A STUDY ON THE WEATHERING OF NORWEGIAN GREENSCHIST

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SUMMARY
This article deals with the history and weathering of Central-Norwegian churches partially built by greenschist between 1100 and 1200. It focuses on the historical implications in the complexity of weathering phenomena to be observed today. Greenschist has often been denominated as somewhat unsuitable for building purposes. It has been has been shown that this is a misconception and that a wide range of historical events, inappropriate conservation measures and particular weathering situations can account for most of the present, severe damages. Reasons for the rather bad reputation of the stone can also be traced back to attempts to reopen the greenschist quarries for restoration purposes. The attempts failed - a fact that can be explained by modern stone working methods not suitable for the treatment of the stone.

1. INTRODUCTION AND PROBLEM

Greenschist, which is a soft metamorphic volcanic rock, was the first stone to be used for ashlars and architectural decorations in the Trondheim region (fig. 1, tab. 1). The greenschist quarries were opened when the erection of stone churches in the region began in the late 11th century. Unlike other local stone quarries (soapstone), which remained important throughout the following couple of centuries and were revitalized for restoration/rebuilding purposes in the late 19th century, the greenschist quarries were more or less abandoned around 1200.

Attempts to reopen the quarries for restoration purposes in the early 20th century failed, mostly because the stone was considered too difficult to quarry, dress and carve. Although some professionals have considered the green and rather soft stone very beautiful and suitable for building purposes (Helland 1893), masons and others have recently maintained that it is less suitable since it apparently weathers very fast - and faster than most soapstones (Alnaes 1995). Soapstone is traditionally regarded as the medieval Norwegian building stone par excellence (Lidén 1974). The two soapstone deposits exploited in Trondheim from the Middle Ages have for instance provided very beautiful and durable stones (Alnaes 1995, Storemyr, in prep.).

Due to the fact that there are also existing extremely well preserved masonry, architectural decorations and sculptures made by greenschist, I found it strange that the stone has achieved a rather bad reputation. Hence, I set out to investigate the use and behaviour of the stone more carefully. Two hypotheses were used as points of departure:

1) It is incorrect to state that greenschist in general weathers fast. The reason why we observe badly damaged stonework made by this stone today is connected with complex historical events and particular weathering situations, often developed as a result of inappropriate conservation measures and faulty craftmanship.

2) It is incorrect to state that greenschist is so difficult to quarry, dress and carve. The reason why the old greenschist quarries were hard to reopen is connected with tradition: The modern stone working technology was different from medieval craftmanship and not adapted to the treatment of greenschist.

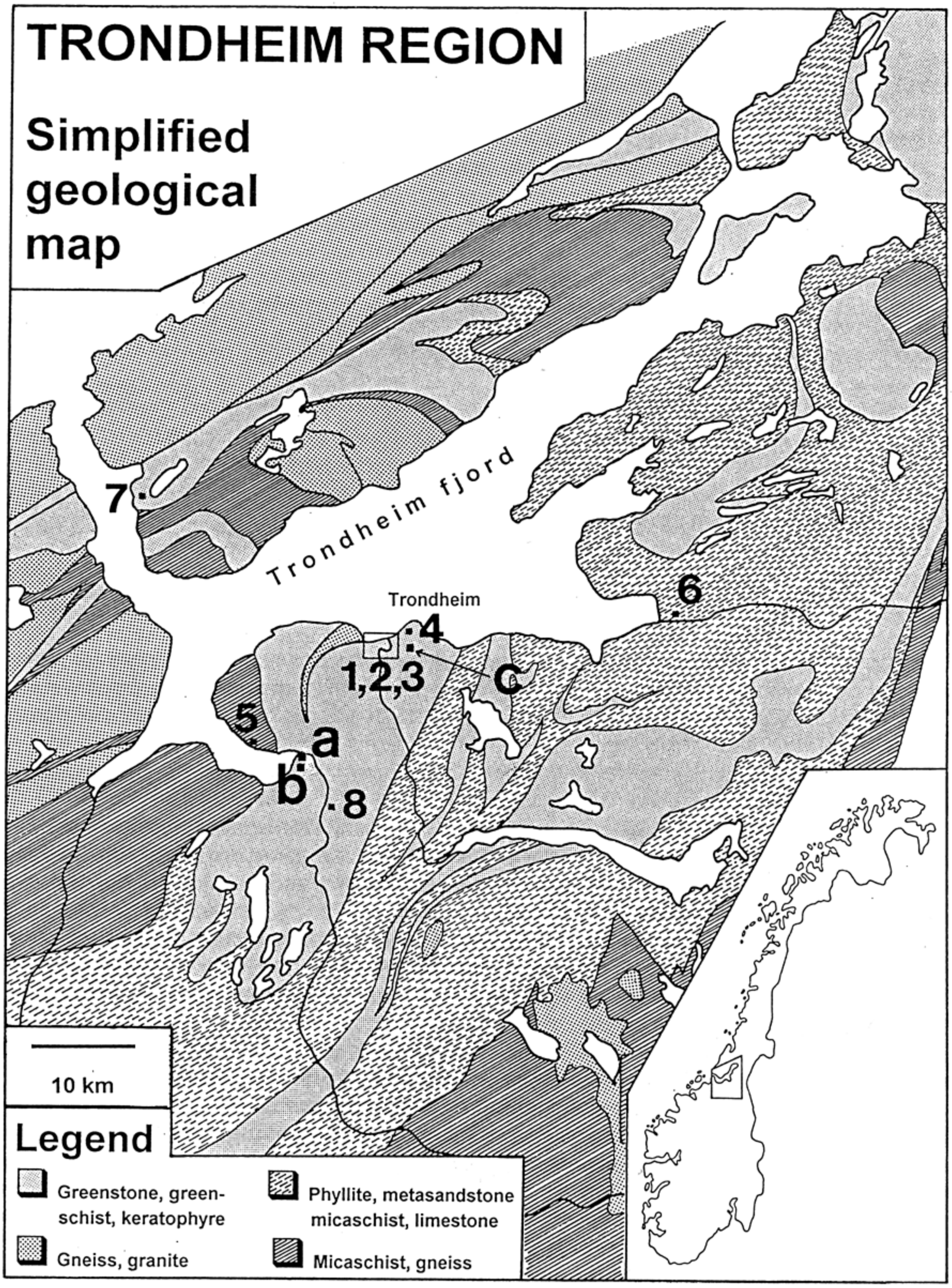


Figure 1:
Location of investigated buildings and quarries. Geological map simplified from Sigmond et al (1984).
1) Nidaros cathedral/Archbishop's palace, 2) St. Mary's church, 3) St. Olav's church (ruin), 4) Lade church, 5) Byneset church, 6) Vaernes church, 7) Rein convent (ruin), 8) Melhus church (demolished and rebuilt), a) Öye greenschist quarry, b) Klungen soapstone quarry, c) Bakkaune soapstone quarry

2. THE HISTORY OF STONE BUILDINGS IN THE TRONDHEIM REGION

2.1 Medieval stone buildings

With a history that goes back to the late 10th century, Trondheim is a trading and university city in Central Norway. The erection of stone churches - for instance precursors of the Nidaros cathedral, which is the northernmost medieval cathedral in Europe - began in the late 11th century when Christianity got a foothold in the country. When in 1152-53 the Archbishop's See was established in the city, it required rebuilding and enlarging the cathedral as well as building the Archbishop's palace. Due to the city's position as an ecclesiastical centre, some 10-12 smaller stone churches and monasteries were erected before the Black Death in 1350 which put an end to much of the building activity. (Lidén 1981, Ekroll, in prep.). In addition to the Nidaros cathedral and the Archbishop's palace, only one church is left today, whereas the ruins of two more also remain.

In the region around Trondheim, several small and rather simple stone churches were also erected between 1100 and 1200. Like the oldest remaining parts of the Nidaros cathedral (transept, chapter house, octagon), they are influenced by Norman and Early English Gothic building styles (ibid.).

The Nidaros cathedral, St. Mary's church and St. Olav's church (now ruin), which are all located in downtown Trondheim, were the only churches built completely by ashlars. Such masonry may originally have been intended in several of the other churches, as shown by a few shifts of ashlars in the lowermost parts of the walls. Plastered and whitewashed random rubble and rag walling were used for the rest of the masonry, which usually included quoins as well.

In the actual group of churches (parts built between 1100 and 1200), bases, ashlars and quoins, as well as portals, architectural decorations and sculpture are, with some few exceptions, made by greenschist (tab. 1).

Table 1: Greenschist in buildings from 11-1200 in the Trondheim region

MONUMENT	GREENSCHIST USED FOR
Nidaros cathedral	Ashlars, decorations, sculpture (chapter house, transept, octagon)
Archbishop's palace	Quoins, windows
St. Mary's church	Ashlars (choir)
Lade church	Base, lower part of walls (ashlars), quoins
Byneset church	Base, lower part of walls (ashlars), quoins
Vaernes church	Base, lower part of walls (ashlars), stairs, quoins, sculpture
St. Olav's church (ruin)	Base, ashlars, decorations
Rein convent. (ruin)	Ashlars, quoins, decorations
Melhus church (demolished)	Ashlars (and other purposes?)

2.2 From medieval fires to the 19th century restoration wave

Many of the Trondheim churches were destroyed by fire already in the late Middle Ages. They were subsequently abandoned or - as the regional churches - rebuilt according to the fashion of the actual period. Similar events took place from the Reformation (1537) and until the 19th century (cf. Lysaker 1973, 1994). These periods are generally conceived as "times of decay" in Norway, partly because of the Black Death, partly because the country was ruled from Copenhagen.

Measures undertaken on remaining medieval churches in the "decay period" included addition of new interiors, roofs and spires. Masonry was consolidated by iron cramps and lime mortar, walls and decorations were plastered, whitewashed and painted. And when new fires hit the churches, similar measures were repeated (ibid.).

Norway became independent in 1814, at a time when the restoration wave started sweeping across Europe. When the wave got a foothold in Norway in the latter half of the 19th century (Lidén 1991), most of the investigated churches were affected. The Nidaros cathedral was completely restored and rebuilt - a process not finished before 1969 (Fischer 1965, 1969). The restoration wave also coincided with the erection of numerous new stone buildings in the country. Since the Middle Ages very few had been built. In contrast to the Middle Ages, hard "granitic" stones were the most popular for new buildings between 1880 and 1914 (Ringbom 1987).

During the restoration wave and later on several important measures were undertaken (tab. 2). Plaster, whitewash and paint were removed from ashlar masonry and decorations, often by redressing stones or cleaning them with hydrochloric acid and sodium hydroxide. Portland cement was introduced for consolidation, repointing and plastering purposes already in the 1860s. Since then mortars based on Portland cement has been almost universally used for repair purposes (cf. Storemyr 1995a, 1995c, 1996, in prep.). All the mentioned measures are naturally of great significance when aiming at reaching a proper understanding of the weathering of remaining medieval stonework.

With regard to the Nidaros cathedral, its roofs were drastically changed during the restoration which started in 1869, leaving several cornices and walls much more exposed than before (Storemyr, in prep.).

Table 2: Some historical events related to medieval greenschist masonry

MONUMENT	F	P	C	R	W	D	
Nidaros cathedral	X	X	X	X	X	X	
Archbishop's palace	-	X	X	X	-	-	
St. Mary's church	X	X	X	X	X	-	
Lade church	-	X	X	X	-	-	
Byneset church	-	X	X	X	-	-	X = Relevant
Vaernes church	-	X	X	-	X	-	- = Not relevant

F = Fire(s)
P = Plastering/whitewashing/painting
C = Removal of plaster/whitewash/paint
R = Repointing with Portland cement mortars
W = Periods with extensive leaks/rising damp
D = Drastical change of roofs

3. GEOLOGY, STONE PROPERTIES AND HISTORY OF QUARRYING

3.1 Regional geology and properties of greenschist

The geology of the region is dominated by metamorphic sedimentary and volcanic rocks of Caledonian (Cambro-Silurian) age (fig. 1). A thick sequence of metabasalt (greenstone) with some metamorphic tuffs, sediments and gabbroic/ultramafic intrusions is to be found around Trondheim itself (Wolff and Roberts 1980). Deposits of soapstone and greenschist are common in such geologic environments.

Present knowledge indicates that the main medieval stone quarries are located very close to the sea at Öye in Melhus, some 15 km south of downtown (fig. 1-3). In a 1 km long and 250 m broad valley there are several old, abandoned soapstone quarries (called Klungen) as well as a large greenschist quarry (Storemyr 1995b).

The greenschist deposit occurs as a 2-5 m thick, almost horizontal bench and is probably originating from basic tuffs (Carstens 1928). Metamorphism and tectonic processes have altered the original mineral assemblage, rendered the deposit very foliated and led to the formation of some intersecting veins of carbonate minerals. The green colour of the stone is mainly caused by the large amount of chlorite in the matrix (tab. 3). Quality variations in the deposit are for instance connected with softness. Large parts - often relatively rich in talc - are very soft, whereas other parts are harder and difficult to scratch with the finger nail.

Although the stone in general must be regarded as dense, its properties are strongly dependent on orientation (foliation). The capillary water absorption is much higher parallel than perpendicular to the foliation planes, while the flexural strength is higher perpendicular than parallel to the planes. In contrast to what might have been expected for such a stone, the hygric dilatation is very low, but higher perpendicular than parallel to the foliation planes (tab. 3).

Table 3: Mineral composition, texture and properties of Öye greenschist. Physical properties determined by Esther von Plehwe-Leisen

MINERAL COMPOSITION/TEXTURE		PHYSICAL PROPERTIES	
Foliated matrix		Density:	2,90 g/cm3
Chlorite (flakes)	30-40%	Open porosity:	0,90 %
Biotite (flakes)	10-20%	Water absorption:	0,25 wt %
Talc (flakes)	0-10%	Capillary water uptake:	0,03-0,1 kg/m2h1/2
Quartz	5-15%	Hygric dilatation:	100-500 microm/m
Plagioclase	5-10%	Diffusion resist. (dry):	650-1050
		Diffusion resist. (wet):	120-150
Larger grains and veins		Flexural strength (dry):	12-26 MPa
Hornblende	5-25%		
Dolomite	10-15%		
Calcite	1-5%		
		COLOUR AFTER EXPOSURE	
Opaque minerals			
Pyrite (euhedral)	2%	Strongly green, with small spots of brown	
Titanite	3%	carbonates and dark amphibole and biotite	

3.2 The selection of greenschist for building purposes

The Öye greenschist is in fact one of the very few easily accessible local stone types which somehow resemble traditional Continental and British building stones like sandstone. The local soapstones are usually more massive, very rich in talc, softer and often lacking the typical schistosity of the greenschist. The schistosity may be looked upon as resembling the bedding planes of sandstone deposits. These are possibly main reasons why the medieval craftsmen selected the greenschist for building purposes. In this connection it should be underlined that foreign masons and craftsmen frequently worked in Trondheim in the Middle Ages (Fischer 1965). They may consequently have have taken part in the selection process. It is also important to note that a local stone building tradition did not exist before the late 11th century.

When the medieval builders eventually abandoned the greenschist quarries and turned to soapstone deposits (for instance Klungen) around 1200, it may have been because of new impulses affecting the old tradition. Although there are still large amounts of good stone left in the Öye greenschist quarry, the reason may also have been that it became increasingly difficult to quarry the stone. Another reason that should be mentioned is the possible discovery at this time of the large and later frequently exploited Bakkaune soapstone deposit, which is located only one km from downtown Trondheim. Since the use of soapstone for pots and vessels has a history of 2-3000 years in Norway (Skjölsvold 1961, 1969), it is, on the other hand, unlikely to assume that this particular deposit was not known before 1200.

With regard to the Nidaros cathedral, we can at present observe diverse soapstones from 20-30 quarries (and more than 30 other stones). Most of these stone have, however, been quarried all over Norway for the purpose of restoration and rebuilding since 1869 and until today. The local Bakkaune and Klungen soapstone quarries were also revitalized during the first phases of the restoration (1869-97) (Storemyr 1995b).

3.3 Working the greenschist in the Middle Ages and in modern times

In order to understand how the medieval craftsmen managed to make proper building stone of the very foliated Öye greenschist - and why attempts to reopen the quarry for restoration purposes failed - we have to consider the whole working process from quarry to finished stone. Because of the lack of space, we have to leave out important aspects of the social and economical contexts.

The quarry must have been a large working place in the Middle Ages - a place where not only quarrying took place, but probably also rough dressing and maybe even finishing of ashlars (reduction

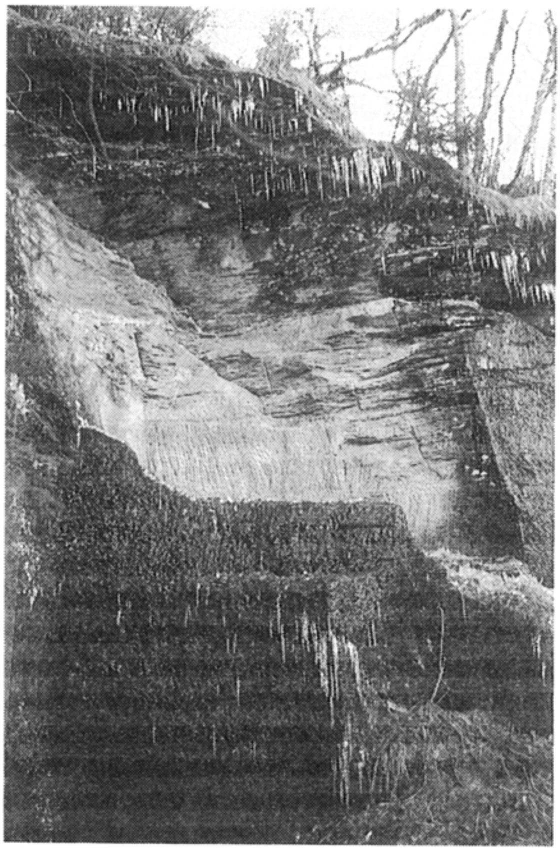


Figure 2:
Part of the Öye greenschist quarry.The stone is sound when exposed (dark areas) and rather disintegrated when sheltered (light area).

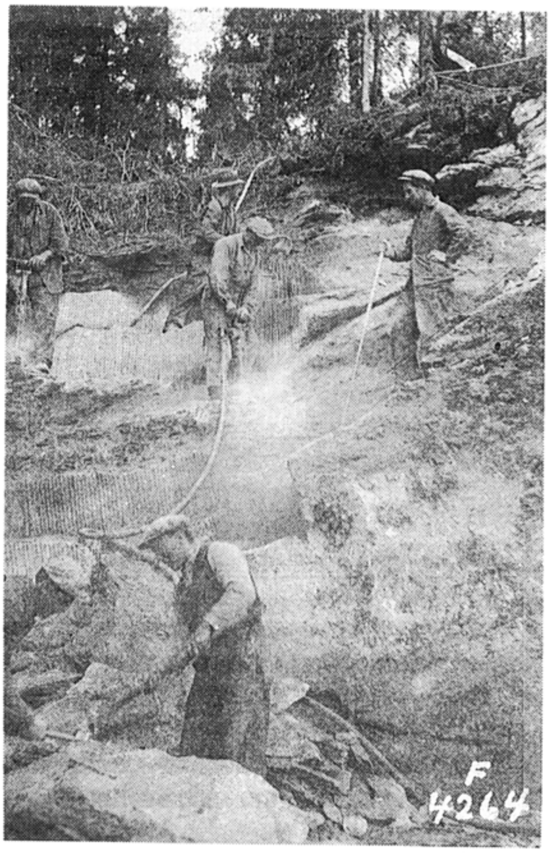


Figure 3:
Quarrymen in the Öye greenschist quarry in 1934. Raw blocks are obtained by manual channeling using pneumatic equipment

Figure 4:
Early Romanesque capital (late 11th century), now in the museal collections of the Nidaros cathedral. The delicate carving shows that medieval stone carvers were able to make beautiful art of the very foliated greenschist (photo: RWNC).

of weight/transportation) (cf. Lidén 1974, Svanberg 1983). Interpreting the marks of medieval quarrying operations, it has been found that the main method of obtaining raw blocks included laborious carving of vertical slits (with pick axes) from accessible corners. The blocks were subsequently loosened horizontally (along a foliation plane) by wedges.

Stone working was a very traditional craft until well into the 20th century, but quarrying methods in the 19th century were nevertheless rather different from the medieval ones. The use of pick-axes combined with manual drilling/gunpowder and wedging were for instance the normal way of obtaining raw-blocks in the Nidaros cathedral's soapstone quarries. Pneumatic equipment was introduced for drilling in the 1930s. Obtained blocks (up to c. 1 m3) were often no longer dressed/finished in the quarries, but transported in their raw state to the workshop at the building site (Storemyr 1995b). All these methods seem to have worked quite well for soapstone. For greenschist, however, the situation was different.

After attempts to reopen the greenschist quarry in 1869, 1885 and 1892, the Restoration Workshop of Nidaros cathedral tried once more in 1913 (ibid.), maybe because a well-known geologist had praised the stone and foreseen a rationally operated quarry some years earlier (Helland 1893). The description of the 1913-"experiment" is symptomatic:

> The stone was so schistose that it was impossible to quarry by using gunpowder. One had to carve slits from corners and use a wedge to loosen the stone horizontally - like "the old" craftsmen did. To use the stone for mouldings is going to be impossible, but it may be suitable for ashlars.[1]

The experiment was terminated after a week or so - maybe it was too laborious to use the old methods? When the next experiment was carried out in 1934 (fig. 3), pneumatic equipment was used to drill closely spaced holes (channelling). The campaign was, however, once more terminated after a couple of weeks, even though a "completely rational operation" had been anticipated for the years to come.[2]

In addition to problems connected with the use of gunpowder, main reasons why the 1934-campaign (and a very minor experiment in the 1950s) failed, seem to have been the large difficulties encountered when dressing the stone, and that more easily workable soapstone could be obtained elsewhere. Masons who have tried to work the greenschist maintain that it "always" tends to delaminate when faces perpendicular to the foliation planes are to be dressed - and that the stone is difficult to saw. Hence, except from a few ashlars, nothing has been produced from the stone after nearly 100 years of infrequent experimentation - an enourmous contrast to what was achieved during a similar time-span in the Middle Ages (fig. 4).

4. WEATHERING OF GREENSCHIST

4.1 Climate and the history of air pollution

The Trondheim region has a maritime temperate climate with wet autumns (the water leak period), relatively cold winters with frequent snowfalls (freezing/thawing on projecting details) and rather dry springs (main salt crystallization period). The annual precipitation lays in the range of 800-1000 mm, the annual average temperature is some 5°C and the average relative humidity is about 80%. One of the main regional weathering problems that can be traced directly to climatic effects, is the heavy crumbling of projecting details on which snow can collect (freezing/thawing). This phenomenon is of course strongly dependent on stone type (Storemyr, in prep.).

The history of local air pollution goes back to the middle of the 19th century when heating with coal became normal and small industrial enterprises were established in Trondheim. SO2-concentrations increased towards the turn of the century, and it has been assumed that average concentrations in the cold season rarely exceeded some 40 microg/m3 between 1920 and the late

1970s(ibid.). Since then there has been a drastical decrease to some 5 microg/m3 at present. Emissions of NOx from traffic have been increasing during the last decades and lays at present in the range of 40-60microg/m3 (cold season) (Hagen 1994). Only downtown churches have been influenced by air pollution, as shown by the presence of black crusts. Otherwise, the effects of air pollution have generally been of relatively minor importance in Trondheim when compared to the effects of other weathering factors (Storemyr, in prep.).

4.2 Weathering in the greenschist quarry

Situated in a humid, north-facing and overgrown hillside, the Öye quarry shows complex weathering phenomena caused by numerous weathering mechanisms. There is, however, a distinct difference between the weathering of (semi)sheltered cliffs and completely exposed rock-faces (fig. 3). Only cliffs and rock-faces relevant for the understanding of weathering on buildings have been considered below.[3]

Whereas semi-sheltered cliffs are strongly delaminated/disintegrated and have lost most marks of medieval quarrying operations, the exposed rock-faces are, although sometimes overgrown by lichens and moss, usually very sound. In this way hundreds - if not thousands - of square metres with quarrying marks have been preserved.

Gypsum, in the form of crusts, efflorescences and tiny crystals within the weathered zones, is very widespread on semi-sheltered cliffs (moisture from "within" the rock). There are also minor amounts of other sulphates to be found (tab. 4). Hence, we have to assume that crystallizing salts are strongly affecting the weathering in such locations (cf. Zehnder 1982, Arnold and Zehnder 1989). Salts are mainly provided from surrounding rocks (especially from nearby keratophyre) and to some extent the greenschist itself. Oxalates can also be found on sheltered cliffs (associated with leprose lichens), but they are more abundant on exposed rock-faces (associated with crustose lichens).

It is important to note that although heavily influenced by rain, snow and ice, completely exposed, semi-vertical rock-faces are not much weathered. Hence, the stone must in general be regarded as quite resistant to freezing/thawing. This feature has also been verified by laboratory experiments (Storemyr, in prep.).

However, when the greenschist is located in overhangs which are moist throughout the year, smaller and larger flakes and pieces tend to fall down when there is nothing to hold them in place. Frost may of course be a main weathering factor in such locations, but also the general low cohesion between flakes may play a vital role when the stone is thoroughly moist. In this connection it should be mentioned that flakes can be removed by hand from a moist greenschist slab, but that this is very difficult to do when the stone is dry. Similar phenomena are to be found in numerous commercial slate quarries in Norway (T. Heldal, pers. comm.).

Table 4: Determined salts (c. 400 samples) in the Öye quarry and on monuments

SALT SPECIES	LOCATION	SOURCES
Sulphates		Stones, air pollution, Portland cement
Gypsum/bassanite	Monuments and quarry	
Epsomite/hexahydrite	Monuments (small amounts in quarry)	
Mirabilite/thenardite	Monuments (small amounts in quarry)	
Aphthitalite	Monuments	
Carbonates		Portland cement
Calcite	Monuments	
Natrite/thermonatrite	Monuments	
Trona	Monuments	
Chlorides		Cleaning (acid/lye), sea salt
Halite	Monuments	
Oxalates		Lichens, other organic growth
Whewellite/weddelite	Quarry (small amounts on monum.)	

4.3 Systematical survey of weathering phenomena on buildings

Although weathering phenomena observed on buildings are resembling those found in the quarry, historical events have seriously altered the general picture. On the basis of 5 years of regular observation as well as investigation of historical sources, a summary of the most important weathering phenomena is given below.[4]

Exposed details not influenced by leaks and salts

Ashlar masonry (with stones bedded horizontally), buttresses, string courses and sculptures exposed to precipitation, but not influenced by leaks, rising damp and soluble salts, are usually very sound (fig. 5, 8). Some of the elements were redressed in the last century, but whitewash and paint were more often removed by mallets or hydrochloric acid. Hence, medieval dressing and masons's marks are beautifully preserved - just like in the quarry.

Some few extremely exposed projecting details like bases and corbels, as well as details located directly below gutters that have been leaking for decades, may, though, develop minor or major delamination - which may represent a security risk when pieces fall down. Recalling observations made in the quarry, we understand that frost and the fact that thoroughly moist elements loose cohesion along foliation planes may account for the weathering. Hygric dilatation, maybe in combination with thermal dilatation, may also be considered as a reason.

Details influenced by leaks, rising damp and salts

Sheltered masonry and decorations, for instance window arches and mouldings on the underside of projecting elements, are often deeply weathered (fig. 5, 6). The weathering usually takes the form of delamination, but granular disintegration, flaking and exfoliation can also be observed.

Major amounts of soluble salts (tab. 4) are almost without exception found in such locations - and their effects must be regarded as the main weathering mechanisms (cf. Arnold and Zehnder 1989). Alkaline salts provided from Portland cement (joints, masonry cores) are the most frequently occuring salt species, but diverse sulphates provided from stones and air pollution are also common. The minor amounts of halite observed may stem from sea salts, but probably more often from cleaning with hydrochloric acid and sodium hydroxide. Even though halite rarely crystallizes in our climate (verified by observations), it may seriously affect other salt weathering phenomena (cf. Cooke and Gibbs 1993). When black crusts have been formed on carved details on the underside of projecting elements, larger pieces tend to loosen, maybe because of a combination of gypsum crystallization and frost?

Direct observation and investigation of historical sources have shown that major water leaks (and sometimes rising damp) have taken place on almost every building part with deeply weathered greenschist. Many leaks, especially in the Nidaros cathedral, are still active.

Particular run-off systems and salts

Inappropriate roofs made during restoration interventions, leaking gutters and complex designs have often given rise to particular run-off systems along walls. The general tendency is that the dense greenschist masonry is sound (except from joint fissures) where water runs freely, but that flaking and delamination take place in the adjacent zones of evaporation. Black crusts and/or diverse types of soluble salts are always concentrated in the zones of evaporation (cf. Zehnder 1982).

Similar phenomena can be observed on corners with quoins. The side exposed to precipitation is sound, whereas salts have concentrated on the less exposed side, which shows diverse weathering forms.

The influence of repointing by Portland cement mortars

Among the many disadvantages of Portland cement mortars (Schaffer 1932, Feilden 1982, Arnold 1985), exfoliation along repointed joints deserve particular attention. On walls frequently exposed to precipitation and in addition to very minor water infiltration from above, exfoliation tend to develop regardless of how the greenschist ashlars are bedded (orientated). We have to assume that the

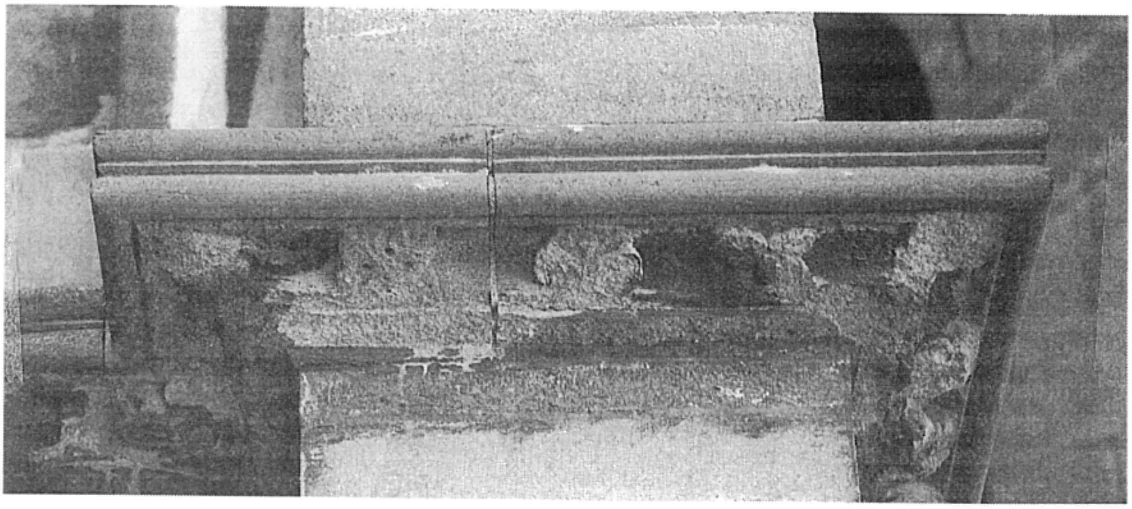
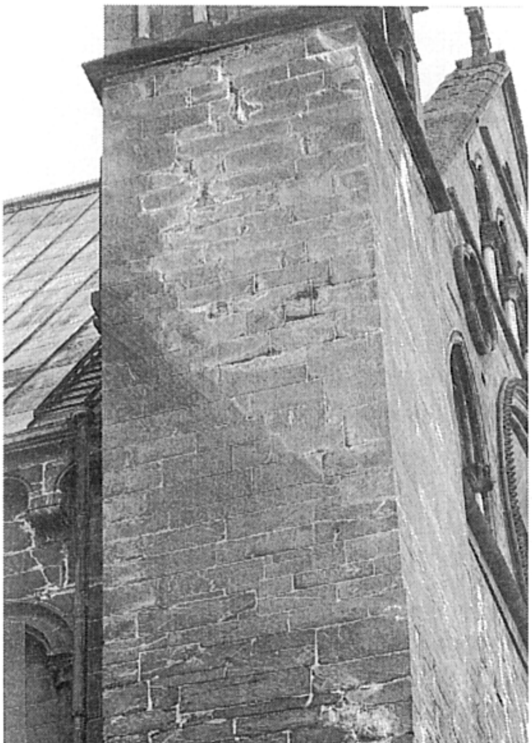


Figure 5:
String course (c. 1190) in the Nidaros cathedral. Very good condition on the exposed part, delamination associated with black crusts underneath.



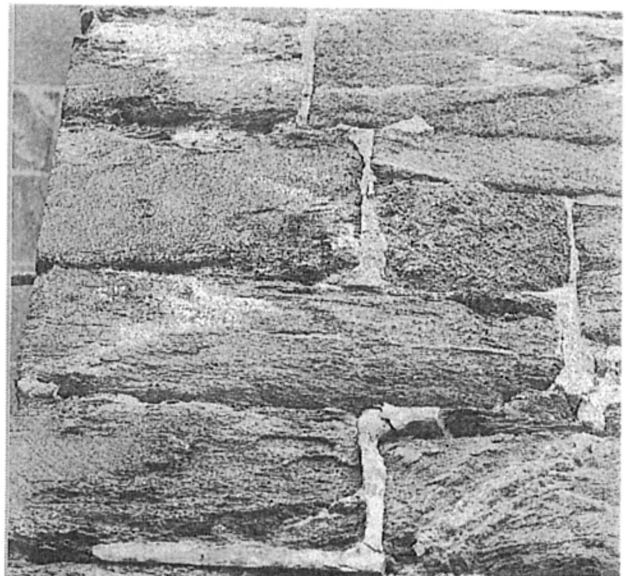


Figure 6:
Left: Soapstone masonry from c. 1900 built with Portland cement on top of Romanesque greenschist masonry. White patches are efflorescences of alkaline salts. Right: Leaks and alkaline salts have made the old masonry weather very fast. (Transept of the Nidaros cathedral).

moisture balance of such walls is seriously distorted by the rather impermeable joints, causing larger stresses on the stones than would have been the case if lime mortars had been used for repointing. Soluble salts may play an additional - if not a major - role in these cases.

The influence of fire on face-bedded ashlars

Masonry and decorations struck by fire (especially Nidaros cathedral and St. Mary's church) are astonishingly sound. A light brown colour (mainly from oxidation of iron in chlorite, biotite and carbonates, cf. Carstens 1924) is often the only resulting feature that can be optically observed today. However, when ashlars are face-bedded (faulty craftmanship, cf. Schaffer 1932), they have usually lost the outermost parts along the foliation planes (fig. 7). In this connection we should be aware of the fact that the walls in question were formerly plastered/whitewashed, and that improper methods of removal may have led to the final breaking apart along minute fissures developed during the fire(s).

The influence of removal of plaster and paint

That inappropriate methods of removal of plaster and paint may lead to delamination of face-bedded ashlars could recently be observed at Vaernes church which is currently under restoration. A combination of pneumatic and hand-held chisels were used to remove the outermost layers of plaster/whitewash and both methods appear to have damaged the stones. Smaller and larger flakes were simply lost during/after the procedure.

In other cases whitewash has not been completely removed from the stones during former restoration interventions. Depending on exposure conditions, thin black crusts tend to preferentially form on the traces of whitewash (abundant calcium), consequently hindering the moisture transport. At the Nidaros cathedral there are several examples of flaking taking place below the remaining whitewash/black crusts, whereas surrounding stone surfaces are sound.

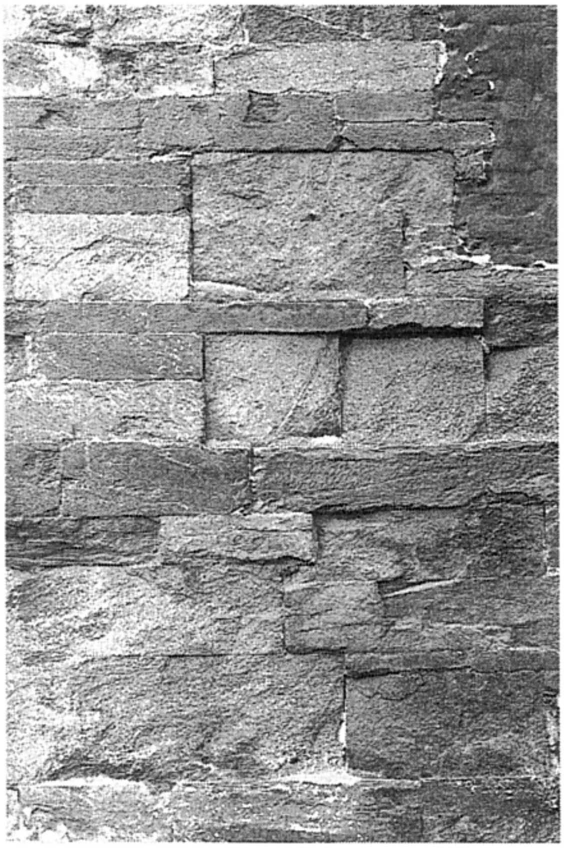


Figure 7:
Romanesque wall with "long and short work" affected by fire (St. Mary's church). The face-bedded, "short" ashlars have delaminated and lost the outermost parts.

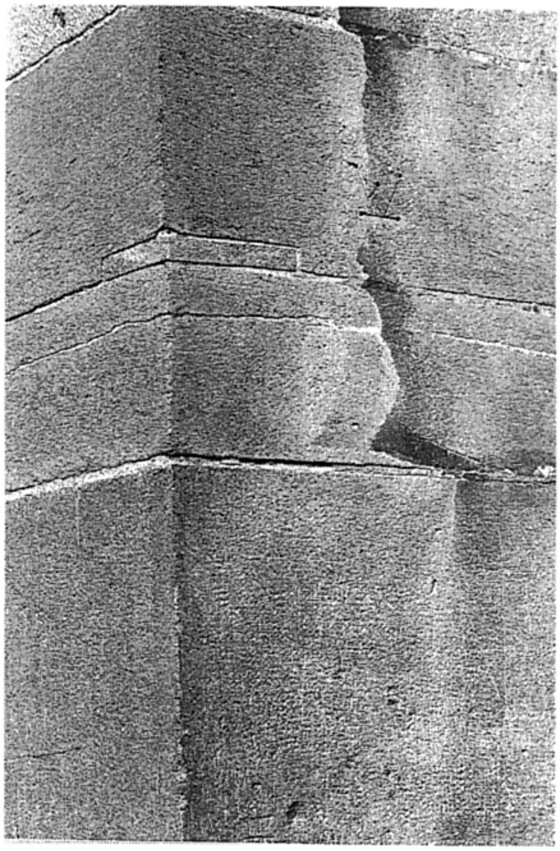


Figure 8:
Very sound greenschist ashlars on a pillar of the south chapel of the Nidaros cathedral. The pillar have been slightly redressed (1872). Note the preserved mason's mark from 1180-90.

The influence of silicone covering for making plaster copies
When making plaster copies of sculptured heads and decorations, the Restoration Workshop of the Nidaros cathedral has lately been using water soluble wallpaper glue in order to preconsolidate weathered surfaces before covering the objects with silicone. Other metods were used earlier. There are a few cases showing that these methods are adversely affecting especially foliated stones like the Öye greenschist. The general tendency is that stones with minute fissures may loose smaller and larger flakes during or after the procedure.

4.4 Weathering of corbel heads - an example
The weathering of several architectural and sculptural details is of course far more complex than indicated by the summary above. As an example we may take 12 Romanesque (1160-70), edge-bedded corbel heads in the south cornice of St. Olav's chapel (Nidaros cathedral, fig. 9) (Storemyr, in prep.).

The cornice was (because of an exterior wooden staircase) struck by fire in the Middle Ages, possibly leading to cracking and subsequent loss of two heads. The rest of the heads only got "fire-brown" surfaces (and maybe minute fissures). They were perhaps originally painted, and certainly overpainted during interventions in the 18th century - measures that may have helped preserve them in an excellent state until the restoration of the chapel around 1880. The paint was not, or only partially, removed in 1880. From the late Middle Ages until the 1880-restoration, the chapel was covered by traditional roofs with eaves protecting the corbel heads from precipitation. This type of roofing was replaced by a much less protective lead roof (later copper), including a stone capped gable, during the restoration. The corbel heads remained well-preserved until perhaps the 1950s, but then problems emerged: the three outermost, least protected heads started to loose large pieces parallel to the foliation planes - and black crusts had also formed on some parts. In the early 1990s the situation was considered acute and the outermost corbel was replaced by a copy.

The "simple" explanations of the rapid weathering since 1880 are the effects of fire, black crusts and frost. When knowing, however, that there has been serious water infiltration from fissures between joints (Portland cement) and copestones on the gable, the picture becomes more complex. And when, moreover, considering the probable adverse effects of at least two incidents of the plaster copy-procedure mentioned above, we understand that there are indeed no simple explanations.

Except from the the fact that the change of roof design appears to have seriously contributed to the weathering, it has not yet been possible to verify the effects of the other events and processes. Investigations are continuing, not least because there are some 20 cornices with similar problems on the Nidaros cathedral.

5. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Weathering of the greenschist
With regard to the first hypothesis that was used as a point of departure in the present work (chapter 1), it has been shown that greenschist typically and naturally develop delamination as the main weathering form. The problems associated with the weathering can be summarized as follows:

Loss of exposed and partially exposed, projecting details like corbel heads. Loss of pieces may occur regardless of how the detail is bedded.

Loss of pieces and flakes along the foliation planes of face-bedded ashlars.

Pronounced loss of material when significant amounts of soluble salts are to be found in the masonry.

According to this summary, one might maintain that the greenschist should never have been used in the actual situations. Considering, however, the historical records, it has been shown that a wide range of

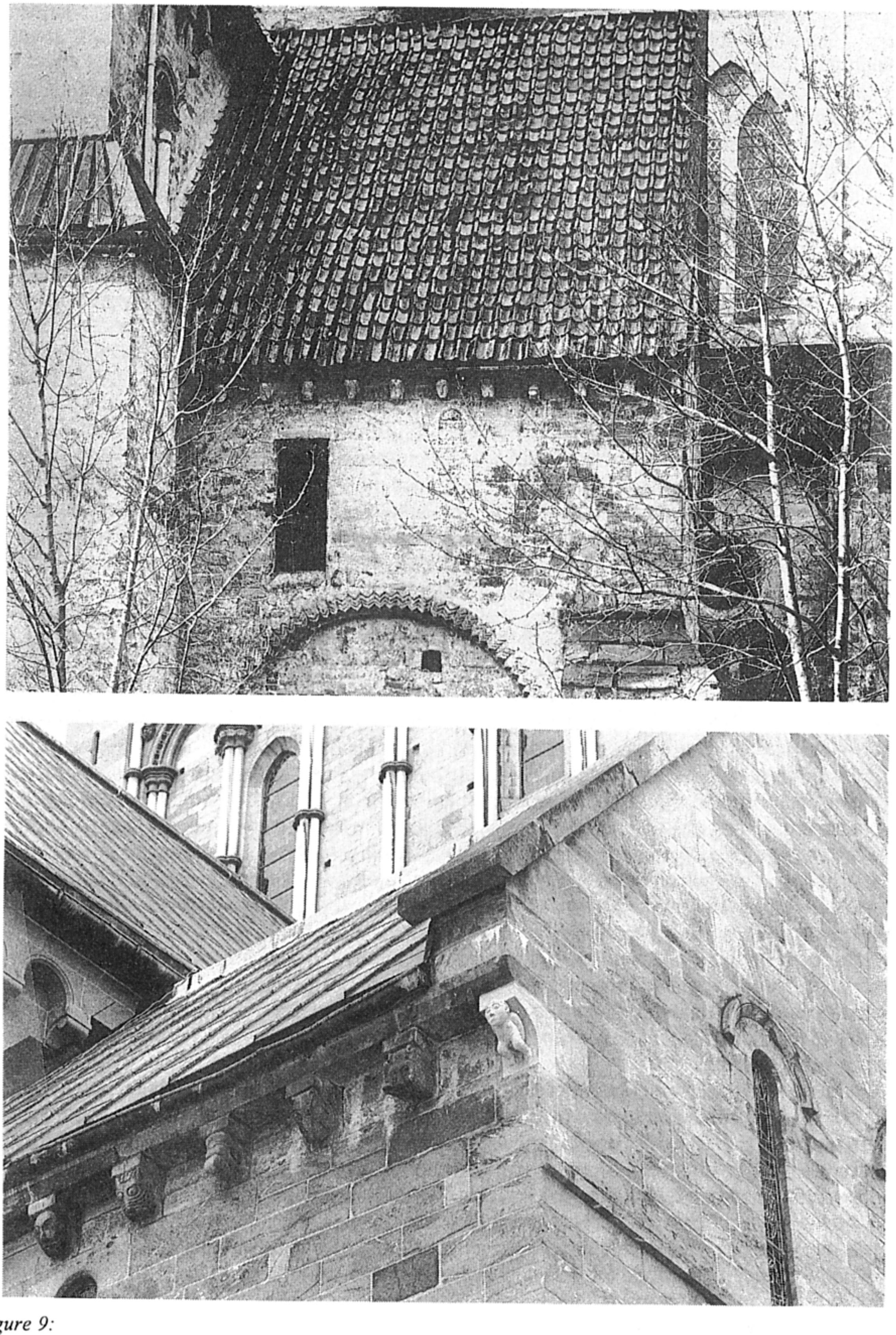


Figure 9:
Corbel heads (c. 1150) in the cornice of St. Olav's chapel (Nidaros cathedral). Above: Condition around 1880. The eaves of the roof is protecting the sculptures which are very sound in spite of a medieval fire. Below: Condition in 1996. The roof was changed in 1880 and the four outermost sculptures are now in a very bad state. The outermost one was replaced in 1993.

events and inappropriate conservation measures have been seriously contributing to the severe weathering. Important factors are for instance fire, inappropriate removal of plaster and paint, change of roof design and the use of Portland cement mortars. Also decades and centuries with leaks and rising damp as well as more than 100 years of air pollution have been very influential.

Details that have escaped the most damaging effects of historical events and processes, as well as ashlar masonry which has been rather thoroughly exposed to precipitation, are usually sound, partly in an excellent condition. As far as I am concerned, this shows that the greenschist is not only an appropriate stone for ashlars and other rather simple details, but also for more delicate ornamentation and sculpture.

On the background of all the problems encountered when it was attempted to reopen the greenschist quarry, as well as difficulties connected with dressing and carving the stone in our century, one should indeed ask what kind of knowledge the medieval craftsmen possessed. They were not only able to make magnificent ashlars, but also succeded in producing durable ornaments and sculptures of the stone. In this connection we should bear in mind that they could not foresee the course that history took during the following 8-9 centuries.

5.2 Working the greenschist

The main problem of the stone in our time, not only with regard to durability, but also to workability, has been the extensive delamination. The stone delaminates when gunpowder is used for quarrying, it delaminates when it is dressed and also when sawing is applied. It is simply a dreadful stone to work - and it is at present nearly unthinkable to try to use the stone for more delicate carving. Hence, a vital question to ask is how the medieval craftsmen managed to "keep the stone together".

Recalling that in our century blocks were transported to the building site where they were stored before further treatment, we have to assume that dressing took place when the stone was rather dry. From observations and some few experiments we know that the stone is relatively hard and brittle when dry compared to the soft character when quarry-moist. This is a normal property of most stones (Schaffer 1932, Winkler 1994), and we have to assume that the medieval craftsmen very well knew how to take advantage of it in our case. We also have to assume that raw treatment of blocks preferentially took place in or near the quarry - soon after quarrying - in the Middle Ages.

Issues regarding workability in relation to dry vs. quarry-moist stones can be summarized in the following questions: Should the stone be seasoned or not? How and when should the seasoning take place? These are in general very difficult questions, not least because numerous inconsistent local traditions are to be found throughout the world (ibid.). It is clear that stones in general are much more workable in their quarry-moist states, but in our case we also have to consider the fact that flakes and pieces may very easily be removed when the stone is thoroughly moist. Maybe the medieval craftsmen treated the stone when it had an "optimum moisture content"?

Seasoning not only affects workability, but also durability. The classical example is to let moist stones undergo freezing winter temperatures and to avoid using those that are spalling. Another example is the so-called "case-hardening" of many stones during seasoning. Case-hardening may affect the durability of the stone both adversely and positively when placed in a building (ibid.). Are such issues of relevance in our case?

Since we have not yet undertaken careful experimentation, it is impossible to answer the question. It is also impossible to state whether other types of treatments (for instance paint) applied by medieval craftsmen are relevant. We do, however, know how the medieval craftsmen quarried the stone. Since all modern attempts to quarry the greenschist failed, we simultaneously know that using medieval quarrying methods ought to be the first step in further experimentation.

I believe that its behaviour strongly suggests that the greenchist cannot be used with success without the existence of a very well adapted craft tradition, as maintained in the second hypothesis (chapter 1). We have not described the behaviour of soapstone - the other important stone in Trondheim in the Middle Ages - in the present work. However, the fact that soapstones in general are significantly easier to quarry, dress and carve - and that some of them have the desired durability - may have contributed to the rather bad reputation of the greenschist. The working of soapstones appears not to need as refined a craft tradition as the working of greenschist does.

5.3 Recommendations

When eventually greenschist is needed for restoration and replacement purposes in the future it is clear that medieval stone working methods have to be revitalized. To revitalize medieval stone working methods and adapt them in our modern world is certainly a difficult task, but it may be of great value also for the general understanding of medieval craftmanship. It may also increase the understanding of the weathering of the stone. However, the first issue on the priority list is to deal with urgent conservation problems. In order to slow down the weathering rate of existing stonework made by greenschist, eliminating water leaks, protecting severely exposed details (change of roof design) and - in some cases - removing Portland cement mortars ought to be included in the conservation strategies.

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NOTES

1) Diary of architect Nils Ryjord. Archive of The Restoration Workshop of Nidaros Cathedral, Trondheim (my translation).
2) Diary of architect August Albertsen. Archive of The Restoration Workshop of Nidaros Cathedral, Trondheim.
3) The investigations have been carried out according to Zehnder (1982).
4) The investigations have been partially carried out according to Arnold (1993). The works of Schaffer (1932) and Kieslinger (1949) have been very important as inspiration. The general historical sources are mentioned in chapter 2-3, while some unpublished sources (the Nidaros cathedral) are given in Storemyr (1995c, 1996, in prep.). Many important clues have been provided by Öystein Ekroll (pers. comm.). Most of the weathering phenomena are described in detail in Storemyr (in prep.)

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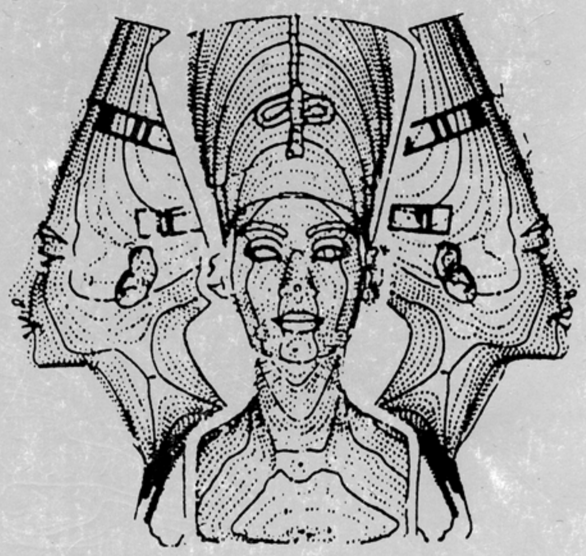

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