright colours. In addition to the restoration of the octagon vault, a significant work was the erection of an enormous spire above the central tower in 1638. This spire was a 69 m high wooden construction, about 20 m taller than the present metal spire!

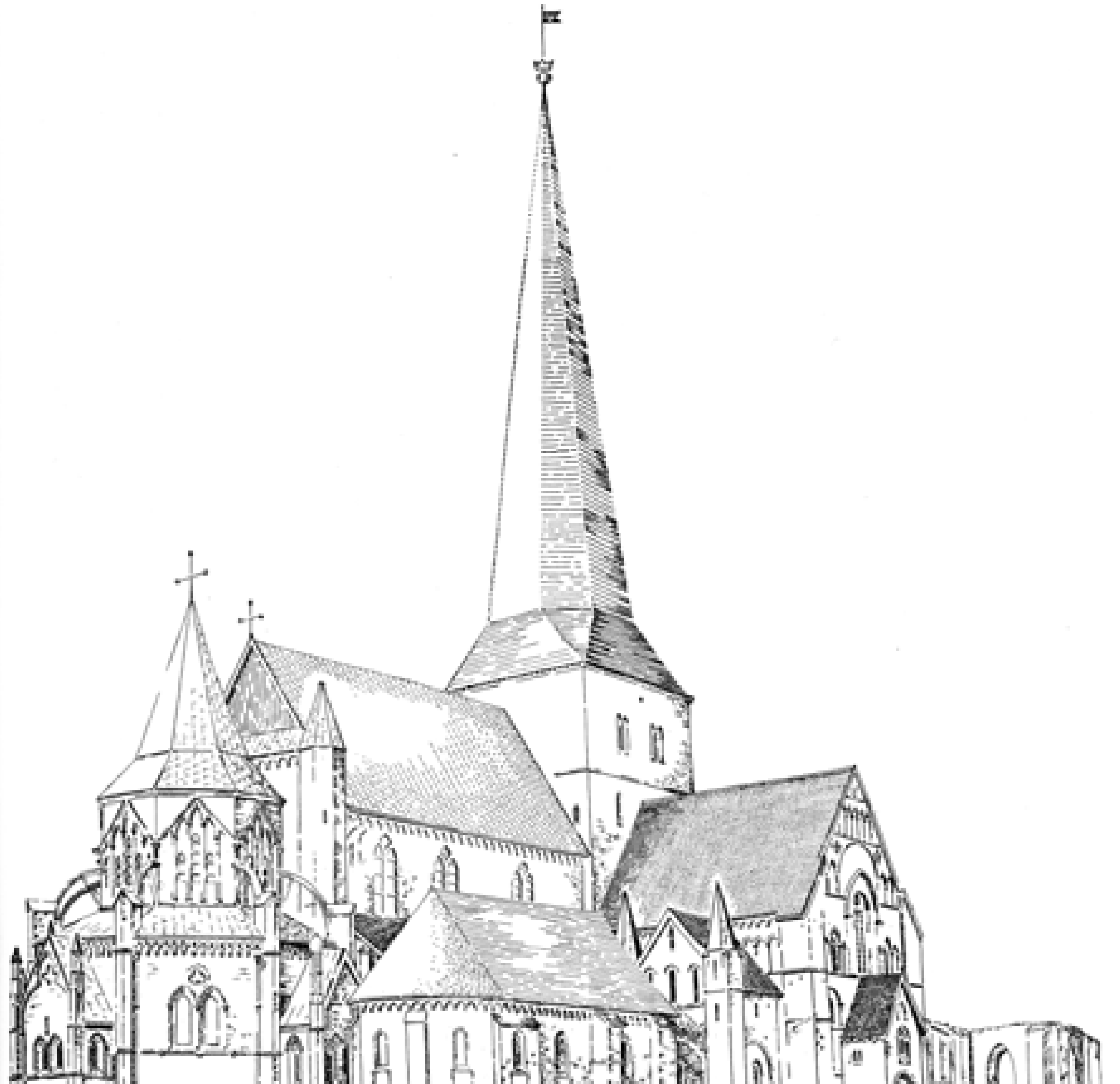


Fig. 4.3: *The cathedral between the fires in 1708 and 1719. Note the tall spire. Reconstructed drawing by architect Arne Berg, published in Lysaker (1973).*

1666: The end wall of the south transept was rebuilt with masonry up to the gable and roofed after the 1531 fire. In 1666 the gable triangle followed. It was built with bricks and plastered. Luckily, the church escaped the ravages of the large town fire in 1681.

1689: During a hurricane on the night of December 12th, the tall spire of the central tower blew down, causing great damage to the roof and masonry of the north transept, the Lectorium and the chapter house. Three bells fell down causing great damage to the interior of the crossing. Due to difficult times after the city fire in 1681, only a temporary spire was erected. Other roofs on the north side of the church were covered with slate. In 1690 a burial chapel was built by the gable wall of the south transept.

1705-1707: New and ambitious plans for restoring the church were made, including for example roofing the remnants of the entire nave. Little was accomplished, but it is worth mentioning that the remaining parts of the west front, which were at the point of collapse, were shored up with solid supporting pillars.

New disasters in an unhealthy church (1708-1814)[8]

1708: The town fire on August 4th destroyed “everything that could be burnt” in the church. It was the fourth town fire in 110 years and this time also buildings situated a little outside the city centre were affected. Luckily, both the Lectorium and the chapter house escaped the flames because of the solid vaults and iron doors. In this way the chapter's library and the archives of various city institutions were saved.

1708-1718: Once again efforts were made to get the different parts of the church re-roofed. The octagon was given an octagonal helmet, while the central tower got a spire which was only a little lower than the previous one that blew down in 1689. Spires, as well as the roof of the choir were covered with copper, while remaining roofs got Dutch tiles. The ruin of the nave was, however, not roofed. The arcades of the octagon were filled with brick masonry in order to strengthen the construction. The interior was largely repaired according to the tradition prevailing before the fire; the masonry was also now plastered or whitewashed, while many remaining decorations were painted.

1719: In 1718 Trondheim was impoverished because of a long Swedish siege and was unprepared for the next catastrophe: On January 25th 1719, at 11 p.m., the spire of the church was struck by lightning during a terrible storm - an unusual event at this time of year - and the roofs and the interior burnt. Once more the chapter house escaped the flames, except its wooden roof.

1719-1740: Due to the effects of the siege, the congregation were the sole source of funding for repairs after the fire. Repairs therefore took many years, and it was not until 1735 that all the roofs were covered with tiles and copper. In this period the church also obtained its characteristic profile which remained until the late 19th century. The octagon was given a copper covered Baroque cupola, topped with an octagonal gallery. The new, low pyramidal roof on the central tower was originally a preliminary solution in order to gain time for repairing the badly damaged masonry below. However, this roof nevertheless became permanent. After the masonry was repaired, using many iron cramps, the roof was given a copper cover in 1734. Similar pyramidal roofs, but covered with tiles, were also built above the remains of the west towers. In this period the first real repairs of the ruined nave and west front were undertaken. The remaining walls were repointed, consolidated by iron cramps before they were whitewashed. In 1739 the walls were roofed - which meant that the remains of the nave were rescued. The interior of the church after 1719 did not differ essentially from the earlier, Baroque interiors.

1740-1800: Throughout the 18th century the church underwent unwholesome changes involving crypts and graves beneath the floor. Four burial chapels had been erected before 1731, and later the entire floor, including the ruined nave, was filled with graves. As many as 1000 people may have been buried in the church before this practice was forbidden in 1805. At that time, the church was quite probably a stinking, humid and unhealthy place to be. The chapter house, which by the 1750s was the very hub for the city's social institutions, also became increasingly damp inside. Because of the dampness, the archives of the institutions gradually decayed. In 1778 the vaults and walls of the chapter house were once again whitewashed and in 1781 a stove was installed in this cold room - the first “heating system” of the cathedral.

From coronation church to historical monument (1814-1869)[9]

1814: Norway declared independence from Denmark on May 17th 1814, only to be forced into a loose union with Sweden which lasted until 1905. The constitution of 1814 was a most important document for the future fate of the cathedral. Due to its age and great size, the church was the only building mentioned in the constitution and appointed as the country's coronation church. In 1818, 1860 and 1873 the kings of Norway-Sweden were crowned in Trondheim as well as in Stockholm. The glorious medieval history of the cathedral was viewed as a support for feelings of national identity, and this must be regarded as a major reason leading to restoration in 1869.

1814-1818: Even if the state felt a certain responsibility for the church after 1814, the church itself was a very sad sight. The nave and west front were in a more ruinous condition than ever and the rest of the church had to be heavily renovated before the coronation in 1818

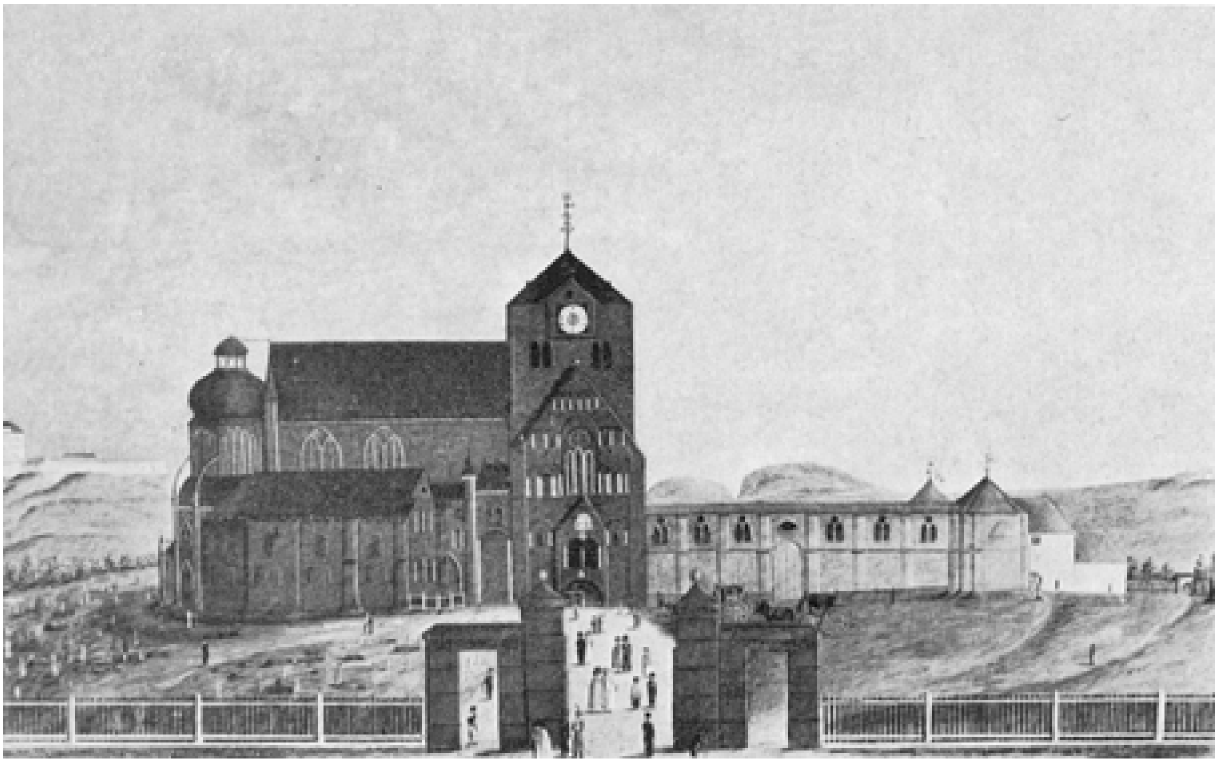


Fig. 4.4: *The north façade of the cathedral, probably in 1818. The dark colour of the church (except the nave) represents the paint applied before the coronation in 1818. Note also that ornaments and columns are painted white. Drawing by P.H. Kriebel.*

All exterior walls (except the nave and west front) were consolidated by lime mortar and painted. Most of the remaining columns were whitewashed and 65 wooden columns, painted as marble, were even inserted to give the church as beautiful an exterior as possible. Moreover, interior masonry was once more plastered and whitewashed and movable decorations were painted in rich colours. This renovation was in reality an extremely superficial one; "underneath" the glorious exterior, which many people protested against, decay was lurking...

1818-1837: Because of the decay, the National Assembly was asked for financial contributions for thorough repairs. The work was planned to follow prevailing traditions, and was merely a proposal for consolidating remaining masonry. The plan was, however, turned down, and the only work undertaken was the renewal of the octagon vault which threatened to collapse in 1834. However, use of inexperienced craftsmen and poor workmanship meant that the vault had to be renewed again by 1875.

1837-1847: The Romantic and Neogothic movements, which were already established throughout Europe by the end of the 18th century, leading to restoration of hundreds of medieval churches,[10] finally started influencing the debate on *why* and *how* the Nidaros cathedral should be treated. Since the cathedral was regarded as a national responsibility, the National Assembly decided in 1841 to finance a preliminary investigation on the condition of the cathedral. The German-born architect Heinrich Ernst Schirmer was appointed for the study.

Schirmer became a most enthusiastic spokesman for the restoration of the cathedral for nearly 30 years, and his first plan was presented in 1842. From a modern perspective it was a terrifying plan! Schirmer regarded the nave as the most valuable part; he wanted to reconstruct it, and was prepared to sacrifice the choir by moving the octagon towards the transept. Luckily, the plan was never realised, partly because the National Assembly turned the plan down, and partly because of pressure from other engaged people - foremost of which was the Norwegian painter J.C. Dahl. Meanwhile, preparations for the next coronation were undertaken. Wooden floors were laid in the choir and the south transept, a brick floor was laid in the very humid north transept and in addition the interior was "beautified". However, the coronation in 1847 of Oscar I never took place in Trondheim.

1847-1860: The coronation interruption gave Schirmer time to become more familiar with the architectural history of the cathedral, and in 1851 he presented a radically new plan for restoration. He no longer found any part of the church of inferior value and proposed to start by restoring the octagon and the choir to their "original beauty". Later on reconstruction of the nave could follow. The plan finally passed through the National Assembly in 1854 when funds were appropriated for preliminary works.

However, objections arose from professional quarters, firstly from N. Nicolaysen, leader of The Society for the Protection of Ancient Monuments which was founded already in 1844. Nicolaysen was sceptical towards the whole idea of restoration. After several years of investigation and debate, he maintained that preservation of what was left of the church was better than restoration. However, Nicolaysen also wanted to remove most parts added to the church after the Reformation. Much of the interior - for instance 50 closed pews by the walls of the choir - were removed in 1860 when a new coronation intermezzo was underway. Schirmer was responsible for this "beautification" of the church and he created a coronation theatre where the setting concealed a less flattering reality - a decaying church.

1860-1869: Awaiting a final decision about the restoration, Schirmer started work on the new furnishing of the church in 1861. In that year the church also got its first real heating system - a coal fired central heating plant located in the corner between the north transept and the nave. Then - in 1862 - experts examined the ground conditions below the church and the stability of the walls. They established that most of the walls inclined outwards considerably

Fig. 4.5: The cathedral from SE in the 1860s (photo: ARW, no. 3593).

and that there was no water drainage system. Opponents of restoration believed these findings would represent the final blow for all restoration plans because it meant that major sections of the walls would have to be dismantled. Schirmer, however, stuck to his conviction "that only a complete restoration can save the church from ruin" and once again undertook careful investigations. These were referred to in 1868 when a committee of enthusiastic citizens of Trondheim managed to turn the tide. The National Assembly gave permission to restore the chapter house. In July 1869 Schirmer assumed leadership of a work programme for which he had fought nearly 30 years.

4.3 The second rise of the cathedral (1869-1969)[11]

Architect Schirmer started work on the chapter house with stylistic ideals in mind. Firstly, he wanted to bring the decaying building back to what it might have looked like in the 12th century. Secondly, he wanted to obtain an architectural and artistic wholeness. Due to the lack of archaeological evidence, he had to use his own imagination when regarding fulfilment of the former aim. Regarding the latter aim, he demolished large parts of the building and rebuilt it with hard sandstone not matching the properties and colour of the old soapstones and greenschists.

Fig. 4.6: *The cathedral from NE in the 1860s (photo: ARW, no. 736).*

A brief note on restoration principles

Schirmer was in practice sacked after only two years because of criticism he received from professional quarters, leaving the way open for architect Christian Christie. During his long reign from 1872 until his death in 1906, Christie achieved a more significant position than any other restoration architect involved with the cathedral later on. He began with restrictive restoration ideals:

> The governing principle was henceforth based on scientific building archaeological investigations before intervention. Restoration measures should only include consolidating masonry, replacing damaged stone and supplementing missing parts based upon archaeological evidences. It was in effect restoration governed by the premises of the building itself, and not by general knowledge about Gothic architecture.[12]

Already in this programme there are significant differences between Christie's ideals and what “real” preservationists such as John Ruskin demanded - to renounce any kind of replacement. Furthermore:

> This programme was only enforced with regards to the medieval sections of the building. Valuable parts added after the Reformation were inexorably removed, such as the beautiful Baroque cupola crowning the octagon, which was replaced by a spire in line with stylistic ideals. This programme was in practice similar to what Schirmer demanded - to complete the building in its medieval form.[13]

Before the reign of Christie ended, he had restored and reconstructed large parts of the building, made plans for further reconstruction work and also added several new compositions.

Roughly summarised, most work undertaken after the completion of the choir in 1890, and particularly after the last plan of Christie was fulfilled (the completion of the nave in 1930), had little to do with restoration or reconstruction. Throughout the rest of the 20th century work on the west front and west towers only included Neogothic building tasks. There were, however, great debates about how to undertake these Neogothic operations, especially concerning the erection of the upper parts of the west front and the west towers.

Fig. 4.7*: The cathedral from NW in the 1860s (photo: ARW, no. 3158).*

The chapter house (1869-1871)

Although Schirmer may be blamed for his hard restoration of the chapter house, it should be remembered that the building was in a dreadful condition in 1869. The walls were inclining because of the heavy vaults, there were large cracks in the masonry, the interior was extremely humid due to rising damp and water leaks, earth covered the base and the upper parts of the two flanking towers were missing. Moreover, Schirmer had to start with an inexperienced workforce because the restoration was one of the first carried out in Norway.

Nonetheless, Schirmer took drastic measures. First he stripped the interior of all parts that were added after the Reformation. Then he pulled down most of the vaults and the northern and western walls. The walls were rebuilt with new stone, but for the interior and parts of the western wall old stones were redressed and used again. Subsequently a new brick vaulting was made before a cellar was excavated in order to house the new central heating plant. Digging out the cellar - and adding a new drainage system - meant that the rising damp problem was eliminated. Finally, two heavy, flanking towers were added.[14]

The only parts left largely untouched were the vaults in the small transept and the walls of the apse. However, plaster and paint were removed and stone redressed. Hence, the chapter house appeared as a new building when its restoration was finished in 1871.

The octagon (1871-78)

The octagon is much larger than the chapter house and thus presented quite different problems. Moreover, the condition of the octagon was not too bad, except that the central vault erected in the 1830s once more threatened to collapse. There were also large cracks in the arcades, and due to inclined outer walls, several pillars in the radiating chapels were out of balance. Exposed elements like the base, the string course and pinnacles were also in a rather poor condition. Being in such a state, the octagon certainly had major water leaks too, in particular from the gable triangles of the chapels.[15]

First, the old graves below the floor were dug out and put in order, foundations were strengthened, the base replaced and proper drainage system installed. Subsequently, the chapels were restored by pulling down the gable triangles, getting the pillars into vertical alignment, repairing the vaults and rebuilding the gables with old stone. String courses were replaced, as were many damaged ashlars and decorative elements. Post-Reformation whitewash was also stripped from exterior and interior masonry, which was subsequently redressed, but only where the surface seemed too weathered.[16]

The restoration of the walls and vaults of the aisle followed a similar pattern, while the interior of the ambulatory, the clerestory and the ambulatory vault presented other problems. As mentioned above, the Baroque cupola was replaced by a lead covered spire. Subsequently, the vault was removed and a new one constructed. Other work included a complete restoration of interior arcades and tracery, together with reconstruction of the marble floor. Finally a new high altar was put in place during 1882.[17]

In conclusion it is possible to state that masonry and decoration were carefully restored in comparison to the chapter house. It is important to note, in a weathering context, that the masonry of the octagon is largely medieval.

The choir (1878-1890)

The difficult octagon restoration took a long time, but it included rather small and simple measures when compared with the restoration and reconstruction of the choir. The only remaining medieval constructions in the choir were the turrets, the walls of the aisles and the lower part of the King's porch. The rest was added after the 1531-fire. In addition to the thick 16th century walls standing on the place of the medieval arcades, both the clerestory and the roof (no vaulting) were post-Reformation. Inclining by as much as 40 cm outwards on the top, the walls of the aisles presented the greatest technical problem. The inclination was probably a result of slender (vertical) buttresses unable to withstand the pressures of the roof and the former, heavy vaults.

Before screwing the walls back into vertical position,[18] the clerestory and the King's porch were demolished, the foundations strengthened and a new base put in place. During subsequent demolition of the thick inner 16th century walls, many mouldings and decorations from the medieval arcades were found embedded in the masonry. These fragments actually represented an “archive” of the Gothic choir.

Before the main work started, Christie rebuilt the King's porch. The lower part was reconstructed using some of the old materials, while the gable had to be rebuilt from scratch. Subsequent work on the interior and upper parts of the choir progressed as if erecting a new building. After having raised the main pillars, the arcades and triforia were built. Then the clerestory with parapets followed. Flying buttresses were also added. They were needed because of the new quadripartite vaults. The roof was made as a cast iron construction covered with copper.

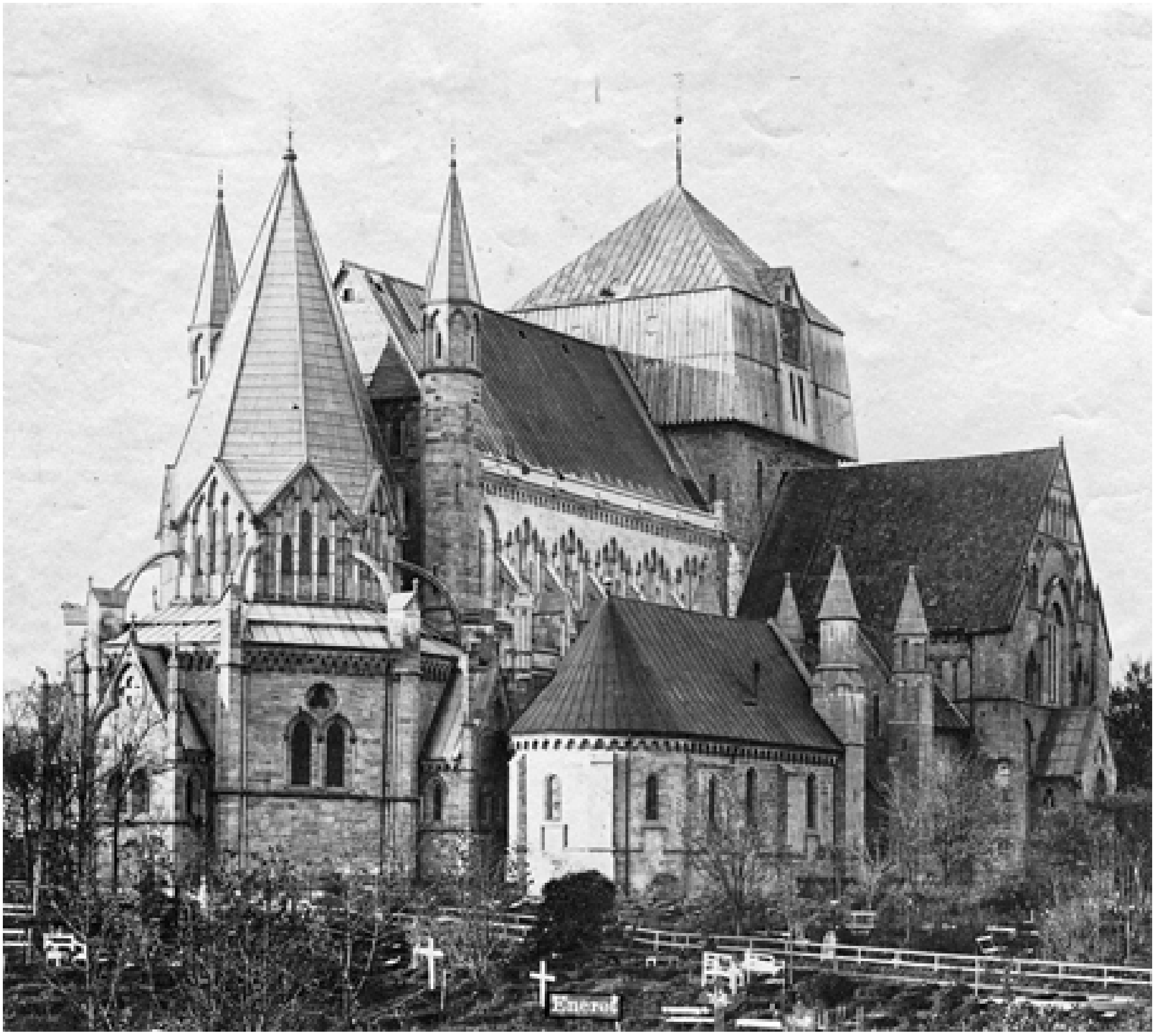


Fig. 4.8: *The restoration of the chapter house, octagon and choir was finished in 1890 (photo: ARW, no. 549).*

Fig. 4.9: *Interior of the restored choir c. 1930. Note the supreme screen wall dividing the choir and octagon (photo: ARW, no. 2762).*

The transept (1870-1905)

Except for the eastern chapels, the transept lacked vaulting and consequently was not affected by inclining walls. However, masonry close to the pillars of the heavy central tower was badly cracked due to differential settlement. Since the wooden roof construction burnt during the fires, cracks in other parts of the masonry had also appeared.

Restoration of the transept commenced by the 1870s, but the main work was not undertaken until the end of the 1890s. The transept's stability was dependent on the stability of the central tower, so large areas had to be restored while simultaneous work was taking place on the tower. The transept is a large part of the cathedral and its restoration is best described by starting with the northern end, including the Lectorium, St. Mary's chapel and the north porch with St. Michael's chapel.

The latter was restored in the beginning of the 1880s. Involving mainly strengthening of foundations, building a new base and replacing ashlars and some decoration in the lower part, the work was done quickly, as were the addition of new pinnacles above the gable of St. Mary's chapel. At the same time foundations and bases were restored. Small works, including the repair of parts of the clerestories and excavating the graves in the Lectorium, occurred from the middle of the 1880s, and in 1898 the main work on the triforia, clerestories and the gable triangle commenced.

However, before concentrating on these operations, which mainly involved cleaning and consolidating masonry and replacing damaged stones and decorations, the upper storeys of the two towers flanking the gable were constructed. Subsequently, the 15th century Gothic window in the gable was removed and replaced by a circular one.

In the southern transept scattered works took place when architect Schirmer was in charge of the restoration. Schirmer cleaned and strengthened St. John's chapel, an operation which included much stone replacement as well as plastering the interior. The chapel above, St. Olav's chapel, was restored at the end of the 1870s. Then, in 1884, massive stone replacement was undertaken in the lower part of the south wall. Due to fires in the chapel (from 1690) by the south wall, the masonry was in poor condition and had to be completely renewed after the removal of the chapel.

The next scheduled work was to remove the upper part of the brick gable dating from 1666. It was undertaken in 1891, but the subsequent construction of a new gable was not finished before 1903. Christie used the north gable of the transept as a model for this reconstruction.

All the new roofs above the transept were constructed from wood, using the medieval roof of Værnes church, 35 km east of Trondheim, as a model. As in the choir, the graves were removed when cellars were excavated below the transept. The marble floor was laid in 1905.

The central tower (1884-1903)

Several building phases could be found in the central tower prior to the restoration. The pyramidal roof was added after the 1719 fire and the upper storey was probably built after the 1531 fire. The inner part of the triforium was Gothic, while the outer part, as well as the pillars had a history dating back to the 11th century. Two of the four large Gothic arches in the crossing were closed with thick walls (the southern and western arches) and the ground was filled with graves which threatened the stability of the foundations.

As mentioned above, the differential settlement of the tower had led to large cracks in the transept's masonry. The main pillars of the tower were also in a rather bad condition, not least because of all the fires. Many cracks were found in the upper storeys, but they were difficult

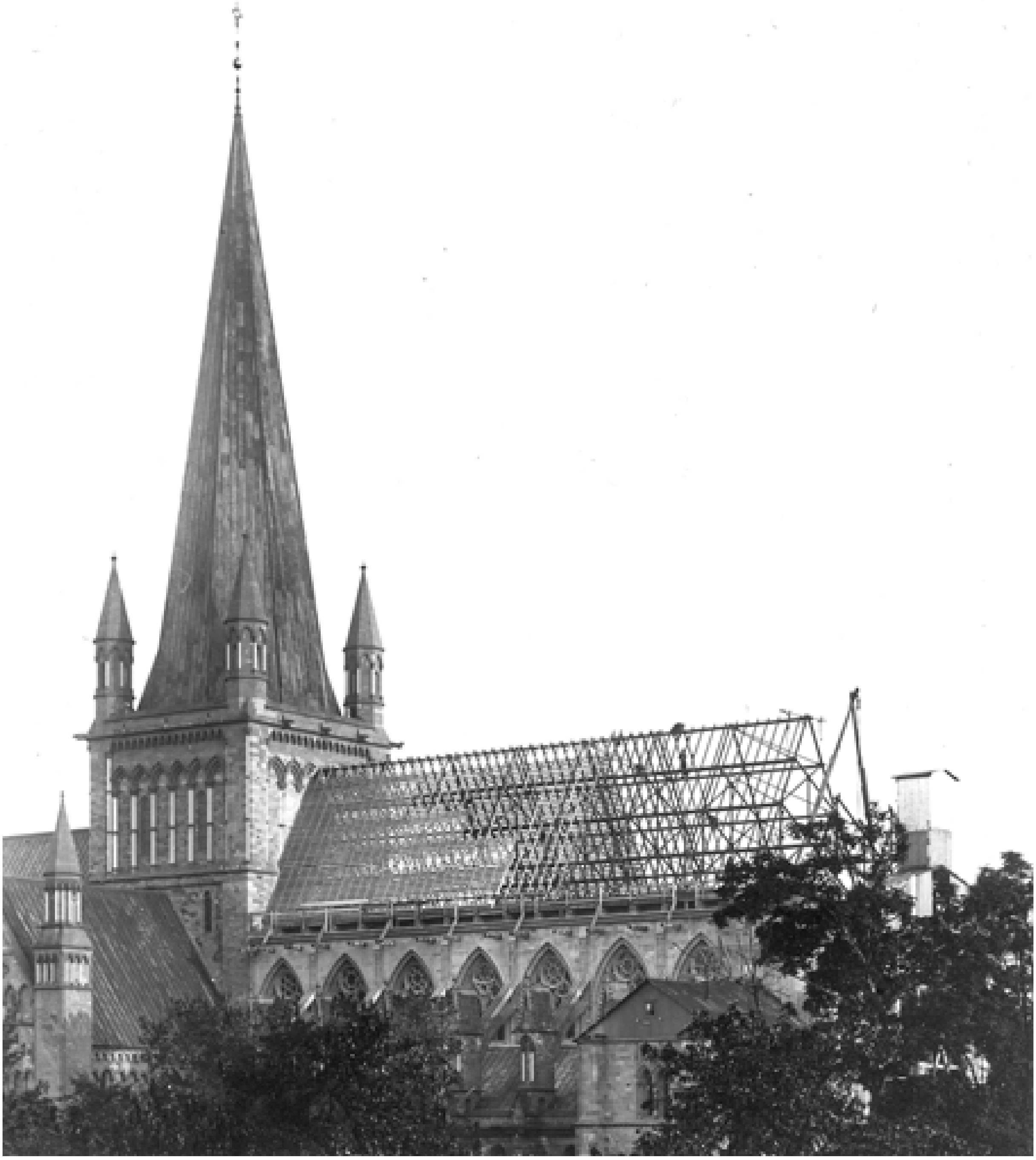


Fig. 4.10: *The north side of the cathedral by 1930. The reconstruction of the nave is almost finished (photo: ARW, no. 3143).*

to discover before the thick layers of plaster were removed. Most iron cramps formerly used to consolidate the masonry were also removed.

Demolishing the pyramidal roof and the upper storey was the first task undertaken. Then followed the removal of the thick secondary walls between the large arches. During this operation many mouldings and decorations of Romanesque and Gothic age were found in the masonry cores - invaluable pieces for further reconstruction work. Furthermore, it was necessary to consolidate the foundations of the tower. This task was undertaken by adding new stone and concrete foundations after the removal of old graves.

Restoration of the pillars followed and then the interior triforium was thoroughly repaired. There were few difficulties involved from this point when raising the Neogothic clerestorium. At the turn of the century the masons were already working on the parapet and the four flanking stone towers. In 1901 the large cast iron spire was erected, followed by the construction of the stellar vault which was finished in 1903.

The nave (1898-1930)

The eastern half of the cathedral was finished before 1905 and an important phase of the restoration was completed. The next important task was to finish as much as possible of the nave before the coronation of king Haakon VII in 1906.

Restoration of the lower part of the nave had begun in 1898 by consolidating the outer walls of the aisles, which were the only parts left (in addition to the two lower storeys of the west front). Again, foundations were strengthened before a new base could be inserted. The walls were generally in a rather good condition, despite the fact that they were damaged by fire and had been standing exposed to the elements in several periods after the 16th century. However, the massive buttresses had to be strengthened by replacing many stones. The string course and numerous pieces in the windows were also replaced.[19] Mouldings in the windows had certainly been heavily altered by the 1531 fire. In this fire other areas had been affected as well, especially masonry and decorations around and above St. Olav's and St. Mary's portals, situated in the north and south walls, respectively.[20]

Having finished the outer walls, the masons began reconstructing the interior parts of the nave by following Christie's plans. The arcade pillars were erected in 1905 and due to rapid progress in the following months, most of the arches and arcades were also finished before the coronation.

The reconstruction of the upper parts of the nave continued until 1930 while simultaneous work was undertaken on the west front. However, because of extremely divergent views on the medieval elevation of the nave and how to rebuild the west front, the work was suspended from about 1915 to 1923. Otherwise there were no particular difficulties and the work followed more or less the same schedule as the reconstruction of the choir. The cast iron roof construction and the tierceron vaults were finished just in time for the 900th anniversary of the death of St. Olav in 1930, while the marble floor was laid at the end of the 1930s.

The west front and west towers (1910-1969)

The two lower storeys of the west front were dismantled (because of being in very bad condition) and carefully rebuilt with the old stone between 1907 and 1910. The rest of the front is actually a result of two architectural competitions held in 1908 and 1928. When Helge Thiis, the winner of the last competition, was appointed architect-in-chief of the Restoration Workshop in 1930, the third storey and the large rose window were already finished.

Thiis built the rest of the west front as a screen front in the tradition of English cathedrals such as Lincoln and Wells. Above the fourth storey, which has deep niches and a parapet on top, the two flanking west towers were erected. They serve as bell towers and have flat roofs. Despite being partly suspended during the Second World War, work progressed quickly and in 1964 the north tower was finished. The south tower followed in 1969 - 100 years after the beginning of the restoration.

The west front is a major work in Norwegian art history, primarily because of the rich iconographic programme in which many eminent Norwegian sculptors participated. The niches of the three upper storeys are filled with life-size statues, but only five of them are actually copies of medieval ones. The last statue was put in place as recently as in 1984.

Fig. 4.11 (right): *The west front finished in 1969 (photo: ARW).*

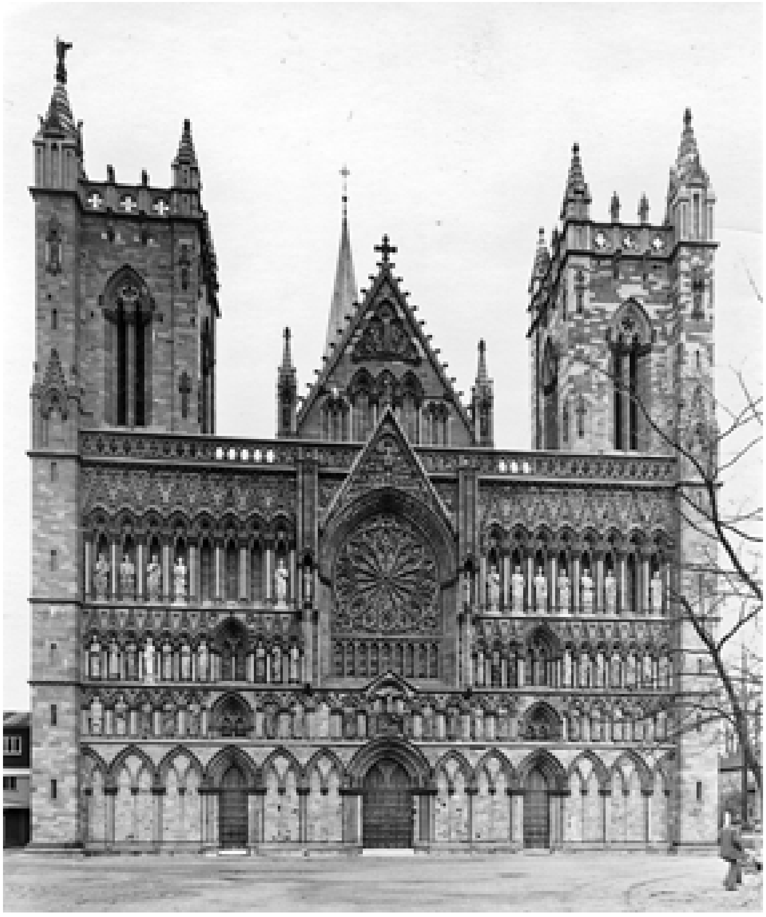


Fig. 4.12 (below): *Review of the restoration of the cathedral 1869-1996. Later repairs have also been included*
(see also appendix 1).

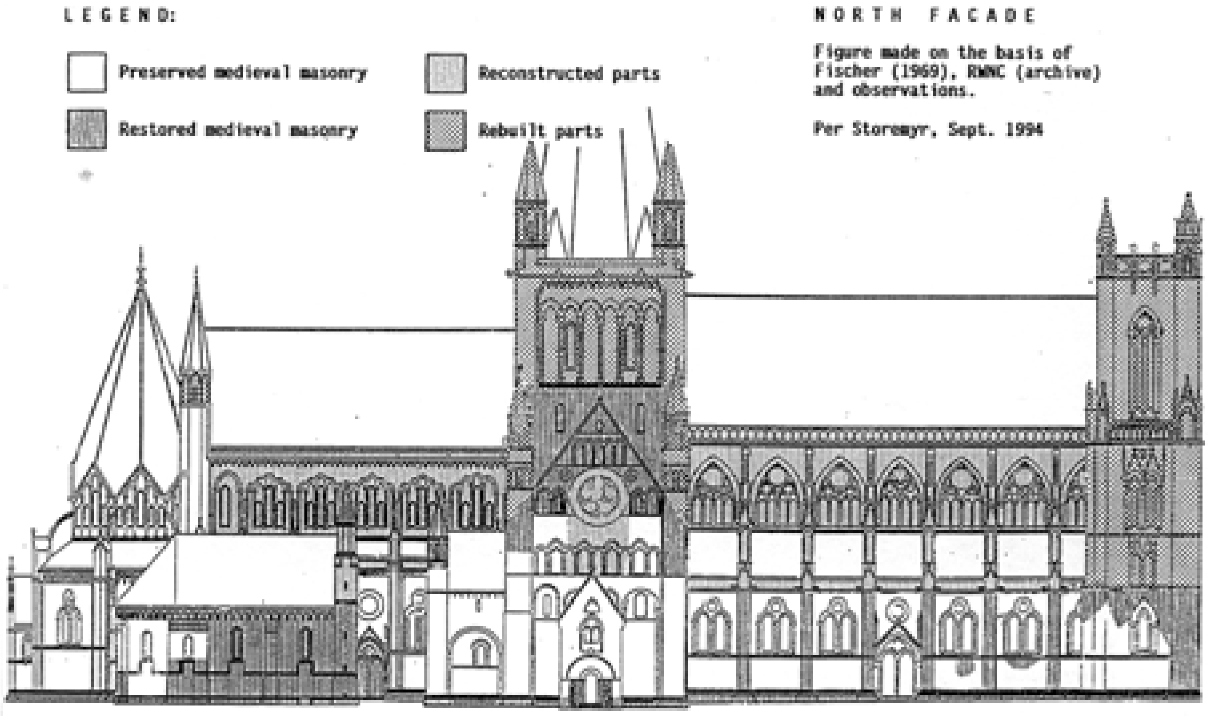


***Fig. 5.1**: East wall of the north transept during restoration in the 1890s. Note the cracks caused by differential settlement close to the arches of the central tower (photo: ARW, no. 661).*

Chapter 5

Building construction and stability problems

As pointed out in the review of methodology (chapter 2) it is necessary to be familiar with large-scale stability problems in order to understand the weathering of the cathedral. The discussion below starts with soils, differential settlement and foundations, before turning to important aspects of the masonry constructions and effects of stability problems. The discussion is not based on a comprehensive investigation of the cathedral's structural behaviour. However, as some parts of the building show severe structural failure, it is recommended that such an investigation is carried out in the future.

5.1 Soils, settlement and foundations

Located at the highest point in the centre of Trondheim, the present elevation of the ground around the cathedral is between 14,5 (west front) and 13,5 m above sea level (octagon). The city rests on a fluvial/glaciofluvial delta, and even where 50 m deep bore holes have been made, solid rock is not encountered directly below the cathedral.[1]

Investigations of soils, settlement and ground water table

Since 1862-65 several investigations concerning ground conditions have been carried out. The first was part of a study connected with verifying the 1851 restoration plan of architect Schirmer. It was found that the ground consisted of compact clay which was strong enough to resist the loading pressure of the building, except below the central tower. The walls were, however, inclining drastically outwards - a phenomenon then attributed to frost heaving in the shallow foundations. Consequently, the foundations were strengthened by supporting brick walls. Simultaneously, a closed drainage system was constructed around the church in order to eliminate surface water which may have caused rising damp problems in the chapter house and Lectorium.[2]

Large foundation and excavation works were undertaken during the restoration from 1869 to 1910, but a thorough soils investigation did not start before 1909. At that time plans were made for building a new storey on top of the reconstructed central tower. Hence, the so-called “stability-committee” had to evaluate the bearing pressure of the ground. Several boreholes were drilled - and with certain exceptions they confirmed what had been found in 1862-65. The ground consisted of a 1-2 m thick layer of dry, compact clay below the c. 2 m deep foundations. Several thinner layers of silt, sand and gravel were found below the clay, but at 4-5 m drilling was terminated because of an extremely compact layer of sand and gravel. The committee nevertheless stated that the ground was sufficiently strong as long as the compact clay was kept dry,[3] but that the foundations of the tower had to be consolidated if the building of a new storey was to be carried out.[4] As previously mentioned (chapter 1), several plans for rebuilding the central tower have been made - but never executed.

On several occasions the plans actualised the need for investigation of the ground conditions, for the last time in the 1970s.[5] It was, however, the erection of the large west towers which gave the impetus for investigation in the early 1950s. During the erection of the towers, differential settlement of the nave, west front and within the west front itself occurred. Hence, a comprehensive levelling programme commenced in 1951 and continued until 1978. The measurements showed rather uniform settlements in the eastern part of the cathedral, including the central tower (3-4 mm), and a gradual increase in the western part of the nave (fig. 5.3). Maximum values were reached at the west front (30-40 mm).[6] Masonry cracks in the western part of the nave and in the rose window of the west front inevitably appeared, and resulted in an extensive restoration programme for the rose window in the 1980s.

During the investigation in the 1950s it was established that the total settlement of the central tower throughout history has been approximately 20 cm.[7] The same investigation also included studies of the soil. Modern drilling equipment was now able to penetrate the compact layer of sand and gravel starting at 4-5 m below the foundations. This layer was c. 5 m thick, and there was a sharp boundary with underlying sand/silt deposits with a total thickness of more than 50 m (fig. 5.2).[8]

The medieval St. Olav's well (11,5 m deep) is a perfect location for ground water level investigations. The well can be found in the corner between the octagon's southern chapel and south eastern wall. Several studies have shown that the ground water level is usually at the division between the compact layer of sand/gravel and underlying deposits; that is about 6 m below the foundations.[9]

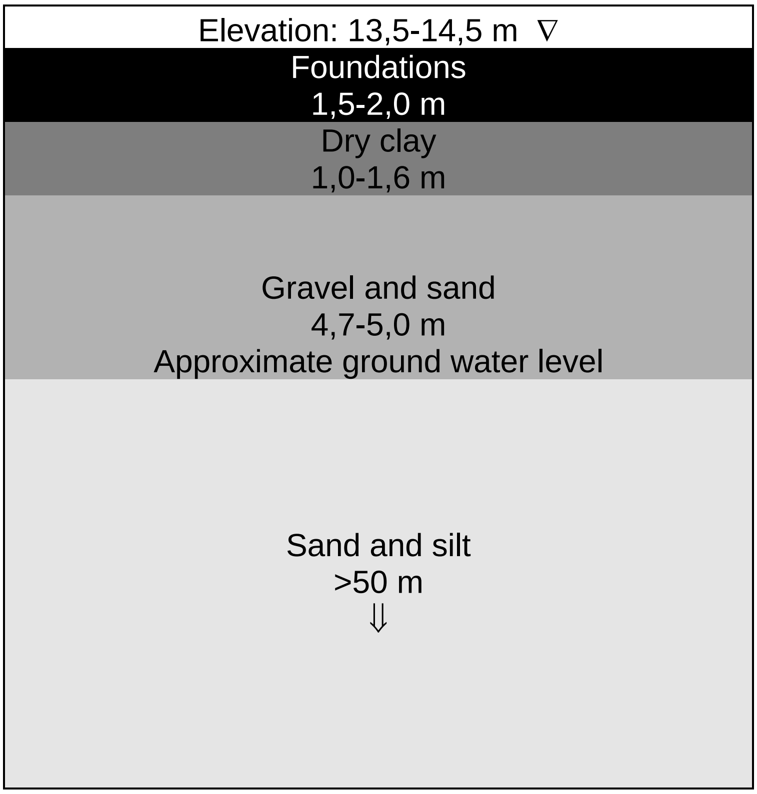


Fig. 5.2: *Schematic representation of the building ground below the cathedral (from Finborud 1967).*

Summarised, the ground below the cathedral consists of some 2 m of clay and anthropogenic material, a 1-2 m thick layer of highly compacted, dry clay, a few thin layers of sand and silt, a 5 m thick layer of extremely compact sand/gravel and more than 50 m of sand and silt. Hence, the cathedral rests on some 6 m of good, stable soil - compact clay and compact sand/gravel. One should nevertheless be aware of possible future problems as a result of changing ground conditions, especially if *major ground water changes occur or if the layer of compact clay becomes too wet*.

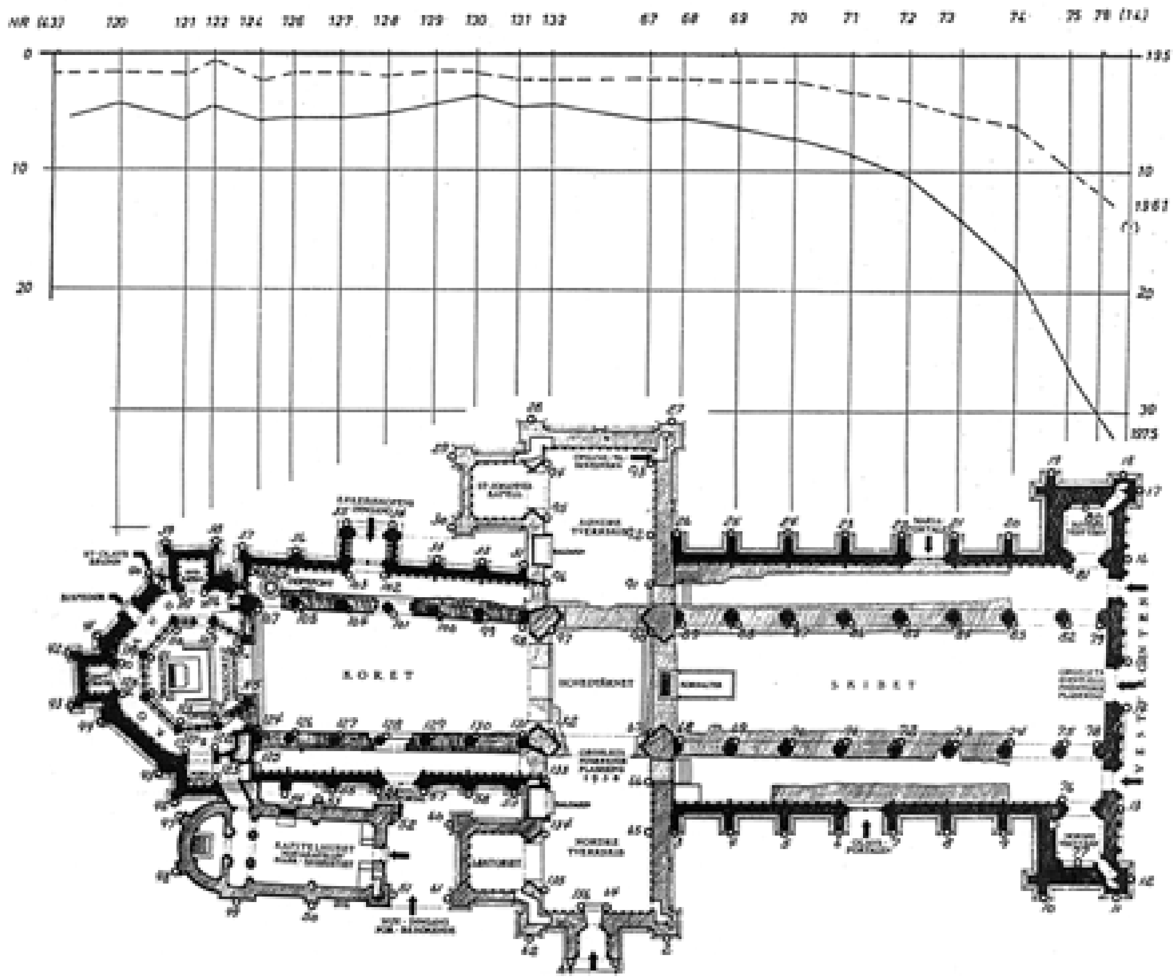


__Fig. 5.3:__ Settlement (in mm) along the northern side between 1951 and 1975. Note the relatively large settlement in the western part of the cathedral (from Rye 1976).

Characteristics of the foundations

The foundations of the cathedral may be subdivided according to several original building phases and restoration operations:

- Foundations of Olav Kyrre's Christ church,
- Foundations of the Romanesque building period,
- Foundations of the Gothic building period (3 types),
- Consolidation work carried out in 1862-65,
- Consolidation and excavation work carried out during the restoration between 1869 and c. 1907,
- Consolidation work carried out in 1984-86.

Below, we will concentrate on the actual foundations of the present cathedral, leaving the earliest foundations out of the discussion.[10]

The general foundation depth is 1,5-2,2 m; effectively rather shallow. Hence, the medieval builders trusted the stiff layer of clay - regarding further digging down to the compact stratum of sand/gravel as unnecessary.

Romanesque foundations below the transept and parts of the central tower are carefully made by so-called “herring-bone” work (*Opus Spicatum*). They are generally some 2 m deep, 2 m wide and laid on a thin stratum of smaller stones in lime mortar. The foundations themselves are built without mortar, by 3-5 alternating layers of inclined, irregular slabs.

Fig. 5.4: *Example of the consolidated foundations. South side of the octagon during archaeological excavation of the late 1940s. Note the closed water drainage system. The gutters are no longer connected to the system (photo: ARW, no. 6307).*

In the outer walls of the octagon, foundations are drastically different, insofar as they are shallower, sometimes only 1,5 m deep, and built with large, erratic blocks pinned with smaller stones - but still lacking mortar. Lime mortar was, however, used when building the shallow, rather poor foundations of the choir's outer walls. Here, it seems that irregular stones - erratic blocks and sometimes even Romanesque decorations - have been thrown in a ditch and cemented together with lime.

A new system was introduced when building the Gothic nave. Where earlier Romanesque foundations seemed insufficient, the builders made a shallow (1,5 m), but wide (c. 6 m) ditch, levelled its floor with irregular stone and sand, and utilised rounded, erratic blocks set in lime mortar for the upper layers.

The foundations of the outer walls of the choir may be regarded as the most problematic ones of the cathedral. Additional problems were introduced in the post-reformation period because of the graves being established inside the cathedral. Graves were often located dangerously close to the foundations and on some occasions even cutting through the medieval stonework, e.g. below the pillars of the central tower. The situation was initially stabilised in the 1860s when supporting brick walls were constructed adjacent to the exterior surfaces of the existing foundations. However, a lot more work had to be undertaken to obtain foundations able to withstand the pressures of the planned, elevated Neogothic parts of the building.

Hence, until the turn of the century, supporting stone foundations (fig. 5.4) were laid next to interior and often also adjacent to exterior parts of the old ones. The supporting foundations were generally made some 2 m deep, 1 m wide and were often constructed on top of a layer of concrete. Moreover, voids in the old foundations were filled with Portland cement mortar, which was also utilised as jointing material in the new foundations.

Subsequent to archaeological excavations, a cellar (1,5-3 m deep) was dug out below most parts of the cathedral. However, this was not the case in the octagon where the ground was “strengthened” by a massive layer of stone, gravel and concrete.

Even though the settlement of the central tower has been uniform since the 1950s, its foundations were consolidated by swelling cement grouting in 1984-86. As the architect-in-chief stated: “The foundations are now sufficiently strong for bearing the pressures of the existing tower. Further works may be postponed until the day rebuilding the tower reappears on the schedule”.[11]

5.2 Masonry construction

Compared with giants like Chartres, Cologne and Lincoln, Nidaros is a small cathedral. Yet it has all the general structural features of its Continental and British counterparts. There is, however, at least one peculiarity about its masonry construction, in that almost every elevated structure was erected during the restoration. From a structural perspective the cathedral is therefore a youthful one, although its construction strongly bears the marks of what was achieved and unachieved in the Middle Ages. There follow aspects of the masonry construction not covered in chapter 4.

Fig. 5.5: *Example of medieval masonry construction with very thin joints (1-3 mm) pinned with schist. Aisle of the nave, north wall (soapstone) (photo: PS 9/95).*

Aspects of remaining Romanesque and Transitional masonry

Remaining Romanesque masonry is primarily to be found in the lower walls, triforia and side chapels of the transept as well as in the triforium of the central tower. Transitional masonry still occurs in the apse of the chapter house and clerestories of the transept. Except in parts with blind arcades and wall passages, the walls are between 1,2 and 2,2 m thick - thinnest in the chapter house, 1,5-1,7 m in the transept and thickest in the tower.[12] In the transept and central tower the walls consist of exterior ashlars of greenschist and some soapstone, interior coursed rubble and rubble-filled cores.[13]

Utilisation of relatively small and irregular greenschist ashlars is probably due to geological circumstances. The nature of the Øye greenschist for instance (see chapter 6 and 8) did not generally permit ashlars longer than 50-60 cm and higher than 15-25 cm to be made. There are nevertheless some giant ashlars reaching lengths/heights of about 150/40 cm. Conversely, some ashlars may be as small as 30/10 cm. Except for the fact that most joints between ashlars are very thin (1-3 mm, today heavily repointed) and often pinned with schist, it is hard to say exactly how the walls are constructed. We know, for instance, very little about the thickness of ashlars (30-40 cm in general?) and the use of stone binders.

The massive appearance of the transept is reinforced by the side chapels and the flanking towers - which may also be regarded as providing structural support to the main walls. Otherwise, there are no wall buttresses to be found in the transept. Such buttresses can, however, be found in the chapter house.

Aspects of remaining Gothic masonry

Contrary to the cathedral's Romanesque masonry (transept), in which the pressures are distributed along most of the walls, the pressures of the Gothic masonry and vaults are directed towards distinct locations due to the application of pointed arches, flying buttresses and wall buttresses. Since the Gothic masonry is divided into sections of similar appearance, it is possible to generalise the appearance of one section - or one bay - over the whole building part.

Remaining Gothic masonry is found in the octagon, turrets, gable of the north transept, triforium arcades and main arches of the central tower as well as in the lower, outer walls (aisle) of the choir, nave and west front. The general building technique is based on rubble filled cores and thin joints between the ashlars (fig. 5.5). It should be noted that virtually nothing is known about how the elevated Gothic parts of the building were constructed in the Middle Ages (clerestories of choir, nave and west front).

Like the Romanesque and Transitional building parts, the octagon is built essentially of greenschist. The outer walls are some 1,3 m thick, while the lower walls of the chapels reach thicknesses of up to 1 m. The clerestory with its Lancet openings and stellar vault may, at a distance, look like a frail structure resting only on interior arcades since the semi-circular flying buttresses are non-supporting. However, there are additional flying buttresses just below, under the roof of the aisle. These buttresses were erected by architect Christie during the restoration.[14]

The lower walls (aisle) of the choir and nave possess similarities and differences. Even if the choir is somewhat narrower and considerably smaller in length, the general layout of the masonry, with its groups of pointed lights below circular openings, is virtually the same. The wall thicknesses (0,8 - 0,9 m) are also similar.

Differences are primarily related to the buttressing system. The wall buttresses in the choir are only 0,2-0,4 m thick - which is hardly enough for bearing the load of the heavy main vaults. Remembering that the medieval foundations below may be regarded as rather poor, we may assume that the choir must have been erected by an inexperienced workforce in times of early Gothic experimentation. If, on the other hand, the wall buttresses of the choir were consciously made as frail as they are, one may indeed ask if heavy stone vaulting was originally intended. Maybe it came about as part of later wishes - or maybe the builders conceived a solution including lighter brick vaults or wooden constructions?

The wall buttresses in the nave are bold and massive, more than 1,5 m thick, showing that the master builders had come to terms with the structural demands of a Gothic cathedral. Judged by visual observations, a puzzling feature is the lack of stone binders between the wall and the buttresses. Nevertheless, this feature has not caused any apparent differential settlement to occur.

Other differences between the choir and nave include that the stone types are different. While in parts of the choir it is still possible to find a considerable amount of greenschist, the lower part of the nave is made almost exclusively of soapstone. When compared with the transept, the ashlar courses of both the choir and nave are more regular and generally consist of somewhat larger stones. There is also considerable pinning to be found between the regular ashlars - especially in the nave where joints are extremely thin.

The aisles of the choir and nave are in fact so well-built that they may serve as outstanding examples of how to make ashlar walls with rubble-filled cores. The original structural soundness of the nave's aisle also helped it survive violent fire (1531) and centuries without roofing.

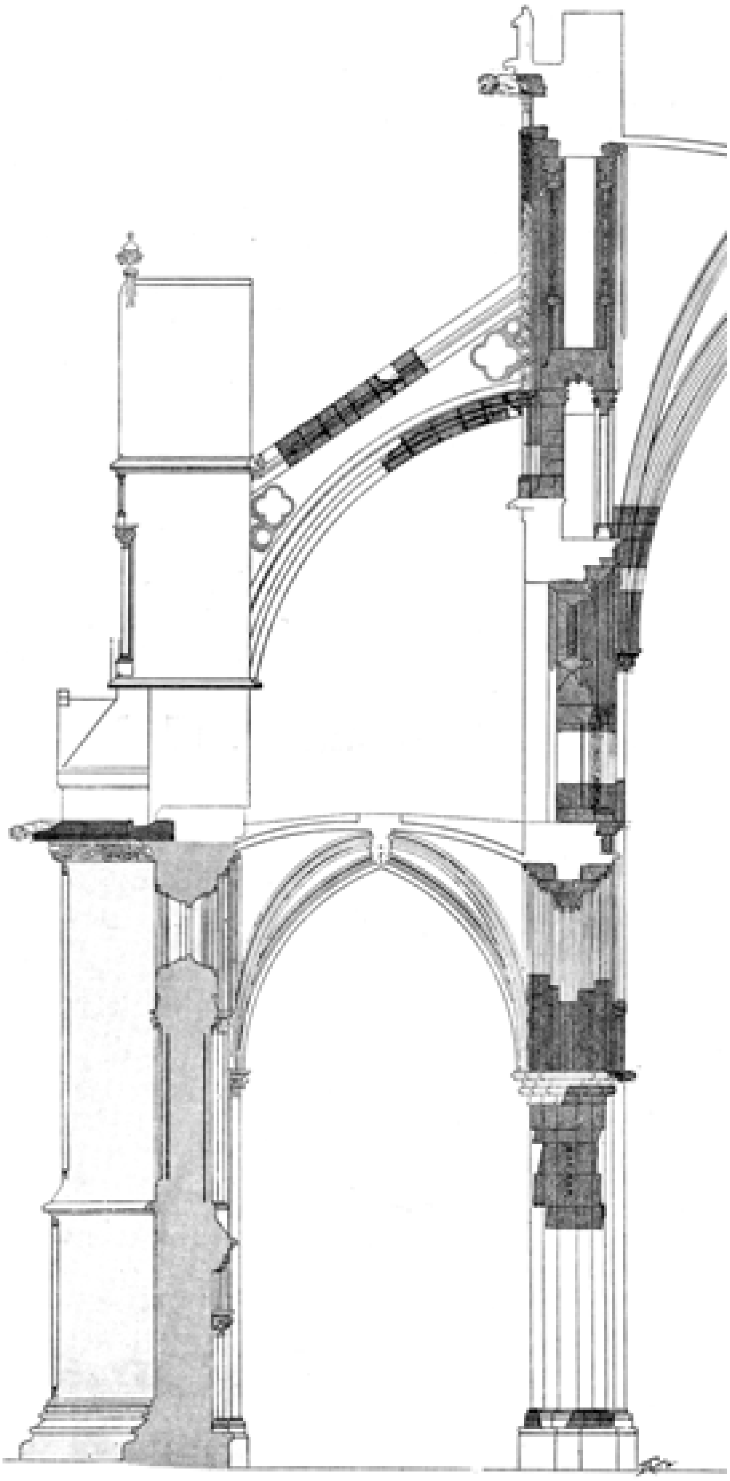


Fig. 5.6: *Cross section of the nave. Note the solid buttresses compared to the choir (cf. fig. 5.9). Reconstruction made by Chr. Christie on the basis of stone finds. The vaults are 21 m high.(ARW).*

Masonry construction during the restoration

Generally, masonry erected during the restoration has little to do with medieval building techniques. Undertaken during the Gothic Revival and in a period of ever increasing industrialisation of the building industry, the restoration was carried out using mainly “modern” building techniques. These are particularly represented by the application of massive walls instead of double walls with rubble-filled cores. The use of massive walls, e.g. brick walls faced with ashlars or coursed rubble, was the normal building technique from the 1880s until the First World War. In Trondheim this is exemplified by Ilen church and the main building of the Norwegian Institute of Technology. In contrast to the medieval walls of the cathedral, walls made during the restoration have rather thick joints between ashlars (5 mm and more). Moreover, no pinning was used in the joints.

The chapter house, which may be regarded as essentially a Neogothic construction, is in fact one of the few parts in which rubble-filled cores were applied during the restoration. In the octagon, where the medieval constructions were largely intact, little rebuilding had to be carried out. The clerestory of the choir is, however, a modern building construction. Rebuilt in the 1880s, the clerestory (except where windows, tracery and wall passages occur) consists of 1,3 m thick massive brick walls faced with c. 30 cm thick soapstone ashlars. This building technique was also applied in the new clerestory of the central tower, as well as in the reconstructed clerestory of the nave. However, in contrast to the choir, large blocks of gneiss and other hard stone were used in the massive walls, which were faced by relatively regular soapstone ashlars. A similar technique was used when erecting the west front and west towers, but since many walls are facing the interior of the churchroom itself (and not lofts), soapstone ashlars were applied also on interior walls. The thin walls of all the stone-capped spires are made of ashlars (exterior) and coursed rubble (interior).

Many wall-heads of reconstructed and rebuilt masonry were covered by a layer of concrete. Concrete was also used when building the upper sections of the west towers in the 1960s. A significant weight reduction was simultaneously achieved because the thickness of the walls could be reduced from 120 to 65 cm.[15]

All vaults constructed during the restoration, e.g. the vaults of the choir and nave, were built using soapstone (ribs) and brick.

5.3 Effects of large-scale stability problems

This section aims at presenting the effects of large-scale stability problems occurring after the restoration of different parts of the building, especially the choir and nave.

Choir and King's porch

One of the first serious events related to the choir's weak building construction took place during a service in 1935 when one of the columns of the triforium collapsed and “almost killed a woman and her son”.[16] At that time it was not yet fully realised that the weak construction was responsible for the “explosion”, even though large cracks in the vaults of the aisles had been observed as early as 1915 (fig. 5.8). It was generally believed that problematic building ground (differential settlement) was the main cause.[17]

It was not before the early 1980s that the differential settlement-theory was proved wrong. The reason was that the levelling programme begun in 1951 showed small and uniform settlements in the choir. Consequently, experts reached the conclusion that the buttressing system was too weak.[18] These experts subsequently investigated possibilities of how to strengthen the whole construction. They finally suggested that a hidden steel construction

Fig. 5.7: *The King's porch (above). The slender Gothic construction - thoroughly restored three times since 1878 - has developed extensive cracks since 1960. Note the bulging of the walls. Cracks preferentially follow joints, but also cut through stone blocks (photos: PS 6/96).*

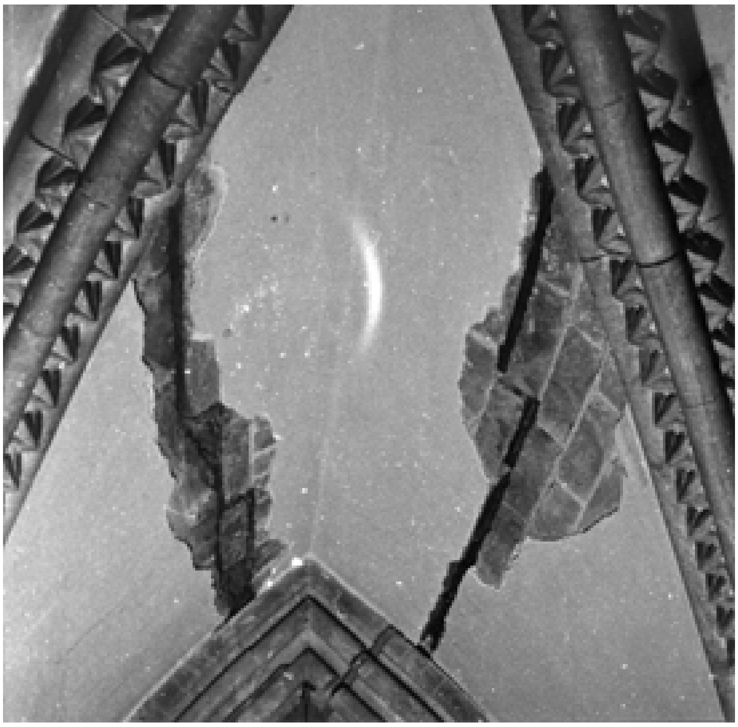


Fig. 5.8: *Example of cracks in a vault of the aisle (choir). Photo probably taken in 1982 (ARW).*

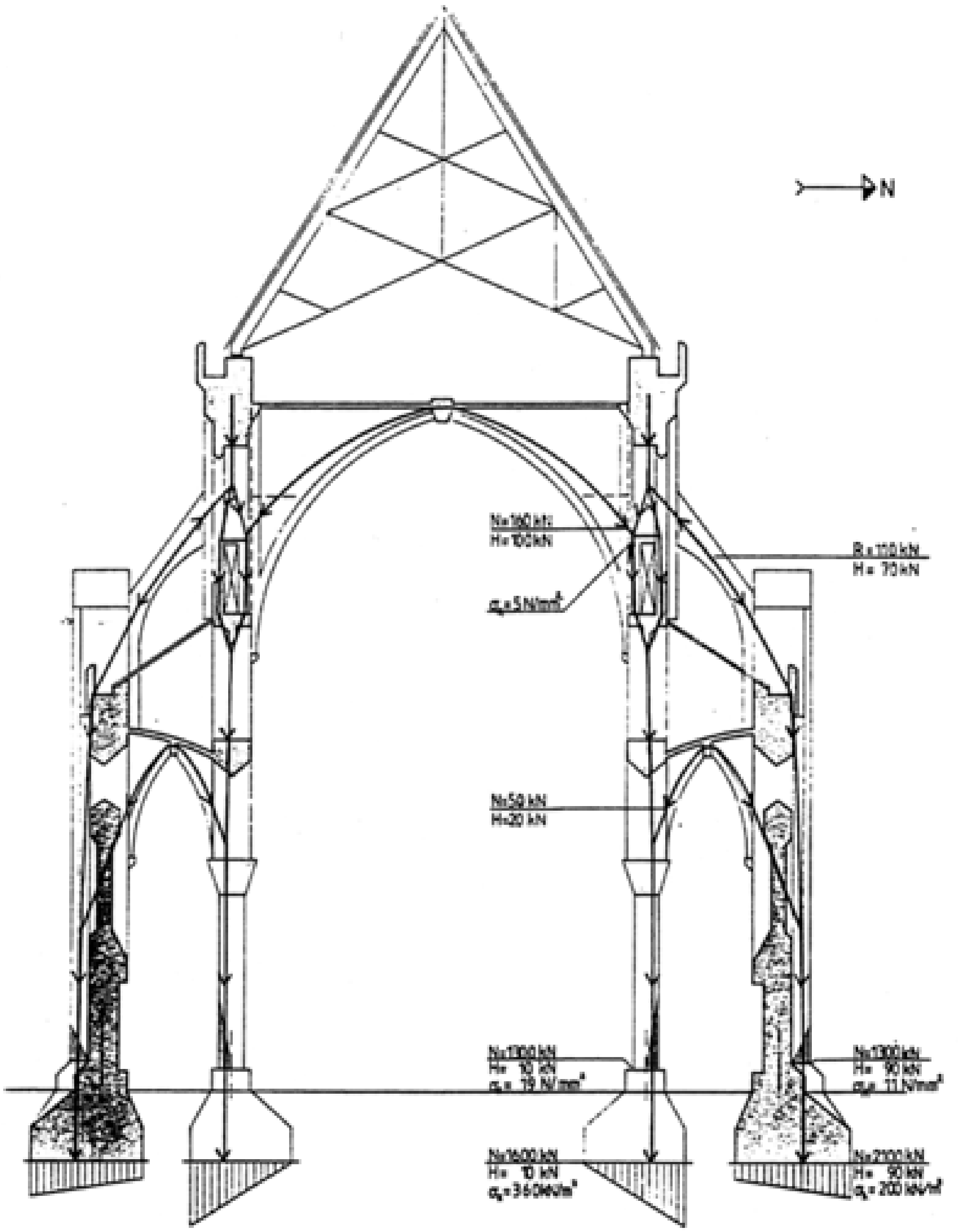
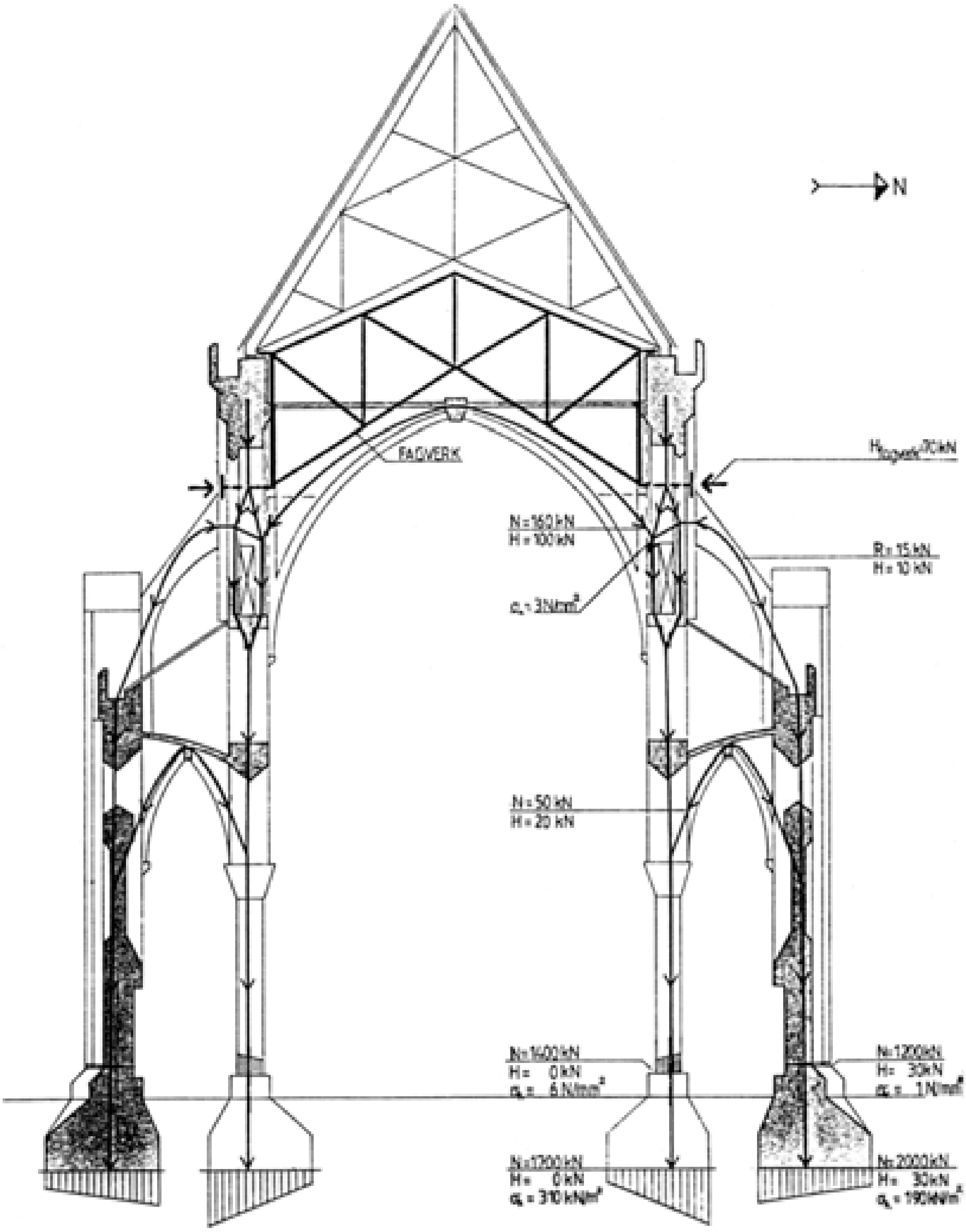


Fig. 5.9: *Above: Schematic representation of the pressure lines in the choir before the construction was secured in 1986. Next page: Similar representation (hypothetical) after the application of a hidden steel construction on the loft (from Løvås 1984).*

above the vaults would be the best solution (fig. 5.9) - a work which was undertaken in 1986.[19] Until 1996-97 it was the view of The Restoration Workshop that the problems in the choir had largely come to a halt, although outward inclination (deviation from plumbline) showed an increasing tendency in 1989 (fig. 5.10). After 1989, no regular measurements of inclination, crack development and settlement have been undertaken. Such measurements are absolutely necessary in order to understand the behaviour of the choir, not least since it has recently (April 1997) been discovered that several columns and capitals in the triforia are in danger of collapsing.[20]



Being a part of the choir, the large and slender King's porch (fig. 5.7) on the south side has been a major concern for The Restoration Workshop since it was restored and its upper part rebuilt by architect Christie in the late 1870s.[21] Large cracks were observed before 1918 - and here it was also thought that problematic building ground, as well as frost heaving, could be responsible for the poor condition. After consolidation of the foundations and restoration of the upper section between 1918 and 1922,[22] the cracking did still not cease. Already in 1931 the cracks had reappeared and the condition was considered so serious that immediate repair was proposed.[23] However, a repair programme did not commence before 1950. It continued periodically until 1959.[24] It was therefore finished long before the differential settlement-theory was proved incorrect in the 1980s. At that time it was maintained that the porch acted as a supporting buttress for the choir, but that it was too weak to withstand the pressures of the vaults and walls.[25]

Since the last repair programme in the 1950s, the porch has developed severe cracks. At present, the slender walls are seriously bulging and several stones in the base have been sliding horizontally. Being in such a poor condition, the porch ought to be stabilised as soon as possible.[26]

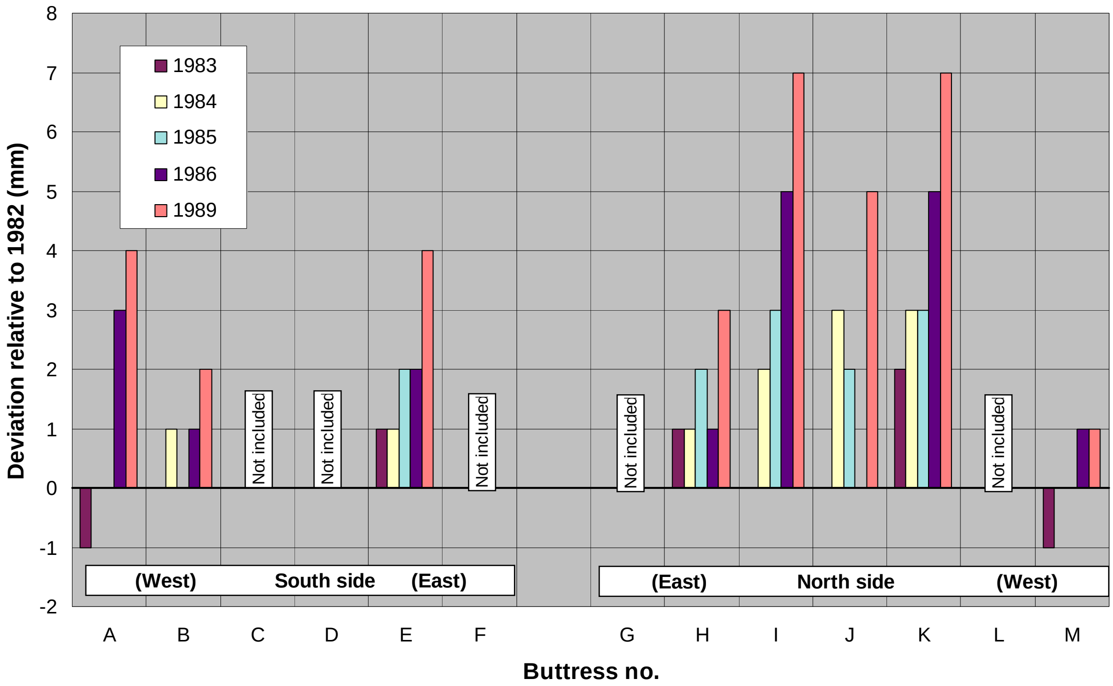


Fig. 5.10: *Aisles of the choir. Development of deviation from plumbline 1983-1989. Note that this deviation did not halt after 1986 (measurements undertaken by The Restoration Workshop).*

Nave and west front

Since the nave is regarded as a well-built construction from a structural point of view, its stability problems have been ascribed to differential settlement between the westernmost bays and the west front/west towers. Recalling that differential settlement took place during and after the erection of the latter parts of the building (chapter 5.1), cracks were first discovered in the westernmost triforia in the late 1940s - 10 years after completion.[27]

Several decorations and columns were subsequently secured, but this did not prevent a major accident in 1980. At that time a marble column by a group of windows in the aisle simply “exploded” because of having been subjected to excessive pressure. On collapsing, the column caused severe damage to nearby chairs, but luckily not to people.[28] Knowing that all columns were set in hard and inelastic Portland cement mortar (and of course secured with metal dowels), the accident must be regarded as a natural phenomenon. Although many marble columns and other vulnerable decorations are secured, there are still problems, e.g. with capitals and arches in the triforia. In March 1997, small stone pieces fell down during a service (without causing injury to people). The event occurred on the north side close to the central tower, and not - as could be expected - in the westernmost bays. Since the settlement in this area has been uniform, it seems that explanations other than differential settlement have to be sought. Investigation is currently underway.

Another problem related to differential settlement within the west front itself occurred just after the completion of the west towers in the early 1970s. The large, beautiful rose window which was built before the Second World War, showed a large crack as well as numerous joint fissures (Portland cement mortars) and gaps between glass and lead.[29] The joints were repaired in 1975, and between 1981 and 1984 a major conservation programme was carried out.[30] Since then large cracks have developed - showing that the nave and west front/west towers remain unstable.

Cracks have also continued to develop in two frail canopies of the west front (fig. 5.11). Put in place just before 1930, the corbels bearing the canopies have been replaced by copies several times (1932, 1935, 1947). Whether large-scale stability problems or - as maintained in 1935 - thermal dilatation due to strong sunshine in particularly warm summers can explain the problem is uncertain as it has not been investigated further.[31]

Fig. 5.11: *Canopy of the west front (from the 1920s) showing cracked columns. One of the corbels bearing the canopy is a copy from 1935, replaced because of cracks (photo: PS 2/96).*

Central tower and octagon

The present central tower was erected on top of old masonry at the turn of the century. Although it has been calculated that the settlement of the tower between the Middle Ages and the 19th century was in the order of 20 cm - leading to the development of severe cracks in the nearby masonry of the transept (fig. 5.1) - it seems that the present tower is quite stable (cf. levelling programme). This is also because the foundations were strengthened in the late 1980s. There can still be observed visible cracks in the nearby masonry (clerestories) of the nave and choir. These are probably old damage, but in wet weather periods they may give rise to water leaks - like most open cracks at the cathedral.

Many cracks can also be observed in the octagon, especially in the vaults of the ambulatory. The cracks seem to have developed after the restoration in the 1870s, but are at present supposedly stable. The outer walls of the octagon are leaning rather seriously outward - a feature which can be traced back to the original building period in the late 12th century. At that time the inner parts (arcade pillars) were built on top of old foundations while the outer walls and chapels were constructed on new foundations.[32] Differential settlement probably occurred before the soils became fully compacted. The only serious stability problem after the restoration (which included consolidation of the foundations and addition of hidden flying buttresses), took place in the south chapel where the pinnacles started to lean seriously outward in the 1950s,[33] possibly as a result of problems in the nearby choir. The pinnacles were secured in the 1980s.[34]

5.4 Summary of construction and stability problems

Situated on a fluvial/glaciofluvial delta, the cathedral rests on some 6 m of compact clay and sand/gravel which is regarded as stable soil. The ground water level is about 6 m below the foundations, which are generally 2 m deep and of a diverse nature. They were all consolidated during the restoration and are at present supposedly in sufficient repair.

Between 1951 and 1978 a levelling programme was carried out, aimed at controlling the settlement of the cathedral. The measurements generally showed small and uniform settlements, except between the western bays of the nave and the west front, and within the west front itself. The main reason why differential settlement occurred in these places is because of the large weight added during the erection of the west towers in the 1950s and 1960s.

Effects of differential settlement included cracks in the masonry of the western bays of the nave as well as in the rose window of the west front. Several marble columns were also subjected to excessive pressure, causing one of them to “explode”.

Similar problems occurred in the choir, but the main cause was of a different nature. The walls of the choir's aisles showed severe inclination before being screwed back into vertical position during the restoration in the late 1870s. Their inclination was probably due to frail wall buttresses. After the rebuilding of clerestory walls and vaults, as well as the addition of frail flying buttresses, the problems of inclination reappeared at the turn of the century, causing large cracks to develop in the vaults of the aisles. In the 1980s it was established that the building construction was too weak and consequently a supporting steel construction was installed above the main vaults. It is not known if the situation is currently stable.

The stability problems of the choir have also been transferred to the King's porch on the south side. Having been subjected to several unsuccessful repair programmes, the condition of the porch is presently characterised by large cracks which seem to be of a rather critical nature.

Fig. 6.1: *Stone for the southern west tower during its erection in the late 1960s (photo: ARW).*

Chapter 6:

Materials and conservation methods

The objective of this chapter is a description of relevant materials and conservation methods. It begins with stonework and aspects of stone working technology. A chapter on mortars, whitewash and paint follows next. Finally a range of particular conservation methods applied during the restoration is described.

6.1 The stones of Nidaros

Describing the stones and stone working technology used to build and restore the cathedral could easily have been the sole theme of this thesis. From the Middle Ages until today, stone has been provided from more than 60 domestic and a few foreign quarries (appendix 2).[1] Combined historical and geological investigation has made it possible to locate most of the stones, with regard to the location of quarries (fig. 6.2), where the stones are to be found in the cathedral (appendix 4 and 5) and in which periods the different stones were used (fig. 6.3, appendix 2).

The geology of the Trondheim region is dominated by metamorphic sediments and volcanic rocks of Caledonian (Cambro-Silurian) age. A thick sequence of metabasalt (greenstone) with some metamorphic tuffs, sediments and gabbroic/ultramafic intrusions is to be found around Trondheim itself (fig. 6.2). Deposits of soapstone and greenschist - the most important stone types used in the cathedral - are common in such geologic environments.[2]

Properties and early use of greenschist

Greenschist was the most important building stone during the Romanesque and Early Gothic periods.[3] Since a great deal of stone must have been reused from the cathedral's precursors, we may assume that the exploitation of greenschist commenced already in the middle of the 11th century.[4] Greenschist may be regarded as a foliated, green stone type which is sometimes quite soft due to a high chlorite content. It is a dense metamorphic stone, originating from volcanic products such as basalt and tuff.[5] The term *greenstone* is normally used for such stones. This is, however, also a field term used for any compact dark-green basic igneous rock.[6] I use the term greenschist to point out that the rock used in the Nidaros cathedral is very soft and foliated.

Despite the fact that greenstone and greenschist are major rock types in the Trondheim area,[7] there are not many deposits which can be used for ashlars and decorations. One of the deposits is situated at Øye, 17 km south of the city. It contains extensive traces of early exploitation and must be regarded as the most important quarry from which greenschist was

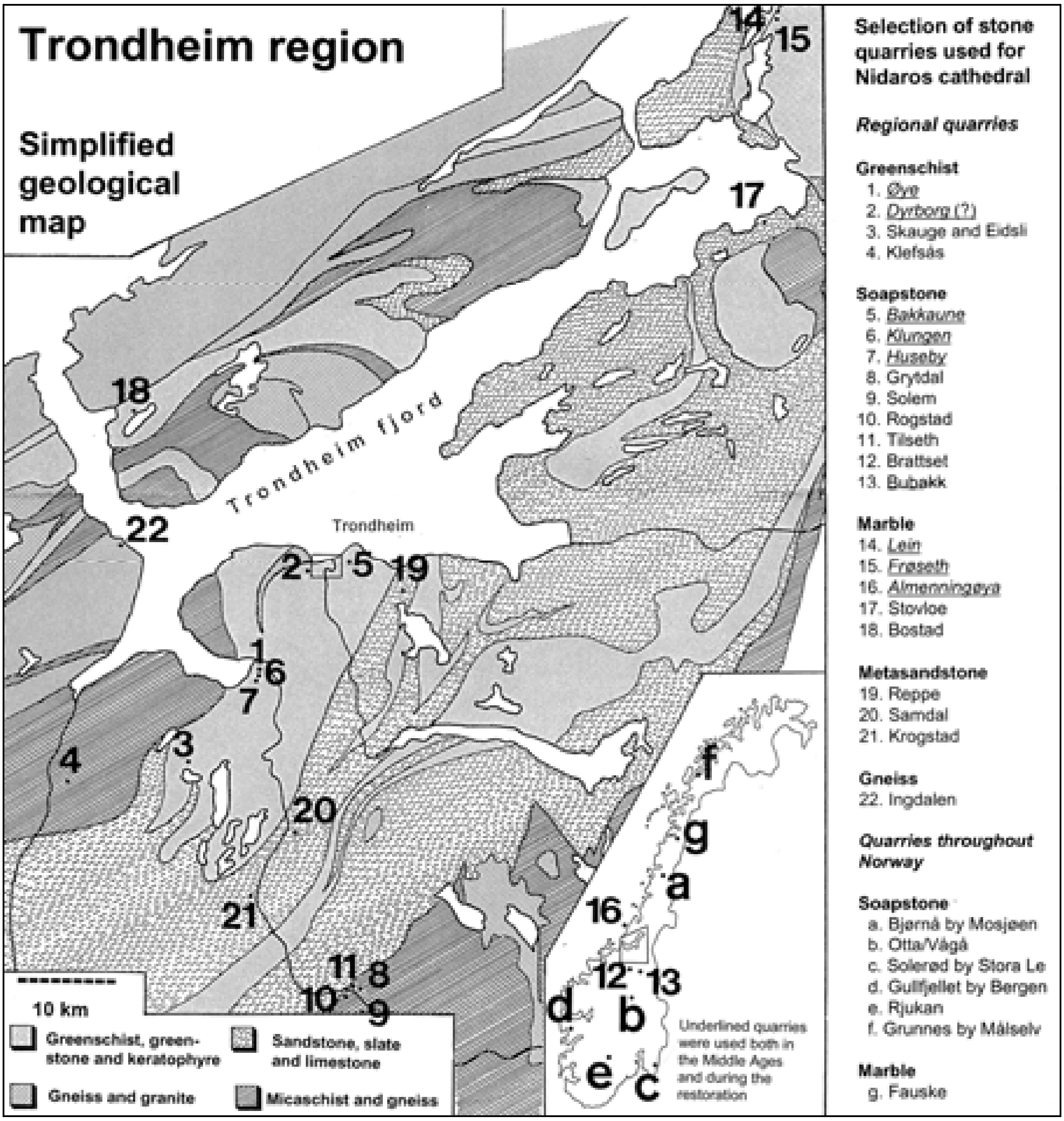


Fig. 6.2: *Regional geological map showing the location of stone quarries used for the cathedral. Geological map simplified from Sigmond et al (1984).*

obtained in the Middle Ages.[8] Smaller quantities may have been provided by other quarries, but this assumption is uncertain.[9]

Greenschist from Øye was the major stone type used for ashlars, mouldings and decorations in the transept, the chapter house, the lower parts of the octagon and some places in the choir. Many other stone types can be found in the walls of these building parts today, but this is mainly due to all the stone replacement carried out later - for instance in the 16th century by Archbishop Valkendorf and particularly during the restoration from 1869.

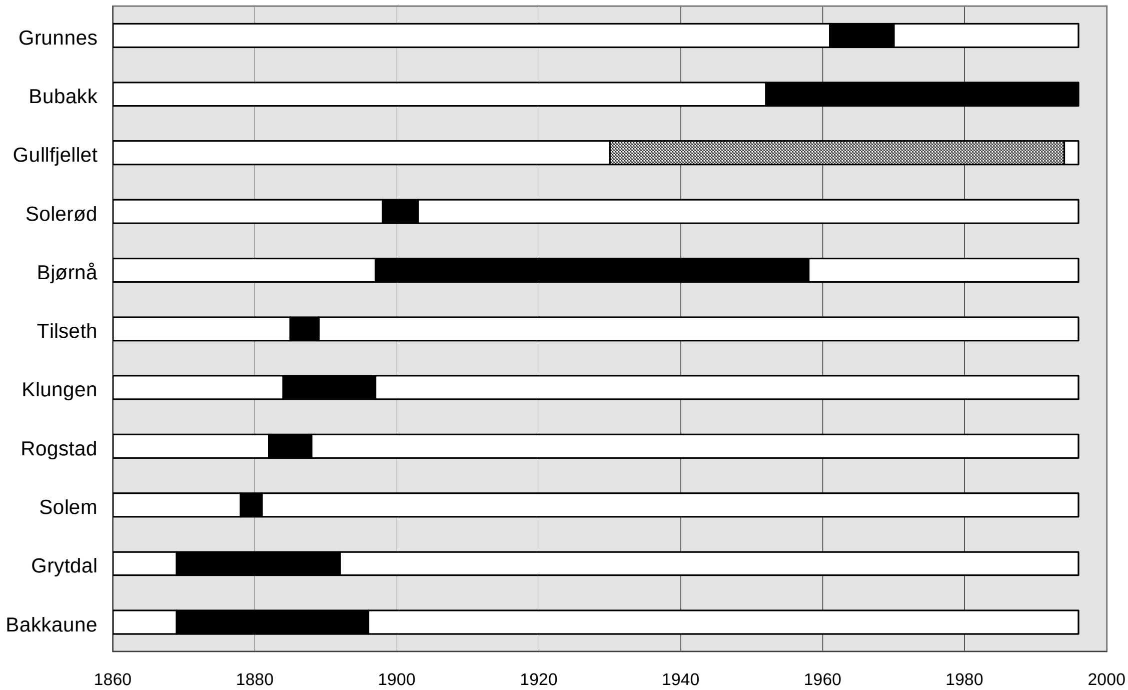


Fig. 6.3: *Major soapstone quarries and their periods of use during the restoration of the cathedral. Sources: see appendix 1 and 2.*

From a geological perspective, the Øye quarry is situated in an interesting area. This is because the greenschist can be found very close to the Klungen and Huseby soapstone deposits.[10] These deposits were probably also exploited in the Middle Ages, but it is difficult to state to what extent. The Huseby soapstone is rather schistose and in many ways resembles the Øye stone, suggesting that it may also have been used during the Romanesque building period.[11]

A note on properties and general use of soapstone

Even though large parts are built of greenschist, the cathedral is traditionally referred to as the "soapstone cathedral". One reason is that soapstone and the type of greenschist which can be found in the cathedral have rather similar properties, making it difficult for lay people to recognise differences. Even among professionals there are diverging opinions as to what the term soapstone (Norwegian: *klebersten*, German: *Speckstein*) actually means. The term is in fact often misleading because it is traditionally (in Norway) used for any kind of soft stone: steatite, talcschist, soft serpentinite and even greenschist.[12] Amund Helland, a geologist who investigated the majority of Norwegian soapstone deposits in the late 19th century, distinguished between "weak stone" (Norwegian: *veksten*) and what we may call "soapstone proper". "Weak stone" for instance included some of the stone types mentioned above.[13]

Soapstone "proper" is metamorphic, mainly originates from ultramafic igneous rocks and contains talc, chlorite, amphibole and carbonate minerals (dolomite, calcite, magnesite).[14] I use the term soapstone for stones with a rather high amount of talc (greater than c. 20%), which excludes serpentinite and greenschist but encompasses the majority of other talc-rich rocks.

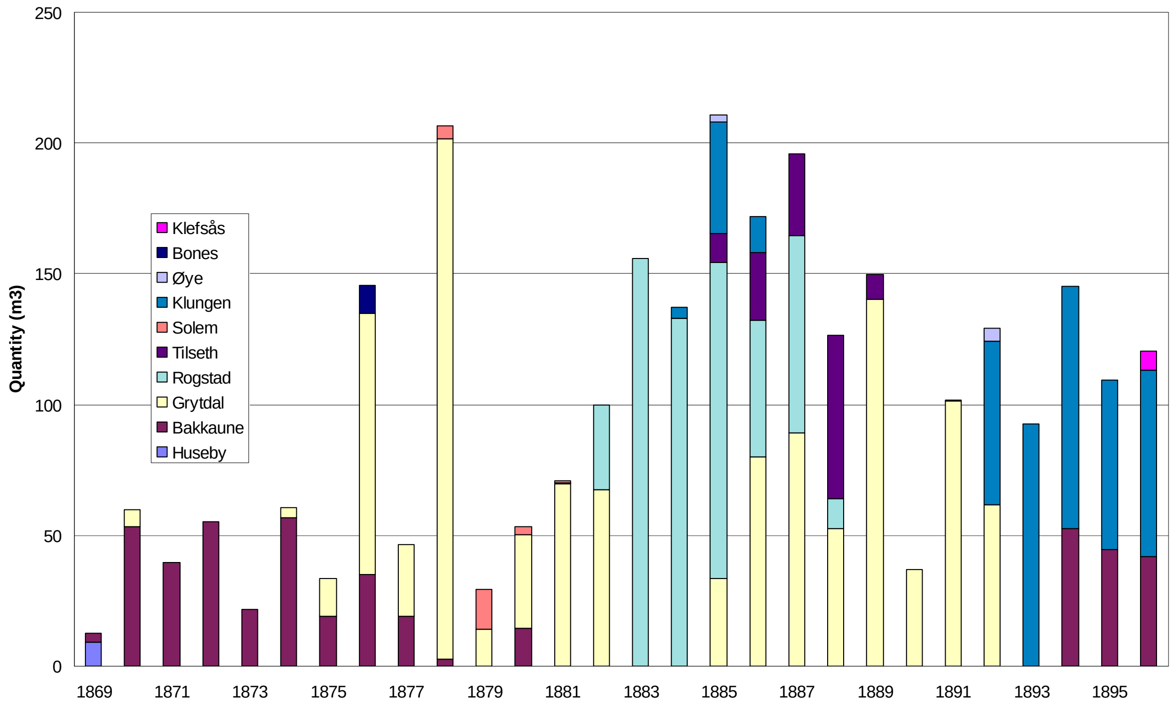


Fig. 6.4:*The most significant soapstone quarries used in the period between 1869 and 1897. Note that work was taking place in several quarries simultaneously. Source: see appendix 2.*

Soapstone is a remarkable rock. It is usually soft enough to be worked with wood carving tools, very heat resistant and has a high heat capacity. Moreover, it is usually very dense and has an extremely low porosity. People around the world have appreciated the combination of these remarkable properties since the dawn of civilisation.[15] Pots and pans, sculptures and decorations, fire-proof plates and fireplaces - and many other objects may be carved from soapstone. Early use of soapstone in Norway is mostly connected with pot production during the Viking Age, but its use extends at least back to the pre-Roman Iron Age.[16]

Although soapstone has been used for architectural and decorative purposes in countries like Sweden,[17] Finland,[18] Switzerland and Italy,[19] USA,[20] Brazil[21] and others, its use has nowhere been as extensive as in Norway. This is explained by the fact that soapstone is found throughout the country, while other soft stone types are not very abundant. As far as I know, Norway is also the only country where soapstone has been used as a construction material.

Soapstone used in the cathedral

The soapstones used for masonry and decorations during the erection of the choir and nave of the Nidaros cathedral are very beautiful ones. They have a rather dull grey-green, sometimes slightly bluish matrix of talc and chlorite, but a lot of intersecting, brown carbonate veins render the masonry extremely lively. The brown coloration of the carbonate originates from oxidation of small amounts of iron in the mineral structure.

The Bakkaune deposit, which is situated in the eastern outskirts of Trondheim, has soapstone which resembles the types found in the choir and nave.[22] However, the soapstone in the Klungen deposit (see above) has a virtually similar appearance, making it difficult to state by visual means alone whether the former, the latter or both (or completely different ones?) have been used.

The local Klungen and Bakkaune (as well as the Øye and Huseby) quarries were opened during the restoration of the cathedral as well (fig. 6.4). They were used while the craftsmen simultaneously opened five new soapstone quarries situated close to one another 70-80 km south of Trondheim.[23] Grytdal and Rogstad were the most important new quarries, they were used particularly for ashlars and decorations during reconstruction of the choir, but also for stone replacement (bases and masonry) in the transept and chapter house.

According to my investigations, the medieval greenschist and soapstone deposits were never emptied during the restoration. There is still good stone to be found in all of them. However, the new, small deposits ran out of good stone in the beginning of the 1890s - at a time when The Restoration Workshop needed enormous amounts of stone for the reconstruction of the transept, the central tower and the nave. It was therefore no wonder that the workshop turned to the very large, newly discovered Bjørnå soapstone deposit from 1897.[24]

Although situated in the Nordland county, 400 km north of Trondheim, the Bjørnå deposit was regarded very suitable for the work. It is a grey-green, rather homogeneous stone with many small carbonate and biotite grains. Although with a massive appearance, the stone often has a distinct foliation. Relatively large raw blocks could nevertheless be obtained and subsequently transported effectively by sea to Trondheim.[25] Being used until 1958, the stone is probably the most frequently encountered in the cathedral today, even when including the medieval stone types. According to my calculations, about 7500 m^3 was delivered to the cathedral - seven times more than the second most important Grytdal quarry delivered during the restoration.[26] The Bjørnå stone was used for virtually everything from copings and plain ashlars to very delicate ornaments.

From the 1930s it became increasingly difficult to quarry blocks of Bjørnå stone large enough for the west front statues. Frequent security problems at the quarry and the rapid weathering of the stone also made The Restoration Workshop start exploration programmes for suitable soapstone deposits throughout Norway.[27] One of the suitable deposits found, Gullfjellet close to Bergen, was tried for a couple of statues in the 1930s, and until about 1950 it remained an important stone source for statues and especially for copings. Quarrying resumed again at Gullfjellet in the 1970s, but after a while the quarry was abandoned.[28]

Following investigations in the late 1940s, it was not until 1952 that a more permanent source of stone turned up. From then on until today, the Bubakk deposit, about 140 km south of Trondheim, has been the main quarry operated by The Restoration Workshop.[29] The Bubakk deposit contains a mixture of very homogenous blue serpentinite and grey soapstone. Discovered at a time when the stone delivery problem was acute, the hard serpentinite became very popular for weather beaten elements, while the soft soapstone was magnificent for delicate carving. However, since the Bubakk soapstone weathers rapidly, it will present a difficult problem in the future.

When erecting the west towers in the 1960s, The Restoration Workshop needed such large deliveries of soapstone that it also had to turn to the Grunnes soapstone deposit in northern Norway. It was extensively used for the upper parts of the towers until they were finished in 1969.[30]

Marble used in the cathedral

The various types of soapstone and greenschist are the most important stones used for structural and decorative elements in the cathedral, but marble is also a very significant stone type, especially used for columns and floor tiles. Marble from as many as 17 deposits has been used, but only three of them - Almenningøya and two deposits in Sparbu - seem to have been exploited in the Middle Ages.

Almenningøya, a tiny island off the coast, 140 km north west of Trondheim, has the main medieval quarry.[31] It contains coarse grained, white dolomite marble with characteristic pink, brown or grey nodules consisting of the minerals chondrodite and olivine, and a little talc.[32] Many small, circular and larger, pointed columns by windows, pillars and buttresses, in portals and in the west front are made of this marble. It was also used for floor tiles and steps in the Middle Ages. The quarry was revitalised in the 1870s,[33] being worked occasionally during the summer seasons until well into the 20th century - and used for the same purposes as in the Middle Ages.

The Sparbu deposits are situated by the farms Lein and Frøseth in Sparbu, c. 120 km north of Trondheim. They contain a layered, coarse grained, white-grey marble with darker "clouds" and bands. In addition to many columns and floor tiles, the marble was supposedly used for the pillars of the nave in the Middle Ages.[34] In 1905 it was certainly used when erecting the new pillars during the reconstruction work - as moulded plates which were put on top of each other.

Introduced in 1876, a loose block of the white Rissa marble (30 km NW of Trondheim) was used for the high altar in the octagon,[35] while most of the large floors of the choir, transept and nave were made by tiles of the famous Fauske marble (Nordland county).[36] The exploitation of the Fauske marble commenced in the 1880s and has since then been exported worldwide.[37] Mainly pink types from Leivseth were used in the choir in 1888-89, while other varieties of "Norwegian Rose" tiles were laid in the nave in the 1930s. Last, but not least: some of the sculptures of the high altar and the altar of the chapter house are made from Cararra marble.

Metasandstone and slate used in the cathedral

In the near vicinity of Trondheim there are quite a few deposits of metamorphic sandstone and greywacke.[38] Since the stones are metamorphic (metasandstones), they are generally harder and more difficult to carve than many of their Continental and British counterparts.

According to my investigations, metasandstones were never used in the cathedral during the Middle Ages. However, architect Schirmer made heavy use of the stone when restoring the chapter house. The stone in question is the grey, sometimes brownish, lime and clay cemented Hovin metasandstone[39] found in the Lundamo-Hovin district, 30-40 km south of Trondheim. In this area there are at least three quarries which have been providing stone for building purposes in Trondheim (for instance 19th century buildings), but only the Samdal quarry was used for the Nidaros cathedral. In addition to the chapter house, Samdal stone was used for replacement purposes in the octagon during the 1870s.[40] The Reppe quarry, situated in the eastern outskirts of Trondheim, also provided metasandstone for a short period of time. This stone is light grey, distinctly foliated and contains much biotite. Several dozen small columns in the chapter house, octagon and transept were carved from Reppe stone during the 1870s.[41]

Slates are commonly found in the vicinity of Trondheim and there are several local deposits which traditionally have been used for roofs. The Stjørdal district, 30-40 km east of the city is especially rich in slate and provided a very dark variety for floor tiles in the cathedral. The variety is called Sorte and was used as a contrast to the light marbles in the choir, transept and nave during the restoration.[42]

Granitic gneiss and hard greenstone used in the cathedral

All stones mentioned so far have been used for decorative or a combination of decorative and structural purposes. Additionally, there are huge masses of stone which only have limited decorative value. Such stones are generally different types of granitic gneiss or hard greenstone which can be found in several interior walls, foundations and masonry cores. All remaining medieval vaults are also made of greenstone slabs.

While interior walls of the chapter house, octagon, choir and nave all have greenschist or soapstone ashlars, the oldest parts - the transept and central tower - were constructed using red gneiss in the Middle Ages. We do not know from where the gneiss was obtained, but presumably it was simply from erratic blocks or from deposits in close proximity to the city. Just across the Trondheim fjord there are several deposits to be found.[43]

During the restoration several local deposits were exploited for varying periods of time. The most important deposit is also a red granitic gneiss, located in Ingdalen, some 15 km west of Trondheim (by boat). The stone was in particular used for the interior walls above the vaults of the nave and in the west front.[44] Gneiss and granite have also been used in the west towers, but not in the clerestory walls of the reconstructed choir where brick was applied instead.

Brick used in the cathedral

Brick has been produced in Trondheim at least since 1277. According to the medieval laws of Norway, the brick works at Bakklandet (fig. 6.5) were established in order to provide brick for the Nidaros cathedral.[45] Whether this actually happened is difficult to figure out since there are no remains of medieval bricks in the cathedral today. We may perhaps assume that the establishment of the brick works was related to the large amount of light material needed to erect the vaults in the nave, maybe also the main vaults of the choir?[46] The heavy medieval vaults remaining in the cathedral today (chapter house, octagon, chapels of transept) are all made by relatively small slabs of irregular slate or greenstone set in an upright manner adjacent to one another.

Since the Reformation, brick has been a very important material for all kinds of repair and building operations. We know for instance that the Late Gothic window inserted in the north transept in the 14th century and later fully repaired after the 1531-fire was made of brick. Brick was also used for rebuilding the gable of the south transept in 1666, as well as for several burial chapels added to the church from the 17th century onwards. Moreover, brick was used for roofs (tiles), for most of the burial crypts below the floor of the church - and for several additional purposes. Some of the red bricks were probably produced in Trondheim (Bakklandet), while large amounts of yellow bricks were imported from the Netherlands and Germany. It is also interesting to note that architect Schirmer's plan for "beautification" of the choir in 1846 included brick as the main building material. The "beautification" was, however, never accomplished.[47]

When the restoration started in 1869, there were several brick works in Trondheim and its vicinity. At Bakklandet, production had taken place with some interruption since the Middle Ages, while works at Stjørdal and Lundamo started in the 1740s and 1850s, respectively. In 1899, a second Trondheim factory was established a little east of the city (Strinda). All of these works remained in operation until the 1960s or early 1970s, when there was no longer sufficient demand for brick in the modern building industry.[48]

Although Trondhjems Aktieteglværk at Bakklandet was probably the main source, all the above mentioned factories provided brick for the restoration of the cathedral. For a layman it is probably difficult to understand the large amount of brick needed for the restoration because it is difficult to see even one single brick when observing the exterior and interior of the church. When, however, studying lofts, cellars and reading account books and diaries, the "brick-cathedral" soon starts to become apparent.

Fig. 6.5: The brick works at Bakklandet in Trondheim, c. 1930 (photo: ARW, no. 3906).

In addition to all the vaults in the choir and nave, including the vaults of the aisles, brick has been used in the restored vaults of the chapter house, octagon (main vault) and central tower. Interior gable walls in the octagon's chapels were constructed using brick, as were the upper part of the southern transept and the walls of the clerestory of the choir. Moreover, all the walls and vaults of the cellar are made of brick. Apart from its lightness and suitability for use in vaults, another reason for using brick may have been connected with occasional difficulties with the supply of stone.

6.2 Dressing of stone and stone masons' marks

This chapter is dedicated to a brief description of how stone surfaces have been finished. I will concentrate on dressing of ashlars made of soapstone and greenschist. It is also necessary to pay attention to the thousands of stone masons' marks at the cathedral. The masons' marks are of great historical significance, increasing the value to otherwise anonymous ashlars.

Another important aspect of stone surfaces is paint. Although we have to assume that many architectural decorations were painted (polychrome treatment) in the Middle Ages,[49] there are at present no remaining traces positively known to be medieval. The few traces that exist are believed to originate from post-Reformation “beautification” projects (fig. 6.6). These painting projects are discussed in section 6.3.

Dressing of stone

Although dressing techniques are important aspects of medieval stone buildings, the cathedral's dressing marks have never been carefully investigated. Since dressing techniques are subject to change as a function of stylistic ideals and available stone working technology, careful studies may in particular give valuable information about building and conservation history.[50]

Moreover, dressing may have a direct impact on the weathering of stone. It has for instance been maintained that modern machine dressing in some situations increases weathering rates.[51] From a weathering perspective it is also important to be aware of the fact that *redressing* of stones has been a very normal procedure at the Nidaros cathedral and elsewhere. Hence, stones commonly thought of as having withstood weathering since the Middle Ages may well appear so good today because of having been redressed in the last century or later. Another important aspect is in which state the stone should be dressed - quarry moist or seasoned (dry)? Such questions are related both to workability and durability. They are very difficult questions and have to be seen in the light of the properties of the actual stone and the whole process of working it - from quarrying to finishing.[52]

The dressing marks to be observed on the cathedral today can be subdivided in three different categories: medieval marks, marks of redressing operations during the restoration and marks on new stones from the restoration. The medieval dressing marks appear to be rather uniform. Axed ashlars with diagonal or vertical toolmarks are almost without exception found in all parts erected between the middle of the 12th century and 1300 (fig. 6.6 and 6.7). It has earlier been maintained that marginal drafts were left on Romanesque ashlars, but removed on Gothic ones.[53] According to my observations this is false - marginal drafts have almost without exception been removed on all ashlars put in place in the Middle Ages.

Fig. 6.6: *Remaining layer of blue-grey paint on a medieval axed greenschist ashlar. The paint was probably applied in 1818 (see figure 3.5). North transept (photo: PS 5/96).*

It may sometimes be very difficult to detect dressing marks on medieval ashlars - the surfaces appear to have been rubbed down. However, careful studies always reveal very fine toolmarks.

Redressing of stone during the restoration is more or less confined to the eastern part of the cathedral (chapter house, octagon, choir and transept). Not all surfaces on these parts have been redressed and it is usually easy to observe where it actually took place. Undertaken in order to remove surface treatments (plaster, whitewash and paint) or to "brush up" the stones, the most widespread technique was to use bush hammers which leave the surface with a "dotted" appearance (fig. 6.8). However, axes, chisels and even rubbing have been applied as well.

Fig. 6.7: *Irregular, medieval dressing marks on a pillar of the east chapel of the octagon (1180s). Note the well preserved masons' mark (photo: PS 8/95).*

New stone put in place during the restoration have chiefly been treated like those in the Middle Ages, especially in the early phases of the restoration. One exception is that the tool-marks are very regular and rather coarse (fig. 6.9) and that bush hammers have been used for relatively hard stones (metasandstones). Another exception is that many ashlars have been cut by saws and subsequently dressed (batted ashlars). A third exception is that a lot of stone, especially in the west towers, have been left with sawed or rubbed surfaces.

The medieval masons' marks

We cannot leave the stones of Nidaros without mentioning a real treasure of the cathedral - the 220 different and a total of more than 5000 medieval masons' marks. The marks have been recorded by Dorothea Fischer and co-workers.[54]

Probably connected with the checking of the work turned in by each mason and/or the rate of pay, the masons' marks in the cathedral are quite unique in a European context, partly because they are so abundant and partly because they are very distinctively carved in the soft soapstone and greenschist. In the Nordic countries, it is only the Romanesque and Gothic Linköping cathedral in Sweden that has a similar number of masons' marks.[55]

By studying the marks, it is possible to follow the work of the different masons from one part of the building to another. When using the Romanesque part of the south transept - where 19 different marks have been found - as the basis, we can for instance see how 16 of these marks also appear in the north transept, while 22 marks are new to this portion. Another

Fig. 6.8: *Ashlar treated with bush hammer during the restoration (1870s), probably in order to remove whitewash. South transept (photo: PS 8/95).*

example is the seven marks in the choir which are also found in the nave, where as much as 70 new ones can be observed. The total number of marks in the nave is more than 1500, while only 22 remain in the heavily restored chapter house. Another interesting feature is that many marks can also be found on other medieval churches in the Trøndelag counties, indicating the intimate relationship between the workshop of the cathedral and the erection of the other churches. Masons' marks have been used as the workers' signatures until the restoration of the octagon in the early 1500s. Recently, the masons have once more started signing their work with masons' marks.

Fig. 6.9*: Regular dressing marks on soapstone ashlars from the restoration (c. 1910, Bjørnå stone) in the northern west tower. The lighter ashlar is a redressed medieval one. Note also the rubbed-down ashlar (photo: PS 8/95).*

In addition to letters (mostly runes), the marks generally show simple geometrical forms, but also some idealised pictures of tools have been found. The latter include axes, compasses and squares. Many of them are carved rather deeply into the stonework and a large number have got shallow drill marks at the ends of straight lines, or where lines cross each other (fig. 6.10).

It is obviously difficult to find all the masons' marks in the cathedral. The building is simply too large and one is dependent on scaffolding or mobile lifts when studying most parts of the cathedral. Additionally, due to missing medieval parts and heavy restoration and reconstruction works, many marks are lost forever. However, when carefully surveying the exterior east wall of the octagon's east chapel (using a mobile lift), we have found 3-4 previously unregistered marks, thus telling us that there were 3-4 masons working on the octagon in addition to the c. 50 already “known”. The east chapel is a tiny part of the cathedral, reminding us that careful observation on other parts may also reveal numerous marks that have not been recorded earlier.

The building history of the cathedral is of course not yet finished - it will undoubtedly be rewritten in the future. Recording masons' marks (and features like dressing marks) before or during conservation interventions is thus still a very important task. Interpreting new and old marks in the light of new or old theories may give new clues about the building history.

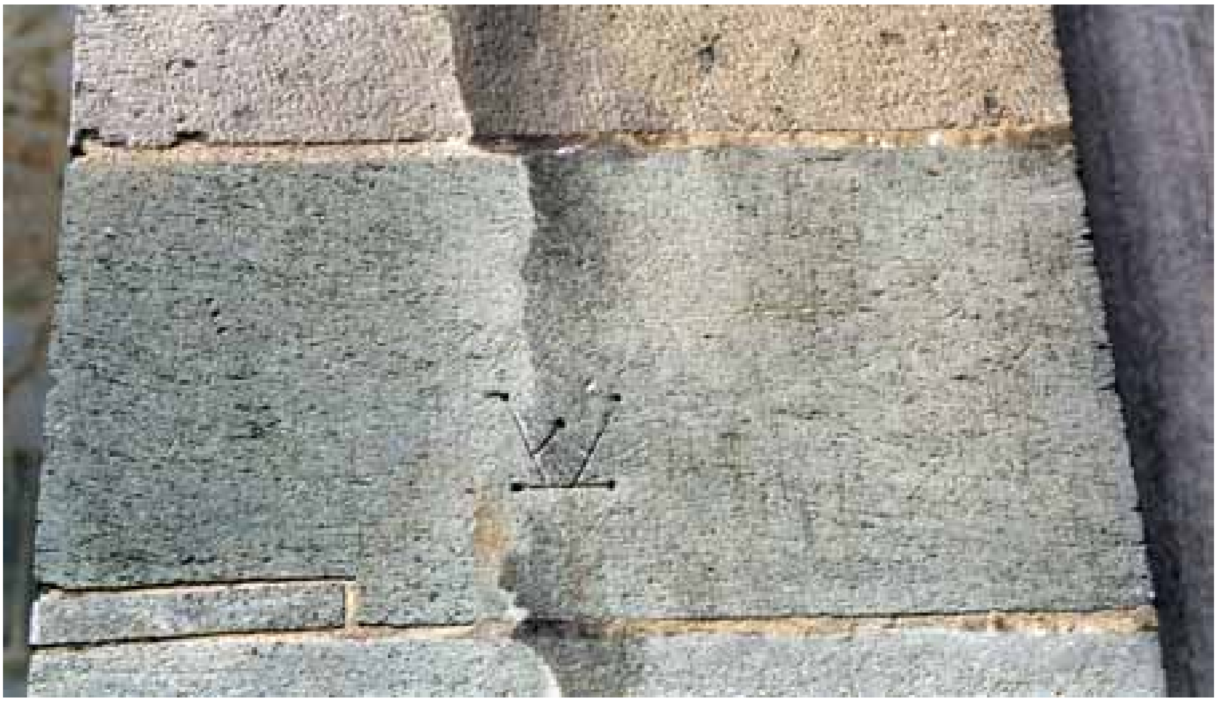


Fig. 6.10: *Typical example of a well preserved masons' mark on a greenschist ashlar. South chapel of the octagon, 1180s (photo: PS 8/95).*

6.3 Mortars, whitewash and paint

Before turning to the characteristics of mortar, plaster, whitewash and paint to be found in the cathedral, it is necessary to recall some general structural features of large cathedrals. It is also necessary to ask what mortar is used for and why it is so.

Cathedrals from a mortar perspective

In walls made of ashlars, mortar is used for levelling purposes - often together with pinning: this is to distribute compressive forces over the entire contact surface between stones. Simultaneously - before it weathers away - mortar prevents water entering joints and thereby the building structure. Mortar is also used in masonry cores and between stones in elements like flying buttresses, pinnacles and tracery. In the latter elements (and several others) mortar is only partly used to bind stones together or prevent them from sliding. Usually metal cramps and dowels serve this purpose. Lead joints as well as cramps and dowels are also commonly applied in features like parapets, tracery and to hold columns in place.[56]

It is important to remember such basic features of large stone buildings, especially as mortar is commonly thought of as the material binding the structure together. However, in a Gothic cathedral the high dead load is the main factor holding the structure in place. If the building is properly constructed, most of its parts will be in compression, which is also the reason why “weak” lime mortars which are not able to withstand tensile stress over a prolonged period of time may behave perfectly in such a building. On the other hand, dozens of examples - including Nidaros - show that Gothic cathedrals often develop large tensile stresses leading to cracks and eventually to collapse.[57]

A note on the history of lime and cement in Norway

When building with stone was introduced in Norway in the 11th century, the use of lime mortars followed as a necessary companion. We know little about the properties of medieval lime mortars in our stone buildings since no systematic analyses have been carried out.[58] From scattered investigations and visual observations we may state that the mortars in general were based on a large content of binder compared to aggregate. It has been maintained that joint mortars in general had a higher amount of aggregate than plaster and renderings, but my investigations in the Nidaros cathedral show that joint mortars were also very “fat” (binder:aggregate = 1:1 - 1:3).[59]

Deposits of limestone, crystalline limestone or marble are available close to our cities and remains of medieval kilns have been found at some places (for instance at Værnes close to Trondheim), but we know very little about the process of making lime mortars in medieval Norway.[60] Our knowledge about old lime mortar production is primarily based on 19th century production and working processes. We know for instance that lime burning in the last century was very often undertaken at sites where also brick was produced. In the vicinity of Trondheim there were at least five brick and lime production facilities at the turn of the century.[61] All of them seem to have been producing lime from rather pure crystalline limestone deposits. The facilities provided primarily burnt lime (quicklime or calcium oxide) in barrels to be air- or pit-slaked at the building sites. Except for Portland cement, no particular (hydraulic) additives seem to have been in normal use. Until after the Second World War Portland cement was used as an additive to lime mortars especially when they were to be applied at exposed places in a stone or brick building.[62]

Although the production of modern Portland cements commenced a little later in Norway compared to England and Germany, general production and pattern of use were the same. Two factories started limited production of natural hydraulic cements close to Oslo in the 1840s and 1850s but the factories were closed by the 1860s. It was not before 1892, when the Christiania Portland Cementfabrik started its operation at Slemmestad near Oslo, that a permanent national manufacturer was established. It is important to note that English, German and possibly Swedish and Danish Portland cements at that time had been imported to Norway for several years.[63]

Generally, the production and use of lime decreased steadily as Portland cement took over as the main building material in the first half of the 20th century. In 1919 the second Norwegian Portland cement factory was established in Kjøpsvik in Nordland county, while the third one followed two years later in Brevik in Telemark county. Together with the Oslo factory, these factories merged in 1968 becoming the Norcem company. Production in Oslo was terminated in 1989 and today our Portland cement generally originates from either Kjøpsvik or Brevik as very little is imported. In the Trøndelag counties and northwards, Portland cement has mostly originated from the Kjøpsvik factory due to national regulations.[64]

Even though the production of lime for building purposes in Norway has been limited in the 20th century it never completely cease. Several factories produced air-slaked lime until well into the 1960s and 1970s and there are still a couple of producers, but the pit-slaked variety went out of use some time after the Second World War. Today, small quantities of factory-made wet-slaked lime can be obtained from the Franzefoss company, but such lime has generally been imported from Sweden and Denmark during the last 20 years when occasionally needed for restoration purposes. It is reasonable to state that the traditional production and use of pit-slaked lime is an almost forgotten craft in present day Norway.[65]

Tab. 6.1: Analyses of a selection of mortars in the Nidaros cathedral.

Medieval lime mortar samples (masonry cores) taken in 1910 (triforium, central tower)

Chemical analyses of:	Sample B 6	Sample B 23
$Ca(OH)_2$	0,06 wt%	0,13 wt%
$CaCO_2$	53,9 wt%	44,7 wt%
Bound SiO_2	2,8 wt%	2,9 wt%
Aggregate	39,9 wt%	0,9 wt%
Moisture+organic sub.	1,6 wt%	5,7 wt%
Total:	98,3 wt%	94,3 wt%
Rest: charcoal, pyrite, iron oxides		

Selected samples (joint mortars) taken in 1990 and 1993

Sample	Location	Used for	Age	Lime	Cem. wt %	Agg.	Mix.
7	Masonry, east chapel, octag.	Old joint	Medieval?	20	10 [1)]	70	1:3
C/s/s/i 13-93	Loft, south chapel, octagon	Plaster/repair	1872	20	20	60	1:2,5
C/n/n/i 18-93	Loft, north chapel, octagon	Plaster/repair	1872	35	15	50	1:2
8	Pillar, east chapel, octagon	Repair, joint	20th cent.	10	40	50	1:2
14	Buttress, north wall, choir	Old joint	Medieval?	30	10 [1)]	60	1:2
9	Flying butt, north wall, choir	Repair, joint	1940s	5 [2)]	40	60	1:2,5
13	Buttress, north wall, choir	Repair, joint	1940s	5 [2)]	35	65	1:2,5

Notes:

- 1) Based on SiO_2-analyses. May originate from hydraulic components in the limestone or from contamination by later repair mortars (Portland cement)
- 2) Cement content may originate from contamination by older mortars or from carbonate reaction.
- Chemical analyses of samples taken in 1910, see Lund et al (1912:appendix 9)
- Chemical analyses of sample 7-9 and 13-14 by SINTEF, Trondheim, see Waldum (1992)
- Chemical analyses of other samples by National Institute of Technology, Oslo, 1994
- Analyses interpreted and corrected by means of historical research and visual/microscopical observations

Medieval lime mortars

Since we know so little about mortar production in the Middle Ages, we can only assume that remaining medieval lime mortars to be found in the cathedral are representative of the generally known methods. The following description of properties is based on very few analyses (tab. 6.1), but as visual observations have been undertaken during five years throughout the cathedral, the description is not completely unfounded. It is clear that many more analyses should be performed to make more robust statements. The cathedral is big - and it was originally built during more than 150 years!

Joint mortars in general have a lime to aggregate ratio between 1:1 and 1:3 (by volume) and according to scattered analyses they contain calcium carbonate in the binder (little or no magnesium carbonates). Some analyses show small amounts of silica in the binder (approximately 2% by weight). There are at least three possibilities when regarding the origin of such silica. The most probable source is from silicate minerals in the original limestone. Another source is added components, for instance brick powder (after about 1280), and the third possibility is contamination by Portland cements used during the restoration. The latter may be a very likely scenario because large parts of the masonry have been consolidated by Portland cement grouting (see below). Occasionally we find small pieces of charcoal in the joint mortars. Charcoal fills up the joints and may increase the moisture content of the mortar (moisture is necessary for setting of the mortar), but it is otherwise unclear why it has been used. We do not know if other additives have been applied in order to increase workability or durability. Aggregates are of a very diverse nature. Some thin joint mortars may contain very fine-grained types, while thicker ones look more like “lime concrete” with very coarse aggregates (5-20 mm).

It is obviously difficult to sample medieval mortars in the masonry cores of the cathedral. I have not undertaken any sampling and we therefore have to rely on a programme carried out in 1909-1912 when the so-called “stability committee” investigated the condition of the central tower.[66] At that time several samples were taken from the cores of the tower's triforium. Subsequent chemical analyses of the mortars showed that they were extremely fat, having a binder to aggregate ratio of 1:1 or even less. Also in these mortars some silica was found (origin discussed above), and they contained limited amounts of pyrite, iron oxides, charcoal and unknown organic substances. It was also found that the carbonation process was still incomplete in some of the samples. This is a well known phenomenon in old, thick masonry which may have had only limited access to air. The investigations also showed that there were often large, open spaces within the cores - a result of the original building process or more probably washing out of the mortar due to numerous water leaks. The investigators found, moreover, a lot of lime mortars which had been affected by cement grouting applied during the restoration.

It should be remembered that many remaining medieval parts of the cathedral have been repaired over widespread periods after the Reformation. Hence, mortars believed to be medieval, may originate from these repair projects. Another important point to note is that medieval mortars may have burnt several times - they may have gone through one or more cycles of reduction to quick lime and subsequent recarbonation.

There is only one small deposit of (crystalline) limestone located in the close proximity to Trondheim. The deposit is situated in Strindamarka, some seven km south of the city centre. Several small, old quarries along the narrow limestone bench suggest that it was an important source of lime in the Middle Ages.[67] It has also been exploited in later periods and was probably one of the sources from which the brick works at Bakklandet (Baklandets Teglværk/Trondhjems Aktieteglværk) in Trondheim obtained its limestone for lime production in the 19th century.[68] Otherwise, medieval lime mortars in the cathedral may have been produced close to the large limestone deposits in Stjørdal and Verdal and transported to Trondheim by boat.

Post-Reformation plaster and whitewash

After the Reformation, the cathedral drastically changed its appearance not only because of fires, destruction and rebuilding operations, but also because of the application of plaster and whitewash.

Masonry constructed as part of repair projects in the late Middle Ages was perhaps plastered, but we have no information about plastering during original building operations whatsoever. We may assume that the interior parts of Romanesque masonry, in particular in the transept and central tower, were originally plastered. The walls here are made of coursed or random rubble (granitic gneiss) with wide joints - a masonry type which was usually plastered in the Middle Ages. If being plastered, we may also assume the walls contained mural paintings. Interior Gothic walls built with ashlars were probably not plastered or whitewashed originally.

What we know for sure is that new building parts erected after the Reformation were plastered since they were all constructed of different kinds of stone rubble or brick. The 16th century clerestory of the choir and the 1666-gable of the southern transept are two examples among many more.

More interesting is the fact that remaining medieval masonry was whitewashed as part of repair work after the Reformation. The first documented whitewashing took place in the 1630s when the octagon underwent a rather thorough repair both inside and outside.[69] After the 1708-fire, the whole interior was plastered/whitewashed - except for decorative stone details of which some were painted. The exterior was repaired in 1717. It was probably not plastered, but rather repaired by filling in cracks and open joints with mortar and subsequently whitewashed.[70] Similar repair operations must have taken place after the 1719-fire.

A very important repair operation took place before the coronation of King Karl Johan in 1818 (see fig. 4.4). Marble columns were whitewashed, and exterior masonry, including some decorations, painted with a grey glue paint,[71] presumably some kind of lime- and glue-based distemper with dark pigments. This repair is important insofar as there are remains of the paint on the cathedral even today. Otherwise, almost every sign of post-reformation plaster and whitewash was removed during the restoration from 1869. The different removal techniques will be described in chapter 6.4.

Lime mortars during the restoration

When the restoration began in 1869, one of the first things architect Schirmer and master-builder Guttormsen did was to dig out a pit for slaking lime in the still ruined nave of the cathedral.[72] Large amounts of quicklime (lump lime) was obtained in barrels from the brick factory in Trondheim and from other local producers at Lundamo, in Stjørdal and in Verdal. Sand was provided mostly from glaciofluvial deposits near Trondheim.[73] We do not know for how long the lime was left in the pit to mature, nor if aggregates were stored together with lime in the pit or added afterwards. What we do know is that the prescribed, minimum time for maturation in the latter half of the 19th century was two months[74] and that subsequent treatment included the traditional chopping, beating and ramming in order to obtain as workable a lime putty as possible. Untrained workers were employed during the first stages of the restoration to undertake this important job.[75]

It is unclear for how long the slaking pit remained in operation on a regular basis. It was probably moved to the cellar below the southern west tower when the restoration of the nave commenced at the turn of the century. The pit is in fact still located here, but according to masons working in The Restoration Workshop today, it has not been used since the early 1960s. At that time the pit probably provided lime for plaster etc. Remaining lime in the pit contains only lime - no aggregates. We may assume that regular operation of the pit was more or less terminated well before the Second World War, as lump lime - according to account books - was bought in very rarely in the 1930s.

Even if lime was an important building material during the first stages of the restoration, the historical documentation on how it was used is limited. Moreover, as Portland cements were imported, for instance from England, by 1869, it is often very difficult to state by visual means alone whether cement was added to the lime mortars when used for joints. As we shall see below, several analyses show that adding cement to the lime must have been the rule rather than the exception.

From Schirmer's restoration of the chapter house we have documentation showing that pure lime mortar was used together with suitable rubble for masonry cores when building the new walls. Joints were made by what is referred to as cement, but it may be lime mortar with a certain amount of Portland cement added.[76] In the octagon, very little pure lime mortar was used during the restoration because the work involved mainly consolidation of existing walls. For these purposes different types of mortars based on Portland cement were used.

From the 1870s and well into the 20th century lump lime was only occasionally obtained from different producers (and subsequently pit-slaked), while barrels of Portland cement were often provided up to several times a week.[77] With regard to the preparation of lime cement mortars, this information points to the normal working process of adding cement to lime putty. However, things may have been different when regarding the reconstruction of the choir. In the account books we find that "lime mixed with sand" has been bought during the period between 1878 and about 1895.[78] It is uncertain what kind of product this was, but since it was delivered in barrels, it may have been a ready-to-use mixture of lime putty and sand ("wet coarse stuff").[79] Observations in the interior of the choir's loft show that lime-based mortars have been used here, while exterior walls have got Portland cement mortars, possibly mixed with some lime.

The transept, central tower and nave were presumably restored and reconstructed with different types of lime cement mortars - at least when regarding the interior of massive walls. As stated above, such mortars were prepared by adding a certain amount of cement to the pit-slaked lime. After the nave was finished in 1930, lime was rarely mentioned in diaries and other documentation. The restoration architects wanted to substitute cement mortars with lime mortars when building the west towers in the 1950s, but the project seems to have been put on ice.[80]

Mortars based on Portland cement until 1930

The properties of mortars based on Portland cement have - as we understand - been appreciated by the architects and craftsmen of The Restoration Workshop since 1869. Unlike elsewhere in 19th century Europe, where heated discussion about the problems of applying modern cements instead of traditional lime mortars were carried out,[81] no particular debate seems to have taken place in Trondheim. On the contrary, Portland cement has "always" been regarded as a suitable material for restoration and reconstruction of the cathedral, and it is only recently that its use has been seriously questioned.[82]

Until the beginning of the 1890s, different types of Portland cement had to be obtained from abroad (tab. 6.2). They were very expensive, often as much as 7-8 times more costly than the same amount of local lump lime (tab. 6.3), but the price difference decreased steadily after the turn of the century when cement became the rule rather then the exception for modern building operations.[83]

Although I have not studied all available historical sources, it seems clear that Portland cements were mostly imported from England and Germany. In the beginning of the 1870s we know that some cement was obtained from Newcastle, while the German variety called “Hemmoor” (factory in Hemmoor near Hamburg) was probably the normal one used at least in the 1890s and probably until about 1910. From then until now, Norwegian Portland cement, mostly from Kjøpsvik, has been used.[84]

Fig. 6.11: *Example of medieval masonry repointed by mortars based on Portland cement during the restoration. South-east wall of the octagon, made by greenschist and some soapstone, restored in the 1870s. The original medieval mortars are extremely thin and they have been widened in order to apply repointing mortars. It is evident that weathering preferentially takes place along the repointed joints (photo: PS 1995).*

Schirmer's use of “cement” for joints between ashlars in the chapter house was rather limited compared to the amounts applied by architect Christie during his work on the octagon. Reading his restoration reports with a mortar perspective in mind, is like studying an advertisement for the diverse possibilities of Portland cement. Firstly, he used Portland cement mortars or lime cement mortars for re-pointing damaged joints (fig. 6.11) and when replacing different features. Secondly, his craftsmen prepared thin groutings (or “soups”) of Portland cement to fill in deteriorated masonry cores. The foundations were also strengthened by Portland cement, while floors mostly got a layer of cement below their new marble tiles. Moreover, several wallheads were covered by early types of concrete based on Portland cement. The upper sides of vaults were also covered by layers of cement in order to “avoid eventual water leaks”.[85]

Tab. 6.2: *Origin of known Portland cements used in the Nidaros cathedral since 1869. Note the analysis of the most frequent Portland cement to be found in the cathedral.*

Name and/or location of factory	**Use period**
"Elephant", Johnson Corp., Newcastle & London, England	1870s
Robinson Allan Corp., Newcastle, England	1870s
"Hemmoor", Hamburg, Germany	1880s-c. 1910
"Germania", Hannover, Germany	around 1905
Christiania Portland Cementfabrik, Slemmestad, Norway	c. 1895-1920
Nordland Portland Cementfabrik, Kjøpsvik, Norway	from c. 1920
Norcem A/S (cement mostly from Kjøpsvik)	from 1968

Portland cement based mortars known to have been used	**Mentioned in**
Ordinary Portland cement	1869-1995
Lime cements (usually wet-slaked + Portland cement)	1869-1930?
Cement "soup" (thin grouting for consolidating masonry	1870-1969
High-alumina cement	1928
Portland cement with silicon carbide (SiCa) (for covering)	e.g. 1928
High-alumina cement with soapstone powder and waterglass	1936
Portland cement and lampblack (dark coloured cement)	e.g. 1944
Portland cement with "Silix" (waterproofing properties)	1946, 1948
Expansive cement (Nonset 50) for grouting and pointing	1987-95
Portland cement with c. 10% latex (enhancing adhesion)	1990s

Normal mortar mix (binder:aggregate): 1:1 - 1:3

Where concrete has been used in the cathedral
Consolidation of old foundations all over the cathedral
Establisment of new foundations and in floors and cellars
Wallheads
Several interior floors in the west towers
The upper part of the west towers (reinforced concrete faced with soapstone)

Typical content of the P30 cement produced by Norcem a/s (weight%)

Oxides:		**Clinker content:**	
SiO_2	20,4	C_2S	18,8
Al_2O_3	5,0	C_3S	52,6
Fe_2O_3	3,7	C_3A	7,1
CaO	62,8	C_4AF	11,1
MgO	2,3		
SO_3	3,2		
Alkalies (eq. Na_2O)	1,2		
Free CaO	1,2		
Loss on ignition	0,8		

Sources:
Historical: DiaGu, DiaRa, AccLu and letters from importers (ARW). Explanation of abbreviations, see notes. See also Gartmann (1990) and Jensen (1993). Analyses: See Jensen (1993).

This general scheme was more or less followed for all remaining, medieval building parts. As regards the structures that had to be reconstructed or rebuilt, we have already mentioned that lime cement was used within the walls. Pointing mortars between exterior ashlars were made by rather "clean" Portland cement, usually with a binder to aggregate ratio of 1:3.[86] This ratio was probably the general one applied when preparing most types of mortars. As I understand,

Tab. 6.3: *Account for the restoration of the north porch of the cathedral in 1880-81, showing that lime and cement were used in combination. Note the large price difference between lime and cement (from account book of manager Lundemo 1869-97, ARW, my translation).*

Work, materials and tools	Work hours	Unit price (NOK)	Price (NOK)
Foundations			
Masonry work	191,7		358,48
Hard stone from old masonry		0,00	0,00
11 barrels of cement		9,50	104,50
36 barrels of lime mixed with sand		1,30	46,80
Base			
Stone carving (profiles)	96,7		232,16
Stone carving (bases)	15,5		45,80
Masonry work	20,5		49,25
Walls			
Stone carving (columns)	51,3		150,27
Stone carving (capitals)	45,7		156,84
Stone piecing (arches and tracery)	50,9		131,32
Stone carving (ashlars)	344,5		685,54
Stone piecing (relief)	48,8		157,90
Stone carving (cover stones)	96,6		214,36
Stone carving (top stone of gable)	21,3		61,88
Masonry work (floor and interior walls)	31,6		178,57
Masonry work (cleaning and plastering)	141,7		294,36
Masonry work (incl. recarving old stones)	258,4		483,08
43 barrels of cement		9,50	408,50
119 barrels of lime mixed with sand		1,30	154,70
309 cubic feet (7,38 m^3) of soapstone		2,00	618,00
Other			
Roof, wood, lead and gutters (incl. work)	69,4		598,62
Scaffolding	44,6		94,57
Tools	21,5		43,00
Gravel and transport of gravel	1,0		2,70
Total	1551,7		5871,20

(Source: AccLu, ARW. Explanation of abbreviations, see notes.)

no particular additives were used in the masonry mortar before 1930. However, mortar for special purposes, like covering of exterior gangways, was added silicon carbide and asphalt. Except for very occasional use of high-alumina cements for unknown purposes, standard Portland cement was the only type of modern cement applied.

Portland cements, additives and concrete from 1930

Standard Portland cement from the Kjøpsvik factory was the usual binder applied in mortars and concrete since 1930. During the erection of the west front and in particular the west towers (from about 1950), the amount of Portland cement used rapidly reached enormous quantities. This was partly because of the large-scale building operations undertaken, but also because the masons used very strong mixes. From masons still working in The Restoration Workshop we know that ashlars were set in the normal 1:3 mix. However, instead of using a real mortar for the narrow spaces between ashlars and “masonry cores”, thin soups of cement with a mixing ratio of 1:1 were applied - obviously in order to obtain “strong” masonry.

Partly due to the time pressure and partly due to stone delivery problems when erecting the west towers which were planned to be finished before the 100 years anniversary of the restoration in 1969, the upper parts were built as reinforced concrete structures clad with soapstone ashlars. As we know today, such a building technique is predestined to give severe problems. And the towers are no exception: The highest weathering rates can in fact be found in these youngest structures of the cathedral.

In addition to masonry mortars and concrete based on Portland cement, several special mortars based on cement have been used at the cathedral during the last 60-70 years - particularly for re-pointing and other types of “re-restoration” purposes. High-alumina cement with soapstone powder and waterglass was tested as well as adding waterproofing agents (“Silix”) to mortars. Silicon carbide and asphalt were also in normal use when preparing mortars for covering purposes, especially before being replaced by diverse types of “pure” asphalt, asphalt glues and finally copper plates at some exposed places (exterior gangways).[87]

During the last decade, the masons have experimented with different modern mortar mixes. Since expansive Portland cement (“Nonset 50”) were introduced for consolidating the foundations of the central tower in 1984-86, some masons have found expansive cement useful for pointing and re-pointing purposes in order to avoid fissures due to shrinking. Adding about 10% latex to the mortar to enhance adhesion between joint and soapstone has similarly become very popular. In 1995-96 hydraulic lime mortar was used for the restoration of the west tower of the north transept.

In conclusion: Since about 1930, building and restoration operations have been carried out with very little reference to the use of traditional mortars. Re-introduction of lime-based mortars for future conservation of the cathedral is therefore going to present enormous difficulties, because it will mean breaking a long, modern tradition and because of technical difficulties: The cathedral is so “infected” by Portland cement that it may be impossible to use lime mortars for conservation purposes - at least when considering the western part.

As regards weathering due to alkaline salts (see chapter 3), ordinary Norwegian Portland cements are known to have a very high content of sodium and potassium. Between 1971 and 1990, the monthly average content of equivalent Na_2O in cement produced at the Kjøpsvik factory fluctuated between 0,9 and 1,3%. The total content of Na_2O and K_2O both varied between 0,5 and 0,8%, but the actual amount available for dissolution and reaction to form secondary products such as salts is not known.[88]

6.4 Particular conservation methods

In addition to strengthening of foundations, widespread replacement of stones, consolidation of masonry with Portland cement, re-pointing of joints and other operations carried out during the restoration, many specific cleaning and preservation measures were undertaken as well. From a weathering perspective such measures are important to note, insofar as they had a direct impact on the nature and rate of weathering.

Cleaning of medieval masonry and decorations

As we recall, the cathedral was subject to numerous whitewashing and painting operations after the Reformation. Following prevailing restoration principles in the second half of the 19th century, an important practical measure was removal of whitewash and paint in order to present “clean” stones. In a practical recommendation from April 1869 we get an impression of how cleaning was supposed to be undertaken:

> Removing whitewash (lime crusts) from masonry shall be undertaken by carefully knocking it off using (wooden) mallets. If this is not sufficient, diluted acid (hydrochloric acid) may be applied and if necessary combined with brushing (steelbrushes). During such work attention should be paid to possible inscriptions, stone mason's marks or mural paintings.[89]

According to reports from the first decades of the restoration we have reason to believe that this guideline was only partly followed. This is because several medieval walls, in particular in the chapter house and the lower parts of the octagon, were cleaned by using chisels in order to remove the uppermost weathered layers of stone. Moreover, in the restoration reports of architect Christie we can find descriptions of how lye was used to neutralise the acid. Even if it is not known whether hydroxides or carbonates of sodium or potassium were used or if the walls were subsequently properly washed by clean water, we should be aware of the fact that several types of soluble salts may have been introduced to the masonry due to these cleaning operations (chlorides and carbonates of sodium, potassium or calcium).[90] According to the restoration reports we know that not only masonry, but also stone decorations were cleaned using acid and lye.

Only certain parts of the masonry and decorations were cleaned using all these rather hard procedures. Several walls, pillars and decorations must have been only carefully treated by mallets or acid with or without lye, which is the reason why large numbers of stone masons' marks are preserved today. A few remnants of interior 18th century painting on stone were also left untouched, especially in the octagon. Moreover, there are still remains of whitewash and greyish paint to be found on exterior masonry, in particular on the north transept. We shall see later that these remains are very important as indicators of how air pollution has affected the cathedral. This is because they readily reacted with sulphur components and soot to become rather dark. At a distance they are in fact easily mistaken for black gypsum crusts located directly on stone.

Piecing-in of weathered or missing parts of stones

Recalling recommendations from the 1870s (chapter 4.3) stating that “restoration measures should only include consolidating masonry, replacing damaged stones and supplementing missing parts”, one of the very important procedures during the first stages of the restoration was careful piecing-in[91] of stone fragments.

The walls of the octagon represent a good example of how piecing-in was carried out in practice. A large number of ashlars were only partially damaged, especially close to corners and joints, before the restoration. Consequently, the damaged parts were carved out and very carefully replaced by new pieces matching the remaining stone. Damaged parts of decorated arches, for instance dog tooth ornamentation around the windows, were treated in a similar manner. These measures were often so carefully executed that even tiny parts of single dog teeth were replaced. Missing parts, like noses, hands, arms and chins of corbels and other small sculptures, presented other problems because a certain imagination was needed when remodelling and subsequently replacing pieces. We may assume that the aim of using the piecing-in technique was connected with retaining the architectural wholeness without too much interference with the historical value of the building (fig. 6.12 and 6.13).

Piecing-in lost its significance during the large-scale reconstruction work on the choir, transept and central tower. However, in the outer, medieval walls of the nave which were restored at the turn of the century, we can still find remnants of the technique - in particular when regarding missing parts of flower capitals. The restoration architects left the piecing-in method when restoring the two lower storeys of the west front.[92] This work was carried out only five years after the restoration of the outer walls of the nave and shows a drastic change in restoration philosophy. It is probably correct to say that the treatment of the lower part of the west front represents the first (and only) practical attempt at following a local variety of restrictive ideals *á la* Ruskin. Remembering that the wall in fact was first pulled down because it needed strengthening before a whole new west front was to be placed on top, the procedure must certainly be regarded as a *very* local attempt.

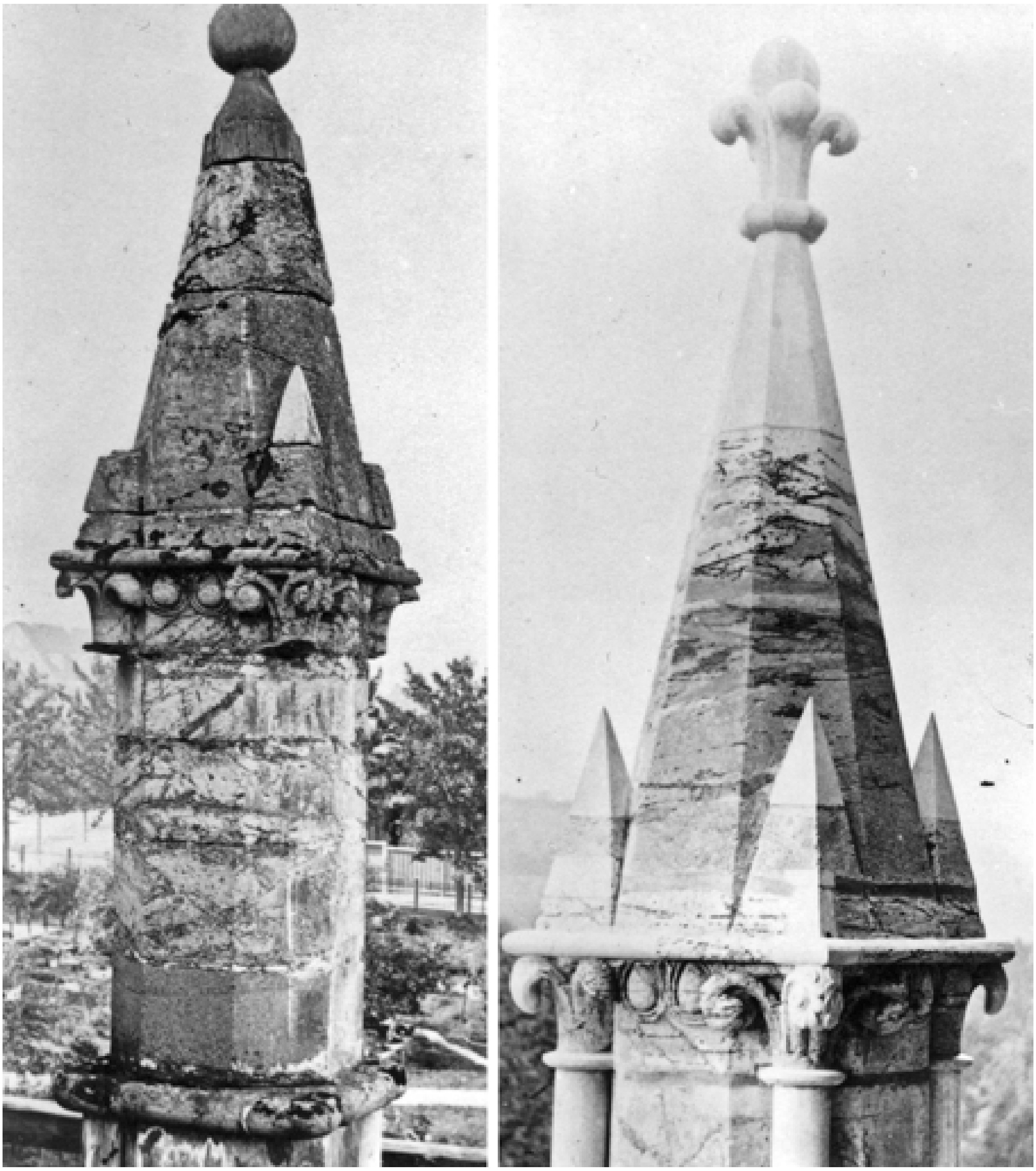


Fig: 6.12: *Example of the principal method of reconstructing decorations during the restoration of the octagon (1870s). New stone pieces have been added (right) where old parts (left) are missing. Pinnacles of the octagon's east chapel. Note that the pictures are showing two different pinnacles (photos: ARW).*

Fig. 6.13: *Example of the principal method of reconstructing sculpture during the restoration of the octagon (1870s). Medieval (1180s) head in string course of the octagon's east chapel. The missing nose and chin (left) have been replaced (right) (photos: ARW and PS 3/90).*

The use of dowels and cramps

Stones in elements like pinnacles, flying buttresses, parapets, string courses, tracery, arches, capitals, columns and sculpture are usually fixed with different types of dowels and cramps. Using dowels and cramps was also extremely important during the restoration - and has remained so until today.

Generally, we know very little about the types of dowels and cramps used in the Middle Ages. According to the restoration reports of Christie, at least two types were found during the restoration of the octagon in the 1870s. One type was the usual iron cramp or dowel bedded in lead which were used for holding together for instance tracery.[93] The other type consisted of small lead dowels bedded in lime mortar, found for example in connection with capitals.

It is difficult to state for certain if these fixings were medieval. During repair works in the post-Reformation period we know that numerous iron cramps were applied in order to bind together crumbling masonry as well as to hold smaller objects like corbels and columns in place. Masonry in the central tower and the clerestory of the octagon as well as the 1834 octagon vault had such cramps. Strips of iron and lead were also used to keep pinnacles and other exposed elements from falling down.[94]

Most of the earlier cramps and dowels were removed during the restoration and replaced by new ones when needed. Then a rather diverse range of dowels were introduced. From the

1870s until the turn of the century we hear of products like lead dowels bedded in Portland cement,[95] copper cramps bedded in Portland cement[96] and copper cramps bedded in lead.[97]

From the turn of the century until recently there exists little written information about the types of dowels and cramps used. We may assume that they usually consisted of iron, steel, copper or brass bedded in Portland cement. Today the masons either use stainless steel or brass bedded in Portland cement when restoring features like flying buttresses, pinnacles, copings and string courses. It should also be noted that a diverse range of iron and steel strips have been used throughout the 20th century to keep exposed elements like gargoyles from falling down because of weathering. Several interior decorations are also secured by steel wire.

Methods of fixing and sealing scales, cracks and joints

Applying Portland cement mortar has during the whole restoration period been the main solution to problems of fixing and sealing loose scales, small stone fragments, cracks/fissures cutting through stones and open joints.

However, a few other materials and techniques have been applied as well. In the outer walls of the choir we observe that some kind of grey putty has been widely used in order to seal larger flakes of stone and many fissures. Whether the putty consist of soapstone powder mixed with waterglass - which is a normal fixing product for soapstone today - has not been verified.

In 1962 so-called “Secco Mastic”, was used to seal the joints in the rose window of the west front.[98] Sealing open joints has otherwise been undertaken by applying different types of silicone rubber, in particular during the last decade (for instance in the west front parapet). Fixing cracks in stones has usually been done using epoxy (for instance “Araldite”) in combination with dowels.

Modern stone consolidants and waterproofers

Having an extremely low water absorption, soapstone (and greenschist) is not easy to treat with modern stone consolidants and waterproofers. Except for one experiment carried out with ethyl silicate some five years ago on a very weathered, 19th century corbel, no such product has recently been applied on stones of the cathedral.

The Restoration Workshop has been approached by numerous companies wanting to sell their “miracle cures” for weathered stones, but according to Torgeir Suul, the architect-in-chief from 1964 to the late 1980s, a firm stand was taken against such products since the 1970s.

In 1957, however, several buttresses at the north side of the choir were treated by so-called “masonry waterproofers”. After removing “saltpetre” (salt efflorescences) and loose mortar, and subsequently cleaning stones by hydrochloric acid/sodium hydroxide, the buttresses were impregnated by “Test silicon” and “Silio 10%”.[99] These products are unknown to me, but according to the masons undertaking the treatment, water subsequently glanced off the buttresses. According to general experience, we have no reason to believe that the agents were very effective for a long period of time.

Concerning stone consolidants, it would be interesting to know if waterglass was applied during the early stages of the restoration. We do know that waterglass was recommended for giving wood (doors?) a “monumental” appearance during the restoration of the chapter house.[100] This indicates that waterglass was a familiar product to professionals involved with the restoration, but so far we have no information about its eventual use as a consolidant.

Recent removal of algae, lichens and moss

Even though organic growth has been a minor problem on the cathedral, cleaning such growth with water lances at low pressures was carried out in 1991-92.[101] Major parts of the building were cleaned in an operation which lasted for several months.

Green algae is confined to particular "wet" areas at the northern side of the cathedral, while lichens often are found on exposed parapets, pinnacles and bases. The growth of moss is more or less restricted to exposed mortar joints. In the belief that all this growth had a negative impact on the weathering of the cathedral, the aim of the cleaning procedure was to remove as much as possible. According to the masons who undertook the operation, it was certainly difficult to remove everything. An additional problem was the constant risk of loosing stone fragments. As the aim of the cleaning was confined to organic growth alone, black crusts were not touched. It is, moreover, worthwhile noting that The Restoration Workshop did not take into account the adverse effects of introducing large amounts of water in the masonry during the cleaning procedure.[102]

Biocides were not applied during the cleaning operation, but has sometimes been tested on the bases of the cathedral, for instance in 1991. The aim was to restrict the growth of lichens and moss, but according to recent observations, no long-term effect can be expected when applying biocides on the very dense stones of the building.

Recent removal of graffiti

The cathedral was subjected to several graffiti attacks in the 1970s and 1980s.[103] The lower parts of the chapter house, octagon and choir were particularly affected. Removing graffiti is a difficult operation and The Restoration Workshop did it "the hard way" by wet grit blasting. Consequently, parts of the soft masonry surface were badly damaged, not only because the outer layers of stone were removed, but also because the masonry drastically changed its colour to become much too light (fig. 6.14).

Fig. 6.14: *The lower part of the north-east wall of the octagon was subjected to a graffiti attack in the 1980s. The graffiti was removed by wet grit blasting which destroyed the surface and rendered it "white" (photo: PS 8/90)*

6.5 Summary of materials and conservation methods

From the perspective of investigation of weathering phenomena, the following features of the cathedral are important to keep in mind:

- Stone has been provided from more than 60 different quarries, but less than c. 20 were actually operated in the Middle Ages. The rest were opened during the restoration from 1869. Greenschist was the most important stone before c. 1200. From then on soapstone can be found in exterior masonry. Marble, metasandstones, slates, gneiss and hard greenstone can also be found in masonry and decorations.
- Brick was a very important building material during the restoration. It was used especially for interior walls of elevated structures (e.g. clerestory of the choir) and for vaults.
- Portland cement was introduced by 1869. Since then it has been extensively used in all areas of the cathedral. The upper sections of the west towers represent a "highlight" of the "cement cathedral": They were made essentially by concrete in the 1960s. Other measures involving Portland cement included the application of thin "soups" in order to consolidate masonry as well as the repointing of most thin, medieval joints. Norwegian Portland cement has in general a high amount of alkalis which may give rise to alkaline salts.
- Plaster, whitewash and paint applied to all parts of the cathedral in the post-Reformation period were effectively removed during the restoration. There are few traces of paint and whitewash to be observed today. Redressing and cleaning with hydrochloric acid (and/or lye) was normally used for the removal of earlier surface treatments.

Fig. 7.1: *The cathedral with a thin snow cover in the 1880s (photo: ARW, no. 582)*

Chapter 7

Weather, air pollution and exposure conditions

This chapter deals with the Trondheim weather and its ever changing character. Attention is also centred on the history of air pollution in the city, deposition of air pollutants and the indoor climate of the cathedral. Moreover, characteristics of the diverse exposure conditions at the cathedral are summarised. Initially, attention is paid to the environmental setting as a whole.

7.1 The environmental setting of the cathedral

Situated on the southern shores of the wide Trondheim fjord, 50 km east of the Atlantic ocean, Trondheim may be regarded as something between a coastal and an inland city. Like most coastal or near-coastal parts of Norway, the city has a maritime temperate climate with relatively mild winters and cool summers.

Norway's climate is rather warm when considering its northern latitudinal position (58-72 Deg.). This is because the North Atlantic ocean current (the Gulf Stream) strongly influences air temperatures. The climate is otherwise dominated by the passage of low pressure areas coming in along the polar front from the Atlantic Ocean. The position of the polar front determines whether warm air from the ocean or cold air from the polar regions affect the country.[1]

Western Norway, from Stavanger to Finnmark, is characterised by steep mountains and deep fjords. Even though Trondheim is situated by a fjord, the immediate surrounding landscape is not especially mountainous. The landscape is best described as undulating, with forested plateaus and hills reaching elevations of 5-600 m.

The city itself is built in a valley between gentle hillsides on and along the delta of Nidelva river which runs quietly through the city, forming a flat peninsula on which the city centre can be found. Located on the highest point of the peninsula, the cathedral is the dominant building in the city. It is situated in a quiet park area (including a cemetery) in the southern part of the city centre. The park is overgrown by large trees which were planted about 100 years ago.

Trondheim has due to its post-war planning policy sometimes been nick-named “Los Angeles of Norway”, and even if the cathedral area is park-like and quiet, it is situated close to busy traffic arteries. A main road (Prinsensgt.), carrying 35.000 vehicles a day in and out of the city centre, can be found only 250 m to the west. Another road (Bispegt.) passing close to the north side of the cathedral carries about 10.000 vehicles a day.[2]

The architecture of the city centre is characterised by a mixture of old wooden buildings, masonry buildings from the turn of the century and modern commercial buildings. As a city with little heavy industry, the main pollution sources are presently traffic and heating. Minor industries were earlier located in and very close to the city centre, but the main industrial area is currently located at Lade, some 2,5 km to the northeast.

7.2 A subjective account of the annual weather cycle

Trondheim is sometimes described as a city with “a lot of weather” because of rapid changes from overcast and raining to sunny (and vice versa) during a single day. As in the rest of western Norway, autumn is the rainy season in the city - the period of gales and occasional heavy storms coming in from the west. The weather is more often just overcast and windy, including numerous small showers. Snow may fall as early as September, but at this time of the year it quickly melts. It is unusual to experience lasting snow cover before late autumn (November/December).

Even though the autumn is normally cool, days like an “indian summer” may appear as late as October. Mild weather with drizzle and fog may also arrive after periods with sub-zero temperatures in late autumn. On approaching Christmas time, winter arrives in Trondheim. The winter may be cold with moderate amounts of snow, but sometimes - as for instance in 1989 and 1990 - it is too mild for the snow cover to last for a prolonged period. In extreme years snow cover may last until May.

The winter may bring long periods of beautiful weather with sunny days and very cold nights. There may be equally long, humid periods with temperatures above or around zero. This means combination of rain, sleet and snow. Although the latter type of weather may characterise the occasional spring, this season is usually the driest and sunniest in the city. As people still tend to drive cars with studded winter tyres on roads free of snow and ice, spring may also be a period of excessive amounts of asphalt dust in the air.

A popular saying says that “there are only two seasons in Trondheim, the white and the green winter, of which the white one is the most pleasant because the indoor heating is then on”. Indeed, some summers are rainy and cool, but it is possible to experience really beautiful, hot weather, especially in July and August.

7.3 Climate seen from a weathering perspective

In the following attention is focused on temperature, sunshine, wind, precipitation and relative humidity, as well their influence on the weathering of buildingmaterials.

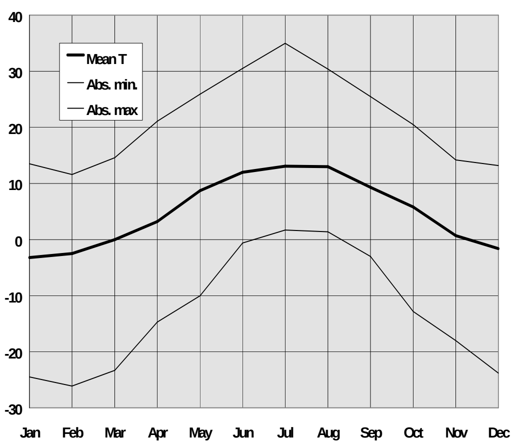


Fig. 7.2: *Mean monthly and absolute maximum/minimum temperatures in Trondheim (after Bjørbæk 1994).*

Temperature

The annual average temperature is about 5°C (fig. 7.2), while the average number of days with sub-zero temperatures is c. 130.[3] It is more interesting to note the number of frost events; i.e. when temperature drops from above to below zero. Such events are the important ones for potential frost damage in building elements exposed to precipitation. It is hard to attain relevant data, but as an example it is possible to study the mild winter of 1990-91. In that season the number of frost events was about 15 according to data on mean daily temperatures.[4] The number is in reality *much* higher, since day/night cycles have to be added, and sunshine and minimum/maximum temperatures considered. A relevant question is whether the number of frost events lay in the same range as in

Central Europe. It is likely that the conditions in Trondheim are comparable to many places in Germany, Switzerland and Austria. An investigation ought to be undertaken in this field, especially since people often maintain that the Scandinavian climate is particularly harsh (to buildings).

An important difference is nevertheless that prolonged periods with sub-zero temperatures in Trondheim may cause large areas of wet masonry structures to freeze, a feature which might cause deep frost damage. Obviously, such events (and many other damaging frost events) only take place when cold weather occurs after wet periods.

Another important temperature phenomenon is inversion which causes a concentration of air pollutants in urban areas, especially if the local/regional topography is favourable. Due to the rather windy conditions in Trondheim, temperature inversions are infrequent, but may take place in cold, stable winter weather. It is unusual to experience inversions during summer and autumn.

Sunshine

Concerning weathering, sunshine is extremely important in tropical climates where variations in surface temperatures of exposed materials may reach extreme values, e.g. when a thunderstorm cools down a hot surface. In this way thermal and hygric dilatation may work together, creating large shear stresses in stone.[5]

Nidaros cathedral is certainly not situated in a tropical climate, but combinations of hygric and thermal dilatation phenomena may nevertheless be of some importance. This is because south-facing, rain-exposed architectural elements (e.g. copings) are also exposed to most sunshine. Rapid temperature change in the frequently changing Trondheim weather is likely on such elements. Such elements also collect snow and ice in the cold season. It is therefore impossible to exclude frost when trying to interpret weathering mechanisms at such elements. A reasonable suggestion is in fact that the melting of snow on exposed elements during daytime can give rise to very damaging frost events at night. This is because the stone may have become soaked/saturated with moisture from the melting snow.

The mean annual number of sunshine hours is about 1350 (35-40% of the maximum possible) in Trondheim. Because of the short days during the cold season at these latitudes, the annual variations are extreme. While in May and June the mean value is more than 200 hours, December brings about only 9 hours of sunshine.[6] However, when considering the number of days with clear sky, they are rather evenly distributed throughout the year (2,5-5 days pr. month). The number of overcast days are also rather evenly distributed (10-12 days pr. month).[7]

Wind

Trondheim is a near-coastal city and much less windy than places along the coast of the Atlantic ocean. The annual average wind speed is about 3 m/s and the annual number of days with strong westerly gales and storms (windspeed above c. 20 m/s) is a moderate three. Most of the storms take place between November and March.[8] At such speeds the wind may be able to cause structural damage to buildings (especially roofs), a phenomenon which happened at Nidaros cathedral in the autumn of 1986 (north turret of the choir).[9]

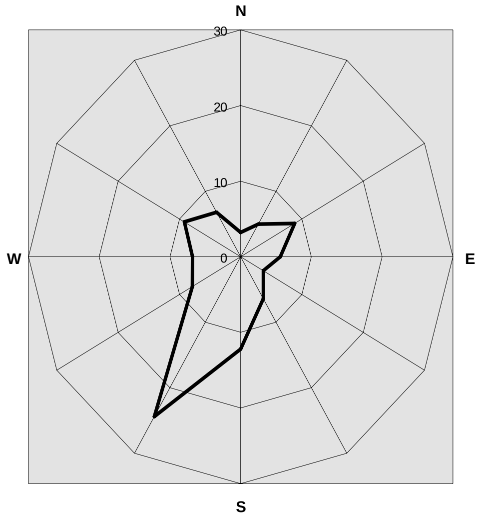


Fig. 7.3: *Wind rose at Tyholt, c. 2 km SE of the city centre. Frequencies normalized to 100%, calm days c. 7 %. (Data from The Norwegian Meteorological Institute)*

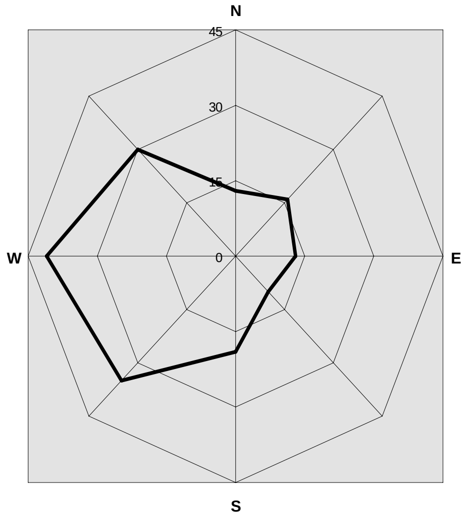


Fig. 7.4: *Number of instances of rain as a function of wind direction (after Helland 1898).*

From September/October to March/April southwesterly winds prevail (20-35% of all observations). In the summer northwesterly winds take over after a spring with rather evenly distributed wind directions (fig. 7.3). These wind directions are valid only for the upper parts of the Nidaros cathedral because the nature of the surrounding physical environment seriously alters the rather uniform pattern observed at the weather station in question (Tyholt). It should also be noted that although southwesterly winds prevail in Trondheim, some years (especially winter and spring) are characterised by very frequent easterly winds - for instance 1995-96.

Excessive wind loads during storms and hurricanes may occasionally cause masonry cracks in elevated parts of large cathedrals.[10] Such phenomena have not been analysed when regarding Nidaros cathedral.

Precipitation and thunderstorms

Even though the prevailing, humid, southwesterly winds bring considerable precipitation, it seems that the possibility of rain/snow is higher when the wind comes from west and north-west (fig. 7.4). Although local variations must be considered, this is an important observation because it determines the general weathering side (German: *Wetterseite*) of the Nidaros cathedral and other buildings in Trondheim. Elevated west- and south-facing walls are usually severely affected by lashing rain, but also north-facing walls may occasionally be affected. East-facing walls are very little affected by lashing rain.

The mean annual amount of precipitation in Trondheim is about 850 mm (fig. 7.5). Compared to a Central European city like Berne (Switzerland), which receives about 1000 mm,[11] and some places close to Bergen in the westernmost parts of Norway which receive 3-5000 mm,[12] Trondheim is in fact a relatively dry city. Monthly mean values range from 40 to more than 100 mm, with April/May the driest and September/October as the wettest months. However, the *number* of days with rain is just as large in June as in September/October. From November/December to April precipitation falls more often as snow than rain (fig. 7.5).

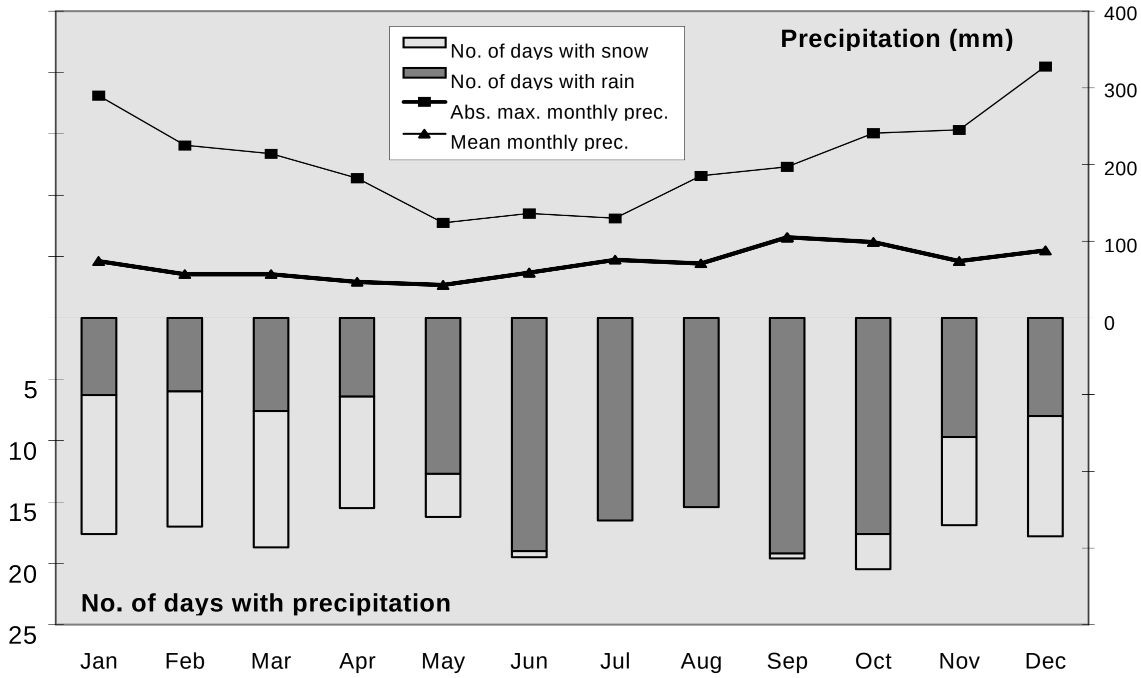


Fig. 7.5*: Precipitation in Trondheim (after Bruun & Håland 1970 and Bjørbæk 1994).*

Thunderstorms are not frequent in Trondheim, but the 1719-fire in the cathedral (see chapter 4) was caused by lightning. The cathedral has also been struck by lightning twice this century (1905, 1982), but installed lightning rods prevented severe damage other than destroying electronic security equipment (1982).[13] On average there are annually 4-5 thunderstorms and most of them take place in the summer months.[14]

Chemistry of precipitation and deposition of salts

The ion content of precipitation in Trondheim is mainly dependent on natural constituents in the air (CO_2), dust and sea salts, while anthropogenic emissions of air pollutants (distant and local sources) play a relatively minor role.[15]

For several decades acid rain has been a serious problem in the southernmost part of Norway. Affected by sulphuric acid from the large industrial regions in Central and Eastern Europe and UK, these regions have experienced large-scale acidification of lakes, rivers and soils.[16] Due to the geographical location and prevailing wind directions, the Trondheim region has not experienced the same acidification. Indeed, from the perspective of acid rain, Trondheim must be regarded as one of the cleanest areas in Norway (and in Europe).[17] Although local emissions of sulphur dioxide may have influenced the pH of precipitation earlier, the pH today is close to what is normal for rain (5-6) (fig. 7.6).

It is primarily the Atlantic ocean and the Trondheim fjord that provide excessive amounts of aerosols and ionic constituents (sea salts) in the precipitation falling over Trondheim. The mean concentration of chloride in precipitation lays between 2 and 4 mg/ml, but during strong westerly winds the level may rise to 10 mg/ml and above. Sulphate is also provided from the sea, but small, local anthropogenic emissions are probably of some importance as well.[18] Sea salts are - as sulphate/sulphur dioxide - deposited dry and wet. When there are excessive amounts of sea salts in the rain due to storms, the dry deposition also increases. Moreover, dry deposition of sea salts may increase during westerly storms without rain.[19]

Sea salts (mainly sodium chloride) may act on stone in different ways. The two main ways are “simple” salt crystallisation and the fact that such salts help to keep the surfaces moist for longer periods because they are hygroscopic. This will for instance increase dry deposition of sulphate/sulphur dioxide.[20] It is important to note that chlorides may be provided from several additional external sources, of which cleaning with hydrochloric acid/lye (see chapter 6.4) and de-icing products are generally important. De-icing salts are not used on streets in the near vicinity of the cathedral, but for many years calcium chloride has been used in order to melt snow on exterior gangways at the cathedral itself (see chapter 11)!

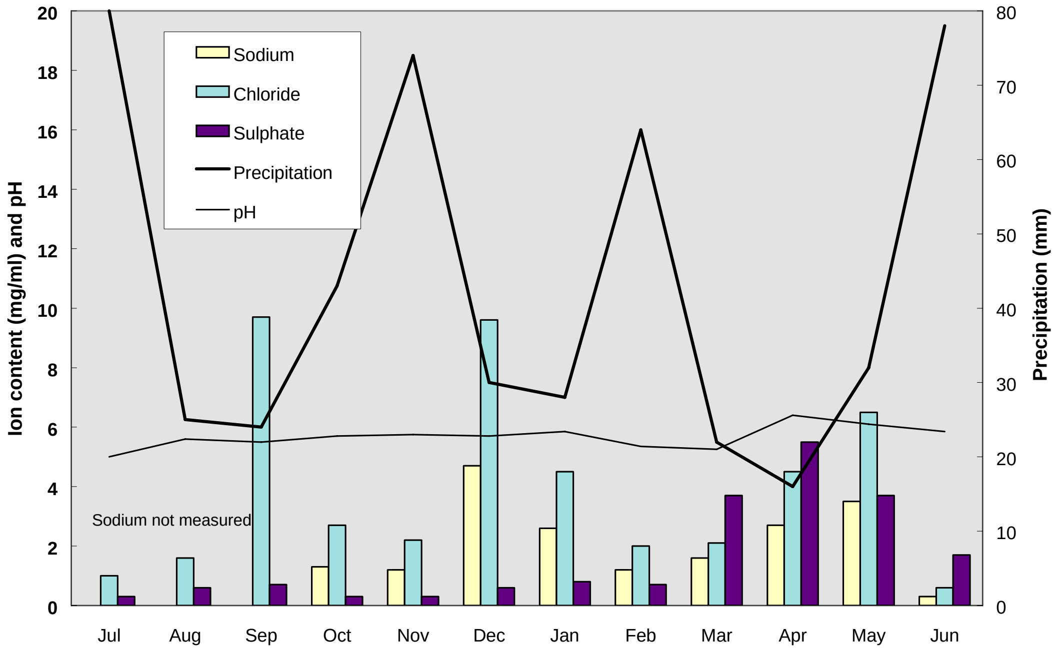


Fig. 7.6: *Chemistry of precipitation in Trondheim 1990-91. Note the occasional high chloride content and the relatively high sulphate content during spring. The latter phenomenon is difficult to explain (after Anda & Henriksen 1992).*

Relative humidity and fog

We have seen above that air concentration and deposition of air pollutants are dependent on climatic factors such as temperature inversions and occurrence of sea salts. Fog is an additional factor to consider because it increases the probability of condensation. The annual average of days with fog (visibility less than 1 km) in Trondheim is about 16 of which most events take place on days with little wind during the autumn (fig. 7.7). This number is low when compared with the lowlands of Central Europe. The city of Berne (Switzerland) has 47 foggy days annually, mostly due to temperature inversions.[21]

Autumn is also the time of year with the highest mean relative humidity in Trondheim. Compared with mean monthly values of about 75% in the relatively dry spring period, autumn brings about an average of more than 80% (fig. 7.7). Fluctuating weather conditions and day/night cycles certainly influence the relative humidity. Rapid changes from 40-50% to more than 90% are not uncommon in all seasons, but usually the mean daily relative humidity fluctuates between 70 and 90%.

Relative humidity is of great importance for salt crystallisation phenomena. Although the real equilibrium relative humidities of salts are strongly dependent on temperature and the actual salt system involved, it is reasonable to maintain that very hygroscopic salts cannot crystallise in the Trondheim climate. Also halite, which has a theoretical equilibrium relative humidity of about 75%, rarely crystallises in Trondheim. However, salts such as sodium sulphates and carbonates frequently crystallise in our climate.[22]

Long-term climatic changes?

During its existence, the cathedral has been subjected to the relatively mild Middle Ages, the "Little Ice Age" between 1550 and 1850, the milder period from 1850 to 1930 and a somewhat colder period until the 1980s. Since the 1980s the mean annual temperature has increased.[23] Comparison of mean values from the 1931-60 normal period with the 1961-90 normal period show that autumn precipitation has increased (10-15%), while spring precipitation has decreased (-10-15%). The temperature has also increased during spring time (0,4%), but otherwise there has been little change.[24]

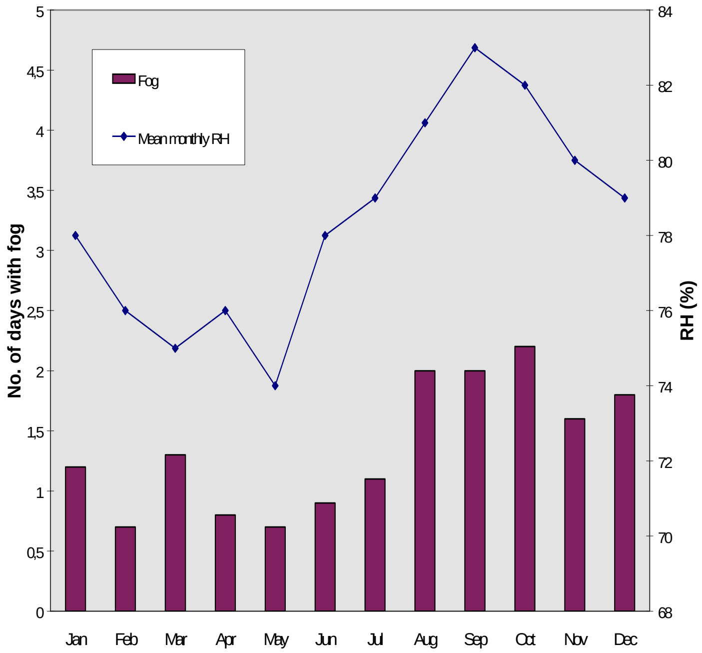


Fig. 7.7: *Relative humidity and fog in Trondheim (after Bruun & Håland 1970 and the Norwegian Meteorological Institute).*

The changes recorded may of course be attributed to normal long-term climatic variations, even though many people (including the UN climate panel) believe that such changes can be traced back to anthropogenic emissions of greenhouse gases. The increasing differences between autumn and spring weather may in both cases be of some interest. Although speculation, it is possible that greater precipitation during the autumn may increase the probability of water leaks, provided that no conservation measures are taken. The drier springs may on the other hand increase the possibility of salt crystallisation.

It is, however, much more likely that large daily and seasonal variations mask any effect of long-term changes. Such changes are also of a rather theoretical significance compared with the importance of human interaction with the cathedral (conservation measures). The wettest and driest years ever recorded in Trondheim were, by the way, 1899 and 1893, respectively.[25] Moreover, the spring of 1997 was exceptionally cold and wet.

7.4 The history of air pollution in Trondheim

Although long range air pollution is of minor importance in Trondheim, the city did certainly not escape the polluting effects of the industrial revolution. However, air pollution due to local emissions of soot and sulphur dioxide arrived much later than for instance in Great Britain which has a history of excessive urban air pollution back to the Middle Ages.[26] This is mainly because the burning of coal (imported from UK) for domestic heating and industrial purposes did not commence before c. 1820 in Trondheim.[27]

Air pollution from industry close to the cathedral

Until the late 19th century Trondheim was mainly a city of trading, shipbuilding, regional administration and communication. However, minor industrial enterprises (partly or completely based on coal consumption) like Bakklandet brick works and "Fabriken ved Nidelven" began before 1850 (see also fig. 7.8). The city's coal-based gasworks at Kalvskinnet was established in 1853, while numerous small-scale craft enterprises in the city centre changed to become minor industrial works around the turn of the century (for instance bakeries, breweries, laundry factories etc.).[28] The railroad started its expansion in the 1860s.

Fig: 7.8*: Location of main industrial areas in Trondheim from the early 19th century . 1: Kalvskinnet, 2: Bakklandet, 3: Ila, 4: Nedre Elvehavn, 5: Lade, 6: Ranheim, N: Nidaros cathedral. Map after Google Maps (http://maps.google.ch) (See text for explanations.)*

Although the largest industry ever in Trondheim, the shipbuilding works “Trondheim Mekaniske Verksted” (TMV, 1843-1983), was established at Nedre Elvehavn when “Fabriken ved Nidelven” went bankrupt in the 1870s,[29] it was not until the advent of hydroelectric power in 1902 that a really polluting industry came to the city: the metallurgical works.

It is a paradox that clean hydroelectric power has been a main reason for excessive local air pollution in Norway. Associated with the construction of numerous power plants after the turn of the century, iron, steel, ferroalloy and aluminium works popped up all over the country.[30] The ferrosilicon works at Ila was the first to be established in Trondheim and after two years of production, in 1910, neighbours complained about the “smoke emissions”. The works later changed to zinc production, but in 1923 economic problems led to bankrupcy.[31]

Production was revived at Ila for a short period in the late 1920s, and a permanent ferro-silicon industry became a reality in 1927 when the Lilleby works went into production at Lade, 2,5 km northeast of the city centre. Although a brickwork (1900-1925) and the gas-works (1916-1960s) were already established at Lade,[32] the foundation of Lilleby ferrosilicon works represents the shift of industrial production to outside the city centre. The relative importance of air pollution (especially SO_2) carried into the city centre by easterly winds drastically increased from the late 1920s.

The Lilleby works (later “Ila og Lilleby Smelteverker”, ILS; today “Fesil”) has never been a large producer of ferrosilicon (max. capacity c. 25.000 tonnes FeSi). This amount is nevertheless enough to cause daily emissions of several tonnes of SO_2 and dust. During peak production periods in the 1950s, the daily emission of dust was in the range of 14-15 tonnes, an amount leading to severe protests, e.g. in 1957.[33]

No attempt has been made at estimating how local industries may have influenced deposition of SO_2 on Nidaros cathedral. However, in the period between the second World War and the 1970s, regarded as the most heavily industrialised, the main SO_2-emitters were located in the city centre (small industry), at Bakklandet (brick works) and at Lade (ILS and others). Taking wind direction and other weather phenomena into account, it is clear that these industries deposited their pollutants mostly during northerly and easterly winds as well as during periods of temperature inversion.

As a result of structural changes, many industries terminated their production in the 1970s and 1980s. The brick works as well as the large shipbuilding industry (TMV) closed down.[34] The 1970s also brought about increasing environmental awareness in Trondheim as elsewhere in Western Europe. In complying with clean air acts, ILS transformed into a cleaner producer of ferrosilicon in the late 1970s.[35] In 1989 the annual emission of SO_2 was reduced to 300 tonnes.[36] The structural changes meant that Trondheim strengthened its position as a university and research city as well as a city of administration, communication and trade.[37]

Before leaving the industry of Trondheim we should mention the wood pulp and paper industry located at Ranheim, about 6,5 km east of the city. Following the making of wood pulp which started in 1884, paper production commenced in 1891. Wood pulp production continued until 1981 and could yield emissions of up to 4 tonnes of SO_2/day. In 1990 the emissions were reduced to about 0,7 tonnes/day.[38] Since the earlier emissions were high, it is probable that the Ranheim factory has had a significant influence on the air quality in the city centre.

Air pollution from heating

Even though industry has been a main contributor to air pollution in Trondheim, heating has probably been of equal, if not greater importance - at least with regard to its influence on Nidaros cathedral. This is because the sources are situated closer to the cathedral. When trying to understand the development of air pollution from heating, it is necessary to consider population development as well as the diverse fuels that have been used throughout the last 200 years.

With a population of 8800 in 1801, Trondheim was then second only to Oslo in size. Until 1890 the population increased to about 35.000, while the largest increase ever occurred between 1890 and 1920, when the population doubled. It doubled again to 135.000 by 1975, but has been rather stable since then. From the 1950s the increase has mostly been concentrated in suburbs outside the city centre.[39]

The traditional heating fuel in Trondheim is wood, but coal was introduced around 1820. From then and until the first World War it is assumed that coal and coke were the dominant fuels for heating purposes in the city - at least for central heating plants. Gas was of relatively minor importance and it took quite some time before electricity (electric boilers) was in normal use. Liquid fuels (heavy fuel oils with some 2-3% S) seem to have been introduced before 1930 and steadily became the major fuel for boilers. As a result of the clean air acts of the 1970s, heavy fuel oil was gradually replaced by lighter fuel oils (0,1-0,2 S) and today district heating and electricity are the major energy sources in Trondheim.[40]

This basic summary shows that between the late 19th century and the 1980s, heating could be regarded as a major source of air pollution in Trondheim (see also fig. 7.9).

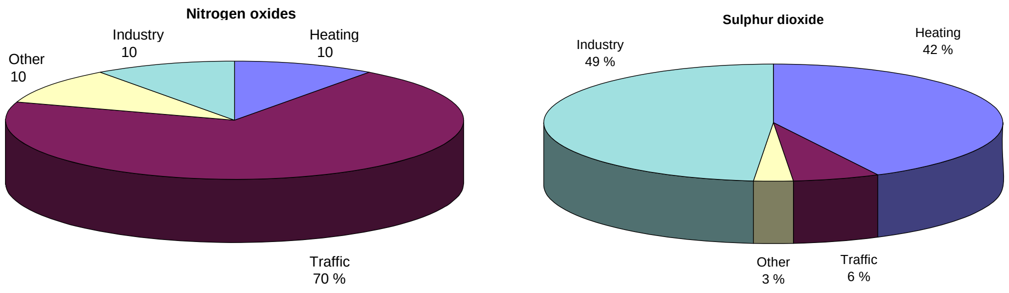


Fig. 7.9: *Calculated annual emissions of SO_2 (right) and NO_x (left) in Trondheim 1989 (after Berg 1989 and Jacobsen 1990).*

The central heating plant of the cathedral

Relatively minor emissions of pollutants can be of great importance to the air quality in the immediate vicinity of the source (dependent on chimney height and weather conditions). Therefore, mention should be made of the central heating plant of Nidaros cathedral itself.

The first heating plant was constructed in 1860 and located in the corner between the north transept and the ruined nave (fig. 7.10). It was moved to a new cellar which was dug out below the chapter house during the restoration in 1869-71. Since then the low chimney on top of the roof of the chapter house has been emitting soot and SO_2 for more than 125 heating seasons (October-May).[41]

As the restoration of the cathedral proceeded, the heating system had to be replaced and enlarged several times (1890, 1909, 1931, 1950, 1965 and 1979). Enlargements until 1931 were undertaken in order to provide “new” parts of the cathedral (choir, transept, nave) with a reasonable indoor temperature. Later replacements were connected with necessary repairs and a desire for higher indoor temperatures.[42]

The plant was coal-fired until 1931, while heavy fuel oil was used until 1979. Since then a combination of light fuel oil and electricity has been utilised. Using available statistics on fuel consumption,[43] it has been estimated that during the first period (1860-1933) annual emissions of SO_2 reached some 3,5 tonnes. In the second period (1933-1979) annual emissions may have been about 5 tonnes, but drastically decreased to less than 0,13 tonnes after 1979.[44] Using these figures it is possible to state that the central heating plant reflects the general development of fuel consumption and emissions of air pollutants in Norway.

The importance of the central heating plant compared with other sources of air pollution for the deposition of sulphate/SO_2 on the cathedral has not been thoroughly investigated. The present emissions are unlikely to have much effect, but former, elevated emissions may have had a relatively great influence. The chimney is, after all, literally located in the middle of the cathedral, and close (10-30 m) to the north and east-facing walls of the transept, choir and octagon.[45]

Air pollution from traffic

While industry and heating are the main sources of SO_2 and soot, traffic is by far the largest contributor of NO_x (excluding sea traffic). Automobile traffic has shown ever increasing trends in Trondheim. Although many major traffic arteries are located outside the city centre, this fact has not led to any decrease in the emissions of NO_x, which are currently between 50 and 80 $\mu g/m^3$ in the winter season.[46] The excessive amount of asphalt dust in the winter season due to use of studded tyres is another factor showing that the total air pollution in Trondheim has not decreased during the last 20 years. The types of pollutants have only changed.[47]

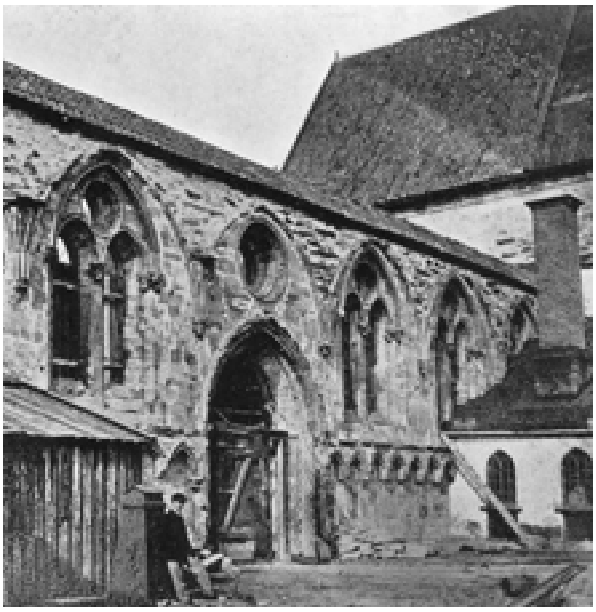


Fig. 7.10: *The first heating plant of the cathedral was located in the corner between the north wall of the ruined nave and the north transept in the 1860s (left, photo: ARW). Since 1870 the heating plant has been located in the cellar below the chapter house (right, photo: PS 8/95). Note the chimney and the discoloured copper plates on the roof.*

Measurements of SO_2 and assumed development from 1800

SO_2 in the city centre has been measured by the Norwegian Institute for Air Research since 1973. When compared with heavily industrialised regions in Central Europe and UK, these air concentrations are very low. Average values of more than 30 $\mu g/m^3$ in the winter season in the 1970s, fell to concentrations of less than 20 during the 1980s and to less than 10 in 1987. At present the average concentration is about 5 $\mu g/m^3$ (fig. 7.11). Note also that daily values exceeded 90 $\mu g/m^3$ several times during the 1970s.[48] It would certainly have been interesting to know something about the SO_2 concentrations in the city centre before measurements commenced in 1973. Since the measurements started before results of the clean air acts could be recorded, it may be possible to assume that the air concentrations measured between 1973 and 1980 reflect the concentrations during most of the post-war period. It should also be considered that several polluting industries were closed down before 1973. Taking into account the great increase in population early in this century, the former location of major industries and wind directions, it is possible to assume that SO_2 concentrations were significantly higher in the city centre from the late 19th century to 1940 than they are today. It should be noted that major industries were closed down during the Second World War. An attempt to picture the development since 1800 has been made in figure 7.12. The assumed development in *air concentration* follows a similar pattern as the historical *emissions* of SO_2 in Norway as a whole,[49] but it is necessary to perform model calculations in order to verify or falsify the assumptions.

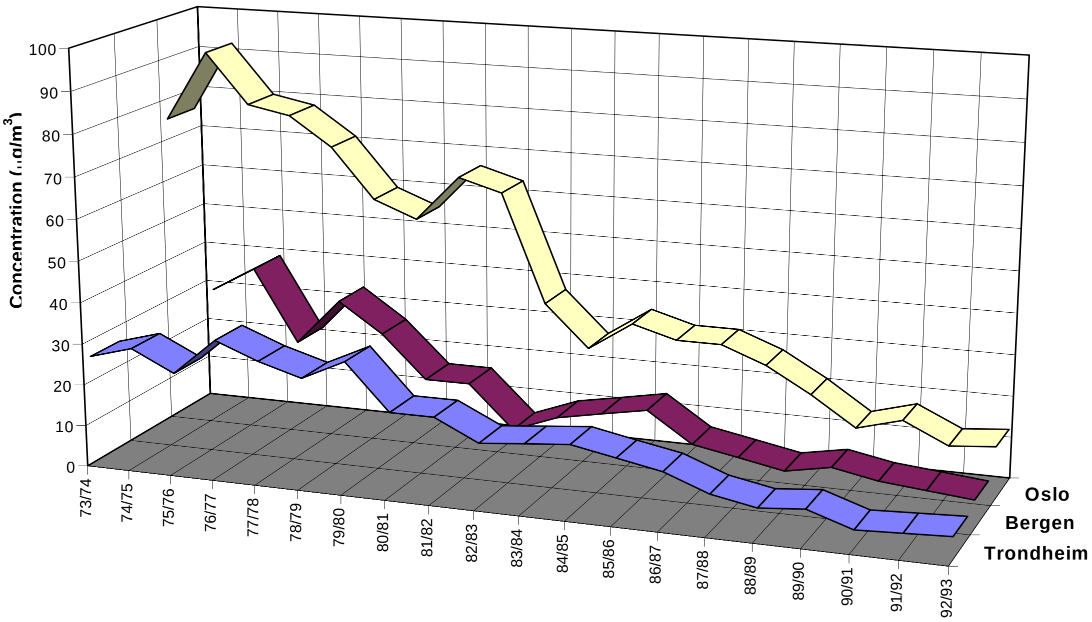


Fig. 7.11: *Mean daily winter air concentration of SO_2 in the city centre for the period 1973-1992 compared with Oslo and Bergen (after Hagen 1994).*

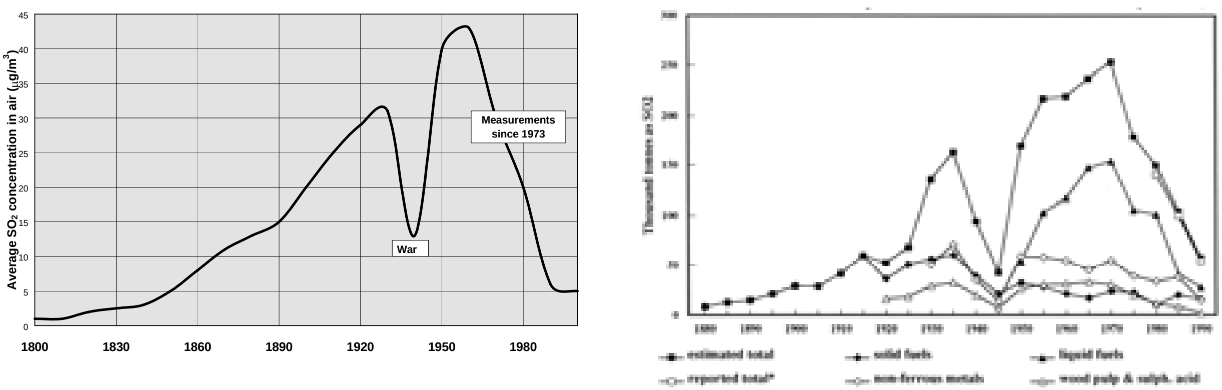


Fig. 7.12: *Left: Assumed development of mean daily air concentration of SO_2 in the city centre of Trondheim from the early 19th century (see text for explanations). Right: Historical SO_2 emissions in Norway (from Mylona 1993).*

Historical development of black crusts on the cathedral

Observations on the development of black (gypsum) crusts using historical photos of the cathedral show that the level of SO_2 and soot was significantly higher at the turn of the century than today. A necessary assumption for making this statement is of course that the level of SO_2 and soot is actually reflected in the distribution and intensity of black crusts. Another assumption is that black areas observed on photos actually represent black crust. However, since analyses have shown that the black areas consist of black gypsum crusts today, there is no reason to believe this was not the case earlier.

An example is the north porch of the cathedral from 1880 until recently (fig. 7.13). Immediately after the porch was restored in 1880, the north wall was very smooth and without traces of former whitewash and paint. 25 years later, in 1905, the wall was much darker and a distinct black line had developed close to the west corner - probably as a result of complex run-off and redistribution phenomena, leading to concentration of gypsum in the actual area. In 1930 the black line was far more distinct than in 1905. There were also significant black crusts just below the copestones of the gable in 1930.

Since no relevant photos taken in the period between 1930 and 1990 have been found, it is difficult to say if the maximum distribution was reached by 1930. It can only be stated that the occurrence of black crusts is far less extensive today than in 1930. As far as is known, the wall was not cleaned between 1930 and 1990. Therefore, it is concluded that the formation of crusts has halted because of reduced levels of SO_2 (and soot), and that already formed crusts have been washed away by rain (run-off).

When studying other historical photos, a similar development can be observed over most parts of the cathedral. However, on several building parts the weathering situations are far too complex to blame air pollution alone for the formation of black crusts (see chapter 11-18).

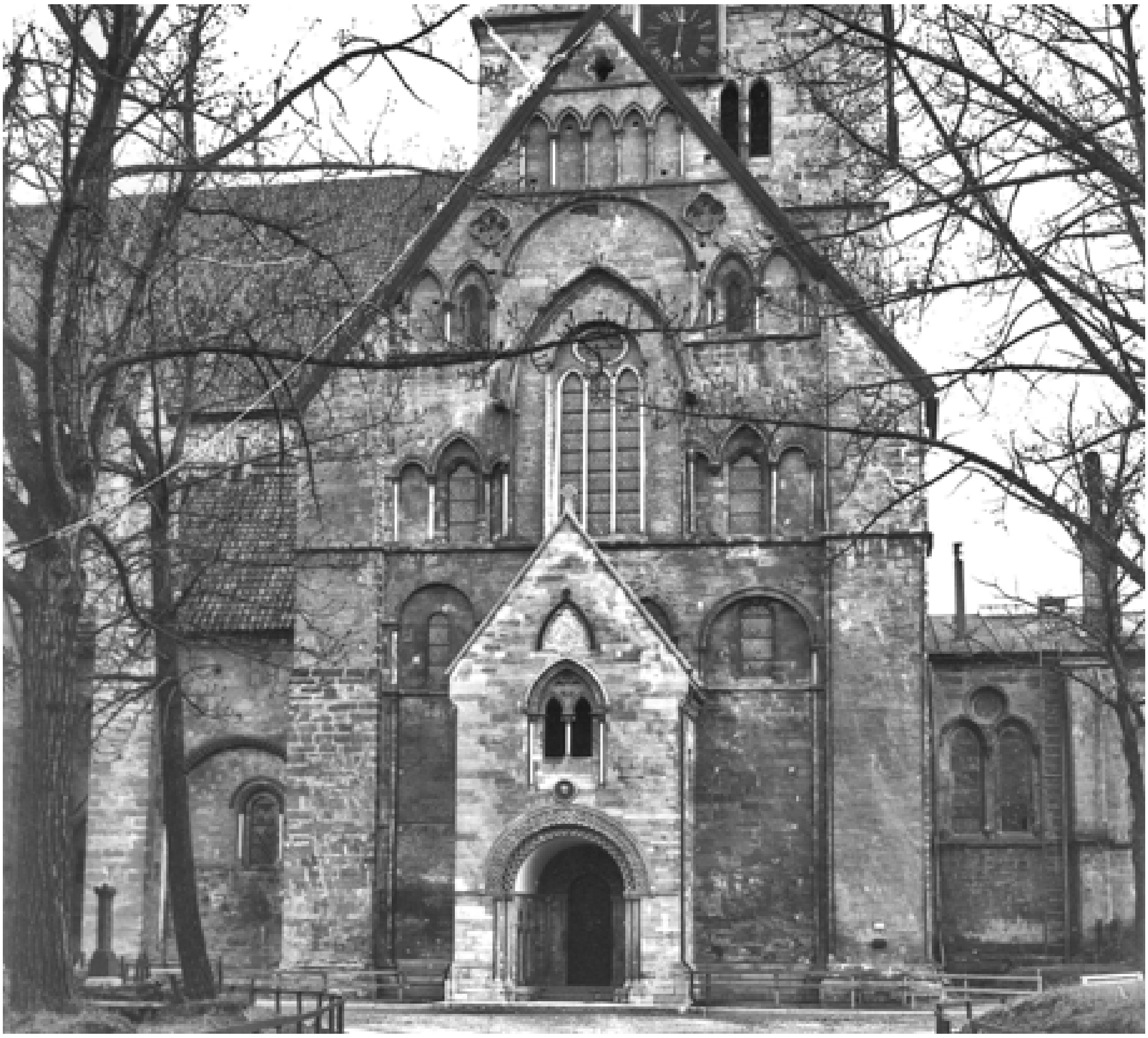


Fig. 7.13: *The development of black crusts on the north porch of the cathedral. Above: c. 1881, just after the porch was restored. Next pages: 1905: There is a distinct line of black crusts along the wall. 1930: Black crusts are very widespread. 1993: The black crusts have largely disappeared, probably due to a combination of decreasing air pollution and rain washing (photos: ARW and PS).*

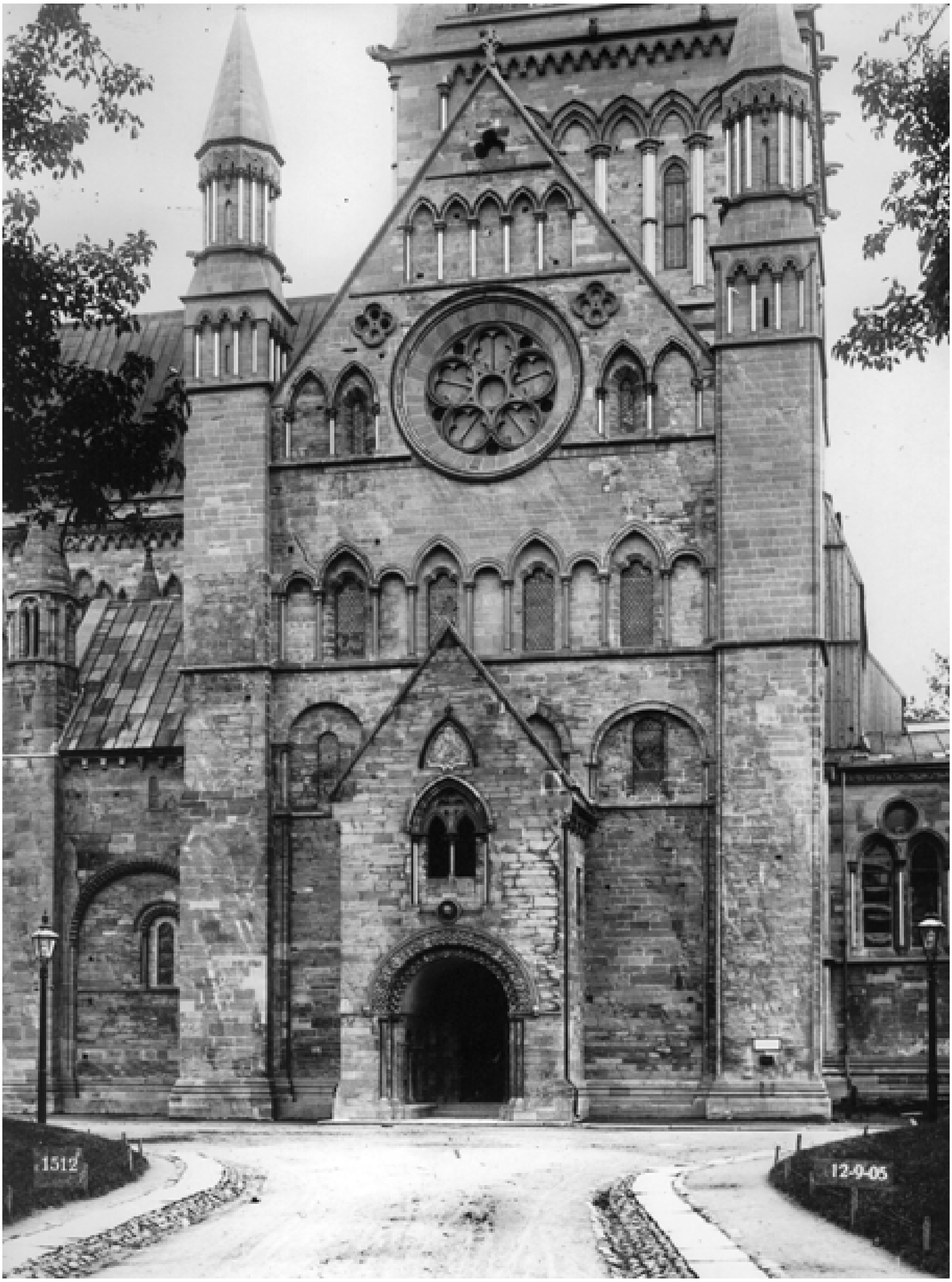


Fig. 7.13 *(cont.): 1905*

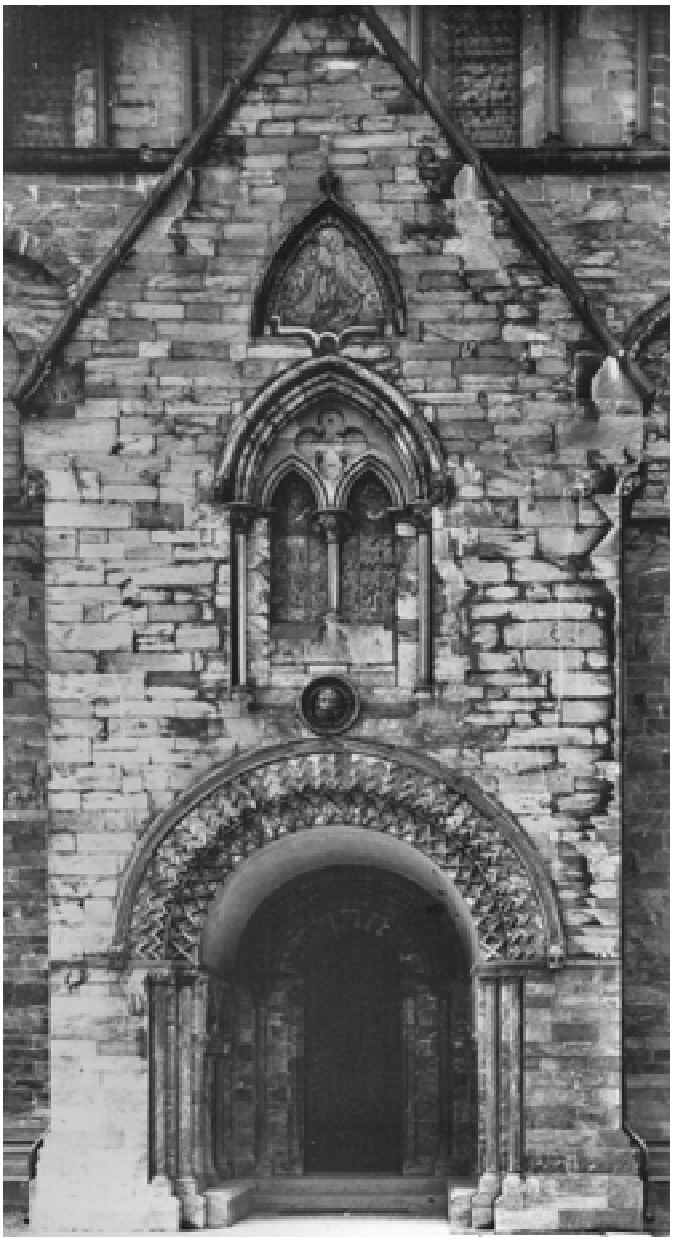


Fig. 7.13 *(cont.). Left: 1930. Above: 1993*

7.5 Indoor climate of the cathedral

The central heating system has provided the cathedral with comfortable indoor temperatures since the beginning of the restoration. Although people, particularly concert musicians, constantly complain about the *low* indoor temperatures, they are in fact more affected by drafts than by cold air. It is, however, clear that the current heating system cannot provide the *desired* indoor temperature of 18°C during concerts and services on very cold days. This is not at all strange, considering that the heating plant itself and the system of radiators are principally the same as in 1931. The system was at that time designed for keeping a minimum "background" temperature of 4°C and a temperature of 14°C during services. Today it is normal to try to keep a constant 16-18°C during the cold season.[50]

Heated areas

The heated areas of the cathedral are provided with water born radiators at floor level and in the triforia, whereas the nave is additionally equipped with electrical floor heating (from 1939) (fig. 7.14). Even if the system provides an average cold season-temperature of 16-18°C (measured in 1993-94, fig. 7.15) where people congregate, the temperature is certainly not uniform in the church.

Whereas the highest temperatures (> 18°C) occur at floor level in the nave and at triforium and clerestory level elsewhere in the church, significantly lower temperatures can be recorded on north-facing walls, along windows (in particular the rose window of the west front) and in a few north-facing corners (north transept, chapter house).[51] However, the room temperature as such is similar throughout the church. It is not much warmer just below the vaults when compared to the floor level. This is in line with observations made in other cathedrals.[52]

Because of the generally high temperature, the relative humidity in the church is low. During the cold season it fluctuates between 25-30 and 50%, with an average of about 40% (fig. 7.15, and additional measurements). Although the relative humidity has not been recorded during the summer season (May-September), it is assumed that it is significantly higher in this period. When the doors are wide open and thousands of tourists visit the cathedral on hot summer days, the relative humidity can become high enough for condensation events to take place (for instance in August 1995). Events of condensation have not been observed in other seasons, but it should be noted that dissolution of hygroscopic salts may easily be mistaken for condensation, also in the winter time.

In order to “protect” the Steinmeyer organ, humidifiers are located close to its pipes in the triforia of the nave and choir, as well as below the organ itself in the western part of the nave. Since the cathedral has such a large volume, the humidifiers are probably not significantly increasing the general relative humidity in the cathedral.

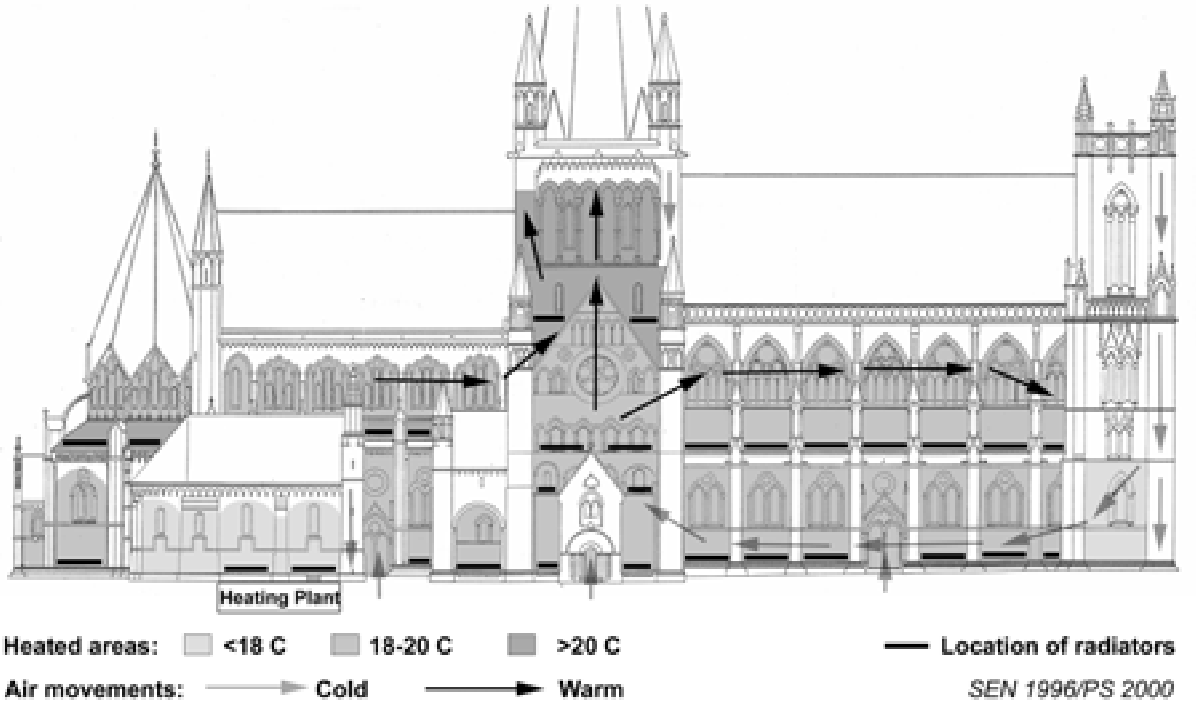


***Fig. 7.14**: Heated parts of the cathedral and main air circulation directions in the heating season. Air movements have been measured, except in the choir and elevated parts of the nave, where the figure reflects assumptions (partly after Nørsett 1996).*

Unheated areas

Partly due to the fact that the cathedral acts like a gigantic “pump” during the cold season (warm air rising in the central tower, cold air drawn from windows, openings in doors etc.), most turrets with spiral staircases work like inverted chimneys (fig. 7.14). Consequently, the climate in the turrets is more or less completely determined by the outside weather - a feature making the walls highly vulnerable to condensation (fig. 7.16). The lowermost part of the turrets in the west towers and transept are especially cold spots.

The climate of the cathedral lofts (nave, choir, octagon, chapter house) are also determined by the outside weather, but it was not always like this. Until quite recently the large vaults of the nave and choir had several small openings (for lightening cables) permitting warm, rising air to enter the lofts.

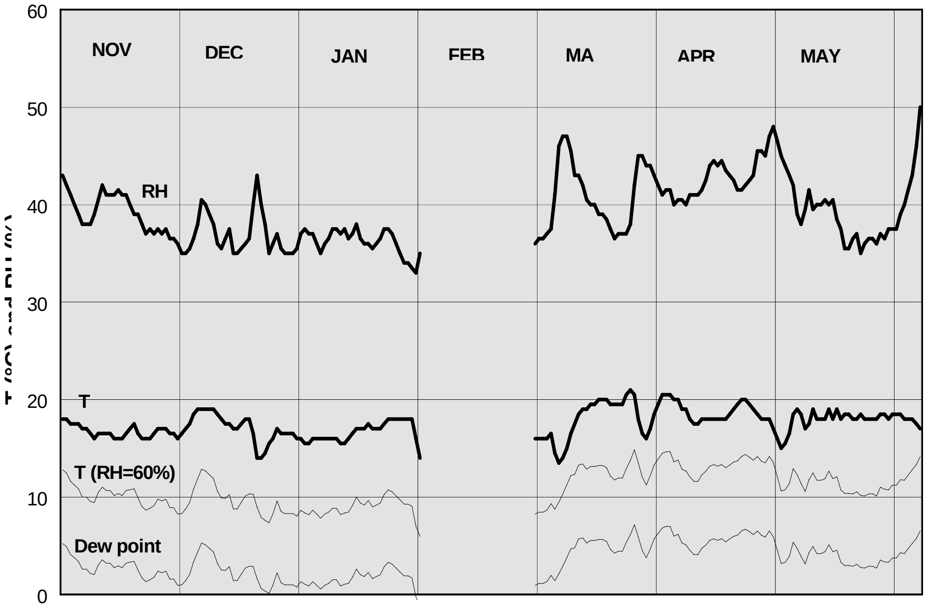


Fig. 7.15: *Mean daily values of T and RH in the north transept 1993-94 (clerestory) The figure also shows dew point and at which T the RH would have been 60% (recorded by RWNC)*

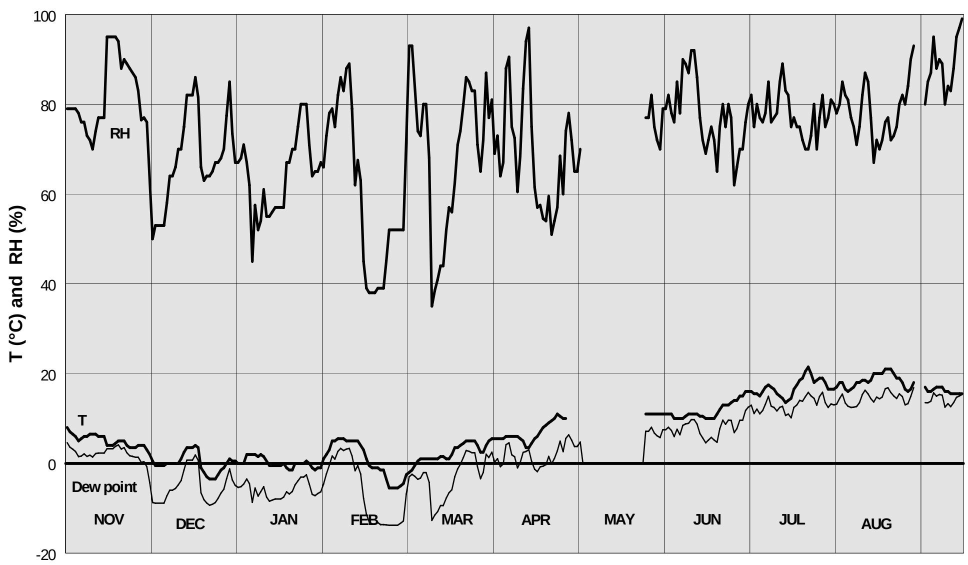


Fig. 7.16: *Mean daily values of T and RH in the upper part of the southern west tower 1990-91.Note that the temperature is frequently very close to the dew point (recorded by RWNC).*

7.6 Typical exposure conditions at the cathedral

Primarily due to great size and complex design, the exposure conditions of the cathedral are extremely diverse. Recalling that Trondheim has a variable climate, the exposure conditions at one part of the building will fluctuate throughout the year. Consequently, it may be rather meaningless to summarise “typical” exposure conditions: they have to be carefully described and analysed for each single part of the building when the objective is to understand the weathering phenomena. In order to give a glimpse of the complexity, some typical examples of how the cathedral is exposed to the changing weather is presented below.

It is worthwhile noting that walls facing south and west are exposed to sunshine, from which it is understood that the humidity is generally higher on the north side of the church. Walls facing north and east are exposed to some sunshine in early morning and late evening during the summer time, but the large trees around the church generally prevent much sunshine reaching the lower parts of such walls.

Highly weather beaten elements

It has been estimated that the cathedral has some 2 km of horizontal and inclining, “linear” elements such as moulded bases, string courses, sills and copings made of stone. There are in addition almost 60 stone capped towers, pinnacles and flying buttresses, as well as thousands of projecting sculptures and decorations. These elements are exposed to virtually every event of rain, drizzle, hail, sleet, accumulating snow, thawing snow, freezing cold nights, ice formation - and sunshine when facing south and west (fig. 7.17).

Since many elements are moulded or with deep, complicated carving, *and have an underside,* they are also vulnerable to dry deposition of air pollutants and sea salts. Indeed, prolonged periods of moist conditions on the undersides make many of the elements extremely vulnerable. This is also because deposited components cannot be washed away by direct rain or run-off, except where open joints or particular designs facilitate such conditions.[53]

Fig. 7.17: *The south transept in Feb. 1995. Formation of icicles from string courses (photo: PS).*

Water leakage and particular run-off systems

To complete the picture of the “linear” and “horizontal” cathedral, we should add that there are some 400 m of exterior gangways and horizontal platforms (west towers) which are exposed to the weather. The gangways of the aisles are, moreover, exposed to relatively elevated temperatures in the cold season because of the heating in the nearby triforia.

“Linear” elements, in particular gangways, parapets and stone capped towers inevitably develop cracks, joint fissures or other damage due to the harsh exposure conditions. Whenever such problems occur, water leaks and/or particular run-off systems are bound to result.

Water leaks and extensive run-off systems are so widespread that they have to be regarded as some of the most problematic features of the whole cathedral (next to stability and safety problems). Since leaks are intimately linked with the most severe weathering problems, they are comprehensively described in later chapters. Leaks taking place as a result of inappropriate water discharge systems and defective gutters and downpipes will also be described later.

Walls exposed to rain

Westerly (SW, W, NW) winds provide most of the rain in Trondheim, and normally it is only elevated, *vertical* masonry structures facing these directions that become wet during strong rainfalls.

Since vertical walls are never plain, but include numerous buttresses, windows, decorations etc., they tend to become very unevenly wetted (fig. 7.18). As an example one of the heaviest rainfalls during the last 5 years could be mentioned. A northwesterly gale on October 8, 1992 brought about 50 mm of rain, making elevated vertical walls as well as projecting elements and the lowermost parts of many walls completely wet. At intermediate elevations and just below projecting elements, most walls remained dry. The lowermost part of the west front stayed completely dry - a phenomenon observed during practically all events of precipitation.

Drastically increasing the possibility of water leaks and problematic run-off phenomena, lashing rain is of great importance in understanding weathering phenomena. However, provided that there are no fissures and cracks in the walls, such events seem to have a minor influence on the vertical walls themselves. In conclusion: Lashing rain increases the possibility of water leaks, but it also cleans many masonry surfaces effectively. The walls also rapidly dry out afterwards - mainly because of the dense stone types used.

Fig. 7.18: *The north transept became unevenly wetted during a northwesterly gale with heavy rainfall on October 8, 1992 (photo: PS).*

Semi-sheltered and sheltered walls

The gale on October 8th 1992 also illustrates how east-facing walls behave. Like the rest of the cathedral, projecting walls members etc. became wet. Other parts of the walls - in particular on the octagon - remained virtually dry (fig. 7.19). After several years of observation under the most diverse weather conditions, it is in fact possible to state that large parts of the octagon are never hit by direct rain.

The significance of this observation is obvious: on walls practically never exposed to rain it is possible for dry deposited air pollutants and sea salts to accumulate.[54] Salts from other sources (water leaks, run-off systems, materials and conservation products) also accumulate on such walls.

Fig. 7.19: *Large parts of the east-facing octagon remained dry during a northwesterly gale with heavy rainfall on October 8, 1992 (photo: PS).*

Condensation, white frost and hygroscopic salts

When the weather changed to become mild after a cold period in February 1953, the architect-in-chief described the white frost that appeared as “making the cathedral look bad because the architecture changes character”.[55] I do not think the building looks “bad” because of white frost, but there is little doubt that the architecture changes character (fig. 7.20-21). Such events are unlikely to occur every year, but after cold periods with night temperatures dropping to -10°C or lower, there is a great chance of white frost when mild and humid southwesterly winds suddenly break in.

As the cathedral is such a complex thermal system, white frost does not cover all the walls. Walls strongly influenced by the indoor heating are often completely unaffected (fig. 7.20). This is usually also the case during events of autumn condensation (fig. 7.20) - which may take place when mild weather occurs after relatively cold periods in October and November.

Autumn condensation is probably a more frequent phenomenon than white frost and it is often associated with fog and slight drizzle - i.e. very high relative humidities. Depending on the actual situation, it may be difficult to distinguish between “real” condensation and wet spots due to dissolution of hygroscopic salts.

Having mentioned salts, we understand that events of condensation or very humid weather are important phenomena involved in the dissolution/crystallisation cycles. Moreover, such events are of prime significance when regarding deposition of air pollutants.

Fig. 7.20: *Left: White frost has completely changed the architectural character of the cathedral. South side of the nave. Note the formation of white frost solely on unheated areas (photo: PS 12/96). Right: Autumn condensation on the south side of the cathedral in November 1995. Note that the heated, lower parts of the walls are not affected (photo: PS).*

7.7 Summary of weather, air pollution and exposure conditions

Situated on the shores of the Trondheim fjord in Mid-Norway, Trondheim has a frequently changeable, cold temperate, maritime climate. Autumn is usually the wettest period of the year, winter is relatively cold with moderate amounts of snow, while spring is the driest period.

In terms of acid rain Trondheim is a clean city. The ion content of the precipitation is, however, characterised by a relatively high amount of sea salts when westerly winds prevail. The most frequent wind direction is southwesterly.

Despite not being influenced by long-range air pollution, Trondheim did not escape the polluting effects of the industrial revolution. Coal burning commenced in the early 19th century and several local, polluting industries operated during the period from 1850 to 1980.

Heating with heavy fuel oils - also in the Nidaros cathedral itself - was normal until the 1980s. Clean air acts have led to a drastic reduction in emissions of SO_2 since the late 1970s. NO_x from traffic is today the main air polluting agent. Study of time-lapse photos indicate that black crusts started to form on the cathedral before the turn of the century. Since the 1970s the extent of such crusts has drastically decreased.

***Fig. 7.21**: Condensation events on the north porch and St. Michael's chapel. Left: White frost when mild weather broke a cold period in January 1996 (photo: Rune Langås, RWNC). Right: Completely wet because of condensation when mild weather broke a cold period in autumn 1995 (photo: PS).*

Strong heating between October and May causes the cathedral to have a low indoor relative humidity. During the summer occasional indoor condensation may occur. Condensation events also frequently occur on indoor walls in unheated areas of the cathedral.

The exterior exposure conditions of the cathedral are extremely diverse, but it is possible to distinguish between:

- Strongly weather beaten elements
- Areas suffering the effects of water leakage and/or particular run-off systems
- Walls, towers and buttresses exposed to rain
- Semi-sheltered and sheltered walls

It is important to note that exterior walls of unheated areas may become strongly affected by autumn condensation and white frost.

Part III

Weathering of stone

Fig. 8.1: *Early Romanesque decorations made of greenschist, probably from the Øye quarry. Despite the pronounced foliation of the greenschist, the carving is extremely delicate. The pieces are presently on display in the museum of The Restoration Workshop (photo: ARW).*

Chapter 8

Weathering of medieval stone

Since the 18th century several authors have commented upon the durability of the medieval soapstones of the cathedral. An interesting description was made by the German art historian Alexander von Minutoli. When visiting Trondheim in 1835 he was impressed by the “most noble monument of the Gothic style”.[1] He worked with the theme for nearly 20 years, and in 1853 he also wrote about the durability of the stone:

> Wir hatten bei näherer Besichtigung der vorzugsweise gut erhaltenen Sculpturen gefunden, dass sie von Talkstein sind, und dies berechtigte zu der Vermutung, dass dieser Stein nicht nur den wechselnden Einflüssen der Temperatur im Norden, sondern selbst der Gluth des Brandes einen bedeutenden Widerstand entgegensetzte. Manche äusserlich angebrachte Sculpturen fanden sich so erhalten, dass sie wie neu erschienen; und nicht einmal Flechten oder Moose hatten sich darauf angesetzt. Der Stein hat die Farbe des Steins von Chiavenna und fühlt sich fettig an.[2]

It seems that von Minutoli was impressed by the behaviour of weather beaten stone: “Even moss and lichens had not found a foothold on exterior sculptures” - the stone “appeared as new”. How do the medieval stone on the cathedral appear today? How do they behave in the quarries? These are the main issues explored in this chapter.

Before turning to the weathering of medieval soapstone and greenschist, concentrating on the Øye, Klungen, Huseby and Bakkaune quarries, the following definitions of structural and textural terms should be noted:[3]

- Massive stone: Stone with no preferred orientation of the minerals.
- Massive and veined stone: Stone with no preferred orientation of the minerals making up the matrix, but with distinct cross-cutting veins of carbonate minerals.
- Foliated or schistose stone: Stone with distinct orientation of phyllosilicate (flaky) minerals, but with little variation in mineral content (no alternating mineral layers).

8.1 Øye greenschist quarry: worked c. 1050-1200

The Øye greenschist quarry is important from both an archaeological and a stone weathering point of view. Its archaeological value is related to the large number of rock faces with quarrying marks which may give valuable information about medieval quarrying techniques. Since some rock faces are very exposed and others hardly exposed to direct precipitation, the weathering phenomena in the quarry are rather distinct and readily comparable to those observed on buildings.

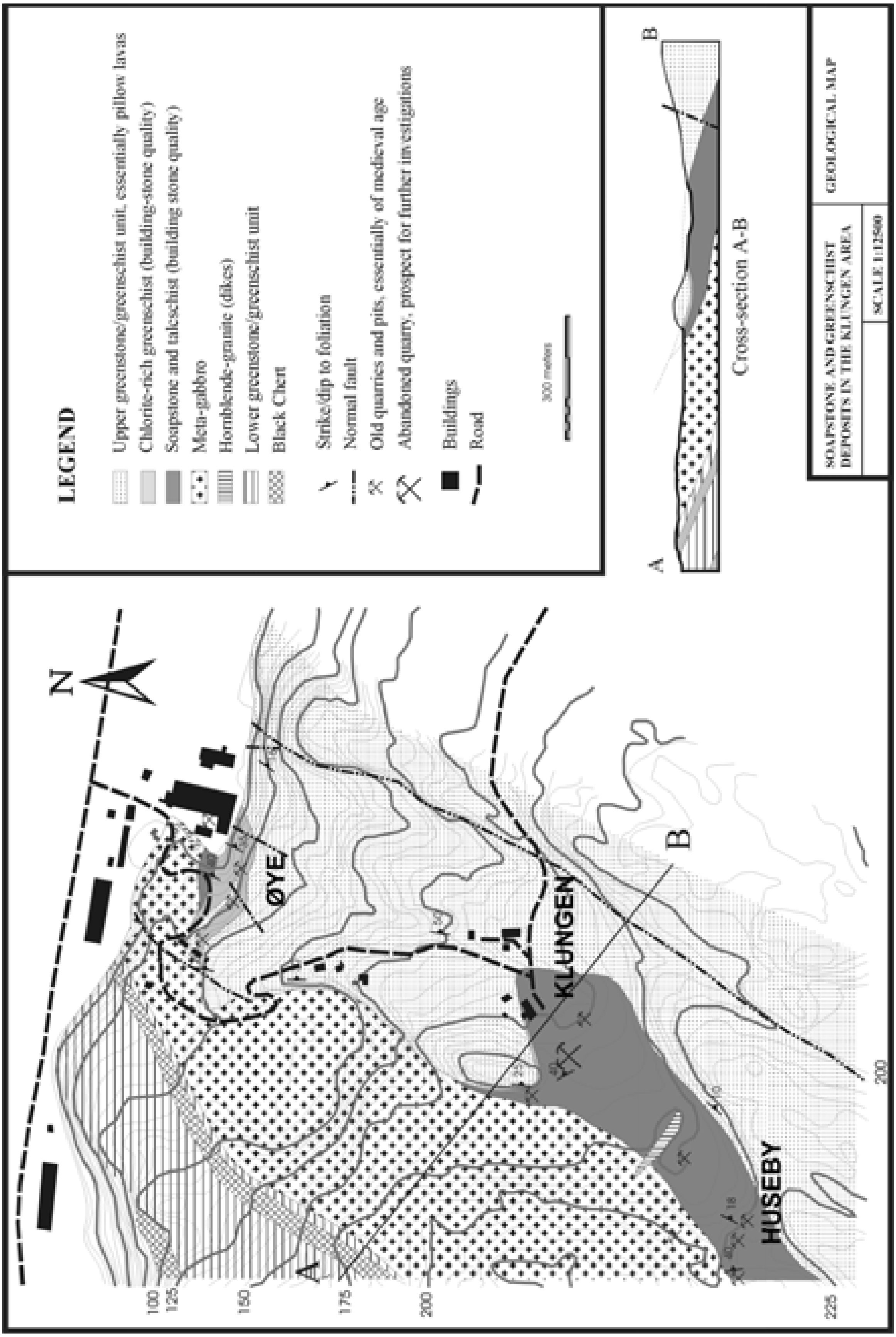


***Fig. 8.2:** Geological map showing the Øye greenschist deposit and the nearby Klungen and Huseby soapstone deposits (mapping by Tom Heldal, Norwegian Geological Survey and Per Storemyr 1996, digital drawing by Tom Heldal).* **Fehler! Textmarke nicht definiert.**

Topography, climate and geology

Including c. 10 main quarrying areas in a north-facing hillside, the Øye deposit is situated near the delta of the Gaula river, about 17 km south of Trondheim (fig. 6.2 and 8.2). Rock faces with old quarrying marks appear as slightly inclined 2-5 m high and 5-50 m long cliffs with overhanging rock above (fig. 8.3). Due to its northern orientation and dense vegetation, the hillside is characterised by a humid micro climate. Sunshine rarely reaches the ground and during the cold season most of the cliffs are surrounded by icicles from the overhanging rock. This means that several cliffs are neither exposed to direct rain, nor to snow in the winter time. However, the topography of the hillside enables moisture to affect the cliffs from "within".

The deposit has recently been geologically investigated,[4] and it seems that the soft greenschist occurs as a 2-5 m thick almost horizontal layer, separating overlying metamorphic pillow-lava from metagabbros and ultramafic rocks below (fig. 8.2). Thin layers of keratophyre as well as cracks and small faults intersect the rock, which is extremely easily split along the near horizontal foliation planes. The geology indicates that the greenschist is a metamorphosed volcanic tuff,[5] but it is also possible that it originates from a tectonically altered basalt.

At some places the greenschist has a relatively high talc content (c. 10%) and appears like a foliated soapstone. Otherwise, chlorite is the main mineral (30-40%) of the rock, which also contains some 10-20% biotite and 15-25% hornblende. Depending on locality, the greenschist also contains aggregates and distinct cross-cutting veins of dolomite and calcite, a minor percentage of quartz and plagioclase and traces of titanite. An important constituent is euhedral pyrite (c. 2%), which seems to be the only common sulphide mineral present.

Fig. 8.3: *View of the central part of the Øye quarry in March 1996. The greenschist horizon can be seen in the centre of the picture, below overhanging rock from which large icicles have formed (photo: PS).*

A brief history of the quarry

As stated in chapter 6, greenschist was the most important building material in the Romanesque and Early Gothic periods (until c. 1200). The transept and the octagon of the cathedral, as well as the choir of St. Mary's church and several other churches in the region were built of greenschist.[6]

Fig. 8.4: *Minor quarrying operation in the western part of the Øye deposit in 1934. Blocks are obtained by manual channelling using pneumatic equipment. The stones were used for a few ashlars in the west front (photo: ARW, no. 4264 D).*

Taking a modern perspective, it is impressive that the medieval craftsmen managed to make proper ashlars, decorations and sculptures using a highly foliated greenschist.[7] Interpreting the well preserved marks of quarrying operations, it seems that the main medieval quarrying technique involved the use of pickaxes to carve conical slits around the desired blocks. Subsequently the blocks could easily be loosened horizontally by employing wedges or similar tools along the weak foliation planes.[8] Other techniques were involved as well, particularly during minor quarrying campaigns in later periods, for instance in the 1770s, in 1884, 1892, 1913, 1934 and the 1950s (a total of c. 15 m^3 was quarried between 1869 and 1934).[9]

Thus, it is important to bear in mind that observed quarrying marks may belong to very different periods, even if later campaigns can be distinguished because of remaining drillholes (fig. 8.4). The importance of this observation is that it helps to determine how long the cliffs in question have been exposed.

General weathering situation

The general weathering situation of *sheltered cliffs* is characterised by intense delamination and granular disintegration. Main features are the occurrence of grey gypsum crusts and gypsum efflorescences. The crusts either cover the surfaces or are intimately intergrown with disintegrated rock. There are also relatively large amounts of oxalates within disintegrated rock, especially in association with the occurrence of leprose (powdery) lichens. Leprose lichens are generally known to occur in shaded crevices with a high humidity.[10] According to my observations, similar phenomena are widespread on sheltered *greenstone* cliffs throughout the Trondheim region.

Cliffs exposed to direct precipitation weather in a rather different manner. The overall tendency is only minor delamination, very well preserved quarrying marks and no gypsum. Many cliffs have a thick cover of biomass, including mosses and crustose lichens with embedded oxalate crystals.

In *overhangs* that are moist throughout the year, pieces of greenschist tend to fall off when there is nothing to hold them in place. Frost may of course be a main weathering agent in such locations, but the extremely low cohesion of the greenschist may also play an important role when the stone is thoroughly moist. It is in fact extremely easy to remove large flakes from a moist greenschist slab by hand. This is difficult to do when the stone is dry.

Weathering of a sheltered cliff

In the western part of the quarry is a cliff which probably originates from a minor quarrying campaign in the 1950s. The 2-3 m high cliff faces east and is sheltered by a small overhang (fig. 8.5). Inclining "medieval" rock-faces surrounding the cliff are covered by biological growth and directly exposed to rain, snow, ice and running water from above. Despite these harsh exposure conditions, the quarrying marks are very well preserved.

Along the distinct boundary between exposed and sheltered areas, thin, grey gypsum crusts cover the otherwise rather sound stone surfaces. Visible gypsum is absent on the sheltered cliff - as are most traces of quarrying which took place in the 1950s. The cliff has a completely disintegrated surface and large amounts of weathered greenschist powder can be found directly below.

Together, the observed features suggest that salts may be a major factor responsible for the weathering. Although visible gypsum is absent, microscopic and microchemical analyses show that significant amounts of gypsum occur within the disintegrated surface layer. Small

Fig. 8.5: *Øye greenschist quarry. Left: Cliff in the western part of the quarry, The light (dry) area is protected from precipitation and weathers much more intensively than rock exposed to rain, snow and ice (dark areas). Right: Close-up showing that delamination is the main weathering form in the sheltered area. The disintegrated surface layer was removed on a test spot June 11th 1993. By 1996 flaking and delamination had made the test spot almost unrecognisable(photos: PS).*

efflorescences of thenardite and other, unidentified soluble salts have also been observed in dry weather periods. Qualitative, micro-chemical analyses show that the surface layer contains, in addition to SO_4^{2-} and Ca^{2+}, significant amounts of soluble Na^+ and Mg^{2+}. Sulphate, calcium and magnesium may originate from surrounding rocks and the greenschist itself, which contains pyrite, calcite and dolomite. Sodium may for instance stem from dissolution of feldspar (albite).

The ions may be transported in solution through fissures and along foliation planes in the rock, as well as along the surface during thawing events in the spring. The sheltered position of the cliff explains why salts accumulate and crystallise here. Moreover, the high amount of gypsum suggests that single crystallisation events of this salt may be a significant weathering mechanism.

Regarding the rate of weathering, it is clear that the c. 1 cm thick, disintegrated surface layer has developed over 50 years. It has also been observed that grains and flakes regularly detach from a test spot prepared in 1993 (fig. 8.5). The weathering is therefore still very much active.

Weathering of a cliff with complex exposure conditions

Although involving similar phenomena as described above, a more complex weathering situation can be found in the eastern part of the quarry (fig. 8.6). The complexity of the situation is largely related to diverse exposure conditions and to the existence of vertical cracks which enhance moisture transport (run-off).

This north-west facing cliff is about 5 m high and has a lower part which is completely sheltered from precipitation. Beside the sheltered cliff is a north-facing cliff which is strongly exposed to precipitation. The latter cliff has extremely well-preserved medieval quarrying marks, whereas the former cliff contains few remains of quarrying operations.

The exposed cliff looks as if painted, but the “paint” is in fact crustose and leprose lichens, which seem to have spread downwards due to run-off. It appears that the lichens, which contain embedded oxalate crystals, act as a “protective” layer, possibly contributing to the preservation of quarrying marks underneath.

Run-off from the top also occurs on the partly sheltered cliff. However, the areas receiving running water during showers are unevenly distributed and related to the geometry of the upper part of the cliff. Instead of white lichens occurring on the “wet” parts, layers of red algae (Trentepohlia sp.) can be found. The rock underneath such areas is quite sound.

Areas partly sheltered from direct precipitation and run-off weather in a rather peculiar way. The main weathering forms are again intense delamination and granular disintegration, sometimes connected with slight exfoliation, but the disintegrated surfaces are all covered with white powder. Analyses show that the powder contains significant amounts of gypsum. This suggests once more that crystallisation of gypsum is a main weathering mechanism. In addition to gypsum, several samples also contain oxalate crystals (weddelite and whewellite). Apart from extracting calcium from the rock it is unknown whether the formation of oxalates play an active part in the weathering process, e.g. by excerting pressures due to crystallisation between the layers of the greenschist.

Typical behaviour of Øye greenschist on monuments

Three representative examples from the Nidaros cathedral, one from St. Mary's church and one from the Reinskloster convent have been selected to show the typical behaviour of Øye greenschist on monuments.

Fig. 8.6: *Øye greenschist quarry. Top left: Exposed, north-facing cliff in the eastern part of the quarry. Crustose lichens and moss cover the cliff and medieval quarrying marks underneath are excellently preserved.*
Top right: Partly sheltered cliff nearby the exposed cliff. Delamination and efflorescences/crusts of gypsum and oxalates are very common.
Right: Close up showing delamination and flaking near a large pyrite aggregate. Gypsum is a main constituent of the flakes (photos: PS 1993-94).

The first example is a strongly exposed, vertical pillar of the octagon's south chapel (fig. 8.7). Parts of the medieval (1180s) pillar were pulled down, cleaned and carefully redressed during the restoration of the early 1870s,[11] but it still has fully intact medieval masons' marks. The greenschist ashlars of the pillar are very sound, except for a few edges along joints.

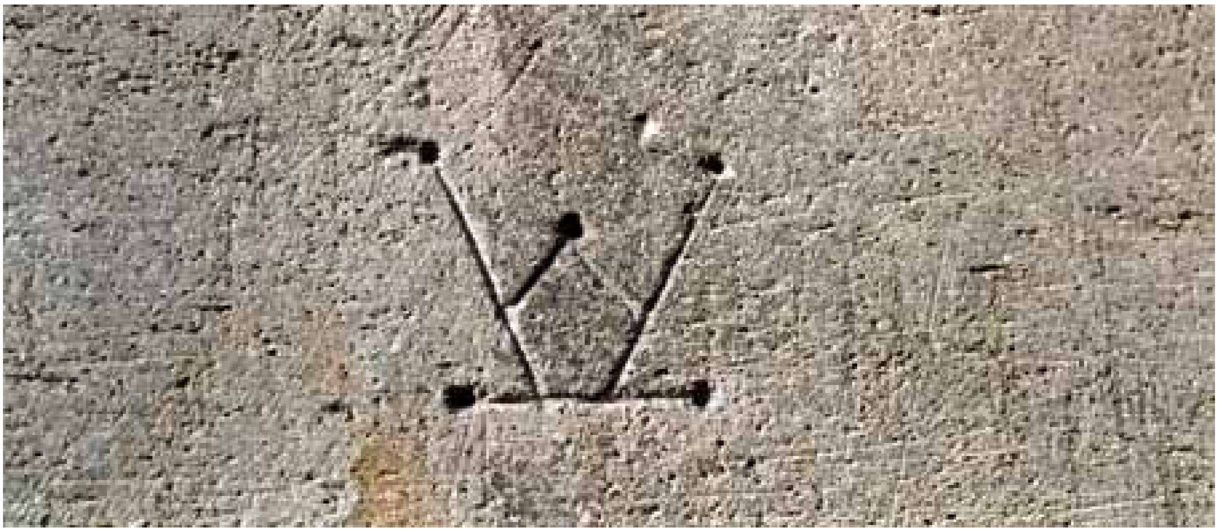


Fig. 8.7: *Detail of severely exposed pillar made of greenschist, octagon's south chapel, Nidaros cathedral. The pillar was erected in the 1180s and carefully redressed/rubbed in the 1870s. Note the excellently preserved medieval mason's mark (photo: PS 8/95).*

In the second example, which is a medieval (1180s) string course in the octagon's north chapel (fig. 8.8), it is possible to observe that the exposed upper part behaves in very much the same way as the vertical pillar mentioned above - i.e. it is well preserved. The sheltered flower ornaments underneath are, however, largely lost due to fissures formed along foliation planes (delamination). Black crusts also prevail in this region, probably contributing to the delamination. It should be noted that the flowers were lost after the restoration of the 1870s - a restoration which probably involved cleaning the string course with acid and/or lye.

Fig. 8.8: *String course made of greenschist, octagon's north chapel (1180s), Nidaros cathedral. The exposed, upper side is in excellent condition, whereas the sheltered ornaments underneath have been lost along foliation planes, probably because of the development of black crusts (photo: PS 8/95).*

Delamination, often in combination with granular disintegration and some flaking, is the main weathering form on partly sheltered ashlar masonry influenced by moisture and salts from “within” the walls (water leaks). Highlighting this phenomenon is the third example taken from the medieval masonry of the north transept's eastern tower (fig. 8.9). Just above the area in question, the tower was rebuilt with new stone and Portland cement mortars during the restoration at the turn of the century. Alkaline salts from Portland cement seem to be the main reason for the heavy delamination.

The choir of St. Mary's church (c. 1200) in the city centre of Trondheim has masonry of so-called “long and short work” made of greenschist. “Long” ashlars are horizontally bedded, whereas the “short” are face-bedded (fig. 8.10). The face-bedded ashlars tend to delaminate and lose the outermost parts, especially in the zone of rising damp. Although the greenschist naturally develops fissures along the foliation planes, the pronounced loss of material in St. Mary's church is also related to complex historical events, for instance fire and removal of former plaster and whitewash.[12]

Fig. 8.9: *Strongly delaminated medieval greenschist masonry (c. 1150) in the eastern tower of the north transept, Nidaros cathedral (photo: PS 8/95).*

Fig. 8.10: *Face-bedded ashlars made of greenschist in the choir of St. Mary's church (c. 1200). Observe that delamination leads to loss of the outermost layers (photo: PS 6/96).*

There are but a few examples of the interaction between Øye greenschist and the growth of lichens on the cathedral. Turning, however, to the masonry of Reinskloster, a ruined medieval convent across the fjord north of Trondheim, large amounts of lichen can be found on exposed ashlars. Here, the occurrence of lichen is obviously related to generally humid conditions due to large trees above the ruin. As on exposed rock-faces in Øye quarry, white, crustose lichens (probably Lecanora átra sp.) predominate on the sound greenschist ashlars. According to XRD-analyses, the lichens contain large amounts of embedded weddelite and whewellite crystals.

The examples indicate that there are remarkable similarities between weathering in the greenschist quarry and on the monuments. Summarised, it can be stated that when exposed, the Øye stone usually behaves well. It is, however, typically showing delamination and granular disintegration in sheltered positions influenced by soluble salts. Also face-bedded ashlars tend to lose their outermost layers.

The main problem of the stone is that it tends to lose details of projecting elements due to fissures which form along foliation planes (cf. the string course mentioned above). In chapter 18 additional examples of this behaviour are presented.

8.2 Klungen soapstone quarry: worked 1200-1350?

As noted in chapter 6, it is difficult to distinguish between soapstone from Klungen and Bakkaune in the cathedral. It is also uncertain to what extent the Klungen deposit actually was used in the Middle Ages. According to local tradition it was an old quarry which was reopened when The Restoration Workshop started quarrying in Klungen in 1884. The old quarry was abandoned by 1886, but a few years later, in 1892, a new quarry was opened alongside the old one. Although The Restoration Workshop planned to use the new quarry later on, it was temporarily closed in 1899.[13]

However, the temporary closure became permanent and, following geological investigations in 1967 which concluded that it would be too difficult to start quarrying once more,[14] the new quarry from 1892 was covered with earth and the land reverted to farming.[15] The old quarry was not touched, and old quarrying marks remain on the walls of the quarry, which appears as a deep pit partly filled with water. The main reason for the close-down in 1899 was not related to the quality of the stone, but rather that the quarry could not deliver the desired quantities for the large reconstruction works that lay ahead at that time. In 1967 a large amount of quality soapstone was found by diamond drilling, but not enough for the planned (but never executed) rebuilding of the central tower. Thus, it seems that the deposit still contains stone for restoration purposes.[16]

Klungen soapstone has in general a bluish matrix of talc and chlorite. It contains amphibole, larger grains and cross-cutting veins of carbonate minerals as well as some sulphide (pyrite) and oxides (magnetite/hematite). There are several varieties of rather massive and more foliated types in the deposit. Situated close to the Øye greenschist quarry and surrounded by greenstone, gabbro and some serpentinite, the deposit seems to originate from an ultramafic parent rock.

The relatively limited outcrops in the "old" quarry (1884-86) are exposed to precipitation, but sheltered from above by trees and bushes. Although it is not possible to use the outcrops for carefully studying the weathering phenomena, it can be stated that all exposed surfaces are very sound in spite of being covered by moss. The only visible changes that can be observed are a slight delamination of more foliated types and some relief connected with dissolution of carbonate veins. Similar observations can be made on abandoned blocks laying scattered around the quarry.

8.3 Huseby soapstone quarry: worked 1150-1200?

When surveying the area around the Øye and Klungen deposits in 1995, I discovered the nearby Huseby soapstone quarries. The existence of several old quarries in the area were known to local people and upon studying written sources more carefully, it was found that the quarries were mentioned in a report from 1869.[17]

It is difficult to state to what extent the Huseby deposit was exploited in the Middle Ages. All the quarrying marks suggest, however, that it must have been subjected to large-scale operation before the minor operations that took place around 1870. This is because the amount of stone obtained during these later operations was very limited (c. 15 m^3).[18] The stone was used for the restoration of the chapter house.

The relatively large outcrops at Huseby look very similar to those at Klungen, but they are generally somewhat harder and more schistose. Since the rock-faces at Huseby are more schistose, they also have a stronger tendency to delaminate along foliation planes. Otherwise, it must be stated that Huseby also contains remarkably good stone: exposed rock faces with quarrying marks resembling those at Øye are extremely well preserved.

Knowing that there are several old quarries in a 1 km long belt from Øye, via Klungen to Huseby, the importance of the area for the medieval builders is obvious. It indicates that the traditional belief maintaining that the Bakkaune soapstone quarry in Trondheim was the most important medieval source of stone probably has to be re-evaluated.

8.4 Bakkaune soapstone quarry: worked c. 1200-1350?

"Probably the best stone used during the restoration", said a former restoration architect about the qualities of the Bakkaune soapstone.[19] Indeed, the stone has, like Klungen soapstone, most of the properties appreciated by masons. It has a soft bluish, rather massive matrix and is intersected by carbonate veins which give the stone a beautiful appearance.

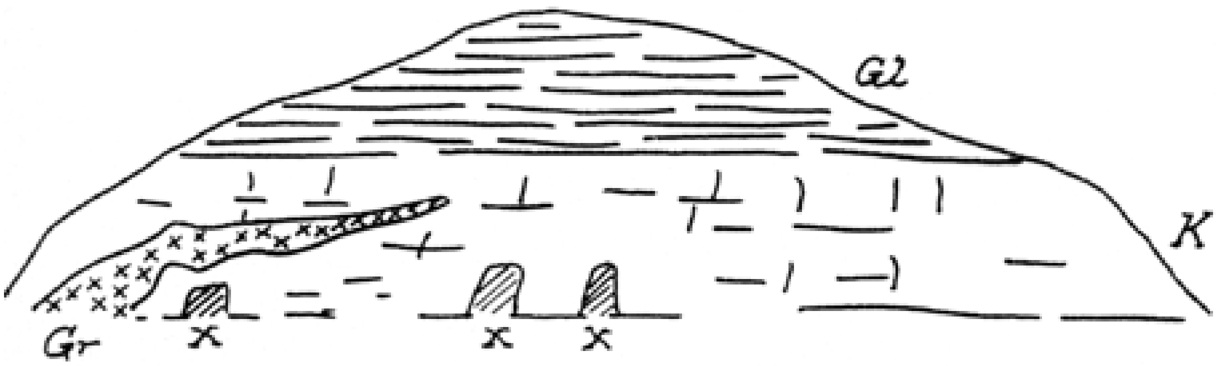


Fig. 8.11: *Geological sketch of the Bakkaune soapstone deposit in the eastern suburban areas of Trondheim. K = soapstone, Gl = greenstone, Gr= granite, X = old adits (from Helland 1893).*

Topography, climate and geology

The deposit is situated below a 30 m high and c. 75 m long, steep cliff (fig. 8.11) in the eastern suburbs of Trondheim, about 2 km from the cathedral itself. Regarded as a transformation zone around a peridotite lens,[20] the soapstone deposit faces north-west - towards the Trondheim fjord and lashing rain from the west. Except for some trees and bushes and a large apartment building just in front of the deposit, there is nothing to prevent sun, rain and snow affecting the bare rock. However, as the soapstone occurs as several 2-5 m high knolls, separated by cracks and small faults with inclined surfaces, there are also a few partly sheltered surfaces to be found.

A main feature of the deposit is smooth, semi-vertical fault or joint surfaces covered by soft, white talc. There are also smooth surfaces on which the colour and structure of the soapstone can be easily observed. On such surfaces, the colour of the matrix ranges from green-blue with a violet or brown tint, to green-grey and dusty grey. The matrix is intersected by a chaotic pattern of carbonate veins of varying thickness, and sometimes by veins of massive talc. Carbonates exposed for a long period of time are always brownish or reddish due to oxidation phenomena.

The mineral assemblage of the matrix is talc (20-30%), chlorite (30-40%), hornblende (10-15%) and some carbonates. The rock matrix is generally massive with no visible preferred mineral orientation, but close to the contact with overlying rocks the soapstone is slightly foliated. Oxides (magnetite and hemoilmenite) are important opaque minerals, but abundant, partly oxidised, subhedral and euhedral pyrite grains can also be observed in the quarry.

A brief history of the quarry

The deposit is much larger than what can be seen at the present surface, on which no traces of former quarrying operations remain. According to reports from the end of the last century, there were at least two adits in the lower part of the cliff (fig. 8.11), indicating that quarrying operations largely took place as underground mining even in the Middle Ages.[21] This indicates that in the present outcrops the stone type is different from the type exploited in the Middle Ages. Observations have also shown that the outcrops contain stone that is slightly harder and more serpentinite-like than stone in the cathedral believed to originate from the quarry (in the choir and nave).

Fig. 8.12: *Part of the Baroque east porch of Kristiansten fortress, built of Bakkaune soapstone c. 1740 (photo: PS 3/94)*

Today the adits are blocked by a scree, and it is unknown how deep they are. However, it is known that during quarrying between 1869 and 1880 as well as between 1894 and the final closure of the quarry in 1897, the craftsmen did not “reach the bottom of the old adits”, a piece of information which suggests that the adits are quite deep, indeed.[22]

Also from the 18th century written information exists about the quarry. It is known that it was operated around 1740 in order to provide stone for the new tower of St. Mary's church.[23] Built at the same time, the east porch of Kristiansten fortress (fig. 8.12) also appears to have been built of Bakkaune stone, and in the 1770s a few blocks were obtained for building the base and a staircase in the so-called Stiftsgården in Trondheim.[24]

It is unlikely that the quarry will reopen in the future. After heated discussions at the end of the 1970s, it was decided to raise a large apartment block very near the quarry. Thus, a unique source of material for restoration purposes, as well as an equally unique cultural monument, was rendered inaccessible.

General weathering situation

Apart from major chipping and spalling of surfaces that are irrelevant in the context of this thesis, the main weathering forms observed in the quarry are carbonate dissolution and flaking/granular disintegration associated with gypsum crusts.

Dissolution of carbonate veins occurs on near-vertical, smooth surfaces strongly exposed to precipitation (fig. 8.13). Some veins are deeply weathered, filled with lichen and moss, leaving a crack-like pattern on the surface. When carbonates are intergrown with massive talc, surfaces tend to develop micro-karst. Originally white carbonate veins are always oxidised (brown/red colour) due to small amounts of iron in the crystal structure. Dissolution and oxidation phenomena - probably connected with frost - may cause total breakdown of many carbonate veins to earthy masses of iron hydroxides and similar minerals. These phenomena often result in major chipping and spalling of the rock structure; relatively large pieces of soapstone may loosen and detach.

Due to the presence of dissolving carbonates and visibly oxidised pyrite, it is unsurprising that gypsum crusts have developed on the few semi-exposed and sheltered surfaces in the quarry. The crusts are generally quite thin, green-grey and usually have a cauliflower-like surface morphology. Behind the crusts there is usually a thin layer of loosely bound flakes (mm-size) and grains from the soapstone matrix. Flaking and minor granular disintegration also occur on some protected surfaces without crusts. Between flakes and grains small, glassy gypsum crystals tend to predominate.

Fig. 8.13: *Part of the Bakkaune soapstone deposit. On exposed surfaces carbonate veins tend to dissolve, leaving a crack-like pattern and sometimes leading to spalling and chipping of the rock (photo: PS 1994).*

Due to the mineral chemistry of the soapstone (much magnesium from dolomite and magnesite and sulphate from pyrite), one would expect to find epsomite/hexahydrite as a main salt phase. During repeated observations in 1994-95 this phase has never been detected. However, there is a great deal of white, powdery material to be found in the quarry, mostly connected with carbonate vein dissolution and sometimes with limited growth of leprose and crustose lichens. The powdery material seems to consist of a mixture of oxalates and gypsum - as determined by microscopic examination.

8.5 Typical behaviour of Klungen/Bakkaune stone on monuments

Three representative examples of how Bakkaune stone behaves at the cathedral are presented. Since it is difficult to distinguish between Bakkaune and Klungen soapstone, the examples may well be representative of the behaviour of Klungen stone also.

The first example is from the east chapel of the octagon before the restoration in the early 1870s (fig. 8.14). On a photo it can be seen that the strongly exposed gable copings are in excellent repair, but several veins - probably carbonate veins - are partially dissolved, just like in the Bakkaune quarry. It can also be seen that several pieces of the moulded sides of the copings have been lost. The copings were probably put in place during Archbishop Erik Valkendorf's restoration in the early 16th century.

__Fig. 8.14:__ The octagon's east chapel just before the restoration in the early 1870s. Note that gable copings made of Bakkaune soapstone have partly dissolved carbonate veins (photo: ARW).

Loss of pieces in connection with dissolving carbonate veins can also be observed on the replaced (1870s) base of the octagon's south chapel today (fig. 8.15). Although some fracture planes cut directly through the matrix of the stone, it is evident that the carbonate veins represent specific planes of weakness, along which fractures preferentially develop. Except for cracking and spalling along the carbonate veins at the most exposed places, the surface of the stone is sound - it has hardly changed in character since the 1870s. The same phenomena can be observed on most medieval soapstone (Bakkaune or Klungen) sculptures of the octagon. Arms, chins, noses - and any other exposed detail - have the tendency to fracture along carbonate veins. At a distance, it is often difficult to observe such phenomena because most lost pieces were reconstructed

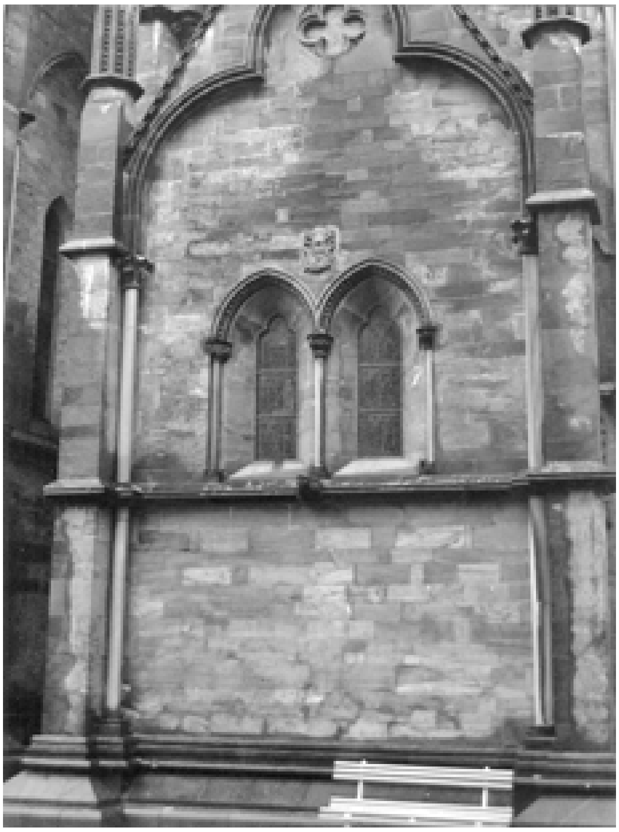


Fig. 8.15: *Top left:The south chapel of the octagon. The moulded part of the base was replaced by Bakkaune soapstone in the 1870s. Archbishop Erik Valkendorf's coat of arms (from the early 16th century) above the windows is also made of Bakkaune stone. Note that the coat-of-arms is only partly exposed to rain. Photo taken during a very heavy shower in 1992 (photo: PS).*
Top right: Carbonate dissolution has led to loss of a strongly exposed edge of the base (photo: PS 3/96).
Right: The crumbling of the lower right side of the coat of arms is mainly caused by soluble salts (magnesium sulphates) (photo: PS 6/93).

during the restoration. It may also be difficult to observe that along many carbonate veins, thin talc veins occur, apparently enhancing the possibility of chipping and spalling. It should be noted that investigations of Brazilian soapstones have shown that large hygric dilatation may be connected with veins of massive talc.[25] Thus, in this case, it is possible that hygric dilatation - in addition to dissolution and frost - is a significant weathering factor as well.

Significant crumbling of the surface of Bakkaune stone - in the form of granular disintegration and flaking - never occurs when the stone is strongly exposed to precipitation. However, in partly or completely sheltered locations, i.e. where salts can accumulate, such weathering phenomena are rather widespread. One example is Archbishop Erik Valkendorf's coat-of-arms on the octagon's south chapel (fig. 8.15) The coat-of-arms was probably put in place during the restoration of the chapel in the early 16th century and it remained in an excellent condition until the restoration in the 1870s.[26] Since then, and for unknown reasons, significant amounts of magnesium sulphate (epsomite/hexahydrite) have formed along a cross-cutting carbonate vein in the coat-of-arms, resulting in granular disintegration and flaking of the adjacent soapstone matrix. Although normally involving salts other than magnesium sulphates, the same phenomenon is widespread not only at the Nidaros cathedral, but also elsewhere in Trondheim (for instance St. Mary's church[27] and the large portal at Kristiansten fortress[28]).

In the introduction to this chapter, reference was made to Alexander von Minutoli who in 1853 was impressed by the durability of the cathedral's stone. Although the soapstones and greenschist tend to lose pieces along dissolving carbonate veins and foliation planes, respectively, the observations of Minutoli were highly relevant - not least because the surfaces of exposed details usually are remarkably sound. However, when affected by soluble salts in sheltered positions - in the quarries as well as on monuments - both stone types may develop pronounced flaking, granular disintegration and delamination.

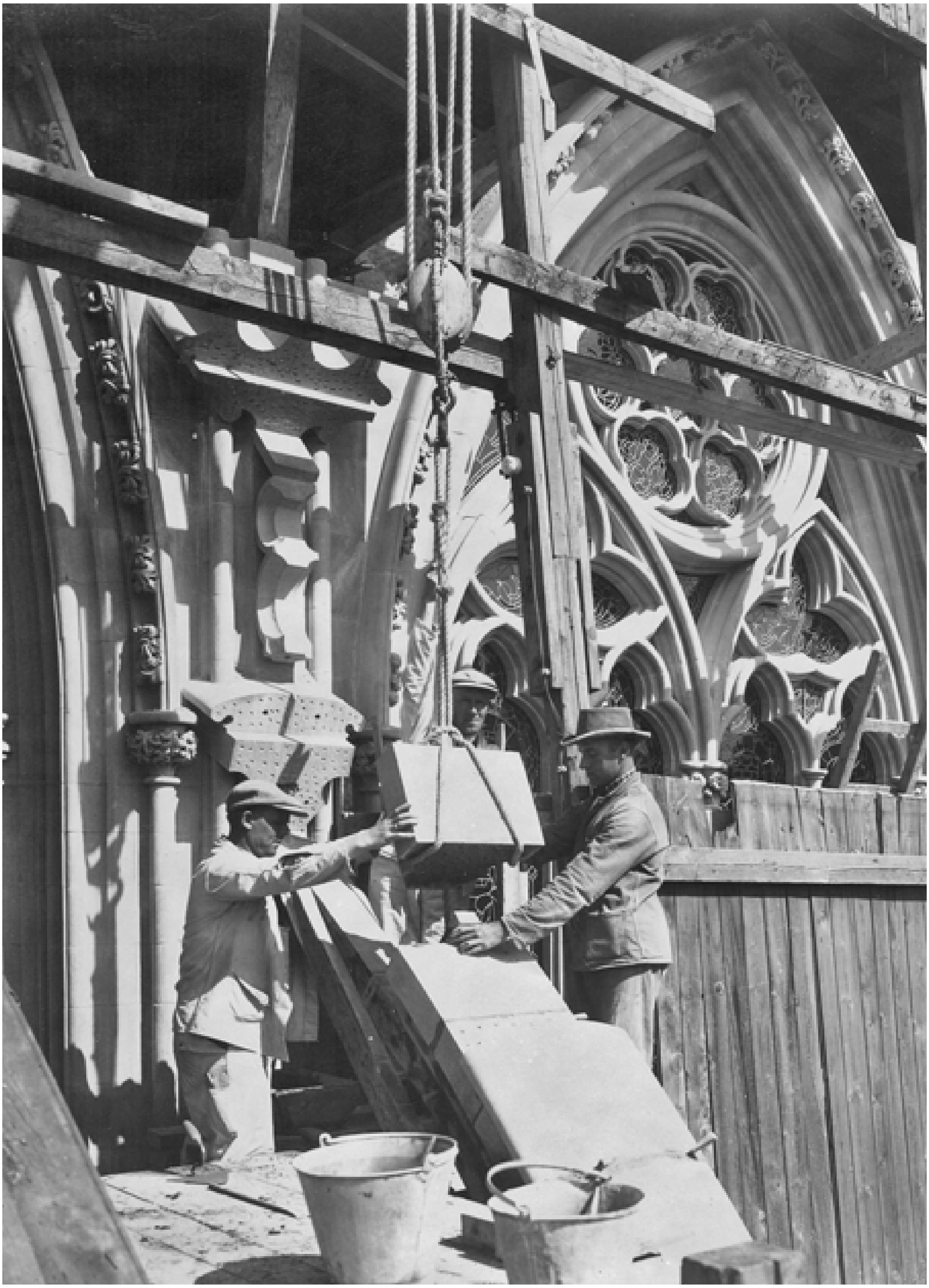


***Fig. 9.1:** Construction of the flying buttresses of the nave in the 1920s. The buttresses are all made of Bjørnå soapstone (photo: ARW, no. 3000).*

Chapter 9

Weathering of stone used during the restoration

Whereas the soapstone quarries used in the Middle Ages are located near Trondheim and in a typical greenstone province, the quarries opened for the restoration of the cathedral are situated in a variety of geological environments. Whether these circumstances are of any relevance to the weathering phenomena observed is uncertain. However, the weathering of the new stone types is very different from the old ones.

Among the c. 20 soapstone quarries opened during the restoration, the five most important ones have been selected for careful investigation. They include soapstones associated with amphibolite relatively close to Trondheim (Grytdal and Bubakk), soapstone found in gabbroic or ultramafic massifs in Nordland (Bjørnå), soapstone originating from pyroxenite in the Bergen region (Gullfjellet) and soapstone within mica gneiss in Troms county (Grunnes). All are located within the Caledonian mountain chain.

9.1 Grytdal soapstone quarry: worked 1869-1892

Known for more than 70 years as the worst stone at the cathedral, Grytdal soapstone is literally “rusting to pieces”.[1] This popular description reflects the fact that Grytdal should have been utilised as a sulphide deposit rather than for building stone! However, natural diversity can also be seen in the quarry. This is because good building stone is found just beside the sulphide ore.

Topography, climate and geology

The quarry is situated in an overgrown, south-facing valley slope in Gauldalen, about 70 km south of Trondheim. The deposit was a near vertical, elongated lens of schistose soapstone embedded in amphibolite[2] before quarrying commenced in 1869. Today the quarry appears as a 40-50 m long and 10-20 m deep cleft perpendicular to the valley slope (fig. 9.2-3). This situation renders the quarry quite wet, but not filled with water. Large icicles form in the quarry during the cold season and during the period of this research (1990-1995), very large blocks of stone have fallen down due to freeze/thaw action in spring.

Petrographic analyses show that varying amounts of chlorite (20-60%) and talc (5-20%) make up the soft matrix of the stone. The matrix is often “disturbed” by visible needles of tremolite (5-40%) and some hornblende (5-10%). Scattered grains and larger, cross-cutting veins of calcite (5-10%) and dolomite (10-20%) are a main feature of ashlars in the Nidaros cathedral. However, these veins are hardly recognisable in the quarry due to growth of lichens

Fig. 9.2*: View of the Grytdal soapstone quarry, looking south. The eastern part of the deposit has abundant pyrrhotite and may be regarded as a small sulphide ore deposit (photo: PS 5/94).* ***Fehler! Textmarke nicht definiert.***

and moss. Smaller amounts of quartz and biotite, as well as magnetite and titanite are also present in some varieties of the stone.

From a weathering perspective, the most important feature of the stone is the extremely high content of sulphide minerals like pyrrhotite, pentlandite, chalcopyrite and pyrite. Anhedral pyrrhotite is the main sulphide mineral, amounting to more than 10% of the stone in the eastern part of the deposit and 2-3% in the western part. The diverse mineral composition apparently controls the colour of the stone. Some varieties are green, some are grey and some are reddish, brownish or yellowish - the latter colours develop due to oxidation phenomena.

A brief history of the quarry

In reports from the end of the 19th century Grytdal was described as a very good stone. It was easy to quarry and raw blocks as large as 0,7 m^3 could be obtained. For the masons it was also important that the stone had

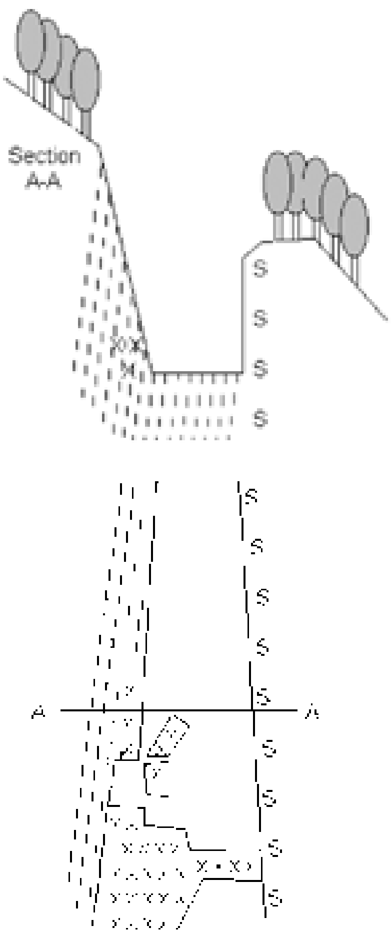


Fig. 9.3: *Rough outline of the geology of Grytdal quarry. Lower part: plan of the quarry which is c. 50 m long. Upper part: section A-A (height c. 10 m). Dotted lines = foliation;*

X = massive soapstone with much tremolite; S = foliated soapstone and amphibolite with much pyrrhotite.

magnificent cutting and carving properties.[3] However, a couple of decades later, other masons were busily occupied with replacing totally disintegrated ashlars and decorations made of this stone.[4]

Quarrying commenced in 1869, probably in the relatively sulphide-poor, western part of the deposit. Using pickaxes, manual drilling and gunpowder, and taking advantage of the foliation of the stone, the craftsmen obtained rather flat raw blocks.[5] Ashlars and bases made during the early quarrying campaigns were used for replacement purposes in the chapter house and transept and are still in excellent condition. Later, and especially towards the close-down of the quarry in 1892, the quality of the stone became much poorer, probably because quarrying had to take place along the sulphide-rich eastern side of the deposit. A total of about 1100 m^3 Grytdal stone was delivered to the cathedral between 1869 and 1892 and from 1878 most of it was used for the reconstruction of the choir's clerestory.[6]

General weathering situation

The 10-15 m high western wall is generally strongly exposed to precipitation and has large cracks along the pronounced, near-vertical foliation planes. It seems that the cracks - or large-scale delamination - has formed mainly due to frost. The wall also has small-scale, widespread delamination and flaking, especially in places only partly exposed to precipitation. Flaking is associated with minor growth of moss and leprose lichens (with embedded oxalates), and often with yellowish gypsum crusts. Thus, in addition to frost and biological weathering agents, crystallisation of gypsum must be regarded as an important weathering mechanism. A few surfaces with quarrying marks are oriented perpendicular to the foliation planes of the western wall (fig. 9.4). Most of these surfaces are in good condition, possibly because they are strongly exposed to running water which may carry salts (gypsum) away.

Fig. 9.4: *Vertical surface in the western part of Grytdal quarry. Although the surface has been exposed for a century, quarrying marks are still very well preserved (photo: PS 3/95).*

As mentioned above, the eastern part of the quarry is a small sulphide ore deposit. According to general text books in ore geology, the weathering zone of such deposits is characterised by complex oxidation of the sulphides which

Fig. 9.5: *Exposed and cracked soapstone slab in the eastern part of the Grytdal quarry. The slab has crispy efflorescences of gypsum during the cold season (photo: PS 3/95).*

Fig. 9.6: *Gypsum in the Grytdal quarry. Left: Amphibolite overgrown with gypsum rosettes. Right: Microscopic view of the gypsum rosettes. Gypsum is intergrown with jarosite (width of field: 8 mm) (photo: PS 1990).*

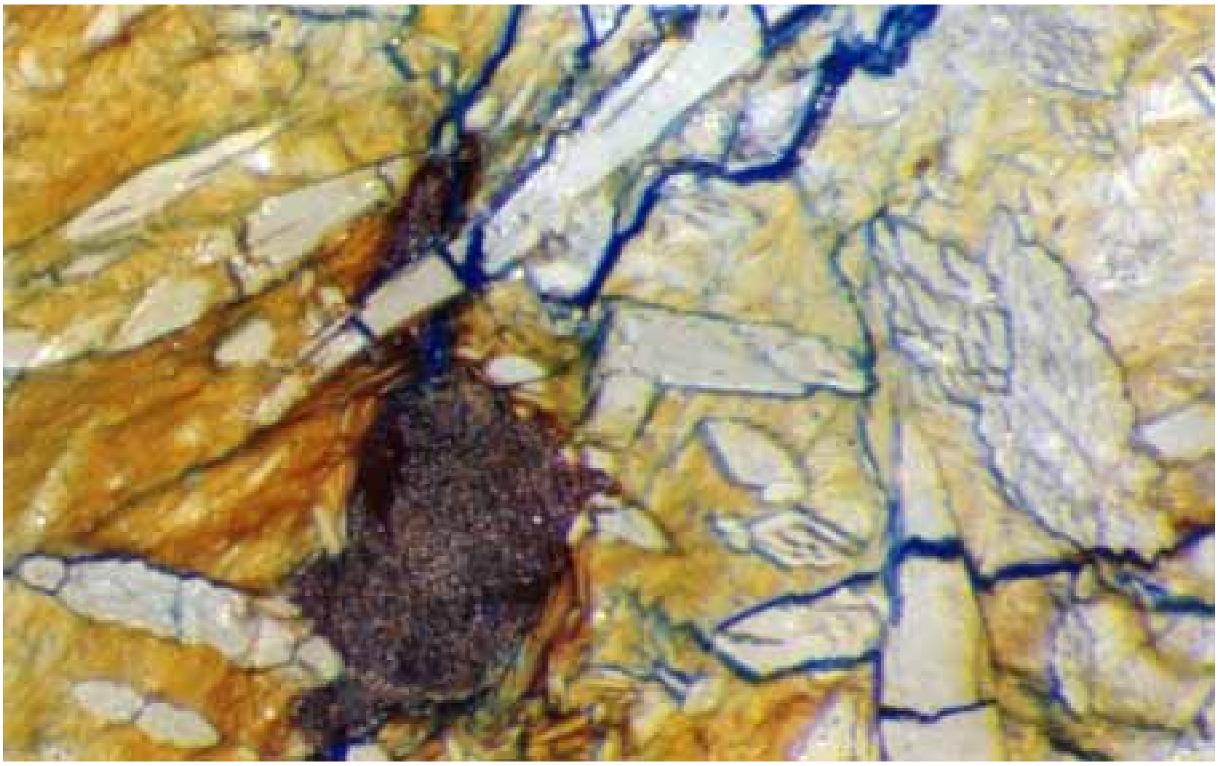


Fig. 9.7: *Microscopic view of cracked Grytdal soapstone. The central grain of pyrrhotite has oxidised to form goethite, whereas fissures are preferentially associated with relatively stiff tremolite needles (width of field: 3 mm) (photo: PS 1990).*

release sulphuric acid to react with iron, copper, calcium, magnesium etc. Thus, secondary minerals, such as several kinds of sulphate salts and iron hydroxides, are formed. The complex dissolution and crystallisation processes lead to radical colour changes, development of efflorescences and crusts and eventually to partial or total disintegration of the rock.[7]

Being partly sheltered from direct precipitation, the eastern wall of the Grytdal quarry shows most of the characteristic weathering phenomena mentioned above. The outermost portion of the rock has usually completely disintegrated to a powdery material (fig. 9.5 and 9.7). The formation of goethite and other iron hydroxides - as well as jarosite - render surfaces brown, reddish and yellowish and large amounts of gypsum can be found. As a result of small variations in exposure conditions, gypsum occurs as large, cauliflower-like crusts, beautiful, needle-like, white rosettes and “mats” of tiny efflorescences (fig. 9.5-6). The latter form seems to flourish on exposed areas in cold, stable winter weather. During thawing and rainy periods the efflorescences dissolve and then reappear the next winter. Epsomite can also be found in the quarry, but in surprisingly limited amounts and only during extended dry periods. The salt occurs like gypsum as “mats” of tiny efflorescences and as thin, but extensive white crusts.

There are obviously mechanisms other than chemical dissolution, oxidation and salt crystallisation involved in the weathering of the eastern wall. Freeze/thaw action should be considered, as well as the influence of bacteria, fungi, algae and lichens.

Behaviour of Grytdal soapstone on the cathedral

It is difficult to describe the weathering of Grytdal stone as a function of exposure conditions. This is because the weathering is much more dependent on primary stone quality than on location at the cathedral. One phenomenon that does preferentially occur when the stone is used for exposed, horizontal elements, is a particular kind of bulging.

Fig. 9.8: Hopelessly lost Grytdal ashlars from the 1880s. North side of the choir of the cathedral. Although it cannot be observed in the picture, the disintegrated surfaces also contain extensive crusts of gypsum and epsomite (photo: PS 1992).

Bulging is characterised by a drastic increase in the volume of the stone, followed by fissures and cracks along foliation planes. The surface is usually strongly yellow or brown, flaking and disintegrating, and larger pieces can easily be removed by hand. Bulging not only takes place in elements like exterior string courses, cornices and copings, but also in stones used for interior bases - i.e. in the zone of rising damp or where frequent condensation events occur. It must be assumed that oxidation of pyrrhotite and subsequent formation of large amounts of gypsum in the stone is a main weathering mechanism.

Otherwise, Grytdal stone appears in all states between totally disintegrated to remarkably sound (fig. 9.8-9). When weathered, the surface or even the whole interior of the stone may have strong yellow-brown colours due to the presence of iron hydroxides and jarosite. The most disintegrated stone is usually hopelessly lost and consists of loose powder which is held in place by extensive crusts of epsomite and gypsum.

Other weathering phenomena include strong yellow discolouring followed by weakening of the surface structure and pronounced pitting when the stone is exposed

***Fig. 9.9:** Weathered Grytdal stone found beside relatively well-preserved varieties in the south wall of the choir of the cathedral (erected in the 1880s) (photo: PS 1991).*

to precipitation. In such cases it is not possible to visually observe salt crusts. Depending on exposure conditions, yellow surfaces may sometimes be covered by dark brown layers of “rust” or by thick, black or grey gypsum crusts.

Although a main feature of Grytdal stone is the pronounced weathering, an equally important phenomenon is that many varieties used for ashlars and decorations remain in excellent repair. Such varieties often possess an extensive network of tiny, glassy tremolite needles. As stated above, the best stones can be found in building sections restored during the early phases of the restoration (chapter house and transept), but even in the clerestory of the choir (late 1880s) good Grytdal ashlars can be found beside completely weathered varieties.

9.2 Bjørnå soapstone quarry: worked 1897-1958

Despite frequent problems with safety and stone quality, Bjørnå was by far the most important soapstone quarry during the restoration of the cathedral. From 1897 to 1958, about 7500 m^3 was quarried - seven times more than what was obtained in the second most important Grytdal quarry.[8] In fact, it is probably correct to state that Bjørnå is the stone type to be most frequently observed in the cathedral today - even when including stone used during the medieval building periods.

Topography, climate and geology

Compared to the small soapstone quarries in the Trondheim region, Bjørnå is huge. It is located near Mosjøen, a small city some 400 km north of Trondheim. Situated in a west-facing valley slope, the deposit lays in the peripheral zone of an ultramafic or gabbroic rock complex, which can be seen just above the 20 m high east wall of the quarry.[9] The west wall is much lower, and in between these walls the quarry forms a 50-60 m long and 10-20 m wide re-entrant in which massive blocks of soapstone have collapsed (fig. 9.10). Knowing that the largest block measures more than 70 m^3, the severity of the safety problems encountered during the

Fig. 9.10: *View of the Bjørnå soapstone quarry, looking north. The large 70 m^3 block seen in the picture has fallen down from the east wall - an event indicating the severe safety problems encountered during operation of the quarry between 1897 and 1958 (photo: PS 5/94).*

operation of the quarry is understandable.

That blocks fall down is partly because of the harsh climate at these northern latitudes. However, the cold winter weather is moderated by closeness to fjords and the Norwegian ocean. The landscape surrounding the quarry is characterised by dense vegetation, but the quarry itself is very exposed to rain and snow.

With a structure ranging from massive to rather foliated, the stone has a matrix of chlorite (30-40%), biotite (20-30%) and talc (10-15%). Talc also occurs as longer fibres perpendicular to the foliation. Dolomite (10-15%) and calcite (1-15%) appear as c. 5 mm large grains scattered within the matrix, sometimes adding variation to the otherwise dull grey-green stone. Small amounts of tremolite (2-5%), klinozoisite (2-5%), magnetite (traces) and hemoilmenite (traces) occur, as well as large, scattered crystals of euhedral pyrite. Traces of chalcopyrite can also be found.

A brief history of the quarry

There are several reasons why the Bjørnå deposit became so important during the restoration of the cathedral. Firstly, at the turn of the century some of the largest reconstruction works undertaken at any cathedral in Europe lay ahead, which meant that a constant and long-lasting supply of stone was needed. The large size of the deposit certainly fulfilled these demands. Secondly, due to 20th century improvements in quarrying and transportation methods, it became increasingly popular to quarry large raw blocks and undertake more of the splitting and dressing operations in the workshop. Relatively large raw blocks could be obtained from Bjørnå and the long transportation distance (400 km) presented few problems (first by ship and from the 1940s by train).[10] Thirdly, the Bjørnå stone was easy to cut and carve - properties appreciated both when making ashlars and decorations.

Fig. 9.11: *Disintegrated surface of a moulded base made of Bjørnå soapstone around 1900. South side of the nave, Nidaros cathedral (photo: PS 8/95).*

Fig. 9.12: *Close-up showing connected pits in Bjørnå soapstone. Base from c. 1920 on the south side of the choir (photo: PS 8/95).*

Due to foliation and cracks in raw blocks, it was not possible to make all the large west front sculptures from Bjørnå stone. In the 1930s this problem was solved by turning to the Gullfjellet soapstone deposit near Bergen. This hard, grey soapstone was, however, not suitable for ashlars. Other problems were the dull colour of the Bjørnå stone and the frequent safety difficulties in the quarry. Severe rockslides took place in 1911-13, 1917, 1939-40 and 1951 and during these periods the craftsmen (normally 15-20 people) were forced to quarry stone of inferior quality compared to what was regarded as “good” stone. To overcome problems with colour and quality, exploration programmes were undertaken throughout Norway. Some suitable deposits were found and old quarries, like for instance Øye (1913, 1934), were also used for obtaining ashlars which could render the masonry more colourful. It was not until 1952, when the Bubakk quarry went into operation, that a new long-lasting supply of stone could be secured.[11]

During the 1950s and 60s it became increasingly clear that exposed sculptures and other elements made of Bjørnå stone had a very poor durability. Gargoyles, modelled by famous Norwegian artists like Gustav Vigeland and Wilhelm Rasmussen, were particularly vulnerable. Parapet copings also weathered rapidly. During the last 30-40 years, elements made of Bjørnå stone have in fact been a constant problem which has lead to major conservation and replacement programmes (see part IV).

General weathering situation

In addition to large-scale delamination, the most striking weathering phenomenon in the quarry is the widespread flaking of surfaces strongly exposed to precipitation. The flakes are normally thin (1-5 mm), up to a few cm long and wide, oriented along the foliation of the stone, and may also occur as several layers on top of each other (multiple flaking). Most of the visible carbonate grains (and thin veins) have turned brown due to oxidation phenomena, they are partially dissolved, giving rather sound surfaces a weak relief.

Fig. 9.13: *Stone gully modelled by Gustav Vigeland and carved in Bjørnå soapstone at the turn of the century. The gully is located by the parapet on the south side of the central tower of the cathedral. It has been secured because a crack has developed along a vein of talc or carbonate parallel to the foliation plane of the stone (photo: PS 3/96).*

When flaking and relief formation occur simultaneously, it is hard to find an apt name for the weathering form as the surface becomes very rugged and full of connected pits. It should be noted that moss and lichens flourish on some stone surfaces. Similar weathering forms, but much less intense, can be seen on some sheltered surfaces. No salt efflorescences or gypsum crusts have been observed in the quarry.

Behaviour of Bjørnå soapstone on the cathedral

The weathering of Bjørnå soapstone used in the cathedral is extremely dependent on exposure conditions. It is possible to state that projecting features strongly exposed to precipitation weather most severely (fig. 9.11-12), while plain, vertical masonry and sheltered decorations usually remain sound.

Representing a great safety problem, gargoyles and moulded copestones put in place between 1900 and 1930 tend to lose large pieces due to fissures developing along foliation planes (fig. 9.13). Along some foliation planes thin talc veins occasionally occur, representing areas of particular weakness, but foliation alone may also lead to loss of fragments. It is evident that harsh exposure conditions involving rapid temperature changes facilitate the development of fissures, but several Bjørnå varieties are nevertheless good enough to withstand rapid weathering for prolonged periods of time.

Clearly, harsh exposure conditions are needed for the development of pronounced surface weathering. However, on the surfaces of bases, copestones and string courses, moss and lichens also tend to find a foothold, making it difficult to blame the quality of the stone alone for the weathering. It is, on the other hand, also clear that elements on which no visual biological growth can be seen may develop strong pitting, flaking and granular disintegration. Pitting appears initially to be connected with dissolution of scattered carbonate minerals within the stone. The same phenomena can also be observed on extremely exposed west-facing vertical masonry.

It is difficult to find Bjørnå stone strongly affected by soluble salts on exterior walls of the cathedral. However, when observing what happens inside towers erected during the restoration, it is evident that the stone is not especially resistant to salt weathering. Enormous amounts of alkaline salts seem to have "eaten" the matrix of the stone, while hard cement joints stand out as frames for each individual ashlar. Thin carbonate veins and large, cubic pyrite crystals are also left more or less unaffected by the salt weathering.

Behaviour of Bjørnå soapstone on other monuments

Bjørnå soapstone has also been used for replacement purposes in other monuments as well as for a number of tombstones in the Trondheim region. The weathering phenomena observed at the cathedral seem to repeat on these objects and there are no major differences between objects situated in the city centre or in the countryside.

One example is the west portal of Stiklestad church, some 100 km north of Trondheim. The portal, which was built in the 1920s,[12] is very simple and features a semi-circular, slightly projecting arch on top (fig. 9.14). The arch, on which moss and lichens flourish and snow collects during the cold season, is the only part of the portal showing any kind of stone weathering. Parts of the arch are totally disintegrated, while others have developed extensive flaking.

Another example is a group of simple tombstones in the cemetery of Havstein church in the western suburbs of Trondheim. The tombstones were made at the turn of the century and some show distinct weathering phenomena related to exposure condition. Sides facing east and north are generally in good condition, whereas the south sides are characterised by connected pits (fig. 9.15). The west sides develop distinct flaking parallel to the foliation of the stones and the tops are usually covered by crustose lichens, which sometimes appear to protect the stone surface. Similar phenomena can be observed on elaborate tombstones at the cemetery of the Nidaros cathedral. Due to the fine carving, the tombstones have often lost pieces of varying size - usually connected with fissures along foliation planes or at exposed edges (fig. 9.16).

Fig. 9.14: *West portal of Stiklestad church. The portal was made of Bjørnå soapstone as part of a restoration programme in the 1920s. The upper side of the portal's arch is deeply weathered, whereas vertical surfaces remain sound (photo: PS 4/94).*

Fig. 9.15: *Tombstone made of Bjørnå soapstone at the turn of the century. Cemetery of Havstein church in Trondheim. The south side of the tombstone is deeply weathered (photo: PS 5/94).*

Fig. 9.16: *Elaborate tombstone made of Bjørnå soapstone, probably from the turn of the century. Cemetery of Nidaros cathedral. The exposed surfaces are deeply weathered and fissures have developed along the foliation planes. More than 10 different species of lichens as well as moss flourish on the tombstone (photo: PS 7/95).*

9.3 Gullfjellet soapstone quarry: worked 1930-50, 1970-74

In the 1930s, when the Bjørnå quarry could not provide stone for the west front sculptures, the Restoration Workshop had to turn to the Gullfjellet soapstone deposit close to Bergen. At Gullfjellet, a local company had started operations at the turn of the century, providing stone for local building and restoration purposes. In this way an odd stone came to the Nidaros cathedral. Odd, because it is very different from other Norwegian soapstones.

Topography, climate and geology

The quarry can be found at an altitude of about 300 m above sea level in the Gullfjellet mountain area, 20 km east of Bergen. Situated in an ophiolite complex with gabbro and serpentinite lenses,[13] the deposit is probably transformed from a pyroxenite parent rock. The stone is massive and contains numerous (25-35%) grey aggregates (diameter c. 5 mm) of microcrystalline talc - probably representing relicts of pyroxene minerals.[14] These talc aggregates give the stone a spotted appearance, especially since the matrix, consisting of biotite (15-25%), chlorite (15-25%), coarse talc, quartz (5-15%) and feldspar (1-10%), is rather dark. Traces of sulphide and oxide minerals are essentially confined to the interior of the talc aggregates. It should be noted that some parts of the quarry have more homogeneous stone, lacking talc aggregates.

Situated in a small valley without large trees, the quarry is about 100 m long. Due to the topography and the humid climate in the Bergen region (annual average precipitation more than 2000 mm) the deposit is overgrown with grass, moss and bushes (fig. 9.17).

Fig. 9.17: *Part of the Gullfjellet soapstone quarry close to Bergen. Manual channelling has been used to obtain raw blocks for several west front sculptures of the cathedral. Note the extensive growth of moss (photo: Tom Heldal 1993).*

A brief history of the quarry

Many west front sculptures have been carved in Gullfjellet stone, and it was a major stone for various restoration purposes between 1930 and the 1950s - and then again from 1970 until today. The quarry was closed in 1974, but until recently, the Restoration Workshop kept a stock of the stone at hand.[15] Although it is much harder to carve than other soapstones (due to the content of quartz and feldspar), several large reliefs could be made from the stone because of its homogeneous structure. The architects and masons also seem to have associated the hardness of the stone with durability. Therefore, they used the stone for many strongly exposed elements - in particular copings and gullies.

General weathering situation

Although involving different weathering forms, the general weathering situation at Gullfjellet is strikingly similar to the Bjørnå quarry. On exposed walls and abandoned blocks in the quarry, weathering takes the form of granular disintegration of the matrix, while talc aggregates usually stand out as relatively unaffected. Hence, the overall weathering form may be

Fig. 9.18: *Exposed rock face in the Gullfjellet quarry. The face contains rather homogenous soapstone which weathers intensively (granular disintegration) (photo: PS 7/95).*

Fig. 9.19: *Sill made of Gullfjellet soapstone in the Church of the Holy Cross in Bergen. The exposed part of the sill shows pitting as the main weather-ing form, while the sheltered part is unaffected. Picture taken during a shower (photo: PS 7/95).*

described as pitting. No flaking and delamination can be observed, features attributable to the lack of foliation. In parts of the quarry lacking talc aggregates, the stone weathers more evenly (granular disintegration, fig. 9.18). In other parts, it can be observed that moss and lichens apparently play a great role in the weathering. When moss and crustose lichens occur side by side, the surface underneath the moss is highly disintegrated, while lichens seem to "keep the surface together".

Due to the wetness and severe exposure conditions - and probably because of the properties of the rock - no gypsum crusts or salt efflorescences can be observed in the quarry. The general weathering rate in the quarry must be regarded as rather high - a feature which can be observed on rock faces with marks of drilling operations. Many marks have disappeared after less than 30 years of exposure.

Behaviour of Gullfjellet soapstone on monuments

The homogeneous structure of Gullfjellet stone prevents delamination and loss of exposed details. Keeping the safety problems of the foliated Bjørnå stone in mind, the architects of the Restoration Workshop made a good choice when they turned to Gullfjellet stone for weather beaten features, even though some surface weathering is to be expected.

Surface weathering similar to that observed in the quarry can be seen on copestones of the west front parapet. Otherwise, the stone has been used for elements which are so sheltered that practically no weathering has taken place after 20-60 years of exposure (west front sculptures and reliefs in the nave's portals).

Gullfjellet stone has also been used for several building and restoration projects in the Bergen region. One example is the replaced sills in the church of the Holy Cross in Bergen city centre. The sills, which are located below large windows in the main walls of the church, seem to have been put in place during a restoration campaign in the 1950s.[16] As expected, only exposed parts of the sills weather. Although less intense, the weathering forms are precisely the same as in the quarry - pitting as a result of granular disintegration of the matrix and talc aggregates which stand out relatively unaffected (fig. 9.19).

9.4 Bubakk soapstone and serpentinite quarry: worked from 1952

Bubakk is a classic, massive soapstone deposit originating from an ultramafic parent rock. It is a zoned deposit, in which soft soapstone surrounds a core of harder serpentinite. "The quality of the stone is among the best in Norway", said geologists after investigations in 1974.[17] Some years earlier it was also stated that the stone had remarkable durability and could be used for exposed architectural elements.[18] Today, only 20 years later, these statements must be regarded as rather optimistic, because once more we are faced with a stone that weathers strongly in the quarry.

Topography, climate and geology

Situated by Kvikne, about 120 km south of Trondheim, Bubakk is nearly 1000 m above sea level in the Central Norwegian mountain area (fig. 9.20). This is an area which receives relatively little annual precipitation (normally less than 500 mm) and where long, cold winters prevail. Warm, and even hot, summer days are, however, not unusual, but frost may also occur in the warm season. Except for a few lichens growing on the surface, the deposit, standing as a small knoll, is completely barren, and consequently severely exposed to precipitation.

Fig. 9.20: *The Bubakk serpentinite and soapstone deposit, looking north. The deposit is located in a barren mountain area c. 120 km south of Trondheim and has extensive traces of pot production in the pre-Roman Iron Age. The height of the knoll is c. 6 m (photo: PS 1990).*

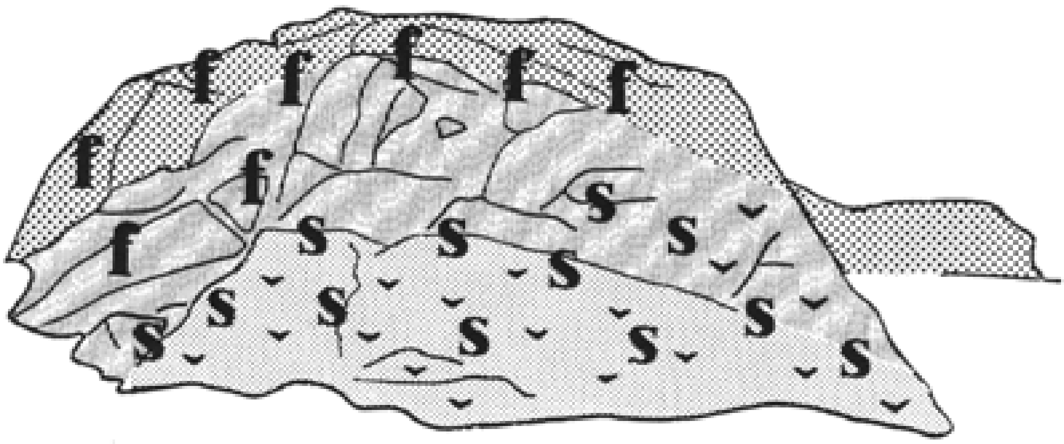


Fig. 9.21: *Weathering of the Bubakk deposit. Coarse dots = serpentinite; vertical lines = transition zone between serpentinite and soapstone; fine dots = soapstone; v = traces of pot production; f = strong multiple flaking of the surface; s = pitting and flaking.*

Bubakk has delivered three different stone qualities to the cathedral. The most common stone is a massive, hard and fine-grained, blue serpentinite found in the deposits' core, which can be seen on top and in the north-western parts of the knoll (fig. 9.20-21). Flaky serpentine (40-50%), which is embedded in a matrix of microcrystalline talc, chlorite, fibrous serpentine and small carbonate grains, dominates the massive rock. Very thin cross-cutting veins consisting of magnesite, fibrous talc and coarse-grained chlorite are also quite common.

Between the serpentinite and the soapstone, which form a spherical shell around the core,[19] there is a transition zone of serpentine-rich soapstone. What is called “real” soapstone is dusty grey and has a matrix of fine grained chlorite and larger flakes of chlorite set in a connected network of microcrystalline talc (25-40%). Carbonates, in the form of magnesite and dolomite (25-45%), occur as separated, small grains and a few thin veins. Oxides and sulphides are common in all Bubakk varieties. Normally the total content lays between 2-5%, with magnetite, ilmenite, pyrite and pyrrhotite as main phases.

In the peripheral parts of the deposit, the otherwise massive soapstone is quite schistose, but this variety has not been quarried. It should be pointed out that even if quarried raw blocks are massive, the deposit is intersected by numerous cracks, joints and large veins consisting either of talc and chlorite or carbonate minerals.

A brief history of the quarry

The discovery of the Bubakk deposit in the late 1940s was fortuitous. This was at a time when the Bjørnå quarry could only deliver stone of inferior quality for the building of the west towers of the cathedral. Following geological investigations and removal of overburden, Bubakk went into operation in 1952 and supplied the three stone qualities until the west towers were finished in 1969. Then quarrying was temporarily prohibited by the cultural heritage authorities.[20]

The reason why quarrying was banned is fascinating. When overburden was removed in 1963, remnants of earlier soapstone pot production were discovered in the lower parts of the deposit. Pot production from soapstone is nothing new in Norway and there are many production marks in numerous soapstone deposits dating back to the Viking era and the Middle Ages.[21] However, C-14 dating of wooden tools excavated in the Bubakk quarry showed that the deposit had a history back to the pre-Roman Iron Age (0-500 BC). Moreover, the number of pots produced was more than 5000 - a number indicating the “industrial” dimension of the enterprise.[22]

Fig. 9.22: *Weathering of Bubakk serpentinite. Multiple flaking is widespread (photo: PS 1990).*

Fig. 9.23: *Weathering of serpentine-rich soapstone at Bubakk. Along joints with carbonate veins and loosely bound talc and chlorite the weathering is severe (photo: PS 1990).*

Subsequent to the findings, parts of the quarry were covered with earth in order to preserve the remnants. However, a few dozen holes, from where pots had been quarried, as well as some abandoned, half-finished pots not loosened from the rock, were left exposed to the elements. According to observations made by craftsmen involved in the work, the exposed remnants had very distinct marks of picks and chisels in the 1960s. As is shown below, these marks have disappeared after 30 years of exposure.

Due to the difficult stone supply situation in the middle of the 1970s, the cultural heritage authorities granted exemption from preservation rules, allowing limited quarrying in the northern part of the deposit. Since then minor quarrying operations have taken place roughly every second year.

General weathering situation

The rapid weathering in the quarry takes one main form, namely extensive, multiple flaking parallel to the stone surfaces, but other forms also exist (fig. 9.21).

Weathering is most pronounced on top of the small knoll where serpentinite can be found. This is the most severely exposed area of the deposit, and the part which has been exposed for the longest period of time (thousands of years?). The surface on the top is heavily disintegrated, full of serpentinite flakes and sand (fig. 9.22). Moreover, multiple flaking and exfoliation tend to occur along joints filled with loosely bound chlorite and talc. Such joints also tend to have carbonate veins (fig. 9.23).

Similar weathering phenomena can be found all over the flat, exposed parts of the deposit. However, the intensity of the flaking is not so pronounced lower down, and pitting is a more widespread phenomenon on the soapstone from which pots have been produced. As mentioned earlier, the latter areas were uncovered only 30-40 years ago (fig. 9.24).

It is reasonable to suggest that frost is the main cause of weathering in the quarry. The role of soluble salts at a few sheltered sites should also be considered. This is because both efflorescences and crusts of gypsum and epsomite have been found in the spring at these sites. However, observations indicate that the salts occur as a mere layer on top of already extremely disintegrated serpentinite.

The presence of salts is better observed at a large dump, located in a marsh close to the quarry, where earthy material and abandoned blocks from quarrying and excavation operations remain. During dry periods in spring and summer a whitish crust of gypsum and

Fig. 9.24: *Soapstone in the lower, south part of the Bubakk deposit. On traces of earlier pot production, marks of picks and chisels could be seen when the area was uncovered in the 1960s. Today these marks have completely disappeared (photo: PS 1990).*

Fig. 9.25: *Exposed surface in the peripheral part of the Bubakk deposit. Note the quality differences of the stone and that some areas weather more rapidly than others (photo: PS 7/95).*

Fig. 9.26: *Crusts of gypsum and epsomite covering the surface of a dump close to the Bubakk quarry (photo: PS 7/95).*

epsomite cover large parts of this dump (fig. 9.26). Such crusts - in Norwegian called "Hakkemette" - are common in arid regions of the country.[23]

Behaviour of Bubakk stone on the cathedral

Due to the fact that the Bubakk stones lack preferential mineral orientation (foliation), they were formerly thought of as not being prone to delamination which could cause loss of carved details (cf. Bjørnå soapstone). This assumption may indeed be valid, but a couple of strongly exposed details made by Bubakk soapstone have nevertheless fallen from elevated areas of the cathedral quite recently (spring 1996). It is possible that fissures developed along initial planes of weakness (thin talc veins) in the stone, but it is also possible that quarrying (drilling and blasting with gunpowder) may have caused micro-fissures to form. Both phenomena are serious and call for a thorough investigation of all projecting details made from the stone.

Fig. 9.27: *Moulding of Bubakk soapstone and serpentinite in the base of the southern side of the choir (Nidaros cathedral). The moulding was put in place 10-15 years ago, and it can be seen that the soapstone weathers rapidly, while the serpentinite remains sound (photo: PS 8/95).*

Otherwise, the intense surface weathering observed in the quarry can also be found on projecting, exposed elements at the cathedral. Despite the short time of exposure, only 5-30 years when regarding weather beaten elements, some Bubakk stones have already weathered so badly that much carved detail has virtually disappeared.

However, the diverse Bubakk varieties weather quite differently and at very different rates. The “real” soapstone seems to be the most vulnerable one - as indicated by replaced stones in bases and string courses of the choir. Put in place 10-15 years ago, these stones show extensive pitting and granular disintegration. Hard serpentinite used just beside the soapstones is on the other hand still sound (fig. 9.27).

Fig. 9.28: *Sculpture and copestone made of serpentine-rich soapstone from Bubakk. Northern west tower of the cathedral, finished in 1964. Note the pronounced flaking on the back of the sculpture as well as on the copestone (photo: PS 5/96).*

The transition variety (serpentine-rich soapstone) is difficult to locate by visual means alone, but it appears that it was used for copestones and sculptures in the parapets of the west towers which were finished in 1964 (N) and 1969 (S). Situated at weather beaten locations about 40 m above the ground, several stones have developed multiple flaking - often associated with growth of crustose lichens (fig. 9.28). It should be noted that the weathering is most pronounced on elements facing south and west and that it takes place preferentially where snow can remain for prolonged periods of time. These observations indicate that rapid temperature changes are very important for the weathering and that frost plays a vital role.

When used as ashlars all Bubakk varieties tend to remain sound. However, in extremely exposed locations, the soapstone, but not the serpentinite, may develop minor flaking and granular disintegration. It also appears that the soapstone is less durable when exposed to moisture and salts in sheltered positions. Under such circumstances the serpentinite remains sound.

9.5 A brief note on Grunnes soapstone: used 1961-1969

There is one particular reason for describing the behaviour of Grunnes soapstone: it appears to weather extremely rapidly under the influence of alkaline salts.[24]

The quarry is situated in the county of Troms in the northern part of Norway and was operated mainly for the building of the upper part of the west towers of the cathedral between 1961 and 1967.[25] Due to a high talc content, Grunnes soapstone is one of the softest stone types ever used in Nidaros cathedral. Masons regard it as extremely soft and easy to carve - many think it is even too soft. The stone is massive and has a dense, grey matrix of intimately intergrown talc (30-40%), chlorite (25-35%) and a little dolomite and magnesite - a matrix which is “disturbed” by larger needles of tremolite (5-10%) and visible aggregates of dolomite (10-15%). Sulphides (pyrrhotite) and oxides amount to 2-5%.[26] When strongly exposed, the dolomite aggregates usually turn brown due to oxidation phenomena. However, when the stone weathers in the presence of salts, the dolomite aggregates tend to be left unaffected and stand out as dark “islands” in a completely disintegrated matrix.

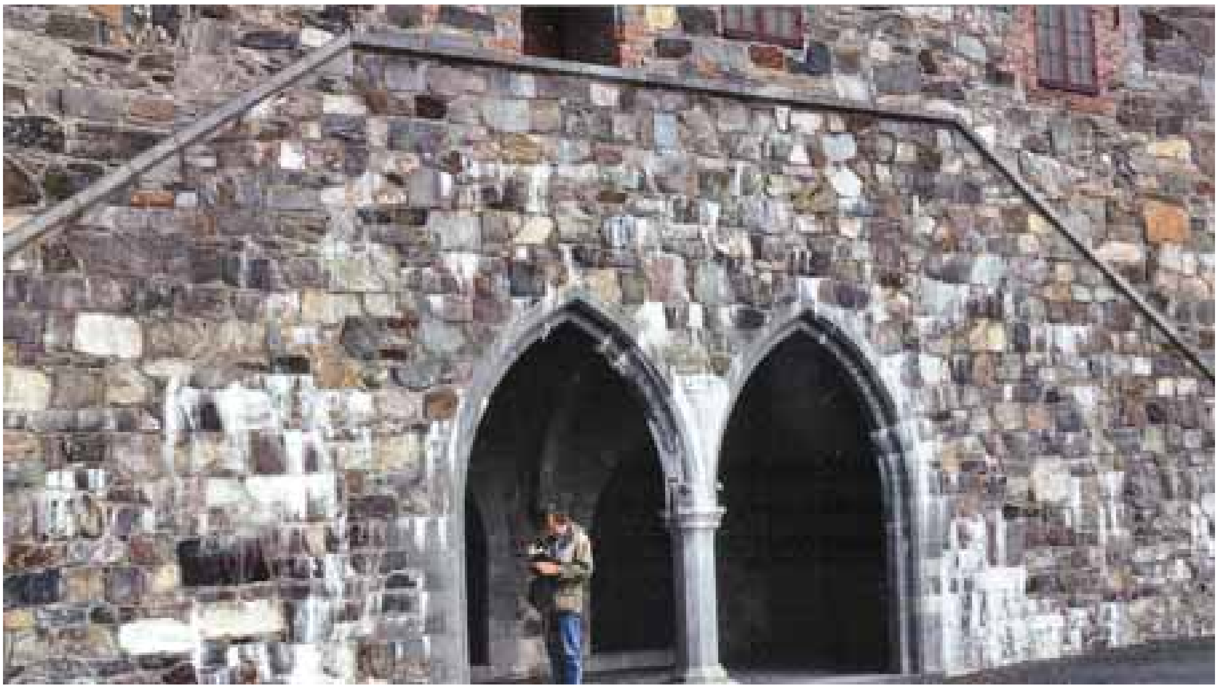


Fig. 9.29: *Double porch and staircase in the Archbishop's palace in Trondheim. The construction was made of reinforced concrete with stone facings in the early 1970s. Grunnes soapstone was used for copestones as well as in the double porch. Leaks have led to the formation of large calcite crusts and alkaline salt efflorescences (photo: PS 1994).*

Fig. 9.30: *Double porch in the Archbishop's palace. Grunnes soapstone flakes due to the presence of alkaline salts (photo: PS 1995).*

Fig. 9.31: *Exposed Grunnes soapstone on the double porch and staircase in the Archbishop's palace is sound (photo: PS 1995).*

A good place to study the behaviour of the stone is in the south-facing double porch and staircase of the Archbishop's Palace close to the cathedral (fig. 9.29). The porch was built during the restoration of the Palace between 1962 and 1975.[27] Built without regard to traditional craft, it was raised as a reinforced concrete construction faced by hard stone. Grunnes soapstone was used for copestones on the banisters as well as for mouldings in the porch itself. Today, less than 30 years later, the porch is in a dreadful condition because of water leaks, large calcite crusts and alkaline salts affecting plaster and stone.[28]

Even though the porch is quite exposed, alkaline salts like trona may nevertheless accumulate on several mouldings and cause distinct flaking of surfaces (fig. 9.30). Given the short time of exposure, the flaking has not yet developed into a real problem, but compared to the west towers of the cathedral (built as reinforced concrete constructions in the 1960s) it is possible that the original surfaces will disappear soon. However, it is entirely possible that this weathering will cease as most of the alkaline components in the concrete seem to have already leached out. Supporting this interpretation is the fact that the weathering has not significantly increased over the last seven years. In the west towers where sources of alkaline salts are almost inexhaustible, several elements made of Grunnes soapstone still weather rapidly (see chapter 14).

Grunnes stone is remarkably sound in weather beaten locations (fig. 9.31), but due to the softness, the stone tends to lose carved edges etc. This can be observed on copestones of the staircase in the Archbishop's palace as well as on the west towers of the cathedral.

Among the new stone types introduced during the restoration of the cathedral (excluding Bubakk serpentinite), Grunnes soapstone is in fact the only one lacking pronounced surface weathering when strongly exposed. Bubakk, Gullfjellet and Bjørnå soapstones develop flaking, pitting and granular disintegration of the surface - a peculiar contrast to the behaviour of the medieval soapstones. The most problematic weathering phenomenon is undoubtedly the loss of projecting details made of foliated Bjørnå stone. Grytdal stone is distinct because of the large amount of pyrrhotite leading to severe dissolution, oxidation and salt weathering.

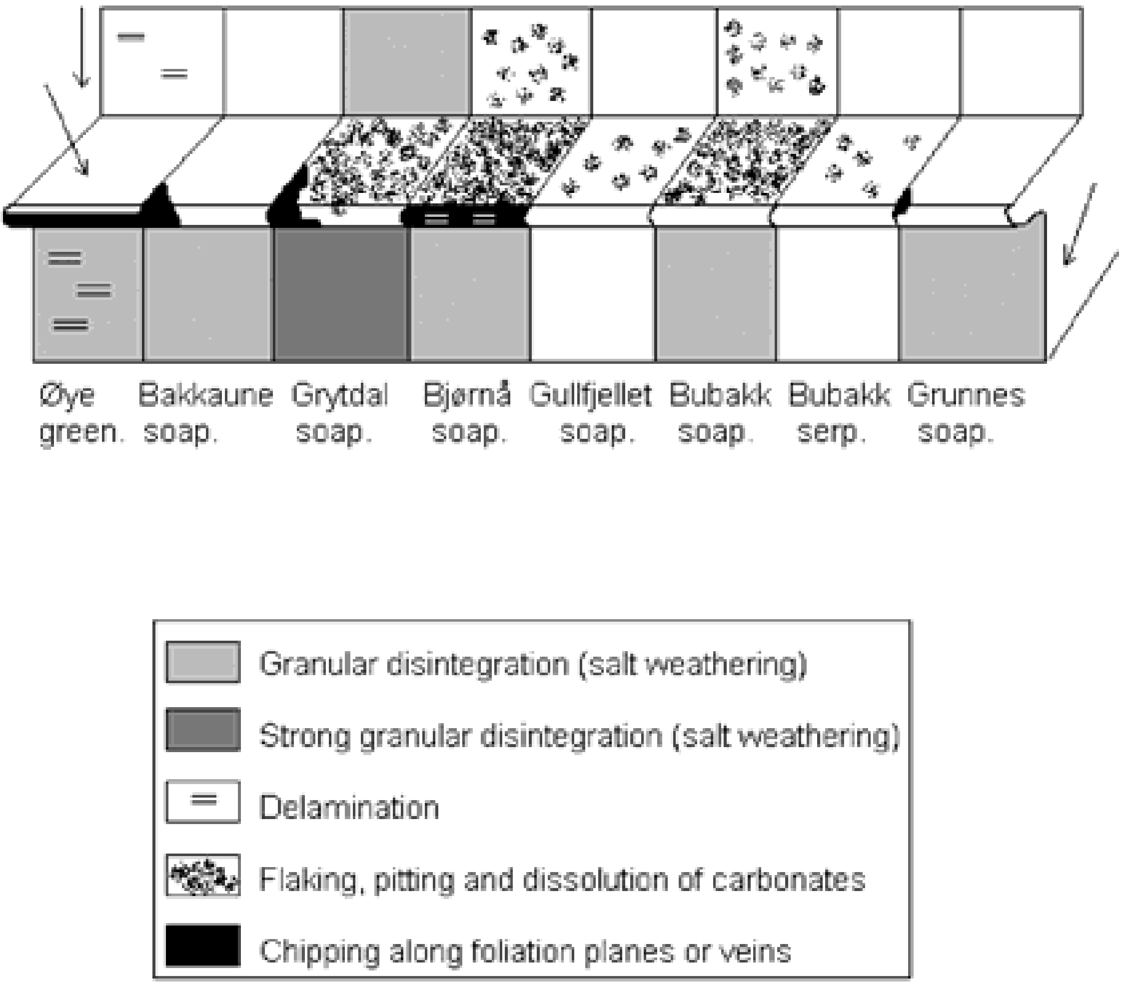


Fig. 10.1: *Typical weathering phenomena of investigated stone types, as exemplified by the behaviour under four different exposure conditions: 1) Exposed, vertical masonry; 2) exposed, horizontal surfaces; 3) exposed mouldings; 4) sheltered masonry influenced by soluble salts (moisture from "within" the masonry).* ***Fehler! Textmarke nicht definiert.***

Chapter 10

Typical stone weathering phenomena, analyses and experiments

The study of stone weathering phenomena described in the preceding chapters has shown that there are large differences between each stone type and even within the same quarry. The weathering phenomena are strongly dependent on geology, petrography, topography and exposure conditions - i.e. the actual situation at a special place. Nevertheless, it seems to be possible to define typical weathering phenomena characterising each stone type. Therefore, it is tempting to try and relate the typical weathering phenomena to the properties of the respective stones in order to reveal aspects of the mechanisms which rapidly turn some of the stones to powder, while others remain sound through centuries. Before the presentation of analyses and experiments related to stone properties, a brief summary of the observed weathering phenomena will be given.

10.1 Summary of observed stone weathering phenomena

First a summary of phenomena related to soluble salts will be given before turning to the behaviour of the stone types under severe exposure conditions (see also fig. 10.1). A summary of the petrography of the stone types can be found in tab. 10.1 and 10.2, while identified soluble salts are summarised in tab. 10.3.

Salts in quarries and stone affected by salts

Sheltered and partly exposed rock faces in the Øye, Grytdal and Bakkaune quarries weather under the influence of soluble salts. In the Øye greenschist quarry, delamination and granular disintegration are usually associated with the presence of gypsum (often in combination with oxalates) and minor amounts of thenardite. The limited flaking and granular disintegration in the Bakkaune soapstone quarry are also followed by gypsum, while totally disintegrated, pyrrhotite-infected soapstone in Grytdal can be found together with large amounts of gypsum and some epsomite. It is not possible to rule out that in addition to the actions of soluble salts, many other weathering agents play important roles - especially frost and biological agents.

The more soluble salt species, thenardite and epsomite, can be found as efflorescences in the Øye and Grytdal quarries, respectively, but only during dry winter and spring periods. In different forms, gypsum can be found year-round in all the quarries. These observations indicate that it is important to investigate quarries in the cold season when the objective is to determine the crystallisation behaviour of salts.

Tab. 10.1: *Summary of macroscopic properties of investigated stone types.*

Stone	Colour after exposure	Structure of matrix	Distribution of carbonates	Probable parent rock/origin
Øye greenschist	Green to green-grey, a few brown carbonate veins	Very foliated	A few intersecting veins, and scattered grains	Basic tuff or basalt
Bakkaune/Klungen (Old) soapstone	Bluish to green-grey, brown carbonates	Massive to slightly foliated*	Intersecting veins and round aggregates	Ultramafite
Grytdal soapstone	Grey to green and brown. Yellow when weathered	Massive to very foliated. Glassy tremolite needles*	Scattered grains, some intersecting veins	Associated with amphibolite
Bjørnå soapstone	Greenish, speckled with white (talc), brown (carbonates) and dark (biotite) grains	Massive to very foliated, some large pyrite grains	Many scattered grains and a few thin veins	Ultramafite
Gullfjellet soapstone	Grey talc aggregates, dark matrix	Massive, porphyr-like	No carbonates	Pyroxenite
Bubakk soapstone	Dusty grey, a few brown spots	Massive*	Many scattered grains, very few thin veins	Ultramafite, serpentinite
Bubakk serpentinite	Bluish, many brown carbonate aggregates	Massive	Small aggregates and a few thin veins	Ultramafite
Grunnes soapstone	Dusty grey, many brown carbonate aggregates	Massive	Many round aggregates	Ultramafite

* The stone is easily scratched with the finger nail

Tab. 10.2: *Mineral composition of investigated stone types. Mineral composition (vol. %) determined by microscopy and XRD. Partly author's own analyses, partly after Alnæs (1995).*

Mineral	Øye green-schist	Old soap-stone	Grytdal soap-stone	Bjørnå soap-stone	Gullfjell. soap-stone	Bubakk soap-stone	Bubakk serpenti nite	Grunnes soap-stone
Talc	0-10	20-30	5-20	10-15	25-35	25-40	5-20	30-40
Chlorite	30-40	30-40	20-60	30-40	15-25	25-40	20-30	25-35
Biotite	10-20		T	20-30	15-25		5	T
Serpentine							40-55	
Hornblende	15-25	10-15	5-10					
Tremolite			5-35	2-5				5-10
Other amphiboles etc. (1)	T	T		2-5	5-15	T	T	2-5
Dolomite	10-15	10-20	10-20	10-15		5-15	5-10	10-15
Calcite	1-5	T	5-10	1-15				
Magnesite		1-5				15-30	5-10	5-10
Quartz	5-15		1-5		5-15			
Plagioclase	5-10				1-5			
Microcline					1-5			
Pyrrhotite			1-10		T	T	T	(T)
Pentlandite			1-5			T	T	
Pyrite	2	2	T	T	T	T	T	
Chalcopyrite		1-5	T	T	T	T		
Magnetite		5		2	T		T	(T)
Hematite		2		1		T	T	
Other (2)	3		T		T			

(1) The minerals are: Bakkaune - possibly cummingtonite; Øye - magnesio-hornblende; Bjørnå - klinozoisite; Gullfjellet - actinolite; Bubakk - magnesio-hornblende; Grunnes - pargasite
(2) The minerals are: Øye - titanite; Grytdal - titanite; Gullfjellet - apatite
T Minor or trace amounts

Limited amounts of gypsum and epsomite are also present in the Bubakk quarry (and in major amounts in the dump close by), but the salts do not seem to be a major cause of the intense weathering of the rock. This must be ascribed to the fact that the whole quarry is completely exposed to precipitation. Salts have not been found in the Bjørnå and Gullfjellet quarries.

Tab. 10.3: *Identified soluble salts and secondary minerals in investigated quarries. Approximately 70 samples analysed by microscopy, microchemistry and/or XRD.*

Salt species	Øye	Klungen	Huseby	Bakkaune	Grytdal	Bjørnå	Gullfjellet	Bubakk
Oxalates	XX	X	X	X	X	-	-	-
Gypsum	XXX	X	X	XX	XXX	/	/	X
Epsomite	-	/	/	/	XX	/	/	X
Thenardite	X	/	/	/	/	/	/	/
Jarosite	/	/	/	/	XX	/	/	/
Fe-hydroxides	/	/	/	X	XXX	/	/	X

Abundance: XXX = very abundant; XX = quite abundant; X = rare; - = not identified by analyses; / = not observed
Oxalates: weddelite and whewellite

Except from Bubakk serpentinite, which seem to be relatively unaffected by salts, and Gullfjellet soapstone, of which we have no examples, all the stones weather in the presence of alkaline salts from Portland cement in monuments. Grunnes soapstone is very vulnerable, but otherwise the weathering forms and rates are completely dependent on the actual weathering situation at hand.

It is evident that salts naturally present (or produced) in Grytdal stone also affect the stone when it is used at the cathedral. Concerning other stone types (Øye, Bakkaune and Bubakk) it is not straightforward to state anything certain about the relative importance of “quarry salts” vs. salts from other sources.

Sources of salts in the quarries

The sources of salts in the quarries are quite obvious. Most stone types contain sulphides (in particular pyrrhotite and pyrite) and carbonates (dolomite +/- calcite +/- magnesite) which are subject to oxidation and dissolution processes in the absence or presence of microbiological agents.[1] At Øye sodium may stem from leaching of feldspars (albite).[2] Oxalic acid needed to form oxalates may be derived from lichens or other types of biological growth (see below).

It should be pointed out that overall climatic and topographic conditions may play a great role in the formation of salts. To take one example, the Øye quarry is situated on a humid valley slope where salt laden surface water and ground water percolate, and naturally come to the surface along cliffs where former quarrying has taken place. A second example is the large amount of sulphate found in the dump close to the Bubakk quarry. The sulphate may be derived from sulphides in the soapstone gravel, but also from surface and ground water because the dump is located in a marsh acting like a “sponge”.

It is very important to note that relatively soluble carbonates (alkali and magnesium carbonates) have not been found in the quarries. One reason is that the stones in question contain too little alkalis and too much sulphate. Alkali carbonates are not stable in the presence of sulphates.[3] The reason why magnesium carbonates are absent is, however, somewhat peculiar, especially because nesquehonite, lansfordite and hydromagnesite have been found in other serpentinite (and soapstone) deposits in Norway.[4] It is at least possible to conclude that the source of alkali carbonates in the Trondheim region is Portland cement or other alkaline building materials.

Behaviour of the stone types under severe exposure conditions

Relevant rock faces strongly exposed to precipitation (rain, snow, ice - and thereby frost) in the Øye, Klungen, Huseby and Bakkaune quarries are generally sound, but often overgrown by lichen and moss. Limited delamination and exfoliation can be found on relevant rock faces in the Øye quarry, while dissolution of carbonate veins and associated chipping are the most common phenomena at Bakkaune. Exposed rock faces in Grytdal show diverse behaviour - some faces are sound, while others are subject to complete disintegration.

On monuments similar phenomena can be found: When excluding Grytdal, the stone types are generally sound, except that they sometimes lose edges and other vulnerable parts - usually along carbonate and/or talc veins. Due to the strong foliation, Øye greenschist tends to lose carved details on the underside of exposed elements, as well as the outermost layers of face-bedded ashlars.

Stone from the Bjørnå, Gullfjellet and Bubakk quarries behave very differently under severe exposure conditions. They all suffer some surface disintegration ranging from multiple flaking, via development of tiny flakes and granular disintegration, to pitting and dissolution of carbonate aggregates and veins. Similar phenomena have been observed on monuments. Being sometimes highly foliated, Bjørnå seems to be the most vulnerable stone when heavily exposed. It often loses carved details and mouldings due to fissures forming along foliation planes. It should be noted that there are large quality differences in the Bjørnå and Bubakk quarries. In the latter quarry this is because soapstone, serpentine-rich soapstone and serpentinite occur side by side.

When compared to Bakkaune and Klungen soapstone (and Grunnes), the soapstone from Bjørnå, Gullfjellet and Bubakk have quite different petrographical textures. The former group of stones are characterised by a homogeneous matrix of talc, chlorite and amphibole, and they have large cross-cutting veins and major aggregates of carbonate minerals. In the latter group, carbonates tend to form part of the stone matrix, as evenly distributed, scattered, small grains. It may be possible to explain the surface crumbling of these stones as a result of dissolution of carbonates. Dissolution may possibly undermine the texture of the surface, leaving the stones more open to the influence of additional weathering agents (frost, biological agents etc.).[5]

Some questions about the role of lichens

In addition to salt weathering (sheltered locations) and thermal/hygric and dissolution mechanisms (exposed locations), there are several other mechanisms to consider when trying to reveal the secrets of stone weathering. One group of mechanisms is connected with growth of lichens, which occur especially on exposed, slightly inclined rock faces in the Øye quarry and on exposed, horizontal elements made of Bjørnå and Bubakk stones. Another group of mechanisms deals with the formation of oxalates due to the presence of lichens.

It may be dangerous to firmly state that crustose lichens found in large amounts in the Øye quarry actually protect stone surfaces, but according to my observations this seems to be so.[6] However, it is probably wise to ask a vital question before making conclusions: Do the lichens protect, or is the stone simply durable when strongly exposed? Moreover, would the stone behave differently under similar exposure conditions, but with another type of vegetation, i.e. other lichens involved?

Similar questions may be posed about the Bjørnå and Bubakk stones. Both weather in the absence of lichens, but also in the presence of a wide range of species (crustose, placodioid, foliose) when exposure conditions otherwise are similar (severe). It has been observed that flakes of both stone types follow the movement of lichens when they shrink in dry weather. Moreover, it is evident that a combination of stone properties, geometry and external factors (moisture, vegetation, bird droppings etc.) govern the development of lichens on Bjørnå and Bubakk stone. When stone properties are concerned, it seems that these stone types have mineral compositions and initial weathering forms providing suitable substrata for the growth of lichens. However, whether the presence of lichens actually increase weathering rates remains debatable.

The formation of oxalates have long been known to be connected with reactions between calcareous materials and oxalic acid provided by a diverse range of lichens. Oxalic acid may also stem from several micro-organisms as well as some organic preservation products.[7] Hence, the occurrence of oxalates (weddelite and whewellite) in the Øye greenschist quarry may not necessarily be connected with lichens alone, but also with other organisms. Moreover, do oxalates actually play a significant part in weathering processes in sheltered parts of the quarry? The normal mode of occurrence of oxalates is as crystals together with leprose lichens and gypsum within delaminated greenschist. Could the oxalates execute some kind of crystallisation pressure when formed like this?

10.2 A weathering experiment

Due to the great difference in behaviour under severe exposure conditions, four stone types were chosen for an accelerated weathering experiment in a weathering chamber in order to determine their relative durability.[8]

Experimental method and stone samples

The chamber used was developed by the Norwegian Building Research Institute (Trondheim) and simulates natural exposure to a combination of sunshine, rain and frost according to the following cycle:[9]

- 1 h in sun light (lamps) by simultaneous heating (effect: 1900 W/m^2, max. T on dark materials: 75°C)
- 1 h in water spray (amount: 15 l/m^{2}h, T: 18°C)
- 1 h in freezer (T: -20°C)
- 1 h in room climate (T: 23°C, RH: 40%)

The samples are first heated in a “desert”, then they are subjected to a “tropical thunderstorm” before “polar” conditions take over. They finally return to what represents room climate - and then the cycle can be repeated for a desirable period of time. The chamber was used for testing sanded, square, vertically standing plates (200-400 cm^2•1,5-2,0 cm, 2-4 samples of each stone) of the following stones during approximately 8 months or c. 1450 cycles:

- ØY - Øye greenschist (without talc)
- OS - Old (medieval) soapstone with carbonate veins, slightly foliated (Bakkaune or Klungen stone)
- BJ - Bjørnå soapstone (foliated variety)
- BUtr - Bubakk transition stone (serpentine-rich soapstone)

These stone types were selected on the basis of their importance at the cathedral. Øye and Bakkaune/Klungen were the most widely used stones in the Middle Ages, while Bjørnå and Bubakk have been most important during the restoration. Grytdal stone - also widely used during the restoration - was omitted because it is so different to the others due to its high pyrrhotite content. The histories of the stone samples prior to the experiment were:

- The Øye sample had been left in The Restoration Workshop since the 1950s when a minor quarrying campaign took place in the western part of the deposit.
- Since it is difficult to distinguish between soapstone from Bakkaune and Klungen used in the cathedral, a sample of “old soapstone” resembling the medieval ashlars of the lower parts of the choir and nave was found in a pile of stone laying by the cathedral. The pile contains medieval blocks removed from the cathedral during the early phases of the resto-

ration. According to the masons of The Restoration Workshop, it is traditionally believed that the blocks originate from Klungen. The blocks in the pile have been exposed to the weather for a long period of time, but today most appear sound. In order to avoid inevitable fissures etc., samples were cut out from the interior of a block.

- The Bjørnå sample was, like the Øye stone, left in The Restoration Workshop from the 1950s
- The Bubakk sample was quarried a few years prior to the experiment (1993).

Results demonstrating in situ observations

After a few weeks, the Bjørnå and Bubakk samples developed slight surface roughening. Later, tiny flakes formed on the Bubakk sample, while minor pitting appeared on the Bjørnå stone. When the experiment was completed, extensive, multiple flaking had formed all over the exposed side on the Bubakk sample, while connected pits and granular disintegration were concentrated at the corners of the Bjørnå sample. Carbonate grains were slightly dissolved and had turned brown on both samples.

The Old soapstone behaved radically differently. While the matrix of the stone remained in excellent condition, the carbonate veins were slightly dissolved and had developed a strong, red-brown colour. Very little happened to the Øye greenschist. Some small biotite grains could be seen standing out on the surface, the carbonate grains had turned brown, but otherwise the stone was in a perfect condition.

Consequently, the tendencies observed in the quarries and on monuments coincided excellently with the weathering experiment.

10.3 Analyses of stone properties - weathering mechanisms

In order to explain the differences between the typical weathering forms observed, a range of stone property analyses were carried out. Brief comments on the experimental methods used as well as the stone types tested are presented below, before turning to the interpretation of the results.

Experimental methods, stone samples and results

The following properties, mostly related to the hygric behaviour of the stones, were tested:[10]

- Density
- Open porosity
- Water absorption
- Capillary water absorption coefficient
- Hygric dilatation
- Water-vapour diffusion resistance (dry-cup)
- Water-vapour diffusion resistance (wet-cup)
- Compressive strength (dry)
- Biaxial flexural strength (dry)

How to perform the tests and subsequently interpret the results (given in tab. 10.4) have been discussed by several authors, and their informative suggestions will not be repeated here.[11] However, it should be pointed out that due to large petrograpic and structural variations within each quarry, it is difficult to obtain representative samples. Therefore, the interpretations below should be regarded as trends. The interpretations may also suffer because of the lack of pore size distribution data. In this connection it should be noted that most of the pores in the actual ("fresh") stones appear as tiny intergranular (and occasionally intragranular) fissures in the matrix.[12]

In addition to samples of three stones used for the weathering chamber experiment (Øye, Old soapstone, Bjørnå, see chapter 10.2), some properties were also tested on samples of the following stones:

- (GY) Grytdal soapstone (rather massive)
- (GU) Gullfjellet soapstone (with large talc grains)
- (BUso) Bubakk soapstone (massive)
- (BUse) Bubakk serpentinite (massive)
- (GR) Grunnes soapstone (massive)

Tab. 10.4: *Physical properties of investigated stones. After Plewhe-Leisen (1995) and Alnæs (1995).*

Property	Øye green-schist	Old soap-stone	Grytdal soap-stone	Bjørnå soap-stone	Gullfj. soap-stone	Bubakk soap-stone	Bubakk serpen-tinite	Grunnes soap-stone
Density (g/cm^3)	2,90	2,62	2,78	2,95	3,06	3,01	3,34	3,03
Open porosity (%)	0,90	0,96	3,60	0,82	0,31	0,95	0,20	0,40
Water absorption (weigth %)	0,25	0,36	1,30	0,15 (0,5)	0,10	0,32	0,12	0,13
Cap. water abs. (kg/m^{2}h$^{1/2}$)	0,03-0,1	0,01-0,07	0,26	0,01-0,03	0,01	0,02	0,01	0,03
Hygric dilatation (mm/m)	100-500	400-2800	-	200-400	-	320	250	-
Diffusion resistance (dry)	650-1050	300-1100	-	600-1400	-	900	600	-
Diffusion resistance (wet)	120-150	150-300	-	250-450	-	250	350	-
Compressive strength (MPa)	-	-	56	53-63	56	38	122	-
Biaxial flexural strength (MPa)	12-26	5-12	-	10-25	-	10-21	27-40	20

Interpretation of strength properties

According to the scattered analyses performed (fig. 10.2), the dry compressive strength of "fresh" soapstone lays within the range of 40 to 65 MPa, which obviously is very low compared to stones like granite.[13] Bubakk soapstone is the softest stone, while Bjørnå - as expected - is stronger perpendicular to rather than parallel to its foliation. Bubakk serpentinite is - also as expected - far stronger than the soapstones (122 MPa).

The dry biaxial flexural strengths show an interesting pattern, insofar as the Old soapstone is the weakest (5-12 MPa). Otherwise, the analyses are very consistent (10-25 MPa), and the foliated stones (Øye, Bjørnå) show the largest differences because of orientation (stronger parallel to rather than perpendicular to foliation). The biaxial flexural strength is in general rather high compared to sandstone and marble (soapstones are "tough").[14]

From strength properties alone, we can conclude that it is unsurprising that the softest Old soapstones (Bakkaune/Klungen) tend to lose fragile, exposed chips, especially where carbonate and talc veins create natural planes of weakness. Moreover, the large difference in flexural strength as a result of the foliation of Øye and Bjørnå stone gives an idea of why these stones tend to lose pieces along the foliation.

The existence of notable flexural strength variation in massive Bubakk soapstone cannot be explained in a satisfactory way. Note, however, that exposed details of Bubakk soapstone have recently developed fissures and fallen from elevated parts of the cathedral (chapter 9.4). Perhaps the variation in flexural strength can be explained by microfissures?

Water and water-vapour transport behaviour

Except for Grytdal soapstone, which is unique, the open (water accessible) porosity, water absorption and capillary water uptake of the stones are generally very low, partly extremely low. There are, however, significant variations between the stone types.

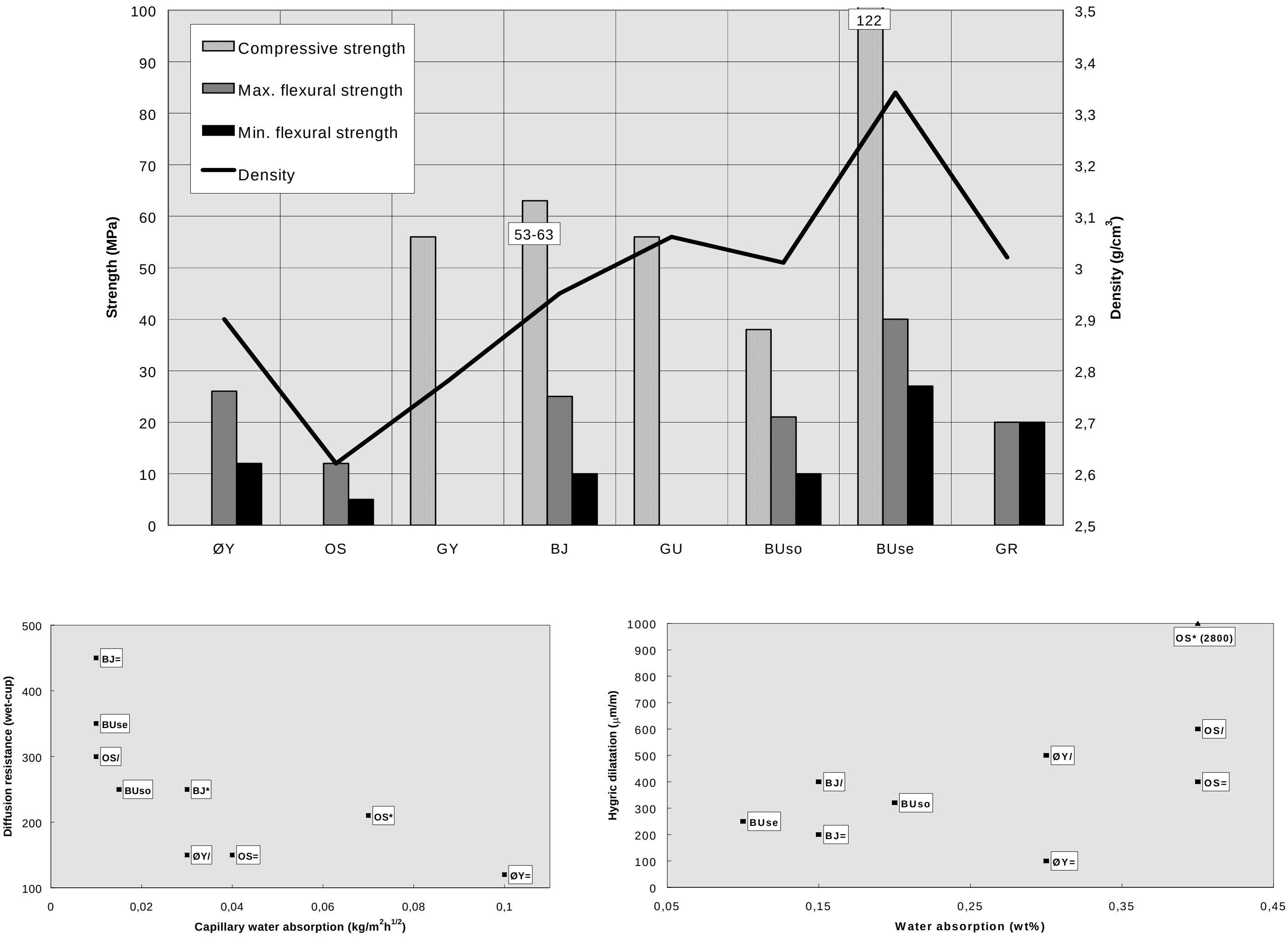


Fig. 10.2: *Relationship between various properties of investigated stone types. Top: Mechanical properties and density. Left: Watervapour diffusion resistance as a function of capillary water absorption. Right: Hygric dilatation as a function of water absorption. =: parallell to foliation, /: perpendicular to foliation, *: apparently without foliation.*

It is especially interesting to note that Øye greenschist and Old soapstone (and Grytdal soapstone) have higher water absorption and capillary water absorption than Bjørnå soapstone and Gullfjellet soapstone. As noted previously, the former stones suffer no or very limited flaking, pitting and/or granular disintegration when severely exposed, while the latter stones typically develop these weathering forms. A possible relationship between low water uptake and weathering forms cannot be properly explained without relevant pore size distribution data. Such data is also necessary for interpreting another important phenomenon, namely capillary condensation.

However, when looking at the water-vapour diffusion resistance, which may be regarded as a measure of how fast water evaporates from stone after wetting, it should be noted that Bjørnå soapstone shows the highest values (fig. 10.2). In short: when water in one way or another has entered pores of this stone, it may be more vulnerable to frost because water evaporates at a relatively slow rate. That moisture evaporates faster from Old soapstone than Bjørnå soapstone can be observed at the cathedral after showers. It should, however, be noted that hygroscopical salts in the masonry may disturb a pattern like the one shown in fig. 10.3.

Showing relatively high water absorption and low water-vapour diffusion resistance, the Old soapstone and Øye greenschist (and Grytdal soapstone) must be regarded as the most "porous" stones, and hence the most vulnerable ones to salt weathering (deeper wetting/drying cycles, dependent on orientation). Note that salts affect these stones - but also note that generally less porous Bjørnå and Grunnes soapstones may be deeply weathered under the influence of (alkaline) salts. Once again: weathering is dependent on site situation.

Fig. 10.3: *Drying out of masonry after a shower. Buttress of the northern west tower, Nidaros cathedral. The central Bjørnå soapstone (inserted c. 1900) remained moist much longer than surrounding Old (medieval) soapstone (photo: PS 1995).*

Hygric and thermal dilatation

It has previously been shown that some Brazilian soapstones generally show rather high hygric dilatation.[15] This feature can be attributed to the presence of talc and chlorite - minerals able to include some water in their structures and thereby swell and execute differential stresses within the stone. Chlorite and biotite are also able to form swelling clays as a result of chemical breakdown,[16] but this feature seems to be unimportant in the context of this thesis since no swelling clays have been observed in the stones (according to XRD-patterns of weathered samples).

However, could high hygric dilatation alone explain why some soapstones (Bjørnå, Bubakk, Gullfjellet) develop flaking and granular disintegration on severely exposed surfaces, while others do not? Considering the hygric dilatation of selected stones in relation to water absorption we have to conclude that it also seems to be unimportant (fig. 10.2). In fact: the generally very low dilatation values are completely dependent on water absorption, and the Old soapstone - which behaves "best" when severely exposed - shows by far the highest values (500-2800 µm/m). Moreover, and as expected, the hygric dilatation is higher perpendicular to rather than parallel to foliation (Øye and Bjørnå).

It should be noted, though, that with regard to stone exposed to heavy rain after sunshine, even low hygric dilatation values should be seen in relation to thermal dilatation. Thermal dilatation has not been tested in the present project, but according to average values of Norwegian and some values of Brazilian soapstones, the dilatation coefficient may lay in the range of $7\text{-}9 \cdot 10^{-6}\ K^{-1}$.[17] This seems low compared with hygric dilatation values, but it is surprisingly high compared to thermal dilatation of many other stone types (e.g. granite and larvikite).[18] Since rain will cool down the stone (thermal contraction) during simultaneous capillary water absorption (hygric expansion), high shear stresses are likely in the near surface zone.[19] This mechanism may partly explain why exposed architectural elements (e.g. copestones) of vulnerable stone types (e.g. Bjørnå and Bubakk) facing south weather at a higher rate than when facing other directions. However, frost is likely to be relatively more important on south facing elements because the number of freezing/thawing cycles are highest here. Generally, in the Trondheim climate frost is probably far more important than combinations of hygric and thermal dilatation.

An additional feature which should be considered is that hygric dilatation generally increases when soluble, hygroscopic salts are present. Another point concerns differential hygric and thermal behaviour as a function of mineral content. What exactly happens at the boundary between brittle minerals (for instance tremolite) and a soft matrix of talc and chlorite?

10.4 Weathering of stone - conclusions

The most important general conclusions with regard to the weathering of *stones* - and of relevance for the understanding of the weathering of the *cathedral* - are summarised as follows:

- Alkaline salts in in the Trondheim region are leached out of Portland cement mortars and concrete or originate from other alkaline building materials. No alkaline salts have been found in the quarries.
- Except for Bjørnå and Gullfjellet, there are large amounts of soluble salts in the quarries. Gypsum and epsomite can be found in Grytdal and Bubakk, gypsum and thenardite occur in Øye, while gypsum is the only salt species found in Bakkaune. Weddelite and whewellite are very common in some of the quarries, but not on monuments. Grytdal stone is special because of its large amount of pyrrhotite which upon oxidation not only gives sulphate salts but also minerals like iron hydroxides and jarosite which render the stone brown and yellow.
- Except for Bubakk serpentinite and Gullfjellet soapstone (of which we have no examples), all stones weather in the presence of salt crusts and salt efflorescences in completely, partly or periodically sheltered locations - both in quarries and on monuments. Weathering forms range from delamination (foliated stones) to granular disintegration and flaking.
- Stones from Bjørnå, Bubakk (soapstone and transition stone) and Gullfjellet may develop extensive flaking, granular disintegration and related weathering forms when strongly exposed to the weather. These phenomena occur in association with the presence and absence of crustose lichens. The stones are generally the less porous ones investigated, and it seems that their relatively high watervapour diffusion resistance can be related to the weathering. Also the dissolution of small carbonate grains in Bjørnå and Bubakk stones may affect the rapid weathering by “undermining” the surface structure. The schistose Bjørnå stone also loses fragile parts parallel to its foliation in such situations.
- Old soapstone (Bakkaune and/or Klungen), Øye greenschist and Grunnes soapstone are generally quite durable when strongly exposed to the elements. Some surface weathering

may occur, as well as chipping parallel to foliation planes (Øye). Bakkaune may lose pieces especially along extensive carbonate (and/or talc) veins. These stones are generally the more porous ones.
- All the investigated stone types may behave excellently when used in the right places on a monument. Some very pyrrhotite rich Grytdal varieties deviate from this general scheme.

The most problematic weathering phenomena *with regard to conservation* are:

- Loss of pieces due to fissures developing along foliation planes of projecting elements (Bjørnå, Grytdal, Øye).
- Loss of pieces due to fissures developing along carbonate (and/or talc) veins of projecting elements (Bakkaune and Klungen).
- Heavy crumbling of surfaces strongly exposed to precipitation (Bjørnå, Bubakk soap-stone/serpentine-rich soapstone, Grytdal).
- Severe salt weathering due to the presence of large amounts of pyrrhotite (Grytdal).

Part IV

Weathering of large sections of the cathedral

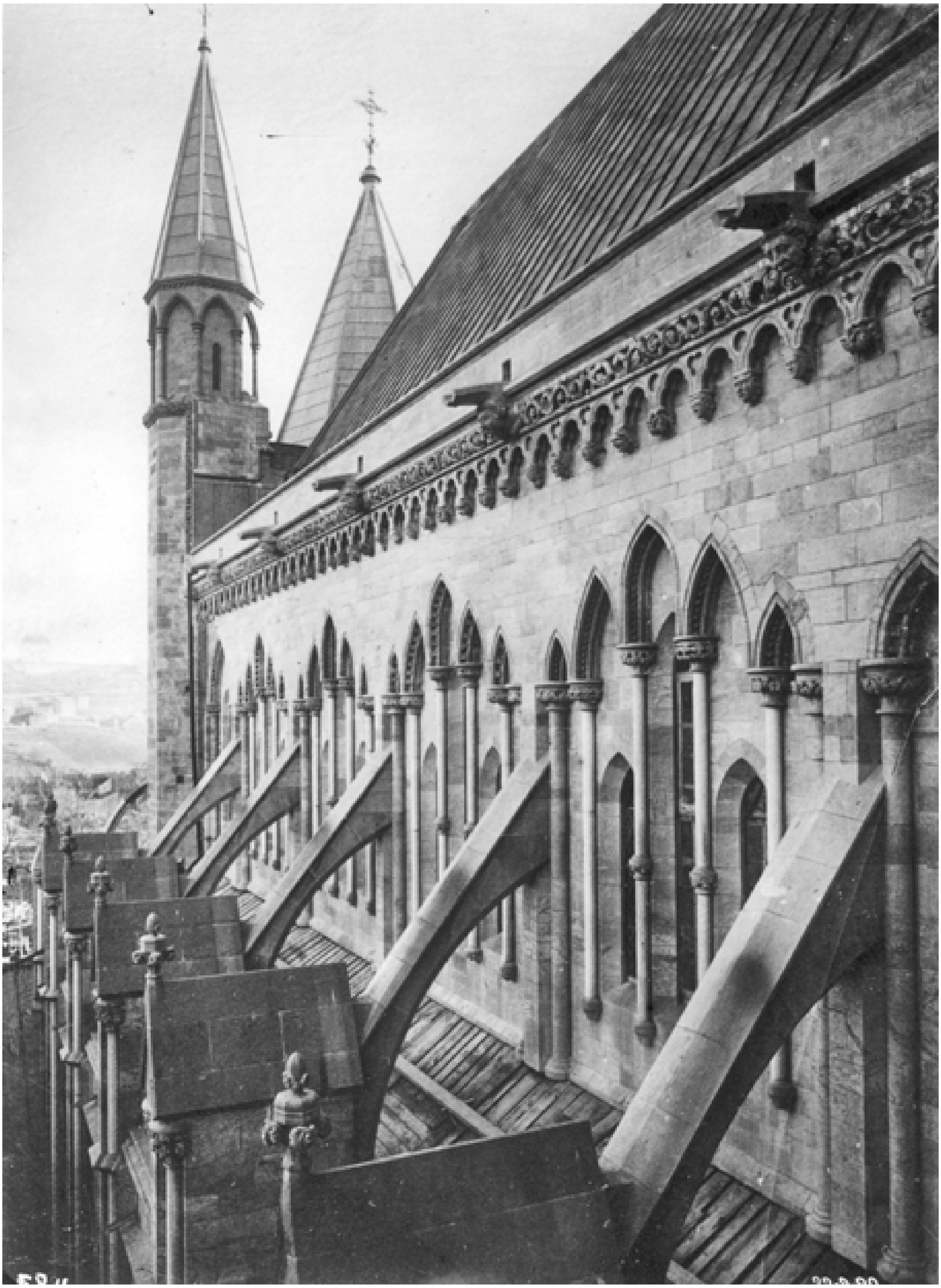


Fig. 11.1: *The north side of the choir just after it was finished in 1890. Note that the stone gullies discharge water directly onto the flying buttresses (photo: ARW, no. 584).*

Chapter 11

Weathering of the choir

The choir is the most problematic part of the cathedral, not only because of large-scale stability problems (chapter 5.3), but also because of rapid weathering. The weathering is most pronounced on the parts erected in the 1880s - the clerestory walls, triforia, gangways, parapets and buttress system. Mainly Grytdal and Rogstad soapstone were used during these rebuilding operations, but part of the clerestory was built as massive brick-walls with soapstone “facings” (chapter 5.2).

When referring to *gangway*, I mean the horizontal “path” on top of the wallheads, behind the parapets. Parapets are located on the heads of the clerestory walls (upper parapets) and aisle walls (lower parapets). The latter walls are medieval, although restored (chapter 4).

The following description starts with a general account of the water discharge system and the history of major water leaks. Then follows a systematic survey of the weathering problems (see also weathering map in appendix 3), starting with the buttress system, before turning to the upper parapets, the clerestory walls, the lower parapets and the aisle walls. A note on black crust formation below string courses is also included in order to show the difficulties in interpreting sources of gypsum at the cathedral.

The King's porch has been omitted from the description below. A note on its severe stability problems can be found in chapter 5.3.

11.1 Water discharge system

The choir appears to have an adequate water discharge system capable of removing rainwater and melting snow from the gangways. From the upper gangways there are five large stone gullies at each side in addition to downpipes at each corner. The lower gangways are provided with 12 copper gullies at each side and a few downpipes. However, when investigating the discharge system more carefully, several weaknesses can be detected (fig. 11.2).

Firstly, water from the upper stone gullies is directed onto flying buttresses which are not designed to receive water (fig. 11.1). They are not provided with water courses, only with copestones, which means that water penetrates virtually every joint - leading to severe weathering of the vertical parts of the buttresses. The flying buttresses are also affected by long icicles developing from the stone gullies in the winter. The downpipes are, moreover, underdimensioned and on the north side designed in an especially inappropriate way. The eastern downpipe in fact discharges water directly onto the masonry of the northern chapel of the octagon(!), which suffers severe salt weathering because of this peculiar design (see chapter 16.7).

__Fig. 11.2:__ An example of the inappropriate water discharge system of the choir: copper gully in the lower parapet on the north side (photo: PS 2/96).

Secondly, many copper gullies of the lower gangways are entirely inappropriate. They are too short and partially damaged, resulting in water running down the walls of the aisles rather than being removed from these surfaces (fig. 11.2). The result is severe weathering in the cornices just underneath.

11.2 Record of water leaks

The record of leaks penetrating the wallheads is long. This must be ascribed the structural instability of the choir (leading to cracks), insufficient covering of the gangways and insufficient inclination (water is not draining fast enough to the gullies). The upper gangways are still only covered with a mixture of cement and asphalt, while the lower has copper plates. Note that water leaks may also originate from joint fissures between copestones in the parapets as well as in the cornices.

The record of leaks and subsequent repairs in the period between 1920 and 1996 is shown in table 11.1.[1]

***Tab. 11.1:** Record of leaks in the choir*

1920-21	Leak in the north aisle. Repaired with cement.
28.06.28	Storm and rain. Leaks “everywhere” in the cathedral, also from the gangways of the choir.
08.07.32	Storm and rain. No leaks. Comment: leaks appear in the winter time.
04.03.38	Leaks between the south turret and the upper gangway have been going on for a long time. Later repaired with plates of lead.
05.03.43	Storm and rain. Catastrophic leaks, also from the gangways of the choir.
1943	Upper stone gullies (Grytdal stone) replaced (with Gullfjellet stone).
03.02.49	Storm and rain. Leaks, also from the gangways.
14.11.49	Leak in the north aisle.
1950	Covering of gangways with asphalt/cement mortars.
04.01.56	Leak in the north aisle.
23.5.58	Leak from downpipe (upper, southern gangway)
04.02.66	Very cold weather. Comment: leaks supposed to be caused by heat from the church which melts snow in the gangways.
23.02.66	As above
09.01.68	Leak in the north aisle.
1966-68	Installation of electrical heating cables in order to avoid ice formation in gangways and downpipes. Their use was terminated shortly afterwards because of increasing problems with ice formation.
1980s(?)	Covering of the lower gangways with copper. Since then no major leaks here.
1976-95	(No record of water leaks - but several have taken place. In this period calcium chloride, a de-icing salt, has been used in order to “avoid” ice formation)
Jan. 95	Catastrophic leak from the upper, southern gangway. Preliminary repair with asphalt glue.
Feb. 96	Leaks from the eastern part of the upper, northern gangway. Cold weather.

Taking the catastrophic leak in January 1995 as an example, it originated from a small fissure in the cement/asphalt covering of the gangway during thawing after a period of moderate snowfall. Water penetrated the masonry of the clerestory wall (6-7 m), appeared in the interior clerestory gangway as well as by the lower part of the vault and finally dripped all the way down to the floor flooding the area by the baptismal font. Several dozen litres of water collected before the fissure was found and could be repaired.

As the records show, leaks usually take place during the cold season. An important phenomenon is that the melting of snow in the gangways seems not only to be connected with natural thawing, but also with heat emanating from the church interior. This phenomenon is especially likely to happen in the lower gangways which are located close to the strongly heated triforia.

In addition to thawing events, leaks naturally take place during periods of heavy rain - especially in the autumn. Problems appear in particular when downpipes fill with leaves and diverse rubbish, making it clear that regular maintenance is of utmost importance on these sensitive parts of the cathedral. The same doctrine applies when regarding the removal of snow, which is a task of high priority for The Restoration Workshop.

Note that the installation of electrical cables (1966-68, see tab.11.1) in order to melt snow in the gangways proved unsuccessful. Since then calcium chloride has normally been used for the purpose of avoiding frost problems.[2] This measure is very dangerous because it potentially increases the already severe salt weathering problems (see below).

11.3 Buttress system

Due to the choir's structural instability and the fact that the flying buttresses are strongly affected by water and ice from the upper gangways, they have been of frequent concern since their construction in the late 1880s. Major opening of joints and formation of large calcite

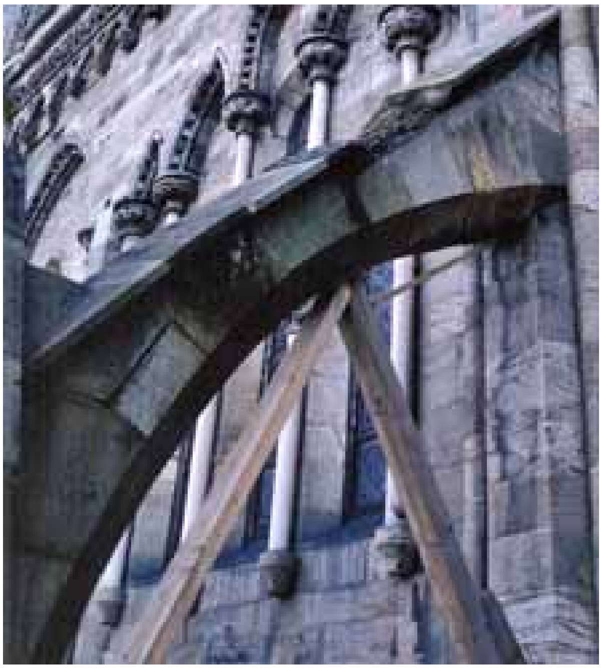


Fig: 11.3: *Flying buttress on the north side of the choir in 1990. The condition is severe! (photo: PS).*

Fig. 11.4: *The north side of the choir in February 1996. The flying buttress has been repaired (stone replacement), but the tower was not included in the programme. Open joints and large calcite crusts remain (photo: PS).*

crusts can be observed on photos taken just after the turn of the century, while rapidly weathering Grytdal stones used for copings were replaced by the 1920s.[3]

Except for a few minor repair programmes, little was done to the flying buttresses between 1920 and 1990 (cf. fig. 11.3). Since then most of the stone on the north side has been replaced (with Bubakk and Gullfjellet stone).[4] However, as nothing was done with the water discharge system - and as strong mixes of Portland cement mortars were used - “old” problems have returned: The joints are opening and resulting in formation of calcite crusts as well as alkaline salt efflorescences on the underside of the flying buttresses. The vertical parts of the buttresses were only partially repaired between 1990 and 1995, meaning that completely open joints and large calcite crusts are still major features (fig. 11.4). When a thorough restoration of the flying buttresses on the south side of the choir is undertaken, it will be necessary to improve the water discharge system simultaneously.

11.4 Upper parapets, cornices and corbel heads

The most apparent weathering phenomena at the upper parapets are those related to the corbel heads in the associated cornices. On the north and south sides there are friezes with about 100 corbel heads carved in Grytdal soapstone. At least 50 have disintegrated to such an extent that they are hardly recognisable (fig. 11.6).

Fig: 11.5: *The upper parapet of the south side of the choir in March 1996. The gangway is covered by cement/asphalt insufficient to withstand snow and ice formation (photo: PS).*

Fig. 11.6: *The problematic condition of corbel heads in the south cornice of the choir in the 1980s. The heads are carved in Grytdal soapstone of variable quality. Note the salt efflorescences on the masonry (photo: Torgeir Suul).*

Being strongly exposed to precipitation, and yet somewhat sheltered because of the complicated geometry, the corbels not only show the “normal”, intense Grytdal (salt) weathering - they are also covered with thick black and greyish (gypsum) crusts. The crusts are more widespread on the north side where they also frequently occur underneath the cornice as well as on plain masonry. A programme aimed at replacing the most damaged corbel heads is currently underway.

The parapets themselves are not in such a bad condition as one would have expected. However, joint fissures, cracking, chipping, bulging and large salt deposits in sheltered locations are major phenomena to be observed. It should be noted that stone of the southern parapet, but not the northern one, have been sliding relatively to one another (fig. 11.5). This phenomenon can be explained by more rapid temperature changes on the south side, although the large-scale stability problems may also play a significant role.

11.5 Clerestory walls

As mentioned previously, a catastrophic water leak originated from the upper parapet in January 1995 and penetrated the southern clerestory wall (second bay from east). The leak has, according to masons of The Restoration Workshop, been periodically active for at least 20 years, causing extreme salt weathering problems to the interior.

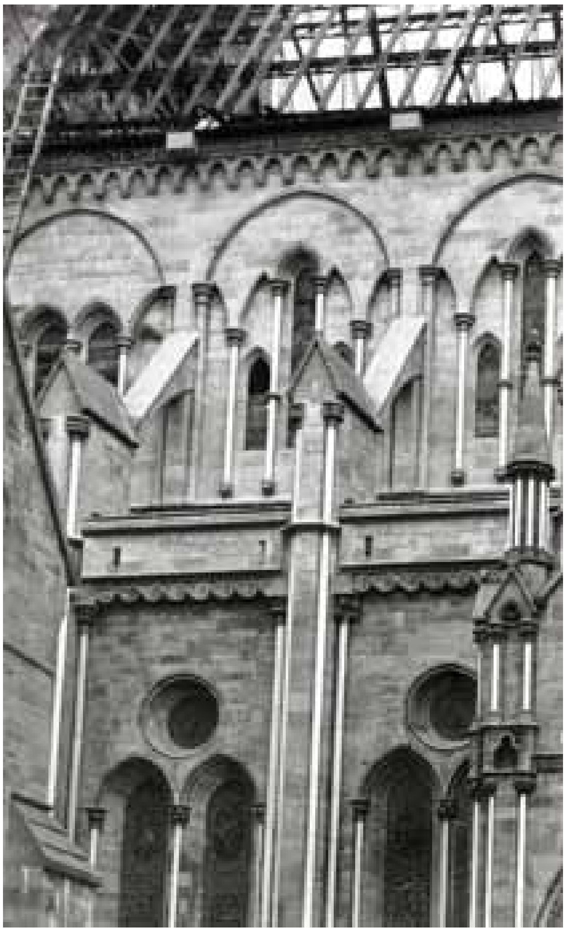


Fig. 11.7: *The south side of the choir during the erection of the roof in 1890 (photo: ARW, no. 531).*

Fig. 11.8: *The south side of the choir in March 1994. Note all the calcite crusts and salt efflorescences (photo: PS).*

Fig. 11.9: *Clerestory of the choir, south side. A leak, active for more than 20 years, has caused extreme salt weathering (photo: PS 3/95).*

Fig. 11.10: *Detail of figure 11.9 (photo: PS 3/95).*

After penetrating the 1,3 m thick, massive brick wall, leaching out lime and alkaline components from the lime-cement mortars, water with a pH of about 12 appeared in the gangway by the clerestory windows where ashlars, capitals and other decorations made of Grytdal soapstone were attacked (fig. 11.9-10).

Within almost completely disintegrated Grytdal stone, hexahydrite (dehydrated from epsomite) is the main salt phase to be found, while cauliflower-like crusts of both gypsum and epsomite/hexahydrite occur on surfaces. Smaller amounts of thenardite are also associated with the disintegrating stones. Beside the main waterways, in which calcite crusts have developed, efflorescences of sodium carbonates are widespread. The occurrence of thenardite within disintegrated Grytdal stone suggests that sodium carbonates from mortars have reacted with sulphate from the stone. However, sodium sulphates may also originate from the bricks in the massive walls. The small amounts of chloride to be found probably originate from deicing salts (calcium chloride - see chapter 11.2). In addition to ashlars and decorations, the leak has also affected the lowermost parts of the main vaults, causing the plaster and whitewash to flake off. Salt weathering can also be found on the plastered brick wall on the loft above the main vaults.

Although less severe, the weathering of other bays in the interior of the clerestory follows the same pattern - both on the north and south sides. A similar pattern can also be found on the *exterior* walls (fig. 11.7-8), especially on the south side. Here weathering is more intense than on the north side, probably due to more frequent and larger temperature changes, and numerous calcite crusts have formed. Indicating from where water leaks occur, the calcite crusts are always connected with joints and usually form as stalactites stuck to the wall. It should of course be noted that interstitial condensation may possibly give enough water to leach lime from the mortars and subsequently form calcite crusts. However, the crusts are so unequivocally occurring below known points of water infiltration, that leaks seem to be the main reason for their formation.

In dry weather periods, especially during spring, powdery salt efflorescences render the southern clerestory wall rather whitish. The efflorescences are connected with heavily disintegrating Grytdal soapstone, but they also occur as mere layers on sound stone - particularly on relatively sheltered masonry just below wall and window arches. In fact, only minor amounts of Grytdal stone are deeply weathered. Noting that a mixture of good and poor quality stone was quarried in Grytdal (chapter 9.1), it is easy to explain the differences. It should also be remembered that before c. 1915, less than 30 years after the clerestory's construction, several ashlars were so disintegrated that they had to be replaced.[5]

10.6 Lower parapets and cornices

The lower parapets show similar weathering phenomena as the upper. A major problem is intense crumbling of the remaining medieval parts of the ornamented frieze in the cornice. The frieze is made of greenschist and has, undoubtedly due to run-off from the inappropriate copper gullies directly above, lost large parts along foliation planes (fig. 11.11). Otherwise, the condition of the parapets is, especially on the north side, characterised by the most widespread development of black crusts on the whole cathedral.

Several repair campaigns have been undertaken at the parapets throughout this century.[6] Parts have been replaced by new stone, but many remaining copestones made of Grytdal stone have lost deeply carved mouldings.

Fig. 11.11: *Parapet and cornice on the south side of the choir. Note the poor condition of the frieze directly below the holes (for copper gullies and gutters)in the parapet (photo: PS 1996).*

10.7 Walls of the aisles

Until now discussion has centred on parts erected during the restoration. Regarding the walls of the aisles, it is important to note that the masonry is medieval (Early Gothic) and consequently has been subjected to nearly 800 years of the most diverse exposure conditions and restoration measures.

Considering historical circumstances and what is already known about water leaks from the parapets, the present condition of the walls is astonishingly good. The eastern part of the north side must, however, be regarded as problematic. This is probably because the wall is located above an earlier vaulted room in the narrow space between the wall and the chapter house.[7] During one or more fires, burning wood must have concentrated above the vaults, causing weakening and discoloration of the medieval stonework. What makes the situation look distressing today is the yellow, disintegrated Grytdal stone which replaced fire-damaged greenschist and soapstone during the restoration. Obviously, salts associated with leaks from the parapet and cornices contribute to the pronounced weathering of already fire-damaged stone (fig. 11.12).

Observing the vaults of the aisles, it is clear that water leaks and associated salt weathering have played very important roles. The leaks may not only have originated from the gangways, but also from holes in the former lead roofs of the aisles. These roofs were replaced by copper in 1966-82 (with breaks).[8] Calcite crusts and salt efflorescences on exterior masonry are found directly above and within window arches. The salts seem to cause moderate granular disintegration of the medieval stone.

Fig. 11.12: *Eastern part of the wall of the aisle on the north side of the choir. The area has been affected by fire, there are leaks, salts, black crusts and strongly weathering Grytdal stone as well as green algae - all giving the masonry a sad look (photo: PS 2/96).*

11.8 String courses and the formation of black crusts

The medieval string courses of the choir were replaced by Grytdal stone during the restoration in the 1880s. Most have been replaced once more during the last couple of decades - now by Bubakk soapstone, which unfortunately weathers rapidly (chapter 9.4). The exposed parts of the string courses are in fact already deeply disintegrated.

Before replacement the Grytdal stone was extremely damaged, especially just below windows (fig. 11.13). An important observation is that black crusts formed preferentially just below the most damaged parts. Associated with flaking and disintegration of the stone work underneath, the crusts are largely gone today, probably because they have weathered away.

It is reasonable to suggest that not only air pollution, but also sulphates from Grytdal stone contributed to the formation of the crusts. The sulphates from the stone may have worked in two ways - directly by providing gypsum (and eventually epsomite) to the crusts and indirectly by making the surfaces hygroscopic (epsomite), thereby enhancing the deposition of air pollutants.[9] A local increase in deposition rate of air pollutants may also be explained by the generally moister conditions below the string course when the Grytdal stone in question became progressively damaged. The conditions were, however, not moist enough to remove the crusts (run-off).

Although most of the cathedral's string courses made of Grytdal stone have been replaced, there remain a few examples of similar phenomena. One example is found on the west wall of the north transept (fig. 11.14). The string course below the clerestory windows is made of Grytdal stone of varying quality (from c. 1890), and a large black crust can be seen just below the most damaged stone (a stone with cracks).

Fig. 11.13: *String course on the north side of the choir, probably in the 1970s. Black crusts have formed just below the destroyed Grytdal stone. The string course was recently replaced by Bubakk soapstone - which is already strongly weathered (photo: Torgeir Suul).*

The same phenomenon could also be observed on the clerestory of the south transept before the Grytdal stone was replaced in 1991. Analyses showed that a rather complex salt system had developed just below the string course in question. The occurrence of gypsum (black and grey-green cauliflower crusts) and efflorescences of epsomite, thenardite, aphthitalite and bloedite suggest that stone, mortar and air pollution were involved as sources.

It is impossible from these observations alone to state anything definite about the relative importance of air pollution vs. sulphate from Grytdal stone. However, they do give an idea about the complexity of the salt systems to be found on the choir.

Fig. 11.14: *String course below the clerestory windows in the west wall of the north transept. Note the black crust that has formed below the Grytdal stone which has a large horizontal crack (photo: Eberhard Wendler, 6/93).*

11.9 Summary and possible conservation strategy

In all its complexity, the weathering of the choir is nevertheless rather simple (fig. 11.15). This is because water leaks from the gangways as well as leaks and run-off associated with gullies and parapets can account for most of the severe damage. Adding that large amounts of rapidly weathering Grytdal stone are to be found in the choir, the general weathering picture is almost complete.

There are, however, several reasons why the leaks have evolved into such a major problem throughout the past century since the restoration was completed in 1890. Large-scale stability problems leading to cracks is one reason, insufficient covering of gangways another and the improper design of the water discharge system a third.

A conservation strategy aimed at slowing down the weathering rate certainly has to include control and improvement of these three basic issues. However, it is also my opinion that the replacement of badly damaged sculptures and architectural details made of Grytdal stone has to be continued (with better stone than Bubakk soapstone!). To replace up to several hundred 19th century details is, however, a question with major ethical, aesthetic and technical implications. It is therefore discussed on a more general basis in chapter 20.

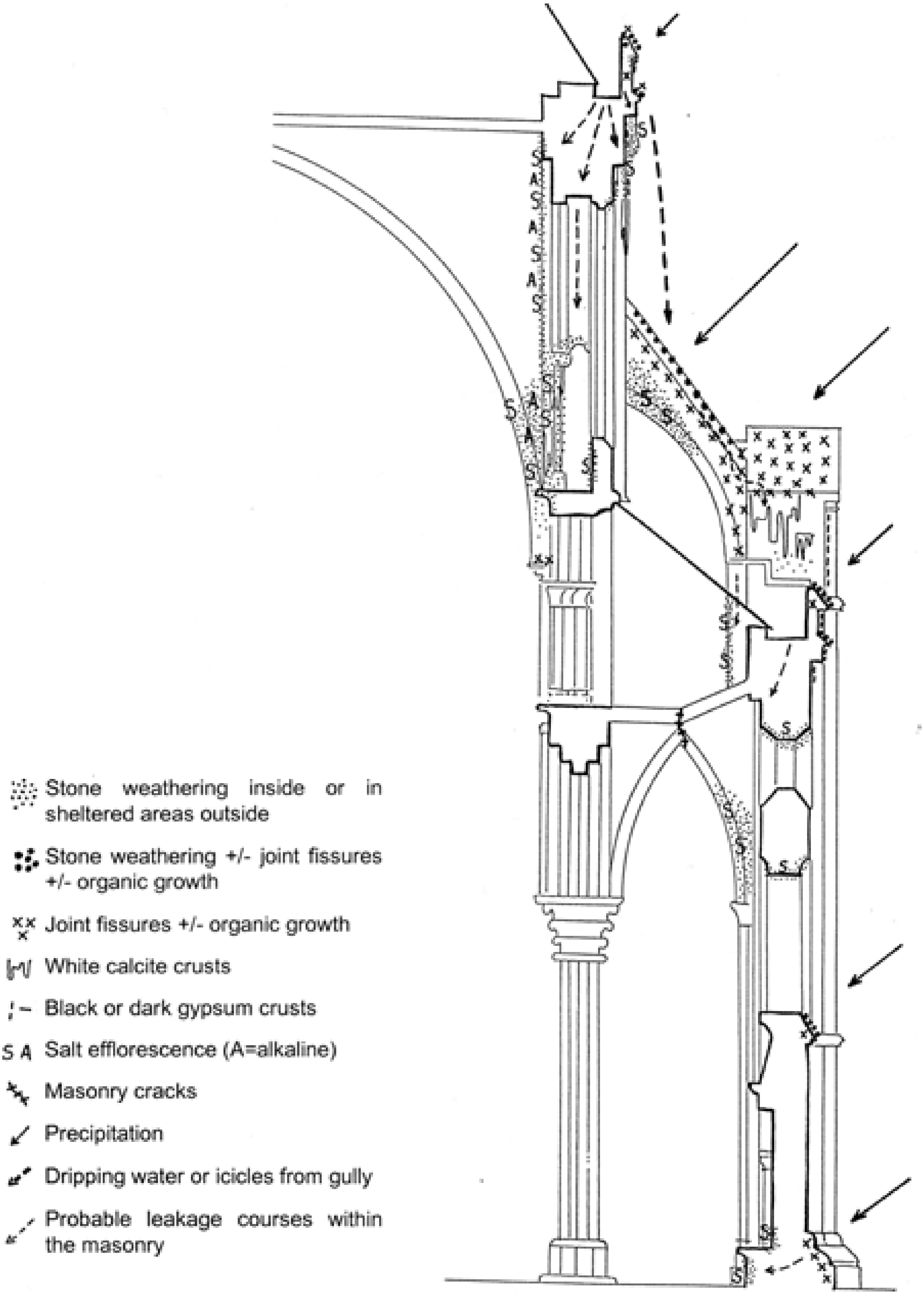


Fig. 11.15: *Transverse section of the choir showing the principal location of various weathering phenomena.*

Fig. 12.1: *Buttress on the south side of the nave in the 1970s. Note that most of the crockets (Bjørnå stone) have fallen down and that one fake grotesque gargoyle has lost its head. The buttress has later been restored (photo: ARW).*

Chapter 12

Weathering of the nave

After the collapse in 1531, the nave remained a ruin until it was reconstructed between 1905 and 1930. The medieval walls of the aisles were restored just before the main reconstruction work took place between 1897 and 1905 (chapter 4). The majority of the work was undertaken using Bjørnå stone and Portland cement or lime cement mortars (chapter 6).

The review below starts with a summary of stability problems, before turning to the water discharge system and record of water leaks. Then follows a systematic survey of the weathering situations. One chapter is also dedicated to a comparison of the choir and nave with regard to the occurrence of black crusts. The weathering of the nave is also compared with similar situations at the central tower and west front. The portals of the nave have not been included in the review as their weathering problems are treated in chapter 17.

12.1 Cracks caused by differential settlement

In chapter 5 it was shown that differential settlement in the western part of the cathedral took place as a result of the large loads added during the erection of the west towers. As a consequence, several decorations (capitals, columns etc.) and load bearing elements (e.g. arches) developed cracks or even collapsed. Also cracks in vaults and the masonry can be traced back to differential settlement. Studying the crack-pattern it can be seen that the western bays of the aisles are particularly affected. The cracks are easily observed in the vaults, and careful studies reveal that they continue in the masonry above the windows - just below the gangways. Mainly following the joints between ashlars, the cracks seem to be a major reason why leaks from the gangways have become a major problem, but fortunately not as grave as in the choir.

12.2 Water discharge system and record of water leaks

Leaks in the nave cannot be attributed to masonry cracks alone. There are several additional reasons, the most important of which must be the inappropriate design of the water discharge system. Investigation reveals that *only two 5'' downpipes* from the lower gangways of each aisle (N and S) are supposed to carry away water from the following areas:

- The main roof of the nave (via the upper gangway).
- The upper gangway (via one downpipe and one stone gully).
- The roof of the aisle.
- The flying buttresses.
- The lower gangway.

The downpipes also receive discharge water from other parts of the cathedral:

- A quarter of the central tower's spire and platform (via stone gullies).
- The platforms of the respective west towers (via one downpipe).
- Half of the gangway of the west front (via one stone gully).

The amount of water which has to pass through both these downpipes during a heavy rainfall has not been calculated, but it seems clear that the whole system is underdimensioned. It should also be added that the inclination of the gangways is insufficient, implying that water has difficulty in reaching the downpipes reasonably fast. Otherwise, the record of water leaks and subsequent repairs show the same general pattern as in the choir. It should be emphasised that the record shown in tab. 12.1 is far from complete:[1]

Tab. 12.1: *Record of leaks in the nave*

3.2.49:	Leaks from the upper gangways affect the clerestory windows.
30.6.50:	Leaks from the upper gangways have resulted in "white excretions" (calcite crusts and salt efflorescences) on the masonry below. How to cover the gangways is discussed.
18.8.50:	After several tests it is decided to cover the gangways with a combination of asphalt and cement mortar.
1.7.60:	Leaks from the lower gangway by St. Olav's portal during heavy showers. Downpipes clogged up.
8.9.61:	Downpipes repaired and cleaned up.
Feb. 66:	Very cold. Leaks in the lower gangways as a result of thawing of snow because of heat transfer from triforia.
1968:	Heating cables installed in order to melt snow in the gangways. Their use was later terminated because of increasing problems with leaks.
1968-94:	No record of water leaks
1980s(?):	Covering of the lower gangways with copper.
1990-96:	Several leaks from the lower gangways. This shows that the copper covering has not been completely successful, probably because the folded lock welts joining plates together allow some water to penetrate. Leaks also from downpipes which are in a rather poor condition.
Dec. 96:	Leaks from both upper gangways affecting interior parts of the clerestories. "A fine spray of water came down during a concert", as reported by the verger.

A good example of how leaks have taken place during the last couple of years can be shown by an event of moderate rainfall in the summer of 1994. Even after 5-6 days with beautiful weather, water continued to drip from an open joint underneath the exterior cornice and onto stonework of St. Mary's portal (see also chapter 17). It should be added that a downpipe had been clogged by pigeon droppings(!) An important feature of the recent leaks from the lower gangways is that they tend to cause run-off along the exterior masonry rather than actually affecting the interior vaults and stonework. There are, however, enough signs showing that leaks also have affected the interior.

Fig. 12.2: *The south side of the nave after a heavy snowfall. Snow collects on the projecting details, contributing to the severe weathering of copestones and fake gargoyles. In such weather there is a high risk of water leaks in the nave (photo: PS 2/95).*

12.3 Grotesque gargoyles - why are they fake?

Having mentioned that the nave's water discharge system is underdimensioned, it is peculiar to observe that the flying buttresses are equipped with numerous grotesque gargoyles (fig. 12.1 and 12.2). The only trouble is that most of them are fake. Gargoyles originally intended to work as such are located at the ends of the two water courses in the flying buttresses. However, as the gargoyles have largely weathered away (rapidly weathering Bjørnå stone), water no longer runs through, but rather over them before being discharged into the lower gangways. The rest of the gargoyles (four on each buttress) are - and have always been - mere decorations.

Since the flying buttresses are equipped with water courses, one would have thought that they were intended for receiving water via stone gullies or gargoyles from the upper gangways. The reason why there are no such gullies/gargoyles may be connected with the poor experiences in the choir which was finished in 1890, many years before the water discharge system of the nave was designed (1910-30). Recalling that discharge water and icicles largely destroyed the choir's flying buttresses, it is possible that the architects tried to avoid the same problems in the nave. It should, however, be remembered that - unlike the nave - the flying buttresses of the choir were never designed to receive discharge water.

12.4 Buttress system

Although the flying buttresses have numerous joint fissures and open joints as well as crumbling stone surfaces, the overall condition must be regarded as quite good. The main problem of the buttress system is connected with the supporting towers, which connect the flying buttresses with the vertical pillars of the aisles.

The towers are decorated by crockets and fake grotesque gargoyles, and the front sides have blind arches and marble columns. The connection between the towers and the vertical pillars is formed by a small, projecting gable. Large, fake grotesque gargoyles modelled by Wilhelm Rasmussen around 1910 can be found just below. All the projecting decorations have been subjected to rapid weathering, involving the loss of relatively large pieces due to delamination (fig. 12.1).

Since 1955 the restoration architects have occasionally recorded when and from where pieces have fallen down.[2] A fine collection of fallen parts of crockets and gargoyles now resides in The Restoration Workshop. The crockets and gargoyles on the south side started to decay less than 40 years after they were carved and emplaced. They are apparently more vulnerable than those on the north side where major falling events did not take place before the 1960s. A reasonable explanation is, when not considering possible variations in stone properties, that the south side is more exposed to rapid temperature changes.

In the late 1960s, the situation was perceived as acute, not least because of safety reasons, and many remaining crockets with marked foliation were taken down.[3] Simultaneously, a programme aimed at complete restoration of the buttresses, including their decorations, commenced. During the last 25 years all 12 towers have been demolished and re-erected again,[4] partly with new stone, and with new crockets made of Bubakk stone. Most of the fake, grotesque gargoyles have also been replaced by copies - many carved in soft Bubakk soapstone which already shows signs of heavy surface weathering.

12.5 Upper parapets and associated cornices

The tracery of the upper parapets are capped with foliated Bjørnå soapstone which have deeply carved, projecting mouldings (fig. 12.3). Similar mouldings can be found in the cor-

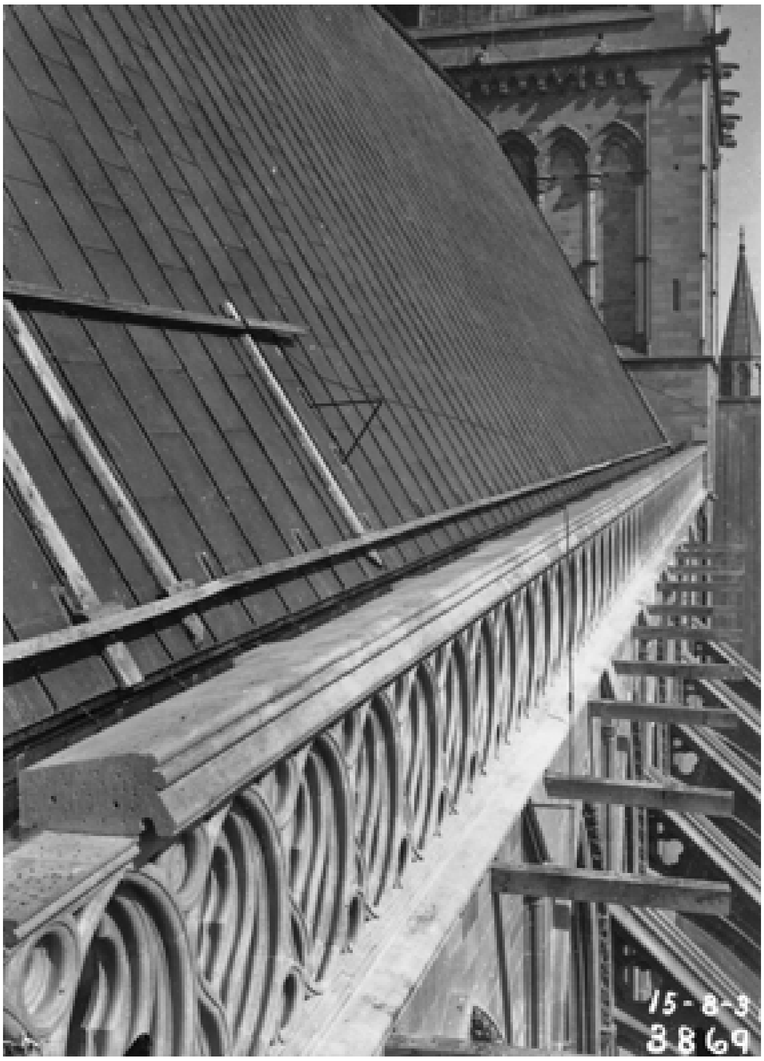


Fig. 12.3: *The upper parapet of the south side of the nave was finished around 1930. Note the deeply carved mouldings of the copestones (photo: ARW, no. 3869).*

nices below the parapets. In the 1950s, when gargoyles and crockets began falling from the buttresses, the deeply carved mouldings followed as natural companions. Perhaps as many as 20 mouldings have already fallen down, and many more have fissures which represent a great safety risk (fig. 12.4). The surfaces of the copestones are, moreover, characterised by heavy crumbling (granular disintegration, flaking and pitting). The crumbling is always associated with organic growth, and while diverse types of lichens prevail on the south side, additional moss is widespread on the relatively more humid north side.

Another problem with the cornices is that they are almost horizontal, so water, snow and ice easily collect here, leading to joint fissures - which again cause water infiltration to the masonry below. This means that it is not only water collecting in the gangways that causes leaks which affect the clerestory walls.

12.6 Clerestory walls

The clerestory walls are characterised by deposits of calcite crusts and alkaline salt efflorescences (fig. 12.5). The deposits have been observed, documented and discussed since 1950.[5] The salts were at that time - as today - supposed to be caused by leaks from the gangways, but otherwise regarded as mere unsightly “saltpetre excretions”. However, in contrast to current knowledge ascribing the origin of most of the salt efflorescences to the properties of certain stones and Portland cement *paste*, a widespread belief in the 1950s was that the excretions originated from sea salts, particularly those thought to stem from aggregate materials in the mortars. Consequently, sandy aggregates for Portland cement mortars were usually thoroughly washed before use - the Restoration Workshop even had its own sand washing facility.[6]

Although the clerestory of the nave is constructed differently to the choir's clerestory, the weathering phenomena are similar. The occurrence of calcite crusts and alkaline salt efflorescences have already been mentioned, but they seem not to do as much harm as in the choir. One reason is that Bjørnå soapstone is less porous than the Grytdal stones of the choir, and

Fig. 12.4: *The upper parapets of the nave in August 1995. Left: South side. Right: North side. Note that many deeply carved mouldings have been lost (photo: PS).*

does not contribute salts itself. Moreover, instead of brick, which was used in the choir, the interior of the clerestory wall is made of large blocks of gneiss. This stone does not contain salts, implying that salts almost exclusively originate from the mortars of the wall. Therefore, a much simpler salt system with less sulphates of calcium and magnesium can be found in the clerestory of the nave. Nevertheless, granular disintegration and flaking are widespread on exterior Bjørnå ashlars.

The interior clerestory walls are - when excluding the stability problems described in chapter 5.3 - rather sound. Water leaks and minor salt weathering occur especially in the westernmost bays - obviously due to differential settlement (cracks) and the poor water discharge system.

12.7 Lower parapets and associated cornices

In contrast to the upper parapets, the lower are massive, but also equipped with copestones including deeply carved mouldings. As expected, the weathering has followed a similar pattern to the upper parapets - loss of mouldings, heavy surface crumbling and joint fissures. In order to brush up the surfaces of the copestones, they were rubbed and treated with “Test”, probably a kind of silicone-based waterproofer, in 1963.[7] The intervention cannot have been

***Fig. 12.5:** The clerestory wall of the nave's north side. Extensive salt efflorescences and calcite crusts cover the wall (photo: PS 5/97).*

***Fig. 12.6:** The south side of the nave in dry spring weather. Extensive efflorescences of alkaline salts are usually observed below the parapets at this time of year (photo: PS 3/94).*

very effective, and since many mouldings soon started to fall, most of the copestones were replaced by Gullfjellet or Bubakk stone in the 1970s and 1980s.

The cornices below the parapets have not yet been replaced. Consequently, the problems of deeply carved mouldings which tend to fall is now acute. During a very wet period with rapid temperature changes centred around 0°C in November 1995, it was possible to pick up pieces on the ground almost every second day. Interestingly, mouldings did not fall during a period with several rapid and extreme temperature changes between -10-20°C and +3-5°C in December 1996. In contrast to November 1995, the weather was not especially wet in the thawing periods, indicating that *dangerous* frost events are - as is generally known - highly dependent on the moisture content of the stone. It should also be mentioned that several pieces of mouldings fell off after a thunderstorm in the very warm July 1997. This shows that wetting/drying and possibly thermal effects play significant roles.

It is important to note that the inclination of the cornices below the lower parapets is rather steep, implying that leaks cannot develop as easily here as from the corresponding cornices below the upper parapets. Leaks do, however, occur because most of the joints are open.

12.8 Walls of the aisles

So far stonework erected during the restoration (1905-30) has been described. Turning to the walls of the aisles, it should be remembered that they are medieval, although restored. Considering the ruinous condition of the nave after the collapse in 1531 and the fact that the walls of the aisles remained unprotected for more than 200 years (see chapter 4), they are in astonishingly good repair.

The nave has never had the same severe stability problems as the choir. Measures such as getting the walls back into vertical positions were therefore unnecessary during the restoration. Otherwise, the restoration measures undertaken in 1897-1905 were roughly the same as those carried out in the choir 20 years earlier. However, instead of Grytdal stone, soapstones from Solerød (Østfold county) and Bjørnå were used for replacement purposes.

Especially inside, much replacement had to be carried out because of fire damage. That the 1531-fire must have been severe can be understood by observing remaining damaged stones. Being heavily cracked and exfoliated, such stones can be found distributed virtually on all parts of the walls - both along the floor and as high up as around the arches of the windows. On exterior masonry, however, there is little fire damage, except around the portals (see chapter 17).

Fire damaged stones are today sound - i.e. they do not weather actively - except at places where additional weathering agents influence the situation. As expected, these places are generally found just below the parapets and cornices. Also medieval stone not influenced by fire may weather actively at such places (fig. 12.6).

Extensive analyses of soluble salts have not been undertaken, but it seems that the salt system is characterised by calcite crusts and efflorescences of sodium carbonates. There are relatively small amounts of sulphates to be found, implying that salts from stone and air pollution have been of minor importance. The largest salt source appears to be Portland cement.

There are notable differences between old stone and stone replaced during the restoration. Just below the parapets almost every old stone shows some kind of flaking, granular disintegration or exfoliation, whereas most of the new soapstones - especially Solerød soapstone - remain in excellent repair. Solerød soapstone seems, in fact, to be a very good stone. On exposed parts of pillars, as well as in the bases of the nave, it is still well preserved.

12.9 Black crusts - the nave vs. the choir

In contrast to observations on the walls of the choir, black crusts are almost absent on the nave. There are some crusts associated with particular run-off systems by the portals (chapter 17), as well as underneath a few cornices and string courses (fig. 12.7). The crusts are generally thin, but often associated with flaking and exfoliation. However, at most places where crusts have formed, there are also major amounts of salt efflorescence (sodium carbonates/sulphates) to be found in dry weather. Therefore, it is impossible to blame the associated flaking and exfoliation on the crusts alone.

A relevant question is why black crusts are so infrequently found on the nave. Important reasons might be:

- The masonry of the nave was not restored using the sulphate rich Grytdal stone. The Bjørnå stone in the nave does not provide significant amounts of sulphate.
- Bjørnå stone is less porous than Grytdal stone. Less porous stones tend to show a lower uptake of air pollutants than more porous ones.[8]
- The ambient conditions on the north side of the choir are generally more humid than on the corresponding part of the nave. Higher ambient humidity generally increases the deposition rate of air pollutants.

- The choir is located very close to the chimney of the central heating plant of the cathedral (see chapter 7.4).
- The new masonry of the nave (everything above the aisles) is younger than the new masonry of the choir. Hence, the choir has been exposed to air pollution 20-40 years longer than the nave.

These considerations are general ones. It should not be forgotten that the formation of black crusts always has to be seen in relation to the actual situation. For example, formation of thick black crusts on Bjørnå stone can be observed on several sculptures and projecting decorations on the lower part of the west front (fig. 12.7). They are not, however, causing significant damage to the stone.

Fig. 12.7: *Black crusts on Bjørnå stone. Left: The underside of a string course on a buttress, south side of the nave. Flaking and granular disintegration associated with black crusts and salt efflorescences (photo: PS 5/96). Right: Thick black crust formed on the underside of a decoration in the lower part of the west front. The crust accumulated as a result of run-off on each side of the stone (photo: PS 4/96).*

12.10 Summary and possible conservation strategy

In addition to differential settlement causing masonry cracks and various interior safety problems, it is evident that there are two major problems at the nave (see also fig. 12.8):

- The safety risks associated with rapidly weathering Bjørnå stone which tends to lose projecting details.
- The poorly constructed and underdimensioned water discharge system which causes leaks and subsequent salt weathering.

As to the first problem, it is necessary to replace many copestones and decorations which have lost - or are about to lose - details. Considering the severity of the safety risks, it is

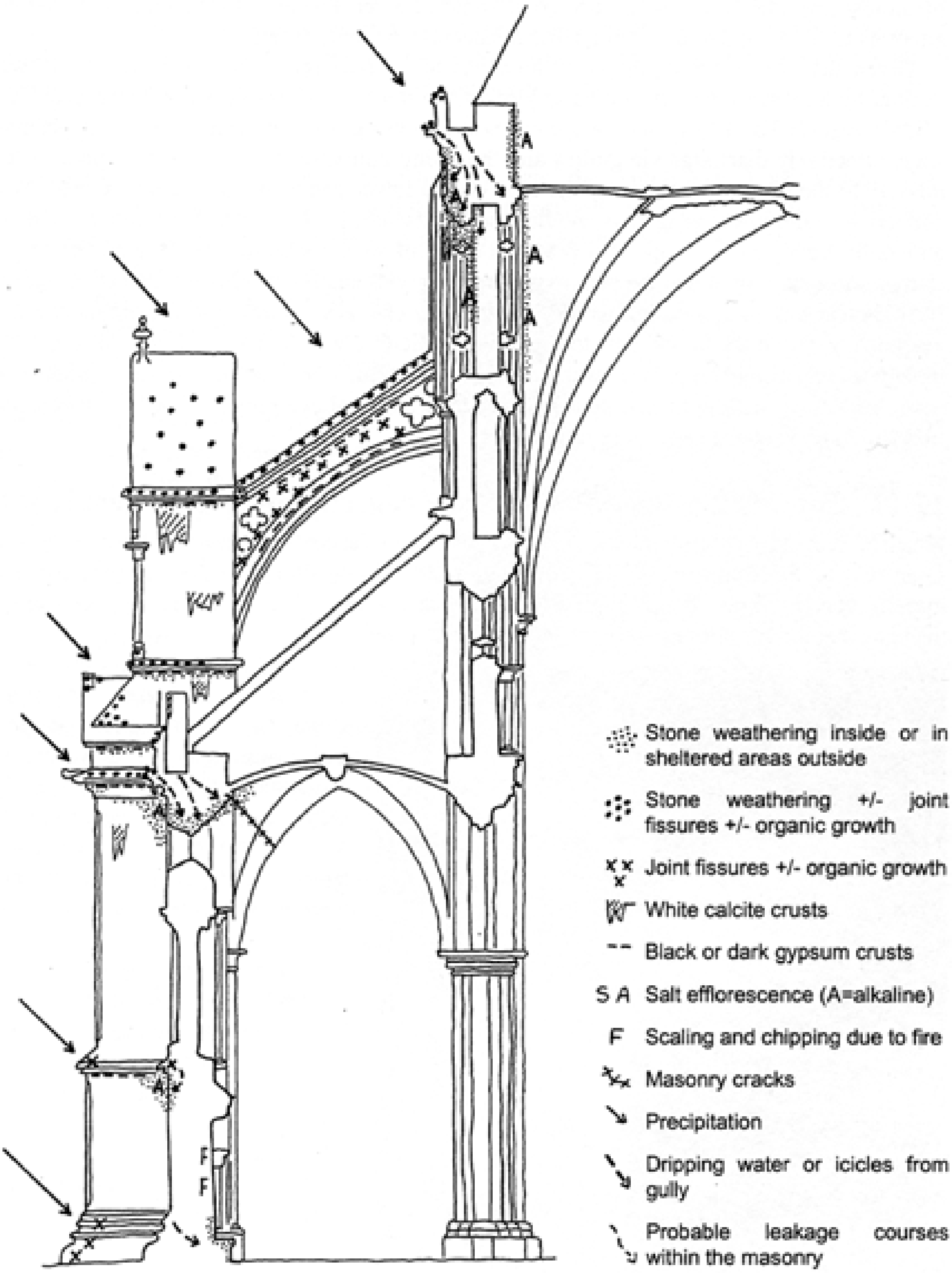


Fig. 12.8: *Transverse section of the nave showing the principal locations of various weathering phenomena.*

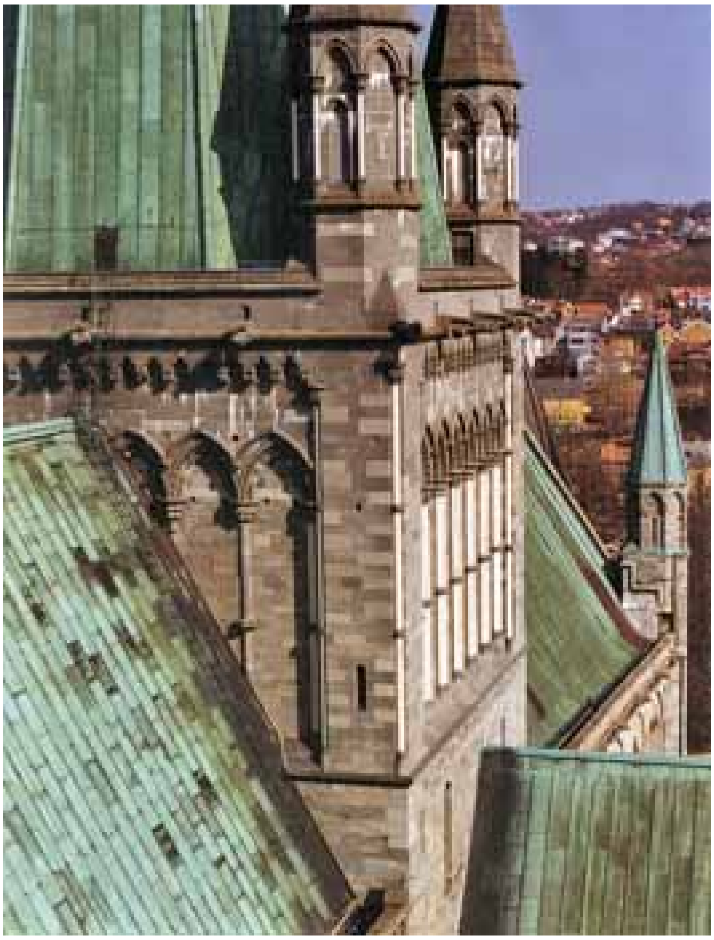
of utmost importance to use a very good stone in a replacement programme. Alternatively, attempts to fix or consolidate vulnerable details may be undertaken.

Given that the water discharge system has to be redesigned, it is probably worthwhile evaluating how stone gullies and gargoyles can be put to work (as they may have been in the Middle Ages?) The key to such a system will be letting water collecting in the upper gangways effectively discharge via gullies and the flying buttresses (covered with copper or lead) *directly* to the ground. In this way the load on the lower gangways would be reduced. Water collecting in the lower gangways should also be discharged *directly* to the ground via several gullies or gargoyles. An important practical detail of such a system would be preventing discharge water running down the walls - gullies/gargoyles should in other words extend far out.

It is clear that such a design would imply major changes regarding to the architectural appearance of the nave. In addition to including difficult craft operations, it would mean completely disregarding the present water discharge system. The present system is modern and poor, but are we willing to change it as drastically as the above proposal? A less drastic solution would be to simply add more downpipes.

12.11 Comparing the nave with the central tower and west front

Finished at the turn of the century, the upper section of the central tower was built in much the same way as the clerestory of the nave (fig. 12.9). The walls above the stellar vaulting are massive constructions “faced” with ashlars of Bjørnå stone. This stone has also been used in the parapets, for copestones and most of the decorations.



Thus, we again meet the delicate weathering problems of Bjørnå stone. The weathering of copestones and decorations is, however, less pronounced than in the nave. This may probably be ascribed to the fact that at the turn of the century the Bjørnå quarry delivered better stone than 10-30 years later (see chapter 9.2).

The central tower seems to have been subject to less water leaks than the nave. Leaks have certainly taken place, but often they have been caused by weaknesses in the large spire.[9] Despite some water infiltration from the tower's platform, the cement/asphalt cover seems to be durable enough.

Fig. 12.9: *The central tower. Note that 3 large stone gullies on each side carry water away from the gangways behind the parapets. This is a very effective water discharge system (photo: 5/96).*

The reasons may be connected with the fact that neither differential settlement, nor other types of large-scale stability problem causing larger cracks and fissures have been recorded in the central tower (see chapter 5) However, the main reason for the relatively good condition is probably that water collecting on the tower's platform is readily discharged via 12 large stone gullies.

We have seen that below all parapets of the nave (and the central tower), salt systems have developed - mainly because of leaks and the use of Portland cement mortars. As a conclusion to this chapter, comparison is made to a similar situation below the west front parapet (fig. 12.10). The situation neatly sums up what happens when water percolates masonry built with Portland cement mortars and serves in this respect as an excellent model.

Below the parapet, which was finished around 1950, there is first a decorated field and then deep niches for the uppermost row of sculptures (“King's row”). Water infiltration originates primarily from open joints in the cornice, but also from the gangway behind the parapet.

On the exposed decorated field there are thick white crusts of calcium carbonate, while in the sheltered niches efflorescences of powdery sodium carbonates prevail - usually associated with granular disintegration of Bjørnå stone.

The explanation of the phenomena is straightforward: Water percolating through the masonry dissolves lime and alkaline components in the Portland cement mortar producing a strongly alkaline solution. According to their respective solubility products, calcite precipitates before sodium carbonates, which can remain in the sheltered areas because there is no water to wash them away.

Fig. 12.10: *The west front. Leaks from the gangway have percolated into masonry built with Portland cement mortars and led to the formation of a classical salt system below the parapet. Large calcite crusts have developed on the exposed masonry, while alkaline efflorescences prevail in the sheltered niches (photo: PS 8/93).*

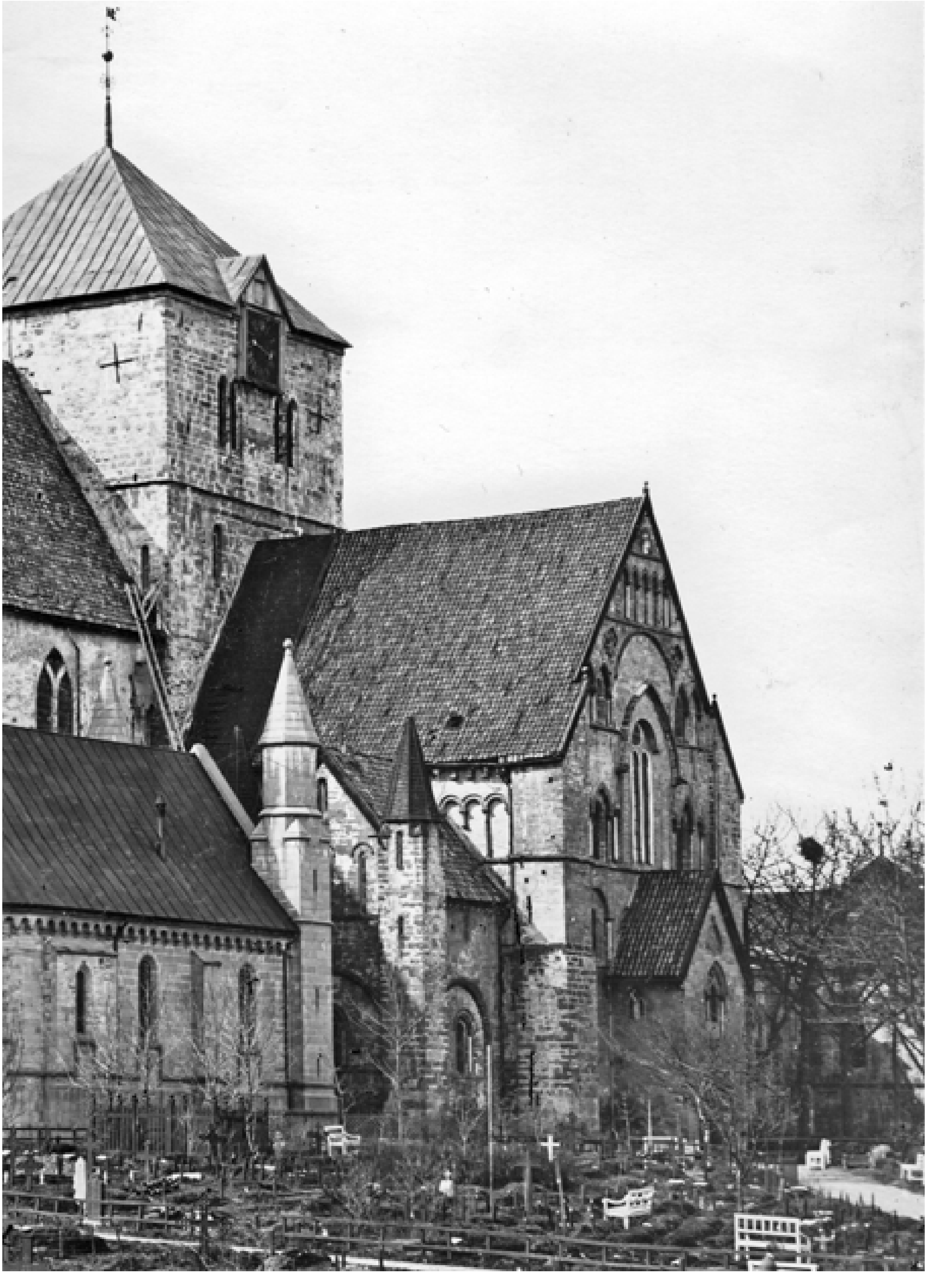


Fig. 13.1: *The north transept in c. 1878, just before the restoration. Observe that the flanking towers are missing, that there is a large pointed window in the gable and that the walls are covered with whitewash (photo: ARW, no. 486).*

Chapter 13

Weathering of the north transept

Unlike the choir and nave, the mixed Romanesque and Gothic transept has - due to the lack of heavy vaults - escaped large-scale stability problems since the restoration at the turn of the century. However, due to differential settlement between the central tower and the transept, major cracks were observed before the restoration (figure 5.1). The central tower has been a reasonably stable construction since then (chapter 5) and new cracks have apparently not developed.

Despite these fortunate circumstances, the transept shows several problematic weathering phenomena, especially related to the new parts added during the restoration. The small towers flanking the north wall are particularly vulnerable, not least because they were made of Bjørnå stone and Portland cement mortars. Otherwise, weathering problems are largely related to restored medieval stonework and decoration. The walls show quite extensive development of black crusts, as well as distinctive weathering in the zone of rising damp. In addition to these phenomena, emphasis in this chapter is also placed on medieval masonry affected by fire.

Only the north transept is described, as the southern part was heavily rebuilt and thus weathers in much the same way as the nave (leaks, alkaline salts, problems with Bjørnå stone). The weathering of valuable Romanesque corbel heads is described in chapter 18.

The north transept is a large part of the cathedral, and even if the design looks simple at first sight, it should be remembered that the thick walls contain passages, arcades and windows both at triforium and clerestory level. There is a large reconstructed rose window in the north wall, which also has a passage leading to the small St. Michael's chapel above the north porch. Two chapels can be found on the east side - the lower chapel is called the Lectorium, which is separated from St. Mary's chapel above by a pointed rib vault.

13.1 Leaks from the towers affecting medieval masonry

Built from Bjørnå stone at the turn of the century, the towers flanking the north wall are severely exposed to precipitation. As expected under such circumstances, projecting details like string courses and fake gargoyles tend to weather rapidly - just as in the nave. Taking the western tower as an example, several gargoyles had to be replaced in 1994-96 because large pieces were about to fall off. Repointing most of the joints in the pyramidal roof was another important measure undertaken during this intervention.[1] The old, open joints (Portland cement mortar) had given rise to extensive leaks and weathering due to alkaline salts on the interior walls of the staircase below. Similar weathering situations can be found below most pyramidal stone roofs covering the cathedral's towers. A thorough description of such a situation is given in chapter 14.

Fig. 13.2: *The north transept in 1905, immediately after the restoration was completed. Note the new parts and that whitewash has been removed. Also note that the roofs have been completely changed (photo: ARW, no. 1518).*

Water infiltration and alkaline salts have not only affected masonry erected during the restoration. The eastern tower, which has medieval greenschist masonry up to the clerestory level, shows sodium carbonates and sulphates accumulating in the contact zone between old and new stonework (fig. 13.3-4). However, the extensive delamination and granular disintegration of the greenschist ashlars are probably not caused by the actions of these salts alone. This is because we must also consider that the upper part of the medieval tower collapsed or was demolished - maybe as a result of the fires in 1432 or 1531. Thus, the masonry may have suffered previous damage before alkaline salts started their work after the restoration.

The tower is not the only source of leaks and salts that affect the actual masonry. Run-off from the corner between the gable and the tower also tends to collect in the area, as can be seen during showers as well as in dry weather periods. In the latter periods, salt efflorescences neatly concentrate in the zone of evaporation beside the main waterways. Black crusts also tend to concentrate in similar areas (fig. 13.4).

On the interior wall of the area in question, large amounts of alkaline salts can be found. This is understandable, considering that some of the run-off waters penetrate the wall and that window arches have been restored using concrete. Large amounts of alkaline salts can also be found just below the exterior part of the rose window (restored with Portland cement mortars), but no major disintegration of the Bjørnå ashlars has so far been observed here (fig. 13.3).

Fig. 13.3: *The north wall on a dry day in March 1993. Note the distribution of salt efflorescences (white patches). The salts occur on and below new masonry from the restoration (photo: PS 3/93)*

Fig. 13.4: *The eastern tower of the north transept. Left: Salts from Portland cement in the rebuilt upper part of the turret have caused weathering of medieval greenschist masonry below (photo: PS 8/95). Right: Run-off from the corner between the gable and the turret has led to the accumulation of salts in particular zones (photo: PS 3/93).*

13.2 Exterior greenschist masonry and black crusts

In chapter 7.4 (fig. 7.13) it was shown that black (gypsum) crusts started to develop on the walls of the north transept (north porch) well before the turn of the century. The extent of the crusts peaked between 1930 and the 1970s, before decreasing due to reduction of SO_2 emissions and rain washing in the 1980s and 1990s.

As expected, black crusts preferentially occur beneath details like arches and string courses. They can also be found in zones beside main waterways (transition zone between "wet" and "dry" stonework), as well as on and along joints on quite exposed masonry (fig. 13.4). In all these situations, the crusts occur directly on greenschist which is the most widely used stone in the Romanesque areas of the transept. Crusts also occur on medieval soapstones, but rarely on soapstones put in place during the restoration (mainly Bjørnå stone). However, black crusts are more frequently found on remaining traces of whitewash and paint. Such crusts tend to occur in two characteristic ways - as thin black layers on relatively thick remains of whitewash and as thin crusts with small "bubbles" on traces of blue-grey paint (fig. 13.5). The "bubbles" are a typical weathering form associated with the black crusts, but minor flaking and exfoliation are also quite widespread. When weathering forms like delamination and granular disintegration occur together with flaking/exfoliation, there are usually salts other than gypsum to be found as well (sodium carbonates/sulphates).

It is reasonable to explain the preferential development of black crusts on traces of whitewash and paint by the abundant calcium provided by these substrates. There are, however, several additional factors to be considered. One is the that dry deposition of air pollutants may preferentially take place on the relatively porous substrate represented by the whitewash/paint (compared to the dense stone). Another is the possible accumulation of chlorides on/in such substrates. Chlorides may either have been provided by cleaning operations (hydrochloric

Fig. 13.5: *Black crusts on the north transept. Left: Thin black layer formed on a substrate of blue-grey paint, probably applied in 1818 (photo: PS 10/94). Right: Thin black layer formed on remains of whitewash. Observe that flaking is not taking place on the "clean" part of the ashlar (photo: PS 8/95).*

acid/lye) during the restoration, or by deposition of sea salts. In both cases they may have rendered the substrate relatively hygroscopic - and thereby more vulnerable to deposition of air pollutants - than surrounding stone.[2] Recalling that large amounts of gypsum were observed in the Øye greenschist quarry, it is possible to assume that the stone contributes some gypsum as well.

13.3 Exfoliation of greenschist ashlars and run-off systems

Medieval greenschist ashlars on the north transept - particularly on the east wall of the Lectorium/St. Mary's chapel - have developed pronounced exfoliation (contour scaling). The ashlars are all horizontally bedded; therefore one cannot explain the phenomenon simply by delamination along foliation planes as would have been the case if the ashlars were face-bedded (chapter 8.1).

Fig. 13.6: *East wall of the Lectorium and St. Mary's chapel. The most pronounced flaking of greenschist ashlars occurs between the main arch and the upper group of windows (photo: Svein T. Dahl 1990). Small picture: Detail of the exfoliation (photo: PS 9/90).*

Generally, exfoliation occurs as a loosening of the outermost 2-5 mm of stone along re-pointed joints, but the central parts of ashlars may also be affected (fig. 13.6). The phenomenon is never observed on the most strongly exposed parts of the walls, nor in sheltered locations, but rather on areas which are partially exposed to precipitation, and in the zone of evaporation beside specific waterways. It should also be observed that the exfoliation preferentially takes place on walls affected by condensation and white frost, for instance on towers and walls which are little influenced by indoor heating in the cold season.

Exfoliation on the east wall of St. Mary's chapel

Using the east wall of the Lectorium/St. Mary's chapel as an example, it can be seen that a major feature of the wall is the distinctive waterways in the corners beside the towers. Run-off is caused by water collecting between the gable and the towers - a problem solved earlier (before the restoration around 1880) by gullies which were able to discharge water away from the wall (fig. 13.9). This system - as well as the design of the roof and towers - was changed during the restoration. Water has since then simply run down the wall (fig. 13.7).

Fig. 13.7: *The Lectorium and St. Mary's chapel during a shower in September 1994. Although the wall faces east, large areas get completely wet during most precipitation events (photo: PS).*

Fig. 13.8: *St. Mary's chapel. Corner between the gable and the north tower in which run-off collects. Note that the greenschist ashlars are very sound in the main waterway. Black crusts (and some other salts) have accumulated in zones beside the waterway, causing flaking and granular disintegration (photo: PS 6/93).*

The most distinctive run-off patterns can be found just below the corners between the gable and the towers (fig. 13.8). Here, water has effectively “cleaned” the ashlars in the central zone, while black crusts and other salt species have concentrated in the adjacent. This zone is characterised by flaking/exfoliation and granular disintegration, obviously caused by the actions of salts.

Moving further down the wall, an area with pronounced exfoliation can be found between the main arch and the windows of the gable (fig. 13.6). According to historical photos, the exfoliation has developed over the last 100 years. Run-off patterns and black crusts are not especially distinctive in this area, but careful studies on rainy days reveal that - although a small, horizontal sill complicate the situation - exfoliation also takes place here beside the main waterways. The reason why run-off patterns are not very distinctive is because direct rain sometimes affects the wall (fig. 13.7). This phenomenon can be explained by turbulent wind conditions in the space between the wall itself and the west wall of the chapter house.

Fig. 13.9*: The Lectorium (lower part) and St. Mary's chapel (upper part) before the restoration (1870s). Gullies are used in order to discharge water from the corners between the gable and the towers (photo: ARW, no. 174).*

Interpretation of the exfoliation

A reasonable explanation for the exfoliation is that gypsum and other salts tend to concentrate in zones beside the main waterways. According to the actual moisture (and thermal) conditions, the salts may concentrate close to the surface of the ashlars or in specific zones below the surface. In the former case, the associated weathering forms seem to be granular disintegration and flaking, while in the latter case exfoliation is the preferential form. Although similar phenomena have been investigated and explained by several researchers (see chapter 3), salt profiles ought to be made in order to verify the above assumptions.

Several additional factors have to be considered in order to reach a proper understanding of the phenomena. Further investigations should include the possible negative influence of joints repointed by Portland cement mortars, the influence of condensation events and frost.

Since exfoliation cannot be observed on old photos, it is quite clear that the change of roof design and removal of gullies during the restoration have contributed much to the weathering over the last 100 years. Thus, when planning future conservation measures, the possibility of re-introducing gullies as well as the old roof design should be considered.

Fig. 13.10: *Narrow space between the Lectorium and choir. Fire has caused severe spalling of ashlars, but the situation is at present quite stable. The most severely damaged ashlars were replaced during the restoration (photo: Svein T. Dahl 1990).*

13.4 Examples of exterior masonry affected by fire

Parts of the north transept have been subjected to perhaps as many as five fires. Obviously, the most severe fire damage can be found inside and on exterior masonry beside which burning wood could collect, especially in the narrow area between the Lectorium and choir. It is known that a burial chapel was raised between the Lectorium and choir in 1731[3] - i.e. after the last fire in 1719. However, it is reasonable to assume that there must have been wooden burial chapels or store rooms in the area also before the last two fires (1708, 1719). Another possibility is that fire damage has been caused by burning wood falling from the roof of the transept, central tower and/or choir. In addition to brown discoloration of stone surfaces, the damage show up as spalling of stonework (fig. 13.10). However, even though the damage may seem severe, there are no significant problems at present. This is because the spalled surfaces are quite hard and stable - they do not actively weather at present. Similar phenomena can be found on the corresponding walls between the south side of the choir and St. John's chapel. In this area we know that there were burial chapels and other structures prior to the last fire (1719).[4]

Fires did not always destroy stone surfaces, even when wooden structures burnt directly adjacent to the masonry. Quite often a slight brown coloration of stonework is the only feature to be observed today. An example can be found in the corner between the east wall of the north porch and the main north wall of the transept. According to the copperplate of J. M. Maschius from 1661 (figure 13.11), there was a pillory in the actual area - a wooden structure that may have burn violently during a fire. Several ashlars were replaced during the restoration, but the remaining old stones show that the damage caused by the fire was very minor, indeed.

Fig. 13.11: *Above: Copperplate by J. M. Maschius from 1661. The drawing is not correct, but a particular construction can be seen in the corner between the north porch and the main north wall of the transept. The construction is a pillory which later burnt, causing only minor damage to the masonry. Right: The only traces of the fire is brown discoloration (photo: PS 6/93).*

13.5 Salt weathering in the zone of rising damp

The north transept is one of the few parts of the cathedral which is affected by salt weathering in the zone of rising damp. However, whether rising damp is actually the main cause of the weathering is uncertain. This is because moisture arising from condensation seems to be of great significance. Major amounts of salts can be found on the interior north wall as well as on the walls of the Lectorium. Although flaking and granular disintegration do occur, the salts are not doing any particular harm to the solid coursed rubble walls (gneiss and greenschist). However, the walls in question are decorated by blind arcades featuring several medieval bases, columns and capitals. Old decorations, as well as new pieces inserted during the restoration, sometimes weather at a rather high rate.

Tab. 13.1: *Post-Reformation history of the Lectorium (partly from Lysaker 1973).*

-1708:	Lecture room for the Latin school. Not badly damaged in the 1708-fire
1708-1783:	Store room. Suffered little damage in the 1719-fire.
1783-1819:	Archive. Iron doors inserted. Very moist conditions.
1819:	Major repairs because of damage due to moisture. Plastering of walls and painting of decorations. Double wooden floor with ventilation made.
1819-1825:	Store room for crown regalia. Regalia damaged because of mould.
1880-1900:	Poor condition of the walls before the restoration. Plaster and paint removed. Large parts of the walls replaced by new stone. Several new columns put in place. Cellar excavated, foundations strengthened and new marble floor laid.
1900-:	Chapel. Weathering in the zone of rising damp can be observed on photos from the early 1900s.

Using the Lectorium (fig. 13.12) as an example, the most active weathering occurs in the north-east corner. Studying the history of the chapel (table 13.1), it can be seen that moisture has been a problem since at least the 18th century. These moisture problems can be attributed to poor drainage of surface water, which may have collected on the layer of clay on which the cathedral is built. However, since the chapel is a cold corner of the church, condensation was probably very important before the installation of heating in the late 19th century. The chapel was heavily restored between 1880 and 1900. Major parts of the badly damaged walls were replaced, and several new columns and other decorations put in place where old ones were missing or damaged.[5] The restoration, which included the use of Portland cement, explains why trona and sodium sulphates are the main salt phases found today. Trona occurs in the form of thick crusts along joints, while sodium sulphates are more evenly distributed on walls and decorations.

The presence of thick trona *crusts* indicate quite moist conditions, indeed. This is difficult to explain because rising damp must have been largely eliminated during the restoration - especially due to the excavation of a new cellar (which is rather dry) and the fact that a new drainage system was constructed to carry away surface water (chapter 5.1). However, it has been observed that occasional events of condensation render the walls extremely moist. Condensation rarely occurs in the heating season (there are even electrical panel heaters along the floor), but instead during hot and humid summer days (fig. 13.13). Sodium sulphates completely dissolve during such events, and the trona crusts also largely disappear - before reappearing when the weather turns colder or drier.

The cleaning routines in the cathedral may also play a role in the weathering. For several decades the normal way of removing dust and dirt has been to use soaking wet cloths - not only on the floor, but also on stonework and decoration.[6] Summer condensation and wet cleaning may explain why the weathering is still developing. Whether these phenomena can explain the *initial* formation of large amounts of salt is, however, difficult to say.

As yet unconsidered is the possibility of water infiltration through open joints in the exterior masonry. Since the exterior joint system is in good repair it seems unlikely that much water penetrates the wall.[7] However, certain ashlars in the zone of rising damp have old (and presently stable) weathering forms, possibly caused by earlier salt weathering. Some efflorescences of sodium carbonates (natrite/thermonatrite) can still be observed along joints.

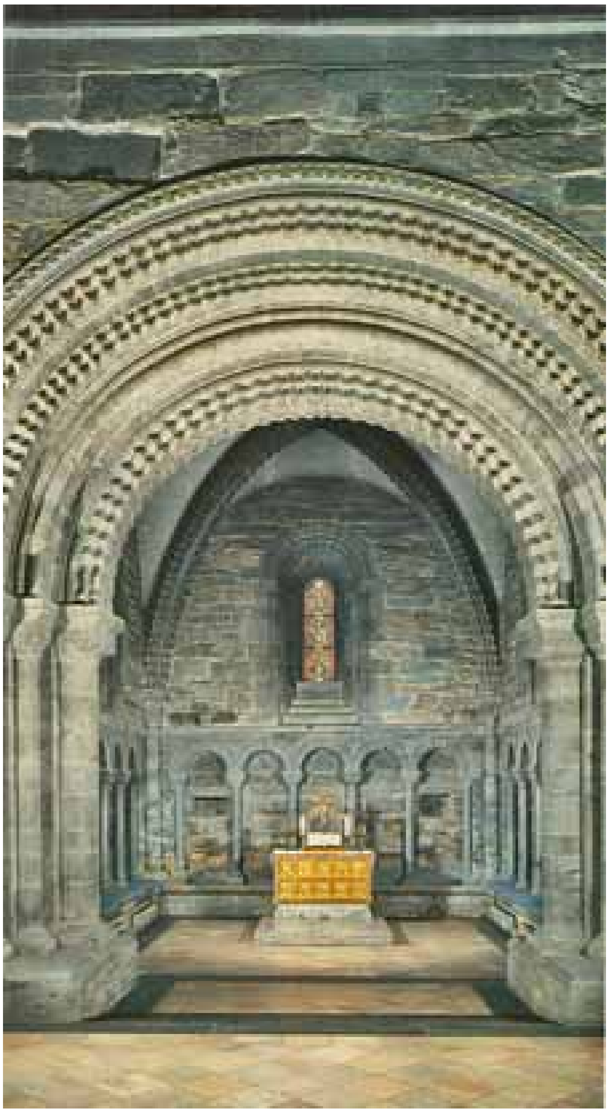


Fig. 13.12: *The Lectorium has suffered dampness problems at least since the 18th century. Bases and capitals of the Romanesque blind arcade are still severely affected by salt weathering (photo: ARW).*

Fig. 13.13: *North-east corner of the Lectorium. During an event of summer condensation in August 1995, the corner became completely wet, causing most of the salts to dissolve (photo: PS).*

13.6 Summary and possible conservation strategy

The most vulnerable structures of the north transept are the rebuilt parts of the towers. Being severely exposed, built with Bjørnå stone and Portland cement mortars, the weathering phenomena resemble those of the nave's buttress system. Leaks in the towers have caused major amounts of alkaline salts to be brought into contact with medieval masonry below. This has led to severe weathering of greenschist ashlars. In the western tower, a restoration programme involving repointing of joints with hydraulic lime mortars has recently been carried out. Prior to undertaking any measures on the eastern tower, careful observation of the effects of this intervention should be made.

Other weak parts of the transept include corners between gables and towers - both on the main north wall and on the east wall of St. Mary's chapel. Run-off tends to collect in the corners, causing a complex distribution of salts and weathering forms beside the main waterways. Pronounced exfoliation of greenschist ashlars are one of the weathering forms believed to be caused by the run-off systems. A main reason why run-off has evolved to become such a problem is due to the fact that the roofs were altered during the restoration. Hence, re-designing the roofs, as well as improving the water discharge system (for instance by using gullies) ought to be considered in order to slow down the weathering rate.

In the zone of rising damp, especially in the Lectorium, there have been weathering problems since at least the 18th century. Rising damp seems to be of minor importance at present, but it has been shown that summer condensation events as well as wet cleaning procedures contribute to the ongoing salt weathering. It would not be difficult to stop or change cleaning procedures. Avoiding or reducing the effect of summer condensation can be done by heating and by closing the doors of the cathedral during these periods - both rather problematic interventions.

One of the most characteristic features of the north transept is the widespread occurrence of black crusts. They are concentrated underneath and below projecting details as well as along main waterways. In addition, it has been shown that black crusts - or thin black layers - tend to occur on whitewash and paint not properly removed during the restoration.

Part V

The historical dimension of salt weathering

Fig. 14.1: *The southern west tower seen from the central tower of the cathedral. The large pointed opening belongs to the belfry. Above the belfry there is a concrete construction - a room which is almost like a "bunker" (photo: PS 6/94).*

Chapter 14

Weathering of the southern west tower

Weathering due to alkaline salts has been mentioned several times in previous chapters - and is also an important theme in the case studies presented later. In order to thoroughly understand the actual salt species and mechanisms involved in such weathering, the southern west tower provides an excellent example. The tower, which is the youngest part of the cathedral, was completed less than 30 years ago and is thus a modern building construction not influenced by complex historical events.

The following concentrates on elevated parts of the tower - especially the uppermost section which was built as a reinforced concrete structure. This construction plays an important role in the rapid weathering of the tower's interior walls. After a presentation of design and exposure conditions, attention is given to the weathering phenomena occurring on exterior parts and in the staircase of the tower. Measurements and analysis of weathered material as a function of climatic conditions and salt habits are also presented, as well as a comparison with the northern west tower.

14.1 General design and building technique

The roughly 50 m high tower is divided into five sections, including a large belfry just above the west front parapet (fig. 14.1). Between the belfry and the exterior platform at the top there is a small room made of reinforced concrete - almost like a “bunker”. The platform is surrounded by a decorated parapet and features four small stone towers of which three are massive and one (the south western) is hollow. The latter tower stands above a turret, within which there is a spiral staircase reaching down to the ground. Supporting buttresses integrated in the walls can be found in the other corners of the tower.

The belfry is built as a massive stone construction (fig. 14.2) with large pointed openings (without glass) on each side. A concrete ceiling with beams supporting the high walls divides the belfry from the “bunker” above. The walls of the belfry are about 120 cm thick, built mainly with ashlars of Bubakk soapstone and serpentinite (exterior) and large blocks of roughly hewn granitic gneiss (interior). Portland cement mortars can be found both in the narrow masonry “cores” and in the relatively wide joints (c. 1 cm)

During the erection of the uppermost section (“bunker”) in 1964, The Restoration Workshop was faced with a serious stone delivery problem. This explains why reinforced concrete was used (fig. 14.3) - a technique which also led to a reduction of the wall thickness by 50% (down to 65 cm). A significant weight reduction was thus achieved (chapter 5.2 and 6.3). The exterior wall was “faced” with ashlars of Bubakk stone, while the interior walls of the turret (spiral staircase) received ashlars of Grunnes soapstone.

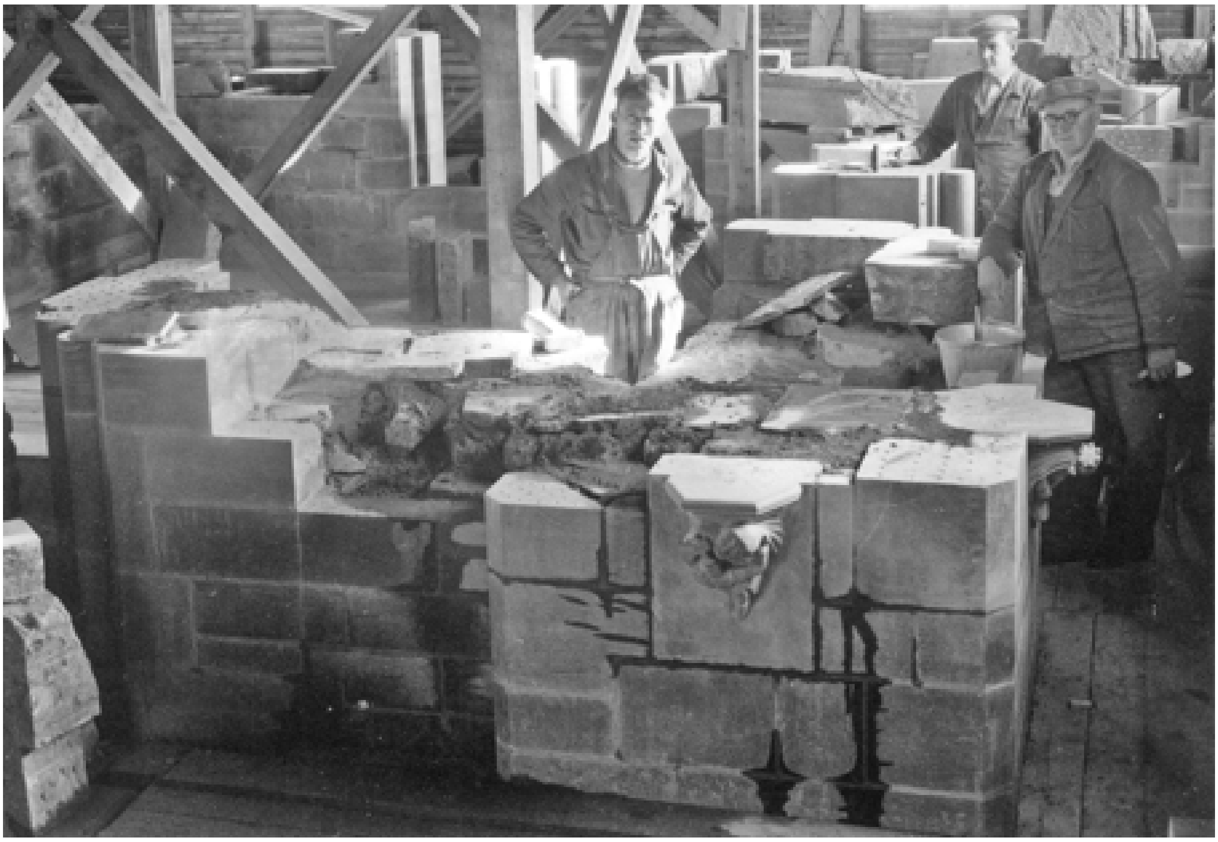


Fig. 14.2: *Masons working on the walls of the belfry in the 1950s. The joints and masonry "cores" were exclusively made using Portland cement mortars (photo: ARW, no. 5194).*

Fig. 14.3: *Interior of the concrete "bunker" above the belfry. The opening leads to the staircase of the turret which is severely damaged because of leaks and alkaline salts (photo: PS 6/91).*

The parapet on top is also largely made of Grunnes stone, but it is capped with diverse varieties of Bubakk stone. Bubakk stone is found in the small towers and cornices below the parapet as well. Joints are exclusively made of hard and inflexible Portland cement mortar.

Representing the end of not only the erection of the tower, but also the completion of 100 years of restoration, the platform was covered with an asphalt/cement mortar in 1968-69. In order to avoid water infiltration, joints between the parapet and the platform were covered with copper plates. Since then the upper section has not been subjected to conservation measures.

The Portland cement used for mortars probably originated from the Kjøpsvik factory in northern Norway. During the 1960s the cement may have contained as much as 0,66 % Na_2O (and 0,66% K_2O) (see chapter 6.3).

14.2 Exposure conditions and water discharge system

At an elevation of 40-50 m above the ground, the exposure conditions are severe. Snow easily collects on the platform and projecting stone details, while every shower thoroughly wets almost all stone surfaces at the top. However, the niches of the small stone towers usually remain dry throughout the year, meaning that soluble salts can accumulate here. Salts can also accumulate on the east-facing, main wall of the tower. This is the only wall not completely exposed to most events of driving rain. The tower being unheated, exterior stonework is frequently subjected to severe events of condensation and white frost.

A major feature is the frequent leaks from joint fissures in the small towers, parapet, cornices and from fissures in the insulation of the platform. The platform has a drainage channel which leads to the one and only downpipe of the tower. Intuition and experience show that only one downpipe is insufficient, but a greater problem seems to be that the inclination of the channel is poor (fig. 14.4). Consequently, water often remains in the channel, causing growth of moss which may clog the downpipe.

A closer look at the design of the tower shows that there are no less than eight (two on each side) large stone gullies in the cornice below the parapet. However, all the gullies are fake, only serving decorative purposes, just like all the fake grotesque gargoyles in the nave (chapter 12). The reason for this is hard to figure out, but it is possible that the inevitable formation of icicles from *working* gullies was regarded as a safety risk for people passing below.

Fig. 14.4: *Drainage channel on top of the southern west tower on a rainy day. The inclination of the channel is insufficient, meaning that water remains and leaks develop through the mortar/asphalt covering (photo: PS 7/91).*

14.3 Indoor climate

In order to understand the weathering of interior walls, a description of the indoor climate of the "bunker" and the spiral staircase is required. As mentioned in chapter 7.5, the climate of most spiral staircases in the cathedral is determined by the outside weather. This is also the case in the southern west tower, which is influenced not only by air drawn in from above (trough a simple wooden construction covering the opening in the ceiling of the concrete "bunker"), but also by air coming in through the opening between the belfry and the staircase.

Under such exposure conditions, it is important to consider the thermal inertia of the walls because they must be regarded as highly susceptible to condensation. On the basis of observations it is possible to describe the general annual cycle like this:

- *Winter*. Generally cold air and cold walls. During milder weather breaks, condensation often occurs. Even white frost can be observed if the weather turns rapidly cold after a major condensation event.
- *Spring*. The air temperature rapidly rises, while the walls warm up much more slowly. Spring condensation is thus likely to occur. Spring condensation may sometimes be so severe that water actually runs down the stairs. It is also possible that the latter phenomenon may be attributed to the melting of ice formed in the walls (from leaks and interstitial condensation) during exceptionally cold winters.
- *Summer*. The air is generally warm and so are the walls. Condensation nevertheless occurs during humid weather after chilly periods.
- *Autumn*. The air temperature rapidly decreases, while the walls remain warm much longer. This means that condensation usually takes place only in late autumn (November-December), when mild and humid weather conditions occur after cold periods.

When referring above to condensation, it should be pointed out that large amounts of hygroscopic salts sometimes make it difficult to distinguish between "real" condensation and dissolution of the salts above their respective equilibrium relative humidities. It should also be noted that in periods with major water leaks, the whole picture becomes totally distorted.

14.4 Exterior weathering phenomena

When excluding the extensive flaking of strongly weather beaten Bubakk stone used for capping the parapet (see chapter 9.4), the weathering phenomena at exterior areas can be subdivided in three categories:

Joint fissures. The exposed small towers, parapets and cornices have extensive joint fissures, through which water infiltration can take place. The most problematic fissures seem to be those between stones in the cornice (fig. 14.5).

Calcite crusts. Such crusts unequivocally occur below joints and points of water infiltration, both on the small towers and masonry below the cornice (fig. 14.5).

Salt efflorescences, often followed by granular disintegration and flaking. In the sheltered niches of the small towers, salts can accumulate and act on the stones. Analyses show that sodium carbonates, sodium sulphates and aphthitalite are the main salt phases. Where Grunnes soapstone has been used, there is usually some flaking associated with the salts (see chapter 9.5). Large amounts of salts can, moreover, be found on the main east wall of the tower. Although they have not been analysed, we may assume that these salts are also alkaline. Occurring mainly on or along joints, the salts on the east wall flourish especially in dry spring weather, while they are absent in humid periods. In the latter periods, the hygroscopic behaviour of the salts can make the wall look completely wet (fig. 14.6). These observations show how difficult it is to distinguish between "real" condensation and dissolution of hygroscopic salts. As can be seen, the overall weathering situation is in principle similar to the situations associated with leaks from gangways in the choir and nave.

Fig. 14.5: *Cornice on the north side of the southern west tower. The picture shows the only downpipe of the tower, a fake stone gully and calcite crusts associated with joints. The joints in the cornice have all got fissures, through which water can infiltrate (photo: PS 5/96).*

Fig. 14.6: *The east wall of the southern west tower. Left: Large amounts of alkaline salts (white patches) prevail in dry spring weather (photo: PS 3/94).Right: Due to their hygroscopic behaviour, the salts have dissolved during a warm and humid day in late august (photo: PS 8/95).*

14.5 Interior weathering phenomena

The interior situation is characterised by extreme salt weathering. Practically all surfaces of the interior staircase from the belfry upwards have disintegrated to such an extent that there are but a few toolmarks left on the stone - less than 30 years after the erection of the tower.

Starting with the "bunker" on top, it can be observed that leaks have led to the deposition of calcite crusts below fissures and cracks in the concrete. The numerous fissures indicate that the quality of the concrete is rather poor. Sodium carbonates tend to crystallise in an almost concentric manner around the calcite crusts (fig. 14.7). This is because of capillary forces and the fact that sodium carbonates are much more soluble than calcite. Needles, whiskers and loosely attached crusts of natrite prevail during wet periods, while in dry periods, e.g. spring and early summer, natrite dehydrates to form powdery efflorescences of thermonatrite. Whereas natrite quickly forms when water evaporates after wet periods, it normally takes quite some time (days, weeks) before complete dehydration to thermonatrite takes place.

Calcite crusts are absent on the walls of the staircase, but sodium carbonates behave in the same manner here. In addition to natrite and thermonatrite, smaller amounts of trona and aphthitalite can be found at several spots. The weathering forms associated with the salts range from granular disintegration to the formation of extensive flakes (fig. 14.8).

Although it seems to be clear that the actions of alkaline salts are responsible for the severe weathering, it should be remembered that the walls are made of an apparently very vulnerable stone, namely Grunnes soapstone (see also chapter 9.5). In this connection it is interesting to observe that a few blocks of Bubakk serpentinite in the staircase are relatively unaffected by salts.

Fig. 14.7: *Wall of the concrete "bunker" of the southern west tower. A leak has brought large amounts of salts to the surface. Explanations: lekk = fissure from which water is brought to the surface, k = calcite, n/t = natrite/thermonatrite (photo: PS 3/93).*

14.6 Analysis of weathering rate vs. climatic conditions

Since the weathering produces soapstone powder which collects on the steps, the staircase is an excellent place to study how fast and under which ambient climatic conditions the weathering takes place. In order to investigate these phenomena, soapstone powder was collected and weighed roughly on a monthly basis between 1991 and 1993. In 1992 measurements of interior temperature and relative humidity was also carried out (thermohygrographs). These measurements were, moreover, related to precipitation and followed by regular observation of salt habits, leaks and condensation events (see fig. 14.10).

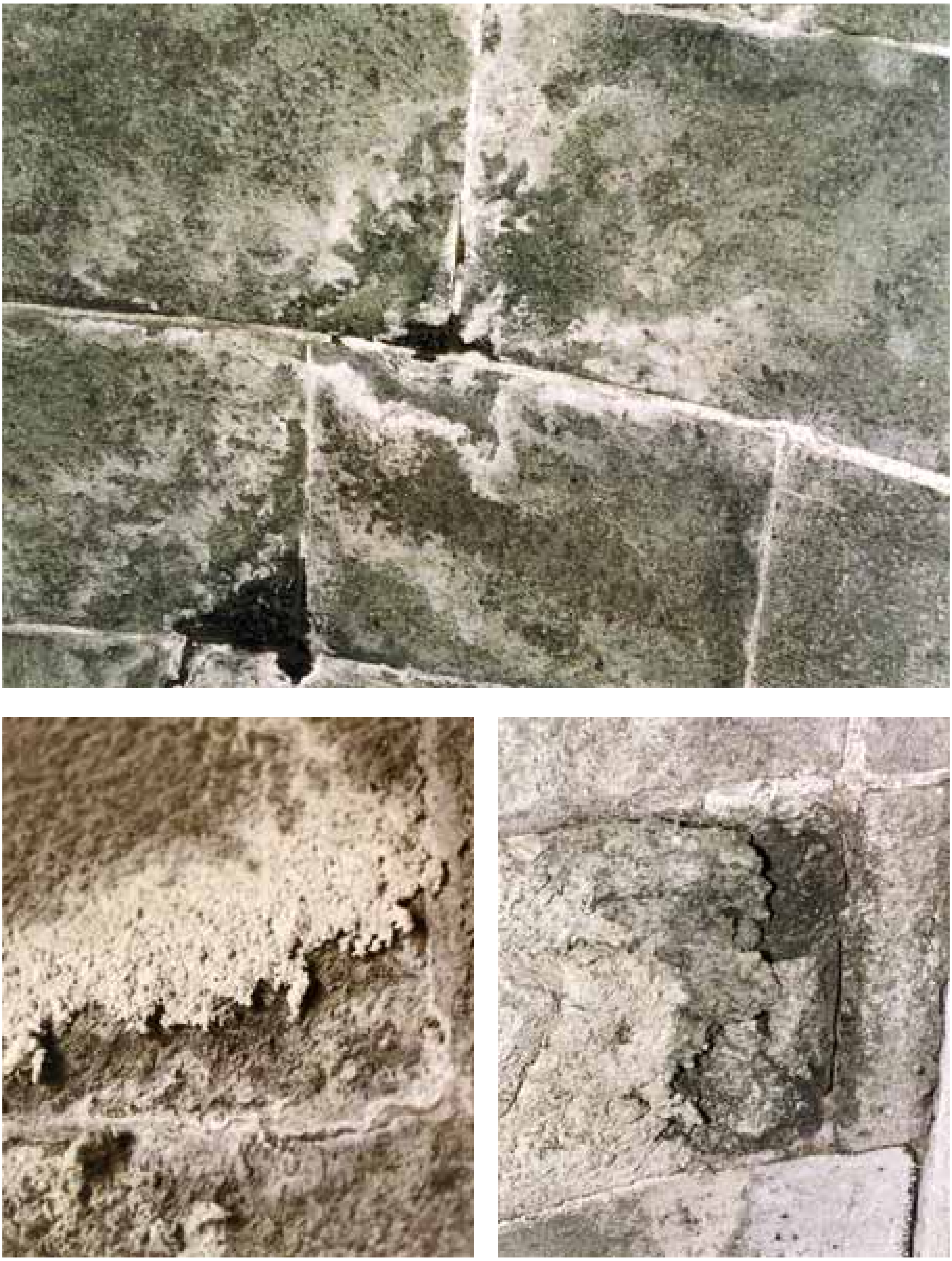


Fig. 14.8: *Weathering due to alkaline salts on the walls of the staircase of the southern west tower. Top: Efflorescences of natrite forming around the joints. The dark areas represent leaks coming to the surface (photo: PS 6/91). Left: Loosely bound crust of thermonatrite dehydrated from natrite (photo: PS 5/96). Right: Large flake about to fall off. Note the salt efflorescences on the surface (photo: PS 2/91).*

Fig. 14.9: *Part of the wall in the staircase on a day with white frost. The white spots are not salts, but ice formed on dolomite grains present in the Grunnes soapstone. The matrix of the soapstone tends to weather more rapidly than the dolomite grains (photo: PS 12/96).*

Collected soapstone powder and surface recession rate

Powder was collected from the steps between the entrance to the belfry and the entrance to the concrete "bunker" above. The height is about 14 m, which corresponds to a surface area of c. 60 m^2. From this area 8 kg soapstone powder was collected in both 1991 and 1992, while 5-6 kg fell in 1993. These figures represent a calculated annual surface recession rate of about 0,05 mm. Assuming that the annual surface recession rate has been constant over the last 30 years, the whole area has lost the outermost 1,5 mm of stone - a figure which roughly corresponds with observations. Assuming that the recession rate is also going to be constant in the future, a predicted loss of 5 mm over the next 100 years can be made. This seems relatively little and not critical when considering that the staircase is an anonymous part of the cathedral.

However, it is incorrect to assume a constant surface recession rate, both with regard to where and in which forms and seasons weathering actually takes place. The latter phenomenon becomes evident when looking at the monthly loss of material and comparing the loss with the seasonal climatic variations, as exemplified by what happened in 1992.

Climatic conditions, salt habits and loss of material

1992 was generally a relatively mild year, but not as warm as the late 1980s and 1990-91. The annual precipitation was a little less than 900 mm, but although this is relatively normal, the distribution throughout the year was quite unusual. January for instance was very wet and mild (200 mm, mostly as rain), while April - and especially September - were very dry months. The summer was rainy and chilly, with August as the worst month. Early October had a heavy storm, but otherwise the autumn weather was rather pleasant before the temperature dropped markedly in late October. Leaks were naturally associated with the wet periods, while frequent events of condensation roughly coincided with the same periods as mentioned in chapter 14.3 (winter/spring, August, late autumn).

Natrite and thermonatrite, considered the most damaging salt pair in this case, behaved roughly in the following manner:

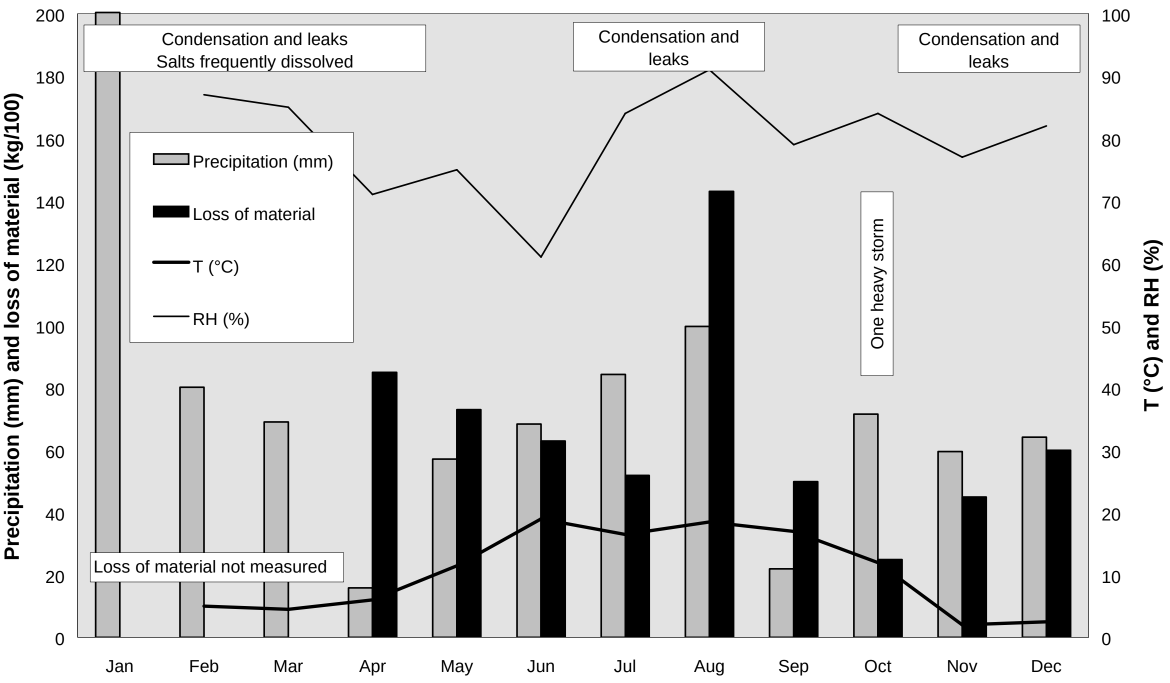


Fig. 14.10: *Southern west tower, upper part of staircase. Loss of material pr. month compared with climatic conditions (mean monthly values). Note that the loss of material is high in - or just after - wet periods. This observation indicates that crystallization of natrite from solution (leaks, condensation) is the main weathering mechanism. Thermohygrograph readings, collection of material and some observations by Erling Refseth.*

- *Winter*. The salt was in solution during the wettest periods, subsequently crystallising as natrite when the walls dried out. Thermonatrite could only very rarely be found.
- *Spring/early summer*. Natrite prevailed until April/May, subsequently dehydrating relatively slowly to form thermonatrite when the fine summer weather took over in May/June.
- *Mid-summer/early autumn*. During the wet summer the salts went into solution. Natrite reappeared in shorter, dry periods, but it was not until September that it dehydrated on a large scale to form thermonatrite.
- *Late autumn/early winter*. Thermonatrite went into solution after the fine early autumn, especially during the heavy storm in early October. Natrite subsequently took over as the main phase, but in several shorter periods the walls were too wet for salts to crystallise.

As can be seen in figure 14.10, the monthly loss of material was steadily decreasing during the fine spring and early summer, before rising dramatically during the wet August. Then it dropped strongly in the dry September and partly wet October, before once more increasing in November and December.

Interpretation of weathering mechanisms

The largest material losses took place in, or just after, the wettest periods. This indicates that the most active weathering occurs when natrite crystallises directly from an evaporating solution.[1] However, in order to thoroughly understand the weathering mechanisms, several additional phenomena should be taken into account (see chapter 3). Above, we have concentrated on the pressure which develops when natrite crystallises, but not considered possible build-up of hydration pressure when thermonatrite eventually takes up water and forms natrite. This mechanism could - although unlikely - take place as a result of daily variations in relative humidity (dry days and humid nights). Hydration of thermonatrite has in fact never been ob-

Fig. 14.11: *Northern west tower on a day with severe white frost (photo: PS 12/96).*

served, neither on the walls of the staircase, nor on other walls of the cathedral. This indicates that hydration is such a slow process[2] that frequent leaks, run-off and condensation episodes prevent or distort the process. Moreover, it is extremely unlikely that direct crystallisation of thermonatrite can take place in the Trondheim climate. That would demand a (theoretical) temperature of some 32°C.[3] As a conclusion it is therefore very important to consider leaks and condensation when interpreting salt weathering mechanisms in the Trondheim climate.

Since the temperature in the staircase frequently drops well below zero, frost should also be considered as a possible weathering mechanism. Recalling that damaging frost events seem to be more severe when salts are present (see chapter 3), there is reason to believe that frost is important in this particular case. An example is a strong frost event in December 1996. After a short, very cold period, mild weather occurred and rendered most of the unheated parts of the cathedral very wet due to condensation. Then, before the walls dried out, the weather changed abruptly becoming very cold again. Hence, the condensation became white frost, even inside the staircase of the southern west tower (fig. 14.9). Although the loss of material was not recorded afterwards, it cannot be ruled out that these rather unusual circumstances were particularly damaging.

14.7 Comparison with the northern west tower

Although its concrete "bunker" is a little smaller, the northern west tower (completed in 1964) was built in roughly the same way as its southern counterpart (fig. 14.11). However, despite leaks and widespread occurrence of alkaline salts, the weathering takes place at a much lower rate in the northern tower.

The most likely reason why the weathering is less intense seems to be connected with the water discharge system. Whereas the drainage channel on the platform of the southern tower has insufficient inclination, this is not the case in the northern tower. Although the northern tower also has only one downpipe, one of the gullies has been put to work, implying that during heavy showers water is effectively carried away from the platform. Moreover, the platform has been covered by a thick layer of asphalt which is in a much better condition than the asphalt/cement mortar on the southern tower.

Together, these features prevent leaks as extensive as those observed in the southern tower. There are for instance only very small leaks observed on the walls of the concrete "bunker". Another reason for the relatively good condition is the fact that the walls of the staircase were not built of the vulnerable Grunnes soapstone, but of Bjørnå soapstone and an unknown harder stone. The latter stone seems especially resistant to salt weathering.

14.8 Summary and possible conservation strategy

The intense salt weathering in the staircase of the southern west tower seems dramatic, yet it does not involve any loss of decoration or other valuable features. Evolving mainly because of severe leaks through concrete and Portland cement mortars, the weathering is especially active during and after rainy periods or periods with frequent condensation events. This indicates that crystallisation of natrite from evaporating solutions is the most important weathering mechanism. Natrite, its dehydrated counterpart thermonatrite, and the minor amounts of trona and aphthitalite observed, originate from the enormous amount of Portland cement in the tower.

Given that the upper section of the tower should be preserved as it is today, several measures may help to reduce the weathering rate:

Eliminate leaks. In order to eliminate leaks, urgent measures ought to include improving the water discharge system and sealing joints. The first measure is relatively simple because it involves improving the inclination of the water channel on the top, covering the platform with a proper material and putting one or more of today's fake stone gullies to use.

Sealing joints is much more difficult, primarily because it is uncertain as to what is causing the joint fissures to develop. One reason is, as in the nave (chapter 12), that hard and inflexible Portland cement mortars are unsuitable. However, with the elevation of the tower in mind, consideration must also be given to pronounced seasonal thermal movements, wind action, frost, as well as combinations of these factors and possibly uneven settlement. Moreover, it is hard to remove and replace joints at this elevation without major scaffolding expenses. Hence, an important task in the near future - also concerning most other parts of the cathedral - ought to be research into such issues (see also chapter 20).

Remove salt efflorescences. Considering the almost inexhaustible source of alkaline salts represented by the concrete "bunker" and the joint system, it is impossible to contemplate major quantitative reductions of salts. However, given that leaks can be virtually eliminated, it may be wise to at least remove (brush away) salts from the walls of the staircase. This is because salts will dissolve and recrystallise due to condensation events even if leaks are completely eliminated.

Reduce the number of condensation events. Reducing the risk of condensation is a difficult issue, not least because it is hard to imagine using heating and dehumidifiers in this anonymous part of the cathedral. A possibility would be to investigate the ventilation of the tower. Perhaps it is possible to reduce the risk of condensation by opening and closing the right doors at the right times of the year?

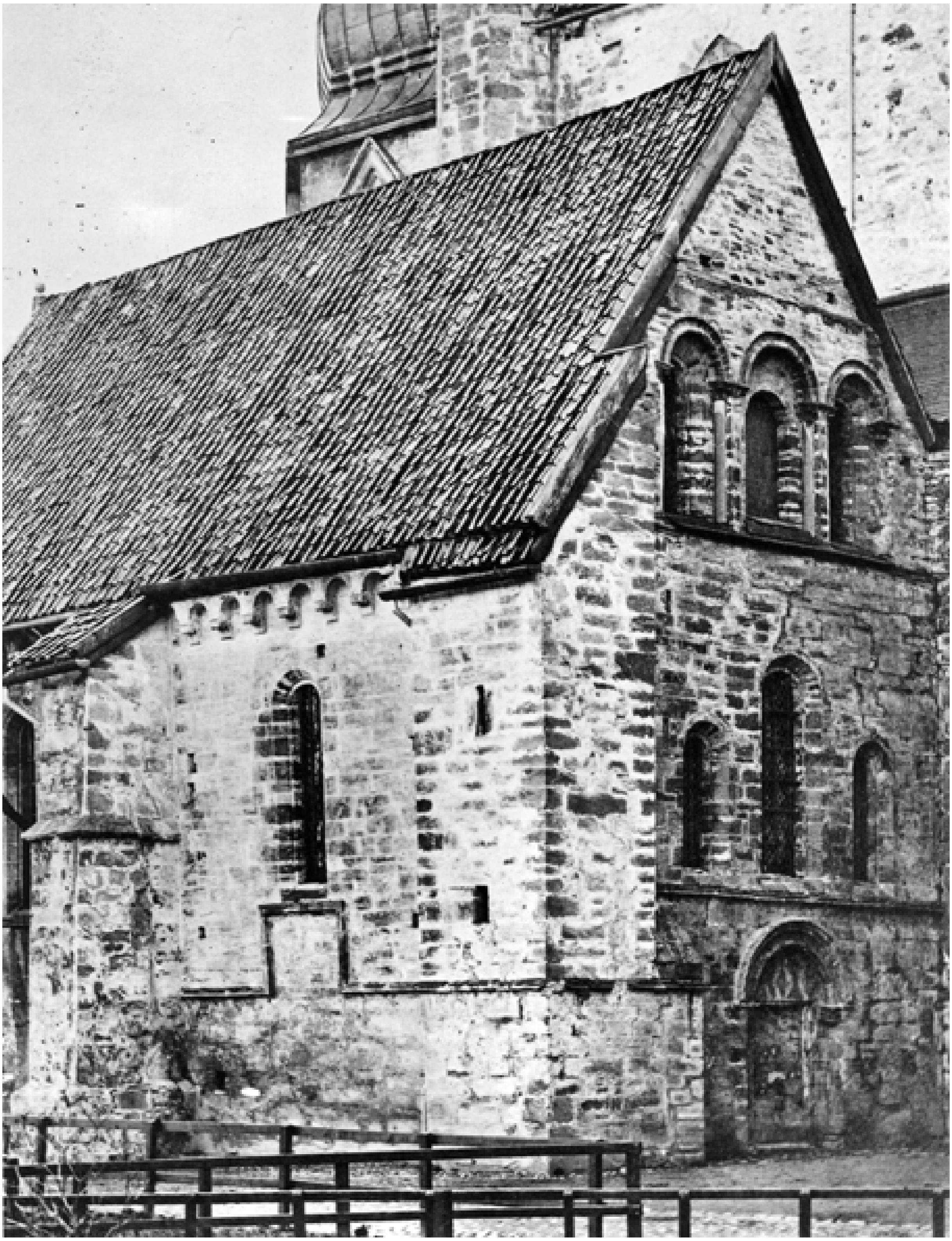


Fig. 15.1: *The poor condition of the chapter house before architect Schirmer's complete restoration in 1869-71 (photo: ARW, no. 738).*

Chapter 15

Weathering of the west wall of the chapter house

The Transitional chapter house was heavily restored by architect Schirmer in 1869-71 (fig. 15.1-2). The west wall was nearly completely demolished and rebuilt with a combination of old and new materials and may therefore be treated as a Neogothic structure. Due to the fact that the restoration, as one of the first in Norway, involved the use of mortars based on Portland cement (chapter 6.3), the west wall today suffers from severe salt weathering. On the basis of historical sources, it can be seen that the weathering has developed over a long period of time and that several unsuccessful interventions have been undertaken in order to stop all the water leaks that inevitably followed the work of Schirmer.

A comprehensive investigation of the restoration history and detailed mapping of weathering forms were carried out in 1995-96. The results are documented in a special report,[1] but the most important maps (stone types/restoration history and weathering forms) can be found in appendix 4.

15.1 Design and exposure conditions

Situated on the north side of the cathedral - in the shadow of the choir and transept, the chapter house appears to be relatively well protected from precipitation. This is the case with regard to the apse and north wall, but for the west wall and flanking towers, the situation is entirely different.

The west wall is divided in three sections. The upper section includes a gable triangle with a group of ornamented openings, the intermediate section has plain windows just below the vaulting of the building and the lower section has a partly restored Romanesque portal. A broad sill below the uppermost openings and a string course above the portal divide the wall horizontally. The northern tower has a staircase inside, whereas the southern tower is not accessible.

Acting as collectors of precipitation (fig. 15.6) and being without metal cover, the horizontal members, as well as the towers, must be regarded as the weak parts of the chapter house. Since the wall is practically never exposed to sunshine, it is one of the coldest parts of the cathedral. Hence, the interior surfaces are occasionally affected by condensation events, especially on warm, humid summer days. The interior wall has also been affected by soot from the central heating system (which is located in the cellar) due to via earlier ventilation openings in the floor(!).[2]

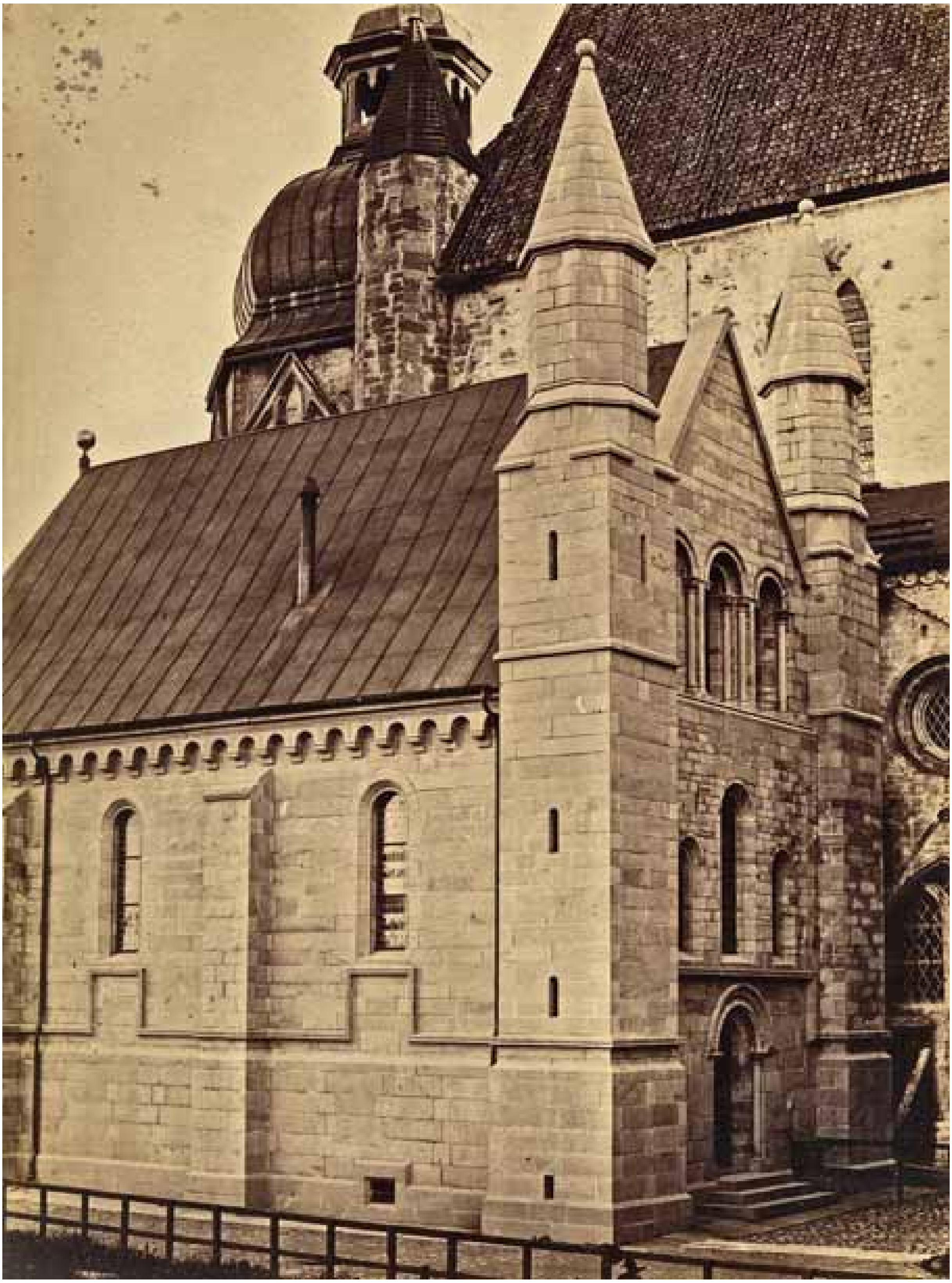


Fig. 15.2: *The chapter house just after the completion of Schirmer's restoration in 1871. It is almost a completely new building! Note the wet spots on areas with reused stones. The spots are probably caused by hygroscopic salts, maybe from cleaning with acid/lye (photo: ARW).*

15.2 Weathering and conservation history 1869-1996

As the rest of the chapter house, the exterior masonry of the west wall consists mainly of the hard and durable Hovin metasandstone (from 1869-71). However, the decoration in the upper group of openings, the intermediate masonry, the portal and the interior stonework are made of a mixture of old and new greenschist and soapstone (appendix 4). During the restoration in 1869-71, the towers and the two upper sections were rebuilt using lime mortars in the masonry cores and lime cement mortars in the joints.[3] Most of the old stones seem to have been heavily redressed during this restoration. Although there are no written sources to confirm it, it is assumed that medieval decorations not replaced or redressed were cleaned with hydrochloric acid, perhaps in combination with sodium hydroxide.[4]

Water leaks appeared a few years after Schirmer's restoration. Photographs show extensive white crusts on the towers in the late 1870s. These crusts were removed around 1890, probably as part of the interventions undertaken in order to stop the leaks.[5] The problems reappeared before 1926 when the joints in the stone capped towers had to be repointed because of the growth of bushes(!) and formation of joint fissures (fig. 15.3).[6]

The next intervention followed in 1932 when copper was applied onto the gable copings, successfully preventing further leaks (fig. 15.4-5).[7] Horizontal members and other parts of the masonry were repointed with Portland cement mortars.[8] These measures were mainly undertaken in order to improve the poor condition due to “humidity” (i.e. salts) on the interior wall (fig. 15.9). Interior surfaces were subsequently cleaned by unknown means.[9] The ventilation of the room was also improved since stagnant air was considered an additional reason for the poor condition.[10]

Fig. 15.3: *Bushes growing on the north tower of the chapter house before intervention in 1926. The repairs involved mainly repointing joints and removing white crusts (photo: ARW, no. 3006).*

Fig. 15.4: *Corner between the south tower and the gable of the chapter house. Note the copper construction applied in 1932, successfully preventing further leaks (photo: PS 9/95).*

More wide ranging measures were carried out in 1948 when joint fissures again had given rise to severe water leaks. The stone capped towers were pulled down and before they were rebuilt, a layer of asphalt was added just below the pyramidal parts in order to prevent further leaks (fig. 15.8). The Portland cement mortar used for rebuilding the towers was mixed with a waterproofing agent - and this mortar was also used for repointing other joints in the wall.[11] No specific interventions have been carried out over the last 45 years - except for occasional removal of calcite crusts on the masonry of the northern tower.

Fig. 15.5: *The gable triangle of the chapter house under restoration in 1932 - a task involving removal of white crusts and application of copper cover on the copestones. (photo: ARW, no. 3856).*

15.3 Present weathering situation

The present weathering situation is principally the same as before 1890, 1926 and 1948: The towers have developed joint fissures which have resulted in water leaks, extensive formation of calcite crusts (fig. 15.8) and moderate salt weathering on the interior walls of the northern tower's staircase. The joints in the broad sill below the upper group of openings have weathered away, and the interior west wall is almost completely covered by salts (fig. 15.11). Sheltered parts of the exterior wall suffer from flaking, delamination and the presence of black crusts. However, the description below will not focus on exterior weathering phenomena.[12] Instead attention will be paid to interior salt weathering.

There are in principle two different weathering situations inside. One is related to the upper section and the corners of the wall, the other to the lower section (see appendix 4). The former situation is obviously connected to leaks from the exterior sill and various parts of the towers. It is characterised by extensive flaking and exfoliation close to (and on) the vault, as well as by peculiar “pop-outs” along mortar joints and fissures in the greenschist ashlars (fig. 15.12). Flaking and exfoliation are always connected with salt efflorescences/subflorescences, whereas the pop-outs consist of salt crusts which cover a mixture of stone powder and salt. Most of the sound parts of the wall are also covered by powdery salt efflorescences which are very tightly bound to the surface of the stone. There is also a thin layer of soot or dust covering the wall.[13]

Whereas the upper section was probably pulled down and completely redressed during the restoration (1869-71), the lower section was only partially redressed and cleaned in order to

Fig. 15.6: *The chapter house today. Note the extensive white calcite crusts below the stone caps of the towers.This shows that the asphalt insulation from 1948 has been ineffective. Note also that thawing takes place from the broad sill (photo: PS 2/95).*

Fig. 15.7: *The chapter house during an event of late autumn condensation. Note that condensation is restricted to unheated parts of the building. The location of the vaulting can also be seen (photo: PS 11/95).*

Fig. 15.8: *Left: White calcite crusts on the southern tower. Note the layer of asphalt which has been pressed out. The layer was applied in 1948 (photo: PS 9/90). Right: “Stalactite” collected from just below the stone cap of the south tower (photo: PS 1/91).*

Fig. 15.9: *The north west corner of the chapter house before cleaning of the walls took place in 1932. Note the extensive distribution of salts (photo: ARW, no. 3070).*

Fig. 15.10: *The west wall of the chapter house, probably in the early 1960s. Note that the extent of salt efflorescences has been reduced since 1932 (photo: ARW, no. 7019).*

Fig. 15.11: *Left: The south west corner of the west wall of the chapter house during an event of summer condensation. Note the wet (dark) spots which are caused by dissolution of hygroscopic salts, mainly mirabilite (photo: PS 8/95). Right: The corner in the winter time when the cathedral is heated. The wet spots have disappeared (photo: PS 1/95).*

remove whitewash. Hence, many “old” weathering forms (due to rising damp and leaks) survived Schirmer’s restoration. The weathering is characterised by deep delamination of the greenschists, but no significant loss of material can be recorded at present - the situation is in therefore quite stable. There are, however, a lot of salts also on this part of the wall - mostly thenardite/mirabilite.[14]

15.4 Sources, distribution and crystallisation of salts

The salt system in the upper section is complex, but it includes two dominant species: trona and aphthitalite. The crusts related to the pop-outs consist of these salts, as needle-like trona and small, hexagonal crystals of aphthitalite. Trona is also present in efflorescences and subflorescences on the vault and close to joints on the wall itself, whereas in the central, rather sound part of most ashlars, powdery thenardite and/or needle-like mirabilite are the most frequent species to be found.

Although it is assumed that hydrochloric acid, maybe in combination with sodium hydroxide, has been used to clean ribs and decorations, no trace of chlorides has been detected. However, the lack of chlorides may be attributed to the actual sampling procedure applied during the investigation, insofar as only distinct efflorescences and crusts were sampled and analysed. Given that chlorides remain in solution throughout most of the year, it is unlikely that they would have been detected using this procedure.

The occurrence of highly hygroscopic salts, e.g. chlorides, can be verified by observing the ribs of the vaults. Some stones in the ribs have wet spots throughout the year, while wet spots on other parts of the wall are only seen during "near" condensation events (fig. 15.11). During such events, for instance in August 1995, the central part of many ashlars become very wet, which indicates that the relative humidity close to the wall becomes high enough for mirabilite to dissolve (theoretically some 90-95% at 20-25°C). Parts of the trona/aphthitalite crusts may also dissolve during such events. They do, however, not dissolve completely and after a couple of days with a drier indoor climate they tend to retain their former structure.

Water infiltration from the broad sill (fig. 15.13) and the towers seem to be responsible for this problematic situation, but water has not actually been observed running down the wall inside. Hence, slow water seepage in the joint system seems able to mobilise and transport the large amount of salt present. It should be remembered that the broad sill is affected by virtually every event of precipitation.

There is little doubt that alkaline components in the Portland cement and lime cement mortars are the main sources of the salts. The interesting questions are why trona has formed instead of thermonatrite/natrite, why aphthitalite appears to be so important and why thenardite/mirabilite occur on the central part of ashlars. Earlier investigations have shown that trona and aphthitalite form a common salt pair when water percolates through the bulk volume of a wall with Portland cement mortars. The actual mechanisms of formation are complicated, but strongly dependent on solution chemistry and temperature.[15] Other investigations have shown that chloride (as sodium chloride) may promote the formation of trona.[16] In this connection it should be noted that instead of trona, thermonatrite/natrite occur on the interior walls of the northern tower. The tower has a conservation history that is similar to other parts of the west wall. However, the climate in the tower is entirely different from the church room. It is humid and cold throughout the year. Moreover, it is highly unlikely that the walls of the tower have been cleaned by hydrochloric acid. The occurrence of thenardite/mirabilite can be explained by reaction between sodium carbonates from mortar and sulphates present in the materials. A small portion may also originate from the greenschist itself (cf. chapter 8.1).

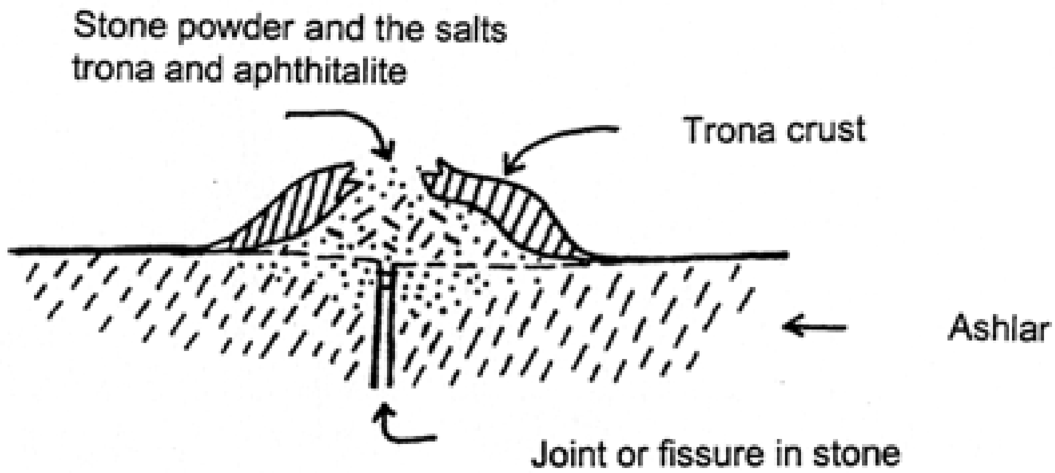


Fig. 15.12: *The west wall of the chapter house. Sketch of pop-outs consisting mainly of the salts trona and aphthitalite. When the pop-outs break up (looking like small volcanoes) granular disintegration of the stones can be seen within.*

Fig. 15.13: The west wall of the chapter house. Open joints in the broad sill below the upper group of openings are the main reason why moisture enters the interior of the wall (photo: PS 9/95).

15.5 Summary and possible conservation strategy

Joint fissures, water leaks and salt formation on the west wall of the chapter house appeared as soon as the restoration of Schirmer was completed. Since then parts of the wall have been repaired every 20-40 years (1890, 1926 and 1948). During these interventions much effort was unsuccessfully made to prevent further leaks from the towers. The broad sill below the upper group of windows appears to have been left to develop ever increasing joint fissures and water leaks, but the joints were probably repointed during the intervention in 1932. During this intervention the interior was unsuccessfully cleaned as well.

The interior wall and the towers have weathered rapidly since 1932 and 1948, respectively. The interior is characterised by intense salt weathering - and as the main salt is trona, Portland cement used during Schirmer's restoration and subsequent interventions must be regarded as the principal salt source. The combination of severe exposure conditions and hard, inflexible joints of Portland cement mortar seem to have contributed significantly to the extensive joint fissures, leaks and calcite crusts on the towers.

Since earlier conservation measures have failed, a new approach ought to be considered when planning future interventions. Water leaks should be eliminated as fast as possible. For this purpose it is probably necessary to apply lead or copper on the most exposed parts, i.e. the towers and the broad sill below the upper group of openings. Since water also penetrates open joints in the vertical part of the northern tower, it may be necessary to remove the joints which were applied during earlier repointing operations. Removal of the joints is a difficult measure and it will be treated on a more general basis in chapter 20. Another difficult issue is which type of mortar should be used for new repointing operations. Whether lime mortars can be used is probably dependent on the nature of the joint system, i.e. whether there is a lot of cement in the deeper part of the joints or not.

Since interior salt weathering seems to be strongly dependent upon condensation events, it is insufficient to only remove as much salt as possible (by dry means, brushing etc.). The indoor climate has to be carefully controlled as well. In order to maintain a suitable indoor climate, a programme aiming at monitoring the present annual variations should be carried out.[17]

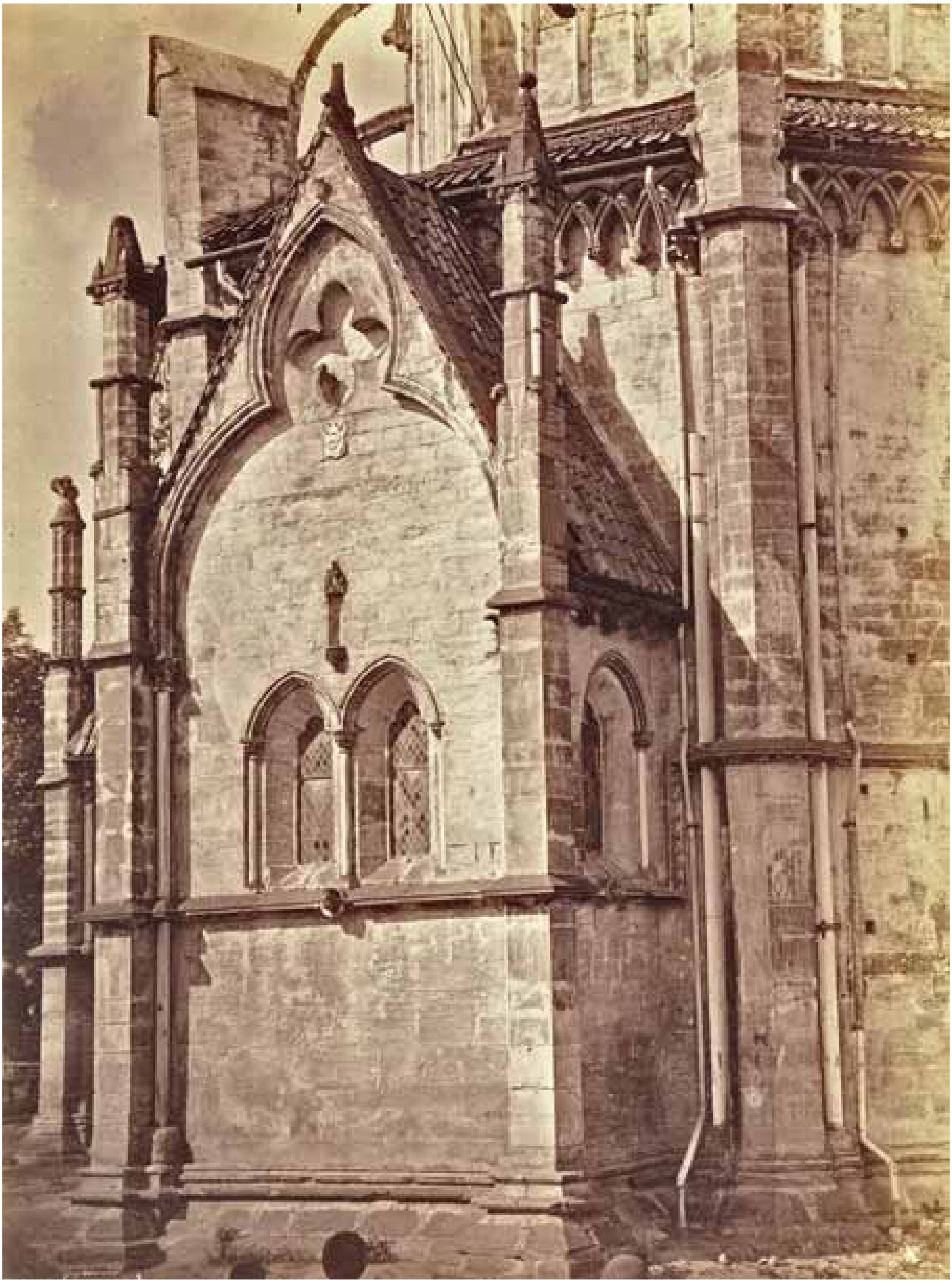


Fig. 16.1: *The east chapel just before the restoration of Krefting and Christie in 1871-73 (photo: ARW, no. 7).*

Chapter 16

Weathering of the east chapel of the octagon

The restoration of the east chapel of the octagon followed immediately after the restoration of the chapter house. Even though the two restorations are close in time, they are very different with regard to the actual measures undertaken. Architect Schirmer had to resign after his hard restoration of the chapter house, leaving the place open for architect Chr. Christie. However, before Christie appeared in 1872, captain O. Krefting was in charge for a year, leading to a relatively moderate restoration of the east chapel. Therefore the present weathering situation must be viewed in the light of centuries of various interventions and weathering problems. In fact, evidence exists from as early as in the Middle Ages - although the last period of 125 years is most important to consider. In this period it is also possible to thoroughly follow the development of black crusts (photos).

Only the east wall is described below, but in order to achieve a thorough understanding of the weathering, a comparison with the north and south chapels will be given. All the chapels have been studied over a period of several years, and detailed maps showing building history, stone types and weathering forms can be found in appendix 4.

16.1 Design and exposure conditions

Like the south and north chapels of the octagon, the east chapel is a small Early Gothic construction framed by a heavily profiled base, two pillars with pinnacles and a gable triangle with copestones (fig. 16.1-3). A string course divides the exterior into a lower and upper section. Four pointed windows with dog tooth ornamentation provide light to the interior. The gable triangle above the windows comprises a moulded trefoil arch and a four-leafed clover form, whereas on the north and south sides there are decorated cornices. Directly above the windows of the east wall there is a small niche with a late medieval canopy.[1]

The interior is divided into a lower and upper part by a quadripartite rib vault and there is a large pointed arch between the chapel and the ambulatory (fig. 16.11). Since the opening towards the loft is a small, four-leafed clover form which has been closed for long periods, the indoor climate of the loft is influenced chiefly by natural climatic variations.

The c. 1 m thick ashlar masonry with rubble cores, as well as all decorations, were originally made of greenschist from Øye. The stones may have been provided directly from the quarries, but it is also possible that some of them were reused from the cathedral's precursors. Marble columns were carved in stone from the Sparbu and Almenningøya quarries. Due to later interventions (mentioned below) there are at present several additional stone types to be found in the chapel (see also appendix 4).

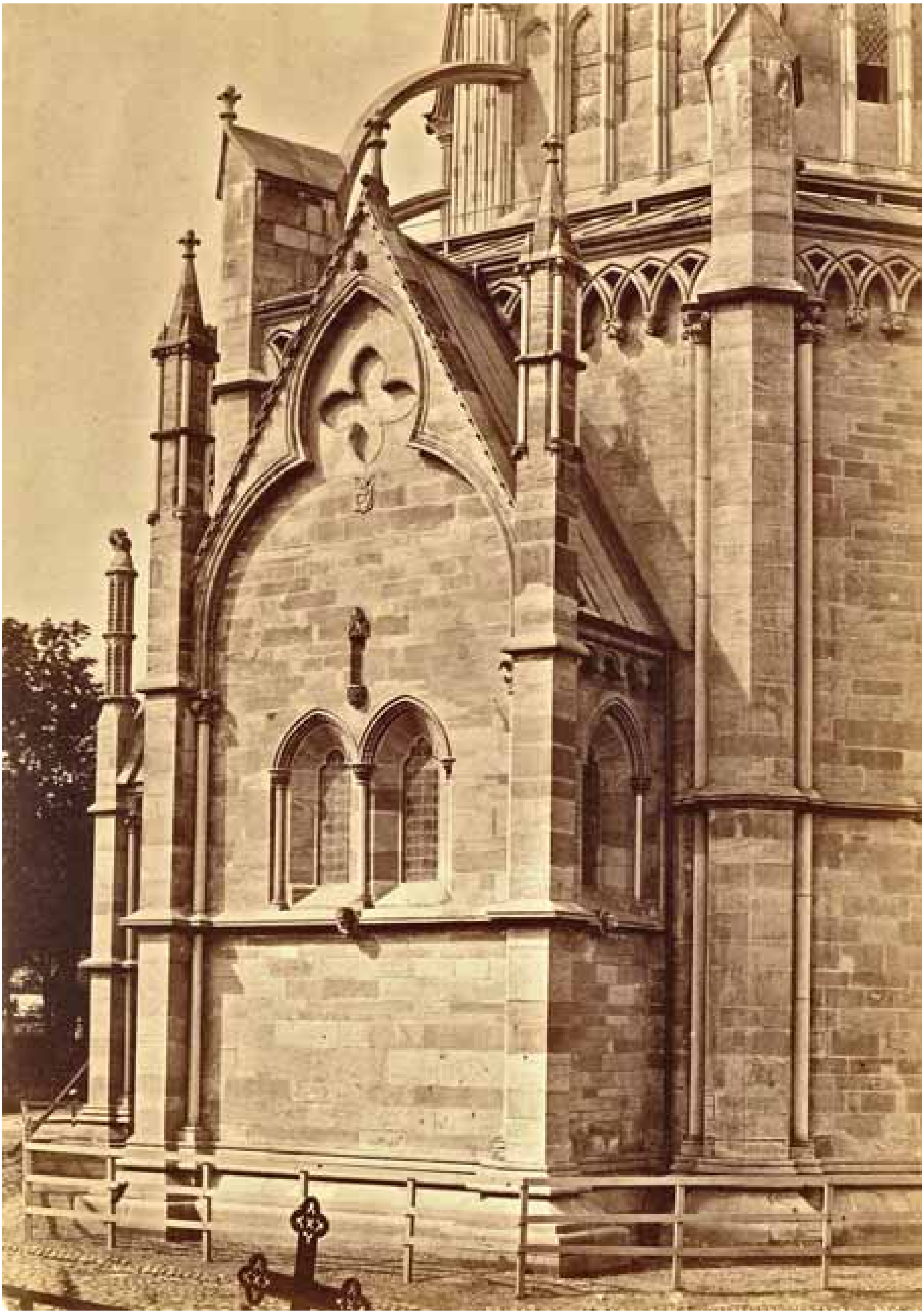


Fig. 16.2: *The east chapel after the restoration in 1871-73 (photo: ARW).*

Situated at the east end of the cathedral, the chapel is in general protected from precipitation. Horizontal elements, gable copings, parts of the pillars and other projecting wall members are the only features affected by most events of rain and snow (fig. 16.6-8). Direct rain has never occurred on other parts the east wall over the last 6-7 years. However, due to the complex design several parts are exposed to run-off - especially the pillars and the corners between the pillars and the copestones. Joint fissures in the string course and between copestones also give rise to minor run-off down the wall. Condensation and white frost occur preferentially on parts which are unheated from inside (fig. 16.7).

16.2 Weathering and conservation history 1328-1996

The weathering and conservation history of the east chapel is long, and various events from as early as the 14th century may be traced.

The Middle Ages to the restoration in 1871-73

After erection in 1183-90, the first really damaging event that affected the chapel must have been the disastrous fire in 1328. On medieval stones in the loft there are distinct fire marks (brown colour), but these may also have been caused by subsequent fires. The gable was probably rebuilt after the 1328-fire, as indicated by the typical 14th century canopy above the windows.[2]

The condition was probably rather poor at the beginning of the 16th century because Archbishop Erik Valkendorf undertook a thorough restoration of the gable in 1510-20. He even signed the work by placing his coat-of-arms (today a copy) just below the four-leafed clover form. It is hard to estimate how much work was actually done, but due to the somewhat “clumsy” form of the trefoil arch, it may be assumed that Valkendorf rebuilt the whole gable.[3]

Apart from the roof, the chapel appears to have escaped the disastrous fire in 1531. After the Reformation (1537), the function of the chapel changed and it was no longer used for services, but as a burial chapel. The first burials took place in 1650, and in 1674 the chapel was closed by large double doors which may have helped to save the interior from the following fires in 1708 and 1719.[4]

The stonework was strongly affected by post-Reformation measures. It was whitewashed as early as the 1630s - a practice repeated several times until the 19th century, especially after fires. The last “beautification” took place before the coronation in 1818 when the walls were painted grey with a “water and glue paint” (chapter 6.3). A photograph taken before the restoration in 1871 shows that whitewash and paint cover the chapel, but that it has weathered away in the lower section and on the pillars (fig. 16.1). It can also be seen that Valkedorf's coat-of-arms is painted white and that decorations on the pinnacles are missing.

The restoration of Krefting and Christie in 1871-73

Despite the fires, the chapel fared pretty well until the restoration. There were nonetheless quite a few problems - all of them painstakingly documented by architect Christie in his restoration reports.[5]

The most urgent problems were structural ones, particularly those connected with foundations, slightly inclining pillars and cracks in the vault. After reinforcing the foundations and replacing the base (with Hovin sandstone), the upper parts of the pillars and the vault were pulled down. Old graves were also dug out and put in order. Subsequently, the pillars and the vault were re-erected using the old materials, except for a few new binders of sandstone which were needed to keep masonry and pillars together.[6]

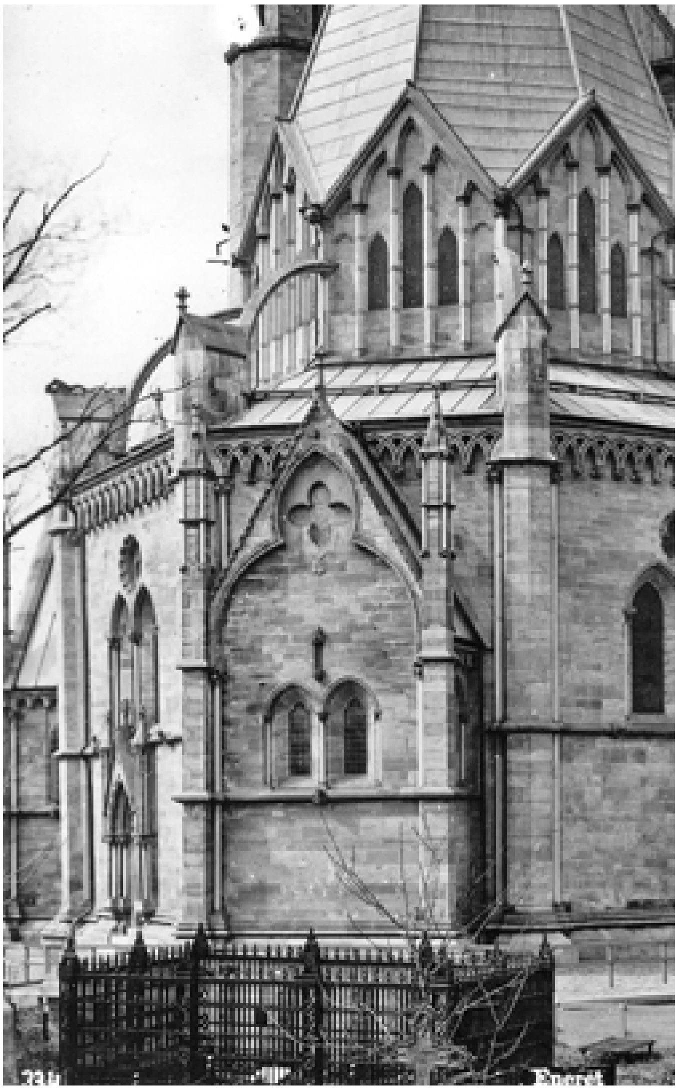


Fig. 16.3: The octagon in the late 1880s. Note especially that the south pillar of the east chapel already has a slight dark cover - probably black crusts (photo: ARW, no. 334).

Architectural features and decorations which were superficially or deeply weathered, for instance the string course, were either totally replaced or subjected to piecing-in, always using Bakkaune soapstone. The latter technique was in particular applied to the window arches, while missing pieces of column bases and capitals as well as the chin and nose of the King's head in the string course were reconstructed. Furthermore, new marble columns were put in place where the old were missing (fig. 16.1-2).[7]

From a weathering point of view, it is of prime importance to know where Portland cement was applied and how the stone surfaces of the chapel were treated. According to Christie's reports and my own observations, stone surfaces below the string course and around the windows were redressed (using bush hammers). Most other parts were washed with hydrochloric acid and sodium hydroxide in order to remove whitewash and paint.[8] Portland cement mortar was used for filling voids in the masonry core of the uppermost part of the gable triangle, while lime cement mortars were applied for repointing most of the old parts. Lime cement was probably also used for the rebuilding of the vault.

Inter restoration period - 100 years of weathering

The introduction of alkaline salts and chloride, as well as increasing air pollution, are important factors to keep in mind, especially because salts cannot be washed away by rain on large parts of the chapel. Studying photographs, we can see that black crusts appeared on the pillars by the 1880s (fig. 16.3). In 1905 the crusts were much more widespread - also appearing along joints around the windows.[9] The following 50 years lack photos, but in the late 1950s the crusts seriously distorted the aesthetic appearance of the chapel. Now it is also evident that masonry above the windows is rather weathered, in particular along joints (fig. 16.4).

The maximum extent of the black crusts was reached in the 1970s[10] - at a time when the gable triangle had been considered problematic because of water leaks for several years. Photos show that a few stone pieces in the gable have been lost, a feature indicating frost problems (due to leaks). Undertaken together with large-scale roof repairs of the whole octagon, the gable and pinnacles were pulled down in 1974.[11]

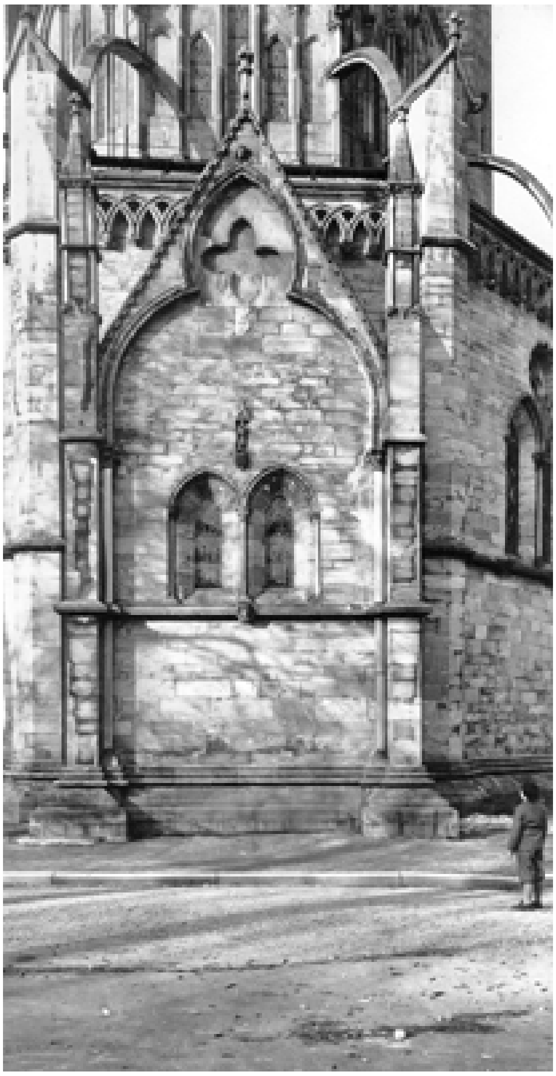


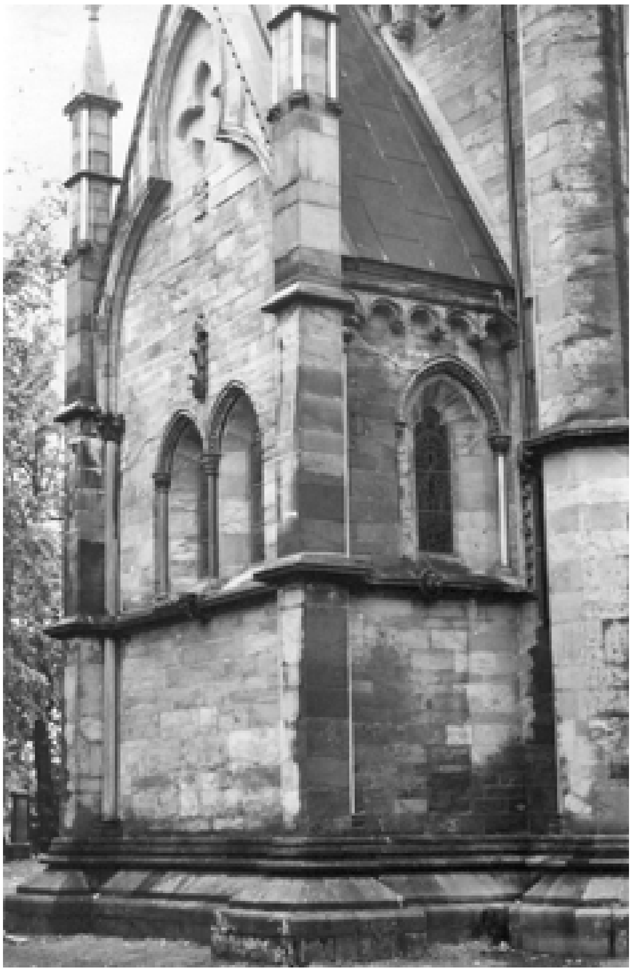
Fig. 16.4: *The east chapel, probably in the late 1950s. Note the extent of black crusts on the pillars. (photo: ARW, no. 6721).*

Fig. 16.5: *The east chapel in February 1990. The upper part of the gable was replaced with new stone (in 1974-76). Note that the extent of black crusts has decreased since the 1950s (photo: Oddgeir Øfsti).*

The restoration in 1974-76 and the last 20 years

In 1975-76 the gable was rebuilt using new soapstone and serpentinite from Bubakk (fig. 16.5). Copings were made of Gullfjellet stone, while for the interior wall brick was applied. According to the masons who undertook the work, Portland cement mortar (1:3) without additives was used for all purposes during the restoration. From a 1996-perspective, the restoration must be considered extensive and “hard”, largely because of all the Portland cement applied and the fact that most of the old stones could have been saved. The restoration also destroyed important evidence of Valkendorf's restoration in the 16th century.

Since the 1970s the chapel has been subjected to a couple of interventions which need attention. In order to remove graffiti sprayed on walls around 1980, masonry just above the base was cleaned by wet grit blasting which removed black crusts and destroyed many stone surfaces. Moreover, the projecting members and in particular the base were “cleaned” by a water lance at low pressure in the early 1990s - an operation aimed at removing moss and



lichens, but apparently not causing any loss of material or removal of black crusts (chapter 6.4). Hence, it is evident that the extent of black crusts has drastically decreased chiefly because of cleaner air and rain washing during the last 20 years (compare fig. 16.4 and 16.5).

16.3 The present weathering situation

The best way to describe the present weathering situation (see also appendix 4) is to distinguish between exposed elements, areas affected by run-off and leaks, and sheltered stonework. Consideration should also be given to the interior conditions and the types of salt present.

Fig. 16.6: *The east chapel during a gale with heavy rain in October 1992. Note that only projecting wall members of the east wall are affected by rain (photo: PS).*

Exposed elements and areas affected by run-off and leaks

After the replacement of the gable in 1974-76, one would have expected the weathering of the masonry just below to slow down for a while. This does not seem to be the case. Tiny joint fissures have developed between the copestones, leading to minor leaks and formation of calcite crusts as well as efflorescences of alkaline salts below. As a result ashlars affected by the salts appear to weather more actively than previously (fig. 16.9).

Except for minor leaks, the gable triangle itself is in good condition. The pinnacles are also sound, but the pillars deserve more attention. Even though they still have extensive, irregular black crusts, the general condition is rather good. The black crusts are not causing any particular damage, except on stone just below projecting wall members. Using the area where the string course winds around the southern pillar as an example (fig. 16.9), it can be seen that the stone has developed some flaking, apparently because of the black crusts. However, the string course is out of alignment in the corner, probably because of very minor settlement of the pillar and frost. The resulting joint fissures have given rise to water infiltration behind the stone, implying that the situation is far too complex to state that the black crusts alone are responsible for the flaking.

Before the restoration in 1974-76, there were distinct run-off patterns below the corner between the pinnacles and the gable (fig. 16.4). The black crusts beside the main waterways have largely disappeared, probably because run-off was eliminated after the restoration and the ongoing weathering of the masonry.

Fig. 16.7: *The east chapel during a white frost event in December 1996. Only walls that are heated from inside remain relatively dry (photo: PS).*

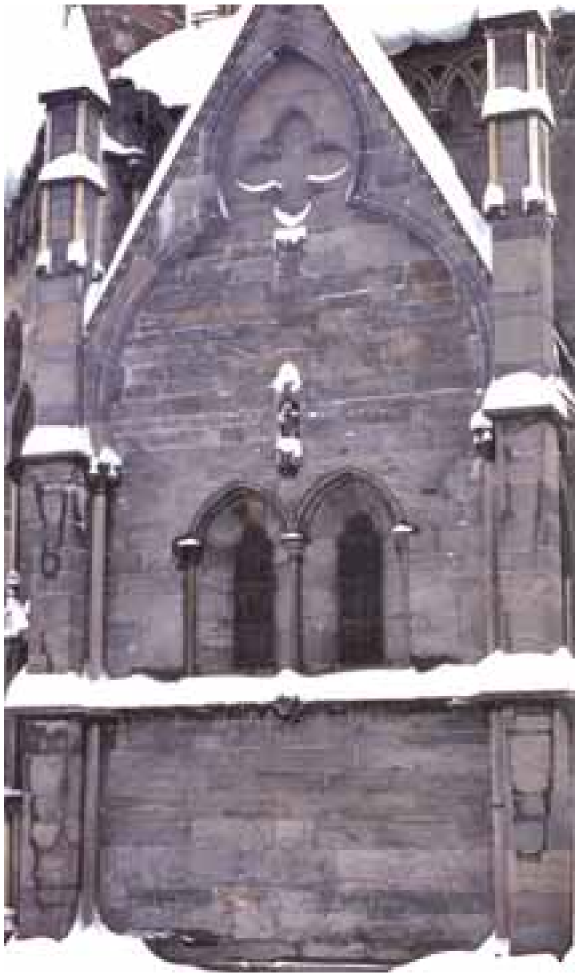


Fig. 16.8: *The east chapel during a snowfall in February 1995. Note how snow affects projecting stonework and decoration. Some decorations are deeply weathered (photo: PS).*

Turning to the base which is made of durable Hovin sandstone, the main feature is the extensive opening of joints. It is evident that moisture enters the masonry from the open joints, resulting in minor salt weathering (sodium sulphates) along the floor inside.

Sheltered masonry and decorations

The masonry of the upper section beside and above the windows is deeply weathered (fig. 16.9). Delamination and granular disintegration - and combinations of both - are the main weathering forms, but flaking is also widespread. “Unweathered” carbonate veins may, moreover, give some weathered ashlars deep reliefs. Several joints (lime cement) from the restoration in 1871-73 have weathered away, making it possible to see disintegrated, old lime mortars behind. The weathering is generally taking place along the joints.

Although the weathering of many ashlars is intense, it cannot be regarded as critical. The situation is, however, entirely different on valuable decorations fully integrated into the wall - especially the dog tooth ornamentation in the window arches (fig. 16.9) and capitals. These features have delaminated to such an extent that some of them are about to disappear. Also the late medieval canopy above the niche is regarded as hopelessly weathered. It should be

Fig. 16.9: *Details of the east wall of the east chapel in 1993. Top left: Condition of the upper section. Note the new stones (from 1974-76) and how the weathering of the medieval greenschists is concentrated along joints. Top right: Arch of the southern window. Note the small stone pieces which were inserted in 1871-73 and the delamination of medieval dog tooth ornamentation (greenschist). Left: Arch of the southern window. Note the salts in a small delaminated zone (thenardite) and underneath the dog teeth (trona). Right: Area below the string course on the southern side. The string course is not in order. There are joint fissures leading to water infiltration, and a lot of black crusts (photos: PS).*

Tab. 16.1: *Salt species at the east chapel of the octagon. c. 60 exterior and 40 interior samples have been analysed. Black crusts have not been counted.*

Salt species	Chemical formula	Frequency (%) Ext.	Int.	Probable origin	Morphology
Carbonates					
Calcite	$CaCO_3$	Not incl.		PC	White crusts
Natrite	$Na_2CO_3 \bullet 10H_2O$	15	2	PC	Needles and whiskers
Thermonatrite	$Na_2CO_3 \bullet H_2O$	3	-	PC	Powdery eff. (dehydrated structure)
Trona	$Na_3H(CO_3)_2 \bullet 2H_2O$	3	-	PC	Powdery eff., whiskers, acicular cryst.
Sulphates					
Gypsum	$CaSO_4 \bullet 2H_2O$	26	17	S, M, AP	Black crusts, cryst. in surface layers
Epsomite	$MgSO \bullet 7H_2O$	-	17	S, M	Glassy crusts and efflorescences
Mirabilite	$Na_2SO_4 \bullet 10H_2O$	26	52	PC, SR, (S)	Needles and whiskers
Thenardite	Na_2SO_4	13	10	PC, SR, (S)	Powdery eff. (dehydrated structure)
Aphthitalite	$K_3Na(SO_4)_2$	8	2	PC	Powdery efflorescences
Chlorides					
Halite	NaCl	4	-	A, SS	Tiny glassy crystals in surface layers

Explanations: PC = Portland Cement; S = Stone; M = Mortar; AP = Air Pollution; SR = Secondary Reactions i.e. reactions between salts from various sources; A = Acid cleaning; SS = Sea Salts

noted that several slightly projecting decorations are affected by snow and therefore subject to freezing/thawing events (fig. 16.8).

Due to the fact that the decorations were restored (piecing-in, cleaning) in 1871-73, it is assumed that they were in good condition afterwards. Since they have been left untouched by human hands since then, the intense delamination must have developed over the last 125 years.

Recalling that the lower section (below the string course) was largely redressed - and not cleaned by acid and lye - in 1871-73, it is unsurprising that the present condition here is good. Some minor delamination/granular disintegration occurs just below the string course, and there are a couple of deeply weathered stones in the lowermost, northern corner which is affected by collecting snow and water splash.

Generally, *the weathering forms very much resemble those observed on sheltered rock-faces in the Øye quarry*, from where most of the remaining medieval stone originates. This is important to bear in mind when attempting an interpretation of the weathering mechanisms.

Salt species on sheltered masonry and decorations

It was mentioned that black (gypsum) crusts preferentially occur on the pillars and beside specific former or present waterways/run-off, i.e. on parts which are frequently moist. Gypsum is also by far the most important salt species on sheltered stonework (see also tab. 16.1). It occurs as tiny crystals within the disintegrated zone of practically all ashlars and decorations, but it seems that it is especially confined to ashlars with traces of former paint and whitewash as well as along joints (abundant calcium).

Sodium carbonates (thermonatrite/natrite and trona) occur just below the replaced (1974-76) gable triangle. In these areas there is also a great deal of sodium sulphate as well as aphthitalite and gypsum. Several samples reveal mixtures of all these salts, a feature indicating that sodium carbonate from Portland cement (1974-76) is about to react with available sulphate to form sodium sulphate.

Very minor amounts of sodium sulphate (thenardite/mirabilite) can also be found on other parts of the sheltered masonry, but only in extremely dry weather periods. Sodium carbonates are generally restricted to areas just below the replaced gable triangle, as well as the most sheltered parts of the window arches (trona) (fig. 16.9).

***Fig. 16.10:** Interior of the east chapel before restoration in 1871. Note the condition of the walls (photo: ARW, no. 27).*

***Fig. 16.11:** Interior of the east chapel, probably in the 1940s. Except for slight salt weathering in the window arches and along the base, the condition is good (photo: ARW, no. 4538).*

Last, but not least, mention should be made of the occurrence of chloride. There is not much chloride to be found, but tiny crystals of halite have been observed together with gypsum. Halite occurs on sheltered masonry known to have been washed by hydrochloric acid and sodium hydroxide (1871-73), as well as on some (cleaned?) medieval decorations. It should also be noted that large amounts of chloride (halite) were found in samples of water used to clean the chapel in the early 1990s.[12]

The walls of the loft

The large amount of salts in the upper section of the chapel can be verified by studying the reverse of the wall (on the loft, fig. 16.12). The weathering of medieval parts of this wall is characterised by deep granular disintegration - the surfaces of the greenschists and soapstones are reduced to a soft powder. This is unsurprising knowing that the stones have been subjected to fire and contain large amounts of gypsum and thenardite/mirabilite (especially in joints) as well as a little epsomite (related to old bricks and lime mortar).

It is assumed that most of the salts were mobilised by water leaks before the restorations in 1871-73 and 1974-76, since there are only minor leaks at present. Related to the most important present leak - which is caused by joint fissures between copestones - sodium carbonates are about to react to form sodium sulphates, as verified by microscopic examination.

16.4 Evolution of the salt system

There is little doubt that salts are responsible for the weathering of sheltered stonework. An interpretation of the evolution of the salt system is given below (see also tab. 16.1 and fig. 16.13).

Salt system prior to the restoration of 1871-73

Due to the situation of the loft, it is assumed that the salt system which prevailed before 1871-73 was characterised by gypsum that stemmed from the building materials - especially the greenschist. It is also reasonable to assume that the minor amounts of epsomite/hexahydrite were part of the old system. In addition to the major quantities of gypsum, very minor amounts of sodium sulphates were found in the Øye greenschist quarry. It is, however, unlikely that the greenschist can provide enough sodium sulphate to seriously affect the weathering.

Halite originating from deposited sea salts was obviously as important in the Middle Ages as it is today. Hence, it is impossible to clearly state that the chlorides were introduced during the restoration of 1871-73. A hypothesis that needs further investigation is that the cleaning procedure must be regarded as a more important source of halite than deposition of sea salts.

Salts introduced during the restoration of 1871-73

In addition to halite originating from the cleaning procedure, the restoration in 1871-73 introduced alkaline salts from lime cement mortars. It seems that most of these salts have reacted with the abundant sulphate to form sodium sulphates (loft), but it is important to note that there are still relatively large deposits of trona just below the window arches. This trona must have arisen from the lime cement used when re-erecting the vault. Aphthitalite must also have been introduced in 1871-73 (from lime cement), while the new Bakkaune stone may have provided a little more gypsum than already present in the masonry.

Air pollution and gypsum

Dry deposition of SO_2 and the development of black (gypsum) crusts have clearly been of major importance on the exterior wall during the last 125 years. However, *how important* is this when compared with gypsum already present in the masonry?

Extensive black crusts have developed where the surfaces are frequently moist

Fig. 16.12: *Loft of the east chapel in 1992. Note the stone powder which has accumulated due to intense salt weathering (photo: PS).*

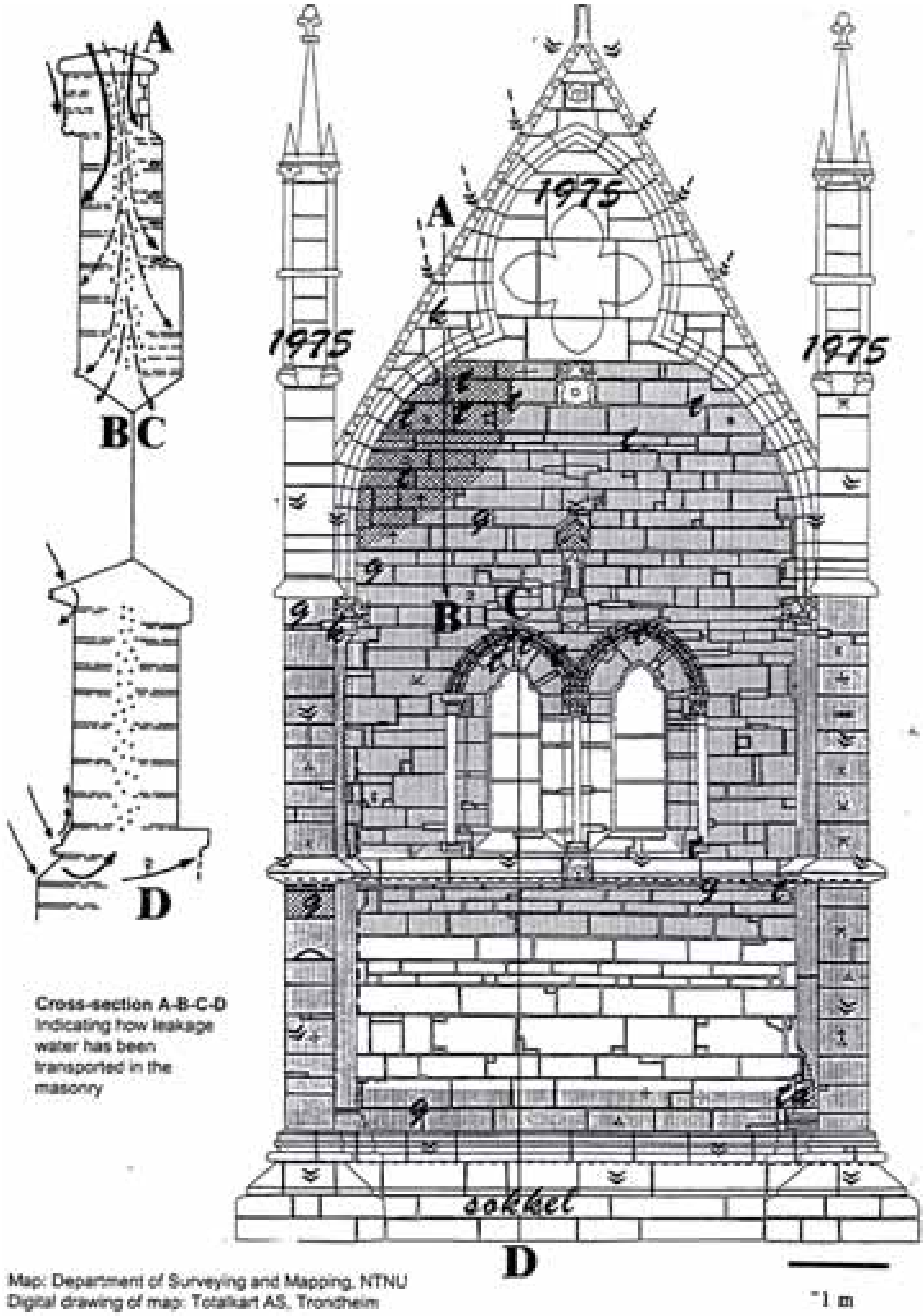
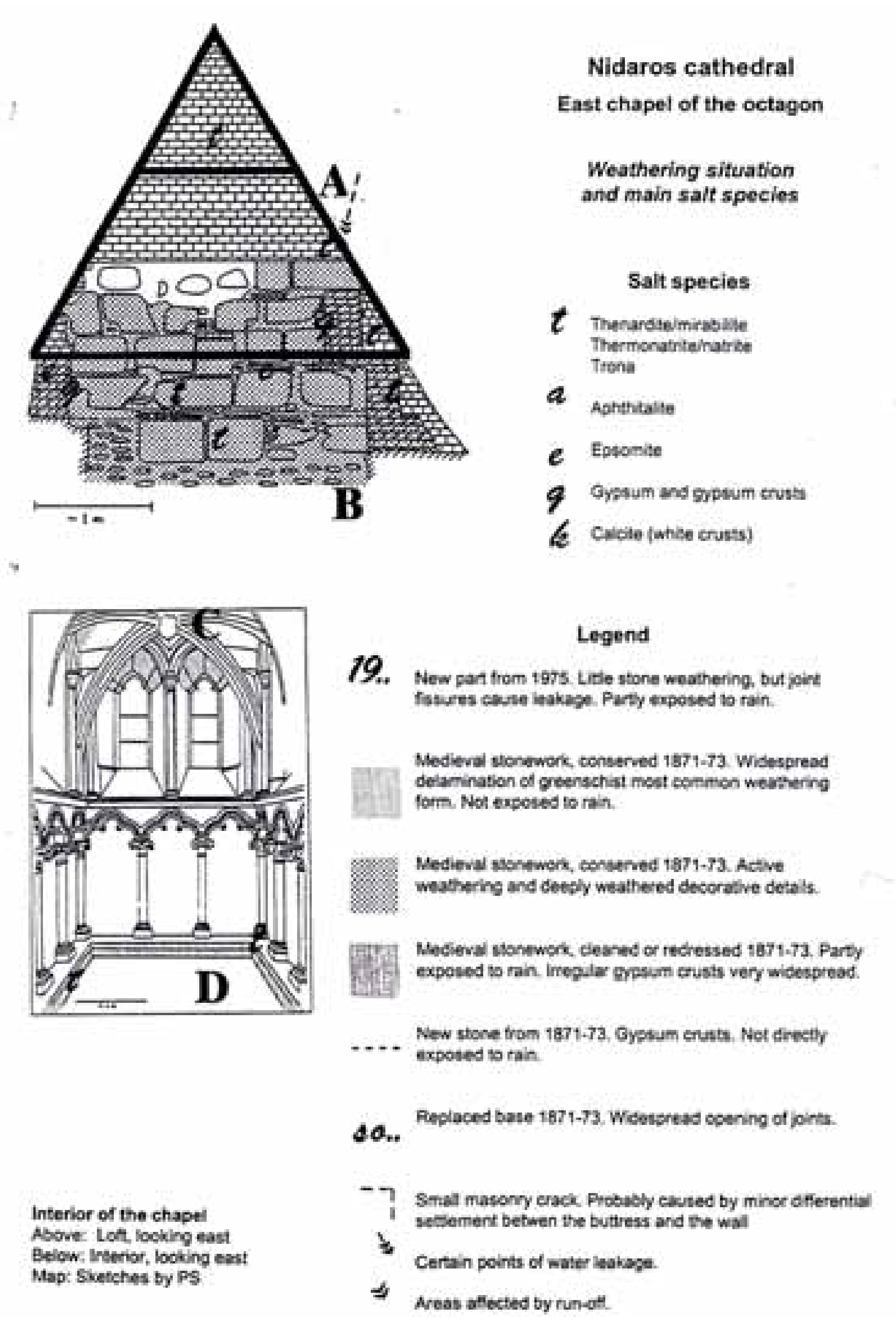


Fig: 16.13 *(this and next page): General overview of the weathering situation at the east chapel. Note that only analysed salt species have been marked on the figure.*

(cf. the pillars). Less extensive crusts and thin black layers have also developed along joints, on marble columns and on parts with traces of whitewash and paint on the sheltered masonry (abundant Ca). Although no specific evidence exists, it may be assumed that hygroscopic salts already present in the masonry have increased the deposition rate of air pollutants.[13]

It is also thought that dry deposition of air pollutants have contributed to the formation of tiny gypsum crystals which are found within the disintegrated zone of ashlars and decorations. We can at the present stage only guess that gypsum provided from the building materials is an equally important, if not more important source.



An interesting question is why the deposits of trona found in the window arches have remained stable for probably more than 100 years. Theoretically, trona should have reacted with available sulphate (building materials, air pollution) to form sodium sulphates, but this has not happened. It is an unresolved question at the moment.

Salts introduced during the restoration of 1974-76

Sodium carbonates introduced during the restoration in 1974-76 are about to react with available sulphate to form sodium sulphates. It also appears that the new salts have caused an increased weathering rate in a limited area just below the replaced gable triangle. Hence, it is likely, provided water leaks are not eliminated, that the large amounts of Portland cement in the gable will be capable of drastically increasing the weathering rate in the future.

16.5 A note on weathering mechanisms

The historical overview and the discussion of the evolution of the salt system point to the following conclusion: Air pollution has been an important source of gypsum, but the weathering of the sheltered stonework must primarily be attributed to the fact that water leaks for decades - or even centuries - have been able to mobilise salts also originally present in the masonry. This means that moisture have been provided from “within” the masonry and led to crystallisation of gypsum and other salts close to the surface of the sheltered stonework.

Supporting this conclusion is the fact that gypsum crusts on exposed pillars, where little or no moisture is provided from “within”, are rather stable (although being washed away at present) and not associated with significant disintegration of the stone underneath. Important exceptions occur just below projecting elements which are out of order. At such places there is minor water infiltration associated with joint fissures - thus moisture here is also provided from “within”.

How sodium carbonates (and chloride) introduced during the restoration in 1871-73 have affected the weathering is not completely clear. Sodium carbonates have obviously reacted with available sulphate to form sodium sulphates and increased the weathering rate on the loft. Except for the area just below stonework replaced in 1974-76, the most weathered exterior stonework has, however, only minor amounts of sodium carbonate/sulphate. Therefore, it may be assumed that direct crystallisation of gypsum (and dissolution/crystallisation due to condensation events) is the most important weathering mechanism in these areas.

Consideration should also be given to the role of frost on decorations subjected to both salt crystallisation and snow. Last, but not least, it should be noted that relatively hard and impermeable lime cement mortars used for repointing joints may have adversely affected the moisture balance of the masonry, leading to larger stresses on the stone just beside the joints.

16.6 Summary and possible conservation strategy

Despite adverse effects of alkaline salts from mortars based on Portland cement, chloride provided from cleaning procedures and black crusts developed as a result of air pollution, the weathering of large parts of the east chapel takes place at a relatively low rate. However, several decorations are presently in very poor condition, especially those affected by both salts and precipitation.

An urgent measure ought to be bringing projecting elements in order, especially the string course, so that water infiltration/run-off and further disintegration/flaking of stonework just below can be mitigated. It is also necessary to rapidly eliminate water leaks from joint fissures between copestones in the gable - otherwise there is a great risk of bringing large amounts of alkaline salt from the gable replacement in 1974-76 into contact with masonry above the windows. Other urgent measures should also include repointing of the base in order to avoid further water infiltration and salt weathering along the floor inside the chapel.

It is hard to say whether removal of lime cement joints in the sheltered parts of the masonry will slow down the weathering rate. I think it is worthwhile to remove some of them and apply lime mortars instead.

If deeply weathered decorations are to be preserved *in situ*, they should be protected from snow (when relevant). Otherwise there is little to be done, considering their advanced state of weathering and assuming that consolidation is too risky (due to high salt concentrations). Another possibility is to replace the decorations with copies.

Removal of black crusts from the pillars must be regarded as principally a cosmetic measure. Parts of the crusts are on the verge of being removed by rain washing, and those remaining are superb documents of historical air pollutant emissions in Trondheim.

16.7 The south and north chapels of the octagon

The weathering situations of corresponding walls in the south and north chapels (fig. 16.14-15) are quite different from what was observed on the east wall of the east chapel. This may be attributed to different weathering and conservation histories and exposure conditions. The chapels were originally erected in much the same way and with similar materials as the east chapel.

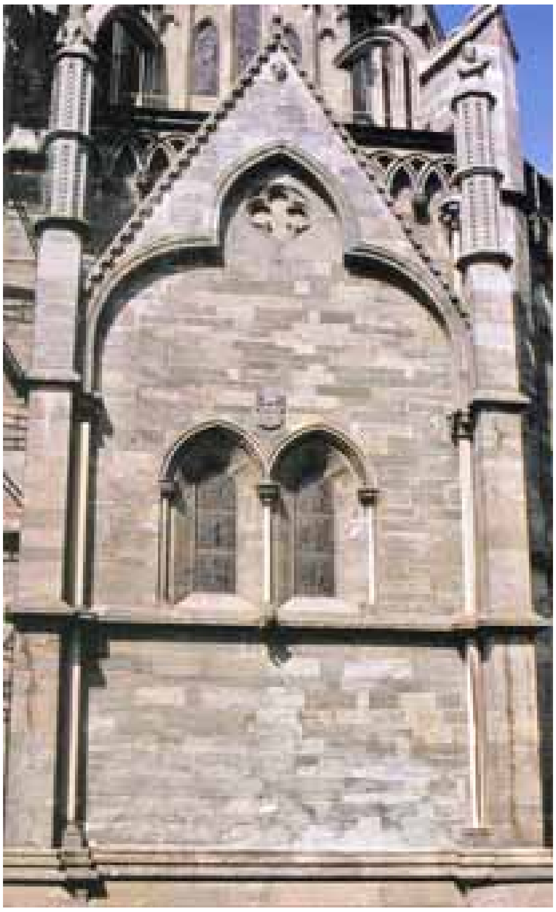


Fig. 16.14: *The south chapel of the octagon. Left: The area below the trefoil arch is exposed to rain and therefore in a rather good condition today. Right: The interior of the chapel is characterised by rapid salt weathering (alkaline salts) (photos: PS 1992-93).*

Weathering and conservation history

The condition of the chapels was very poor before the restoration in 1871-73, mainly because of inclining pillars - especially in the north chapel. Therefore, larger parts had to be demolished and rebuilt than in the east chapel. Masonry and decorations were also subjected to more redressing, more stone replacement and less piecing-in.[14] Since extensive measures were carried out, much more alkaline salts from lime cement mortars were introduced than in the east chapel.

Fig. 16.15: *The north chapel of the octagon. Left: Situation after a downpour in October 1992. Observe the wet area just above the windows of the north wall. Right: Water is provided from a downpipe coming down from the upper parapet of the choir! Observe that masonry affected by the run-off is sound while the adjacent stonework is characterised by salt weathering along joints. The salts mostly originate from lime cement mortars due to water infiltration through large joint fissures in the gable (June 1993) (photos: PS).*

Very little has been done with the north chapel during the last 125 years. In the south chapel, however, it was observed in the 1950s that the western pillar inclined to such an extent that intervention was necessary. Two sculptures on top of the pinnacles (from Valkendorf's restoration in 1510-20) were also quite weathered. However, it was not before the late 1980s that the pinnacles were replaced by new stones. Simultaneously, the copestones of the gable were replaced - a measure indicating that water leaks had been a major problem.[15]

Weathering situations

The loft of the south chapel is characterised by intense weathering caused by alkaline salts. More important is the fact that interior window arches and capitals are severely weathered (fig. 16.14), obviously because of water leaks from the corners between the pinnacles and the gable. The salt system consists of sodium carbonates and sodium sulphates, but also gypsum, magnesium sulphates and a little chloride can be found. The evolution of the salt system has in principle been the same as in the east chapel, but with the important exception that much more sodium carbonate has been provided from lime cement mortars.

Fig. 16.16: *The loft of the north chapel of the octagon in March 1993. Large amounts of alkaline salts can be seen (photo: PS).*

The exterior stonework is rather sound (fig. 16.14). There is much less delamination and granular disintegration below the trefoil arch than in the east chapel. The situation comes as no surprise as this part is exposed to rain (salts are washed away, black crusts cannot accumulate) and that the masonry was largely redressed during the restoration in 1871-73.

In the north chapel both interior and exterior walls are quite weathered (fig. 16.15-16). The interior situation is similar to the south chapel, but on exterior masonry there is a distinct difference between weathered and sound masonry. The explanation is straightforward: The north wall of the chapel is situated very close to the apse of the chapter house - and in the narrow space there is a downpipe from the upper parapet of the choir(!). Cleaning the masonry effectively, water from the downpipe splashes literally directly onto the masonry of the chapel. Since the joints between copestones of the gable are wide open, severe water infiltration from above has occurred. Thus, a distinct weathering zone with abundant sodium sulphates and gypsum has developed below the trefoil arch of the wall (fig. 16.15).

The last observation makes it evident that salt is indeed the most important weathering agent on sheltered masonry of the three chapels. This observation also exemplifies that greenschist masonry exposed to rain water tends to remain sound.

Fig. 17.1: *St. Mary's portal before the restoration at the turn of the century (photo: ARW, no. 954).*

Chapter 17

Weathering of St. Mary's portal

The south portal of the nave, or St. Mary's portal, was severely affected in the 1531-fire, meaning that several parts were lost forever and had to be replaced or reconstructed during the restoration. New compositions were also added to the portal in this century. Weathering at a relatively high rate, the few remaining medieval parts were put in place during the building of the nave's aisle in 1230-50.[1] The portal occupies the entire space between two of the solid buttresses and is completely integrated with the building structure. This fact is of great importance when trying to understand the weathering phenomena.

17.1 Design and materials

Like the north portal of the nave (St. Olav's portal), St. Mary's portal comprises a broad, stone capped gable with a heavily moulded, pointed arch above rows of slender marble columns. A new, ornamented relief can be found in the gable, and below the main arch there is a modern relief of the Madonna and Child. Slender pinnacles occupy the corners between the wall and the buttresses of the aisle, while between the gable and the pinnacles there are sculptured heads, probably originally intended as working gargoyles. Plates of marble separate arches and capitals, whereas the mouldings behind the columns are designed in such a way that they bind into the buttresses.

The portal was originally made of soapstone, either from Klungen or Bakkaune. Recalling that it is difficult to distinguish between the two stone types, it is suggested that Klungen is the more probable origin. The original joints between individual stones are very thin (1-3 mm), made of fat lime mortar and often include pinning (dark schist). Whether the portal was painted in the Middle Ages remains an open question. However, extensive traces of whitewash, probably from the post-Reformation period, can be found on the vertical, moulded sides of the portal.

17.2 Weathering and conservation history 1328-1996

It is assumed that the portal escaped the fire in 1328 and perhaps also the next one in 1432. After the 1432-fire a porch or a burial chapel was built in front of the portal. It is still possible to observe remains of ribs (made of greenschist) on the buttresses, which indicate that the main arch of the portal served as a transverse rib for a simple pointed cross vault (fig. 17.1). Archaeological excavations during the restoration showed that foundations exist in front of the portal. Three graves were also found.[2]

Fig. 17.2: *St. Mary's portal in 1930, after the restoration of the nave's aisle, which took place at the turn of the century (photo: ARW, no. 3518).*

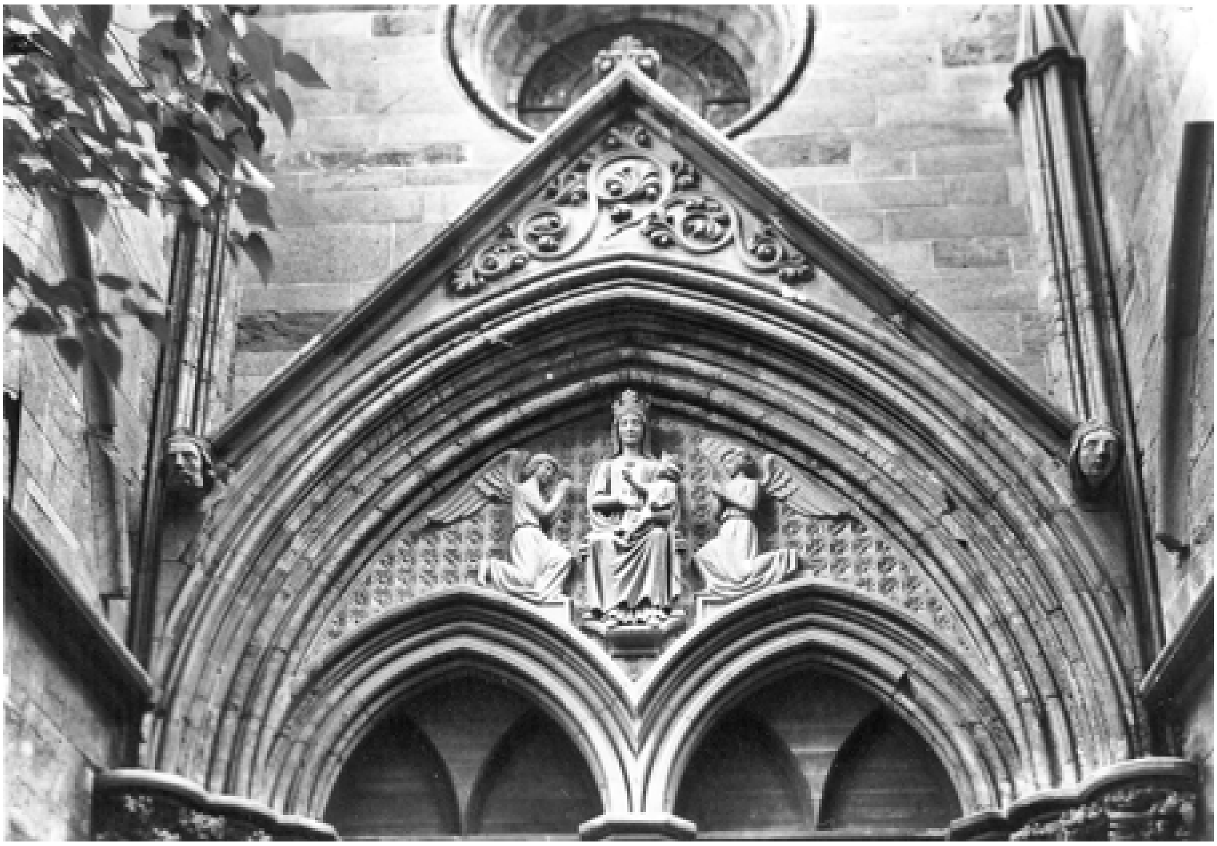


Fig. 17.3: *St. Mary's portal, probably in the 1950s. The relief showing the Madonna and Child was modelled by Nic. Schiøll and put in place in 1945 (photo: ARW).*

The 1531-fire and subsequent covering of wallheads

The porch/burial chapel was probably destroyed in the 1531-fire. Especially on the wall above the portal there are still extensive traces of fire (brown colour of stone surfaces) - such traces are almost absent on other bays of the nave. If the vault collapsed, it is assumed that the arches and moulded vertical sides of the portal were affected - although there are few traces of fire observed at present.

The whole nave remained a ruin after the 1531-fire and it was not before c. 1590 that the wallheads of the aisles were covered by simple roofs.[3] The walls were described as being in a very bad condition and in great need of repair at the beginning of the 18th century. Saving the walls from total collapse and further exploitation as a stone source, the west ruin was repaired and partly roofed in 1739.[4] In the late 1750s a large burial cellar was built along the south wall, within the ruin.[5] This situation prevailed until the restoration of the nave commenced in the 1890s.

The restoration in 1898-1905

The building of the chapel/porch in the 15th century involved removal of several parts of the portal, and although it was severely affected by the 1531-fire, the condition of the remaining medieval stone seems to have been astonishingly good before the restoration (fig. 17.1 and 17.8). Mouldings in the main arch were somewhat cracked and spalled, but the vertical sides were hardly damaged at all. The marble plates above the capitals, as well as the capitals themselves, had, however, lost the most exposed details.

The first phase of the restoration involved consolidation of the foundations, as well as replacement of the base and a lot of stone in the buttresses. The wall above the portal

Fig. 17.4: St. Mary's portal in the autumn. Picture taken during a gale in October 1992. Note the parts which are protected from rain, especially the east side beside the columns (photo: PS).

followed next - many ashlars between the gable and the circular window were replaced because the old stones were considered too severely (fire) damaged.[6]

After the reconstruction and repair of the gable and the pinnacles, new marble plates were inserted above the capitals. The capitals and several parts of the main arch were partly reconstructed. All medieval mouldings were cleaned, but the method is unknown. New marble columns were also put in place (fig. 17.2).[7] As in the rest of the nave Bjørnå and Solerød soapstone and Portland cement or lime cement mortars were used for most of the measures mentioned above.

Interventions and weathering 1905-1990

Until 1930, the main work at the cathedral was connected with rebuilding the nave. St. Mary's portal was also subjected to intervention - the arches above the doors as well as the dividing “pillar” and the doors themselves seem to have been inserted just before 1930. A photo taken at this time (fig. 17.2) shows that the condition of the medieval parts of the portal was good, except that there were some white spots (salts) on the arches just above the east capital plate.

Immediately after the Second World War, in September 1945, a tymphanum picturing the Madonna and Child flanked by two angels was inserted in the portal.[8] Carved in the hard Gullfjellet soapstone, the insertion of the relief marked the completion of St. Mary's portal (fig. 17.3).

A photo taken in the 1960s[9] show that parts of the moulded copestones made of Bjørnå soapstone have been lost. Consequently, the copestones of the portal, as well as the sculptured heads between the gable and the pinnacles were replaced, probably around 1978.[10] Gullfjellet soapstone was used for the copestones, whereas Bubakk serpentinite was applied for the copies of the heads.

From the perspective of salt weathering, which is discussed below, it is important to note that no salts prevailed on the eastern, vertical flank of the portal in the 1960s. The wall above the portal was also quite sound and apparently hardly affected by salts.[11]

Before leaving the historical review, mention should be made of the last intervention in 1991. A leak originating from the gangway behind the parapet caused a lot of water to run down the wall above the portal. During the repair of the leak, it was found that the masonry around the circular window had joint fissures. The joints were subsequently “repointed” with silicone rubber.[12]

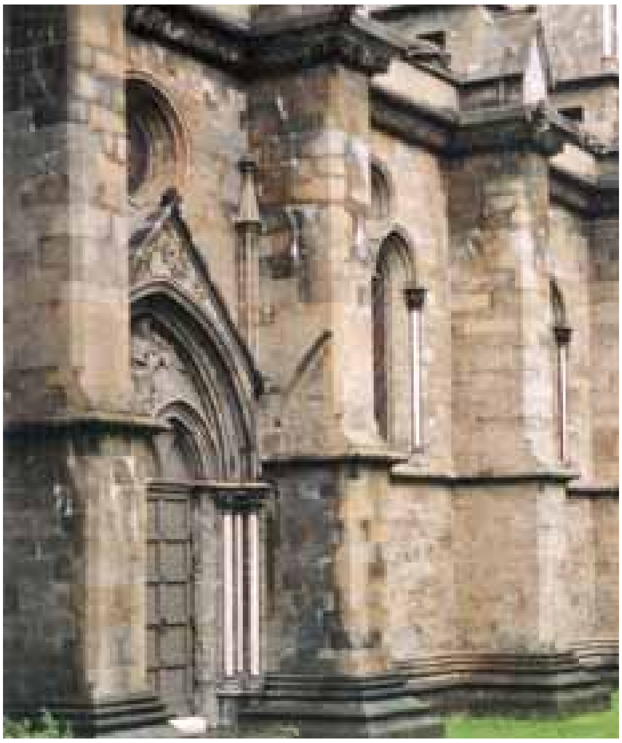


Fig. 17.5: *St. Mary's portal during "near" condensation events. Above: November 1995. Note the occurrence of wet spots below the parapet and on the buttresses on each side of the portal. These areas are literally full of hygroscopic salts. Right: August 1995. Note that there are wet spots also on the east side of the buttress near the portal. This area is strongly weathered and full of hygroscopic salts (photos: PS).*

It is worthwhile to remember that the nave's gangways and parapets have been problematic since they were finished before 1930. In chapter 12 it was shown that the general situation of the nave is characterised by the occurrence of alkaline salts just below the parapets (fig. 17.6). Problems with leaks and salts can be traced back to cracks formed as a result of differential settlement after the erection of the west towers in the 1960s.

17.3 Weathering situations and weathering rates

Observations on the portal and its immediate surroundings began in the winter of 1990. It was possible to locate three areas in which the weathering apparently took place at quite a high rate:

- Medieval ashlars below the parapet.
- The lower, eastern part of the main arch.
- The eastern, vertical flank and the adjoining buttress.

The western side of the portal (arch, vertical mouldings) also weathers actively, but at a very slow rate.

Fig: 17.6: *St. Mary's portal in spring (March 1994). The masonry has dried out and there are large amounts of salts below the parapet as well as beside the marble columns (photo: PS).*

Fig. 17.7: *Dry spring weather. Efflorescences mainly of thermo-natrite and flaking of burnt medie-val soapstone (photo: PS 4/94).*

Medieval ashlars below the parapet

The weathering of the semi-sheltered area above and around the circular window is characterised by flaking and exfoliation. It is usually the outermost, burnt layers (brown colour) that tend to exfoliate, whereas the stone underneath shows granular disintegration (fig. 17.7). Between 1990 and 1997 some flakes have been lost and it seems for the first time that replacement stones also start to weather actively. Alkaline salts (sodium carbonates, aphthitalite) originating from leaks in the gangway above, as well as from joint fissures in the cornice below the parapet must be regarded as the main cause of the weathering. However, it is not possible to rule out the action of frost (due to occasional severe leaks).

The salts appear (as usual) in dry winter, spring and summer periods (fig. 17.6), tending to disappear in humid autumn weather and obviously during condensation events (fig. 17.5). They often reappear at different places during dry weather periods and sometimes they are even completely absent in very dry weather. This phenomenon is ascribed to the fact that lashing rain (fig. 17.4) is sometimes able to remove salts provided during particular events of water leakage or run-off. Hence, the salts may be transported down the wall to the portal itself.

Medieval mouldings in the main arch

Medieval mouldings in the eastern part of the arch are strongly cracked showing flaking and granular disintegration or combinations of these forms (fig. 17.8). It is sometimes possible to observe sodium sulphates literally lifting up individual or multiple flakes. The lowermost area by the marble plate above the capitals is characterised by a typical "rising damp" distribution of salts: The mouldings are sound just above the plate, then comes a distinct zone in which relatively thick, cauliflower-like black crusts prevail. In the zone above there are large amounts of sodium sulphates (on stone) and sodium carbonates (on joints). That the weathering is very active can be confirmed by observing the ever increasing amount of stone flakes and stone powder collecting on the marble plate.

One of the reasons for the weathering must be related to the condition of the copestones of the gable before they were replaced in 1978. There is little doubt that the joints between the copestones were open (as they are today). Hence, the open joints were able to effectively lead water through the joint system (Portland cement) and allow alkaline salts to accumulate underneath the arch.

Water collecting on the marble plate stems from several additional sources. In order to understand the weathering of the vertical parts below, it is necessary to explore the actual sources of both water and salts (see below).

The east flank and the adjoining buttress

The east flank and the buttress beside belong to the same weathering situation. It is characterised by a peculiar run-off system, in which water provided from the marble plate runs down the corner between the portal and the buttress. Ashlars and mouldings located in the main waterway (zone A, see fig. 17.9) are sound. However, they are overgrown by green algae, whereas lichens, fern and moss prevail in the open joints. Narrow zones (B) with black (gypsum) crusts can be found on each side of the main waterway. It is easy to observe the black crusts on the buttress, but harder to see a similar pattern on mouldings behind the marble columns. This is because the complex geometry and traces of old whitewash disturb the system. Where black crusts prevail, the stone exhibits some flaking.

Beside the zones with black crusts, there are new zones (C) in which the stone is characterised by granular disintegration, flaking and exfoliation. On the buttress, the surfaces are nevertheless "hard", indicating that the weathering is relatively inactive. This is not the case on the opposite side. In the course of the last 5-6 years several flakes have been lost in this area. Behind such flakes there are always salts, mostly thenardite/mirabilite, but also a little trona, thermonatrite/natrite and aphthitalite (fig. 17.10).

It seems to be clear that we are dealing with a classic run-off system in which salts are transported "outwards", mostly in the relatively porous joints, and deposited according to their solubility products: gypsum first, then the more soluble salts and last the very soluble (highly hygroscopic) ones - salts that never crystallise on our climate. The latter zone (D) also seems to be present in this case, as shown by frequent wet spots on the replacement stone in the buttress.

The reason why there is no active weathering in zone C on the buttress is straightforward: soluble salts are unable to accumulate in this area because frequent rain washes them away. The situation is entirely different on the other side. During 6-7 years of regular observation rain has never actually affected this area. Hence, new run-off events from the marble plate provide ever increasing amounts of salts.

The actual salt species indicate that Portland cement (carbonates), stones (sulphate) and some air pollution (sulphate) are the sources. The problem is that only minor amounts of

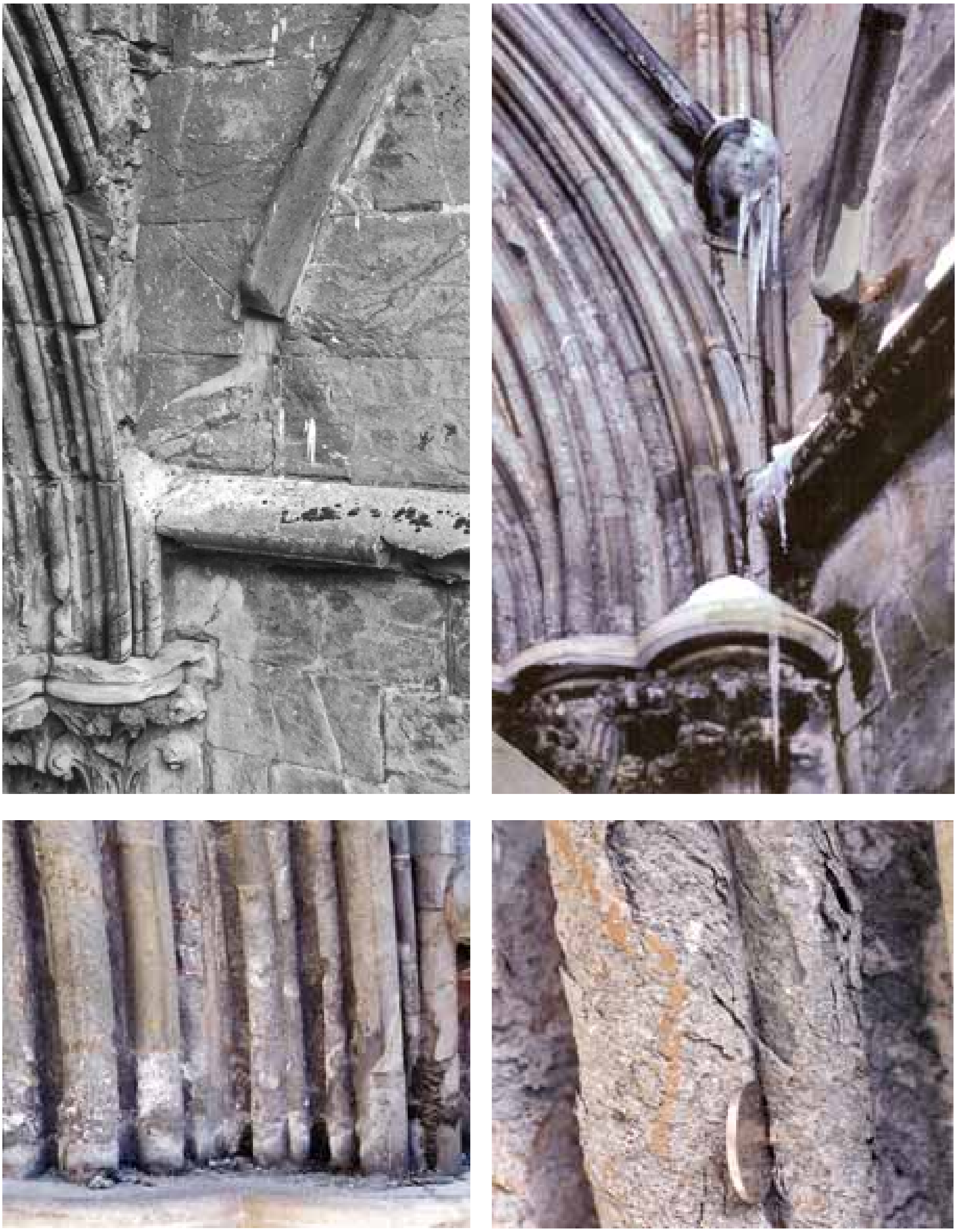


Fig. 17.8: *Weathering of St. Mary's portal, east corner.Top left: Condition before the restoration (c. 1900). The head between the gable and the pinnacle is missing (photo: ARW, no. 1188). Top right: Ice formation in February 1995. The partially reconstructed capitals have lost several pieces after the restoration, probably due to frost. Left: Salt weathering in the moulded arch just above the marble plate. Right: Detail of the moulded arch (April 1994). The cracked moulding was initially "weak" due to the 1531-fire - since c. 1900 it has been destroyed, mainly due to alkaline salts (photos: PS)*

Portland cement were used to repoint medieval joints in this actual area (below the marble plate). Hence, the salts must stem from above the marble plate.

When considering the design of the stonework, it is understood that precipitation which affects the buttress, the wall and the gable copings drains directly onto the marble plate, primarily because the sculptured head does not work as it was originally intended to - as a gargoyle. Moreover, knowing that both the buttress and the wall were subjected to massive replacement - including the application of Portland cement in joints - during the restoration in 1898-1905, it is assumed that alkaline salts stem from these areas. Leaks from the parapet also seem to be important. All the water inevitably drains into the corner between the buttress and the portal.

Fig. 17.9: *The lower, east part of St. Mary's portal and the adjacent buttress during fine weather in June 1993 (left) and very humid weather after slight rain in August 1995 (right). Observe run-off from the marble plate above the capitals. The distinct run-off pattern has developed because water from several sources collects in the corner by the marble plate. Ashlars in the actual run-off area (A) are sound. Beside the main waterway (on the buttress) there are three different zones: B) a narrow zone with black crusts which are associated with flaking of the stones; C) a broader zone characterised by granular disintegration and salt efflorescences (in dry weather); D) a zone with highly hygroscopic salts (seen on the "new" stone from c. 1900. The particular zoning has developed because of the different solubility products of the salts. Note that the salts close to the door cannot be washed away by rain (photo: PS)*

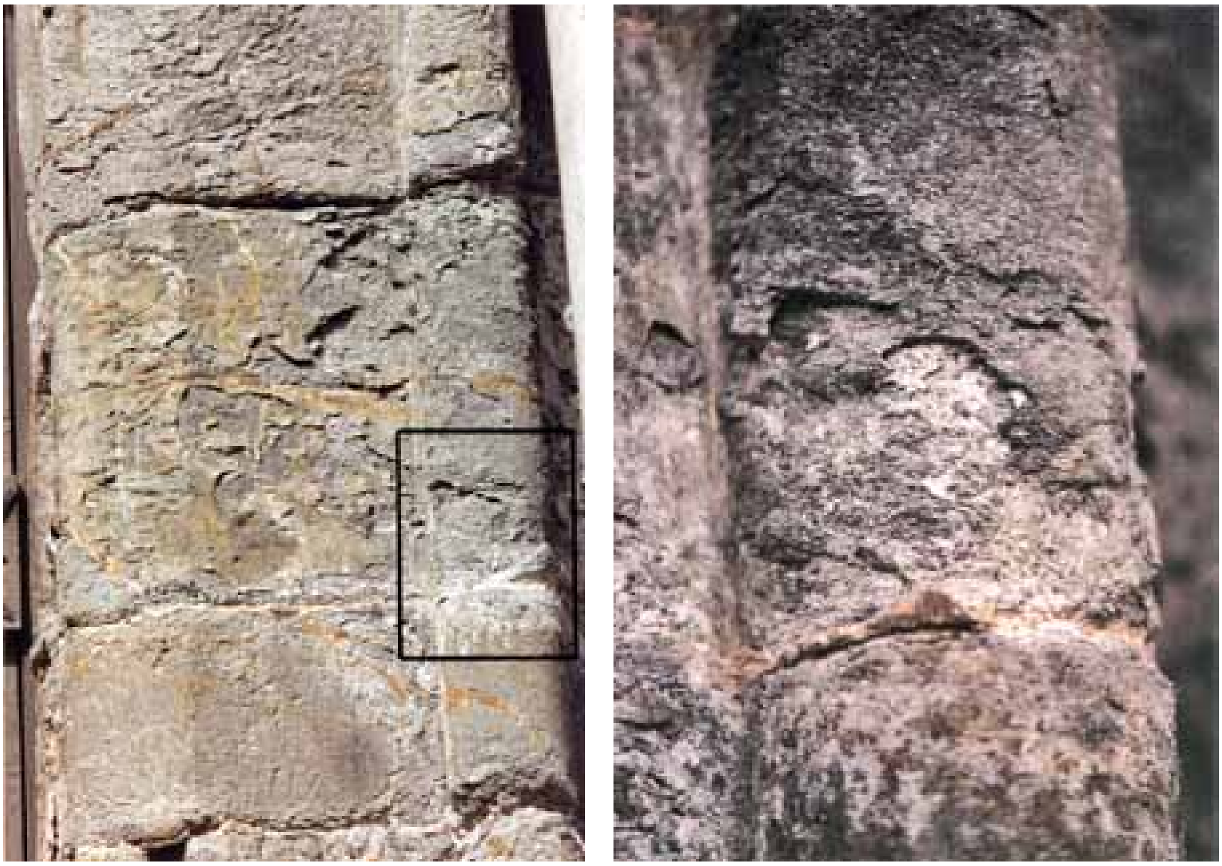


Fig. 17.10: *The east flank of St. Mary's portal is affected by "horizontally" migrating salts because of the run-off system in the corner (fig. 17.9). Left: Extensive flaking and granular disintegration in June 1993. Right: Detail in March 1990. Note all the salts and that the weathering has proceeded rapidly between 1990 and 1993 (photos: PS).*

Other weathering problems

The run-off system not only causes weathering problems below the marble plate, but also on the east side of the buttress. This is because open joints in the actual run-off area allow moisture to penetrate the bulk volume of the buttress. Comparison of this buttress with other buttresses in the nave shows that this is the most likely explanation as corresponding parts of the other buttresses are sound (fig. 17.5). Exfoliation, flaking and granular disintegration are the main weathering forms. There is much salt present, accumulating because the area is normally protected from rain.

The western side of the portal, including the arches, the buttress and the vertical flank weathers largely in the same manner as the eastern side. The reason why weathering is not as extensive as on the eastern side must be ascribed to the exposure conditions: Lashing rain preferentially affects the eastern part of the wall above the portal itself since the prevailing wind direction is south-westerly.

As expected, the outermost (reconstructed) leaves of the capitals have been lost (east side), obviously due to frost. It is normal for icicles to develop from the marble plate in the cold season (fig. 17.8). The reconstructed leaves were fixed by dowels (brass or copper) during the restoration in 1898-1905, and it is not possible to rule out that the dowels play a part in the weathering process.

17.4 Summary and possible conservation strategy

The weathering of St. Mary's portal may initially appear to be not so problematic. Considering, however, that specific areas with high weathering rates survived both the 1531-fire and 350 years of decay and neglect, the situation must be regarded as acute. Adding that many stone mason's marks and other inscriptions are about to disappear, it becomes clear that action is necessary.

It is probable that the areas in question weather particularly fast since the stonework was somewhat weakened (by microfissures etc.) during the 1531-fire. Frost may have played a role during the subsequent 350 years, but it was not before the restoration (1898-1905), and especially from the 1960s, that weathering rates really increased, partly due to salts originating from Portland cement. Other reasons for this sad development include leaks from the parapet and opening of joints in the gable before 1978. However, the most important reason is probably that the gargoyles in the corners between the gable and the pinnacles are fake.

Hence, improving the water discharge system ought to be the central element in a conservation strategy. Leaks from the parapet should be eliminated, as well as the run-off in the corners. There are several options when regarding the last issue, of which the most obvious is to turn the sculptured heads into working gargoyles. This option may, however, be insufficient alone. It is probably necessary to design additional discharge systems in order to keep most of the run-off away from the corner. Adding a protective roof should also be considered.

An important question is whether it is possible to reduce the quantities of salt in the stonework. The salts will still work effectively according to condensation events and changes in temperature and relative humidity since they prevail in areas sheltered from rain. If intervention are to be undertaken *in situ*, it will be very difficult to remove salts in the arches - except for those that can be brushed away. However, on the vertical part it might be possible to apply water in such a way that it slowly runs down the mouldings, hopefully removing the salts. Such an intervention might be viewed as a risky endeavour, but probably less hazardous than letting the salts remain to weaken the stonework. Removing salts by compresses or clay must also be regarded as risky since the stonework in question is so fragile.

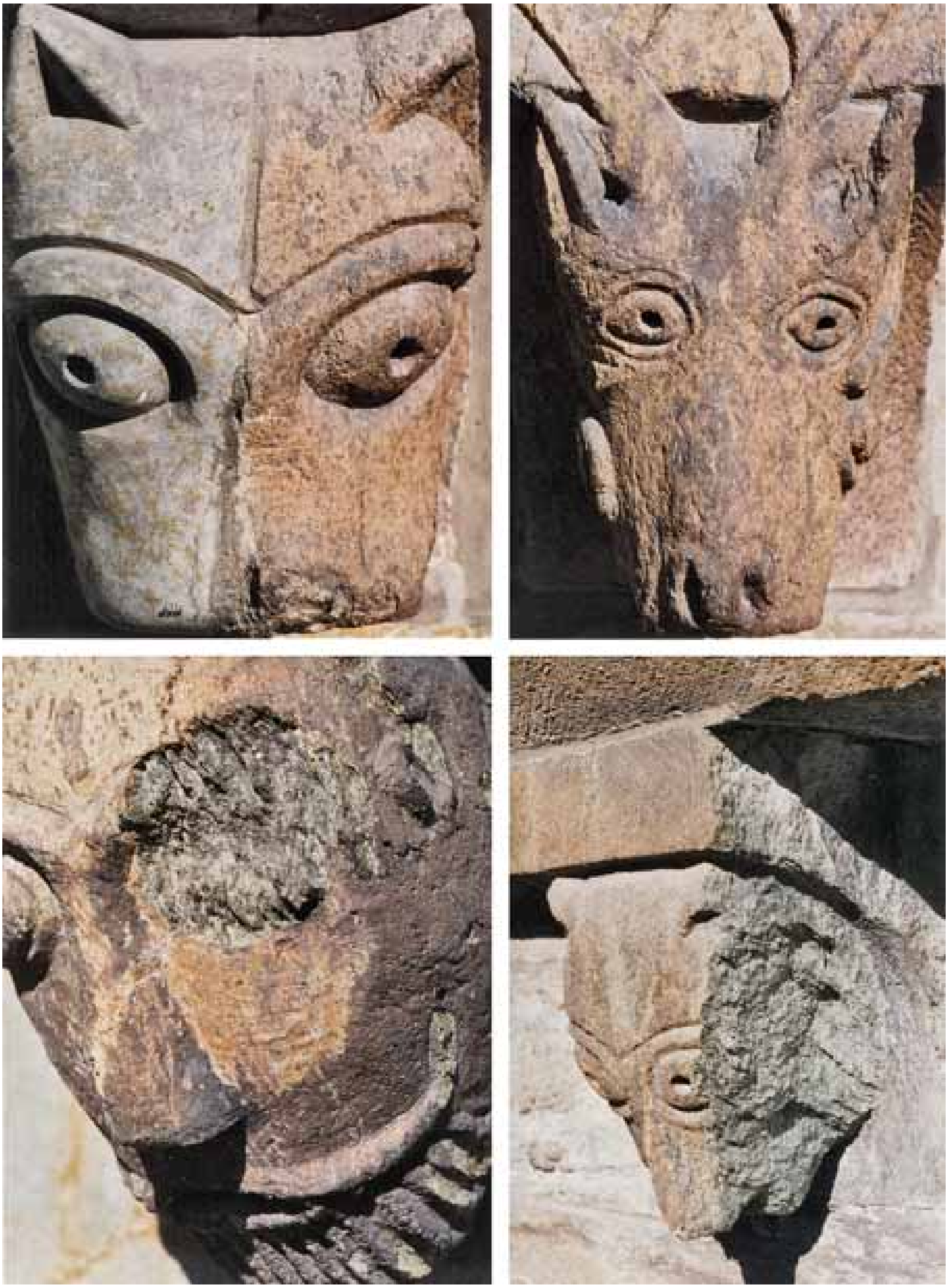


***Fig. 18.1:** Four corbel heads in St. Olav's chapel in September 1995. Top left: Half the face lost before 1870, probably due to fire, reconstructed in the late 1870s. Top right: No particular change since 1870. Left: Eye lost before 1870. Note the paint layer partly covering the face. Right: East side lost between 1960 and 1990 (photos: PS).*

Chapter 18

Weathering of Romanesque corbel heads

Romanesque corbel heads are some of the most valuable medieval sculptures of the cathedral. They are mainly located in the cornices of the transept's chapels and include some 50 masks of fabulous beasts and humans as well as human bodies. As such they are typical representatives of Romanesque art. Similar masks are found in many English and Norman churches from the first half of the 12th century.[1]

Since the restoration of the transept's chapels in the 1880s, many corbel heads have weathered rapidly, while others still remain sound. In order to understand this difference, attention will be paid to the corbels located in the south cornice of St. Olav's chapel (south transept). A brief note on the corbels in the cornices of St. Michael's chapel (above the north porch) will also be given.

18.1 Corbel heads in St. Olav's chapel

The 12 corbel heads in the south cornice of St. Olav's chapel were carved in greenschist, probably from Øye, and put in place during the building of the chapel around 1150.[2] The corbels are edge-bedded, which means that they tend to loose pieces parallel to their sides or develop vertical delamination. Only the three easternmost corbels have suffered from serious loss of material, insofar as large pieces have been lost along their sides. The state of the other corbels is presently excellent (fig. 18.1).

Weathering and conservation history until 1880

There exists practically no written information about what the corbels have been subjected to since the Middle Ages.[3] Consequently, when trying to unravel their history, we have to rely on old photos, observations and what is known about the general history of the cathedral.

It is assumed that the first really damaging event that affected the corbels was a medieval or a post-Reformation fire. A large area of the wall below the corbels, as well as most of the corbels themselves, have a brown surface stain - a feature indicating a serious fire. The reason why fire struck the masonry is a door in the western part of the wall. Thus, an exterior wooden staircase which could have easily burnt must have led up to the door.[4]

The fire seems to have especially damaged the corbels located right above the door. Photos taken before the restoration show that two corbels have lost large areas. One of them was replaced during the restoration around 1880, while the other was partially reconstructed. The medieval original was stored in the museum collection where it can still be enjoyed.

It is not known whether the corbels were originally painted. However, after the fire they must have been overpainted, probably in the 18th century and perhaps also before the

Fig. 18.2: *St. Olav's chapel, looking west. Condition in c. 1870, before the restoration. Note that gableboards and eaves protect the corbels in the cornices (photo: ARW, no. 997).*

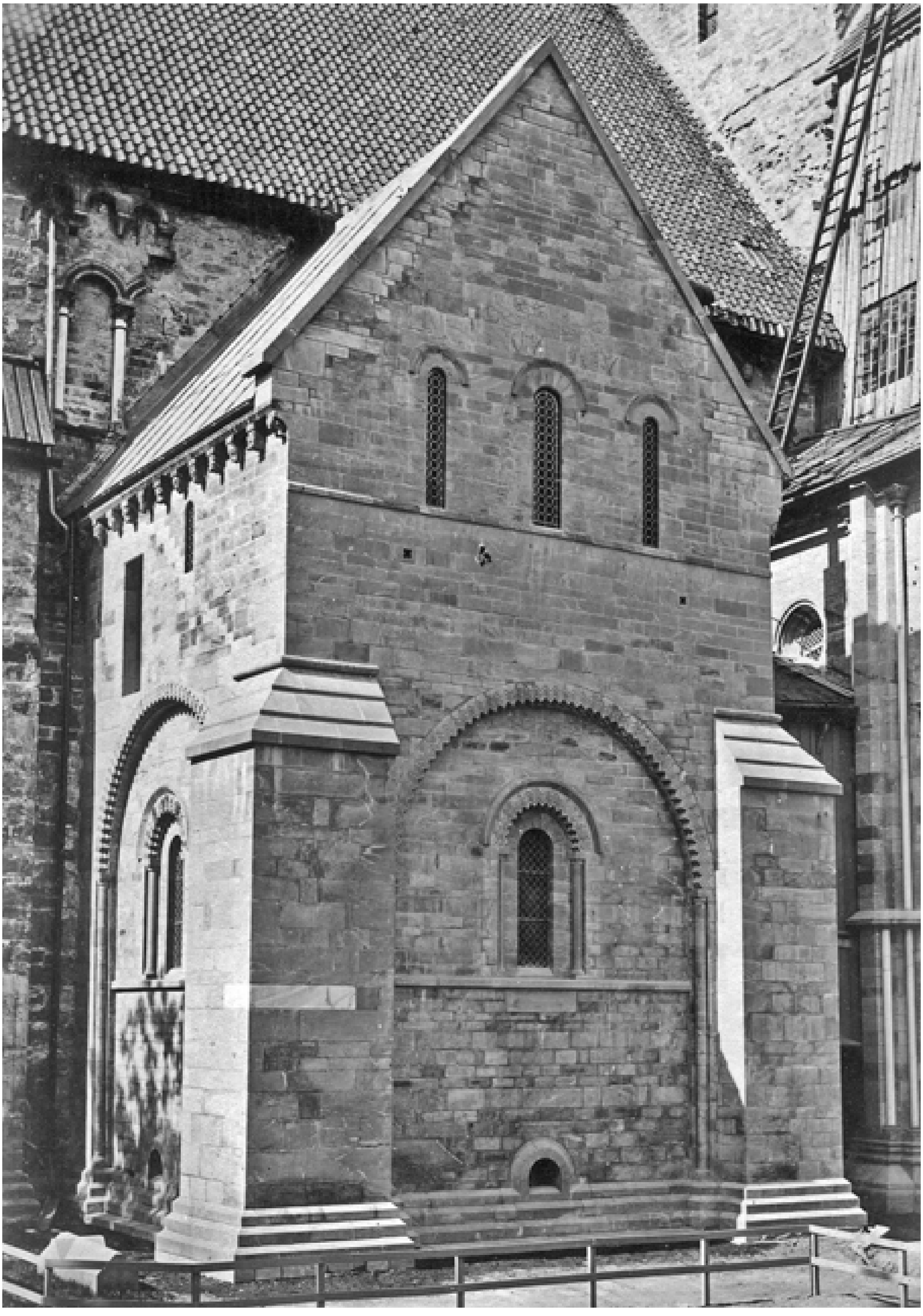


Fig. 18.3: *St. Olav's chapel around 1880, after the restoration during which the gable and the roof were changed. Note that the corbels are less protected than before the restoration (photo: ARW).*

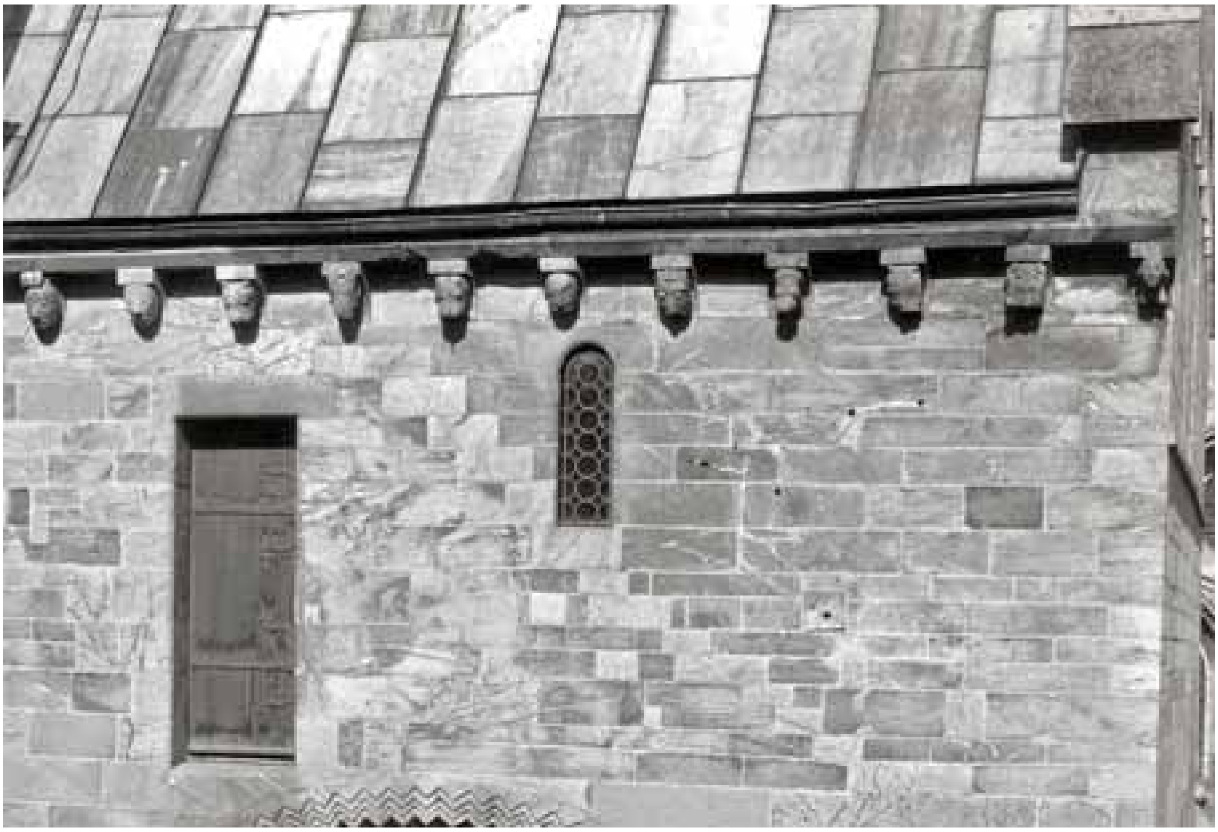


Fig. 18.4: *St. Olav's chapel in c. 1920. Note the distinct colour differences of the masonry. The darker colour (brown) is a result of fire, showing that there must have been an exterior wooden staircase which burnt in the Middle Ages. Several ashlars were replaced during the restoration in c. 1880. All the corbel heads, except the easternmost one, show distinct traces of fire. Note also the limited extent of black crusts on the masonry (photo: ARW, no. 2632).*

coronation in 1818 (see chapter 6.3). It is still possible to observe distinct traces of brown-violet colours on many corbels. Medieval pieces in the museum collection also show extensive paint layers which probably originate from overpainting measures.

Except for those located directly above the door, the corbels appear, according to old photos, to have been in an excellent condition before the restoration.[5] Therefore, very few conservation measures had to be undertaken. Since some of the corbels may have been covered by whitewash before the restoration, it is assumed that the layer was removed, probably by hydrochloric acid. There are no traces of whitewash today.

The most important measure undertaken during the restoration was not related to the corbels themselves, but to the fact that the design of the roof above was drastically changed. After the fires in 1432 and 1531 it is reasonable to assume that the chapel was roofed in much the same way as after the fires in 1708 and 1719. Photographs taken before the restoration (fig. 18.2) show that the chapel was covered by a tile roof with eaves protecting the corbels. Such roofs covered almost the entire cathedral before the restoration. The gable was completely rebuilt during the restoration. It was raised almost half a metre and covered by copestones. In this way the easternmost corbels became much more exposed to rain and snow than before (fig. 18.3).

Fig. 18.5: *St. Olav's chapel, probably in the 1960s. Left: The black crusts on the easternmost part are more widespread than in the 1920s. Note that the lower copestone of the gable appears to have an open joint. There is also a white calcite crust just below, indicating that water has been seeping through the joint system and affecting the easternmost corbel heads (photo: ARW, no. 7011). Right: Close-up showing white patches (salts) along joints and on the corbel (photo: ARW).*

Weathering and conservation history 1880-1996

A photo taken in the 1920s (fig. 18.4) shows that very little has happened to the corbels since the restoration. Some black crusts have formed on ashlars below the easternmost part of the cornice, but not elsewhere. The reason why black crusts have accumulated in this particular area must be related to the frequently moist conditions here. The area appears, however, not to receive enough rain for the crusts to be washed away.

The extent and intensity of the black crusts increased towards the 1950s and 1960s (fig. 18.5). Now it is also evident that they cover some of the corbels themselves. A more important observation is that the joints (based on Portland cement) around the lowermost copestone of the gable are open and that white calcite crusts have formed just below.

Thus, it seems that run-off carrying alkaline salts has directly affected the easternmost corbels. Water may also have been seeping into the joint system around the beams above the corbels, carrying alkaline salts into the masonry (fig. 18.5). In this connection it should be noted that during the last five years occasional observations revealed a great deal of salt efflorescences on the masonry during dry weather periods.

In the early 1980s the copestones on the gable were in such a bad state that some of them had to be replaced. The joints were simultaneously repointed (Portland cement mortar), whereas plaster copies were made of the three easternmost corbels.[6] 10 years later, in 1993, the outermost corbel was in such a bad condition that it was replaced by a copy carved in Bubakk soapstone.

The two corbels next to the easternmost one had lost large fragments by 1990. Therefore, it is evident that the severe loss of material took place chiefly between 1960 and 1990. Since 1990 very little has happened (fig. 18.6).

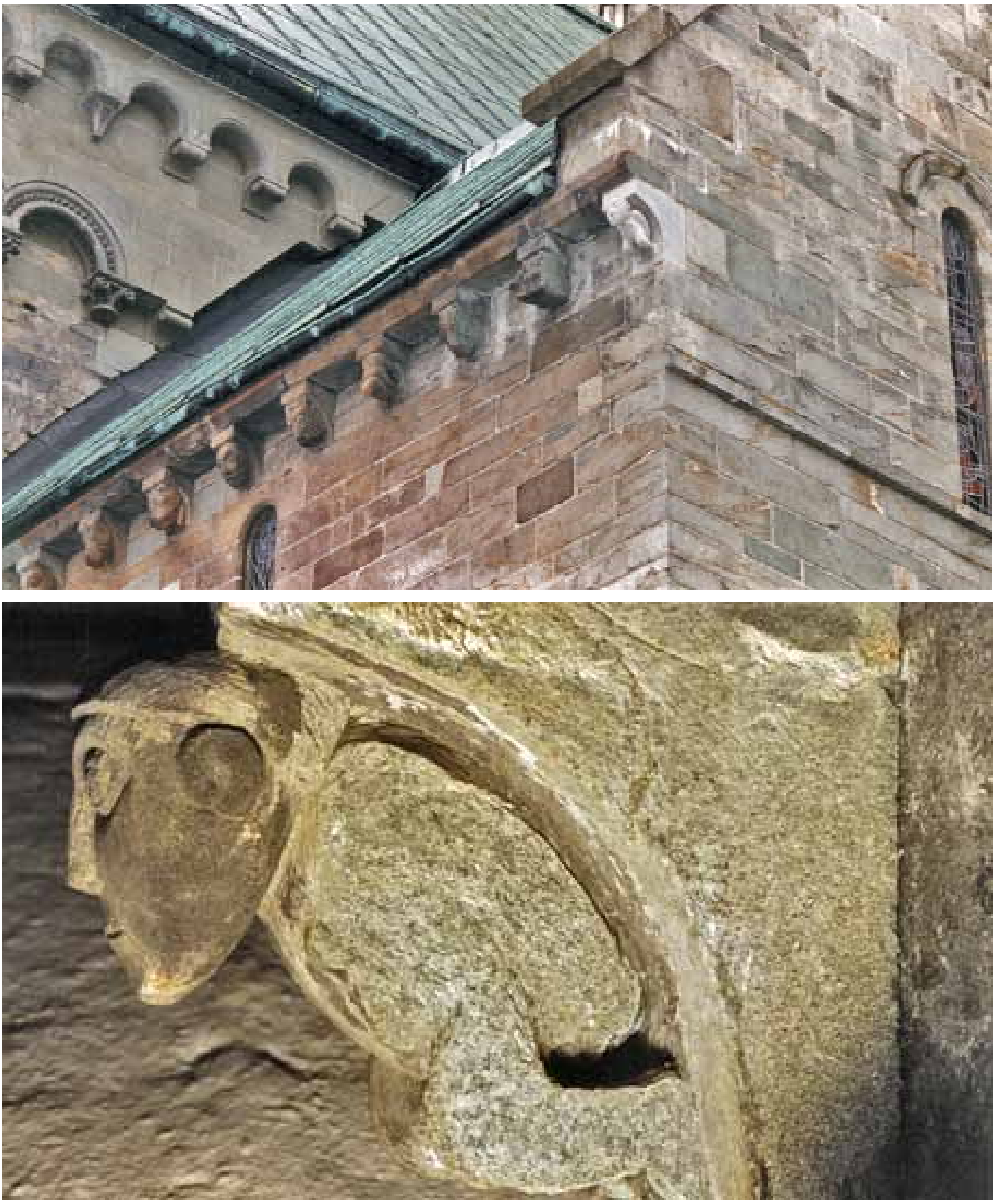


Fig. 18.6: *Top: St. Olav's chapel in September 1995. The gable was restored (stone replacement, repointing) in 1983, while the easternmost corbel was replaced by a copy in 1993 because it was strongly weathered. Note that the extent of black crusts has decreased since the 1960s and that there are some specific light traces beside the easternmost corbels. The traces originate from silicone applied onto the corbels in order to make plaster copies in the 1980s. Below: The original easternmost corbel has lost one side and is partially covered by black crusts. It can presently be seen in the museum collections (photos: PS).*

Interpretation of the weathering

It is clear that the three easternmost corbels have weathered extremely rapidly over the last 120 years. There are at least seven factors to consider when trying to interpret why the weathering has evolved so rapidly:

- The fire that struck the corbels appears to have destroyed those located right above the door. The others may have developed microfissures which made them vulnerable to additional weathering agents.
- Post-Reformation overpainting may have adversely affected the corbels, but it is more probable that the paint protected the corbels from further weathering.
- Since the most exposed corbels have weathered much faster than the others, it is evident that the drastic change of the roof during the restoration is the main "weathering factor". The erection of the stone-capped gable, which gave rise to leaks through open joints, may have increased the likelihood of frost damage. Alkaline salts originating from the Portland cement should also be considered.
- Black crusts may have caused direct loss of material (crystallisation of gypsum). It is also reasonable to assume that gypsum may have closed surface pores, leaving the corbels more vulnerable to frost damage. That black crusts are restricted to the easternmost part must be associated with the relatively moist conditions here: frequently moist means a relatively high deposition rate of air pollutants.
- The deposition rate of air pollutants may also have been enhanced due to the possible presence of hygroscopic salts from cleaning procedures (hydrochloric acid).
- When making plaster casts the Restoration Workshop cover objects with silicone. Other examples show that this procedure is dangerous and may cause loss of material, especially on objects which are already weakened because of weathering.[7]
- It is obvious that the stone quality is of major importance to weathering. In this case the corbels are made of greenschist without significant quality variations. The easternmost (original) corbel appears to have a somewhat higher content of scattered carbonate grains than the others, possible explaining why this corbel has fared the worst. This particular corbel was little affected by the fire, but it has the most delicate carving of all the corbels: fine details are more easily lost than the "bulk" volume of sculptures.

Summary and possible conservation strategy

The interpretation shows that there is no simple explanation of the rapid weathering of the three easternmost corbels. However, given that the change of roof design was the most important event affecting the corbels adversely, it is important to consider this aspect when aiming at preserving the corbels in-situ.

Hence, a possible solution would be to remove the uppermost part of the gable and re-introduce a roof similar to the one removed during the restoration in the 1880s. This solution would completely change the architecture of the chapel. An important document of architect Christie's restoration philosophy will also be lost. Knowing that the roofs of Christie have caused large problems on several other parts of the cathedral as well, a major discussion about this issue is likely in the future.

It is certainly possible to propose less drastic solutions than to completely re-restore the roof. However, in order to let the corbels survive for a prolonged period of time, it is absolutely necessary to protect them far better from rain and snow than today. It is probably also necessary to remove remaining black crusts on parts of the corbels. Consolidating or even painting the corbels should also be considered.

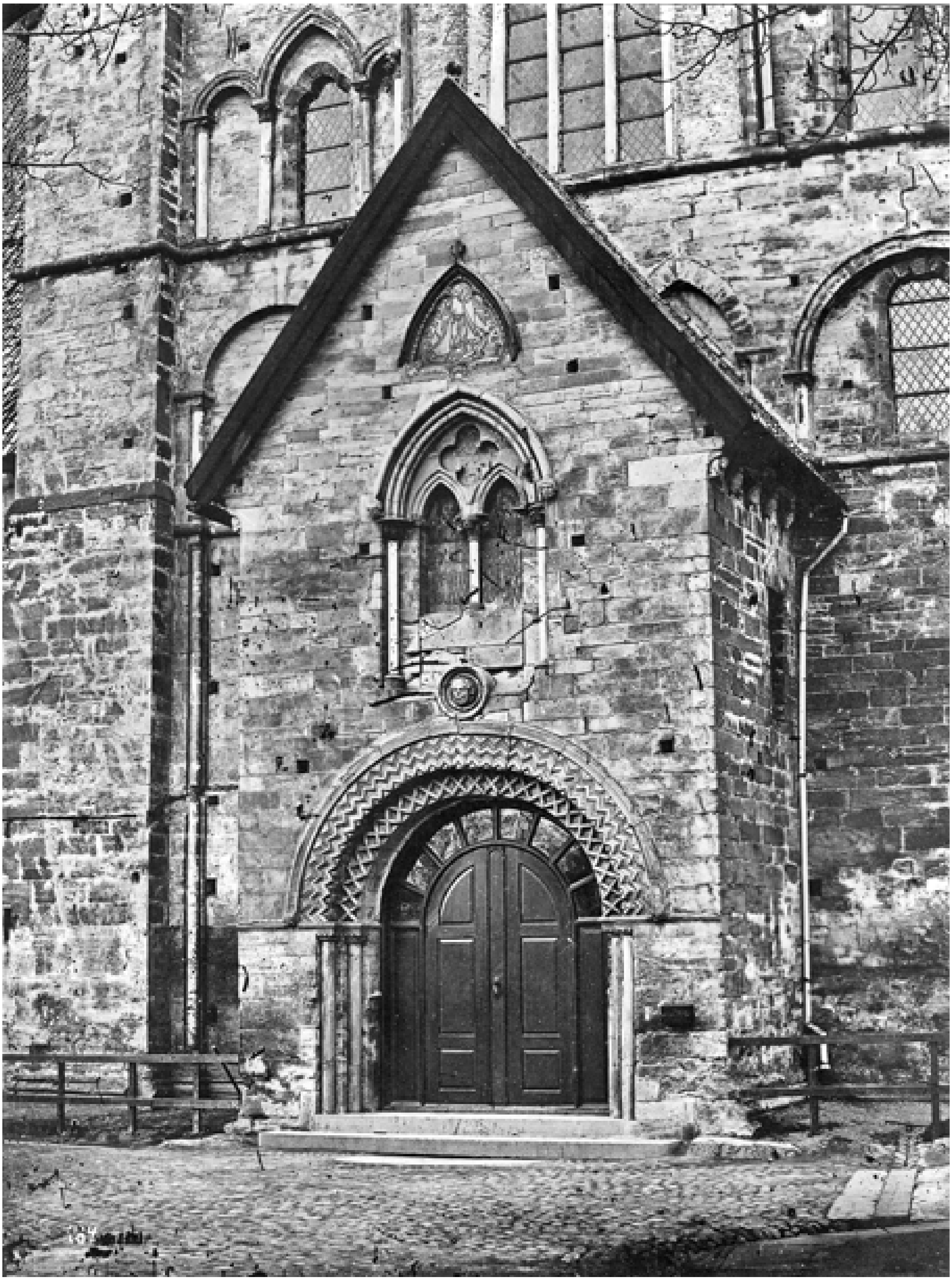


Fig. 18.7: *St. Michael's chapel and the north porch. Condition before the restoration (c. 1870). Note that the tile roof, possibly constructed after the fire in 1719, is effectively protecting the Romanesque corbel heads from precipitation (photo: ARW, no. 184).*

18.2 Corbel heads in St. Michael's chapel

The history of the Romanesque greenschist corbels in the western and eastern cornices of St. Michael's chapel is quite similar to the corbels in St. Olav's chapel, but there are some important differences (see next page):

Fig. 18.8: *Corbels in the western cornice of St. Michael's chapel. Top: The three outermost corbels are in a much worse condition than the other two (photo: PS 5/96). Left: The outermost corbel in 1961. Note the extensive delamination and the black crust below the head. The black crust has largely disappeared today, and the condition is otherwise slightly worse than in 1961 (photo: ARW, no. 7090). Right: Except for a major crack along a foliation plane, the second corbel from south is sound (photo: PS 5/96).*

***Fig. 18.9:** Two corbels in the eastern cornice of St. Michael's chapel in August 1995. Left: The condition of the third corbel from north is excellent. Right: The outermost corbel just below the gable copings is quite good, but pronounced delamination has taken place at the most exposed places (photos: PS)*

- The corbels have not been affected by fire.
- There are no clearly identifiable traces of paint on the corbels today.
- It is unclear whether one corbel in the eastern cornice was replaced during the restoration around 1880.[8] There are no close-ups showing the condition of the corbels before the restoration. However, since most of the corbels are medieval, it is assumed that they were in a rather good condition before the restoration - otherwise they would have been replaced.
- The beams above the corbels were partially replaced by Grytdal soapstone during the restoration, indicating that the old beams were in a poor state. Afterwards, the Grytdal stones may have provided salts (sulphates) to the corbels because of water seeping in via the joint system.
- The corbels seem have been subjected to diverse in-situ conservation measures in this century. Some cracks have been filled with unknown materials.
- The corbels have probably been subjected to higher levels of air pollution than the corbels of St. Olav’s chapel, simply because they are situated on the northern side of the cathedral.
- The downpipes located in between the two easternmost corbels (see fig. 18.8) on each side may have had leaks affecting the corbels. In connection with this it should be mentioned that the copestones on the gable had to be repaired in 1984, mainly due to joint fissures and leaks.[9]

The most important feature of the present weathering situation is that the corbels in the western cornice are in a much worse condition than the corbels in the eastern cornice (fig. 18.8-9). Moreover, the most exposed corbels in the western cornice must be regarded as being hopelessly weathered when compared with the more protected ones (fig. 18.8). These features indicate that exposure to precipitation is the main factor governing the weathering rate.

Otherwise, most of the issues mentioned in chapter 18.1 should be considered when interpreting the weathering situation and weathering rates. Even though the circumstances are more complicated than in St. Olav’s chapel, there is little doubt that the change of roof design during the restoration (fig. 18.7) led to strongly increased weathering.

Hence, again arises the difficult question of whether to re-restore the roof or not. In addition, it is clearly necessary to undertake several direct conservation measures (cleaning, consolidation) in order to save the most weathered corbels.

Part VI

Discussion, recommendations and conclusions

Fig. 19.1: *Typical problems at Nidaros - water, open joints, indoor salt weathering and decaying medieval sculpture. Top left: St. Olav's portal (1995); top right: north turret of the choir (1991); left: chapter house (1995); right: St. Michael's chapel (1996) (photos: PS).*

Chapter 19

Summary and discussion of typical weathering phenomena

Although the weathering situations at the cathedral are complex, it is possible to define typical situations or zones at risk at a specific building site, and situations that repeat over the entire cathedral. In this chapter a summary and discussion of situations described in chapter 11-18 will be presented. First, however, there is a need to summarise issues related to structure, design and indoor climate - issues of great importance for understanding the weathering phenomena. Moreover, weathering phenomena strongly related to air pollutant emissions will be discussed in-depth. How the most important stone types behave under different exposure conditions have been summarised in chapter 10 and are not repeated here.

19.1 Structure, design and indoor climate vs. weathering

In order to maintain functionality and keep the walls in good repair, a building requires sufficient structural stability, a good system for discharging precipitation, as well as an adapted indoor climate. Nidaros cathedral only partially fulfils these basic, yet difficult requirements.

Stability problems

Large historic stone buildings often have stability problems related to excessive dead loads and differential settlement - sometimes developed as a result of recent addition of heavy towers. Such problems may not endanger the building as a whole or lead to collapse, but they may cause masonry to crack, loss of delicate stonework and weathering problems associated with penetration of water through the cracks.

The Gothic and Neogothic parts of the cathedral - notably the choir, the King's porch, the nave and the west front all suffer from stability problems (chapter 5, 11, 12). The situation is particularly difficult in the choir where the frail buttresses are not able to balance the excessive pressure of the vaults which were built together with the clerestory walls in the 1880s. As a consequence the following problems have occurred:

- Outward inclination of the walls of the aisles.
- Collapse of capitals and marble columns inside the choir.
- Development of cracks in the main vaults as well as in the vaults of the aisles.
- Development of cracks in the upper and lower gangways and parapets.
- Development of severe cracks in the King's porch on the south side of the choir.

In 1986, 70 years after the first cracks were observed, the situation was considered acute and the choir was secured by a steel construction above the main vaults. Since few recent measurements have been undertaken in order to control subsequent development, it is difficult to state whether the crack development has been ended or not.

The stability problems of the nave and west front are of a different nature and mainly related to differential settlement (c. 5 cm) occurring during and after the building of the west towers (1950-1969). Also differential settlement between the central tower and the nave may have led to recent stability problems. The following problems have been observed:

- Collapse of capitals, marble columns and mouldings inside the nave on several occasions since the 1950s.
- Development of cracks in the western bays of the nave (vaults, gangways and parapets, window tracery and triforium arches)
- Development of cracks in the bays close to the central tower.
- Development of cracks in the west front, especially between the west towers and the nave, as well as through the rose window.

Many capitals and columns have been secured, but pieces continue to collapse within the nave, representing a major safety risk. Although no recent measurements (levelling) have been undertaken, it is obvious that differential settlement is a major cause of the problems. It is not really known if the weight of the heavy west towers is the only factor to consider. Changes in ground water level may also make a considerable contribution to crack development - a factor that should be carefully evaluated soon.

The main effects of cracks caused by the cathedral's stability problems are water leaks from exterior gangways and parapets. However, it is not always straightforward to blame the development of cracks at these sensitive building elements on stability problems alone. Frost and thermal movements may play vital roles, especially on the south side of the cathedral. The design of the water discharge system, as well as the insulation (covering) of the gangway floors also have to be considered (see below).

Roof design, exterior gangways and parapets

Although the copper covered roofs of the cathedral appear to be in sufficient repair, copper plates frequently lift or are otherwise destroyed during storms. Excluding the spire of the central tower, which is inaccessible without major scaffolding, such damage does not normally cause great problems because they are easy to detect and repair. Those parts of the cathedral which received lead roofs during the restoration (octagon, aisles of the choir) were formerly subjected to major water infiltration. Since the 1960s most of these roofs have received copper plates.

Thus, present problems with the roofs are not related to copper plates, but generally to their Neogothic design and the fact that they are not properly protecting stonework below. In principle, the design of roofs can be divided in three categories:

- Copper covered cast iron roofs including gangways and parapets on top of the wallheads (choir, nave, central tower).
- Copper covered (and a few lead) timber- and cast iron roofs with stone capped gables (octagon, transept).
- Flat roofs covered by cement/asphalt and surrounded by parapets (west towers).

All the roofs were built during the restoration. The roofs prior to the restoration had “traditional” (post-Reformation) design and were without gangways and parapets.

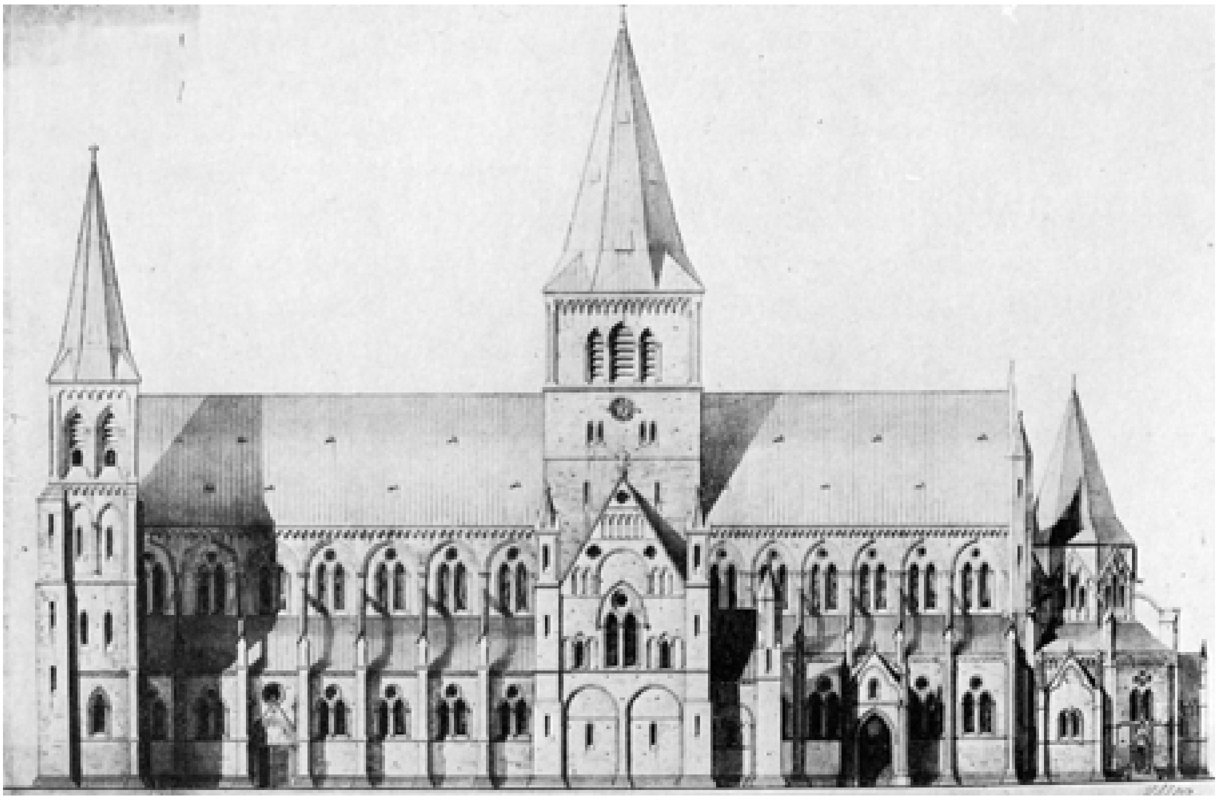


Fig. 19.2: *Architect Schirmer's 1851-reconstruction plan of the cathedral* **-** *a plan that was never executed. Note that parapets are omitted. Schirmer believed they would become a constant nuisance due to the harsh climate in Trondheim (ARW, no. 57h).*

The principles of roof design seem not to have been a major issue of concern during the restoration. However, in his 1851-reconstruction plan for the cathedral (which was never executed, see fig. 19.2), architect Schirmer did not include exterior gangways and parapets. Based on written sources, Trygve Lysaker notes that:

> Schirmer was familiar with the idea of adding exterior gangways and parapets. However, even if it were possible to prove that the cathedral had parapets in the Middle Ages, he advised against building new ones. He believed that they would become almost impossible to maintain because of exposure to ice and snow.[1]

The issue was also brought up during the erection of the west towers in the late 1940s. Critics maintained that architect Thiis' design, which included flat roofs, would be a problem in the Trondheim climate with its rapid temperature changes.[2]

According to the case studies (chapter 11-12) which show that the gangways and parapets are indeed extremely susceptible parts of the cathedral, the predictions have certainly proved to be correct. In addition to exposure conditions - and stability problems leading to cracks and allowing water to penetrate the floors of the gangways - the problematic condition should also be viewed in the light of the poor insulation of the gangways (cement and asphalt), as well as the malfunctioning and underdimensioned water discharge systems.

Another issue is whether exterior gangways and parapets are suited to the rather cold Scandinavian climate. The generally milder climatic conditions in other European countries, lead colleagues in The Restoration Workshop maintain that the probability of water leaks from exterior gangways are much higher at Nidaros than in Central and Southern Europe. However, it is impossible to verify such a statement without comprehensive comparative investigations. On the basis of studies in Austria, Alois Kieslinger noted for instance in 1932 that:

> Besonders häufig weisen Kirchen, vor allem alt- und neugotische, offene Dach- und Turmgalerien auf, deren Wasserableitung entweder schon von Anfang an oder durch spätere Schäden unzureichend ist. Das Wasser (besonders des schmelzenden Schnees) dringt in das Mauerwerk ein und führt zu Krustenbildung, Ausblühungen, Frostsprengungen u.ä. Natürlich leidet nicht nur das Innere, sondern auch die Aussenarchitektur unter diesen Galerien.[3]

My own observations of the condition of interior vaults at different cathedrals in Central Europe show that leaks from exterior gangways are rather uncommon.[4] It is, however, my impression that most of the studied cathedrals have far better water discharge systems than that at Nidaros.

It should also be recalled that the frequency of major water leaks has been reduced after the lower gangways at Nidaros were covered by copper plates in the 1980s. The fact that leaks still occur can be explained by folded lock welts (joining plates together) which allow some water to penetrate, plus stability problems, poor water discharge system and open joints in the nearby cornices.

Roof design and stone capped gables

The transept and octagon were also subject to major roof changes during the restoration. Prior to the restoration most of the roofs were the traditional type, covered with tiles and including eaves which protected sculptured corbels below. Moreover, very few stone capped spires (small towers) flanking the gables remained from the Middle Ages.

Generally, the restoration of all parts of the transept and octagon included raising the gables and capping them with stone. Most of the stone capped towers flanking the gables were also rebuilt. Instead of protective eaves, the copper and lead roofs received gutters, meaning that sculptured corbels, both old and new, became more exposed to precipitation and frost than before, especially the “outermost” ones or those located directly below the stone capped gables.

In addition to severe problems with joint fissures, leaks and salts in stone capped towers, the most significant effects of changing the roof design were:

- Rapid weathering of corbel heads.
- Leaks and run-off from the corners between the towers and stone capped gables, leading to interior and exterior weathering problems.

The rapid weathering has certainly been influenced by other factors as well - for instance black crusts (air pollution) and salts from Portland cement mortars.

Water discharge systems and the record of leaks

As mentioned above, the water discharge systems of the cathedral are generally underdimensioned and suffer from insufficient repair, especially in the choir and nave.

Initially the discharge system of the choir seems quite capable of carrying away precipitation affecting the roofs and exterior gangways. There are many stone gullies and copper gullies discharging water from the upper and lower gangways, respectively. The stone gullies, however, discharge water onto the flying buttresses which, as a consequence and especially due to the formation of icicles in the cold season, have been rapidly destroyed. Moreover, the copper gullies are generally in such a poor condition that they have led to severe weathering problems in the cornices below. This situation has prevailed since the choir was finished in 1890. Frequent severe water leaks affecting interior vaults and stonework below the parapets can be traced back to the turn of the century.

The water discharge system of the nave is different to the choir. There are no gullies or gargoyles, but an underdimensioned system of downpipes which has to carry away water not only from the roofs and gangways of the nave itself, but also from several other areas (central tower, west towers, west front). Severe water leaks occurred 10-20 years after the nave was finished in 1930 and since then similar problems have arisen as in the choir.

Although the central tower has suffered similar weathering problems to the nave, the weathering is less intense. This phenomenon can be explained by the fact that there are 12 large stone gullies (from c. 1900) which readily discharge precipitation collecting in the gangway surrounding the base of the large spire. In contrast, precipitation collecting on the flat roofs of the west towers (from the 1960s) is supposed to be carried away by a single downpipe at each tower. Especially in the southern west tower, this situation has led to extreme water infiltration and weathering problems.

Corners between gables and stone capped towers (transept, octagon, chapter house) are very vulnerable with regard to water leaks, not least because of open joints and joint fissures. It is evident that such sensitive corners ought to be equipped with special water discharge systems. A copper construction, which successfully reduced the frequency of water leaks, was installed on the chapter house in 1932, but so far this is the only place where specific measures have been undertaken. Pictures taken before the restoration show that copper gullies were in use between the gable and the towers of St. Mary's chapel, but they were removed when the chapel was restored.

In order to avoid ice formation and leaks from gangways, gutters and downpipes, The Restoration Workshop has, in addition to normal maintenance, tried to use both electrical cables and de-icing salts - with limited success. No attempt to fundamentally change the water discharge systems has been made. Considering the frequent water leaks and their effects, it is strongly recommended that such changes should be made in the near future.

Compared to cathedrals throughout Europe, at sites where grotesque gargoyles are normally used, it is possible to state that Nidaros cathedral has one of the most poorly constructed water discharge systems. Considering that Trondheim has a relatively harsh climate, it is no wonder that water leaks have become such a major problem at Nidaros.

Indoor climate and central heating system

The indoor climate of the cathedral is characterised by:

- Heated parts: Warm (15-22°C) and dry (25-45% RH) in the heating season (October-May). Relatively cool and humid in the summer. Infrequent summer condensation events in cold corners.
- Unheated parts: In principle completely dependent on the exterior climate. Frequent condensation events in turrets and towers, especially in late autumn and spring.
- Draughts: Due to large-scale thermal movements (cold air drawn in from openings and windows) the nave is severely affected by draughts in the heating season.

Generally, cracking and flaking of painted wooden objects are the most significant adverse effects of a warm and dry indoor climate. In the Nidaros cathedral there are few such objects and instead the organs suffer the most. The state of the organs is, however, beyond the remit of this thesis.

Other adverse effects of the warm indoor climate during the heating season are related to thawing of snow and ice on heated building parts. The exterior gangways of the choir and nave (especially the lower gangways) are probably strongly affected because of radiators located in the nearby triforia. Also snow on string courses and sills in the transept and chapter house seem to melt more rapidly than on building parts which are not heated. The effect is more frequent freeze-thaw cycles and more problems with leaks.

Whether the warm and dry indoor climate during the heating season causes more rapid salt weathering on parts affected by leaks is hard to say. A positive effect of heating (compared with unheated areas) is that it reduces the number of condensation events inside the church, as well as on outside walls of the heated areas. Condensation and white frost are far more frequent on exterior walls of unheated areas, contributing significantly to the salt weathering of these parts.

19.2 Typical weathering situations

The discussion above concentrates on problematic design factors or weaknesses of building construction which may explain several weathering phenomena at the cathedral. Below a summary of typical weathering situations are given. The central elements of any weathering situation are the exposure conditions, and the following classification scheme is used (see also appendix 3):

- Weather beaten architectural elements
- Areas exposed to leaks (and condensation)
- Areas exposed to run-off/transition zones
- Zone of rising damp
- Complex weathering of sculptured details

Weather beaten architectural elements

Stone capped towers, flying buttresses, parapets, cornices, stone capped gables, pinnacles, string courses and projecting decorations are all strongly exposed to rain, snow and ice. These elements are mostly found in elevated areas reconstructed or rebuilt during the restoration. Almost without exception, the elements show some kind of surface weathering of the stonework, biological growth (moss and lichens) and severe opening of joints.

Critical stone weathering such as the loss of large fragments of mouldings and projecting decorations (e.g. fake gargoyles, bases and capitals), is normally strongly related to the primary properties of the stone (chapter 8-10). Bjørnå soapstone, used between 1897 and the 1960s, is by far the most problematic stone. First, its use has been extremely widespread in elevated architectural elements (central tower, transept, nave and west front). Second, the loss of large stone fragments represents a risk for by-passers.

Also poor varieties of Grytdal soapstone, used between 1869 and 1892, tend to lose larger fragments when severely exposed to precipitation. The associated risks are no longer very serious because most of the stones in question (especially in the choir) have been replaced by other stone types. One of these stone types is Bubakk soapstone (used since 1952), on which strong surface weathering can be observed. Recently this stone has also started to lose larger fragments due to minute fissures - a problem which may become critical in the future.

The existence of open joints and joint fissures is related to dense, inflexible and poorly adhering mortars containing Portland cement. Since all elevated parts of the cathedral were restored and rebuilt either using Portland cement mortars or lime cement mortars, it is understood that the problem is extremely widespread. It may be difficult to assess the relative importance of the various possible causes of why joint fissures develop. One possibility is that cement mortars shrink on setting, another is the action of leaks, frost, thermal movements and wind (and perhaps vibrations), and a third is large-scale stability problems. In many cases it is reasonable to maintain that all these factors work together.

Many severely exposed elements treated in this section are secured by different types of metal dowels and cramps. Since copper, brass and stainless steel have been used instead of traditional iron dowels (chapter 6.4), there are practically no problems with cracking as a result of oxidation/rust. Such problems are extremely widespread throughout Europe.[5] A sad Norwegian example is Stavanger cathedral where hundreds of decorations were fixed by iron dowels during the restoration in 1867-71. Today there are massive weathering problems because of the iron dowels and dozens of stone fragments have fallen down.[6]

Leaks and salts I: Masonry and vaults below parapets

As a result of all the joint fissures in flying buttresses, parapets and cornices, as well as fissures in the gangways, major and minor water leaks have inevitably occurred, affecting both exterior and interior masonry.

Stone towers or pinnacles associated with the flying buttresses of the choir and nave (and octagon) are characterised by large deposits of calcite due to water seepage through the joint system. Representing a major feature of the whole cathedral, calcite crusts are excellent indicators of former and present water leaks through masonry with Portland cement. Importantly, such crusts are not observed on photos taken before the restoration - implying that lime mortars rarely lead to the formation of calcite crusts. Their formation is related mainly to dissolution of portlandite ($Ca(OH)_2$) in the cement.[7] Having entered the joint system of the flying buttresses/associated towers, water seeps downwards, leading to salt weathering problems on the walls of the aisles and nearby vaults. However, these parts are also affected by leaks from the lower gangways, parapets and nearby cornices.

In addition to calcite, which is also present on the walls below the parapets, a wide range of salt species have formed as a result of the leaks and other factors, such as air pollution. According to observations, it is possible to distinguish between the following salt systems (see also tab. 19.1):

- A "sulphate" system, mainly containing Ca, Mg and SO_4
- A "carbonate" system, mainly containing Ca, Na, K, CO_3 (and some SO_4)
- A secondary reaction system formed as a result of reactions between sulphate and sodium carbonates.
- A chloride system (together with the other systems)

The *"carbonate" system* especially prevails on masonry erected after 1890, i.e. on masonry built of stone containing only very little sulphide (giving sulphate). Carbonates (trona, natrite/thermonatrite) are clearly related to leaching of alkaline components in Portland cement. Trona is usually accompanied by aphthitalite, which may also stem from Portland cement, while natrite/thermonatrite is often followed by mirabilite/thenardite. Although the latter salt pair mainly develop as a result of chemical reactions between natrite/thermonatrite and sulphates from stone and air pollution, it is reasonable to maintain that mortars alone may give rise to some mirabilite/thenardite.

The *"sulphate" system* mainly occurs at places where sulphide-rich Grytdal stone (and black crusts developed as a result of air pollution) have not come in contact with alkaline salts from Portland cement. The system is found especially at particular places in the choir.

***Tab. 19.1**: Salt systems at Nidaros catheral*

“Sulphate” system
Primary source 1: stone, especially Grytdal, and brick (choir). Ions: *Ca, Mg,* SO_4 *, (Na)*
Primary source 2: air pollution. Ion: SO_4
Species: *gypsum, epsomite/hexahydrite, (mirabilite/thenardite)*
“Carbonate” system
Primary source: Portland cement. Ions: *Ca, Na, K,* CO_3 *,* (SO_4)
Species: *calcite, natrite/thermonatrite, trona, aphthitalite, (mirabilite/thenardite)*
Secondary reaction system
Reactions between “sulphate” and “carbonate” system. Na-carbonates not stable in the presence of sulphates.
Species:*mirabilite/thenardite, bloedite, (aphthitalite*)
Chloride system
Primary sources: sea salts, cleaning agents (hydrochloric acid), de-icing salts + secondary reactions (Cl & Na).
Species: *halite, antarcticite* (rarely crystallise)

As a result of chemical reactions between the first and the second salt system, rather complex systems of carbonates and sulphates have developed. All salt species mentioned in tab. 19.1 are e.g. found on the vaults and walls of the choir. Generally, there are no soluble carbonates left when large amounts of sulphates are present (they cannot coexist). Considering the minor amounts of chloride detected, halite seems to be the most frequent species - originating either from deposition of sea salts or cleaning procedures during the restoration of medieval walls. Calcium chloride possibly also originates from de-icing salts used to melt snow in the gangways. The reason why salts can remain and act on the exterior walls is because they prevail in partly sheltered locations rarely affected by lashing rain. The major period of crystallisation/efflorescence is the relatively dry spring, but frequent events of condensation/hygroscopic dissolution also seem to be of great significance in connection with the actual weathering processes taking place. Whether frost plays a significant role has not been investigated.

The effect of the salts is diverse, but generally not causing any great harm to the fabric of plain walls without architectural decorations. Important exceptions can be found on walls containing poor-quality Grytdal stone which tends to totally disintegrate and cause trouble to the structure as a whole. Another exception is related to fire-damaged medieval walls (aisles). They disintegrate quite rapidly under the influence of salts. Plastered vaults are also quickly damaged by leaks and salts. As all the vaults in question were built during the restoration, the associated loss of historic value cannot be considered dramatic.

Calcite crusts must be regarded as highly unsightly as they frequently disturb the architectural character of the cathedral. However, the crusts are not significantly damaging the fabric of the stone, as long as they are not removed. When removed by chisels, stone surfaces tend to follow.

Leaks and salts II: Stone capped towers and gables

The stone capped towers and gables were built during the restoration. They are found in the octagon, chapter house, transept, central tower and west towers. Simplified, it is possible to characterise the weathering problems caused by joint fissures/leaks as follows:

- Exterior and especially interior salt weathering of the stone capped towers themselves, as well as of staircases directly below.
- Salt weathering on medieval masonry located directly below towers and gables.

Almost without exception, the stone capped towers have major deposits of calcite below their cornices (fig. 19.3). The deposits are frequently so large that they seriously disturb the architectural character. Calcite crusts also prevail inside several towers, indicating the severity of the leaks. In addition, enormous amounts of soluble carbonates (natrite/thermonatrite, trona) have accumulated on the walls of the staircases immediately below the towers. Sulphates are not very frequent, and when they do occur, they mostly originate from the Portland cement as well (aphthitalite, some mirabilite and thenardite). Apart from a few exceptions, the salts are associated with extremely rapid weathering of ashlars. Grunnes soapstone is particularly vulnerable, but Bjørnå soapstone also shows serious weathering. Although leaks seem to be of particular importance for the weathering, effects of frequent condensation events should also be considered. Such phenomena have been observed, especially in the southern west tower.

Fig. 19.3: *White calcite crusts on one of the central tower's small towers. Even though the weather was fair when the picture was taken, moisture arising from condensation runs down along the crusts. Generally, condensation - in addition to leaks - must be regarded as a significant cause of the white crust-problem at Nidaros (photo: PS 3/96).*

Despite the rapid weathering, the risks of losing valuable stone surfaces are low. The staircases are luckily hidden parts of the cathedral, meaning that there are few adverse aesthetic implications.

Medieval stonework located below stone capped towers is fortunately in rather good repair. Salt weathering due to leaks (and condensation) do occur, but it is only below the eastern tower of the north transept that the situation is critical. Exterior masonry is crumbling at a high rate here because there are severe leaks from the corner between the tower and the stone capped gable.

Generally, such corners represent weak parts of the cathedral. Severe leaks took place from such corners in the chapter house before the water discharge system was changed in 1932. At present it is the chapels of the octagon that particularly suffer from similar leaks. The most serious result is that not only vaults, but also interior medieval decorations weather rapidly due to salts. The salt systems in question are complex, involving various carbonates, sulphates and chlorides. It is also clear that Portland cement mortar is the most significant salt source.

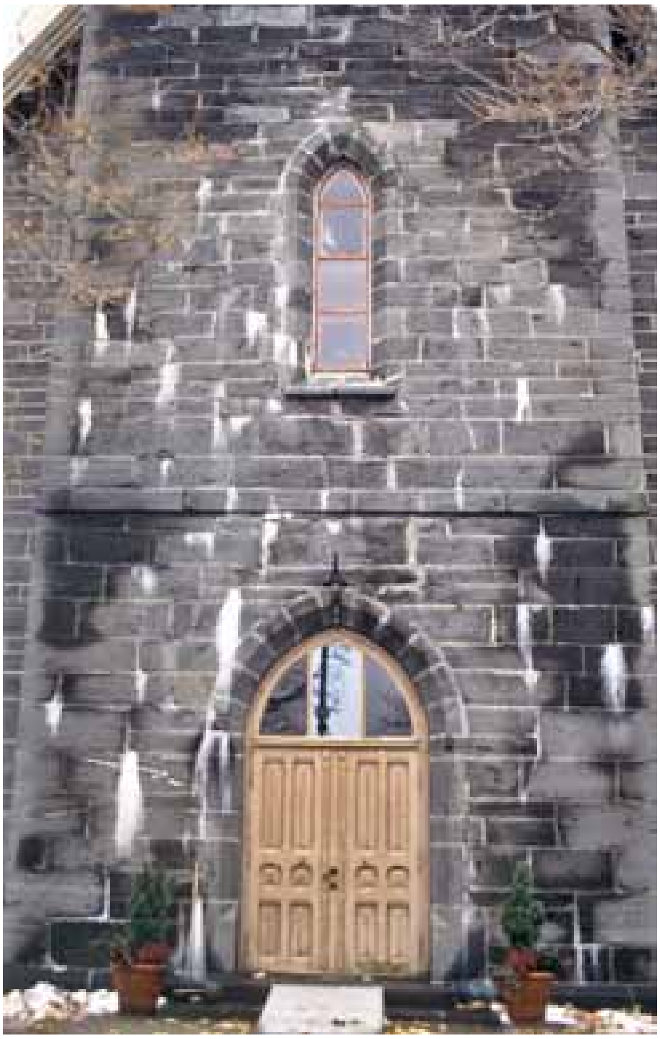


Fig. 19.4: *White calcite crusts at the west tower of Orkdal church near Trondheim. The tower was built with local greystone and mortars containing Portland cement towards the end of the 19th century (photo: PS 10/94).*

Leaks from joint fissures in stone capped gables may also be critical, especially when considering the octagon's chapels. These leaks not only affect the masonry as such, but also medieval decorations integrated with the walls - in particular window arches. Again, the salt systems are complex, many of which have developed through centuries (east chapel).

Leaks and salt weathering are certainly found at places other than those associated with towers and gables. The poorly insulated window sill on the west wall of the chapter house is only one example.

Nidaros cathedral is not the only building in the Trondheim region that suffers weathering problems due to the combined effects of the use of Portland cement mortars, joint fissures, leaks, condensation and alkaline salts. According to my investigations similar problems can be found at the Baroque tower (1740) of St. Mary's church,[8] the towers of Neogothic stone churches such as Ilen (1889), Melhus and Orkdal (1893),[9] and at Gulfossen stone bridge (1922) (fig. 19.4-6). The problem is also widespread in other parts of Europe.[10]

Parts exposed to run-off and transition zones

It may sometimes be difficult to distinguish between run-off and leaks because of the close relationship between the two phenomena. Run-off means water running on the surface of stonework, either as a result of rain or melting snow collecting on elements above. Run-off often creates typical transition zones between “wet” (exposed) and “dry” (sheltered) stonework in which black crusts prevail. Similar transition zones can also be found at several other places. The architectural elements in question are mainly:

- Corners between gables and towers/pinnacles
- The underside of string courses and cornices
- Stone work below/beside joint fissures in string courses and cornices
- Buttresses, pillars and (marble) columns
- Decorations and sculptures

Generally, the stonework is usually clean and sound where either water runs freely or where the masonry is completely sheltered. Between these two end members, there may be several additional zones depending on the actual situation. Relatively thick black crusts usually

Fig. 19.5: *Salt weathering problems at the west tower of the Neogothic Ilen church in Trondheim. Right: Although most calcite crusts seem to have been removed from the masonry, there are still numerous remains, seen as white patches. Above: Inside the tower there are enormous amounts of alkaline salts, sometimes giving rise to significant weathering problems (photos: PS 1994 and 1995).*

accumulate beside the main water flow, thinning towards progressively sheltered areas. This general picture coincides with observations made world-wide (see chapter 3.6).

When other, more soluble salts than gypsum are present, they tend to concentrate in zones beside the accumulated black crusts (according to their solubility products and the actual exposure conditions). Associated weathering forms like granular disintegration and flaking etc. are mainly confined to such zones. Otherwise, the black crusts rarely cause any particular harm to the stone fabric. There are, however, some important exceptions, mainly related to the properties of the stone.

Whereas dense stones like Hovin sandstone and Bjørnå soapstone remain sound when thick black crusts are present, the more porous Grytdal stone may develop significant flaking and disintegration. In such cases it is

Fig. 19.6: *Strange pattern of alkaline salt efflorescences inside the 18th century tower of St. Mary's church in Trondheim. Plaster containing Portland cement applied at the turn of the century has apparently led to moisture problems (photo: PS 6/96).*

assumed that - in addition to air pollution - sulphate/gypsum is also provided from the stone itself (see below). Øye greenschist is, moreover, frequently delaminated where black crusts prevail. The greenschist cannot be considered porous, but due to its pronounced foliation, gypsum may enter microfissures in the stone fabric.

The origin, distribution and effects of black crusts are often more complex than described above. It is therefore discussed in greater depth below.

Zone of rising damp

Fortunately, the cathedral is little affected by rising damp and associated salt weathering phenomena. It is in fact hard to say whether rising damp is a problem at all. This is because condensation may well be the dominant weathering agent in the *zone* of rising damp.[11] Both the transept and the octagon show minor weathering problems in this zone.

Dampness has been a problem for centuries in parts of the transept. Today, the most affected parts are the Lectorium and St. John's chapel where medieval decorations crumble quite rapidly. Since the associated salt system is characterised by large amounts of trona, Portland cement used for consolidation purposes (masonry, foundations) is likely to be the main source. The salt weathering seems to be triggered by infrequent events of condensation affecting these cold corners of the cathedral.

In large parts of the cathedral, the heavy, moulded bases have widespread joint fissures where moisture (rain, snow) can easily enter. However, associated indoor salt weathering only occurs on a somewhat greater scale in the octagon. Here Portland cement in foundations and joints also seems to be the main source of the salts. The weathering develops at a very low rate and cannot be considered dramatic.

Complex weathering of sculptured details

Architectural decorations and sculptured details are usually considered the most valuable parts of Nidaros cathedral's stonework. What makes the weathering of such details so difficult to understand is the intimate relationship with the behaviour of surrounding masonry and design of the building. There may be some justification to view the entire cathedral as a “sculpture” - implying that it is necessary to investigate the weathering of decorations by considering the whole context in which they occur.

This section is limited to the presentation of medieval, relatively free-standing sculptured details. The weathering of decorations more or less completely integrated in the masonry, such as window arches and blind arches, or decorations like string courses and cornices, are not considered. Their weathering is completely dependent on the behaviour of surrounding masonry and have been properly treated above.

Relatively free-standing details added during the restoration will also be left out. Their weathering is extremely dependent on the primary properties of the stones. One example is Grytdal stone and the dreadful condition of all the corbel heads in the frieze below the upper parapets of the choir, another example are the thousands of projecting details made by rapidly weathering Bjørnå stone. A third example is the excellent condition of the protected, very young west front sculptures.

Hence, this section concentrates on probably the most valuable decorations of all - the Romanesque corbel heads of the transept (chapter 18). They were all made from greenschist around 1150 and have been affected by the most diverse historical events and restoration measures - ranging from fire and overpainting to partial replacement and temporary silicone coverings in order to produce plaster copies.

The single most important event affecting the weathering of the corbels was the change of roof design in the 1880s. Until then, the corbels were protected from precipitation by tile roofs with eaves and in excellent repair. The new Neogothic roof design with stone capped gables rendered the corbels not only more exposed to precipitation, but also to leaks and salts. Moreover, as the most exposed corbels are partly covered by black crusts (transition zones, see above), air pollution seems to have been of some importance as a weathering agent as well. Today, several corbels must be considered badly weathered.

Although more research on actual weathering mechanisms has to be carried out in order to fully understand the poor state of the corbels, I believe that my investigations could be used as a basis for other exploratory research campaigns, e.g. for the several dozen weathered, Gothic corbel heads in the octagon.

19.3 Distribution, origin and effects of black crusts

Compared to stone buildings in heavily industrialised regions, where whole façades may be completely covered by black crusts, Nidaros cathedral is in a favourable situation. The distribution of black crusts is limited - a feature mainly related to the fact that emissions of air pollutants have been low in Trondheim.

The historic development of black crusts at the cathedral is nevertheless very clear: Their formation began as the industrialisation accelerated in the latter half of the 19th century. A peak in distribution was reached between 1950 and 1980, while during the last 20 years a notable reduction has taken place - in accordance with lower emissions of SO_2. Rain washing seems to be the major reason for the removal of black crusts, but at many places they may also simply have weathered away (flaked off). It is also clear that the accumulation of black crusts is related to particular run-off zones and transition zones between “wet” and “dry” stone work.

This section summarises and discusses the formation of black crusts from other relevant perspectives, such as:

- Orientation of the church - or general exposure conditions - and proximity to (former) sources of air pollution.
- History of restoration and rebuilding.
- The presence of sulphide-rich stone and marble.

The relationship between black crusts and associated weathering forms is also discussed. At last an important question is raised: Is air pollution a problem today?

Exposure conditions and proximity to pollution sources

Black crusts occur almost unequivocally at the eastern parts of the cathedral, on façades facing N, NE, E and SE. Elsewhere, the crusts are extremely thin and mainly found underneath string courses and other projecting elements.

This mode of distribution can be explained by the fact that former industrial and domestic sources of SO_2 were located in the city centre and to the northeast of the cathedral. Although the dominant wind direction in Trondheim is south-westerly, northerly and north-easterly winds occur about 30% of the time. Operated since 1871, the coal/oil-fired central heating plant of the cathedral may also have contributed significantly to the development of black crusts. This is because its chimney is located on the roof of the chapter house (by the north side of the choir).

Another reason is that the ambient air on the northern and eastern sides of the church is in general relatively humid and cold compared to other areas, thus rendering the stonework more susceptible to dry deposition of air pollutants. It should be strongly underlined that lashing

Fig. 19.7: *Black crusts at the north wall of St. Mary's church in the city centre of Trondheim. The crusts prevail on lime mortar joints and whitewash around the windows, but are washed away at the corner of the wall (photo: PS 6/93).*

rain rarely affects façades facing north and east thus preventing rain washing, except in particular zones of run-off.

A similar pattern can be found on several buildings in the city centre of Trondheim. The north façade of St. Mary's church has for example more black crusts than the south façade (fig. 19.7). However, the actual process of black crust formation is very complex in this particular case. Although it is unconfirmed, there is information indicating that plaster and whitewash were removed by *sulphuric acid* in the 1950s![12]

History of restoration and rebuilding

Since black crusts preferentially occur on remaining medieval stonework, it is assumed that their formation is strongly related to the history of restoration and rebuilding.

Firstly, the medieval parts of the cathedral, mainly restored between 1869 and the 1880s, have been exposed to air pollution much longer than the upper parts of the nave and west front which were built in this century.

Secondly, except for the lower parts of the nave on which black crusts are almost absent, medieval stonework was covered with whitewash and paint before the restoration. Although these surface treatments were removed during the restoration, there are still many traces to be observed. Due to the available calcium, it is no wonder that black crusts are frequently associated with such traces. However, traces of paint may at a distance also be mistaken for black crusts.

Thirdly, whitewash and paint were often removed by hydrochloric acid and/or lye, cleaning agents producing hygroscopic salts (mainly halite). It may be suggested that the cleaning procedures rendered the stonework more susceptible to deposition of air pollutants. Since deposition of sea salts may interact as well, it is difficult to confirm this theory.

The presence of sulphide-rich stone and marble

Air pollution (SO_2) is not the only source of sulphate at the cathedral. Stone, mortar and brick also provide sulphate, in particular the notorious Grytdal soapstone which has an extremely high content of pyrrhotite (up to 10%). Grytdal stone is associated with extreme development of dark or grey gypsum crusts - both in the quarry and at the cathedral.

Fig. 19.8: *Two different forms and origins of gypsum crusts at Nidaros cathedral. Top: At the west wall of the chapter house "normal" black crusts caused by air pollution prevail on the hard Hovin sandstone below the string course. Below: At the base of the King's porch on the south side of the choir grey gypsum crusts prevail on the sheltered part of a rather weathered Grytdal stone. An important reason why it is assumed that the crust originates from sulphides in the stone is that there are no other gypsum/black crusts nearby the area in question (photos: PS 1992 and 1996).*

Assuming a pyrrhotite content of 5% by volume, 100 kg of Grytdal stone - a relatively large ashlar - contain some 8 kg pyrrhotite or 2,5 kg sulphur. All this sulphur is certainly not available for the formation of gypsum, but if it is assumed that only 1% is available, 100 kg of Grytdal stone is in fact able to produce more than 100 g of gypsum.

Assuming that the “ashlar” in question has a surface area of 0,2 m^2, that the annual dry deposition rate of sulphur from air pollution is a relatively high 1 g/m^2 pr. year[13] and that all sulphur - which is very unlikely - reacts to form gypsum, it would take more than 100 years to produce 100 g of gypsum.

Although hypothetical, these figures indicate that Grytdal stone is an extremely important source of black crusts in the choir where its use has been most widespread. However, Grytdal stone may act not only as a source of gypsum, but also as a sink for dry deposition of SO_2. This is because it is relatively porous when compared to other stone at the cathedral.[14] The fact that Grytdal stone may also provide hygroscopic salts such as epsomite (and other types when secondary reactions take place), may possibly enhance deposition of pollutants. However, only isotope studies may give further indications with regard to the actual sources of sulphate.[15]

Øye greenschist, Bakkaune soapstone and several soapstones used during the restoration contain moderate amounts of sulphide, mostly in the form of pyrite and pyrrhotite. Noting that gypsum is quite widespread in several quarries, it is reasonable to maintain that these stones also contribute some sulphate at the cathedral. Compared to Grytdal stone, the amounts are probably very small.

Fig. 19.9: *North-east side of the octagon.Typical occurence of black crusts on marble columns. The crusts are extremely thin and accumulate on sheltered sides and especially right above the zone of water splash (photo: PS 1997).*

The presence of calcium is a prerequisite for the formation of gypsum. Calcite/dolomite in soapstones, greenschist, mortars and whitewash are key sources, but nowhere is the availability of calcium as great as in the marble columns of the cathedral fig. 19.9). Depending on actual exposure conditions, marble columns may be completely covered by black crusts. However, the general pattern of distribution - widespread black crusts at the eastern ends and little at the western areas of the cathedral - also repeats when marble columns are considered.[16]

Black crusts have also formed at the two marble buildings in downtown Trondheim (located in Søndre gt.). Built at the turn of the century, the buildings are typical representatives of Norwegian rubble architecture.[17] One of the buildings (*Gildevangen hotel*) was cleaned a couple of years ago, but the other one (formerly *Trondheim Handelsbank*) still shows large deposits of black crusts below projecting elements (fig. 19.10).[18]

Black crusts and associated weathering forms

Depending on exposure conditions and stone properties, weathering forms associated with black crusts range from granular disintegration and flaking to delamination. However, the occurrence of crusts do not necessarily produce any significant loss of material. Firstly, weathering is strongly related to porosity of the stone. Grytdal soapstone and Øye greenschist are in this respect the most vulnerable ones because sulphate may penetrate deeply into their fabric. Secondly, weathering especially takes place where moisture is provided also from "within" the masonry, either because of leaks or because of particular run-off systems. Hence, salts other than gypsum interact as well. Thirdly, when black crusts occur underneath projecting elements such as string courses, frost may also be an important weathering agent. This is because such elements are strongly exposed to rain, snow and ice. In these situations, perhaps the most important effect of black crusts is that they may block pores, thus rendering the stones more vulnerable to frost? Finally, when black crust occur "alone", e.g. on pillars, columns and buttresses made of stone of very low porosity, they may be regarded as mere layers stuck to the surface. Whether this is a problem or not is thus mainly an aesthetic question.

Is air pollution a problem today?

The historical development of black crusts on the walls of the cathedral is excellently proving that the present level of SO_2 is a very minor threat - and that black crusts observed today mainly formed in the century between 1880 and 1980. The *already formed* black crusts still represent a risk ("memory effect"), especially in places where dissolution/redistribution/recrystallisation of gypsum can take place (for instance in run-off zones). Whether the current level of some 5 $\mu m/m^3$ SO_2 in the ambient air has any effect on the fabric of the cathedral *at all*, is another question. Observations of Bubakk stone put in place 5-10 years ago show that extremely thin, grey layers of gypsum sometimes form in sheltered locations.[19] Since Bubakk stone contain pyrrhotite and other sulphides it is, however, impossible to state if air pollution (SO_2) alone (or at all) is responsible for the sulphur contribution.

Fig. 19.10: *Large areas with black crusts below sills on the north side of former Trondheim Handelsbank in the city centre (photo: PS 5/94).*

Knowing that the relatively high levels of NO_2 and dust from traffic represent a problem for the *people* of Trondheim, it should be noted that NO_2 and soot seem to act as catalysts in the process of gypsum formation (chapter 3.6). Given the low levels of SO_2, it is very unlikely that NO_2 is a significant problem in this connection. Other possible effects of NO_2 are largely unknown. The dust in the Trondheim air during the cold season is certainly deposited on the cathedral (observations on the west front). In conclusion: *If the emissions of SO_2 are kept at the current low level*, the "crumbling cathedral" cannot be used as a reasonable argument for further reductions.

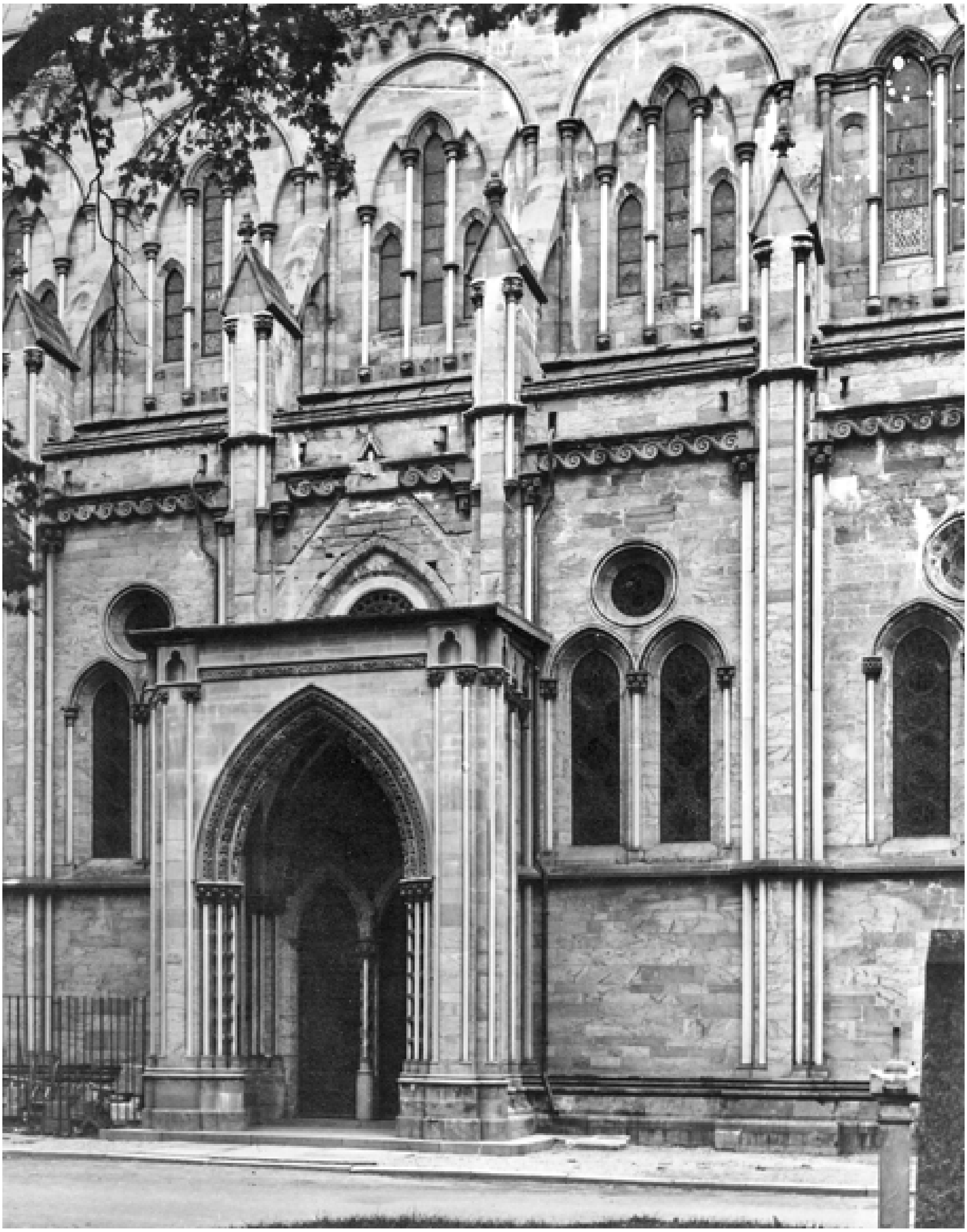


Fig. 20.1: *In the 1950s the King's porch had to be partially demolished in order to secure the structure. Today the same problems as earlier have reappeared. Will it be necessary to once more demolish the porch? (Photo: ARW).*

Chapter 20

From weathering to conservation

The main objectives of this thesis were to locate weathering situations, understand the historical evolution of the weathering phenomena, assess the risks and recommend conservation measures. This chapter - following on the interpretations from chapter 19 - deals with the main risks, possible measures and recommendations.

Firstly, general risks and measures related to building construction and design are discussed. Secondly, attention will be paid to the typical weathering situations - or zones at risk. Thirdly, a discussion about the selection of appropriate stone and mortar for future interventions will be presented. Details will not be considered as they have been discussed in the respective case studies.[1] Technical details related to craftsmanship can be found in texts like *Conservation of Historic Buildings* by Bernard Feilden and *Conservation of Building and Decorative Stone* by John Ashurst and Francis Dimes, which have been used extensively as sources of inspiration.

Recalling that historical values and age values are to be given top priority, the recommendations primarily aim at eliminating the causes of decay and/or at hindering the evolution of weathering processes. However, wherever necessary, recommendations involving stone replacement and even larger measures which will seriously alter the present fabric/design are also put forward.

20.1 General risks and possible measures

Previous chapters clearly show that the cathedral has many problems related to structure, design and indoor climate. It has also become clear that without solving these problems it may be rather meaningless to undertake interventions related to several specific zones at risk.

Stability problems

The greatest stability problems are without doubt to be found in the choir, including the King's porch which, in a worst case scenario, may be close to collapse. The eventual fulfilment of this scenario is strongly dependent upon whether the steel construction installed above the choir's main vaults in 1986 has been able to prevent the walls from inclining further outwards (chapter 5.3). In order to control the subsequent evolution, *the most urgent measure ought to be following up earlier measurements of deviation from the plumbline as well as of crack development*.[2] *Moreover, recent investigations show that the structure of the King's porch is so seriously damaged that comprehensive investigation, involving experts on structural behaviour of large masonry buildings, is absolutely necessary*.[3]

The differential settlement of the west towers/west front and nave, and associated loss of stone fragments inside the church, also calls for comprehensive investigation, even if the settlement is expected to slow down or come to a halt in the future. *Precision levelling,* *carried out regularly between 1951 and 1978, ought to be continued on a long-term basis* - especially in order to be able to understand the reasons for possible development of new masonry cracks. In this connection it should be mentioned that when excavations were undertaken at *Katedralskolen* (Cathedral school, 100 m to the north of the cathedral) in the 1980s, very minor settlements could be measured at the cathedral. The excavations caused a temporary lowering of the ground water table, a feature indicating that ground water changes may indeed be a threat to the cathedral.[4] *Hence, this risk should be considered in town planning policies*.

Until the cathedral can be regarded as a reasonably stable construction, it is expected that water leaks may develop as a result of evolving masonry cracks. It is also expected that decorative details (columns, capitals, mouldings etc.) may continue to collapse inside the church. *Controlling and securing such details ought to be given extremely high priority if major accidents like those in 1935 and 1980 are to be prevented* (chapter 5.3).

Poor design of main roofs

Apart from the fact that the Neogothic roof design facilitates the evolution of major water leaks, leading to exterior and interior weathering problems and loss of pieces of plaster and stone, the roofs themselves represent no major danger to people (although copper plates may fly far away during storms!).

Considering the choir and the nave, a relevant question is whether it is possible to change their roofs completely, omit gangways and parapets, and in this way avoid leakage problems - the major reason for salt weathering below?[5] Since such a solution will seriously violate the historic values of the cathedral, as well as change its architectural character completely, I would not personally recommend such a drastic measure. *Instead, it is recommended to insulate gangways with proper materials. Insulation with copper plates has strongly reduced the number of leaks in the aisles (choir and nave), but since leaks still occur due to the difficulty of making folded lock welts water proof, a better solution is perhaps to apply modern membranes?*

Fig. 20.2: *Gargoyles on the north side of Notre-Dame in Paris. Should similar working gargoyles be employed at Nidaros? (Photo: PS 12/94.)*

Fig. 20.3: *At the choir of St. Vitus in Prague downpipes can be found at each bay. Should a similar solution be applied to Nidaros? (Photo: PS 10/96).*

Considering, however, the transept - and especially the transept's chapels - serious thought should be given to the option of changing the roof design. Knowing that the weathering of Romanesque corbel heads below Neogothic stone capped gables has proceeded very rapidly since the restoration (1880s), one possibility is to re-introduce the traditional roofs with eaves prevailing prior to the restoration. *If nothing is done to protect the corbels from precipitation, it is predicted on the basis of the historical evolution that many of them will be hopelessly lost in 50-100 years*.

Insufficient water discharge systems

From the perspective of water leaks and salt weathering, there is an intimate relationship between poor roof design and insufficient water discharge systems. Assuming, however, that most of the roofs have to remain as they are today, insulating exterior gangways and changing the water discharge systems may lead to a reduction of the number of water leaks in the first instance.

In order to discharge water efficiently from roofs and gangways, there are in principle two possible solutions: either to omit gutters and downpipes and put gullies and gargoyles to work (fig. 20.2), or to add more downpipes than currently exists. Experience from the UK indicates that:

> Wherever a roof can discharge harmlessly by means of widely projecting eaves or frequent spouts and gargoyles, it is sound policy to omit or even to remove eaves gutters [and downpipes, *my comment*] entirely.[6]

There is little doubt that frequent gullies and gargoyles would be a very good solution in parts of the cathedral (cf. the central tower). However, the problem at Nidaros is that not only rainwater, but also snow, ice and icicles have to be taken into account. When large icicles form from gullies at high elevations, they may not only represent a danger for stonework below (cf. flying buttresses at the choir), but also to passers by (cf. west towers). Hence, considering that the consequences of re-designing the water discharge systems are very different at various parts of the cathedral, it is incorrect to propose a standard system.

Another problematic issue is that employing gullies and gargoyles may imply major architectural changes, not least in the nave where all the fake gargoyles (aisles) would have to be remade. Considering that the water discharge system of the nave is underdimensioned, and that the gradient of the gangways is insufficient, a better solution is perhaps to add downpipes at each bay. This solution can be found at several European cathedrals (fig. 20.3).

With regard to leaks and run-off along stonework, corners between stone capped towers and stone capped gables represent another problematic feature of the cathedral (octagon, chapter house, transept). In order to stop the leaks, there are in principle three possible solutions:

- Cover the stone capped gables with copper (or lead) and allow water collecting in the corners to drain into gutters along the eaves of the roofs (cf. chapter house).
- Insert gullies in order to hinder water and ice reaching stonework directly below (cf. St. Mary's chapel before the restoration).
- Put gargoyles at work where possible (cf. the portals of the nave before the restoration).

As can be seen, there are many possibilities for changing the water discharge systems of the cathedral. *A general recommendation is that before undertaking large repair programmes, comprehensive investigations, including ethical, technical and aesthetic consequences of major changes, ought to be carried out*. Moreover, the importance of regular maintenance of water discharge systems is self-evident.

Poor heating system and dry indoor climate

From the perspective of its poor condition and high energy consumption, it is clear that the current 60 year old central heating system has to be renewed.[7] Other simple reasons include:[8]

- The emission of minor amounts of air pollutants in such close proximity to the cathedral.
- The dry indoor climate which adversely affects the organs and other moveable objects of art (wooden).
- The comfort for people, especially related to draughts.

Apart from the fact that heat transfer from triforia and other strongly heated parts of the cathedral tends to melt snow on exterior parts, leading to more frequent leaks and stronger ice formation, particular problems of stonework clearly related to heating have not been detected. Positive effects of heating include an almost complete absence of autumn/winter/spring condensation.

When designing a new indoor heating system/indoor climate all the preceding factors have to be considered. On the basis of current knowledge, it is possible to suggest that the system - and the indoor climate - should meet the following criteria during the cold season:

- Background temperature of 8-10°C in order to avoid major condensation events. The relative humidity at these temperatures is about 60% during the heating season.
- Temperature as low as possible during services, for example 12-14°C.
- Temperature not higher than 18°C during concerts and other performances.
- No emissions of air pollutants and staining of walls and vaults.
- Low energy consumption.

It should be noted that a general lowering of the temperature inside the church will reduce the problems with draughts. This is because large temperature differences facilitate the occurrence of draughts.

In practice, it is perhaps impossible to meet all the criteria mentioned above. Hence, one has think in terms of a flexible heating system and try and reach the best possible solution based on a discussion of preferences, including:

1. avoiding damage to moveable objects of art;
2. avoiding damage to the fabric of the building;
3. avoiding conditions too uncomfortable for the congregation, audiences and visitors.

However, before designing a new indoor climate, much more ought to be known about the current situation, by recording temperature, relative humidity, air movements etc. on a long-term basis. Until now the climate during one heating season in a limited part of the church (transept) has been recorded.

20.2 Typical zones at risk and possible conservation measures

In this section attention is given to the pros and cons of various direct conservation measures related to the typical zones at risk.

Weather beaten architectural elements

The elements in question were almost without exception added during the restoration. They include:

- Stone capped towers and pinnacles.
- Flying buttresses.
- Parapets.
- Cornices, string courses and copestones in general.

Although the weathering of these elements varies widely from place to place, they have several features in common. Weathered Bjørnå stone - and some Grytdal stone - about to lose lesser or larger details represent the most obvious risks. Portland cement mortar joints are, moreover, in a very bad state of repair, mostly because of fissures, which again lead to serious water infiltration. The principal alternative conservation measures may be summarised as:

- Replacement of copestones about to lose mouldings.
- Consolidation of strongly weathered stone.
- No measures related to stones.
- Repointing of joints.
- Covering by lead, copper or zinc.
- Removal of lichens.

Restricting stone replacement to an absolute minimum was considered an important aim of this thesis. However, investigations have shown that severely exposed elements made of Bjørnå stone may have a life-time of only 30-60 years before losing mouldings etc. In situations where mouldings have been lost or are about to fall off (cf. nave's parapets and cornices), replacement with a more durable stone (see chapter 20.3) seems to be the best solution. It may be perfectly possible to consolidate or fix mouldings - if they have not already been lost - by applying suitable chemical products, dowels and cramps, but such a solution seems less attractive, primarily because it is very difficult to assess the associated future risks. However, in situations where there is no risk of losing fragments from high

Fig. 20.4: *For decades, copper and lead have been applied in order to prevent water leaks at the south turret of the choir of Nidaros cathedral. As can be seen, the copper cover is so poorly designed that water leaks nevertheless occur through all the open joints below (photo: PS 3/96).*

elevations, consolidation should perhaps be tested - and weighed against replacement and letting the stones weather away without any intervention. *It should be noted that consolidation calls for comprehensive experimentation with suitable products*. The same arguments may be applied to Grytdal stone (and Bubakk stone).

Weather beaten architectural elements may also be protected by plates of copper, lead or zinc - traditionally a widespread solution to weathering problems even at Nidaros (fig. 20.4-5). In this case metal coverings may protect the stones themselves, but an equally important aspect is that they will prevent water leaks through joints/joint fissures which may be difficult to repair using mortar. Stone capped towers and cornices, which are notorious with regard to water leaks, are the primary candidates for such measures, but also stone capped gables, flying buttresses and parapets should be considered. However, due to complex architectural design, involving sculptured details, it is not always possible to apply metal coverings. Moreover, if such measures are used, one has to remember that they will change the architectural character of the cathedral. The risks of severe staining (e.g. copper salts) should also be considered.

It is expected that the most important - and the most difficult - solution to prevent the numerous water leaks will be re-pointing. There is little doubt that The Restoration Workshop faces a great challenge in this area. The challenge is three-fold:

1. How to gently remove Portland cement mortars which usually have a fissure at one flank and strongly adhere to the stone at the other?
2. How to select repair mortars compatible with the rest of the masonry?
3. How to decide where the best way of working is to demolish (for instance a tower) and rebuild with old stones and new mortars, and where the best way is to restrict the measures to re-pointing (or covering with metal)?

There is no standard solution to such problems, but the selection of repair mortars in general is discussed later in this chapter.

Fig. 20.5: *During the recent restoration of the west tower of the north transept, zinc was applied in order to prevent water leaks from projecting cornices and rapid weathering of Bjørnå stone. It has not yet been verified whether this solution is sufficient (photo: PS 6/96).*

Fig. 20.6: *Strongly weathered copestone of serpentine-rich soapstone from Bubakk at the southern west tower. It may seem that lichens enhance the weathering rate, and the question is whether they should be removed or not. Removal by mechanical means is out of the question in this case. Moreover, given the low porosity of soapstone, it is to be expected that biocides will be ineffective (photo: PS 6/93).*

Most severely exposed elements at high elevations show intense growth of lichens together with flaking, pitting etc. (fig. 20.6). A relevant question is whether such growth should be removed in order to slow down the weathering rates. Removal might be undertaken by mechanical means, implying that flakes of stone will be lost simultaneously, or by applying biocides. Given the low porosity/absorption of the soapstones, treatment with biocides cannot be expected to be particularly effective for long periods of time - such measures would have to be repeated at short intervals (one year?). Knowing that removing lichens is not necessarily going to slow down weathering rates (the opposite my in fact be the case), *it is possible to conclude that lichens should remain on exposed stonework at Nidaros.*

Leaks and salts

The typical zones at risk either belong to structures built (or completely restored) during the restoration or to medieval stonework immediately below such new parts. They include:

- Stonework below parapets.
- Vaults below parapets.
- Masonry/staircases below stone capped towers.
- Stone work below specific points of water infiltration.

It may be meaningless to undertake direct conservation measures on such strongly salt-laden stonework before leaks are eliminated. Thus, as a prerequisite for the measures suggested below it is assumed that leaks are no longer active. Principal alternative conservation measures include:

- Removal of salts/reduction of salt quantities.
- Control of ambient climate (indoor).
- Replacement of irretrievably lost stone/details.
- Plastering and whitewashing of vaults.
- Consolidation of weathered stonework?
- No action

Even though masonry beneath parapets is strongly influenced by leaks and salts, the weathering generally proceeds rather slowly. But there are important exceptions, particularly related to fire-damaged medieval stonework (aisles in choir and nave) and extreme leaks together with Grytdal stone (choir). In the former case there is little that can be done with the salts, but it is hoped that elimination of water leaks will slow down the weathering. In the latter case the weathering has become such a problem that significant stone replacement cannot be avoided. Stonework at particular places inside the clerestory of the choir is so badly damaged that fragments may fall off, *thus representing a risk to people's safety*.

Leaks and salts have strongly affected many vaults. Flaking and large cracks (due to stability problems) have made them look rather unsightly, and *it is thought that most simply need to be whitewashed and where necessary consolidated by lime mortar and re-plastered*. The last whitewashing took place around 1930,[9] implying that the colour of the vaults have turned grey-brown due to dirt and dust (heating!) - a feature not exactly improving their aesthetic quality. One should remember that the vaults of the choir have many painted decorations (architect Christie, 1890) below the present whitewash. Perhaps the decorations should be resurrected?

Neogothic masonry below stone capped towers, especially in the staircases, present different problems. The weathering is by and large rapid, but there are no great risks of structural failure or of losing valuable decorations. It is nevertheless recommended to *remove as much salt as possible - a task which can be done by simply brushing away efflorescences during dry weather periods*. Another proposal would be to try and reduce the frequency and intensity of condensation events by intelligent ventilation.

Compared to the nave and choir, problems arising from leaks and salts are of a different nature in the octagon. This is because the octagon comprises a large number of slowly weathering medieval decorations, such as window arches and capitals, intimately integrated in the masonry. Thus, the risks of slowly losing such very valuable details are high - especially in the chapels. Except for eliminating water leaks it is difficult to propose efficient conservation measures. With regard to interior stonework, it is however clear that the indoor climate also has to be controlled.[10] Furthermore, exterior details which are exposed both to leaks/salts and direct precipitation should, wherever possible, be protected from rain and snow.

The issue of desalination and consolidation should also be addressed. It is possible that desalination with various compresses and clay could be efficient in some cases. However, such a measure induces risks of losing small fragments. Thus, pre-consolidation has to be considered - a risky endeavour on salt-laden stone work. *To "permanently" consolidate salt-laden decorative details is probably not a good idea - at least when considering that so far there is no experience of consolidation of weathered soapstone and greenschist whatsoever*.[11]

One of the most characteristic features of the cathedral as a whole is white calcite crusts. Being excellent indicators of former and present water leaks, the crusts are not causing any particular harm to the stonework, but they may seriously distort the architectural character of many façades. They are on the other hand most significant from the perspective of age values and have become true historic documents of the "Portland cement cathedral". Should they be removed or not? It is relatively simple to remove calcite crusts by chemical means (for example by diluted acids), but it may be difficult to assess the consequences of such treatments. Mechanical means are not particularly effective, insofar as underlying stonework will have to be redressed in order to completely remove the white patches (fig. 20.7). Perhaps modern means such as micro air abrasive cleaning and laser cleaning should be tested?[12]

Fig. 20.7: *An attempt at removing white calcite crusts with chisels was made on a buttress of the nave some years ago. As can be seen, the attempt was unsuccessful, implying that other methods should be sought (photo: PS 5/96).*

Parts exposed to run-off and transition zones

To clean or not to clean is also an important issue where black crusts are concerned. In contrast to white crusts, black crusts are - in particular places - not only an aesthetic nuisance (for some people), but may often significantly contribute to the weathering processes. Rapid weathering is restricted to medieval parts - to places exposed to run-off and in transition zones between “wet” and “dry” stonework:

- Corners between gables and towers/pinnacles.
- The underside of string courses and cornices
- Stonework beneath joint fissures in string courses and cornices.

It is very important to remember that in such zones not only black crusts, but also a range of other salts contribute to the weathering. Hence, re-pointing joints and improving rain water disposal systems in order to prevent run-off (and leaks) should, wherever possible, be considered first (see chapter 20.1). The second most important measure ought to be removing the black crusts. However, since the crusts are frequently associated with granular disintegration and flaking of the underlying stone fabric, it may be difficult to avoid losing stone fragments. Pre-consolidation is also a risky endeavour.[13] *In summary: when the risk of losing much material is great, it is perhaps better to leave the crusts alone*.

In most cases black crusts are not causing any particular harm to the stone fabric. Examples include buttresses, pillars and marble columns which are not influenced by other salts or by moisture from “within” the masonry structure. As with white calcite crusts, many people might consider the crusts unsightly, giving façades a dirty appearance.[14]

My personal attitude is that the crusts in question have become part of the cathedral and as such important documents of a century of industrialisation and air pollution in Trondheim. *When not causing any additional weathering problems, they should therefore remain on the stonework*. Given that emissions of air pollutants are kept to a minimum in the future, many crusts will also be naturally removed by rain washing.

Zone of rising damp

Salt weathering problems in the zone of rising damp are restricted to the transept and the octagon. The weathering proceeds so slowly in the octagon that there is no need for specific *direct* conservation measures. However, in order to reduce the weathering rates even further, *it would be wise to repair the numerous joint fissures in the exterior base, from which the moisture originates* (fig. 20.8).

Another wise idea would be to keep downpipes in good repair, preventing rain water channelling directly onto bases with joint fissures. The downpipes are at present not connected to the closed drainage system around the octagon. Perhaps they ought to be re-connected?

Presumably due to infrequent, but severe events of condensation, the weathering along the lower walls of the transept proceeds much more rapidly than in the octagon. Given the warm and dry indoor climate of the cathedral, it is not easy to prevent condensation during the heating season. In the summer season either heating or preventing hot and humid air entering the cathedral would have to be tried. Both measures are difficult to efficiently put to work. However, as much salt as possible ought to be removed by gentle mechanical means. In addition *it is very important to avoid wetting salt-laden surfaces during weekly floor-cleaning operations*.

Fig. 20.8: *The salt weathering proceeds very slowly along the base in the octagon (above), but in order to reduce the rate even more, joint fissures in the exterior base (below) should be repaired (photos: PS 1993 and 1990).*

Sculptured details

During more than 125 years of restoration, most medieval sculptures and decorations were replaced by copies. In return, a wealth of beautiful new details modelled by famous Norwegian artists and carved by dozens of skilled craftsmen have been supplied. Unfortunately, hundreds of new sculptures and decorations have weathered so rapidly that they are already close to being completely lost. Since the 1970s large numbers of new sculptures have also been replaced by copies. The most rapid weathering is at present related to:

- Medieval originals made of Øye greenschist and Bakkaune/Klungen soapstone.
- Copies of medieval sculptures and decorations as well as 19th century original details made of Grytdal stone.
- 20th century originals made of Bjørnå soapstone
- 20th century originals made of Bubakk soapstone

Although they are far from being totally lost, remaining medieval sculptures and decorations in the transept and octagon have generally weathered very rapidly since the restoration in the 1870s and 1880s. A main reason for this is that all roofs were changed during the restoration, leaving for instance corbel heads much more exposed than previously. Leaks, salts and black crusts are also important causes of this rapid weathering.

Given the massive replacement programmes that have already been carried out, I personally think that *it is very important to preserve remaining medieval sculptures* in situ *and avoid moving them to the museum collections*. Preserving the sculptures *in situ* will demand much effort, both with regard to protection from precipitation and leaks, and direct conservation measures like cleaning, desalination and consolidation. The latter measures will, moreover, have to be undertaken *by expert stone conservators and involve a lengthy phase of experimentation with suitable methods and products*.

According to the principle of “historical equivalence”, sculptures from the restoration ought to be treated just like medieval sculptures. However, when studying the actual conditions of the sculptures, it is clear that this ideal is difficult to follow in practice. Many sculptures, especially those made of Grytdal stone in the choir and several strongly projecting details made of Bjørnå stone elsewhere, are so thoroughly weathered that solutions other than letting them remain in place have to be sought. This is also because fragments tend to fall off due to fissures developing along foliation planes. As a general rule one has to carefully investigate the actual situations, evaluate the risks and choose measures from the following list of options:

- Protection from direct precipitation, run-off and leaks.
- Cleaning, desalination, consolidation.
- Reconstruction of missing details.
- Replacement by (reconstructed) copies.
- Replacement by new sculptures.
- No action.

The option “replacement by new sculptures” deserves further comments. Since the last west front sculpture was put in place in the middle of the 1980s, no attempt has been made at creating new sculptures. Except for the carving of ribs and bosses for new vaults in the west towers, replacement of strongly weathered sculptures by copies has been the rule (cf. the current programme of replacing the corbel heads in the friezes of the choir). Perhaps it would be an idea re-introduce the artistic aspect of conserving the cathedral by in some cases designing completely new sculptures for replacement of hopelessly weathered ones?

In order to have a sound basis for reconstruction and copying, plaster casts have been made of numerous sculptures. Recalling that the disastrous 1983-fire in the Archbishop's Palace destroyed hundreds of such plaster copies, a new rolling programme for making plaster casts has begun. *It seems that the current procedure involves the risk of losing already weak parts of the fabric of the sculptures (cf. chapter 18.1), implying that one ought to carefully evaluate the procedure in order to suggest improvements.*

20.3 Selection of stone, mortar and other materials

The selection of stone for replacement purposes and mortars or other materials for repair will be a great challenge for The Restoration Workshop. This section gives some recommendations on the basis of investigations in the stone quarries and at the cathedral.

Selection of stone for replacement purposes

Appropriate stone is especially needed for the following replacement purposes:

- Strongly exposed, moulded copestones as well as other projecting architectural elements and decorations/sculptures.
- Less exposed sculptures and decorations, such as 19th century corbel heads.
- Ashlars and other elements completely integrated into the masonry.

Until recently Gullfjellet soapstone, Bubakk soapstone and Bubakk serpentinite were used for these purposes (see chapter 6 and 9). Today the situation has changed and Gullfjellet soapstone is no longer available. The Bubakk quarry is also about to run out of good serpentinite so that the only readily available stone for the future is Bubakk soapstone. Knowing that this stone weathers at quite a high rate when strongly exposed, the stone supply situation is in fact very serious. Moreover, the situation will become acute if the cultural heritage authorities prohibit quarrying at Bubakk in the future (see chapter 9).

Facing this difficult situation, The Restoration Workshop has started evaluating the possibility of reopening medieval quarries or quarries used during earlier phases of restoration. The ideas governing the evaluation are that traditional quarries should be preferred and that different stone is needed for different purposes. Put succinctly: *The right stone is needed for the right purpose*.[15] It is clear that architectural elements and decorations/sculptures which are strongly exposed require the highest standard of stone. In this respect, the most important criteria are:

- No risk of losing stone fragments from high elevations, or no risk of fissures developing along foliation planes.
- Limited risk of rapid surface weathering.

In practice, considering availability and economy, the only stone types meeting these criteria are - in addition to Bubakk serpentinite - the Hovin metasandstone (see chapter 6.1) and certain varieties of the Klungen soapstone (see chapter 8.2).[16] Recalling that Klungen is situated in the main medieval quarrying area (together with Øye greenschist and Huseby soapstone), the deposit is considered so interesting that a major geological and archaeological mapping programme has begun.[17] The aim is not only to be able to quarry suitable stone for future replacement purposes, but also to learn more about medieval stoneworking techniques.[18]

One task for the future ought to be establishing suitable infrastructures in the Bubakk, Klungen and Hovin (and perhaps also Øye and Huseby) quarries, making it possible to undertake small-scale quarrying operations whenever the respective types of stone are needed. In this way The Restoration Workshop would be able not only to supply the cathedral, but also other Norwegian monuments/restoration projects with “the right stone for the right purpose”.[19]

Selection of repair mortars

Using “the right mortar for the right purpose” should also be considered an important aim. The cathedral features such a wide range of building and restoration phases, exposure conditions - and mortars (see chapter 6.3) - that it is difficult to maintain that traditional lime mortars should be used for all repair purposes. Following the recommendation given in the *Amsterdam Declaration* (1975), stating that “new materials and techniques should be used only after approval by independent scientific institutions”, it is necessary to ensure that new mortars are better than those in service at the cathedral today.

Medieval masonry and lime mortars

With regard to indoor purposes and medieval parts, especially the octagon and transept, using lime mortars with properties similar to the medieval mortars should present few major problems. The problems in these areas are primarily related to the removal (wherever necessary) of damaged Portland cement/lime cement mortars used during earlier repointing operations. Another problem is related to the availability of lime mortars. The easy option is to buy modern, factory-made lime mortars, but a better one seems to be producing specifically adapted lime mortars in The Restoration Workshop.[20] Naturally this demands much research and practical experimentation, but it represents an important aim also from the perspective of revitalising traditional mortar production techniques. To once more quote from the *Amsterdam Declaration*: “Steps should be taken to ensure that traditional building materials remain available and that traditional crafts and techniques continue to be used.”

Weather beaten elements and tracery

Real difficulties arise on moving to all the parts of the cathedral which were built or completely restored using Portland cement mortars or lime cement mortars. The most difficult architectural elements are strongly weather beaten ones, many of which are simultaneously affected by stability problems, and include:

- Flying buttresses.
- Parapets and cornices.
- Stone capped towers and gables.
- Sills and string courses.

Fig. 20.9: *During recent restoration work at Basler Münster in Switzerland joints in parapet tracery were pointed with lead - a traditional joint material in Europe. The picture shows a detail from the east end of the cathedral (photo: PS 3/92).*

Window tracery and other types of tracery can also be counted as difficult elements. Today either standard or expansive Norwegian Portland cement mortars (sometimes with latex as part of the binder) are used when restoring such elements. When used for pointing joints in the base of the cathedral, the different varieties of Portland cement mortar often seem to work fine (cf. the choir). However, this is about the only place where their use have been successful (not considering that alkaline salts are provided to the interior). Thus, during the restoration of the west tower of the north transept in 1995-96, hydraulic lime mortar (Swiss *Jura Kalk* blended with Norwegian factory-made lime putty) was tested.[21] Due to the short time that has elapsed, it is impossible to state whether this measure has been successful.

Due to the fact that Portland cement mortars give rise to so many problems, silicone rubber has recently been extensively used in order to seal open joints from which leaks have developed. Silicone has to be regarded a reasonable *emergency* measure, but it is not recommended that the cathedral be massively treated with silicone.[22] Hence, at present there are few other options than to *recommend that research and experimentation with hydraulic lime mortars and other mortars should be intensified*. As an aid to experimentation, the following performance criteria can be listed to produce ideal repair mortars (see also chapter 3.6):

- They should be flexible or able to deal with movements in the masonry structure.
- They should properly adhere to the "slippery" (cf. soapstone and talc) and dense stones of the cathedral, and not give rise to fissures along the flanks of the joints.
- They should be permeable and not allow moisture to be trapped.
- They should not give rise to soluble (alkaline) salts and calcite crusts.
- They should be durable, especially when used in elevated areas. At such places the joints cannot be repaired frequently due to high scaffolding costs.
- They should be easy to remove.

It is certainly difficult to imagine a mortar fulfilling all these criteria simultaneously. Perhaps the closest is in fact lime mortars or hydraulic lime mortars? Perhaps it is also a misconception to think in terms of developing *modern* "super mortars" for these difficult architectural elements? After all, the use of mortars has to be seen in relation to the possible application of metal coverings (see chapter 20.2). In such situations traditional lime mortars may well serve the purpose. At some places (e.g. tracery, parapets) it may also be an idea to test the use of lead. Lead seems to be an old jointing material, used traditionally and during recent restoration works in parapets of the *Basler Münster* in Switzerland (fig. 20.9).[23]

Whether lead joints were used at Nidaros in the Middle Ages has not been investigated. However, due to difficulties with excessive pressure on marble columns set in Portland cement mortars (see chapter 5.3), many columns are today restored by using lead instead of cement.

Damp walls made during the restoration

Another difficult issue is how to repair joint fissures at strongly exposed, damp walls full of Portland cement and alkaline salts. Examples include the north tower of the chapter house (fig. 20.10) and several other towers. The greatest problem in such situations is not how to select a suitable mortar, but how to prepare the joints before re-pointing operations commence. It is extremely difficult to remove old Portland cement mortars without damaging the soft stone, not least because the cement tends to bind very tightly to the ashlars (on one side only).

If successful in removing old cement joints to a reasonable depth, it appears that lime mortars represent the best option for re-pointing. If this seems difficult in practice, other mor-

Fig. 20.10: *On the north tower of the chapter house virtually every joint has thin fissures through which moisture can penetrate. Repairing such joints is will be very difficult and represents a major challenge for The Restoration Workshop (PS 9/95).*

tars fulfilling the criteria mentioned above should be tested. As a general rule: *If the mortars have to be based on smaller or larger quantities of Portland cement (to give hydraulic properties), ensure that low-alkaline cements are used!*

Mortar in combination with a dense and impermeable stone such as soapstone is a difficult issue. Compared to a sandstone building with lime mortar joints, in which the entire masonry has rather even physical properties, a soapstone building never shows such "evenness". Lime mortars are much more permeable and pure Portland cement mortars, the other end member, much "harder" than soapstone. In the former case most stresses related to moisture (frost, condensation, salts) influence the masonry preferentially through the joints. In the latter case, the masonry will have limited flexibility with regard to large-scale movements. Fissures and cracks, mainly developing along the joints, are the likely results - followed by the problems related to moisture.

Hence, *a soapstone building simply needs high-quality joints because most of the damaging, physical stresses concentrate within the joint system.* In this respect it would be very interesting to investigate more closely how the medieval builders solved this problem.

20.4 Conserving a complex environmental system

Following up the suggestions and recommendations given in this thesis - discussing them, testing them and undertaking further investigations and practical work - will be a great challenge for The Restoration Workshop. It will take time, perhaps 20-30 years or more, to deal with all the problems presented in this work. In the meantime, new problems, new perspectives and new solutions will inevitably occur. It is hoped, however, that the evaluation of the risks, as well as the recommendations given, will be valid for a longer period of time than a few years only.

A possible strategy for organising the work laying ahead, is to define co-ordinated projects or programmes dealing with the main groups of risks. It is suggested that the following *conservation programmes*, roughly following the layout of chapter 20 of this thesis, should be considered:

Urgent measures.
Secure details about to detach or fall and eliminate extreme leaks. Also secure and restore the King's porch.

Programmes related to general risks.
- Monitor, control and understand stability problems, especially related to differential settlement and crack development.
- Establish appropriate repair programmes related to roofs, exterior gangways and water discharge systems in order to eliminate water leaks and reduce the rate of weathering of affected stonework.
- Monitor the indoor climate in order to design a new heating system.

These programmes should involve external consultants able to understand the nature and requirements of a large medieval building.

A programme related to specific zones at risk:
A good idea is to start a rolling programme at the chapter house, continue to the octagon, the choir and so on - and to treat, wherever necessary, the zones at risk: Weather beaten architectural elements, leaks and salts, run-off and transition zones, zone of rising damp, sculptural details.

A programme related to weathered decorative and sculptural details:
In order to be able to undertake direct conservation measures on decorative and sculptural details, expert stone conservators are needed. It is also necessary to run a research project on cleaning and consolidation of weathered objects made of soapstone and greenschist.

Programmes related to selection/production of materials
- Stone for restoration purposes: In addition to reopening the relevant old quarries, measures should be taken to ensure that “the right stone is used for the right purpose”
- Mortar for restoration purposes: The way forward seems to be to experiment with a range of relevant repair mortars in order to secure that “the right mortar for the right purpose” is used. Building up facilities for lime mortar production at The Restoration Workshop should also be considered an important aim.
- The use of materials such as modern membranes, metal coverings, lead for joints and silicone rubber for joints should not be used without appropriate experimentation and testing.

Regular inspection and maintenance programmes
The importance of regular inspection and maintenance has to be underlined. It is recommended that the check-lists developed by Bernard Feilden should be implemented at Nidaros.[24]

These programmes also have to be seen in relation to issues not treated in this thesis: stained glass windows, organs, moveable objects of art, fire protection, alarm systems, sanitary systems etc.

Dealing with all the problems first of all demands a readiness to treat the cathedral as a complex environmental system, in which the “large” phenomena are seen in relation to the “small” and vice versa. It may be meaningless to conserve a valuable medieval decoration before making sure that leaks, water discharge systems and run-off are under control! Hence, a great challenge is to ensure that a good conservation organisation is at hand - an interdisciplinary organisation in which teamwork between competent craftspeople, conservators, engineers, architects, scientists and managers is considered an important aim - and not only a means.

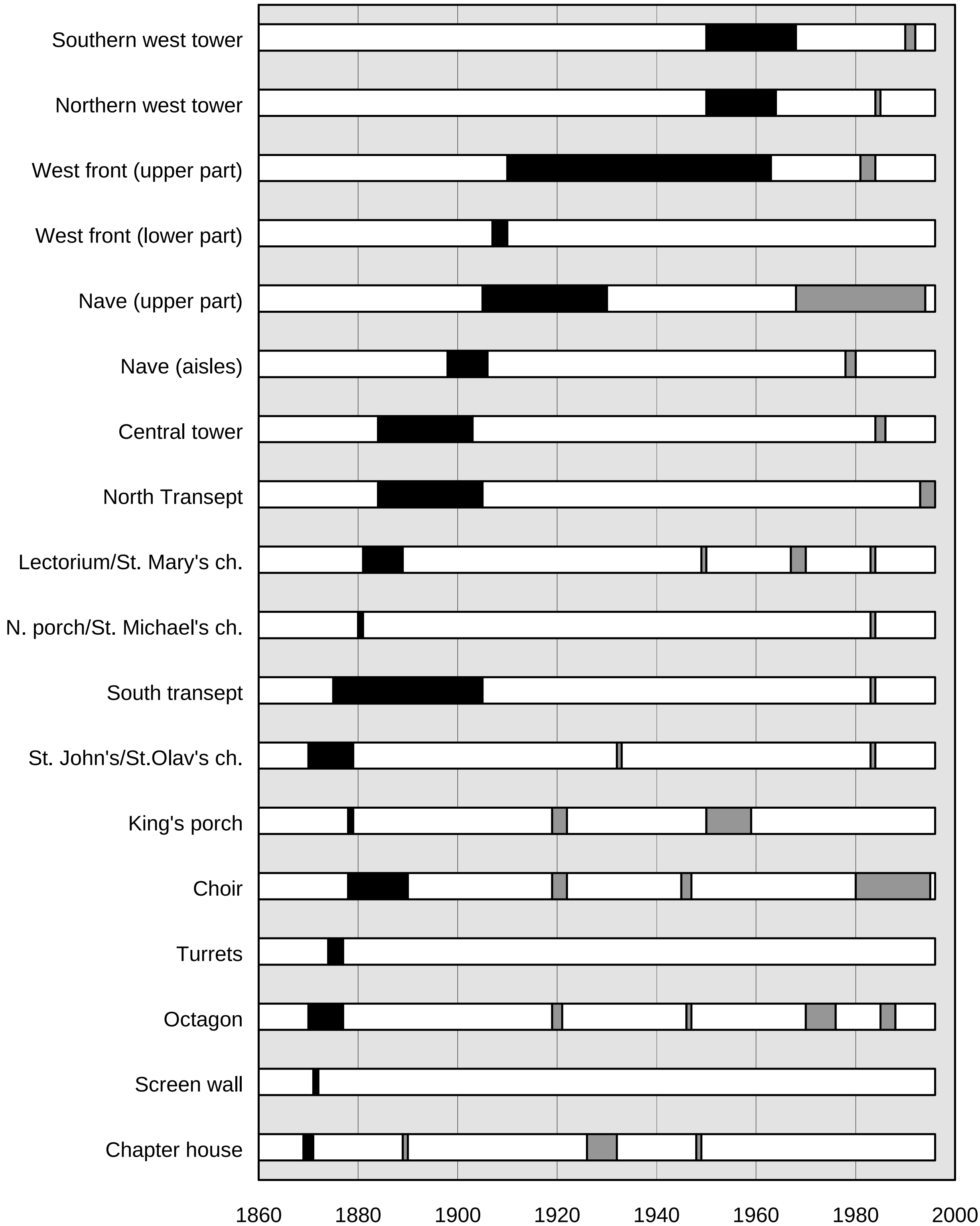


Fig. 21.1: *Overview of the main restoration phases of each building part (black) and subsequent repair phases (grey). Although not shown on the figure, the subsequent repair phases were undertaken at roughly the same locations at the respective building parts each time. Sources: see appendix 1.*

Chapter 21

Conclusion

In their excellent report on the scientific and political context of stone weathering and air pollution, Cooke & Gibbs maintain that the origin of many weathering situations at English cathedrals is very old, that particular weathering phenomena cluster at certain building parts and that many phenomena have relatively little to do with air pollution.[1] This thesis shows that particular weathering situations at Nidaros indeed occur at specific building parts and constitute part of both the cathedral's and the local environment's history. In this respect, the methodology guidelines derived from Andreas Arnold highlighting the context-dependent nature of weathering phenomena have proved extremely useful for the investigations which have been undertaken at Nidaros. The evolution of many weathering situations can in fact be traced through centuries, although the last 130 year period of complete restoration of the partially ruined cathedral and simultaneous industrialisation in Trondheim provides most clues to the currently observed weathering phenomena. In this context industrialisation not only means increased air pollution, but also profound changes in building practice. Since the historical records have been so important in understanding various weathering situations and risk factors, this concluding chapter summarises the results of this thesis as viewed from a historical perspective.

21.1 Structural problems and historical context

Bernard Feilden maintains that without considering the historical evolution of the structural behaviour of a large stone building, there is serious risk of misjudging its current situation.[2] This thesis did not attempt a comprehensive investigation of structural issues, but it has nevertheless been shown that such issues are of prime importance in understanding weathering phenomena, especially those related to water leaks. Due to a frail buttressing system the choir appears to have suffered structural problems since the Middle Ages. Since the reconstruction of the choir's upper levels in the 1880s, water leaks from the exterior gangways have caused frequent problems, partially due to severe cracks related to increasing outward inclination of the walls. This have resulted in relatively rapid (salt) weathering of vaults and stonework below. Similar problems, although less severe, are encountered in the rebuilt nave. Water leaks occurred almost from the day rebuilding operations were completed in 1930, but the masonry cracks have a different cause to those in the choir. As the nave is essentially a well-built construction, the cracks mainly relate to differential settlement caused by the addition of the heavy west towers, which were completed in the late 1960s.

The unstable construction have also caused other, much greater problems than water leaks. On several occasions since the 1930s marble columns, capitals and other decorations have fallen, sometimes from elevated areas, inside the cathedral. Apparently these problems are due to cracks related to excessive loads. Although no people have been injured yet, the risk of interior stonework detaching is still the most severe safety problem at the cathedral.

21.2 Introduction of new designs, modern materials and heating

After visiting the cathedral in the late 19th century, the famous preservationist William Morris stated:

> I saw Trondheim - big church, terribly restored, but well worth seeing.[3]

Morris perhaps thought of the gigantic reconstruction and rebuilding work as such, but with his background he may well have had Neogothic designs and modern materials on his mind too.

From a weathering perspective it is important to note that most elevated building sections, including towers and pinnacles, date from the restoration. According to 19th century principles of masonry construction, these sections often feature massive walls (not medieval double walls with masonry cores) with Portland cement or lime cement mortars (not lime mortars) in the joints. Although brick (the choir), hard stone and even concrete (the west towers) were used occasionally, soapstone from about 20 different quarries throughout Norway was the most important building material during the restoration. In contrast to the local greenschist and soapstone used in the Middle Ages, which tend to delaminate along foliation planes and lose pieces along dissolving carbonate veins, respectively, many of the new stone types are also subject to intensive disintegration of exposed surfaces. Moreover, two new soapstone types, Grytdal (1869-92) and Bjørnå (1897-1958), are notorious for their poor durability. Grytdal soapstone contains extremely large amounts of iron sulphide (pyrrhotite) giving rise to severe salt weathering in parts of the cathedral. The greatest problem of Bjørnå stone is that exposed stonework tends to delaminate an fall from elevated areas.

Many water leaks and salt weathering problems could be avoided if the cathedral were equipped with a proper water discharge system and better roofs. The new parts feature parapets and external gangways or platforms; a debatable design in the relatively cold and humid Trondheim climate. As the gangways and platforms always have been improperly insulated (and due to structural problems), leaks naturally occur from these sensitive areas. The roofs of sections without parapets, especially the chapels of the transept, were completely altered during the restoration in the late 19th century, causing the stonework in cornices to become much more exposed than before. Mainly due to these alterations, medieval sculptures weather at an alarming rate. Towers, gables and large sills capped with stone during the restoration show different problems. Inflexible, high-alkaline Portland cement mortars were used in the joints, resulting in unavoidable water leaks and giving rise to massive salt weathering and formation of many rather unsightly white calcite crusts. The same phenomena are also encountered in other areas subject to water leakage. In addition to relatively poor roofing, the cathedral generally received *extremely* poor water discharge systems during the restoration. There are very few gargoyles and gullies. Instead precipitation is carried away via an underdimensioned system of gutters and downpipes. It is evident that this poor system is responsible for many water leaks.

Among the materials and techniques introduced during the restoration, mention should be made of the cleaning practices. Prior to the restoration most stonework was covered with several layers of whitewash or paint. The normal methods of removing whitewash and paint included careful treatment with wooden mallets or less careful redressing of stone surfaces with chisels. Much stonework was also cleaned by hydrochloric acid and lye. Therefore, it is reasonable to suggest that the relatively minor amounts of chloride found on stonework today partly stem from this source. Consequently it is not straightforward to maintain that the source of chloride is airborne sea salt.

Luckily, stonework was not attached using iron dowels and cramps during the restoration. Instead, more durable metals such as brass and copper were used. Hence, the cathedral has escaped the dramatic effect of rusting iron which is so widespread in Europe.

The restoration included installation of a water-born central heating system. Although the system is old and in urgent need of repair, it provides a warm and dry indoor climate in the cold season. Except for the negative effects this indoor climate has on wooden objects of art and organs, few problems other than melting of snow, and thereby more rapid frost weathering, on exterior parts strongly influenced by heat transfer have been detected. According to current knowledge the dry indoor climate reduces the number of damaging condensation events and events related to dissolution/recrystallisation of soluble salts. Observation shows that such events are frequent in unheated parts of the cathedral.

21.3 Air pollution, salt weathering and the historical dimension

Related to stone weathering in a historical (and biological) context and probably not without an ironical undertone, Wolfgang Krumbein maintains that:

> Air pollution is nothing new [and] nothing serious.[4]

Regarding Nidaros, this statement neatly summarises the findings in this work. The cathedral did not escape the polluting effects of the industrial revolution in Trondheim, but on the basis of reconstruction of historical emissions it has been shown that air concentrations of SO_2 were considerably higher in the period between c. 1890 and 1980 than they are today (c. 5µg/m^3). On the basis of historical photos it has also been shown that the distribution of black crusts on the walls of the cathedral peaked between 1950 and 1980. The current less extensive distribution may be attributed partly to rainwashing and run-off, and partly to loss of scales etc. on which black crusts prevailed. Compared to stone buildings in heavily industrialised regions, Nidaros is indeed in a favourable situation since black gypsum crusts are not disturbing the appearance of the walls to a large degree. Hence, there is no need for large-scale cleaning operations. Moreover, damage to stonework underneath black crusts is relatively infrequent - a fact which may be attributed primarily to the dense stone types of the cathedral. When damage, be it flaking, delamination or granular disintegration, associated with black crusts do occur, it is usually related to the relatively more porous stone types, specific design factors giving rise to run-off along the walls, water leaks, the presence of salts other than gypsum and the presence of traces of whitewash and paint. Moreover, it is not always straightforward to blame air pollution alone for the occurrence of gypsum crusts. This is because a stone like Grytdal also produces much gypsum.

Gypsum, magnesium sulphate and some sodium sulphate (the “sulphate system”), mostly originating from combinations of air pollution, Grytdal stone, other stone types and brick, were introduced on a large scale during the restoration. The other main salt system at the cathedral is associated with the large amounts of Portland cement used to build new sections and consolidate medieval masonry. It is characterised by extreme development of calcite crusts, large amounts of sodium carbonate and some aphthitalite. Damage caused by the “carbonate system” is found on stonework below water leaks, inside turrets and towers and in the contact zone between old and new stonework. Apart from leakage water, it appears that frequent condensation events is a main factor governing the weathering process. When the “carbonate system” comes in contact with the primary “sulphate system”, for instance on medieval stonework, secondary reactions take place and large amounts of sodium sulphate tend to form.

In this thesis it has been shown that most salts were introduced during the restoration. Hence, it is possible to state that salt weathering was a relatively minor problem prior to the restoration and before emissions of air pollutants became a problem in the late 19th century.

21.4 Learning from past failures

Given that age value and historical value are of top priority, the famous thoughts of John Ruskin may well represent a good guideline for future conservation work at the cathedral:

> Take proper care of your monuments, and you will not need to restore them. A few sheets of lead put in time upon the roof, a few dead leaves and sticks swept in time out of a water-course, will save both roof and walls from ruin. Watch an old building with an anxious care; guard it as best you may, and at **any** cost, from every influence of dilapidation.[5]

In order to prevent further weathering or mitigate the evolution of weathering processes, one should take seriously this simple piece of advice. In addition one should learn from all the failures related to insufficient repair of water leaks in the past. This implies that many roofs, stone capped gables and towers, exterior gangways and water discharge systems may have to be altered in order to let stonework, including medieval sculpture, below survive. It also means that one of the most important tasks in the future is to experiment with adapted mortars or other materials for repairing cracks and joint fissures. Moreover, suitable means of reducing and controlling the effects of salt weathering have to be found.

At a large cathedral such as Nidaros it is impossible to avoid direct measures aimed at strengthening the stonework and materials against weathering. In this respect excessively weathered stone and stone about to detach represent the most important challenge, especially since weathered stone at high elevations may represent a hazard to passers-by. Replacing such stone or consolidating with suitable methods has to be decided on a case to case basis. Concerning stone replacement one should think in terms of using “the right stone for the right purpose”, which implies that the possibilities of reopening the medieval quarries of the cathedral should be explored.

Although the weathering of the cathedral is a very significant problem, other deterioration issues represent a much greater challenge. Parts of the building show severe structural failure, implying that controlling the development of fracturing and preventing major accidents should be given the highest priority possible.

Notes

Abbreviations:

ARW: Archive of the Restoration Workshop of the Nidaros Cathedral, Trondheim
AccLu: Account book of manager Lundemo 1869-1897 (*Stenbruddene. Oversigt, Opgjør og Opgaver. Domkirkens Restauration*), in ARW
DiaGu: Diaries of masterbuilder Guttormsen 1869-1874, in ARW
DiaRA: Diaries of the architects and masterbuilders in charge of the restoration, in ARW:

Book 1: 1865-1890: William Bergstrøm
Book 2: 1890-30.06.1892: William Bergstrøm
Book 3: 01.07.1892-30.06.1904: William Bergstrøm
08.07.1904-20.07.1907: August Albertsen
Book 4: 20.07.1907-31.12.1909: August Albertsen
01.02.1926-30.06.1931: August Albertsen
Book 5: 06.12.1909-17.09.1915: Nils Ryjord
Book 6: 01.07.1931-01.07.1943: August Albertsen
Book 7: 01.07.1943-15.03.1948: August Albertsen
15.03.1948-22.03.1962: Wilhelm Swensen
Book 8: 24.03.1962-31.08.1964: Wilhelm Swensen
01.09.1964-1987: Torgeir Suul (from 1974 only annual reports)
1988-1989: Alf J. Solem (annual report 1988)
01.12.1989-15.01.1995: Arne Gunnarsjaa (incl. annual reports)

RR: Semiannual or annual restoration reports of the architects in charge of the restoration, 1872-1906: Chr. Christie. 1915-1926: Olaf Nordhagen and Nils Ryjord (in ARW)
STv: Collection of various unpublished sources related to the restoration of the chapter house. By John Tverdahl 1948 (in ARW)

In Storemyr (1995d) a survey of most conservation measures undertaken between 1904 and 1995 can be found. The survey is in particular based on the diaries of the architects and masterbuilders in charge of the restoration. See also appendix 1.

*Chapter 1*Fehler! Textmarke nicht definiert.**: Introduction**

1. The description is based on Fischer (1965) and Ekroll (1995a,b). For stylistic terms, see Trachtenberg and Hyman (1986). I use the term Neogothic for building parts which are entirely new compositions from the period of restoration between 1869 and 1969. For stone buildings influenced by the Gothic Revival in Scandinavia, see Ringbom (1987).
2. Fischer (1969).
3. See in particular Lidén (1972). Careful building archaeological studies and comparative art historical studies made the basis for the restoration and reconstruction. About stylistic restoration in general, see Kåring (1992).
4. Fischer (1965) and Lysaker (1973).
5. Lysaker (1973).
6. The Reformation in Norway “officially” took place in 1537.
7. Fischer (1965, 1969).
8. Lysaker (1973).
9. Ekroll (1997), Lidén (1974, 1981) and Ringbom (1987).
10. Vogt (1897).
11. Alnæs (1995).
12. Fischer (1969:101). See also a note from architects Helge Thiis and Torgeir Suul, dated November 12, 1971, ARW.
13. Thiis and Suul, ibid. See also DiaRA from May 20, 1955 and until recently.
14. DiaRA, in particular June 30, 1950.
15. See *Aftenposten*, November 11, 1971.
16. Haagenrud (1973).
17. See Løvås (1984) and *Adresseavisen*, November 21, 1980.
18. See Lysaker (1995).

19. Dahlin (1988) and an informal report (in English) from geologist Tore Prestvik about investigation of fire-damaged soapstone, dated July 8, 1988, University of Trondheim (also in ARW).
20. For background information about the programme, see Andersson (1988). For results, see Gullmann (ed. 1992) and Österlund (ed. 1996).
21. Dahlin & Kjeldsberg (1990).
22. See Cooke and Gibbs (1993).
23. Publications include: Anda & Henriksen (1992), Alnæs & Storemyr (1990, 1992), Holt et al (1993), Storemyr (1991, 1993, 1995a,b) and Storemyr et al (1992).
24. I have taken up these problems in my unpublished essay: *Bevaring av Nidaros Domkirke: Om prinsipper, praksis, vitenskap og begrepsbruk*, Department of Architectural History, University of Trondheim, 1992.
25. Architect Thiis' plan from 1969 was approved by the Parliament May 19, 1971.
26. On the basis of *Stortingsmelding* no. 73 (1980-81), the plans were shelved by the Parliament April 20, 1982.
27. Lidén (1972).
28. Myklebust (1984).
29. Riegl (1903, 1905).
30. Mörsch (1988, 1989).
31. Murtagh (1988:20).
32. See note 24.
33. See Feilden (1982).
34. ibid. I have not included natural and man-made disasters, such as earthquakes, floods and fire, in this scheme.
35. Feilden (1982:21).
36. See for instance *Webster's Encyclopedic Unabridged Dictionary of the English Language*, Gramercy Books, New Jersey, 1989.
37. See also a discussion about this theme by Krumbein (1988).
38. See Schaffer (1932:3).
39. See also Schaffer (1932:3) and Honeyborne (1990:153). Comments on the difficulties of reaching consensus with regard to what is conceived as “bad” weathering or deterioration see chapter 2.
40. See Arnold (1993a).
41. See Feilden (1982).
42. ibid.

Chapter 2: Methodology for applied weathering studies

1. See Tranøy (1986).
2. Kåring (1992).
3. Kåring (1992) and Lowenthal (1985)
4. See Lidén (1991).
5. Anshelm (ed.)(1993) and Mörsch (1988).
6. See Næss (1989).
7. Lowenthal (1985).
8. Feilden (1988) and Vetter (1989).
9. See e.g. Weber (1995).
10. Mörsch (1988, 1989).
11. Anshelm (ed.)(1993) and Lowenthal (1985).
12. Kåring (1992).
13. Langberg (1975).
14. Kåring (1992) and Larsen (1992).
15. Larsen (1992).
16. Arnold (1987).
17. See the *Amsterdam Declaration* (Council of Europe 1975).
18. See Rosvall (1988). The same author has also briefly presented the flora of international charters and declarations.
19. Feilden (1982).
20. Feilden & Jokilehto (1993).
21. Larsen & Marstein (eds.)(1994).
22. See Lowenthal (1985).
23. These issues have been discussed by several writers. Some examples: Arnold (1987), Feilden (1988), Lowenthal (1985), Mörsch (1989), Neuwirth (1988) and Pieper (1987).
24. See e.g. Lewin (1988).
25. Feilden (1982) and Arnold (1987).
26. See also Arnold (1987).
27. Modified after Arnold (1987).
28. See proceedings from the *7th and 8th Int. Congress on Deterioration and Conservation of Stone*, edited by Rodriguez et al (1992) and Riederer (1996), as well as *Jahresberichte Steinzerfall - Steinkonservierung* (Snethlage (ed.) 1991, 1992, 1993, 1994).
29. See Snethlage (1989) and Snethlage (ed.)(1992). For an example of the method, see Leisen and Mirwald (1992).
30. See especially Arnold (1987).
31. Arnold (1987, 1988, 1993a, 1993b, 1993c).
32. Arnold (1993a:12).
33. For discussions about *authenticity*, see Jokilehto (1985), Larsen (1992) and Lowenthal (1992).
34. Arnold (1987).
35. Arnold (1993a:11).
36. Arnold (1993a). An evaluation (done by myself) of 269 publications from two international congresses on deterioration and conservation of stone (Rodrigues et al (eds.) 1992 and Thiel (ed.) 1993) is partly justifying the assertions of Arnold: About 50% of the publications dealt with the development of technological conservation systems. The other publications focused on laboratory experiments (12%), studies of single deterioration phenomena in-situ (12%), applied interdisciplinary case-studies (15%),

descriptions of stone conservation projects on portals etc. (7%) and other (7%). It is rather thought provoking that 50% of the publications dealt with new technology when conservation authorities fight for the use of traditional crafts and materials in conservation.
37. Arnold (1987).
38. ibid.
39. Arnold does not use phenomenology in a philosophical way (cf. Edmund Husserl), but rather as a method using "practical" *gestalt-thinking*. In such thinking the aim is firstly to *observe and describe* (as objective or as inter-subjective as possible) the many *qualities* that a monument possesses (architectural design, material types, deterioration forms etc). Moreover, it is the aim to be able to see the relation between "big" factors such as design, setting in the environment and exposure conditions, and "small" factors such as deterioration forms, hence being able to grasp a *situation*. The maxim: *The whole is more than the sum of the parts* might illustrate this way of thinking. See also Naess (1989). About gestalt thinking in biology (which has inspired Arnold), see e.g. Lorenz (1983).
40. See also Næss (1989).
41. Arnold (1987, 1988). Such a *Beweispflicht des Neuerers* is also found in most ecophilosophies (cf. Naess 1989) and environmental programmes.
42. Arnold (1987).
43. Arnold (1987, 1993a).
44. See Arnold (1993a:11).
45. See a further discussion of this theme in Storemyr (1994).
46. See definition of weathering in various dictionaries of geological terms, for instance Bates & Jackson (1984).
47. See Næss (1989) and Ariansen (1992).
48. Arnold (1993a:14).
49. Feilden (1982), Mark (1982) and Mark (ed.)(1993).
50. Feilden (1982), Pieper (1983) and Ashurst & Dimes (ed.)(1990).
51. Feilden (1982:25ff).
52. ibid.
53. ibid.
54. ibid.
55. ibid. and Mark (ed.)(1993).
56. Feilden (1982:203ff).
57. Arnold (1993b:13).
58. ibid.
59. Zehnder (1982:28).
60. Bläuer (1987).
61. Arnold (1993b:13).
62. Arnold (1993a:14).
63. ibid.
64. ibid.
65. See Wessmann (1996).
66. The example is taken from Franziskanerkirche in Solothurn, Switzerland, see Arnold (1993b).
67. See also Arnold (1993a).
68. ibid. and the history of Cleopatra's Needle (Winkler 1980, 1996).
69. See Arnold (1993a).
70. For overview, see Feilden (1982), Pieper (1983) and Ashurst & Dimes (ed.)(1990).
71. For overview, see Feilden (1982). Overview of contemporary methods, see Anda & Henriksen (1992).
72. For overview, see Feilden (1982), Massari & Massari (1993) and Arendt (1993).
73. For overview, see Poschlod (1990), Herkenrath (ed.)(1994) and Alnæs (1995).
74. For overview, see Herkenrath (ed.)(1994). About determination of soluble salts, see Arnold (1984a).
75. Overview of standard durability tests, see Poschlod (1990) and Alnæs (1995).
76. Arnold (1987).
77. Aristotle: *The Nicomachean Ethics*.
78. See also Zehnder & Arnold (1995).
79. Zehnder (1982).
80. See especially Wendler (1991) and Wendler et al (1990).
81. Bläuer (1987).
82. del Monte et al (1987).
83. Ettl & Zehnder (1993).
84. Knapp (1992).
85. Among several papers, see Fitzner & Kownatzki (1991).
86. The ground conditions were under further geological investigation in 1992.
87. Winkler (1980).
88. ibid.
89. ibid. Also described in Winkler (1994).
90. Winkler (1996).
91. According to Clayton (1987:58), one of the obelisks fell over due to the great earthquake in 1301.
92. Richard Lepsis (1852), cited in Clayton (1987:58).
93. Andreas Arnold, pers. comm.
94. Lowenthal (1985).
95. Storemyr (1995c,d).
96. Storemyr (1995e).
97. Plehwe-Leisen was for several years involved in work on weathering and conservation of Brazilian soapstone monuments (Plehwe-Leisen et al 1992), whereas Alnæs in her recent thesis (1995) on durability of Norwegian building stones has included several material analyses also to be found in the present work.

98. See Arnold (1984a) and Bläuer Böhm (1994, 1996). Sampling procedures are also described here.
99. Anda & Henriksen (1992).
100. Storemyr (1995e).
101. Storemyr (1993). See also Arbeitsgruppe Steinzerfall Steinkonservierung (1992) and Löfvendahl et al (1994).

Chapter 3: Theories of selected weathering processes

1. Carstens (1924) and informal report from geologist Tore Prestvik, dated July 8, 1988, University of Trondheim (also in ARW).
2. See Krumbein (1988).
3. See review of salt weathering in Duttlinger & Knöfel (1993). See also Arnold (1992).
4. Except where other references are given the description is based on Arnold & Zehnder (1989).
5. Arnold (1985), see also Jensen (1993).
6. Arnold (1985), Charola & Lewin (1979).
7. Arnold (1985).
8. Cooke & Gibbs (1993), Winkler (1994). Cleaning masonry with sodium chloride has been very widespread.
9. Zehnder & Arnold (1988).
10. Arnold (1984a).
11. See Arnold (1992).
12. Charola & Weber (1992). The thermodynamics of such systems have recently been studied by Steiger & Zeunert (1996).
13. Arnold (1985).
14. Laue et al (1996).
15. See Arnold & Zehnder (1989).
16. Honeyborne (1990).
17. Wessmann (1996). See also Löfvendahl (1996).
18. See Krumbein (1988:188), Bock (1986) and Arnold (1992:2f).
19. Stordal & Hov (1991).
20. See Mylona (1993) about trends since the 19th century. See also Cooke & Gibbs (1993). For trends since the Middle Ages, see Brimblecombe & Rodhe (1988).
21. Stordal & Hov (1991).
22. Mangio (1991).
23. ibid.
24. In some cases gypsum may also be deposited directly from the atmosphere (Arnold, pers. comm.).
25. Kieslinger (1949).
26. Arnold (1984b).
27. ibid.
28. ibid.
29. Feilden (1982:72).
30. The strengthening of the foundations of York Minster is a good example, see Feilden (1982:77f, 345ff).
31. Jensen (1993).
32. von Konow (1989).

Chapter 4: General building history

1. This chapter is based on Fischer (1965). A new short form of the medieval history can be found in Ekroll (1995a).
2. Including Norway, Iceland, Greenland, the Faeroe Islands, Orkney, the Hebrides and Isle of Man.
3. Trachtenberg and Hyman (1986).
4. ibid.
5. Based on Fischer (1965) and Lysaker (1973).
6. Lysaker (1973:361).
7. Based on Fischer (1965) and Lysaker (1973).
8. Based on Lysaker (1973).
9. Based on Lysaker (1973). See also Wexelsen (1978). Concerning the rise of the restoration movement in Norway, see Lidén (1991).
10. See Kåring (1992).
11. Based largely on Fischer (1965, 1969). A short form can be found in Ekroll (1995b).
12. Lidén (1972:88), my translation from Norwegian. The restoration programme was based on the views of N. Nicolaysen, leader of the Society for the Protection of Ancient Monuments.
13. Lidén (1972:88), my translation from Norwegian.
14. STv, as well as *Schirmers innberetning av 26.11.1869*, (restoration report of Schirmer 1869), ARW.
15. See also RR 1872-1878.
16. See also RR 1872-1873.
17. RR 1873-1882.
18. How the difficult operation was undertaken, see RR 1879-80.
19. Based on RR 1898-1905 and my own observations.
20. Based on my own observations.

Chapter 5: Building construction and stability problems

1. Skaven-Haug (1952) and Finborud (1967).
2. Lysaker (1973:320f).
3. Wet clay has caused numerous construction failures in Trondheim, e.g. Lademoen church which was erected c. 1905.
4. Lund et al (1912).
5. Several reports have been made, e.g. Finborud (1967) and Rye (1976).

6. Levelling was carried out by Martin Hetland of the Norwegian Institute of Technology. All reports are in ARW.
7. Skaven-Haug (1952).
8. ibid.
9. ibid.
10. Descriptions of original foundations can be found in Krefting (1885) and Fischer (1965:25ff). Consolidation work undertaken during the restoration is documented in the restoration reports of architect Christie (RR).
11. DiaRA 1986.
12. All wall thicknesses have been obtained from Fischer's plan of the cathedral, dated 1942-43 (Fischer 1965).
13. For definition of wall types, see Hill (1990).
14. RR 1875/2.
15. DiaRA December 1960.
16. DiaRA July 13, 1935.
17. Article by Axel Krefting in *Morgenbladet* January 7, 1930.
18. Løvås (1981).
19. Løvås (1984).
20. A comprehensive monitoring programme aimed at controlling the subsequent development is currently underway.
21. About the restoration and reconstruction, see Fischer (1969:27ff).
22. RR 1918-22.
23. DiaRA September 2, 1931.
24. See DiaRA December 11, 1950 and August 22, 1959.
25. Løvås (1981).
26. A thorough investigation programme aimed at finding the best conservation methods is currently underway. See Bjørlykke et al (1996).
27. DiaRA February 7, 1949.
28. *Adresseavisen* November 21, 1980.
29. DiaRA October 15, 1971.
30. DiaRA 1981-84.
31. See DiaRA February, 1932, April/May 1935 and July 29, 1947. In 1932 the problem was attributed to weak construction and the foliation of Bjørnå stone, while in 1935 strong sunshine was thought to be the main reason. See analysis report (letter) from Ing. E. Bjørnstad, 13.5.1935, journal no. 89/35, ARW. The same explanation was put forward in 1947.
32. Fischer (1965:134).
33. First observation, see DiaRA January 20, 1953. See also DiaRA June 3, 1955 and September 27, 1961.
34. Replacement took place in 1985-88 (DiaRA).

Chapter 6 : Materials and conservation methods

1. Storemyr (1995c).
2. Wolff & Roberts (1980).
3. See also Storemyr (1996).
4. See also Carstens (1927).
5. Carstens (1939).
6. Bates & Jackson (eds.) (1984).
7. Wolff & Roberts (1980).
8. Gerhard Schöning mentions in the 18th century that Øye was an important source of stone in the Nidaros cathedral. See Schöning (1762:27ff and 1775:201). Later authors who have described the quarry include Helland (1893) and Carstens (1927).
9. Schöning (1775:193f) mentions that stone was quarried at Steinberget in Trondheim, but I have not been able to confirm this.
10. See also Helland (1893) and Carstens (1927, 1939).
11. Krefting (1869) and my own investigations.
12. Bates & Jackson (eds.) (1984).
13. Helland (1893).
14. Wiik (1953).
15. Wiik (1953), Bowles (1939), Skjølsvold (1961).
16. Skjølsvold (1961, 1969).
17. For instance decorations in the medieval Uppsala cathedral.
18. Wiik (1953), Ringbom (1987).
19. de Quervain (1969).
20. Bowles (1939).
21. Plehwe-Leisen et al (1992).
22. The Bakkaune quarry and its use for the cathedral is mentioned by Schöning (1762:27ff, 1775:7). Helland (1893) and Carstens (1927, 1939) have also described the quarry.
23. RR 1869-1897, AccLu and Krefting (1869). See also Helland (1893) and Carstens (1927).
24. About the Bjørnå deposit, see DiaRA (1904-60) and Smedseng (1994).
25. See DiaRA 1905 and later.
26. Calculated from figures in DiaRA and AccLu. See also appendix 2.
27. DiaRA in several periods.
28. DiaRA 1970-74.
29. DiaRA 1952-95.
30. DiaRA 1960-69.
31. Schöning (1762), Vogt (1897) and Carstens (1927).
32. Mineral composition determined by Alnæs (1995).
33. AccLu.
34. Vogt (1897) and Carstens (1927).
35. ibid.
36. Carstens (1927), RR 1888-90.

37. Vogt (1897).
38. Oftedahl (1981), Wolff & Roberts (1980).
39. Properties determined by Alnæs (1995).
40. Krefting (1869), AccLu and DiaGu.
41. ibid.
42. Helland (1893), AccLu.
43. Oxaal (1916).
44. Carstens (1927), Oxaal (1916), DiaRA 1915-39.
45. Zakariassen (1980:197f). About medieval brick production in Norway, see also Lidén (1974).
46. Suggestions based on discussions with Øystein Ekroll.
47. Lysaker (1973) has several passages about the use of brick in the cathedral after the Reformation.
48. Zakariassen (1980:197ff).
49. About the polychrome dimension of cathedrals in general, see Sedlmayr (1950).
50. Several textbooks and articles treat traditional stone working techniques. See for instance Lidén (1974) about Norwegian examples. Rockwell (1988) and Hill (1990) describe stone working from a more general perspective.
51. See Schaffer (1932).
52. Schaffer (1932) and Winkler (1994). With regard to specific properties of Øye greenschist, see Storemyr (1996).
53. Lidén (1974).
54. Fischer D. (1965).
55. Cnattingius et al (1987).
56. See Mark (ed.) (1993).
57. ibid.
58. Lidén (1974) and Moestue & Waldum (1986).
59. ibid.
60. General information about the production of old lime mortars may be found in Perander & Råman (1985). Their report also contains numerous literature references to other works.
61. Vogt (1897:275). See also Zakariassen (1980).
62. About 19th and 20th century use of lime in Norway, see Kolderup (1891), Bugge (1918) and Holmgren et al (eds.) (1949).
63. About the general history of Portland cement, see Ashurst (1990a). The history of Norwegian Portland cement can be found in Gartmann (1990). Examples from Sweden are described in Engman et al (1991). We know about import of Portland cement from England and Germany to Trondheim in the second half of the 19th century. Such cements were used at the Nidaros cathedral - see below.
64. Gartmann (1990).
65. During the last 5-10 years several medieval churches and other Norwegian stone buildings have been restored by using factory-made, pit-slaked lime for plaster. Research programmes are also undertaken to enhance workability and durability of lime plaster. So far the research has focused on plaster, while very little has been done regarding joint and repair mortars.
66. Lund et al (1912).
67. See also Carstens (1939:3f).
68. See Vogt (1897:275).
69. Lysaker (1973:74f).
70. ibid., 145ff.
71. ibid., 246f.
72. From the restoration report of architect Schirmer, November 26, 1869, ARW.
73. See in particular DiaGu.
74. Kolderup (1891:16).
75. Schirmer's restoration report, November 26, 1869.
76. ibid.
77. Account books in the actual period, ARW.
78. AccLu.
79. The assumption has not been checked by analyses.
80. DiaRA, August 18, 1950.
81. See Kåring (1992).
82. Based on discussions with craftsmen at The Restoration Workshop.
83. AccLu.
84. About English cement, see DiaGu. About German cement, see account books (ARW) and DiaRA (e.g. April 3, 1905).
85. RR 1887/1 (and other RR in the period 1872-1904).
86. Lund et al (1912:21ff).
87. DiaRA in several periods.
88. Jensen (1993:39ff).
89. Letter to the Church Ministry April 30, 1869 from Mr. Nicolaysen, Mr. Christie and Mr. Nordan, ARW. My translation.
90. Wihr (1980:96ff), Ashurst & Ashurst (1989:55f) and Arnold (1985).
91. About piecing-in as a technical problem, see Ashurst (1990b:11ff).
92. See also Fischer (1969:62ff).
93. The use of iron cramps and dowels bedded in lead reaches back to ancient Greek architecture, see e.g. Mark (ed.) (1993:74ff).
94. Observations on photos taken before the restoration (ARW).
95. String course and tracery, octagon (RR 1873).
96. Columns, octagon (RR 1875).
97. Corbels, transept (RR 1892).
98. DiaRA, December 15, 1962.
99. DiaRA, copy of report on the cover of book no. 7, 1948-62.
100. See note 89.

101. DiaRA, 1991-92.
102. Based on personal communication with stone mason Atle Elverum who carried out most of the cleaning.
103. DiaRA 1978, 1982.

Chapter 7: Weather, air pollution and exposure conditions

1. Aune (1993).
2. Jacobsen (1990).
3. Bruun & Håland (1970).
4. Anda & Henriksen (1992).
5. Plehwe-Leisen et al (1994).
6. Johannessen (1977).
7. Bruun & Håland (1970).
8. ibid.
9. DiaRA 1987.
10. Mark (1982).
11. Bläuer (1987).
12. Aune (1993).
13. DiaRA August 8, 1905 and 1982.
14. Bruun & Håland (1970).
15. Anda & Henriksen (1992).
16. Mylona (1993).
17. ibid.
18. Anda & Henriksen (1992).
19. ibid. General information on sea salts can be found in Cooke & Gibbs (1993).
20. Cooke & Gibbs (1993).
21. Bläuer (1987).
22. According to my own observations.
23. Aune (1993).
24. ibid.
25. Bjørbæk (1994).
26. See Brimblecombe & Rodhe (1988) and Cooke & Gibbs (1993).
27. Schmidt (1945).
28. See Helland (1898), Norges industri (1930), Neuman (1953), Mykland (1955), Danielsen (1958), Zakariassen (1980), Sandnes (ed.) (1992) and Sandvik (1994).
29. Hansen (1995).
30. Hertzberg (1977).
31. Sellæg (1988).
32. Neuman (1953) and Sellæg (1988).
33. Sellæg (1988:75f).
34. Zakariassen (1980) and Sandnes (ed.) (1992).
35. Sellæg (1988).
36. Jacobsen (1990).
37. Sandnes (ed.) (1992).
38. Kaldal (1994) and Jacobsen (1990).
39. Population figures from Sandnes (ed.) (1992).
40. Based on the author's assumptions as well as on Jacobsen (1990) and Hagen (1994).
41. Storemyr (1995d,f) and Storemyr & Elverum (1996).
42. ibid. and Watzinger (1935).
43. Statistics can be found in Jacobsen (1990) and Storemyr (1995d).
44. Calculations performed using guidelines given in Jacobsen (1990).
45. See also Jacobsen (1990) and Anda & Henriksen (1992).
46. Anda & Henriksen (1992) and Hagen (1994).
47. Data on dust can be found on a daily basis in *Adresseavisen*.
48. Hagen (1994).
49. According to calculations, see Mylona (1993).
50. Watzinger (1935), Storemyr (1995f) and Nørsett (1996). Indoor climate in large buildings in general, see Arendt (1993). See also Massari & Massari (1993).
51. See also Nørsett (1996).
52. See Künzel & Holz (1991).
53. See chapter 3 for more detailed information.
54. ibid.
55. DiaRA February 4, 1953.

Chapter 8: Weathering of medieval stone

1. Quoted from Lysaker (1973:277), my translation.
2. von Minutoli (1853).
3. See also Bates & Jackson (1984).
4. Heldal & Storemyr (1997).
5. See also Carstens (1927, 1928, 1939).
6. Storemyr (1996).
7. More about craftsmanship vs. properties in Storemyr (1996).
8. See also DiaRA April 9, 1913.
9. See appendix 2.
10. Hawksworth & Hill (1984).
11. RR 1872 (fourth quarter).
12. Ekroll & Storemyr (1996).
13. Storemyr (1995c).
14. Hultin (1967a,b).
15. Martin Klungen (pers. comm.).
16. Storemyr (1995c).
17. Krefting (1869).
18. See appendix 2.
19. Letter from restoration architect Torgeir Suul to geologist Chr. Oftedahl, November 25, 1965, in ARW.
20. Carstens (1927, 1939).
21. Helland (1893).
22. Ibid. p. 146
23. Schwach (1838), cited in Lysaker (1973:173).
24. Schöning (1775:7).
25. Plehwe-Leisen et al (1992).
26. Cf. photo no. 1549, ARW.
27. See Ekroll & Storemyr (1996).
28. See Solnes (1995:65ff).

Chapter 9: Weathering of stone used during the restoration

1. Prior to 1920 it was known that the Grytdal stone was “rusting”. See RR 1918-19.
2. The regional geology of the area, with particular reference to deposits of economic interest, is described by Nilsen (1991).
3. Helland (1893).
4. RR 1918-22.
5. Based on my own observations in the quarry.
6. See appendix 2.
7. See Craig & Vaughan (1981) and Battey (1981). About various minerals, including soluble salts, found in weathered Norwegian sulphide deposits, see Neumann (1985)
8. See appendix 2.
9. About the surrounding geology, see Grønlie (1975:441).
10. DiaRA in several periods. See also Smedseng (1994) about how the quarry was worked.
11. Fischer (1969).
12. DiaRA July 4, 1929.
13. Hultin (1972) and Ragnhildstveit & Naterstad (1993).
14. Tom Heldal (pers. comm.).
15. See appendix 2.
16. Margrethe Moe (pers. comm.).
17. Frigstad (1974).
18. See note from architects Helge Thiis and Torgeir Suul, dated November 12, 1971, ARW.
19. Frigstad (1973, 1974).
20. DiaRA July 30, 1969.
21. Skjølsvold (1961).
22. Skjølsvold (1969).
23. “Hakkemette” occurs particularly in areas receiving annually less than 500 mm precipitation, e.g. in Vågå and Lesja in the south-central parts of Norway. See Neumann (1985).
24. Since I have not visited the Grunnes quarry, the natural weathering of the stone has been omitted.
25. See appendix 2.
26. Mineral composition determined by Alnæs (1995).
27. Lysaker (1995).
28. Solnes (1995:47ff).

Chapter 10: Typical stone weathering phenomena, analyses and experiments

1. See Winkler (1994:218ff) about the actions of sulphur bacteria.
2. A brief summary of the weathering of feldspars can be found in Alnæs (1995).
3. Arnold (1985).
4. Neumann (1985:101f).
5. A similar explanation has been put forward by Fitzner et al (1994) who investigated the weathering of soapstones in Brazil.
6. A discussion on whether lichens protect stone surfaces or not can be found in Jones (1988). See also Hawksworth & Hill (1984:83ff).
7. See Hawksworth & Hill (1984), del Monte et al (1987) and Jones (1988).
8. The experiment is also described in Alnæs (1995).
9. Gjelsvik (1985).
10. Experimental methods used:
    Density (a): DIN 52102 (1988)
    Open porosity (a): DIN 52102 (1988)
    Water absorption (a,b): DIN 52103 (1988)
    Capillary water absorption coefficient (b): See Poschlod (1990:34f)
    Hygric dilatation (b): 1 day under water, see Poschlod (1990:40f)
    Water vapour diffusion resistance (dry-cup) (b): RH 0-50%, DIN 52615 (1987), Poschlod (1990:35f)
    Water vapour diffusion resistance (wet-cup) (b): RH 50-100%, DIN 52615 (1987), Poschlod (1990:35f)
    Compressive strength (a): DIN 52105 (1988)
    Biaxial flexural strength (b): DIN 52112 (1988)
    (**a**) Partly after Alnæs (1995), partly author’s own analyses.
    (**b**) Analyses conducted by Esther von Plehwe-Leisen, Untersuchungslabor für Fragen der Natursteinerhaltung, Köln, Germany. See Plehwe-Leisen (1995).
    DIN-standards are described in Poschlod (1990) and Alnæs (1995).
11. Relevant literature: Poschlod (1990), Herkenrath (ed.) (1994) and Alnæs (1995).
12. Alnæs (1995).
13. ibid.
14. ibid.
15. Plehwe-Leisen et al (1992).
16. Schweda & Sjöberg (1996) explain the weathering of rock art on metapelites (metamorphic mudstones) in Sweden by the formation of swelling clays from chlorite.
17. See Plehwe-Leisen et al (1994) and Alnæs (1995). During investigations in 1935 it was found that the thermal dilatation of Bjørnå soapstone was on average $7{,}8 \bullet 10^{-6}$ K^{-1}. It was subsequently concluded that fractures developing in a fragile structure (canopy bearer) on the west front of the cathedral could be explained by thermal expansion during periods of strong sunshine. See analysis report (letter) from Ing. E. Bjørnstad, 13.5.1935, journal no. 89/35, ARW. I have not tried to confirm the conclusion.

18. See Alnæs (1995).
19. Plehwe-Leisen et al (1994).

Chapter 11: Weathering of the choir

1. Water leak record made on the basis of information in DiaRA and RR. See also Storemyr (1995d).
2. Based on information from masons.
3. RR 1918-22.
4. DiaRA 1990-95.
5. RR 1918-22.
6. DiaRA in several periods. See also Storemyr (1995d).
7. See Fischer (1969:27ff). The vaulted room must have been demolished after the Reformation. In the 1960s a sacristy was built in the narrow space between the choir and chapter house (see DiaRA 1962-65).
8. DiaRA in several periods. See also Storemyr (1995d).
9. I have assumed that magnesium sulphates (epsomite) and perhaps other soluble salts act in the same manner as halite with regard to hygroscopic behaviour and enhanced deposition of air pollutants. See Cooke & Gibbs (1993).

Chapter 12: Weathering of the nave

1. Record made on the basis of information in DiaRA. See also Storemyr (1995d).
2. DiaRA from 1955 and later. See also Storemyr (1995d).
3. DiaRA August 21, 1967.
4. DiaRA from 1968 until 1994.
5. DiaRA e.g. June 30, 1950 (and later).
6. Indicated in DiaRA September 18, 1956.
7. DiaRA October 2, 1963.
8. This phenomenon has been shown by testing undertaken by Jan Henriksen of the Norwegian Institute for Air Research. The dry deposition rate of SO_2 on Grytdal stone was found to be about 7 times higher than on Bjørnå stone. See also chapter 19.
9. DiaRA in several periods, e.g. 1928, 1932 and 1942-43.

Chapter 13: Weathering of the north transept

1. Hydraulic lime mortars were used to repoint the old joints.
2. Chlorides and air pollution, see Cooke & Gibbs (1993).
3. Lysaker (1973:216ff).
4. ibid., 214ff.
5. RR in several periods and Fischer (1969:34ff).
6. See Storemyr (1995): *Tillegg 1 til rengjøringsinstruks for Domkirken*. Note, ARW.
7. The situation is different in the octagon, where open joints in the large base give rise to water infiltration which causes salt weathering along the floor (see also chapter 16).

Chapter 14: Weathering of the southern west tower

1. Similar observations concerning sodium sulphates (mirabilite/thenardite) have been made by Arnold & Zehnder (1985:275f). See also chapter 3.
2. Similar considerations concerning hydration of thenardite to form mirabilite, have been made by Charola & Weber (1992). See also chapter 3.
3. Arnold (1985). See also chapter 3.

Chapter 15: Weathering of the west wall of the chapter house

1. Storemyr & Elverum (1996).
2. DiaRA November 3, 1927.
3. Architect Schirmer's restoration report, dated 26.11.1869 (ARW).
4. Storemyr & Elverum (1996).
5. Based on observations made on historical photos.
6. DiaRA August 13 and 20, 1926.
7. DiaRA April 19 and May 4, 1932.
8. Storemyr & Elverum (1996).
9. DiaRA May 19 and 27, 1932.
10. DiaRA September 2, 1927.
11. DiaRA June 30 and September 25, 1948.
12. Storemyr & Elverum (1996) also describe exterior weathering phenomena.
13. ibid.
14. ibid.
15. Charola & Lewin (1979).
16. See information in Gmelin (1966), in the chapter about “Natriumhydrocarbonat”.
17. See Storemyr & Elverum (1996) for a more thorough description of possible future measures.

Chapter 16: Weathering of the east chapel of the octagon

1. Fischer (1965:400).
2. ibid.
3. ibid.
4. Lysaker (1973.

5. RR 1872-74.
6. ibid.
7. ibid., see also DiaGu.
8. RR September 1973.
9. See various photos, ARW.
10. See photo no. 7199, ARW.
11. DiaRA 1974.
12. The water was collected by accident. Analyses can be found in Anda & Henriksen (1992).
13. Cooke & Gibbs (1993), see also chapter 3.
14. See RR 1872-74, DiaGu and photos from the restoration.
15. DiaRA, first mentioned January 20, 1953. For repairs, see DiaRA 1985-88.

Chapter 17: Weathering of St. Mary's portal

1. Fischer (1969:280ff).
2. ibid., 386ff.
3. Lysaker (1973:56ff).
4. ibid., 171f.
5. ibid., 228ff.
6. RR in the actual period. See also chapter 4.
7. ibid.
8. DiaRA September 20, 1945.
9. Photo no. 7156, ARW.
10. DiaRA 1977-78.
11. Photo no. 7156, ARW.
12. DiaRA 1991.

Chapter 18: Weathering of Romanesque corbel heads

1. Fischer (1965:67).
2. About the building of the chapel, see Fischer (1965:66ff).
3. In the restoration reports of architect Christie there is only a general description of the restoration around 1880.
4. Øystein Ekroll (pers. comm.).
5. See photo no. 61 (ARW), reproduced on p. 66 in Fischer (1965). The original glass plate from the 1860s is in such bad condition that it is impossible to make good copies.
6. DiaRA 1983.
7. One example is the Baroque portal at the Austrått castle north of Trondheim. See Storemyr (1995g).
8. The restoration took place between 1880 and 1881 (Fischer 1969:36f). See also Christie's restoration reports.
9. DiaRA 1984.

Chapter 19: Summary and discussion of typical weathering phenomena

1. Lysaker (1973:305), my translation.
2. Fischer (1969:146).
3. Kieslinger (1932:13). See also a description by Kieslinger (1948) of similar problems at St. Stephan in Vienna.
4. Examples include Berner Münster (Switzerland), St. Vitus (Praha, Czech Republic), Freiburg Münster (Germany), St. Stephan (Vienna, Austria), Nortre Dame and St. Denis (Paris, France). All these cathedrals have exterior gangways. I have also studied a dozen or more cathedrals without exterior gangways in Sweden, Germany, Switzerland and Italy. Water leaks heavily affecting interior vaults seem to be rare at these cathedrals.
5. Schaffer (1932) and Kieslinger (1932). About particular problems related to the use of cramps in parapets and other projecting elements, see Smith (1982).
6. Storemyr & Ekroll (1996).
7. See also Charola & Lewin (1979).
8. Ekroll & Storemyr (1996).
9. For brief descriptions of Ilen, Melhus and Orkdal churches, see Ringbom (1987). About weathering problems at Ilen church, see Solnes (1995).
10. Two well documented examples: Nydegg-bridge in Bern, Switzerland, see Bläuer (1992) and Pilsum church in Germany, see Rösch & Schwarz (1994).
11. About condensation in the zone of rising damp, see Arendt (1993) and Massari & Massari (1993).
12. See Ekroll & Storemyr (1996).
13. At Nidaros cathedral dry deposition rates of 200-1500 $\mu g/m^2$day were measured on *porous filters* in 1990-91, see Anda & Henriksen (1992). 1000 $\mu g/m^2$day corresonds roughly to 0,37 g/m^2year. It is reasonable to maintain that the dry deposition rate is much lower on dense soapstone than on porous filters. For comparison: Dry deposition rates on porous *Molasse sandstone* in the western part of Switzerland were between 0,08 g/m^2year (countryside) and 1,57 g/m^2year (Geneva) in the beginning of the 1980s, see Girardet & Furlan (1982).
14. This feature has been verified by a laboratory experiment performed by Jan Henriksen. See note 8/Chapter 11.
15. See Buzek & Šrámek (1985) and Pye & Schiavon (1989).
16. See Alnæs (1995:376ff).
17. See Ringbom (1987).
18. See Alnæs (1995:377f).

19. These observations correspond with results from a national exposure programme started in 1990 and involving several soapstones/serpentinites. See Alnæs (1995).

Chapter 20: From weathering to conservation

1. Most recommendations can also be found in Storemyr (1995e)
2. Measurements to be found in ARW.
3. A project description has already been made by The Restoration Workshop. The first phase of the project, involving mapping of damage, has also been carried out, see Bjørlykke et al (1996).
4. Alf J. Solem, pers. comm.
5. A solution proposed by Øystein Ekroll, pers. comm.
6. Insall (1972), cited in Feilden (1982:283).
7. Nørsett (1995).
8. ibid. and Storemyr (1995f).
9. DiaRA in the actual period (around 1930).
10. Experience from preservation of mural paintings vs. control of indoor climate can be used in this connection. Among a large number of case-studies carried out in Europe, see Arnold et al (1991).
11. For methods of desalination of stonework, see Fichtner et al (1994).
12. About such clenaing methods, se overview in Ashurst (1990c).
13. Currently, conservator Margrethe Moe works on a research project aimed at finding suitable cleaning and consolidation methods for sculptured soapstone objects covered by black crusts. Special attention is paid to the 17th century north portal of the Church of the Holy Cross in Bergen, Norway.
14. See proceedings from “Stone cleaning and the nature, soiling and decay mechanisms of stone”, Edinburgh 1992 (Webster, ed. 1992).
15. Storemyr (1995c).
16. ibid.
17. See Heldal and Storemyr (1997) and Storemyr (1997).
18. About medieval stone working techniques at Øye, see Storemyr (1996).
19. See also Storemyr (1995c)
20. Plans for making traditional lime mortars by pit-slaking methods in the Restoration Workshop are currently underway.
21. See also Magnussen (1995) about hydraulic lime mortars.
22. At Cologne cathedral this issue is treated differently. *Dombaumeister* Arnold Wolff (pers. comm.) regards the use of silicone rubber for sealing joints as unavoidable, especially since there are few other durable options.
23. About the use of lead in tracery at Basler Münster, see Lopez & Meles (1990). General information about the use of lead in joints, see Smith (1982).
24. See Feilden (1982:217ff).

Chapter 21: Conclusion

1. Cooke & Gibbs (1993:17).
2. Feilden (1982:203ff).
3. William Morris 1896, cited in Tschudi-Madsen (1976:94).
4. Krumbein (1988:182).
5. Ruskin (1849:196).

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Abbreviations:

FNFB: Yearbook of the Society for the Protection of Ancient Monuments, Oslo.
NDRr: Reports from the Restoration Workshop of the Nidaros Cathedral, Trondheim
NGU: Norwegian Geological Survey, Oslo/Trondheim
NGUr: Technical reports from Norwegian Geological Survey, Trondheim
NILUr: Reports from the Norwegian Institute for Air Research, Lillestrøm/Kjeller

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Appendix 1

Conservation history of each part of Nidaros Cathedral

With emphasis on interventions after the main restoration phases.

THE CHAPTER HOUSE

1160-1180:	Original building period.
1328-1531:	Little affected by fires in 1328, 1432 and 1531.
1689:	Roof destroyed by the spire of the central tower which blew down during a hurricane.
1708/1719:	Roof destroyed by two fires.
17th cent.:	Used as archive, which was destroyed by dampness.
1869-1871:	Architect Schirmer's restoration. Masonry and vaults cleaned (acid/lye?), recarved, consolidated and/or largely replaced. Towers erected. New roof made. Cellar for central heating plant excavated.
1890-1966:	Heating plant and chimney replaced/repaired seven times.
1926-1932:	Towers and gable restored because of leaks. Copper plates applied on gable copings. Interior walls cleaned and vaults whitewashed.
1948:	Towers once again restored because of joint fissures and leaks. Asphalt insulation applied.
1963-1966:	Erection of sacristy between the south wall and choir.
1982-1989:	Smaller roof repairs.
1995:	Towers and west wall in bad condition due to joint fissures, leaks and interior salt weathering

THE OCTAGON

1180-1220:	Original building period.
1328-1350:	Heavily destroyed by fire in 1328. Large-scale repairs.
1432:	Only little affected by fire.
1510-1521:	Interior and gables of the chapels restored by Archbishop Erik Valkendorf
1531:	Only little affected by fire
1630s:	Various repair works. Whitewashing. Main vault replaced
1708/1719:	Two fires. Erection of Baroque copola.
1834:	Main vault replaced
1870-1878:	Restoration of Krefting and Christie. Consolidation of foundations. Masonry, vaults and decorations cleaned (acid/lye), recarved, consolidated by cement and sometimes replaced. New lead roofs. Clerestory and main vault supported by wooden buttresses. Heating installed.
1880-1960:	Frequent repointing. Repair of lead roofs.
1919-1921:	Flying buttresses, pillars and roofs repaired
1930:	Vaults whitewashed.
1946:	Repair of some flying buttresses and pillars.
1960-1979:	Replacement of lead roofs by copper. Main work in 1975.
1974-1976:	Gable triangle and pinnacles of the eastern chapel replaced.
1978-1981:	Some flying buttresses and pillars repaired.
1981-1988:	Gable triangle and pinnacles of the southern chapel restored.
1995:	Main problem is leaks in the chapels (esp. northern) and weathering of medieval decorations

THE CHOIR

1200-1240:	Original building period.
1330-1350:	Repairs after the fire in 1328.
1531:	Inner and upper parts destroyed due to fire. Rebuilt in new style.
1708-1719:	Two fires and subsequent repairs. Baroque interior.
1878-1890:	Architect Christie's restoration of aisles and reconstruction of inner and upper parts.
1915:	Cracks in the vaults of the aisles observed.
1916-1922:	Repair of the southern wall. Replacement of Grytdal stones. Restoration of the King's porch.
1920-:	Very frequent problems with leaks from exterior gangways.
1930:	Vaults whitewashed.
1931:	King's porch: Stone relief inserted. Large cracks.
1932-1938:	Turrets repaired because of leaks.
1943-1947:	Walls, parapets and buttresses subjected to stone replacement.
1950-1959:	Thorough restoration of the King's porch.
1976-1984:	Bases and string courses subjected to stone replacement.
1986:	Steel construction applied above the main vaults in order to secure the outward inclining walls.
1989-1991:	Repair of the north turret after damages due to storm.
1990-1995:	All flying buttresses on the north side replaced.
1995:	Disastrous leak from the upper gangway on the south side temporarily repaired.

THE CENTRAL TOWER

1070-1150:	Erection of the first tower.
1210-1240:	Rebuilding of the tower in Gothic style.
1432/1531:	Upper parts destroyed by fires.
16th century:	Addition of an upper storey above the triforium after fires. Main arches (S and N) closed.
1638:	Erection of very tall spire (69 m).
1689:	The tall spire blew down during a hurricane.
1689-1719:	Two fires and building of provisional spires.
18th century:	Building of pyramidal roof.
1884-1903:	Architect Christie's thorough restoration and building of new clerestory and spire.
1909-1912:	Thorough investigation of the tower's stability, which was considered satisfactory
1928-1932:	Major leaks through the copper covered spire. Subsequent repairs.
1942-1943:	Serious leaks through the spire. Internal protective roof constructed.
1949-1952:	New investigation of the tower's stability.
1966-1976:	Once again investigation of stability in order to plan measures necessary for possible addition of a new upper storey.
1984-1986:	Consolidation of the foundations. The stability of the tower is satisfactory.

THE NORTH TRANSEPT

1140-1160:	Lower parts and chapels built.
1160-1220:	Clerestory and gable triangle built.
1328:	Damaged by fire.
1432:	Damaged by fire. Large late Gothic window inserted in the gable wall.
1689:	Spire of central tower blew down. Damage to the north transept.
1708/1719:	Partly damaged by two fires.
18th century:	The Lectorium used as fire-proof room. Damages due to dampness.
1870-1905:	Thorough restoration, mainly under architect Christie. Addition of flanking towers and circular window in the gable.
1921:	Described as "in good repair".
1949-1950:	St. Mary's chapel: Replacement of the southern flanking tower.
1967-1970:	St. Mary's chapel: Replacement of the northern flanking tower.
1983-1984:	Replacement of gable copings on St. Michael's chapel.
1993-1996:	Western flanking tower repaired.
1994:	St. Michael's chapel covered by copper.

THE NAVE

1240-1280:	Original building period.
1328:	Fire. Probably minor damage.
1432:	Fire. Uncertain how much damaged. Used throughout the 15th century. Porch or burial chapel built by St. Mary's portal.
1531:	Fire. Inner and upper parts collapsed or demolished because of the damages.
1590:	Walls of the aisles protected by roofing.
1739:	Walls of the aisles in bad repair. Consolidated and roofed once again.
1740-1805:	The ruined nave used for burials.
1872:	Roofed and used as restoration workshop.
1898-1905:	Architect Christie's restoration of the walls of the aisles.
1905-1930:	Reconstruction of the nave after architect Christie's plan.
1945-1946:	Stone reliefs iinserted n St. Mary's and St. Olav's portals.
1949:	Leaks from the parapet and stability problems (differential settlement) recorded for the first time.
1950:	Exterior gangways insulated with asphalt.
1950-1962:	Gable triangle of the nave built.
1950-:	Very frequent problems with decorations and mouldings made of Bjørnå stone, leaks from exterior gangways and storms affecting the copper covered roof.
1955:	Decorations in the triforia started to fall down. Subsequently secured.
1968-1994:	Restoration of the buttress system. Exposed details made of Bjørnå stone replaced.
1978-1980:	Details of St. Mary's portal replaced.
1995-1996:	Still great problems with decorations and mouldings which tend to fall down.

THE SOUTH TRANSEPT

1140-1160:	Lower parts and chapels built.
1160-1220:	Clerestory and gable triangle built.
1328:	Fire. Probably minor damage.
1432:	Fire. Probably minor damage.
1531:	Fire. The gable strongly damaged.
1666:	The gable rebuilt with brick.
1690:	Burial chapel built alongside the gable wall.
1708/1719:	Gable wall damaged in two fires.
1870-1905:	Extensive restoration, mainly under architect Christie. Gable and flanking towers rebuilt.
1921:	Described as "in good repair".
1932:	Gable copings on St. Olav's chapel replaced.
1983-1984:	Gable copings on St. Olav's chapel replaced. Repointing of joints.
1990-1991:	String course on west wall replaced.

THE WEST FRONT AND WEST TOWERS

1240-1300:	Original building period. Uncertain whether the towers were erected.
1328/1432:	Fires. Uncertain how much damaged.
1531:	Fire. Upper part of nave and west front collapsed or demolished due to the damages.
1590:	The two remaining storeys protected by roofing.
1705-07:	Very bad condition. West front suppored by masonry buttresses.
1739:	New roofs over the masonry heads.
1899-10:	The two lower storeys restored.
1908:	First architect competition about the design of the new west front.
1912-16:	Third storey of the west front almost completed.
1915-23:	Work on the west front discontinued (*Systemstriden*).
1925-30:	The rose window built.
1929:	New architect competition about the design of the west front.
1934-69:	Building of the upper part of the west front (finished 1950), northern west tower (1964) and southern west tower (1968).
1932:	Corbel carrying a fragile canopy on the west front fell down. Subsequently replaced.
1935/1947:	Cracks formed in corbels carrying canopies on the west front. Subsequently replaced.
1965:	Leak in the new northern west tower. Repaired.
1971-80:	Frequent repointing of rose window and exposed details, often by silicone.
1981-84:	Thorough restoration of the rose window.
1984:	Concrete floor made in the belfry of the southern west tower.
1990:	Rib vault made in a room of the southern west tower.
1994-95:	Insulation of the exterior gangway of the west front in order to prevent leaks.
1996:	Extreme leaks and weathering in the towers have been going on for several years.

Sources:
DiaRA, RR, Fischer (1965, 1969) and Lysaker (1973). See also Storemyr (1995d,e). *See notes and bibliography for references*

Appendix 2

Stone types used at the cathedral since the Middle Ages

QUARRY/NAME	***COUNTY***	***USE PERIODS***	***m^3***	***MAINLY USED FOR****Fehler! Textmarke nicht definiert.*
		GREENSCHIST		
ØYE (*)	ST	M: 1050-1200?		Transept, chapter house., octagon, choir
		R: 1869, 1885, 1892, 1913, 1934	15	Chapter house, nave (a few ashlars)
DYRBORG (*)	ST	M: 1050-1200?		?
		R: 1894	2	?
SKAUGE (*)	ST	M: ?		?
		R: 1869, 1897, (1933)	15	Chapter house
KLEFSÅS (*)	ST	M: ?		
		R: 1897, 1914-1915	10	Nave (a few ashlars)
REUSE		M: From Olav Kyrres Christchurch and other buildings. R: From the cathedral		
		SOAPSTONE/TALCSCHIST (/SERPENTINITE)		
BAKKAUNE (*)	ST	M: 1150-1350? (+1700)		Decorations, masonry nave?
		R: 1869-80, 1894-97	460	Octagon, transept (all purposes)
KLUNGEN (*)	ST	M: 1150-1350? (+1700?)		Decorations, masonry nave?
		R: 1884-86, 1892-99	440	Transept, choir (all purposes)
HUSEBY (*)	ST	M: 1050-1200?		Transept, chapter house
		R: 1869	15	Chapter house (aslars, decorations)
GRYTDAL (*)	ST	R: 1869-70, 1874-82, 1885-92	1130	Chapter h., choir, transept (all purposes)
BONES (*)	ST	R: 1876	10	South transept
SOLEM (*)	ST	R: 1878-81	25	High altar etc. (decorations)
ROGSTAD (*)	ST	R: 1882-88, 1960	580	Choir (all purposes)
TILSETH (*)	ST	R: 1885-89	140	Choir (all purposes)
BJØRNÅ (*)	NO	R: 1897-1958	7500	Transept, central tower, nave, west front, west tower (all purposes)
OTTA	OP	R: 1898-99	?	Central tower?
Unknown	ØF	R: 1898-99	35	Central tower, nave?
SOLERØD	ØF	R: 1900-03	65	Nave and west front (bases, ashlars)
SØMNES (*)	NO	R: 1910	2	Nave (a few ashlars)
BRATTSET (*)	ST	R: 1920-21	3	King's porch?
GULLFJELLET	HO	R: c. 1930-50, 1970-74	500	West front statues, copings etc.
VÅGÅ	OP	R: 1945-46	15	West towers
MYSEN	ØF	R: 1952	?	West towers
BUBAKK (*)	HE	R: 1952-70, 1976-95	1000	West towers, replacement all over
RJUKAN	TE	R: 1958	?	West towers
FINLAND (loc. unknown)	FI	R: 1959, 1963	15	West front, west towers
STOLPELIA (*)	NO	R: 1960	1	?
GRUNNES	TR	R: 1961-67	500?	West towers
REUSE		M: From the cathedral after fires. R: From the cathedral and other churches		

EXPLANATIONS
(*) Quarries mainly operated by the Restoration Workshop of Nidaros Cathedral (during the restoration)
M = Middle Ages, R = Restoration, m^3=approximate quantities quarried during the restoration
Counties (countries when not domestic): BE=Belgium, BU=Buskerud, FI=Finland, HE=Hedmark, HO=Hordaland, IT=Italy, MR=Møre og Romsdal, NO=Nordland, NT=Nord-Trøndelag, OP=Oppland, ST=Sør-Trøndelag, TE=Telemark, TR=Troms, VE=Vestfold, ØF=Østfold.

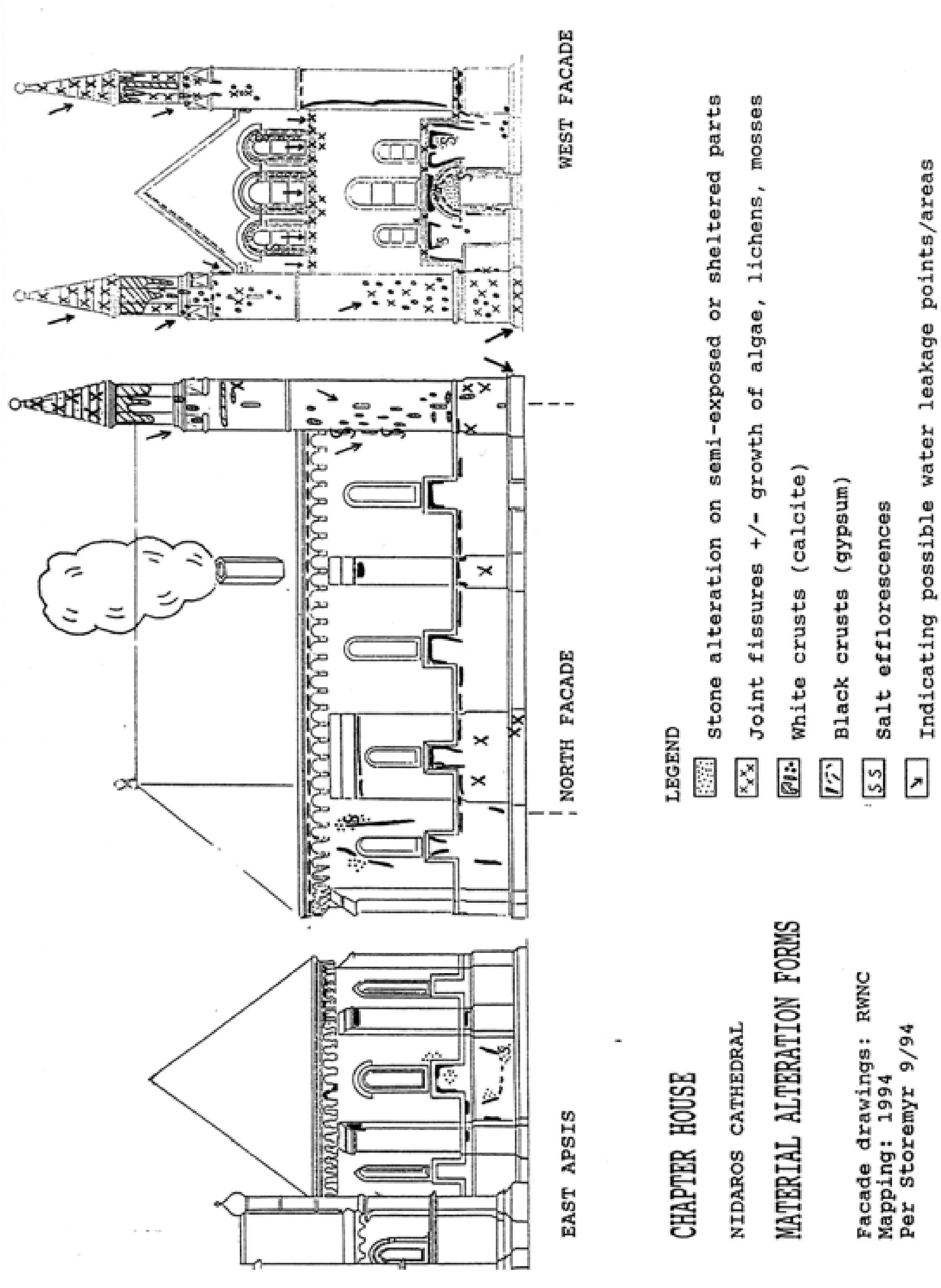
Source: Storemyr (1995c) *See bibliography*

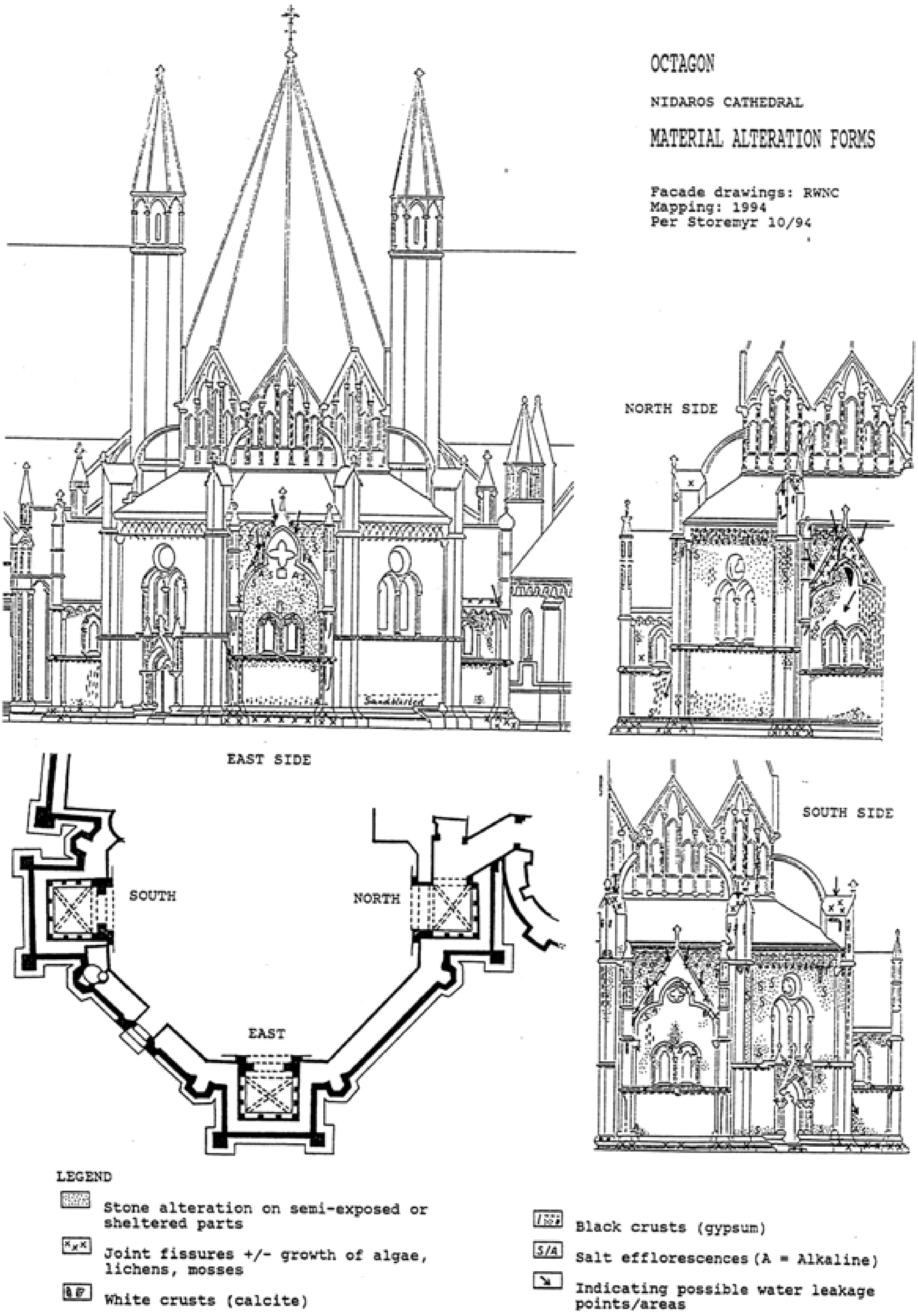
QUARRY/NAME	COUNTY	USE PERIODS	m^3	MAINLY USED FOR
LIMESTONE AND MARBLE				
LEIN & FRØSETH (*)	NT	M: 1180-1350? R: 1872-75, 1902-07	 >270	Floor tiles, columns, pillars Do.
ALMENNINGØYA (*)	ST	M: 1180-1350? R: 1874-88, 1900-11	 >200	Columns, floor tiles, steps Do.
STOVLOE (*)	NT	M: ? R: 1870-71	 5	 Floor tiles (?)
CARARRA (Statuario + others)	IT	18th and 19th cent.? R: 1872?, 1878, 1939	? ?	Possibly floor tiles Possibly floor tiles, sculpture
BOSTAD (*)	ST	R: 1878	30	High altar, div. for floors
Div. foreign	-	R: 1878	?	For high altar
FAUSKE (Leivseth)	NO	R: 1888, 1902, 1930s	>100	Floor tiles (choir, transept, nave)
FAUSKE (Furuli)	NO	R: 1930s	?	Div.
FAUSKE (Antiq.Verd.)	NO	R: 1930s	?	Div.
BELGE BLEU	BE	R: 1930s	?	Floor tiles (nave), altar
BELGE NOIR	BE	R: 1930s	?	Altar
TJØTTA	NO	R: 1930s	?	?
EIDE	MR	R: 1930s	?	?
TOTEN	OP	R: 1939	?	?
REUSE		M: Possibly floor tiles. R: Replacement of floor tiles		
SANDSTONE / METASANDSTONE				
REPPE (*)	ST	R: 1869-74, 1888 + ?	>20	Columns (chapter h., transept, oct.)
SAMDAL (Krogstad?)(*)	ST	R: 1869-74, 1882-99, 1908-1915	>600	Aslars, binders etc. (chapter h., oct., nave)
RINGERIKE	BU	R: 1882	?	Floor tiles, King's porch
STJØRDAL	NT	R: 19th cent. ? 1935	?	Central tower?
GRANITIC GNEISS, HARD GREENSTONE AND OTHER HARD STONES				
VARIOUS	ST	M: Yes R: Yes	? ?	Interior walls, masonry cores, foundations Do.
BAKKAUNE (*)	ST	R: 1869-1875	?	Do.
HØVRINGEN	ST	R: 1890s	?	Do.
INGDALEN (*)	ST	R: 1915-20, 1926-28, 1938	?	Interior walls (loft of nave etc.)
BJØRNÅ (*)	NO	R: 1946	?	?
REUSE		M: From the cathedral after fires. R: From several local buildings		
SYENITE AND HYPERITE				
LARVIKITE	VE	R: 1905	0,1	Baptismal font
SOLVÅG	NO	R: 1930s, 1950s	5	Statues and reliefs (west front)
SLATE				
Unknown	-	M: Yes	?	In joints, div. for floors
SORTE	NT	R: 1888 and later	5	Floor tiles, choir
ALMLIA	ST	R: Yes	?	Div.
OPPDAL	ST	R: Yes	?	Div.

Appendix 3

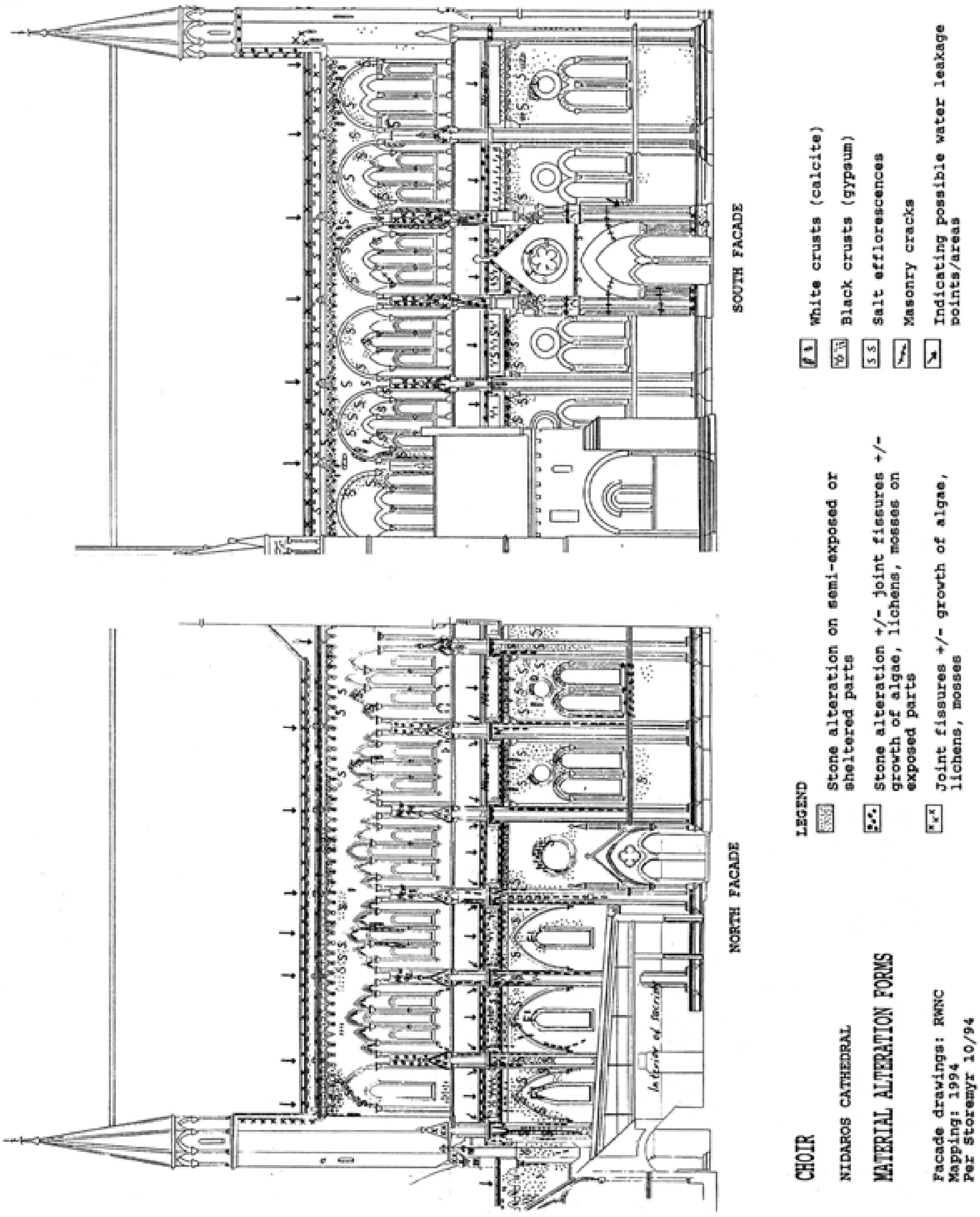
General weathering maps of each part of the cathedral

The chapter house
The octagon
The choir
The central tower
The north transept
The south transept
The nave
The west front and west towers


WEST FACADE
NORTH FACADE
EAST APSIS
LEGEND
Stone alteration on semi-exposed or sheltered parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences
Indicating possible water leakage points/areas
CHAPTER HOUSE
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 9/94

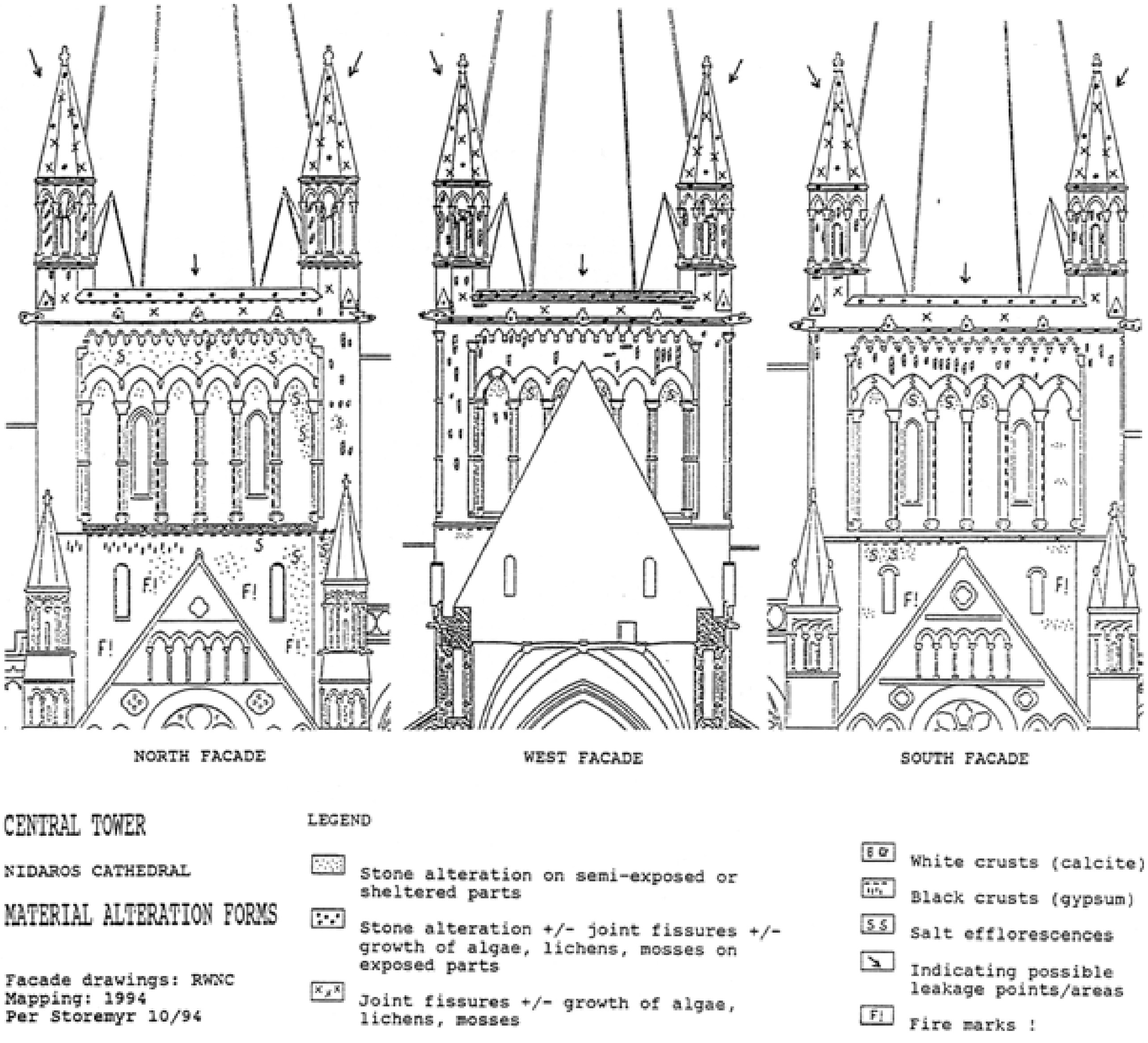

OCTAGON
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94
NORTH SIDE
EAST SIDE
SOUTH SIDE
SOUTH
NORTH
EAST
LEGEND
Stone alteration on semi-exposed or sheltered parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences (A = Alkaline)
Indicating possible water leakage points/areas

Appendix 3



SOUTH FACADE
NORTH FACADE
LEGEND
Stone alteration on semi-exposed or sheltered parts
Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences
Masonry cracks
Indicating possible water leakage points/areas
CHOIR
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94

Appendix 3

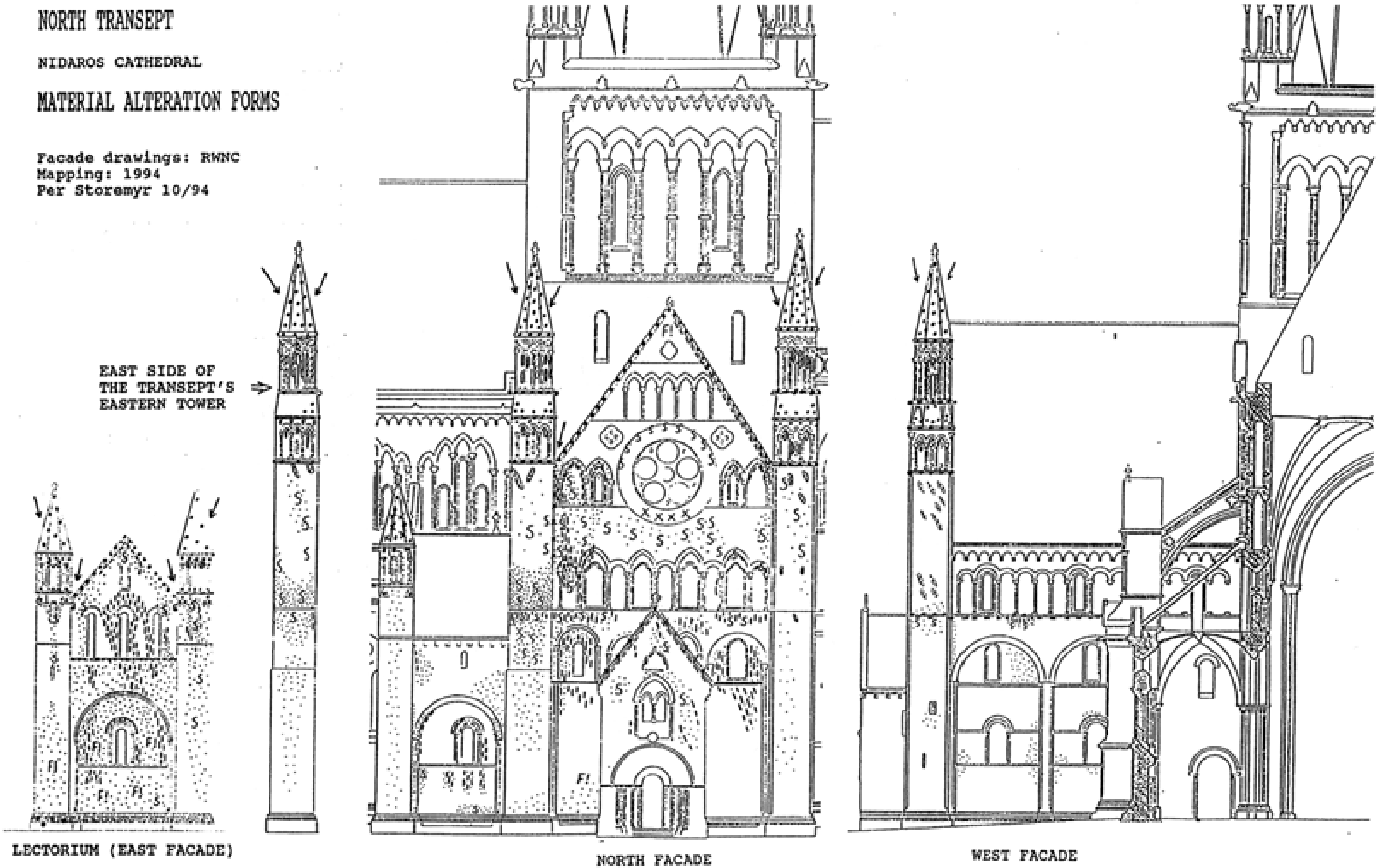

NORTH FACADE
WEST FACADE
SOUTH FACADE
CENTRAL TOWER
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94
LEGEND
Stone alteration on semi-exposed or sheltered parts
Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences
Indicating possible leakage points/areas
Fire marks !

NORTH TRANSEPT

NIDAROS CATHEDRAL

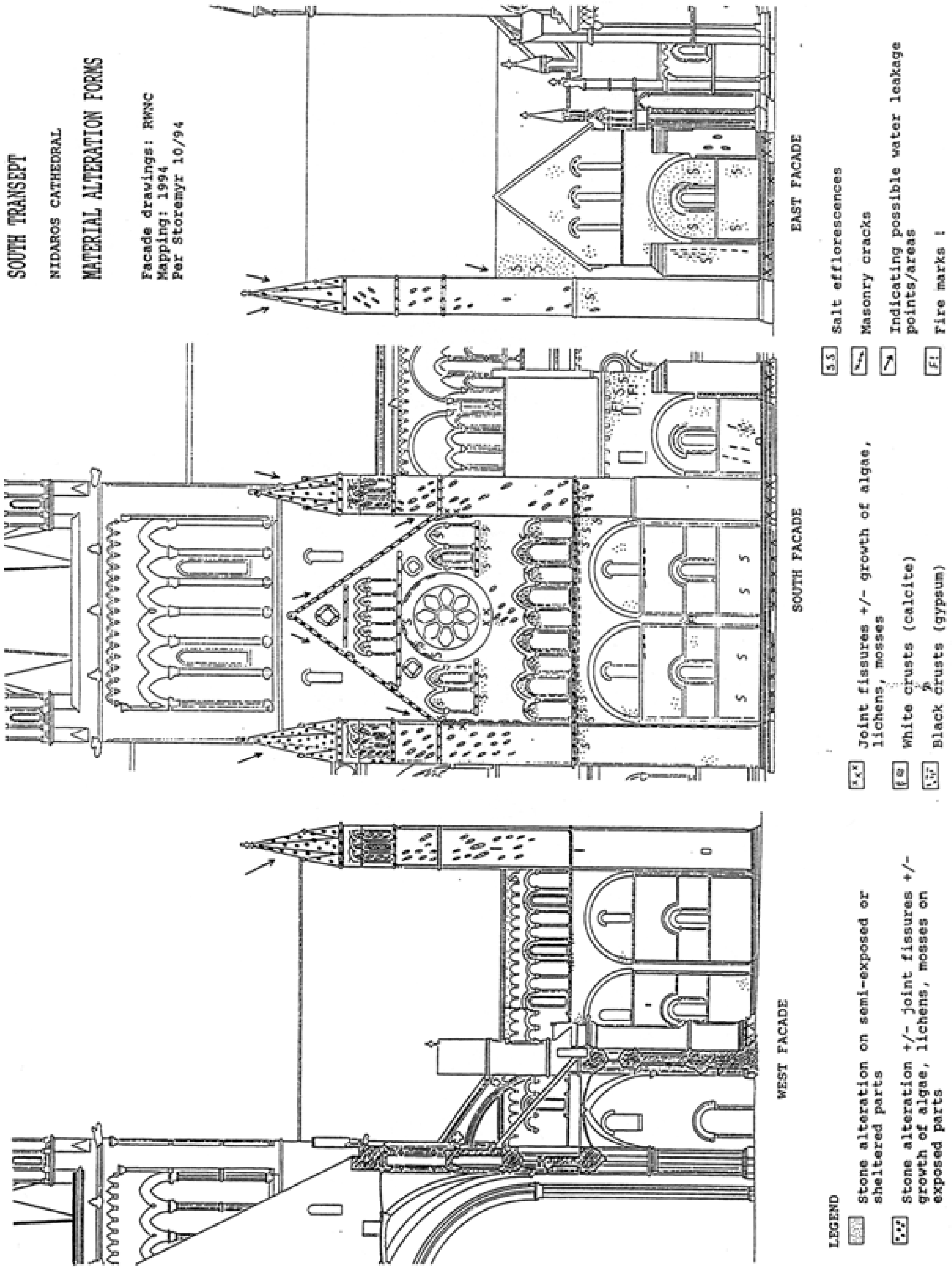
MATERIAL ALTERATION FORMS

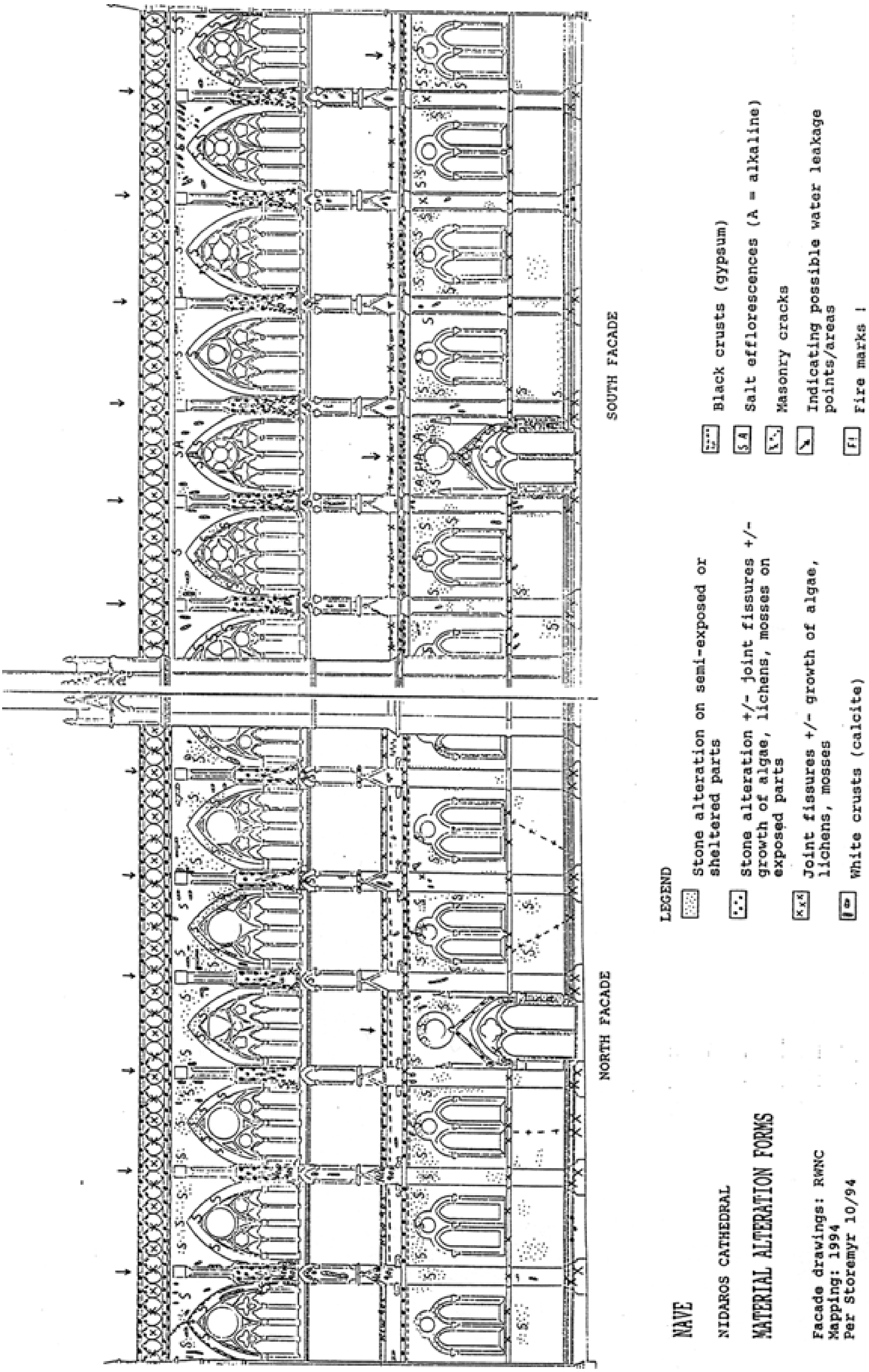
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94

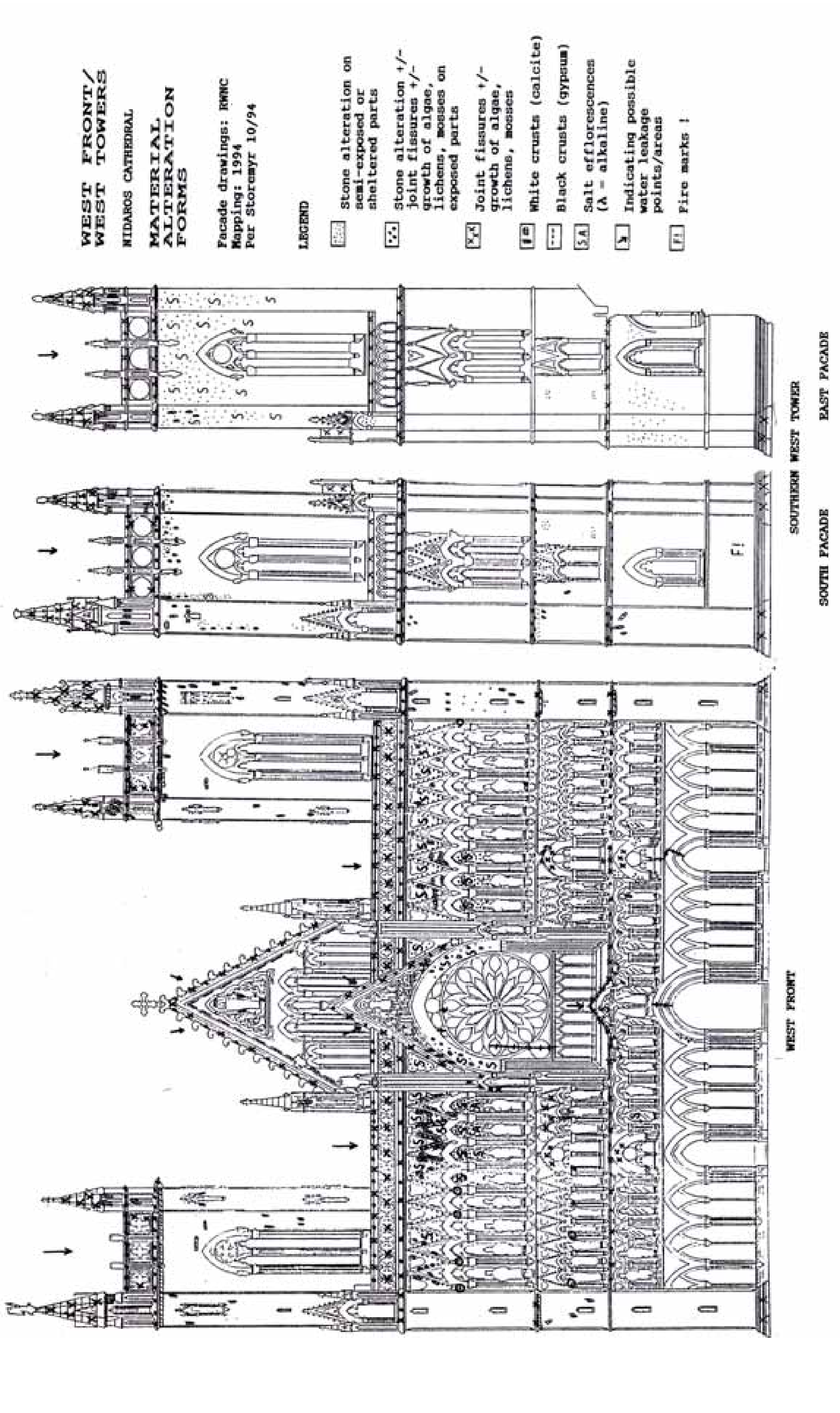


LEGEND

- Stone alteration on semi-exposed or sheltered parts
- Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
- Joint fissures +/- growth of algae, lichens, mosses
- White crusts (calcite)
- Black crusts (gypsum)
- Salt efflorescences
- Indicating possible water leakage points/areas
- Fire marks !

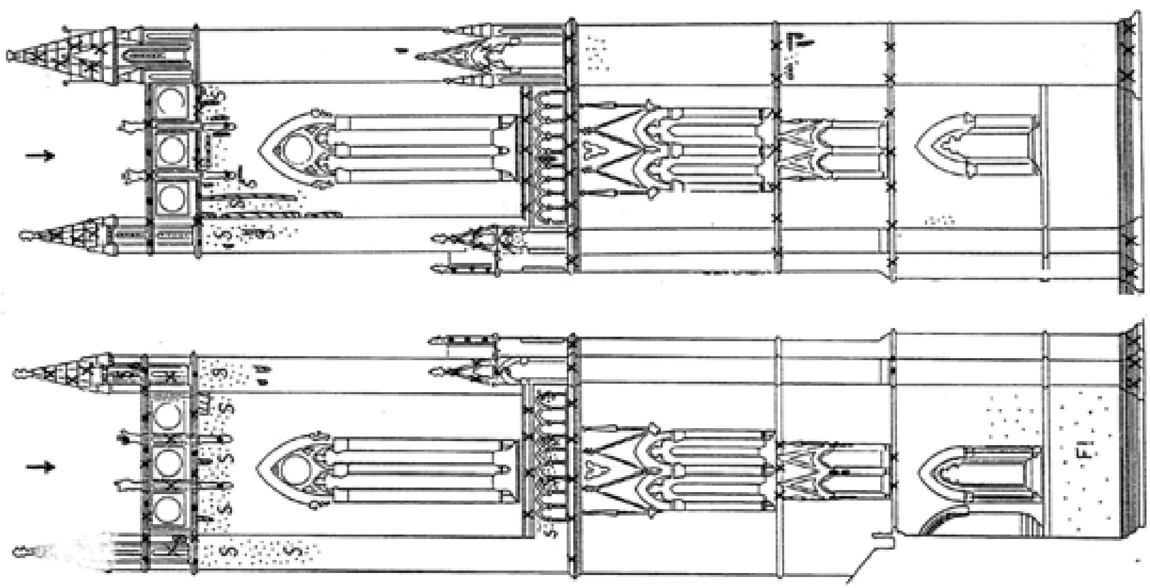

SOUTH TRANSEPT
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94
WEST FACADE
SOUTH FACADE
EAST FACADE
LEGEND
Stone alteration on semi-exposed or sheltered parts
Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences
Masonry cracks
Indicating possible water leakage points/areas
Fire marks !


SOUTH FACADE
NORTH FACADE
NAVE
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94
LEGEND
Stone alteration on semi-exposed or sheltered parts
Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
Salt efflorescences (A = alkaline)
Masonry cracks
Indicating possible water leakage points/areas
Fire marks !



WEST FRONT/ WEST TOWERS
NIDAROS CATHEDRAL
MATERIAL ALTERATION FORMS
Facade drawings: RWNC
Mapping: 1994
Per Storemyr 10/94
LEGEND
Stone alteration on semi-exposed or sheltered parts
Stone alteration +/- joint fissures +/- growth of algae, lichens, mosses on exposed parts
Joint fissures +/- growth of algae, lichens, mosses
White crusts (calcite)
Black crusts (gypsum)
SA
Salt efflorescences (A = alkaline)
Indicating possible water leakage points/areas
F!
Fire marks !
WEST FRONT
SOUTH FACADE
SOUTHERN WEST TOWER
EAST FACADE

Appendix 3



NORTHERN WEST TOWER

EAST FACADE

NORTH FACADE

Appendix 4

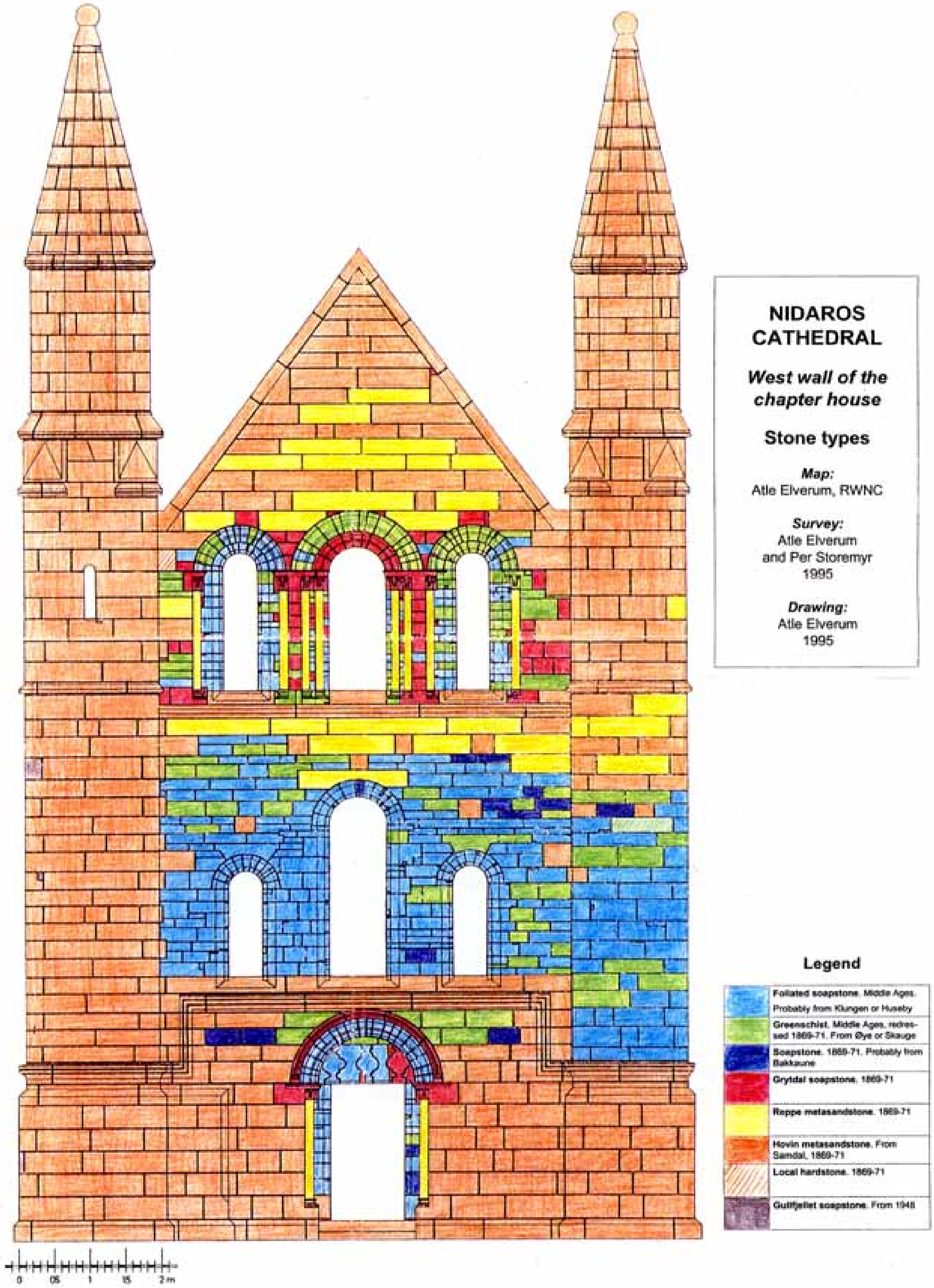
Graphic documentation of selected parts of the cathedral

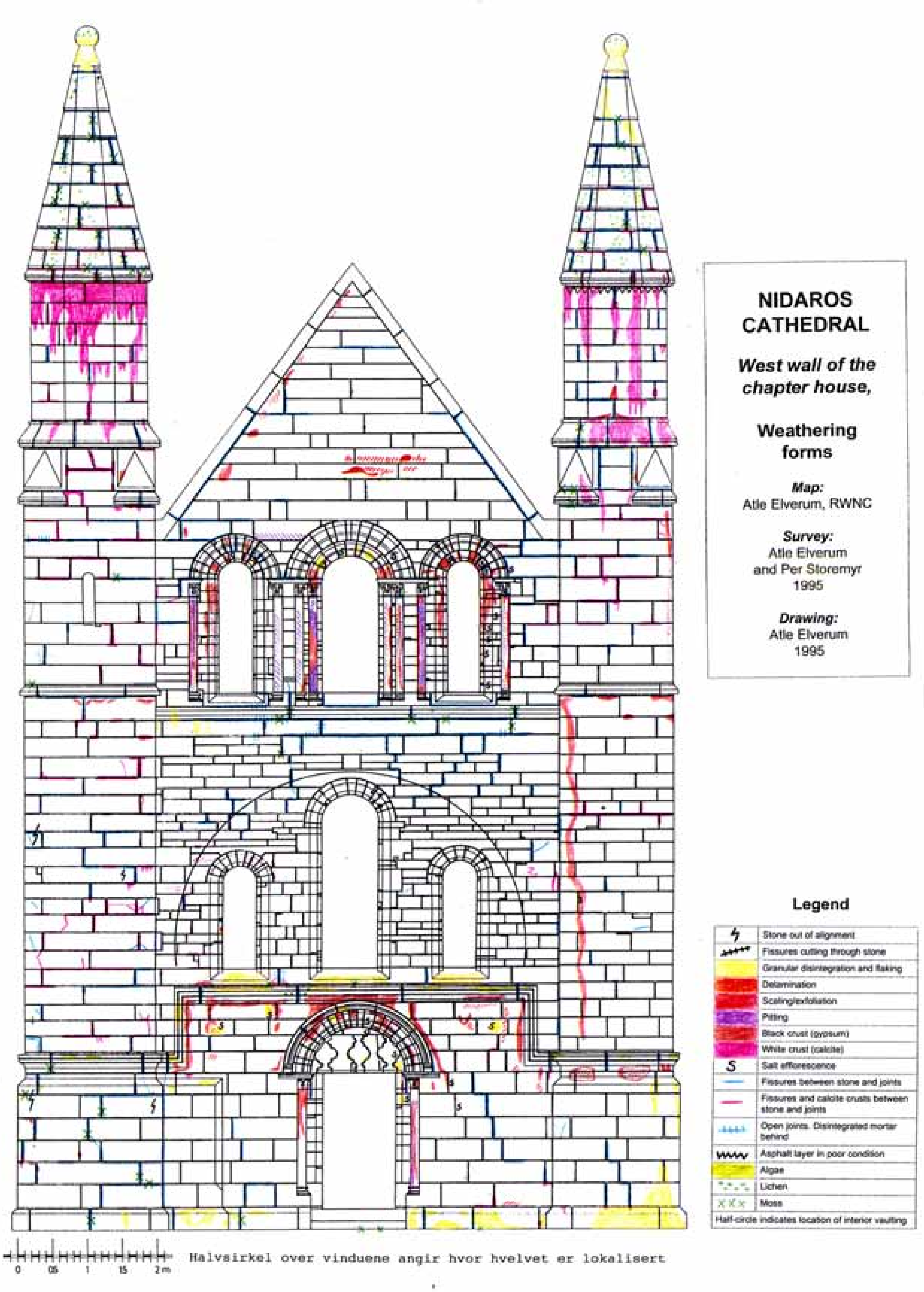
The west wall of the chapter house

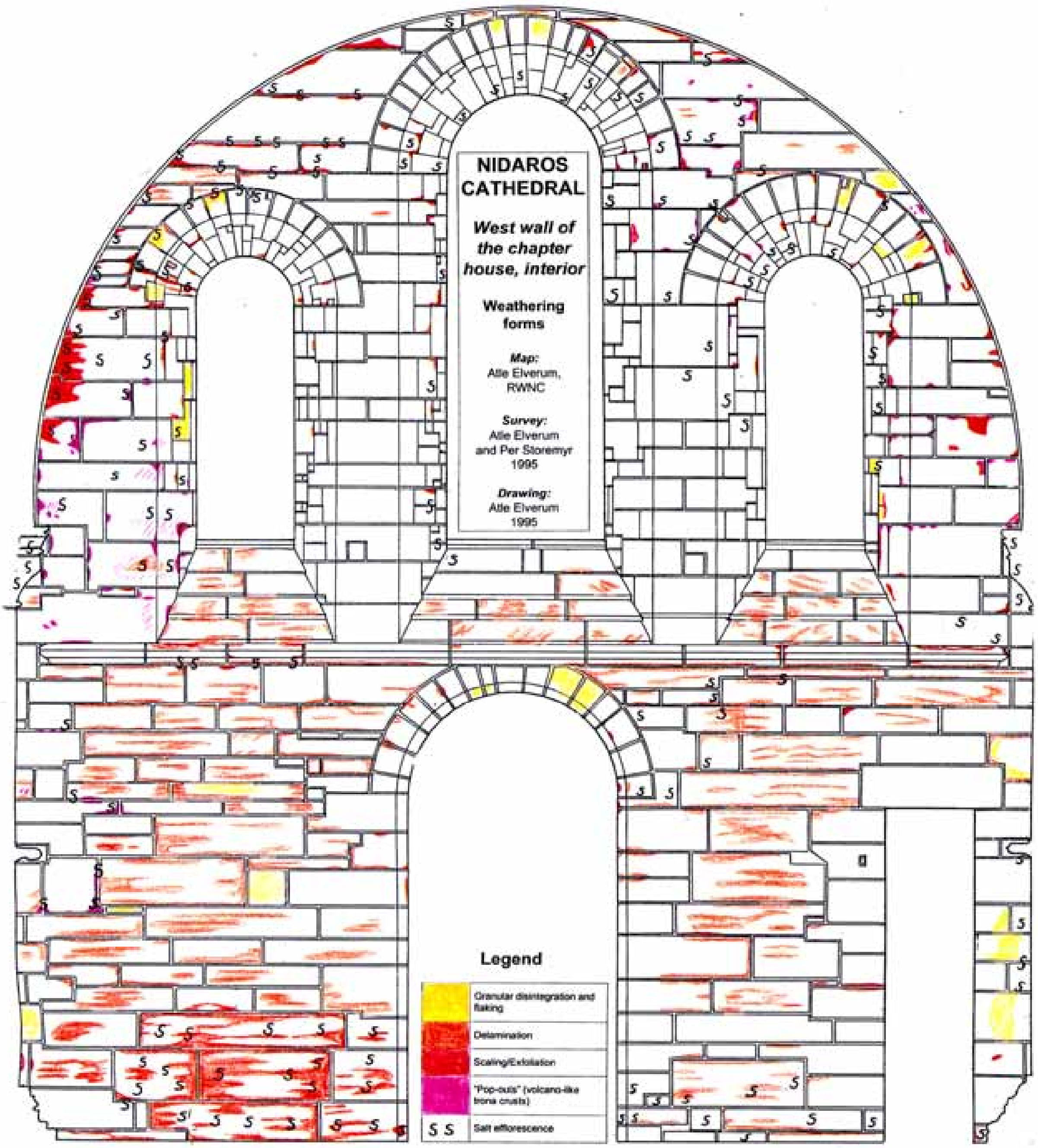
Stone types of the exterior west wall
Weathering forms on the exterior west wall
Weathering forms on the interior west wall

The east chapel of the octagon

Stone types of the exterior east wall
Weathering forms on the exterior east wall
Mortars and weathering of joints - east wall
Materials of the east wall of the loft
Weahering forms on the east wall of the loft


NIDAROS CATHEDRAL
West wall of the chapter house
Stone types
Map:
Atle Elverum, RWNC
Survey:
Atle Elverum and Per Storemyr 1995
Drawing:
Atle Elverum 1995
Legend
Foliated soapstone. Middle Ages. Probably from Klungen or Huseby
Greenschist. Middle Ages, redressed 1869-71. From Øye or Skauge
Soapstone. 1869-71. Probably from Bakkaune
Grytdal soapstone. 1869-71
Reppe metasandstone. 1869-71
Hovin metasandstone. From Samdal, 1869-71
Local hardstone. 1869-71
Gullfjellet soapstone. From 1948
0
0.5
1
1.5
2 m


NIDAROS CATHEDRAL
West wall of the chapter house,
Weathering forms
Map:
Atle Elverum, RWNC
Survey:
Atle Elverum
and Per Storemyr
1995
Drawing:
Atle Elverum
1995
Legend
Stone out of alignment
Fissures cutting through stone
Granular disintegration and flaking
Delamination
Scaling/exfoliation
Pitting
Black crust (gypsum)
White crust (calcite)
Salt efflorescence
Fissures between stone and joints
Fissures and calcite crusts between stone and joints
Open joints. Disintegrated mortar behind
Asphalt layer in poor condition
Algae
Lichen
Moss
Half-circle indicates location of interior vaulting
0
0.5
1
1.5
2 m
Halvsirkel over vinduene angir hvor hvelvet er lokalisert


NIDAROS CATHEDRAL
West wall of the chapter house, interior
Weathering forms
Map: Atle Elverum, RWNC
Survey: Atle Elverum and Per Storemyr 1995
Drawing: Atle Elverum 1995
Legend
Granular disintegration and flaking
Delamination
Scaling/Exfoliation
"Pop-outs" (volcano-like trona crusts)
S S
Salt efflorescence

Nidaros cathedral

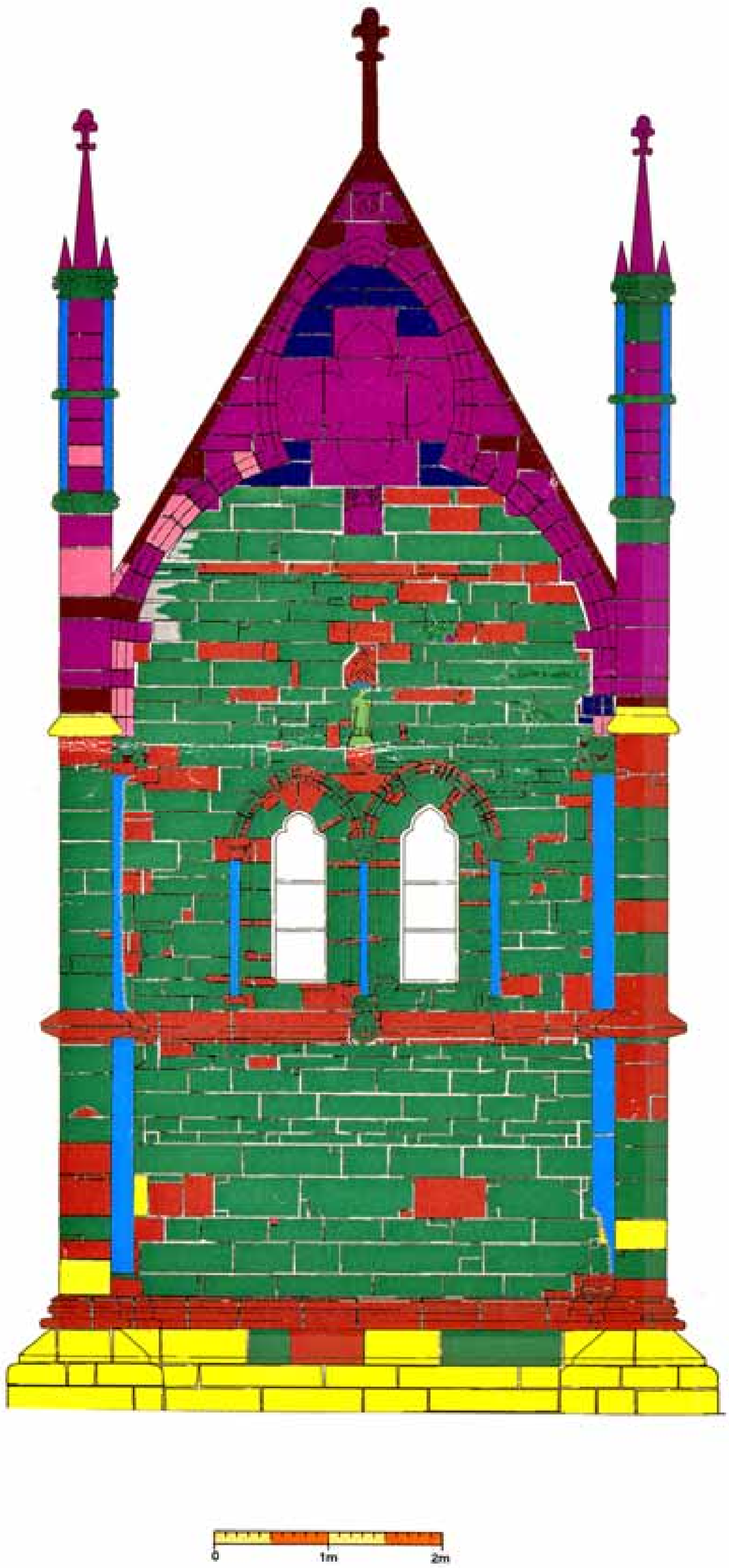
East chapel of the octagon

Stone types

Map:
Department of Surveying and Mapping NTNU

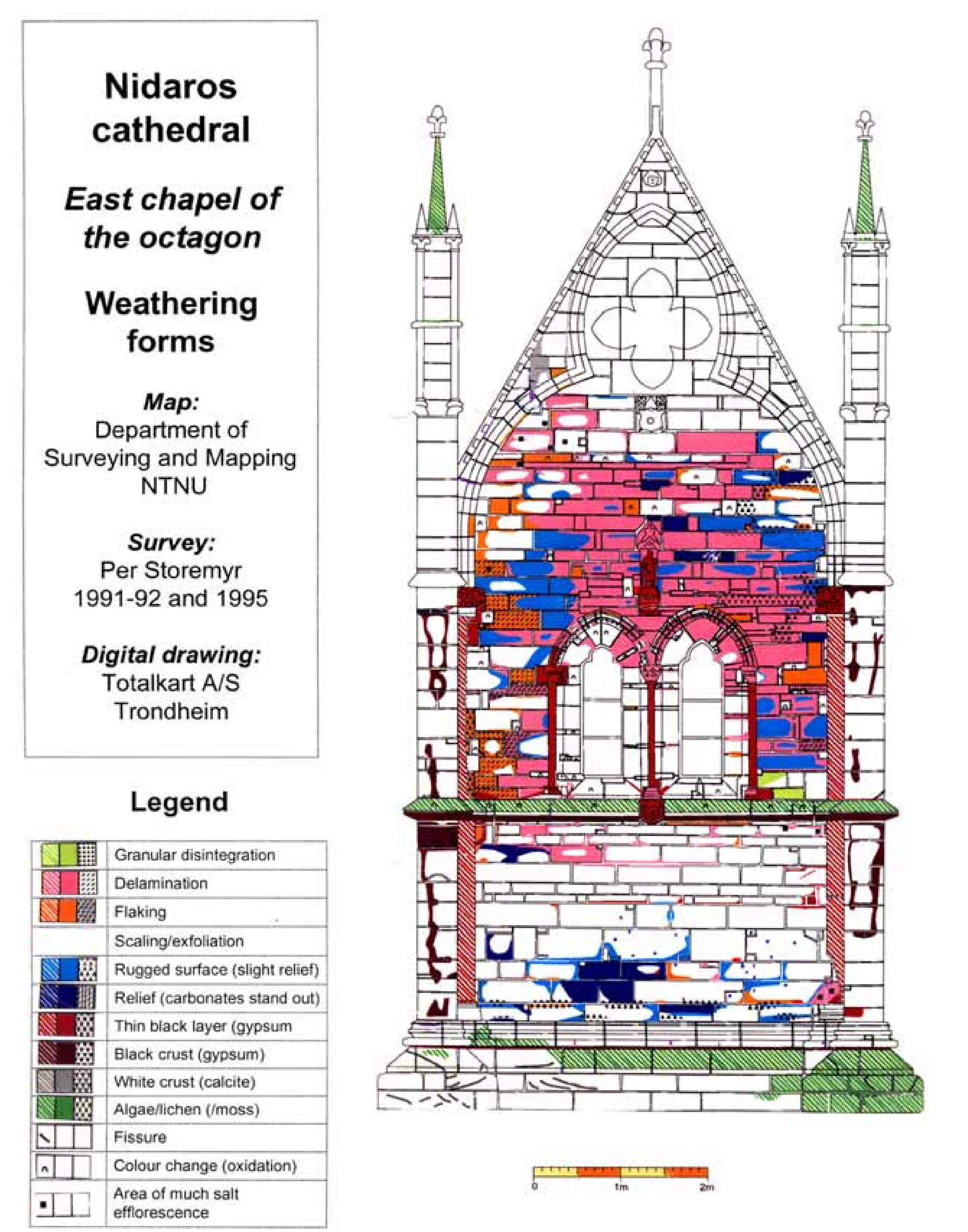
Survey:
Per Storemyr
1991-92 and 1995

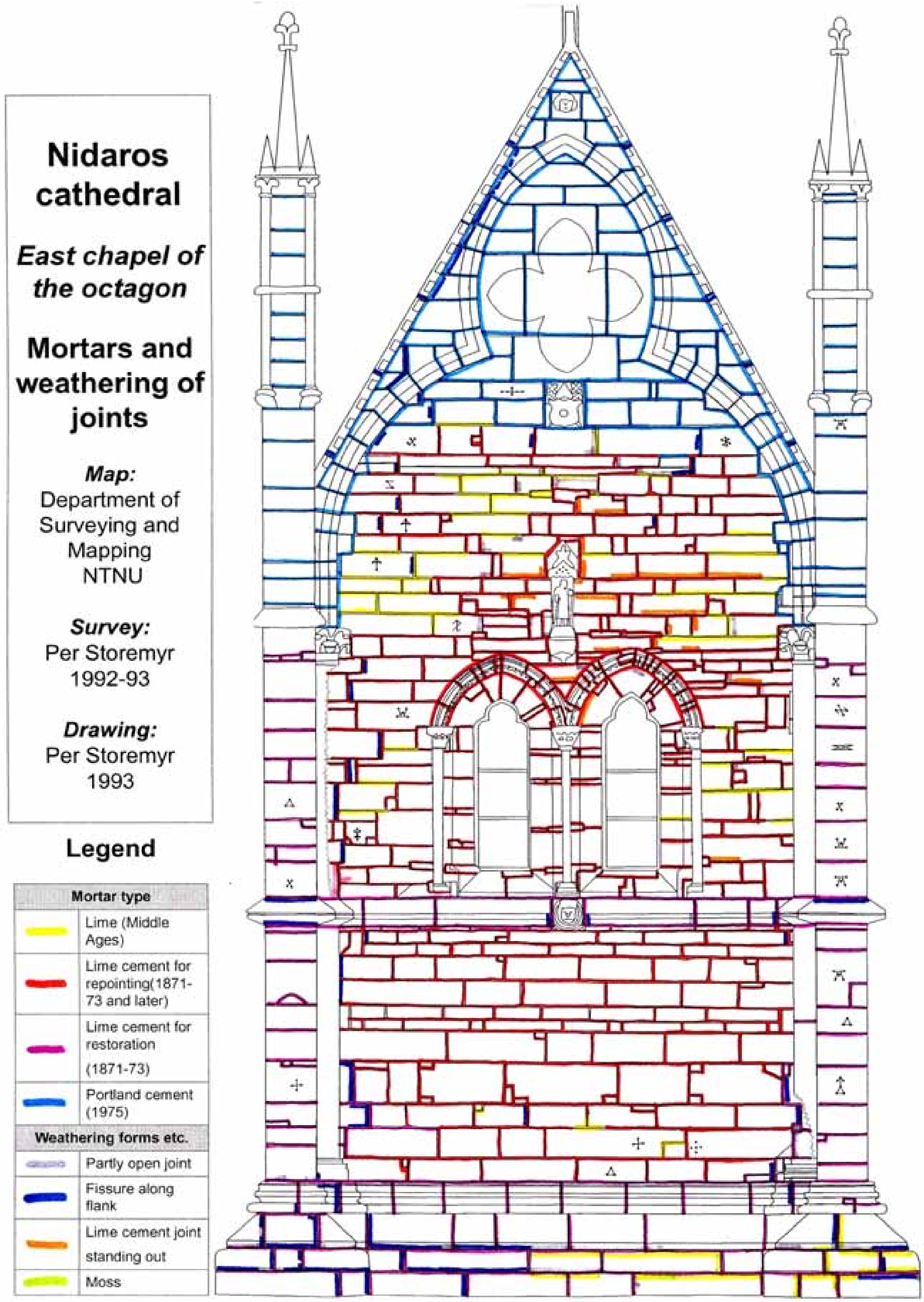
Digital drawing:
Totalkart A/S
Trondheim



Legend

Colour	Stone type	Quarry	Age
Green	Green-schist	Øye	Middle Ages
Light blue	Marble	Lein/ Frøseth	Middle Ages/ 1871-73
Light brown	Soapstone	Bakk-aune	1871-73
Yellow	Sandstone	Samdal	1871-73
Pink	Soapstone	Bubakk	1975
Violet	Serpen-tinite	Bubakk	1975
Dark blue	Soapstone	Bubakk/ Grunnes	1975
Dark brown	Soapstone	Gullfjellet	1975
Grey	Traces of post-Reformation whitewash		

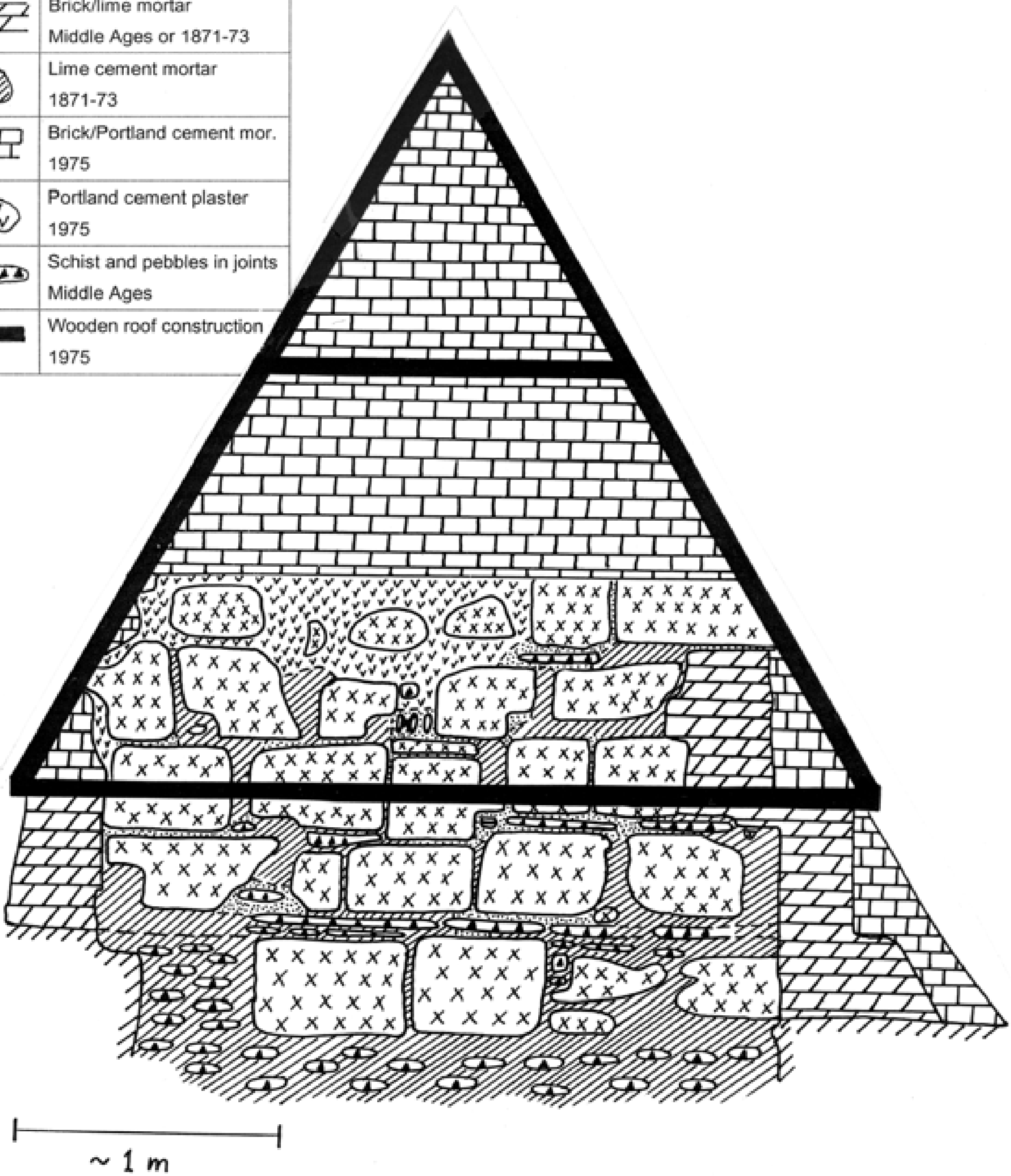

Nidaros cathedral
East chapel of the octagon
Weathering forms
Map:
Department of Surveying and Mapping NTNU
Survey:
Per Storemyr
1991-92 and 1995
Digital drawing:
Totalkart A/S
Trondheim
Legend
Granular disintegration
Delamination
Flaking
Scaling/exfoliation
Rugged surface (slight relief)
Relief (carbonates stand out)
Thin black layer (gypsum
Black crust (gypsum)
White crust (calcite)
Algae/lichen (/moss)
Fissure
Colour change (oxidation)
Area of much salt efflorescence
0
1m
2m



Nidaros cathedral
East chapel of the octagon
Mortars and weathering of joints
Map:
Department of Surveying and Mapping NTNU
Survey:
Per Storemyr 1992-93
Drawing:
Per Storemyr 1993
Legend
Mortar type
Lime (Middle Ages)
Lime cement for repointing(1871-73 and later)
Lime cement for restoration (1871-73)
Portland cement (1975)
Weathering forms etc.
Partly open joint
Fissure along flank
Lime cement joint standing out
Moss

Legend

	Soapstone/greenschist, Middle Ages
	Lime mortar Middle Ages
	Brick/lime mortar Middle Ages or 1871-73
	Lime cement mortar 1871-73
	Brick/Portland cement mor. 1975
	Portland cement plaster 1975
	Schist and pebbles in joints Middle Ages
	Wooden roof construction 1975

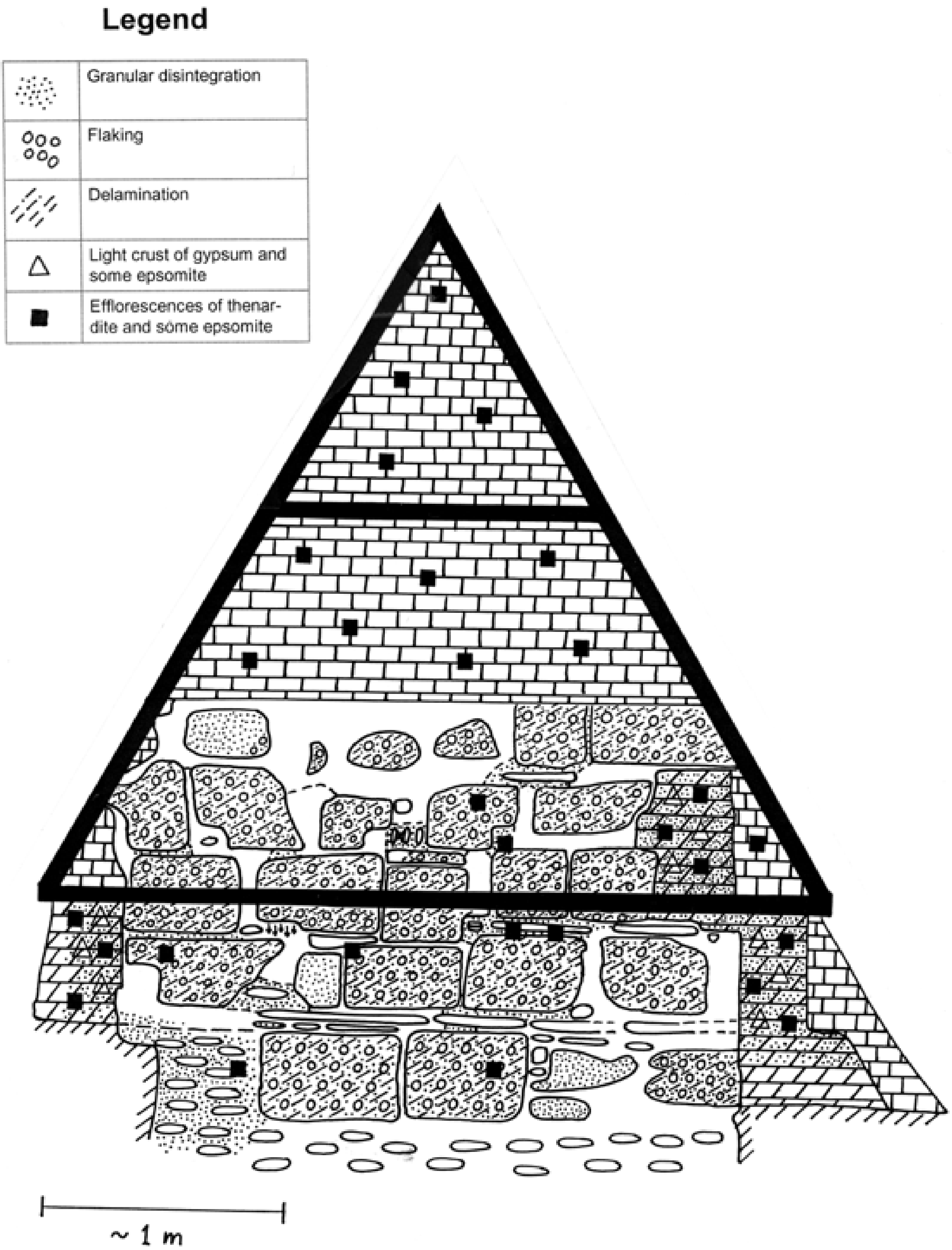


Nidaros cathedral

East chapel of the octagon, gable wall on the loft

History and materials

Survey: Per Storemyr 1992-93



Nidaros cathedral
East chapel of the octagon, gable wall on the loft
Weathering forms and salts
Survey: Per Storemyr 1992-93

Appendix 5

General graphic documentation of the north side of the cathedral

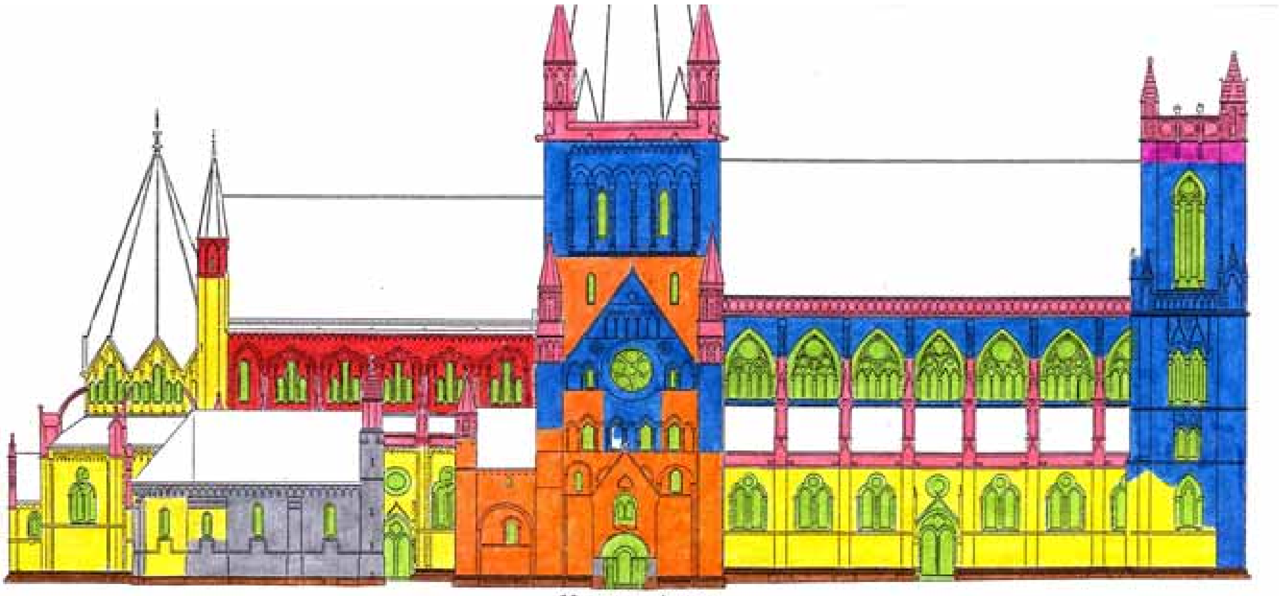
Original building periods
The restoration 1869-1969
Masonry types
Stone types in exterior walls
Exposure conditions
Weathering

Original building periods

- 1140-1160 Norman
- 1160-1180 Transitional
- 1183-1200 Gothic (Early English)
- 1200-1240 Gothic (Early English)
- 1240-1260 Gothic (Early English)
- 1260-1280 Gothic (Decorated)
- 1869-1969 Neogothic
- 1869-1969 Copper roofs

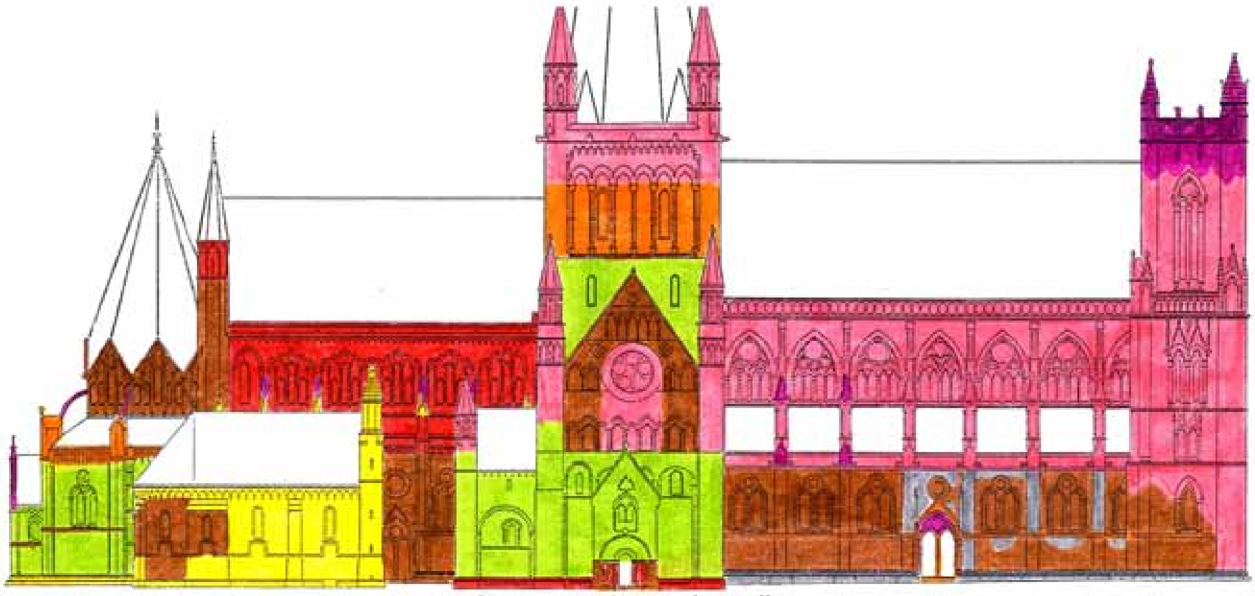
The restoration 1869-1969

- Areas affected by fire
- Preserved medieval masonry (cleaning with acid/lye, redressing, consolidation with cement, repointing and/or stone replacement, 1869-1905)
- Restored medieval masonry (extensive stone replacement, 1869-1905)
- Reconstructed medieval masonry (on the basis of archaeological investigation and analogies, 1869-1930)
- New compositions from the restoration, 1869-1969



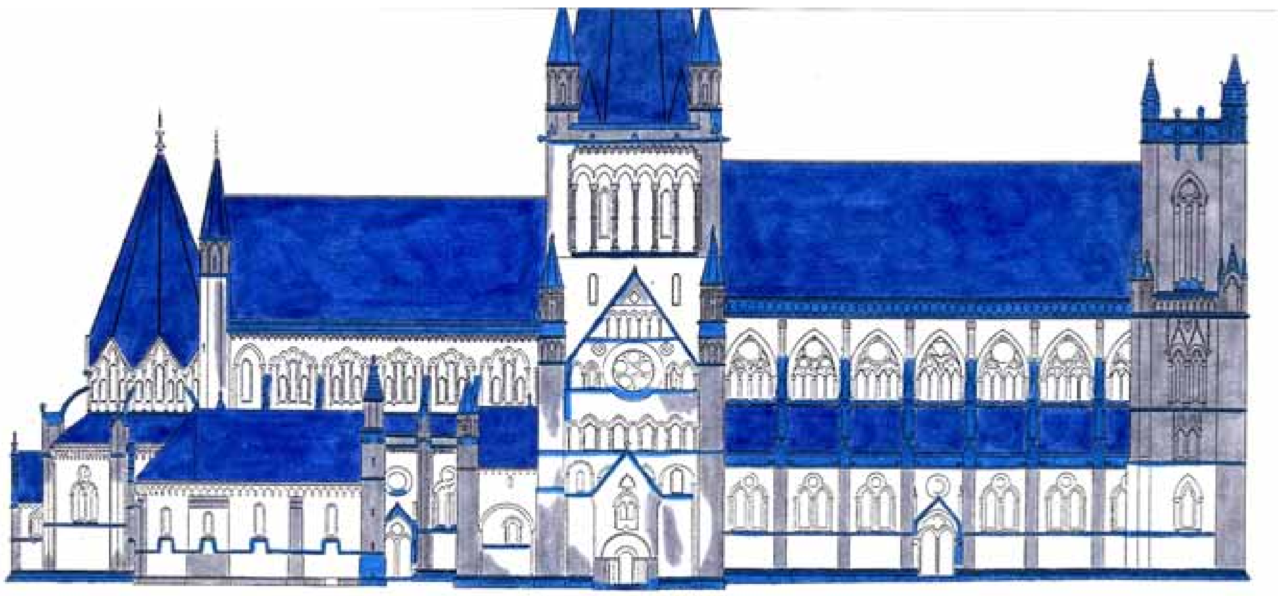
Masonry types

- Double walls (0,8-1 m) with ashlars and lime mortar cores. Repointed with cement mortar
- Double walls (1-2 m) with exterior ashlars, interior coursed rubble and lime mortar cores. Repointed with cement mortar
- Double walls (1-1,3 m) with ashlars and lime/lime cement mortar cores. Pointed with cement.
- Massive walls (1-1,3 m) with exterior ashlars, interior brick and lime/lime cement mortar cores. Pointed with cement
- Mainly massive walls (1-1,3 m) with exterior ashlars, interior coursed rubble and lime cement mortar cores. Pointed with cement
- Towers, parapets and flying buttresses. Mainly cement mortars
- Bases replaced during the restoration. Mainly cement mortars
- Tracery, windows and portals



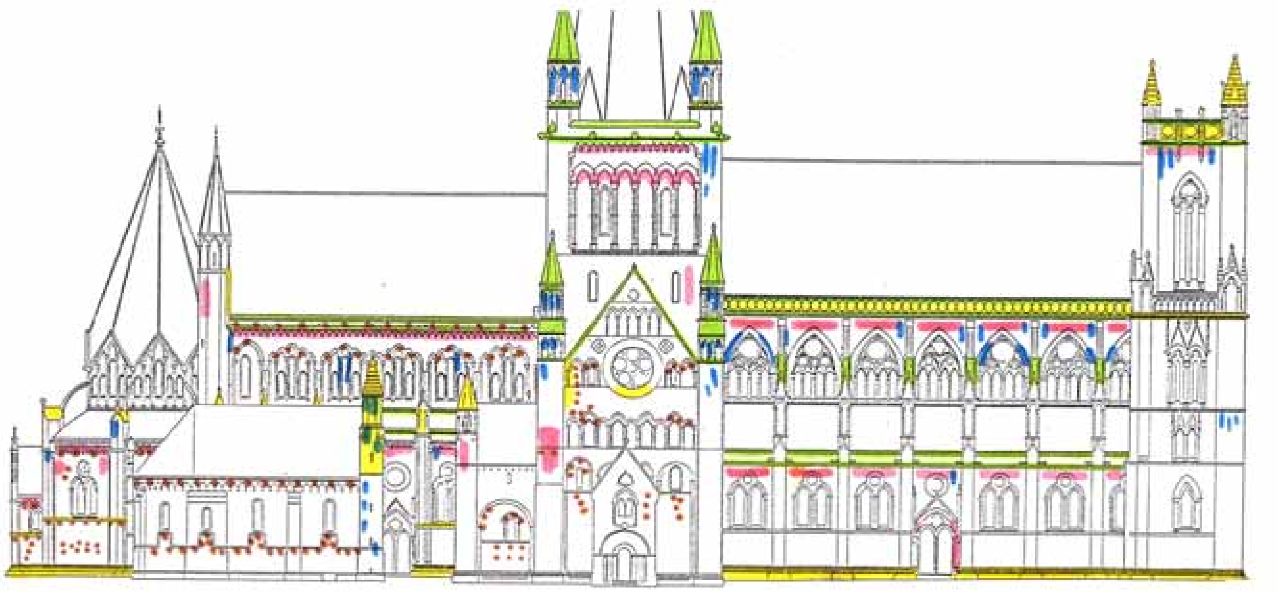
Stone types in exterior walls

- Øye greenschist and other greenschist. Some Klungen/Huseby/Bakkaune soapstone
- Klungen/Huseby/Bakkaune soapstone. Some Øye greenschist and other stone
- Hovin metasandstone
- Grytdal, Rogstad and/or Tilseth soapstone
- Bjørnå soapstone
- Solerød soapstone
- Bubakk soapstone/serpentinite, Grunnes and/or Gullfjellet soapstone
- Various stone



Exposure conditions

- Roofs with copper plates
- Areas always wetted during precipitation
- Areas usually wetted during precipitation. Dependent on wind conditions
- Areas rarely wetted during precipitation.



Weathering

- *Strongly exposed to precipitation*
  Joint fissures, loss of carved details, surface disintegration, lichen and moss.
- *Strongly exposed to precipitation*
  Joint fissures, lichen and moss. Little stone disintegration
- *Usually sheltered from precipitation, affected by leaks*
  Salt weathering, white calcite crusts
- *Affected by leaks*
  White calcite crusts
- *Usually sheltered from precipitation, affected by run-off*
  Black gypsum crusts