Rock properties and wedging: some ancient and modern examples

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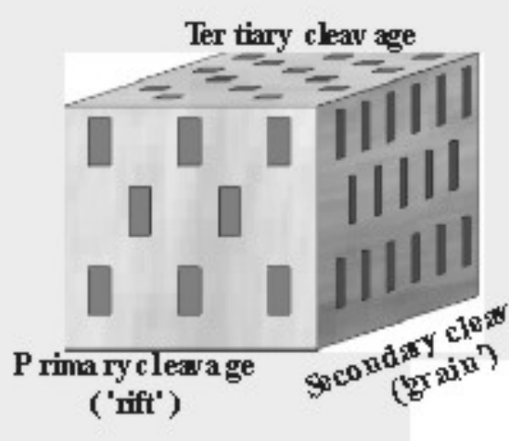
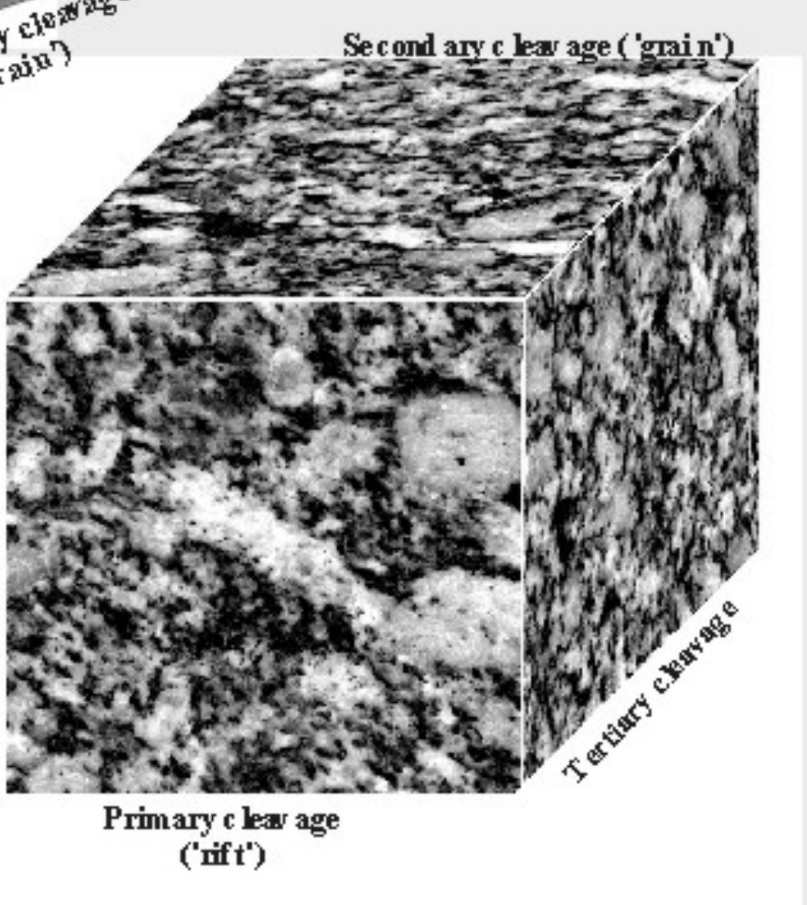
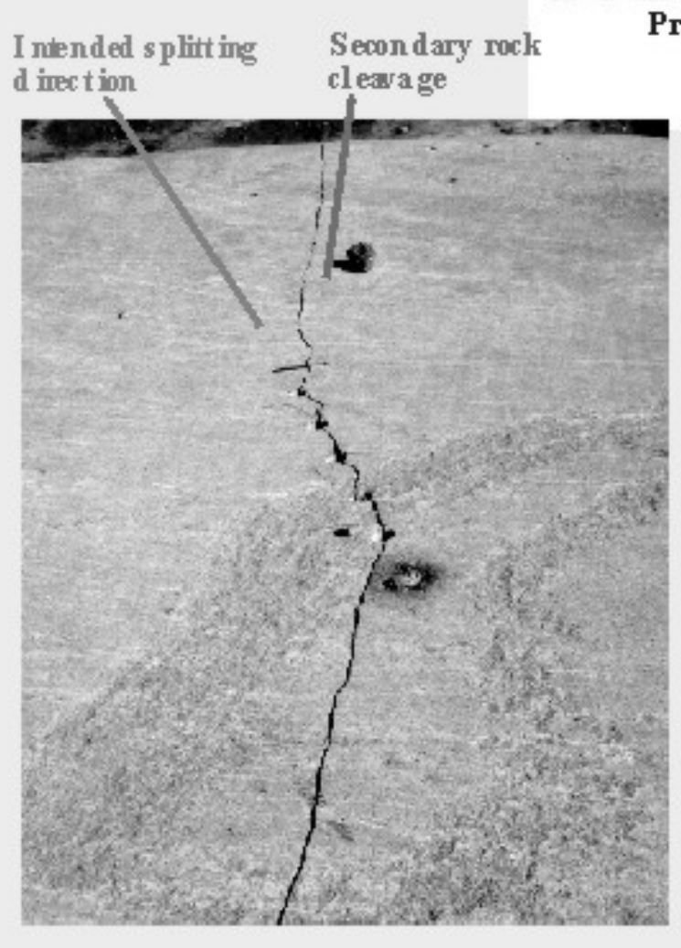
Rock Cleavage



Simplified sketch of cleavage directions in granite, following the orientation of the feldspar crystals. The largest surface of the crystals defines the primary cleavage.



The 'true' case - a cube of coarse-grained granite showing the primary cleavage (parallel to feldspar orientation), secondary cleavage (perpendicular to the mineral orientation along the long axis of the crystals) and the tertiary cleavage.



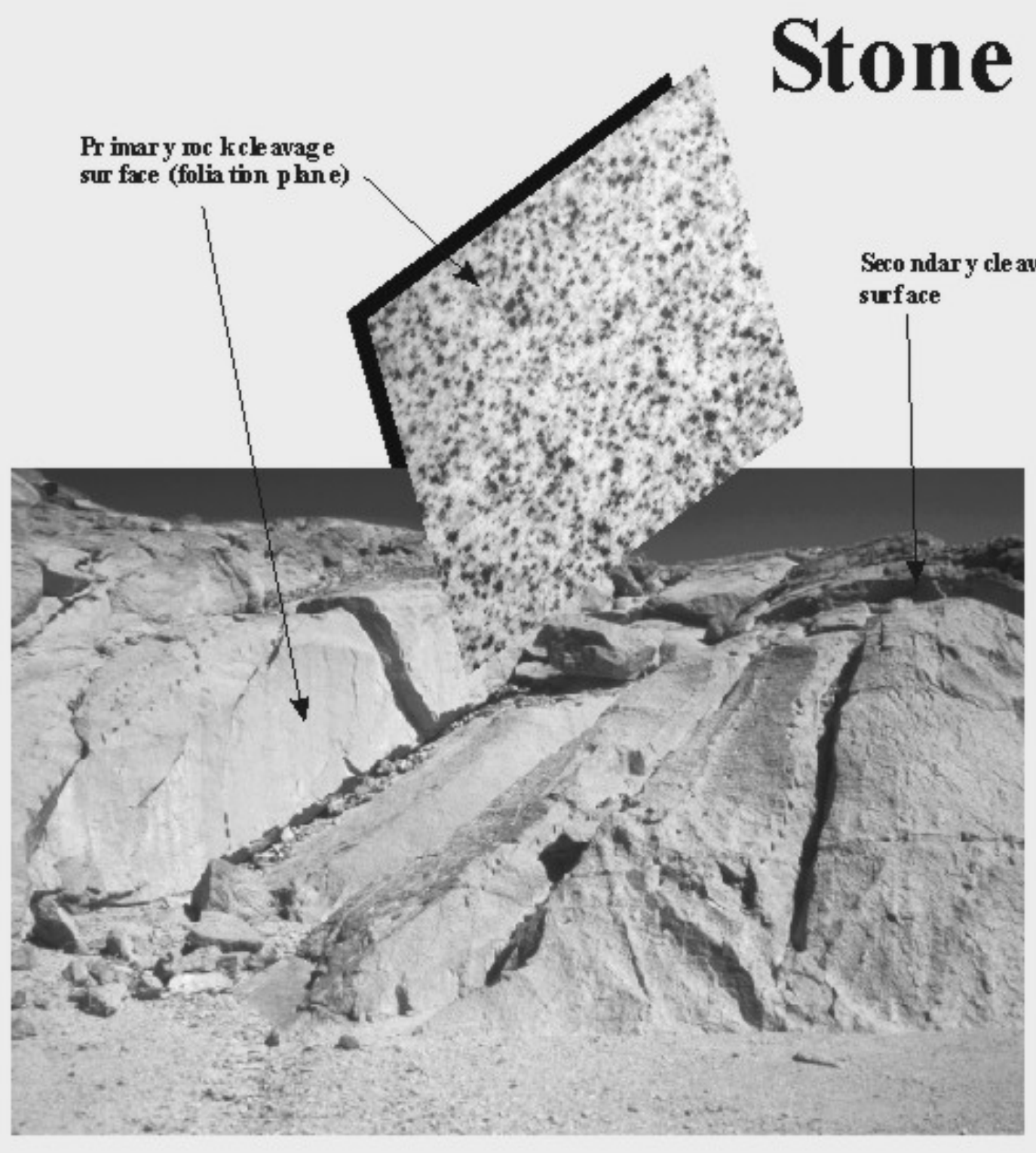
What can happen when the rock 'refuses' to split along intended directions? The example to the left shows drillholes (wedging line) set 20 degrees oblique to the secondary cleavage in a granite. The granite splits along the cleavage and not along the continuation of the wedging line, as intended. Example from granite quarry, south-east Norway.

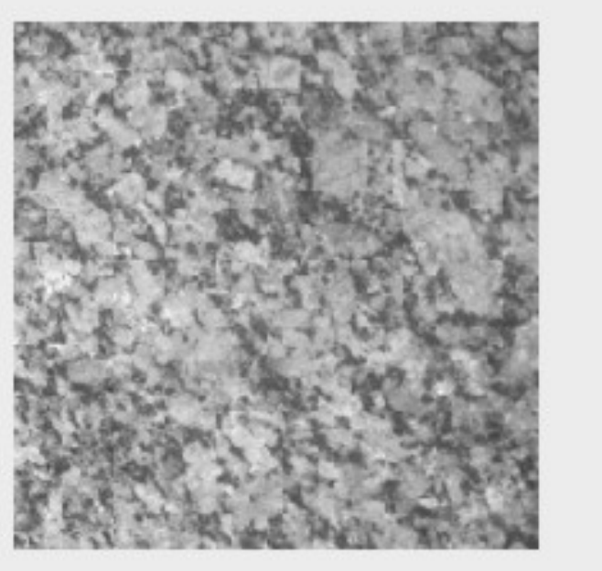
Rocks behave differently in different directions, due to anisotropic features such as preferred orientation of minerals and micro-fractures. Thus, the rocks will split better in some directions than others. The best direction for splitting is often referred to as the **primary cleavage** or the **rift**. The second best direction is called the **secondary cleavage** (or **grain**) and the third best is called the **ternary cleavage**.
Granites tend to have three splitting directions at right angles to each other, following the orientation of feldspars and micas and micro-fractures formed by solidification of the granitic magma. Generally, splitting is fairly easy along all these directions, but can be difficult at oblique angles to them.
Metamorphic rocks have a stronger anisotropy due to the development of metamorphic foliations, and thus the difference between cleavage directions can be significant, the 'easiest' being along the foliation.
For **sedimentary rocks**, the cleavage directions can be less obvious, but where present they tend to follow sedimentary layering, pores and fractures.

Introduction

Wedging of rocks as a method of extracting building stone has been used since before the roman period in the antiquity. For many rock types, especially hard, siliceous rocks, manual wedging has shown to be a highly efficient method of extraction, and is still used, even in some technically sophisticated quarry operations.
The splitting characteristics of rocks vary significantly, according to rock type and mineralogy, structure, texture and micro-fracture pattern within the rocks. Furthermore, even the most isotropic-looking rock will behave differently in different directions, so that there are 'easy' and 'less-easy' directions of wedging. Optimal extraction of rocks is thus a complicated art!
Skilled quarry workers 'know' by experience the rocks they are working, and will with time develop locally adapted methods of extraction, specially suited for 'their' rocks. Traces they leave behind can give valuable information about skills, technology and 'industrial attitude'. Sometimes, the rock itself can help us in understanding such marks, since knowledge of rock properties leads to a better understanding of the people who worked them.
Obviously, quarry marks in roman quarries witness a high level of technology and skills, and several authors have investigated and described roman extraction methods in detail. However, it could be that a geological perspective can contribute to enlighten some of the unsolved problems related to ancient quarries, for instance which tools were employed and why the romans did not develop an optimal way of wedging hard rocks, but instead continued using oversized wedges in hard rock quarrying during the whole period.
This poster does not intend to present any solutions to such problems, but show some examples related to rock properties and wedging, comparing modern and ancient quarries (predominantly in Egypt) and briefly discuss some aspects we believe could be valuable for future research on the subject.

Stone for pillars





Primary cleavage surface of the Aswan granite (polished slab).

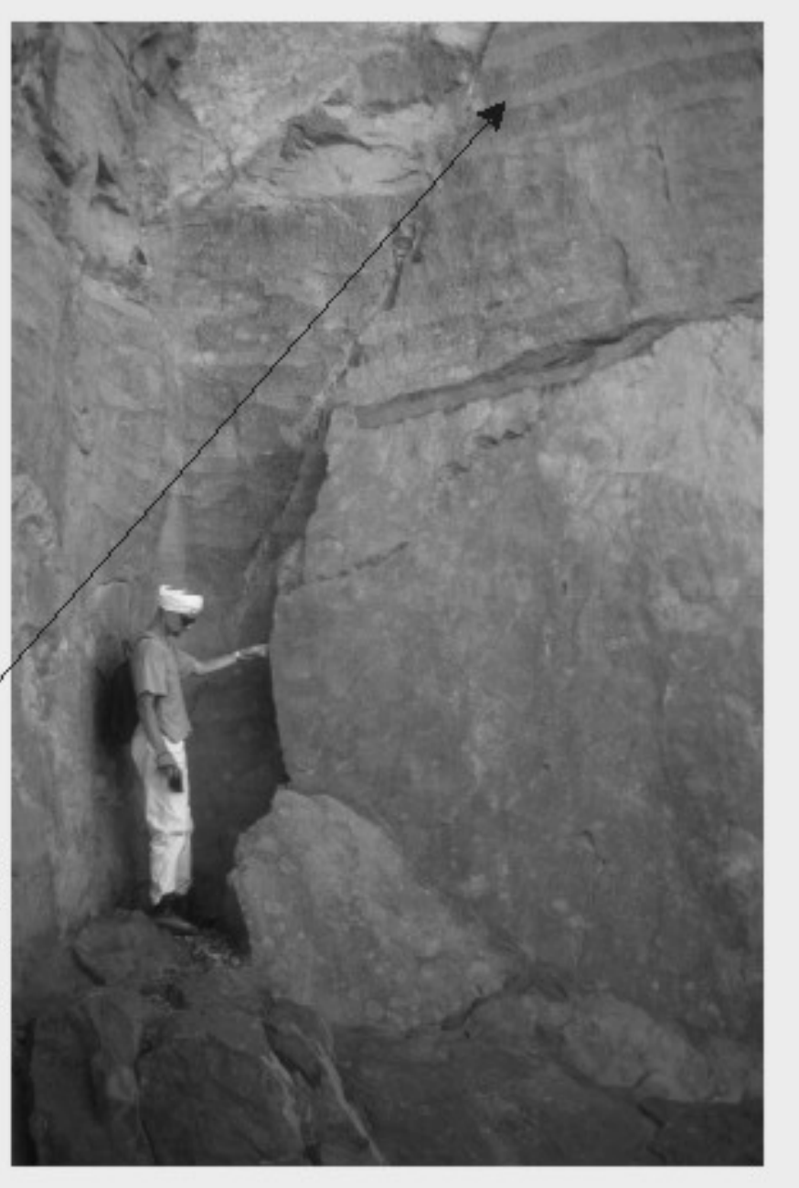
The Mons Claudianus 'granite' has a distinct metamorphic foliation which defines the primary cleavage and thus the long axis of the extracted blocks. Flaky grains of biotite mica are oriented along the foliation. This strong anisotropy makes the rock specially suited for the extraction of pillars and other long format blocks. The secondary cleavage is found parallel to steeply inclined fractures perpendicular to the foliation.

One of the minor quarries at Mons Claudianus, illustrating how extraction followed the structure of the rock.

'Tough' and 'easy' rocks

Granites with excellent splitting properties can be worked with small wedges placed in shallow holes. As in this Norwegian granite, where the wedge holes only measure 5 cm (see arrow).

Marbles are often difficult to split, and in modern quarrying long wedges ('plug and feather' type) are used in closely spaced, block-penetrating drill holes (lower block).



The dacite porphyry at Mons Porphyritus in Egypt has very poor splitting properties. In the roman period, continuous grooves for wedging was need in the primary extraction (see arrow).

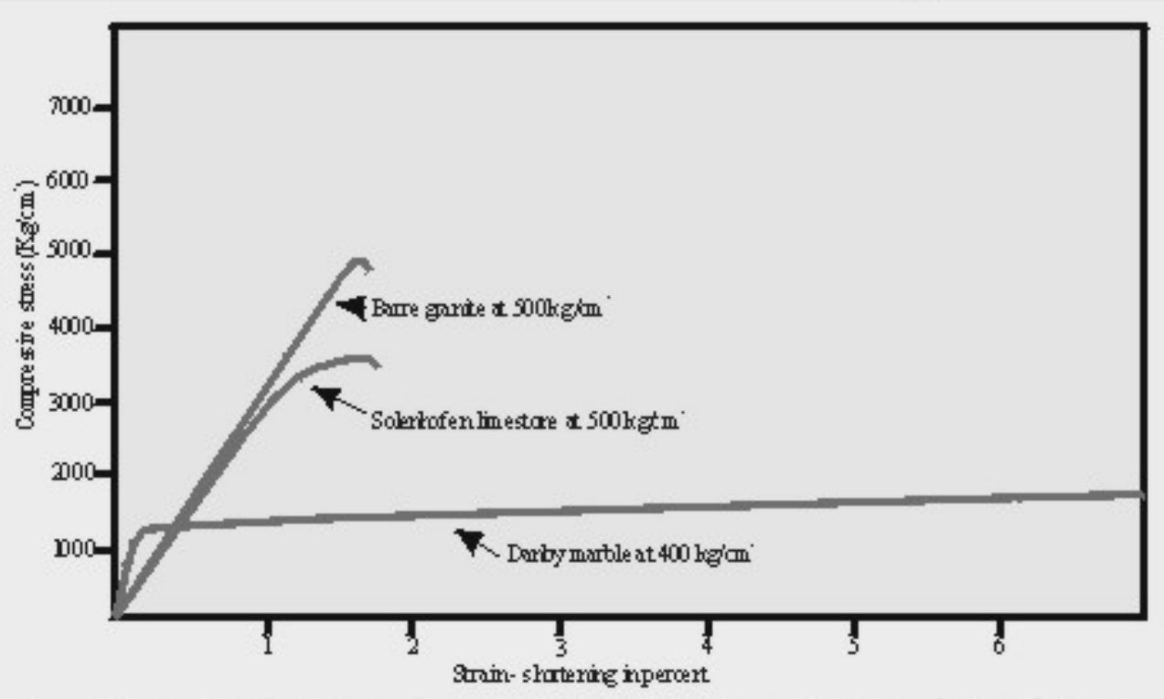
Rocks may be categorised as 'tough' or 'easy' according to their ability to split by wedging. Hard and brittle rocks such as granites can be split by small wedges in shallow holes by (carefully) creating an even pressure along the wedge line. In softer rocks and other rocks with poor splitting properties, either larger, longer or more closely spaced wedge holes are needed. Furthermore, since 'soft' minerals may be deformed or crushed during wedging, heavy strokes with sledge hammers are often necessary to perform the splitting. In some cases, especially for dense rocks with extremely poor splitting properties, continuous grooves are needed.

Rocks' response to stress

When stress is applied to rocks, they will start to deform **elastically**, followed by a **plastic** stage before rupture is caused by **brittle** deformation. Different rocks behave differently. Although no direct correlation between stress-responce and splitting properties has been established, it seems clear that rocks exhibiting a short transition from elastic to brittle behaviour are easier to split than rocks which deform more plastically. Furthermore, the more stress involved before reaching the elastic-plastic transition, the 'stronger' rock.

Rocks may be grouped in the following order according to their response to stress from 'brittle' and 'strong' to 'soft' and 'weak' (room temperature at low confining pressure; from Davies, G. H. 1984 - Structural geology of rocks and regions):

Quartzite ('strongest)
Granite
Quartz-cemented sandstone
Basalt
Limestone
Calcite-cemented sandstone
Scist
Marble
Shale/mudstone ('weakest')



Stress-strain diagram for some rocks. The transition from elastic to plastic deformation occurs where the curve start to bend over, whilst brittle deformation is indicated at the point where the curve move downwards. From the diagram, the granite show a more brittle behaviour than limestone and marble. From Robertson, E. 1952 - An experimental study of flow and fracture in rocks. Dr. thesis, Harvard Univ.

NAME	ROCK TYPE	QUARRYING PERIODS	SPLITTING PROPERTIES	OTHER
Aswan granite	Granite	Pre-roman, roman, modern	Fairly good (3 directions)	Boulders common, vertical fractures in bedrock facilitiates extraction
Shuleman 'granite'	Quartz diorite	Modern	Moderate to weak	Boulders common
Mons Claudianus 'granite'	Metamorphic granodiorite	Roman, modern	Good along metamorphic foliation, weaker in other directions	Fractures along foliation and spaced fractures perpendicular. Lack of horizontal fractures. Few boulders. Extremely suitable for extraction of pillars.
Wadi Hamamat sandstone	Greywacke	Pre-roman, roman	Almost isotropic, porous and easy to break, but difficult to split straight faces	Highly fractured rock, extraction of large blocks between natural fracture planes.
Mons porphyritus	Dacite porphyry	Roman, modern (1930's)	Dense and extremely difficult to split	Highly fractured rock, extraction of large blocks between natural fracture planes. Continuous grooves for wedging necessary.

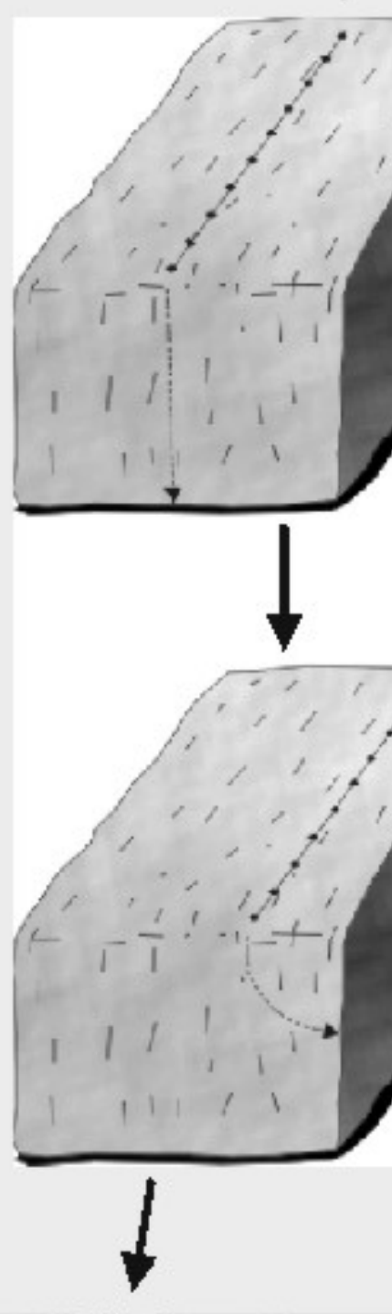
Splitting properties for some Egyptian rocks

Wedging of boulders and blocks

Giant granite boulders worked with hammer, chisel and short wedges. Southeast of Aswan, Egypt.

Giant boulders, formed by weathering, commonly occur in granite deposits in hot and dry climates. Such boulders are favourable for the extraction of building stone with simple tools, and were appreciated for such in ancient times as they are today. In many cases, granite boulders are slightly weathered and easier to split than 'fresh' rock. Furthermore, an 'extra' surface parallel cleavage, caused by heating/cooling cycles, is often present. Large, loose blocks (f.ex. pieces of solid granite between natural fractures) are worked in similar ways as the boulders.
Short (5 cm) and narrow wedges placed in a groove (to remove weathered or loose rock) is sufficient for splitting boulders and blocks of granite. The wedges are commonly set in a groove in order to secure that neighbouring wedges are placed at the same level, and to avoid weathered rock or loose rock along fractures. In roman quarries, quarry marks witness that roughly the same extraction method as in modern ones were applied. However, if metal wedges were used, they must have been 'oversized' to their function, and roman block production must have been far more labour demanding than necessary.

The edge-problem: splitting of blocks is easy as long as there are sufficient weight on both sides of the wedging line (top). If the wedging line is placed close to the edge of blocks, the crack caused by splitting tends to curve towards the block face (bottom)



A granite boulder (modern quarry) split by short wedges set in a groove, southeast of Aswan.

Roman wedge holes and groove at fracture surface on a granite block, Aswan.

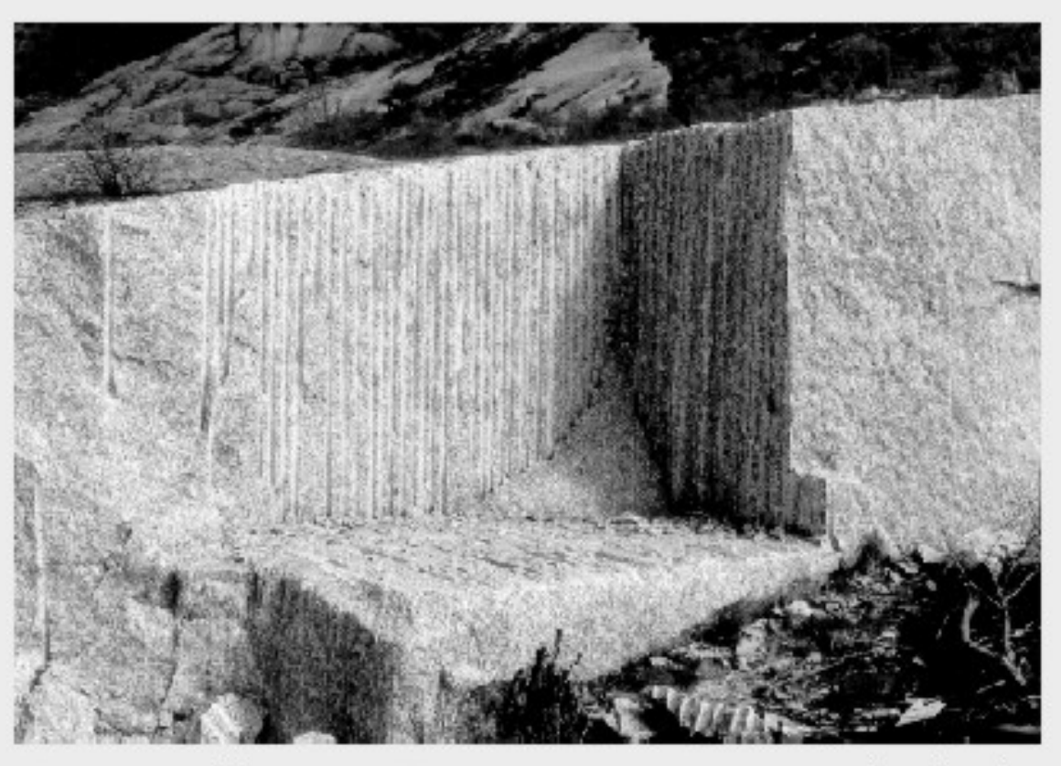
Detail of groove and wedge holes from a modern quarry, southeast of Aswan.

Detail of roman wedge holes and groove on fracture surface, Aswan.

Edge-problem in a roman granite quarry, Fawakhir, Egypt. The broken face is curving towards the former block face.

Extraction from solid rock

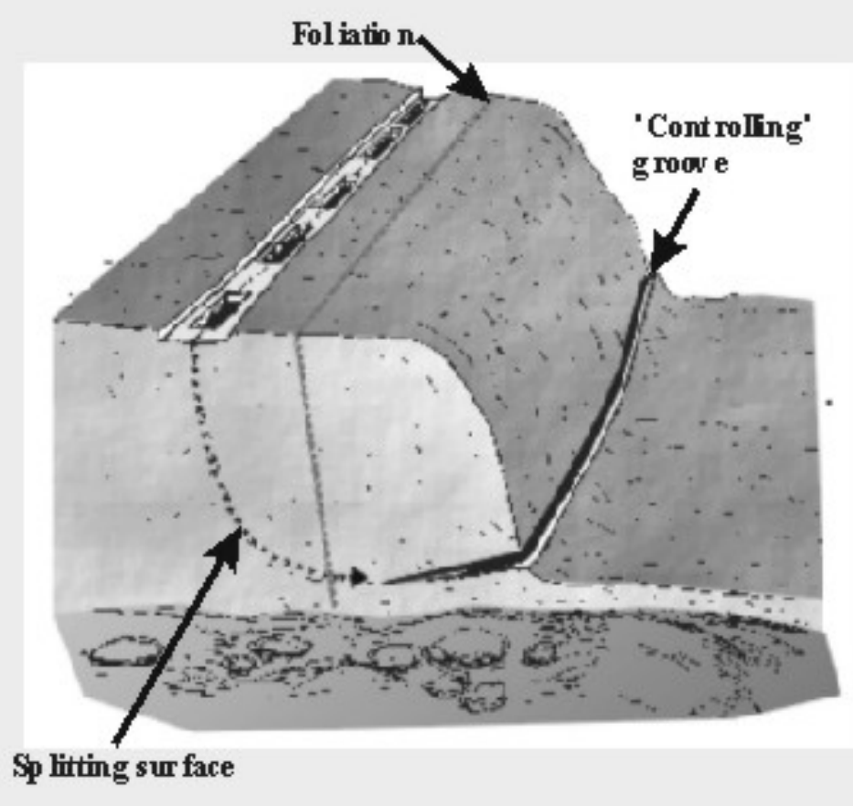
When blocks have to be wedged out of the solid bedrock without the 'help' from open fractures and weathering, some problems arise. Especially, the extraction from deposits where horizontal fractures are missing is difficult. One solution is the wedging of horizontal faces simultaneously with the vertical, as seen in several roman granite quarries. Angles between the faces need to be more than 90 degrees, if not parts of the rock mass will be 'trapped' and remain fixed to the bedrock, resulting in unintended breakage of the block. Furthermore, it is highly important to follow the natural cleavage directions in the rock to secure a 'best possible' result.
As do the modern, the roman quarries bear witness on many failed attempts of splitting, where the problem with angles count for a large portion. In addition, failure can often be related to ignoration of natural cleavage directions in the rock.



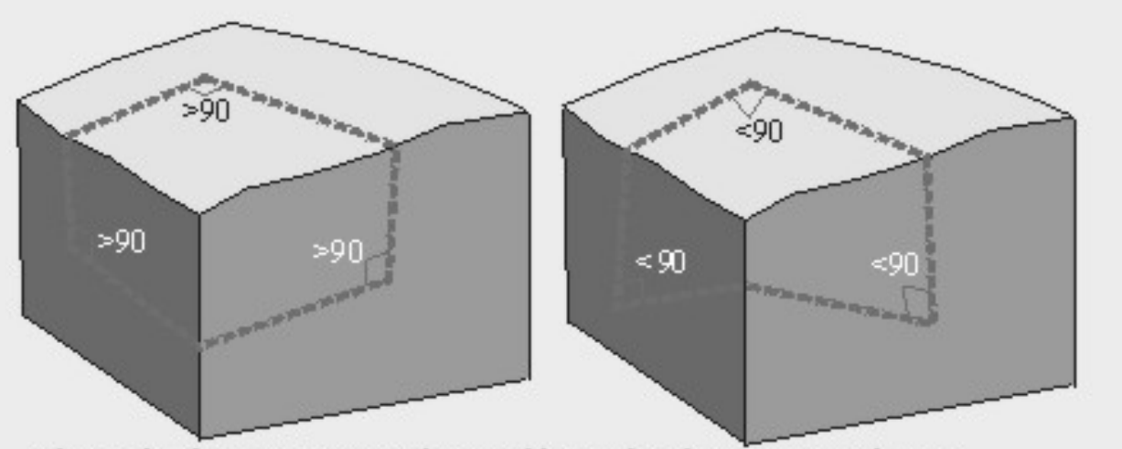
'Corner problem' in a Norwegian granite quarry (modern). To be sure of obtaining blocks, long and very closely spaced wedge holes have been made, even though this granite easily can be worked with short wedges. Still, the bottom corner of the block remains fixed to the bedrock, since the angles between the faces are less than 90 degrees.

Modern quarry (Shuleman 'granite') southeast of Aswan, Egypt, where breakage occurred after blasting (along drill line to the right) due to the lack of horizontal fractures. Blasting of horizontal cuts was not carried out either.

Similar problem as above, but this time in a roman diorite quarry at Wadi Semna, Egypt. Even the most closely spaced wedges will not split a 'trapped' piece of rock.



Site were a pillar block has been extracted in the roman Mons Claudianus quarry (top left). Split faces are curved due to the lack of horizontal fractures, a quite practical situation in the production of pillars. The sketch to the left illustrate the principle of such extraction. In several cases, horizontal or inclined grooves has been made for controlling the splitting process.



The 'ideal' situation, where all angles between splitting surfaces are larger than 90 degrees (left) and the 'trapped' situation with angles smaller than 90 degrees (right).

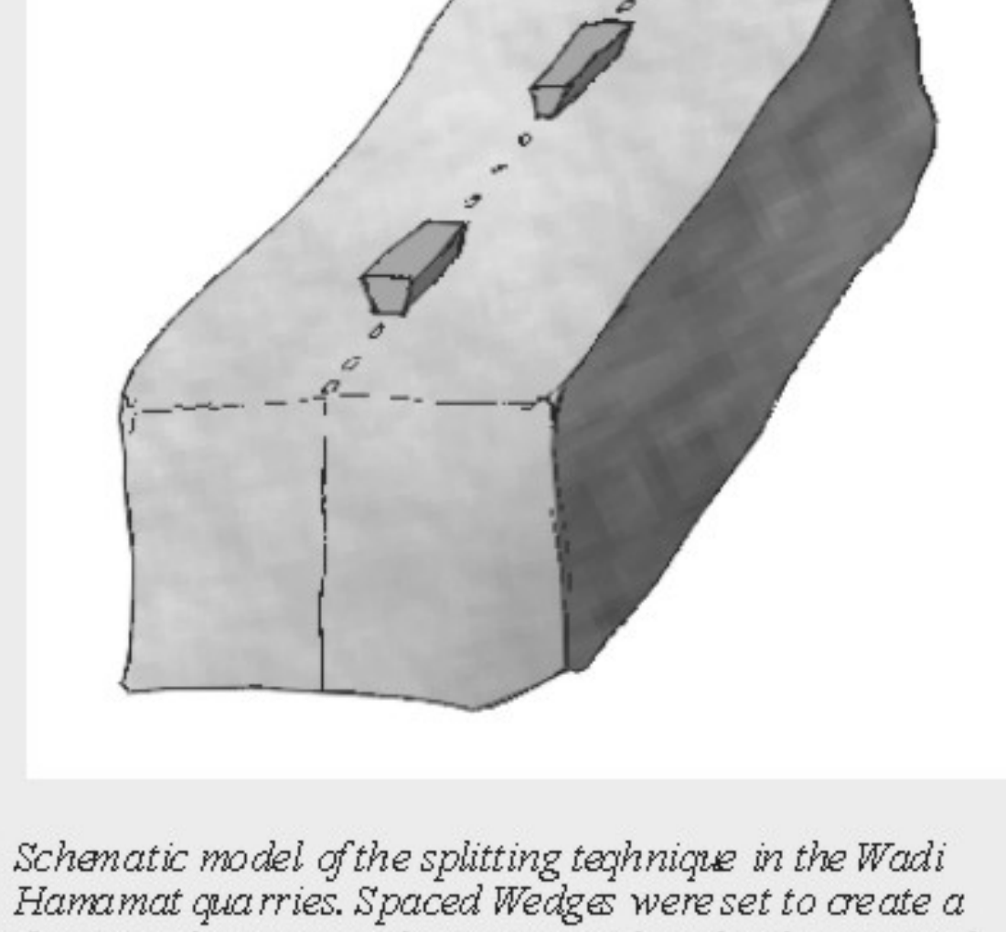
The Wadi Hamamat example

Wedging leaves plumose marks on the split surface, radiating from the point where rupture initiated. In this case, the sandstone block was splitted by only applying one wedge.

The Wadi Hamamat sandstone (Eastern Desert, Egypt) has been extracted from pre-roman periods, but the roman quarry marks are of particular interest, since they differ from the wedge marks in granite quarries. The sandstone is highly fractured, so that the extraction of primary blocks was easy - using the natural fractures as 'quarry faces'. A special technique was applied for the further partition and shaping of the blocks. With the exception of the weak, slightly inclined metamorphic foliation, there are no distinct cleavage directions in the sandstone. It is therefore difficult to split straight faces. As the photos show, wedges were used to create a pressure in the rock, but the splitting was 'helped' by using a point head chisel repeatingly along the line of splitting.
The Wadi Hamamat deposit is an excellent example of how pretty 'standardized' techniques were modified to fit local rock properties.

Failed attempt to split a sandstone block due to a 'hidden' crack on the left side. But we can clearly see the marks of a point head chisel between the wedge holes.

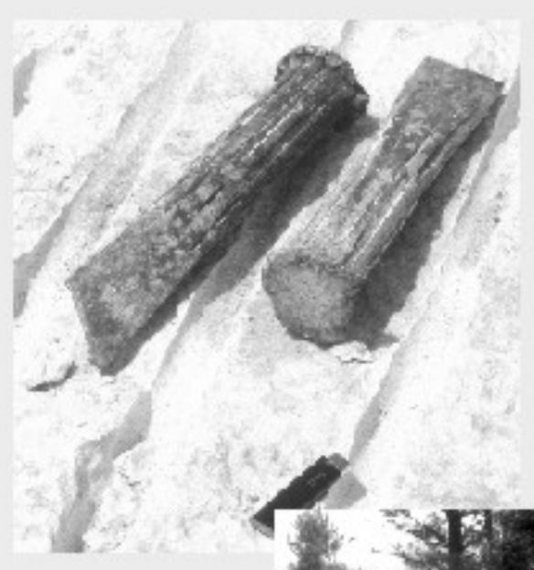
Block split by combining wedges and chiseling. The plumose marks have their origin at all of the chisel marks, indicating that rupture started simultanuously at all these points. This gave a much more even split face than if only spaced wedges were employed.



Schematic model of the splitting teqhnique in the Wadi Hamamat quarries. Spaced Wedges were set to create a directional pressure. Then a point edge chisel were used repeatingly along the line of splitting until rupture occurred. This teqhnique clearly saved a lot of work, gave smooth working faces on the block and caused a low waste ratio.

Wedging tools

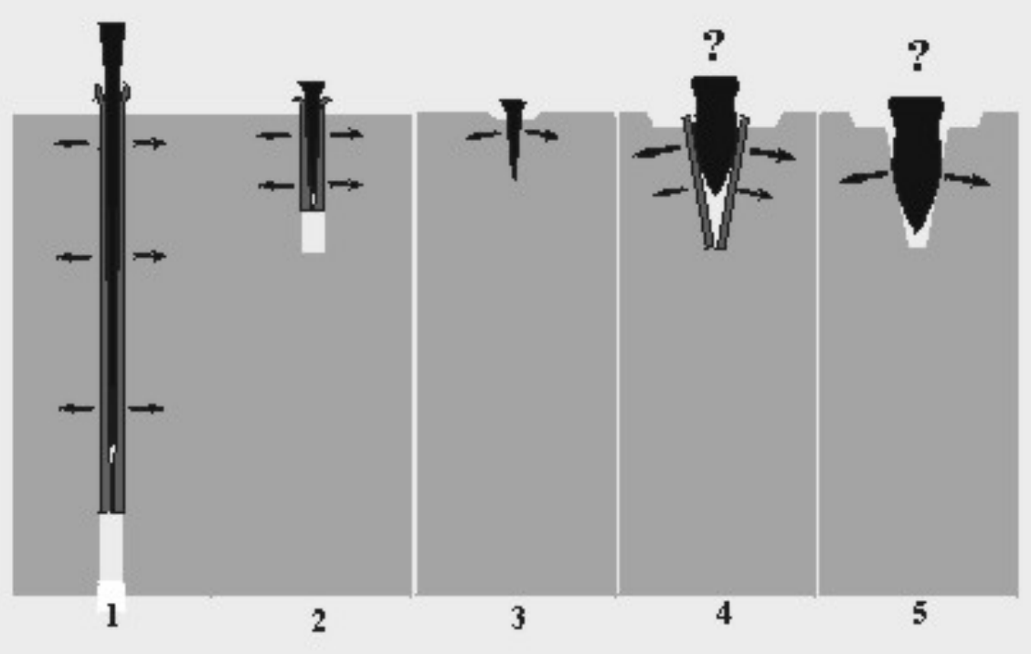
Large marble/limestone wedges, used in modern quarry operations in Egypt



Wedging tools have probably not changed much during the years, except in modern industrialised quarries where different types of 'plug and feather' type wedges are set in drillholes. For more manual work, larger and heavier wedges are applied for soft rocks such as marble and limestone, whilst small wedges generally are sufficient for splitting of granite. Therefore, the wedge marks in roman granite quarries seem 'oversized' with respect to the fairly simple task of splitting such brittle rocks. From a modern perspective the wedge marks are at least "oversized" if iron wedges alone were used. However, if wooden or metal wedges were employed in combination with feathers, the wedge marks appear more suited to the task (see also sketch to the right).

Wedging of granite block with small (5-7cm) wedges, Spain.

Hydraulic wedging in a modern, industrialised quarry in a monzonite with poor splitting properties, Norway. Wedges of 'plugs and feather' type is set in closely spaced, block penetrating drill holes.



Different principles for wedging.
1. Long, 'plug and feather' type wedge set in penetrating drillhole. Modern, industrialized quarry.
2. Short, 'plug and feather' type wedge set in short drillhole. Modern, industrialised quarry.
3. Short and narrow wedge set in chiseled hole. Modern granite quarry (not industrialised).
4. Possible(?) principle for roman wedges combined with 'feathers'. Note that the flat or slightly curved base of the wedge hole (commonly seen in roman quarries) in this case has a meening.
5. Possible(?) principle for roman wedges without the use of 'feathers'.

Arrows illustrate direction and relative amount of stress..

Discussion

In many cases, it seems that studying rock properties can be helpful in understanding how they were worked in ancient quarries, and if and how new techniques were developed by the workers. Furthermore, modern, manually operated quarries are interesting arenas for understanding the ancient - the present might be a key to the past. In fact, today's quarry-workers are facing the same rocks as their colleagues in antiquity!

A fascinating aspect about roman hard-rock quarries is the apparently oversized wedges they employed. If these were made of metal, why bother to use a lot of labour to carve large holes for big wedges when they could manage with a quarter of the size? Without drawing any kind of conclusion, it reminds the technically sophisticated part of the modern stone industry, which to a great extent use 'standardised' methods of diamond wire sawing and hydraulic drilling for any kind of rock, leaving the skills to care for the machinery. Often, this shows to be highly profitable, but in many cases the costs pr. cubic metre block is far more than necessary. In other words, they are 'breaking a butterfly on a wheel'.

One way of getting closer to find out which tools the Romans employed in stone wedging is to find out how the different tools work. Experiments regarding this would be of great interest, but it is important that highly skilled quarry workers take part in such experiments, and that directional properties of rocks are carefully evaluated. The problem is not to show that granite can be split by wooden wedges (which in Norway was done as recently as in the last century) but to find out if this is a practical method applicable to every-day extraction.