

Weathering and Conservation of Soapstone and Greenschist used at Nidaros Cathedral

Brief Summary of Investigations 1999-2000

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Introduction

The main building material at Nidaros cathedral is soapstone and to a lesser extent greenschist (chlorite schist). Soapstone is a soft and dense metamorphic rock used extensively in Norwegian architecture and can also be found at some few buildings in other Scandinavian countries, Brazil, the Alps and elsewhere. Due to its limited use worldwide, little is known about its properties, weathering and conservation in comparison to for instance sandstone, limestone, marble and granite. Current knowledge mostly derives from the work of Storemyr (1997), Moe (1998) and Alnæs (1995), as well as from Plehwe-Leisen *et al* (1992).

At the medieval and reconstructed parts of Nidaros cathedral there are several types of damages to stonework made from soapstone and greenschist that potentially require direct conservation measures like cleaning, desalination, structural consolidation and fixing of scales and delaminated areas. At present there are no "safe" conservation products available to deal with such problems.

Thus, a joint research project between *Institut für Denkmalpflege*, ETH Zürich, *Fachlabor für Konservierungsfragen in der Denkmalpflege*, München and the Restoration Workshop of Nidaros Cathedral was established within the framework of the Raphaël project at Nidaros cathedral. The aims were to:

- undertake weathering experiments and supplement former investigations of petrophysical properties in order to be able to interpret observed weathering phenomena more accurately;
- test various conservation products in the laboratory in order to find a potentially useful "palette" of products to be tested *in-situ*.

The aims and planned content of the studies are thoroughly described in the project description dated 7. September 1999. It concerns the first phase of the Raphaël project only (1999-2000). As it became clear that the project was to be extended (2000-2001 and probably further), the weathering and conservation studies were incorporated in the Test Restoration project at the chancel at Nidaros cathedral (from spring 2000, see project description dated 22.11.1999). This implies that a comprehensive final report with full documentation from the project will not be written before the end of 2000/beginning of 2001. Below, we will only briefly summarise the most important results so far. Attached to this paper are also a summary

of soapstone weathering written before the project started (appendix 1) and a short report dealing with aspects of an overall conservation strategy for the cathedral (appendix 2).

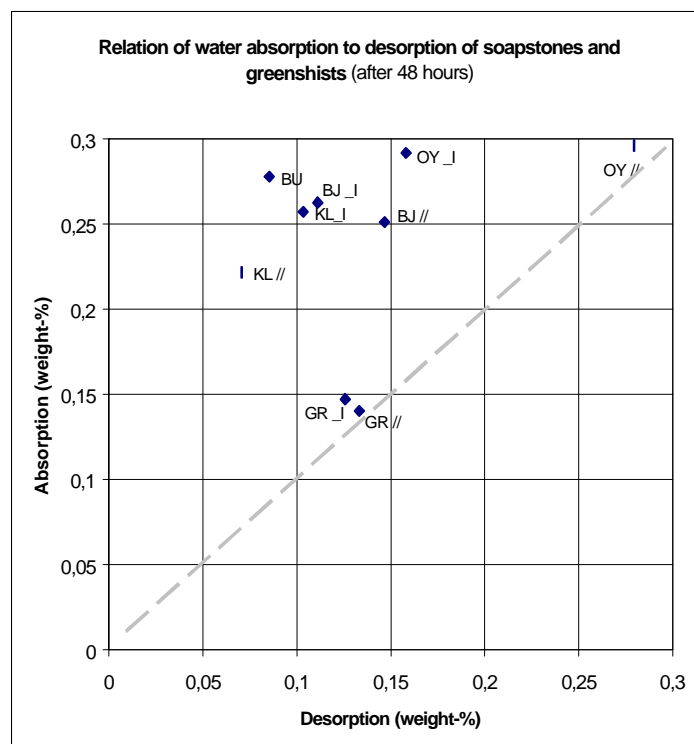
Results from supplementary stone characterisation and weathering studies

The supplementary stone characterisation experiments were undertaken on a range of important soapstones and one greenschist used at the cathedral.

Water accessible porosity was measured under vacuum in order to fill the pores completely. The maximum accessible porosity is low (0,62-1,1% by volume), but for several stones there is a considerable increase of the water content (between 3 and 14%) after a longer period of time. This means that it takes a very long time (weeks) to fill the smallest pores.

Mercury porosimetry was undertaken in order to investigate the pore size distribution of various stones. The total mercury accessible porosity is in the range of the water accessible porosity, with the exception of Klungen stone that has a mercury accessible porosity of only 30% of its water accessible porosity. Except for Bubakk soapstone, which has a characteristic bimodal pore size distribution, there are no distinct tendencies, i.e. no distinct pore classes. This probably means that the porosity is mostly confined to micro fissures and that Bubakk in addition has some intergranular porosity. This is interesting because Bubakk shows weathering forms that are distinctively different from other soapstones.

Capillary water absorption is usually very slow (see figure below). As usual, the *desorption* (or evaporation) is slower than the absorption, and dependent on the orientation of the stones, i.e. water is more rapidly desorbed parallel to the distinct foliation in some stones. This means that once filled with water, the stones keep it for a long time. This is for instance relevant for the frost resistance of the stones.



Water vapour diffusion investigations confirm the desorption studies. There is a large difference between the wet and dry diffusion coefficients (much larger than for sandstone and limestone), implying that the transport of water takes place due to surface transport (water

film in microfissures/pores) and to a lesser extent as vapour diffusion. Vapour diffusion is a more rapid process than surface transport.

Hygric swelling is to be expected in soapstone and greenschist because of their content of chlorite and other phyllosilicate minerals. Surprisingly, and in spite of their low water uptake, the soapstones show swelling rates in the order of many sandstones (500 to more than 1000 $\mu\text{m}/\text{m}$), which have a much higher water uptake. Generally, this may be explained by intracrystalline water uptake in e.g. chlorite. Earlier, it has been shown that the hygric swelling of soapstone is reversible when no salts are present, but that the presence of soluble salts makes the swelling process irreversible. The explanation of this behaviour is not yet clear.

Cation exchange capacity (CEC). In order to try to understand the swelling properties of soapstone (and the behaviour when subjected to soluble salts), the cation exchange capacities were determined. The CEC is very high, much higher than in most sandstones. The cations released from soapstone are mostly Mg and Ca, but the implications of this are not yet properly understood.

Weathering experiments with soluble salts. Only two stones (Øye greenschist and Bubakk soapstone) exhibited strong "reaction" with various soluble salts in a simple weathering experiment. Interestingly, when "fed" with sodium sulphate, efflorescences of *magnesium sulphate* could be observed on the stone after some weeks. This behaviour strongly points to cation exchange processes in the stone.

Dry and wet biaxial flexural strength. Due to its large amount of phyllosilicate (flaky) minerals, soapstone has a very high biaxial flexural strength - it is a "tough" stone. It was shown that the investigated stones had a broad area of plastic flowing, and that this behaviour was more pronounced when the stones were wet. These results confirm most stone masons' experience; that soapstone is easier to carve when wet.

Thin section microscopy on fresh and weathered samples has been started in order to supplement earlier investigations. So far the microscopy shows that the porosity is mostly confined to microfissures. These investigations will have to be intensified later.

Results from introductory conservation studies

The introductory conservation studies were undertaken in the laboratory in order to build up a palette of promising products. So far products based on ethyl silicate have been tested, as well as products for desalination. Some initial considerations about lime-based products have also been undertaken.

Conservation products based on ethyl silicate. Normal ethyl silicate (in this case Funcosil 300 E) is not able to bind to the minerals in soapstone and greenschist. However, it was found that when adding an adhesive coupling agent (in this case 1-3% propyl amino silane, PAS), the ethyl silicate may work perfectly also in real situations.

Another problem is that ethyl silicate has a low viscosity and is not able to bridge distances between minerals larger than, say, 50-100 μm , i.e. it is not able to fill most fissures. The problem can be overcome by using a precondensed ethyl silicate and add fume silica - a product which is able to bridge somewhat larger distances.

For larger fissures an injection grout based on ethyl silicate was developed. Moreover, in order to protect *strongly exposed*, weathered surfaces, a "wash" also based on ethyl silicate was proposed.

Thus, the product palette to be tested *in situ* looks very simplified like this:

Weathering form	Product
Granular disintegration, microfissures	Precond. ethyl silicate + PAS
Thicker, visible fissures, delamination	Precond. ethyl silicate + PAS + fume silica
Small cracks, larger scales	Precond. ethyl silicate + PAS + fume silica + quartz + clay + glass spheres
Crumbling surfaces at exposed places	Precond. ethyl silicate + PAS + fume silica + quartz + clay + soapstone powder

It should be noted that these products cannot be used on surfaces on which there is high biological activity. Thus, for instance algae have to be eliminated first, preferably by using hydrogen peroxide (H₂O₂).

Conservation products based on lime. Lately, there has been considerable development in the field of using dispersed lime for conservation purposes (Jägers, ed. 2000). It seems that dispersed lime has a much higher reactivity (i.e. more rapid carbonisation) than "normal" lime. Some initial tests are being performed at the moment in order to optimise this product also for conserving weathered soapstone. The aim is to include dispersed lime in the product palette to be tested *in situ*.

Desalination products. Weathering at Nidaros cathedral is strongly influenced by salts and there are lots of unsightly calcite crusts originating from Portland cement mortars. A cation exchange compress has been developed for taking away the remaining parts of calcite crusts, which stick to the stone surface after they have first been mechanically removed. Likewise, a cation exchange compress for reducing the amount of soluble salts in weathered masonry has been proposed. This compress will be tested along with sacrificing plasters at the cathedral.

Further work - field tests of conservation products

The next step in the project is to test the product palette at the cathedral by establishing long-term test fields. 12 test fields have been selected, mostly at the chancel, but also at other parts of the cathedral. The field tests will commence in July 2000. Only by realistic *in situ* testing will it be possible to obtain information about the vital long-term durability of the proposed products.

Other important work to be done include supplementing the petrophysical data about soapstone, undertaking some few extra weathering tests and carrying through the thin section microscopy. A seminar is planned in 2001 in order to discuss the results of the project (after the main report has been prepared).

Concluding remarks

The most important achievement in the project so far is the conservation product palette based on ethyl silicate that has been developed. This is the first time realistic conservation/-consolidation products for soapstone are available. Hopefully, the products will also pass the *in situ* field tests. However, it may of course take many years before the product palette can be used in real situations on valuable soapstone objects.

Another important achievement in the project is the results from the cation exchange investigations. When properly interpreted, these results might significantly contribute to our understanding of soapstone weathering in situations with or without the presence of soluble salts.

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- Test Restoration of Nidaros Cathedral Choir. The Raphaël Programme of the European Union Project: Nidaros Cathedral Restoration (2000-2001). Trondheim: The Restoration Workshop of Nidaros Cathedral (22. November 1999).

Appendix 1

- Storemyr, P (1999): Weathering of Soapstone at Norwegian Monuments: An Overview of Current Knowledge. Report, Trondheim: The Restoration Workshop of Nidaros Cathedral

Appendix 2

- Zehnder, K (1999): "Weathering and conservation of soapstone": Report on the fieldwork at Nidaros cathedral, Trondheim (N), 15 - 19 June 1999. Zürich: Institut für Denkmalpflege ETH

Weathering of Soapstone at Norwegian Monuments***An Overview of Current Knowledge****Per Storemyr**The Restoration Workshop of Nidaros Cathedral**N-7418 Trondheim - Norway**storemyr@online.no**May 1999*

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.

*Alexander von Minutoli (1853)**about soapstone at Nidaros Cathedral, Trondheim***Contents**

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Introduction

Weathering of stone at monuments cannot be properly understood without due reference to the actual situation in which the weathering occurs and the often complex history of the situation (Arnold 1993, Storemyr 1997). However, many weathering phenomena may be elucidated by first considering the properties of the stone in question, subsequently studying its typical behaviour under various exposure conditions (or vice versa). Normally, such investigations are carried out both at monuments and in the quarries from where the stones were extracted (Zehnder 1982, Storemyr 1997).

The latter approach is employed in this paper. It describes and explains the typical behaviour of nine selected Norwegian soapstones (fig. 1), most of which have been used for building and restoring the medieval Nidaros Cathedral in Trondheim, Central Norway (Storemyr 1997). A few other stones have been included as well, for instance soapstone used at the medieval Stavanger Cathedral in the southern part of Norway and soapstone from a 17th century portal at the Church of the Holy Cross in Bergen.

Introducing first the general use of soapstone and the Norwegian climate, this paper subsequently gives a summary of the selected soapstones' petrography and structure. The main sections describe and interpret their typical behaviour in locations ranging from completely exposed to the weather, to sheltered from precipitation, but influenced by water leaks and salts.

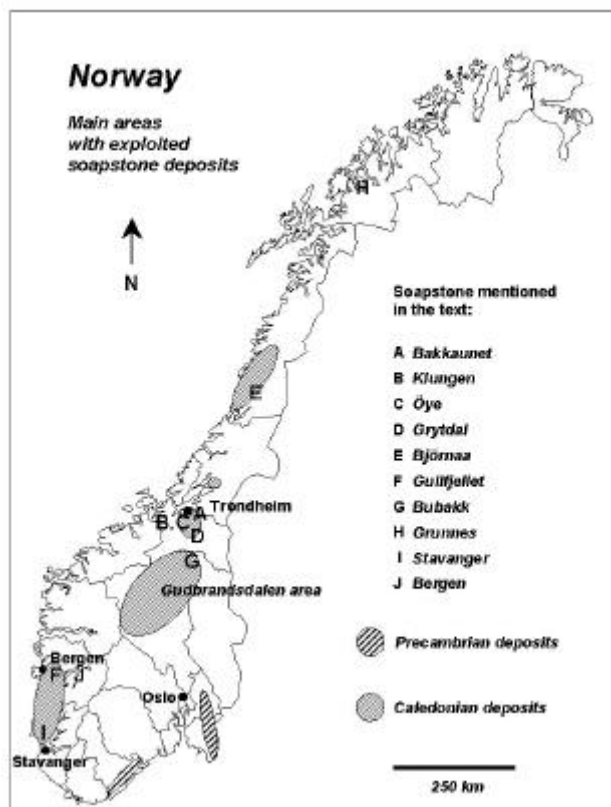


Fig. 1: Areas with soapstone deposits in Norway and investigated stones. (Klungen not studied.)

Bergen. An obvious reason for the widespread use of soapstone in Norwegian architecture, is the numerous small deposits along the Norwegian Caledonides as well as in the Precambrian basement (fig. 1), but also the lack of other readily available soft building stones such as sandstone and limestone (Ekroll 1997, Storemyr & Heldal *in print*).

General properties and use of soapstone

Soapstone has been quarried, used and appreciated throughout the world since the dawn of civilisation. This talc rich metamorphic rock, mostly derived from ultramafic parent rocks (peridotites), is usually soft enough to be worked with wood carving tools, very heat resistant and has a high heat capacity. It is also dense and has an extremely low porosity. In ancient times these remarkable properties made soapstone a perfect material for vessels and cooking pots, fire plates and lamps, moulds and pipes, as well as small sculpture (Storemyr & Heldal *in print*).

In some countries soapstone has been used in architecture, mostly for decoration, and in Norway, as perhaps the only country in the world, also for structural purposes in the Middle Ages and later. Three outstanding examples of Norwegian "soapstone architecture" are the medieval cathedrals of Nidaros (fig. 2) and Stavanger, as well as St. Mary's church in

The Norwegian climate

Generally, soapstone is a very durable rock. But like all other stones its behaviour is strongly dependent on the ambient climate - or better: climatic events and processes. 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 crystallisation 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% (data from the Norwegian Meteorological Institute - DNMI).



Fig. 2: Nidaros Cathedral in Trondheim, Europe's northernmost and Norway's largest medieval cathedral

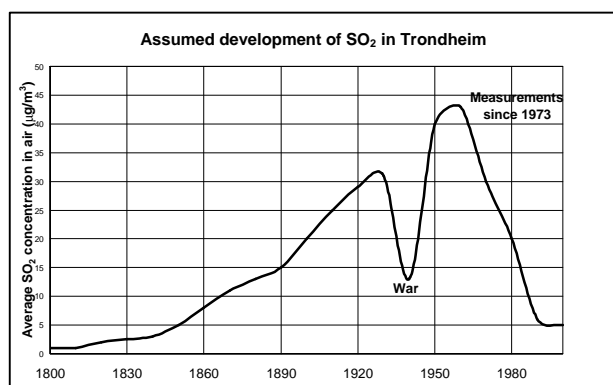


Fig. 3: Assumed development of SO₂ in Trondheim (from Storemyr 1997)

The history of local air pollution in Trondheim goes back to the beginning of the 19th century when heating with coal became normal and small industrial enterprises were established in the city. 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 µg/m³ between 1920 and the late 1970s (Storemyr 1997). Since then there has been a drastic decrease to some five µg/m³ at present (fig. 3). Emissions of NO_x from traffic have been increasing during the last decades and lays at present in the range of 40-60 µg/m³ (cold season) (Hagen 1994).

As can be seen, Trondheim is and has been a relatively "clean" city. Moreover, it has not been affected by acid rain from the European Continent and UK, implying that dry deposition of locally produced pollutants has been the major effect on buildings. Situated in the south of Norway, both Stavanger and Oslo have been affected by long-range air pollution. Generally, these cities, as well as Bergen on the West Coast, have been a little less "clean" also with regard to local air pollution (Hagen 1994). Stavanger is somewhat wetter and warmer, Oslo is slightly drier and warmer, while Bergen is much wetter and slightly warmer when compared to Trondheim (data from DNMI). All cities experience storms which bring in excessive amounts of salts from the sea, but this phenomenon is probably much more pronounced in Bergen and Stavanger than in the other cities. Moreover, it may be difficult to interpret whether chloride derives from sea salts or from former acid cleaning of the monuments (Storemyr 1997, Moe 1998).

Petrography and structure of selected soapstones

Even though most soapstones are soft, dense and relatively durable, there are often extreme variations between different deposits and within the same deposit. One reason is that the term "soapstone" (Norwegian: "kleberstein") is a very broad one, in Norway encompassing the majority of talc-rich, metamorphic soft rocks used for various purposes. However, much soapstone used in Norwegian architecture should rather have been designated for example talc schist, chlorite schist or serpentine-rich soapstone. Some of these latter rocks are often well suited in architecture, since they may be "harder" or "stronger" than soapstone "proper" (for definition and origin of soapstone, see Bates & Jackson 1984 and Storemyr & Heldal *in print*, respectively).

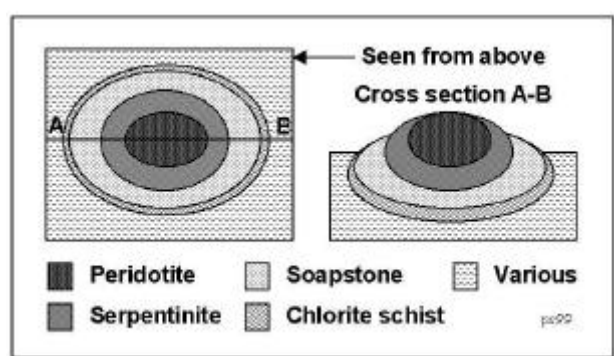


Fig. 4: Geology of a typical soapstone deposit derived from alteration of peridotite. Tectonic movements may have rendered the structure much more complex than shown on the picture



Fig. 5: Ashlars of Øye chlorite schist (dark) and Bakkaunet soapstone (light) side by side in the Octagon of Nidaros Cathedral. Note slight weathering along repointed cement joints.

The soapstones described in this paper show great variation in properties (tables 1, 2; only stones from Nidaros Cathedral), and hence reflect a great variation in geological history and environment. Only three of these stones, Bakkaunet (fig. 5), Bubakk and Grunnes, may be correctly described as relatively massive soapstone "proper". But while Bakkaunet has a matrix of talc and chlorite intersected by numerous, relatively broad veins of carbonate minerals, Bubakk, which has a similar matrix, lacks intersecting veins. Instead, the carbonate minerals are usually distributed as relatively small grains "within" the matrix. In Grunnes soapstone the carbonates are typically distributed as relatively large, easily observable aggregates (Storemyr 1997).

Three of the other stones may correctly be described as chlorite schist (Øye, fig. 5), talc-rich chlorite-tremolite schist (Grytdal) and talc-rich chlorite-biotite schist (Bjørnå), even though parts of the quarries may contain stone resembling soapstone "proper". Øye is peculiar because of its very pronounced foliation, developed as a result of its origin as tectonically altered basalt (Heldal & Storemyr 1997). Grytdal is also peculiar, first of all because of its large content of pyrrhotite (up to 10%), which upon oxidation and chemical reactions produces large amounts of gypsum. Tremolite needles are also a characteristic feature of Grytdal stone. Bjørnå stone apparently derives from an ultramafic parent rock, but has a low talc content and a high content of chlorite and biotite. One may wonder whether part of the deposit is developed as the typical rim of chlorite schist usually to be found in the peripheral areas of most soapstone deposits (fig. 4). Otherwise, Bjørnå typically contains small grains of carbonate minerals embedded in the matrix, and only a few thin veins of such minerals (Storemyr 1997).

Gullfjellet may correctly be described as soapstone (derived from pyroxenite), but is peculiar since it does not contain carbonate minerals. Instead, the stone contains relatively

large amounts of biotite and even some quartz. Large, evenly distributed aggregates of light-coloured talc give the stone a porphyritic appearance (Storemyr 1997).

Table 1: Summary of macroscopic properties of investigated stone types (only stones from Nidaros).

Stone	Colour after exposure	Structure of matrix	Distribution of carbonates	Probable parent rock/origin	Use periods at Nidaros Cath.I
Øye chlorite schist	Green to green-grey, Few brown carbonate veins	Very foliated	Few intersecting veins, and scattered grains	Tectonically altered basalt	Middle Ages
Bakkaunet soapstone (1)	Bluish to green-grey, brown carbonates	Massive to slightly foliated*	Intersecting veins and round aggregates	Ultramafite	Middle Ages, restoration (19th c.)
Grytdal talc-rich chlorite-tremolite schist	Grey to green and brown. Yellow when weathered	Massive to very foliated. Glassy tremolite needles*	Scattered grains, some intersecting veins	Associated with amphibolite	Restoration (19th c.)
Bjørnå talc-rich chlorite-biotite schist	Greenish, with white (talc), brown (carb.) and dark (biotite) grains	Massive to very foliated, some large pyrite crystals	Many scattered grains and a few thin veins	Ultramafite	Restoration (20th c.)
Gullfjellet "soapstone"	Grey talc aggregates, dark matrix	Massive, porphyritic-like	No carbonates	Pyroxenite	Restoration (20th c.)
Bubakk soapstone	Dusty grey, a few brown spots	Massive*	Many scattered grains, very few thin veins	Ultramafite, serpentinite	Restoration (20th c.)
Grunnes soapstone	Dusty grey, many brown carb. aggregates	Massive	Many round aggregates	Ultramafite	Restoration (20th c.)

* The stone is easily scratched with the fingernail

(1) The stone is difficult to distinguish from another soapstone named Klungen (quarry 17 km south of Trondheim)

Table 2: Mineral composition of investigated stone types (only stones from Nidaros). Mineral composition (vol. %) determined by microscopy and XRD (Alnæs1995, Storemyr 1997).

Mineral	Øye chlorite schist	Bakkaunet soapstone (1)	Grytdal talc-rich chl.-tr. s.	Bjørnå talc-rich chl.-bio. s.	Gullfjellet soapstone	Bubakk soapstone	Grunnes soapstone
Talc	0-10	20-30	5-20	10-15	25-35	25-40	30-40
Chlorite	30-40	30-40	20-60	30-40	15-25	25-40	25-35
Biotite	10-20		T	20-30	15-25		T
Hornblende	15-25	10-15	5-10				5-10
Tremolite			5-35	2-5			2-5
Other amphiboles etc. (2)	T	T		2-5	5-15	T	
Dolomite	10-15	10-20	10-20	10-15		5-15	10-15
Calcite	1-5	T	5-10	1-15			
Magnesite		1-5				15-30	5-10
Quartz	5-15		1-5		5-15		
Plagioclase	5-10				1-5		
Microcline					1-5		
Pyrrhotite			1-10		T	T	(T)
Pentlandite			1-5			T	
Pyrite	2	2	T	T	T	T	
Chalcopyrite		1-5	T	T	T	T	
Magnetite		5		2	T		(T)
Hematite		2		1		T	
Other (3)	3		T		T		

(1) The stone is difficult to distinguish from another soapstone named Klungen (quarry 17 km south of Trondheim)

(2) The minerals are: Bakkaunet - possibly cummingtonite; Øye - magnesio-hornblende; Bjørnå - klnzoisite; Gullfjellet actinolite; Bubakk - magnesio-hornblende; Grunnes - pargasite

(3) The minerals are: Øye - titanite; Grytdal - titanite; Gullfjellet - apatite

T Minor or trace amounts

The various soapstones at Stavanger cathedral have not been included in tables 1-2. Contrary to most of the “soapstones” at Nidaros Cathedral, the quarries from where the stones at Stavanger were extracted in the Middle Ages are not properly known, although it may be assumed that the quarries are local ones of Caledonian age. The most common stone at the High-Gothic choir is a soapstone proper (hereafter named “Stavanger soapstone”, fig. 6). It is a very soft, slightly foliated stone with a matrix of relatively fine-grained talc and chlorite, and very large aggregates and intersecting veins of carbonate minerals (mostly dolomite). Carbonate minerals may also occur as well-developed, millimetre-large crystals within the matrix. Many stones contain characteristic “pockets” of very compact and soft green talc/chlorite. Pyrite is a common trace mineral.

Several soapstone deposits can be found in various altered ophiolite fragments around Bergen. One of these stones, perhaps originating from a quarry called Kvernes, has been used at the 17th century north portal of the Church of the Holy Cross in the city centre (hereafter named “Bergen soapstone”, fig. 7). It is a foliated soapstone proper, very much like the Stavanger soapstone, with intersecting veins of dolomite and magnesite. However, contrary to Stavanger, Bergen soapstone contains no sulphides at all, but large amounts of magnetite (Storemyr and Bredal-Jørgensen in Moe 1998).



Fig. 6: Stavanger soapstone



Fig. 7: Bergen soapstone

Typical exposure conditions

The exposure conditions of stone in architecture are extremely diverse and dependent on the design of the building as well as the ambient climate. Bläuer (1987) in her thesis on weathering of *Berner Sandstein* defined eight typical exposure conditions, on which the weathering forms of the stone are dependent, while Zehnder (1982) in his work on *Molasse Sandstein* distinguished between four basic exposure conditions. Adopted from Zehnder, the following scheme has proved helpful for Norwegian conditions (cf. Storemyr 1997):

- Weather beaten architectural elements
(E.g. stone capped parapets, gables cornices, pinnacles etc.)
- Transition zones between exposed and sheltered areas
(E.g. beside run-off zones, sculpture under cornices etc.)
- Relatively sheltered areas exposed to water leaks
(E.g. exterior and interior walls)

Weather beaten architectural elements

A weather beaten architectural element is typically a capstone, a cornice or an ornamental detail completely exposed on top, but relatively sheltered underneath. Such elements actually exhibit all the typical exposure conditions in the scheme mentioned above.

Depending on the actual stone type and the time it has been in service, the typical weathering forms are (fig. 8): 1) Slight to heavy crumbling of the upper surface, usually combined with growth of lichens. 2) Loss of mouldings (or other projecting details). 3) Thinner or thicker black crusts underneath, often combined with various forms of flaking and delamination. It must be noted that the foliated stones usually are horizontally bedded - and not face-bedded - when used in such situation.

Generally, there are very few medieval weather beaten features left on the medieval cathedrals (Nidaros, Stavanger). They have either weathered away or been lost in catastrophic events that affected the whole building, like fire. Thus, most of the weather beaten elements were put in place during restorations in 19th and 20th centuries. Some of the “new” elements weather rapidly - Bjørnå stone for example has a lifetime of 30-60 years before it is so damaged that it has to be replaced. Varieties of Grytdal stone, which is described in a separate section, may have a lifetime of only 10 or 20 years (Storemyr 1997).

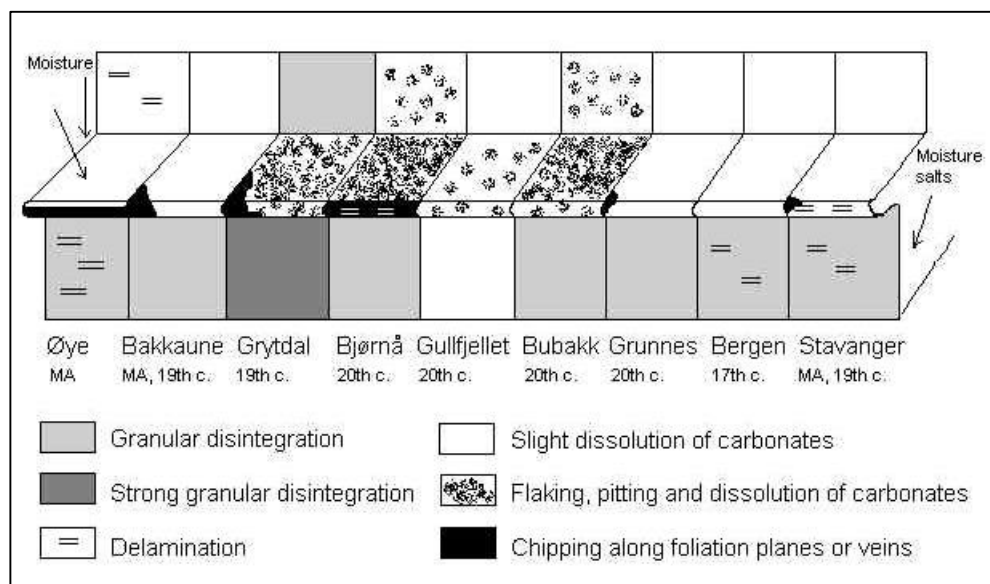


Fig. 8: Behaviour of the investigated stones under typical exposure conditions. Observations have been made both at buildings and relevant quarry faces.

Crumbling of the upper surface

The most universal weathering form, affecting all the stones except Gullfjellet, is dissolution of carbonate minerals on exposed surfaces. Stones with large carbonate veins or well-defined carbonate aggregates (Bakkaunet, Grunnes, Bergen and Stavanger - all soapstone proper) normally show only this type of weathering. The upper millimetre or so of the veins/aggregates dissolves, a strong brown patina develops on the carbonate minerals due to oxidation of trace amounts of iron in the carbonates, but there is no, or very limited, flaking or disintegration of the matrix of the stones.

The rate of carbonate dissolution is generally dependent of the type of carbonate mineral present (calcite dissolves for instance somewhat faster than dolomite), the texture of the rocks, the pH of precipitation and the presence or absence of other acids; for example derived from biological growth. However, the slightly acid nature of “clean” rain is enough to dissolve carbonate minerals relatively fast (as observed at buildings and quarries in different environments). Moreover, taking a broad view, the structure, grain size and distribution of the carbonate minerals are probably of far greater importance for the dissolution rate than the eventual presence of moisture with somewhat lower pH than in “clean” rain. On the other hand, it is clear that the presence of more acid moisture will dissolve carbonates in the same stone at a higher rate than less acid moisture.

Perhaps the lack of disintegration of the matrix in the above-mentioned cases can be attributed to the well-defined distribution of the carbonate minerals. This theory is supported by what happens on stones where carbonates are rather distributed as small grains “within” the matrix (Bjørnå, Bubakk, fig. 9-10). In these cases it may seem that the carbonates dissolves, subsequently “undermining” the rest of the matrix, leaving it open to additional weathering agents, for instance frost and lichens, which may produce flaking and other weathering forms in the stone (cf. Fitzner et al. 1994, Storemyr 1997).



Fig. 9: Crumbling of exposed Bjørnå stone at Nidaros Cathedral



Fig. 10: Crumbling of exposed Bubakk stone at Nidaros Cathedral. The stone to the right is a serpentine

However, in addition to Bjørnå and Bubakk, Gullfjellet (with no carbonate minerals) also exhibits some flaking and disintegration when exposed to the weather. These weathering forms typically develop around the “islands” of rather compact talc aggregates that give the stone a porphyritic appearance. Normally, biological growth (mosses, lichens) leaves the talc aggregates relatively unaffected, while the matrix around crumbles. The mineralogy of the matrix around the talc aggregates consists of biotite, chlorite, coarse talc, some quartz and feldspar. A multitude of weathering processes may be active in this case, of which we could mention a few: Acids (e.g. oxalic acid) from biogenic processes (e.g. lichen formation) may attack the minerals, for instance biotite (cf. Friedl 1999); biotite may break apart by other processes; and chemical dissolution of feldspars may produce very small amounts of swelling clays (although none has been detected by analyses). It is, however, unlikely that chemical dissolution of chlorite and subsequent development of swelling clays (smectite/vermiculite) have taken place.

The latter argument seems to hold for all the stones in question. This is because no such clays have been detected in any of the stones. Since it is known from Norwegian Stone Age rock art sites that after a very long time of exposure, chlorite minerals dissolve or break down in other ways (Walderhaug & Walderhaug 1998), one might argue that the time of exposure in our cases has been too short, and that “soapstones” typically contain Mg-rich rather than less stable Fe-rich chlorite (usually clinochlore).

With regard to (oxalic) acid attack due to biogenic processes, it may also be argued that other stones, perhaps particularly biotite-rich ones and notably Bjørnå and Øye, should become affected. Bjørnå stone is notorious for its “affinity” to biological growth (lichens and mosses), hence the crumbling of exposed surfaces of this stone could partly be attributed to oxalic acid. However, exposed surfaces of Øye stone usually remains very well preserved, even after centuries. This can also be observed in the Øye quarry where enormous amounts of lichens and oxalates (weddelite and whewellite) are present on sound surfaces (cf. del Monte et al. 1987). Additionally, weathering experiments (imitating “natural” cycles of rain, frost and strong sunshine) show that Bjørnå stone, but not Øye, develops flaking and disintegration of the surface when no biogenic processes could have been active (Alnæs 1995, Storemyr 1997). However, in the same experiments it has also been observed (under the stereo microscope) that small biotite grains in Øye stone tend to break apart and “swell” without causing any further damage to the surface. This breaking apart of biotite along the basal planes have not been further analysed. The absence of further damage in the stone may be caused by a stone/pore structure allowing biotite to “swell” without inducing much stress on neighbouring minerals.

In conclusion, it seems that dissolution of the small carbonate grains are indeed responsible for at least the “initial” weathering of Bjørnå and perhaps Bubakk stones. Frost and perhaps mechanical stress induced by the lichens’ hyphens may then cause further weathering. Moreover, biotite may break apart also under no influence of biogenic processes. Whether this is a problem or not seems to be dependent on the stone type in question.

So far only the petrography of the stones (except Grytdal which will be treated separately) have been considered in the effort to explain the weathering forms and mechanisms. Much work remains to be done, though, especially on the texture and structure of those stones that do weather actively at exposed places. Particular attention should be paid to the matrix of intergrown talc, chlorite and other minerals. Furthermore, mineral alterations, especially with regard to the phyllosilicates, should be much more thoroughly investigated.

In addition to petrography, one has to consider the pore structure and the water vapour behaviour of the stones in order to explain the weathering. Obviously, the very low porosity (usually 0,2-1%) in such metamorphic, phyllosilicate stones is more or less confined to micro cracks along the foliation planes. This explains why flaking (and delamination, see below) is such a widespread weathering form.

There are notable differences in capillary water absorption for the stones tested (Stavanger and Bergen have not been analysed yet). Bjørnå, Gullfjellet and Bubakk generally have the lowest absorption, while Grunnes, Bakkaunet and especially Øye show higher values (fig. 11). The more foliated stones of course also have a higher capillary water absorption parallel than perpendicular to the foliation. Moreover, the water vapour diffusion resistance is generally higher in stones with a low capillary water absorption. In conclusion (note that not all stones have been analysed for water vapour diffusion), Øye, Grunnes and Bakkaunet seem to have slightly more open pore structures than Bjørnå, Gullfjellet and Bubakk. This also indicates that when moisture in one way or another has entered the pores of the latter group of stones, it will have relatively more difficulty getting out, leaving the stones more prone to frost weathering at the right time of the year. As can be seen, the weathering forms observed support this explanation.

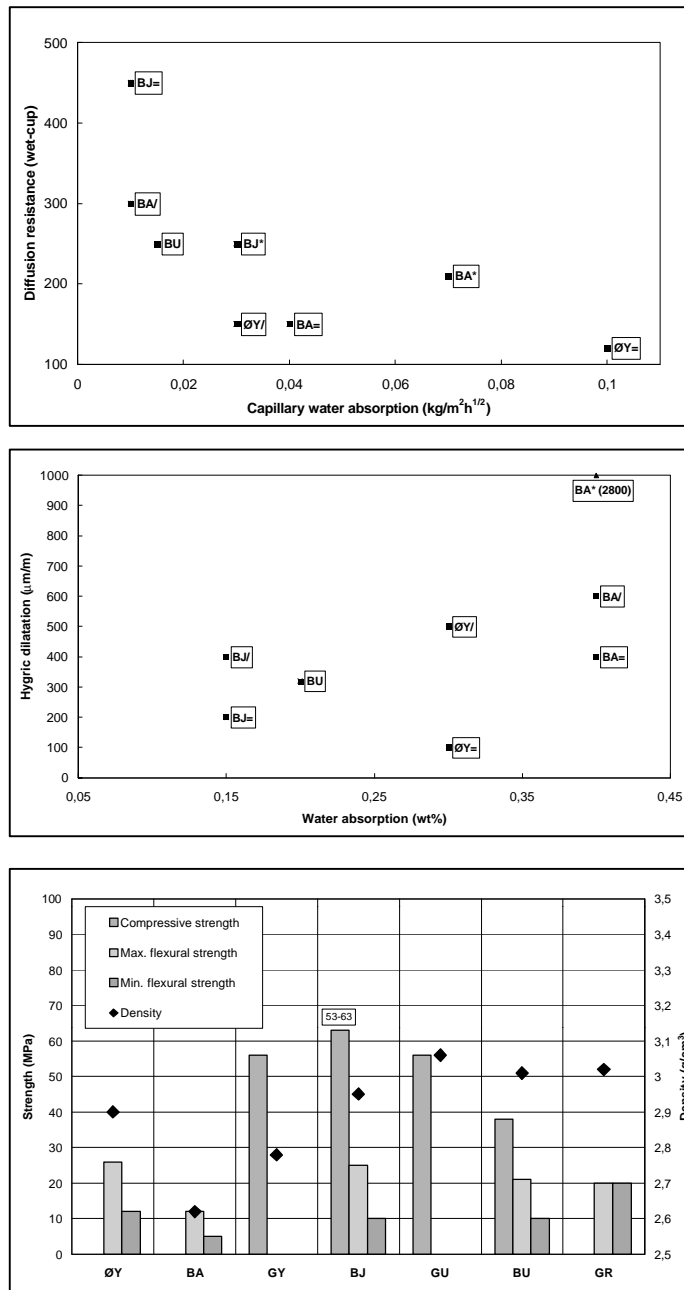


Fig. 11: Water vapour diffusion resistance (top), hygric dilatation (middle) and mechanical properties (bottom) of investigated stones. ØY=Øye, BA=Bakkaunet, GY=Grytdal, BJ=Bjørnå, GU=Gullfjellet, BU=Bubakk, GR=Grunnnes.

*: no foliation, =: parallel to foliation,

/: perpendicular to foliation

Analyses partly by Plehwe-Leisen (1995)

Although no swelling clays have been observed in the weathering zone of the stones, a very interesting question is nevertheless whether hygric dilatation plays a role in the weathering, also because a range of Brazilian soapstones show very high dilatation values (Plehwe-Leisen et al. 1992). Judged from tests of some stones it seems, however, that hygric dilatation is relatively unimportant (fig. 11). Generally, the dilatation values are very low, normally 100-500 $\mu\text{m/m}$ depending on orientation, and particularly water absorption: The higher the water absorption, the higher the hygric dilatation - meaning that the stones which behave “best” under severe exposure conditions show the highest values.

Another phenomenon that should be paid more attention to, is the stone masons’ general experience that especially slates and schists are very soft when wet, but relatively hard and brittle when dry. This is also the case with regard to most stones described in this paper; especially the more foliated ones. In the Øye quarry it can for instance be observed that constantly wet rock fragments are very low in cohesion and extremely easy to break apart along foliation planes, but much more solid when dry (Storemyr 1996). Apart from the fact that when drying out for the first time, a stone often becomes harder since the so-called “quarry-sap” crystallises (Schaffer 1932, Winkler 1994), it is difficult to scientifically explain this phenomenon. And how does it influence the weathering at exposed places - for instance when seen in relation to hygric dilatation and frost?

Loss of carved details at exposed places

The upper surface of a cap stone, a cornice or an ornamental detail eventually passes into carved details, such as mouldings, which are exposed on top, but relatively sheltered underneath. The most severe weathering of such often deeply undercut details is related to the most foliated stones. Typically, stones like Øye, Bjørnå, and sometimes Bakkaunet and

Stavanger (as well as Grytdal that will be treated separately) lose the whole detail or parts of the detail after some decades of exposure. Stones with a more massive structure, such as Gullfjellet and Bubakk, tend not to lose such details.

Normally, pieces are lost along foliation planes alone, or along carbonate veins or thin talc veins running parallel to the foliation. These are natural planes of weakness, but it may be difficult to explain the actual weathering mechanisms in every particular case. Obviously, the pores, which normally appears as micro cracks along the foliation planes, play a great role: Once “saturated” with moisture and subsequently affected by a dangerous frost event, cracks may widen and eventually open completely. It has been observed that frost plays a significant role in this type of weathering of Bjørnå stone (Storemyr 1997:224, fig. 12), but it has also been observed that such weathering of the same stone proceeds rapidly during heavy rain on warm summer days (ibid.). This suggests that swelling/contraction may play a role as well, although, as shown above, the hygric dilatation is very low. In order to explain such weathering forms, one should perhaps once more pay attention to the generally low cohesion of wet, foliated stones (se above). Also, one should investigate the relationship between hygric and thermal dilatation, as has been done on Brazilian soapstone objects (Plehwe-Leisen et al. 1994).



Fig. 12: Icicles forming from string courses made of Bjørnå stone, Nidaros Cathedral. The mouldings had recently to be removed due to dangerous cracks along foliation planes.

Contour scaling is another weathering form that sometimes appears on mouldings or carved details (Bjørnå, more rarely Bubakk). Except for the general theory suggesting that repeated cycles of wetting and drying, without or more often with salts, can produce such forms (Zehnder 1982, Wendler et al.1991), no particular explanation for the phenomenon has been found yet. In the Bubakk quarry, multiple contour scaling is also a widespread weathering form. Here one could suggest that frost play a major role (Storemyr 1997).

Having mentioned salts, one should of course be aware that especially gypsum might form in the more sheltered areas of for instance a moulding. Gypsum may stem from air pollution or from oxidation of sulphides in the stones. In theory it could be possible that gypsum also

forms within the micro cracks of the foliated stones, hence contributing to the loss of carved details along foliation planes. However, in cases where mouldings have been lost, gypsum crystals (or other salts) have not been detected along the opened foliation planes. At Stavanger cathedral, there is a greater possibility for gypsum to form along the foliation planes because many mouldings can be found at somewhat less exposed places, for instance in connection with niches.

Black crusts underneath mouldings and other carved details

The formation of black crusts underneath mouldings and other carved details is not straightforward. It is dependent on the level of air pollution, properties of the stones, former conservation measures, and particularly on the actual exposure conditions (see also Arnold 1984). Generally, in Trondheim, Stavanger and Bergen, it has been observed that the following scheme applies:

1. Water runs freely from the exposed parts to the sheltered parts and further away: very little accumulation of black crusts and rarely any additional weathering problems.
2. The sheltered parts receive little running water, but become wet during precipitation (for instance along open joints): accumulation of black crusts, often followed by various additional weathering forms.
3. The sheltered parts remain relatively dry during precipitation: very little accumulation of black crusts and rarely any additional weathering problems.

Clearly, it is the most foliated stones and those with a relatively open pore structure, that become most damaged under the influence of accumulating black crusts. A few remaining medieval Øye string courses at Nidaros Cathedral are some of the worst damaged (fig. 13): Their finely carved undersides have lost most details, apparently due to formation of gypsum also along foliation planes. Alternatively, it might be that black crusts on the surface have “blocked the pores”, making the details more vulnerable to frost damage. One would suspect that the history of the mouldings also plays a role; they were probably cleaned with hydrochloric acid and lye in the 19th century in order to remove whitewash. This procedure may have rendered the surface more hygroscopic and enhanced deposition of air pollutants (cf. Cooke & Gibbs 1993).

Bjørnå stone from the early 20th century has typically developed black crusts that sooner or later lifts from the surface, a process which also removes a certain surface-near volume,



Fig. 13: Loss of carved detail underneath string course made of Øye stone, probably mainly due to the formation of black crusts.



Fig. 14: Weathering at niches on the east front of Stavanger cathedral. Parts of mouldings are lost in the blind gable

leaving the new surface somewhat disintegrated. However, there are many examples showing that Bjørnå stone often is too dense for gypsum to do any particular damage. This is also the case with many other stones at Nidaros Cathedral. Moreover, some stones (notably Bubakk and Grunnes) have been in service for such a short period of time that black crusts have not been able to form yet - a phenomenon of course also related to the low level of air pollution (SO_2) in recent decades. Some slight flaking connected with gypsum formation has nevertheless been observed at Bubakk stone; this might also be related to oxidation of pyrrhotite in the stone itself.

Black crust formation is a greater problem at parts of Stavanger Cathedral. Typically, the lower parts of mouldings are lost along foliation planes or in a very disintegrated state (fig. 14). In the latter case, relatively "hard" gypsum crusts might conceal a completely disintegrated stone, making it very difficult to remove the crusts without causing a lot of damage. Formerly, such areas were simply removed and replaced by new stone (piecing in). The reason why this problem is so pronounced in Stavanger is manifold, but particularly related to the fact that the actual mouldings are sloping, as they are part of wall niches or other architectural features. This implies that moisture have easier access to the underside of the mouldings where black crusts can accumulate.

In most cases where formation of black crusts and gypsum seems to be the major weathering agent, the actual weathering mechanisms are largely unknown. In addition to the common theory suggesting that crystallisation and/or the thermal behaviour of gypsum is responsible for the breaking apart of stone, several of the mechanisms mentioned earlier in this paper might of course be active. It is also very important to note that there is virtually no new formation of black crusts derived from air pollution in Norway at present. The actions of such crusts/gypsum must therefore be seen in view of for instance dissolution/recrystallisation - in other words a kind of "memory effect" (cf. Cooke & Gibbs 1993).

The Grytdal case

The weathering of exposed elements made from Grytdal stone deserves particular attention since the amount of gypsum produced from the stone itself almost overshadows all other weathering mechanisms that might be active (fig. 15). Moreover, the weathering is sometimes so intensive that it becomes meaningless to distinguish between severely exposed and sheltered areas.

First, it is important to note that there are large variations in stone quality in the Grytdal quarry. Some varieties are quite good; behaving like proper soapstone when used for weather beaten elements. Other varieties might behave like Stavanger or Øye stone. One of the more common varieties, however, completely breaks apart after a few decades of exposure (Storemyr 1997). It is evident that the amount of pyrrhotite plays the greatest role, but also the degree of foliation and other factors might influence the weathering forms and rate. In the discussion below, the pyrrhotite-rich varieties are considered.

Pyrrhotite is an iron sulphide mineral that is unstable under atmospheric conditions. It oxidises to



Fig. 15: Typical appearance of the worst damaged Grytdal stone.

produce sulphuric acid, which will react with available cations from other minerals; in our case notably with calcium and magnesium from dissolving calcite and dolomite. This means that not only gypsum is produced, but also magnesium sulphates (epsomite and hexahydrate). Upon oxidation pyrrhotite also produces iron hydroxide (goethite), which again may oxidise to produce hematite. Another process that apparently takes place in Grytdal stone is the formation of jarosite, which is a water free potassium iron sulphate. The occurrence of jarosite and iron hydroxide renders the stone yellow or brownish.

Once Grytdal stone has been “opened” due to oxidation and subsequent crystallisation of gypsum and other salts, it is likely that the weathering proceeds rapidly also because of other agents, notably frost. However, in some cases the weathering apparently slows down after some decades, especially at more exposed places. Although it has not been investigated, one might presume that gypsum and other salts has been largely washed out, or that the pore system has become so open that neither frost nor crystallising salts can do much more damage. However, in such cases the matrix is usually so fragile that it is possible to break the stone apart by hands alone.

The Grytdal case is extreme, but it shows also what to a lesser degree might happen with stones containing much smaller amounts of pyrrhotite. The important point is that in such cases it may be very difficult to interpret whether gypsum is derived from pyrrhotite or air pollution. Only sulphur isotope analyses can give a correct answer. When other sulphide minerals are concerned, they are usually not doing any particular harm. Pyrite, for example, usually occurs in so well crystallised forms in these metamorphic rocks, that it is rather the minerals around that undergo changes.

Transition zones between exposed and sheltered areas

The discussion in the last chapter touched the weathering in transition zones between exposed and sheltered areas. In this chapter more complex weathering situations in such transition zones will be treated. One typical situation is related to zones of rather well defined, often unwanted run-off, and water splash on stonework, another is related to weathering of complex sculptural and decorative details (fig. 16). Larger, vertical masonry areas exposed to run off/water splash and direct precipitation simultaneously will not be considered. Such areas are normally in very good condition, usually because they are effectively cleaned by rain. This implies that no salts can prevail for longer periods of time.

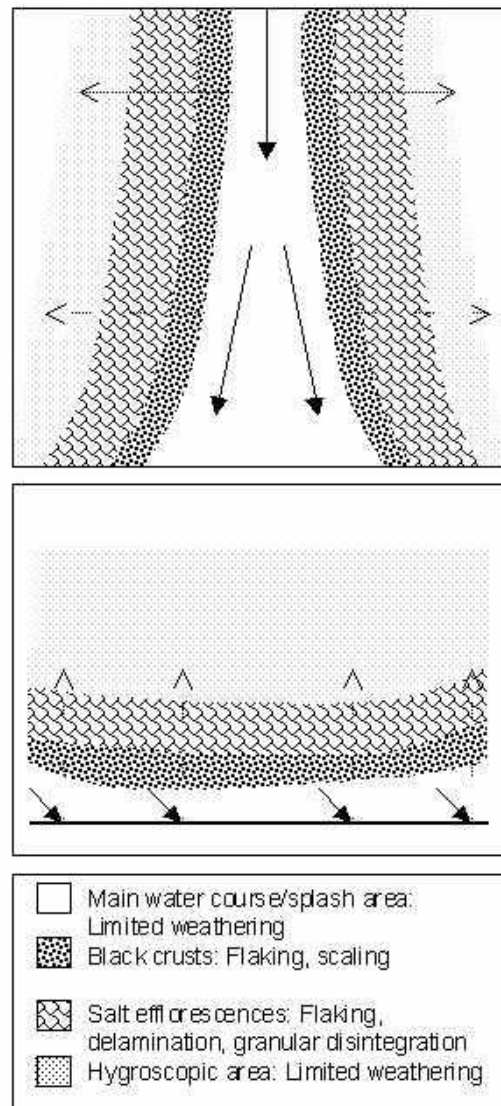


Fig. 16: Idealised representation of weathering in transition zones between exposed (run-off, water splash) and sheltered stonework. In actual cases two or more transition zones may be absent or overlap, creating a more complex picture

Zones of run-off and water splash on stonework

Clearly, once the whole stonework is taken into account, the possible explanations of weathering multiply. It is necessary not only to consider the fact that different stones may be present; one also has to bring in the joint system and the possibility that moisture and salts might be provided not only from “outside”, but also from “within” the masonry.

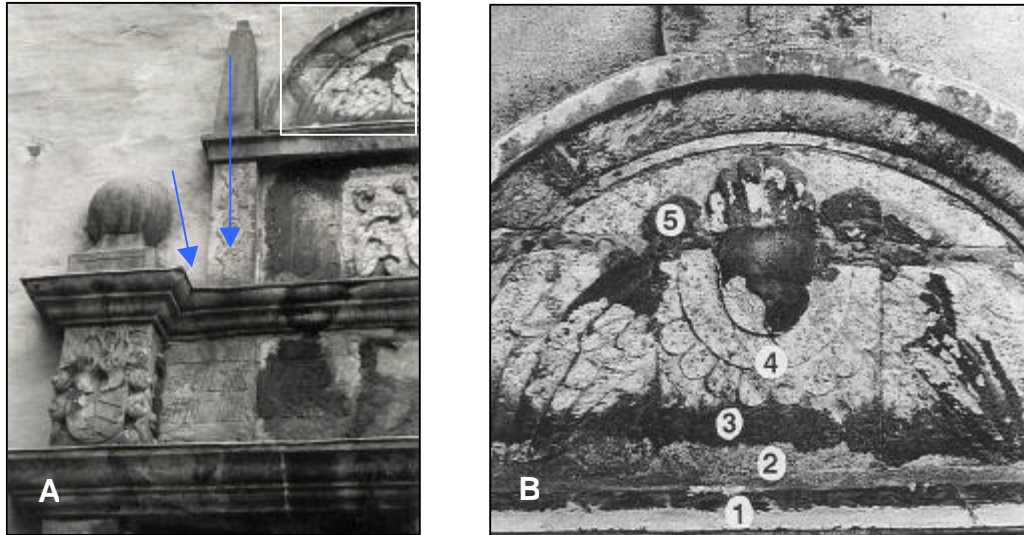


Fig. 17: Weathering at the north portal of the Church of the Holy Cross in Bergen. A) Black crusts accumulate beside water course (arrows), B) Weathering in splash zone; 1) Sill, 2) Washed part, 3) Accumulating black crusts, 4) Areas with salts (gypsum/chlorides) and delamination, 5) Slightly projecting details with black crusts. Black crusts have probably accumulated here because the details are projecting, but not completely exposed. (Photo B from Moe 1998)

The general picture is quite simple, though. If the stone is able to withstand the actions of precipitation alone (for instance Stavanger, Bergen and horizontally bedded Øye stone) the main watercourse or the zone directly hit by water splash will normally be in excellent condition (except for dissolution of carbonates and biological growth). The problems usually begin beside or above this zone. Close to the main water course/splash area is another zone in which black crusts accumulate, normally followed by slight weathering in the form of flaking, delamination and granular disintegration. Further away, the black crust fade out and gypsum crystals or other, more soluble salts take over. At Nidaros cathedral these salts are often sodium sulphates (see below). At Stavanger cathedral and the north portal of the Church of the Holy Cross in Bergen it is more difficult to detect salts in this zone, but in the latter case both chlorides (halite, sylvite) and gypsum are present in great amounts (Moe 1998). This zone is often, but not always, characterised by the most intensive weathering (fig. 17). Depending on the stone type and its orientation, weathering forms range from granular disintegration to heavy delamination, especially when the stones are face-bedded or edge-bedded. In the outermost zone one may sometimes find (unidentified) hygroscopic salts, but otherwise there is normally no severe weathering in this zone, since it gradually passes into either completely exposed or completely “dry” stonework.

Such a system may of course be much more complex than described above. However, it is clear that it represents a salt system in which the capillarity of the stones drives the salts outwards and upwards. The salts are then deposited according to their respective solubility products. For possible sources of the salts: see below).

Similar weathering situations may be found in the zone of rising damp at other buildings than those mentioned above. Bakkaunet and particularly face-bedded Øye stone at the medieval choir of St. Mary’s church in Trondheim for instance show intensive weathering in the zone of rising damp (Storemyr 1996, 1997).

Complex weathering of sculptural and decorative details

Combinations of nearly all exposure conditions and weathering situations described until now may be found at delicate stonework such as sculptural and decorative details. This makes it very difficult to describe the weathering of such details in general terms. Thus, in this section only Romanesque corbel heads made from Øye stone will be described. The corbels are located below cornices in the Romanesque parts of Nidaros Cathedral.

Earlier it has been shown that the change of roof design during the restoration in the 19th century seriously altered the weathering situation and increased the weathering rate (Storemyr 1996, 1997). The old roofs protected the corbels from direct precipitation, whereas the new ones left several corbels more, but not completely, exposed to the weather. Thus, we are confronted with complex transition zones between exposed and sheltered stonework.

Most of the corbels in question are edge-bedded which may initially explain why the most common weathering form is slight to severe delamination. In the worst cases large pieces have been lost along foliation planes, whereas other corbels look like collections of paper with little cohesion between each sheet (fig. 18). In many places black crusts have also accumulated in “micro”-transition zones between exposed and sheltered parts. In contrast to these partly exposed corbels, sheltered ones are still in very good condition. There are, moreover, no black crusts at these corbels.



Fig. 18: Corbel heads made of Øye stone in St. Michael's chapel, Nidaros.

Clearly, the weathered corbels are today situated at very unfavourable locations. The lack of protective roofs and the corbels' edge-bedded nature implies that moisture has easy access to the pore structure: Frost may in other words play a great role. Moreover, gypsum derived from air pollution must be considered, although it has not been investigated whether gypsum actually forms between the “sheets” opening along the foliation. With regard to the source of gypsum, it should also be mentioned that in some of the cornices Grytdal stone was inserted directly above the corbels during the restoration in the 19th century. Consequently, one cannot exclude that seeping water has brought gypsum from this stone in contact with the corbels. To gain more knowledge about the weathering of the corbels and not least which conservative measures that could be applied is of great importance: The 50 corbels in question are some of the most valuable medieval features of Nidaros Cathedral.

Sheltered areas exposed to water leaks and salts

Water leaks bringing large amounts of salts in contact with relatively sheltered stonework, or stonework inside a building, is clearly one of the major dangers for Norwegian soapstone architecture, not least at Nidaros Cathedral. In contrast to most of the exposure conditions treated above, moisture is in the water leak cases provided from “within” the masonry and not from “outside”. Generally, the salt systems that have been found can be classified according to the most common salts present in each system (Storemyr 1997, see also Arnold 1985 and Arnold & Zehnder 1989):

- The carbonate system (alkaline carbonates)
- The gypsum system (with or without chlorides)
- The secondary reaction system (mainly sodium sulphate)

The carbonate system

The simplest and youngest salt system at Nidaros Cathedral is derived from the use of high alkaline Portland cement mortar and concrete during restoration and reconstruction work. It is characterised by two major zones from the leakage point downward (fig. 19): 1) A zone in which calcite crusts (“stalactites stuck to the wall”) originating from dissolution of calcium hydroxide in the cement prevail. 2) A zone in which sodium carbonates (thermonatrite, natrite, trona) and some aphthitalite derived from alkaline components in the cement occur. The solubility products of the salts can explain the reason why calcite crusts usually occur above soluble carbonates. The more soluble salts are able to move farther away from the moisture source. Moreover, calcite crusts are not able to form without the presence of running water, and are therefore rarely present inside the building.

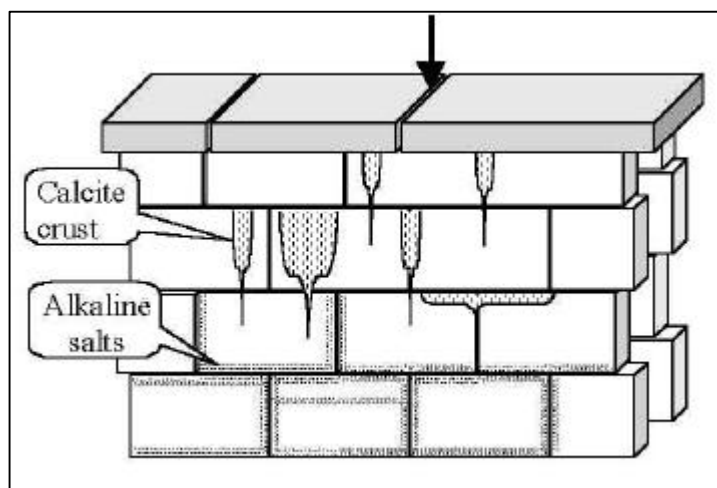


Fig. 19: Schematic representation of the carbonate salt system. The arrow indicates water leakage through open joints.

Particularly Bjørnå and Grunnes stone, but also Øye and Bakkaunet stone, occur in areas with this salt system. These stones weather actively when attacked by sodium carbonates, but it seems that Grunnes is particularly vulnerable. The weathering forms range from the building up of salt crusts (especially trona/aphthitalite), via granular disintegration and delamination, to flaking and slight exfoliation. It is usually only the matrix of intergrown talc and chlorite that is lost, whereas carbonate veins and aggregates are left untouched. It has been observed that when salts for one reason or another are washed away and there

apparently are no soluble alkaline components left in the cement the weathering will come to a halt.

Following the general theories on salt weathering, crystallisation, hydration and dehydration are the active mechanisms in such cases; in other words processes dependent on water leak periods, changes in ambient temperature and relative humidity, and condensation



Fig. 20: West wall of the chapter house at Nidaros. The carbonate salt system consists mainly of trona and aphthitalite from cement mortars, but also some sodium sulphates can be found.

episodes (Charola & Lewin 1979, Arnold 1985, Charola & Weber 1992). Moreover, it cannot be ruled out that frost plays a significant role together with the salts. The question is only how this eventually takes place.

Moreover, there are several additional possible mechanisms to consider in these rather extreme cases: What about hygric dilatation, for example connected with ion-exchange processes, when such large amounts of alkaline salts are present? Could chemical effects play a role, for instance like alkali-aggregate (alkali-silica, alkali-carbonate etc.) reactions in concrete (cf. Jensen 1993)? In this connection it should be mentioned that brick apparently breaks down under the influence of alkaline solutions when no crystallisation processes could have been active (von Konow 1989).

The gypsum system

Contrary to the carbonate system, the gypsum system preferentially occurs at the older parts of the buildings not much affected by Portland cement during restorations. The system may contain gypsum alone, but some magnesium sulphate (epsomite, hexahydrate) and chloride (halite) is often present as well.

The sources of these salts are relatively straightforward: Gypsum and magnesium sulphate may be derived from the stones

(sulphides; cf. the Grytdal case), from (lime)mortar and brick in the walls and from (former) air pollution. Chloride may stem from the sea or from former acid cleaning (hydrochloric acid and sodium hydroxide in combination). It should be stressed that although air pollution is mentioned as a possible sulphate source (dry and wet deposition), there are rarely black crusts present in these cases. One reason may be that the weathering proceeds relatively rapid, making it difficult for black crusts to "find a foothold".

Apart from the notorious Grytdal stone, there are examples of Øye, Bakkaunet and Stavanger stone located in masonry affected by this salt system (fig. 22). One of the most common features is that although the stones weather in the form of granular disintegration and delamination, it is almost impossible to observe salts with the naked eye. Since gypsum and talc have quite similar optical properties, it is also very difficult to observe gypsum under the microscope. However, once X-Ray Diffraction or chemical analyses are done, one detects relatively large amounts of gypsum in nearly all cases. Moreover, other salts are usually present only in trace amounts. This type of weathering is very similar to what can be observed at relevant sheltered quarry faces (Øye, Bakkaunet, fig. 21), implying that the stones themselves must be considered very important salt sources (Storemyr 1997).

Interpreting the actual weathering mechanisms is not as difficult as with the alkaline salt system, since we are probably mainly dealing with crystallisation and dissolution/-

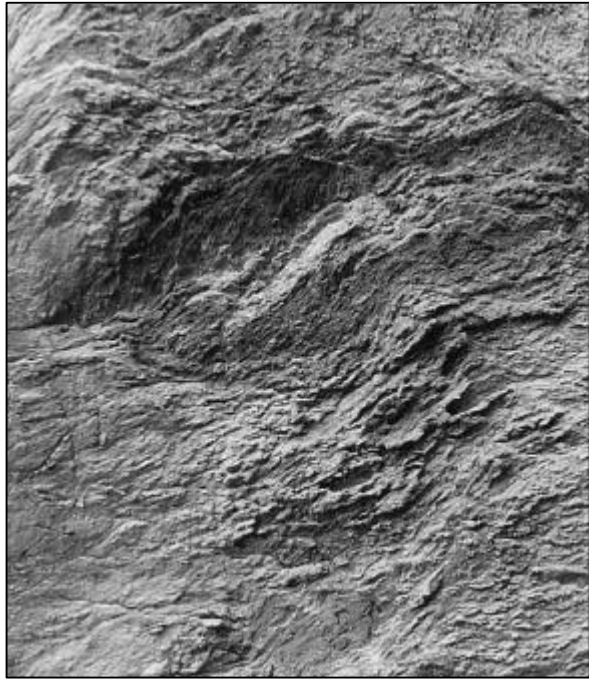


Fig. 21: Flaking and delamination at a sheltered rock face in the Øye quarry. Gypsum seems to be responsible for the weathering. Note pyrite aggregate (light/yellow).



Fig. 22: Granular disintegration and delamination at a sheltered part of the south wall at Stavanger Cathedral. Former leaks may have brought large amounts of gypsum into the stonework.

recrystallisation of gypsum (and other salts). However, the role of the other salts, for instance the possible increased deposition rate of SO_2 in the presence of chloride (Cooke & Gibbs 1993), are largely unknown, as is the role of frost (cf. Wessmann 1996).

The secondary reaction system

When the carbonate and gypsum systems come into contact with each other, for instance due to water leaks penetrating a new part of the building situated above an old one, chemical reactions take place. Alkaline carbonates are not stable in the presence of sulphates, thus the most common salt encountered in such areas is sodium sulphate (thenardite/mirabilite) (Arnold 1985, Arnold & Zehnder 1989). Depending on the design of the actual area, availability of moisture and different ions, the typical salt system consist of thenardite/mirabilite, gypsum, perhaps some epsomite/hexahydrate, and remains of thermonatrite/natrite about to react with sulphate.

This salt system is very common at Nidaros Cathedral (fig. 23) and many other medieval buildings in Norway. The weathering forms and problems in interpreting weathering mechanisms should be more or less the same as described above.

Other weathering phenomena: fire and corroding dowels

Two additional weathering phenomena are important in Norway and therefore deserve attention: The effect of fire on soapstone and the effect of corroding dowels and cramps.

Due to the fact that Nidaros Cathedral has burnt five times (for the last time in 1719) masonry affected by fire can be found in several distinct places. However, except for cracks and colour change to brown and red, there are normally no problems in such areas. The surface of the stone is in other words rather stable if not additional weathering agents, such as



Fig. 23: The choir at Nidaros cathedral. Reconstructed in the 1880s (left), the choir today exhibits severe salt weathering (right). Salts present include calcite crusts, some sodium carbonates, but first of all gypsum, magnesium sulphates, sodium sulphates and a little chloride (secondary reaction system). The most important salt sources are Grytdal stone, brick in the inner walls and Portland cement mortars.

salts, are effective. When salts are present, it seems that the weathering proceeds relatively rapid, probably due to a more open pore structure (micro cracks) produced by fire.

The effect of fire was investigated by Prestvik (1988) following the fire in the Archbishop's Palace in Trondheim in 1983, which destroyed hundreds of soapstone sculptures. Although soapstone is rather heat resistant, Prestvik showed that at 700-800°C, chlorite breaks down to an X-Ray amorphous phase which optically resembles ferrichlorite. Moreover, carbonate minerals oxidise and undergo grain-size reduction (calcination). He explained the colour change as oxidation of Fe^{2+} to Fe^{3+} both in chlorite and carbonate. Fe^{3+} seems to enter the crystal structure of altered chlorite or occur as a fine-grained stain of hematite. Talc, amphibole and biotite appear not to be affected at these temperatures (see also Carstens 1924).

Dowels and cramps used to fix decorative and sculptural details are very common at medieval cathedrals and other stone buildings. Fortunately, dowels and cramps made of iron have since long been replaced by brass, copper or stainless steel at Nidaros Cathedral, implying that there are very few corrosion problems at present. However, at Stavanger Cathedral and a couple of 17th and 18th century portals in Bergen there are many iron cramps with much corrosion, resulting in major cracking and loss of details. At Stavanger the iron cramps are currently being replaced with stainless steel. One must presume that air pollution and perhaps sea salts have accelerated the corrosion of iron cramps and dowels.

Summary and outlook

This paper has given an overview of the current knowledge about the weathering of Norwegian soapstone. It has been shown that the term soapstone also encompasses various talc-rich schists and that the major weathering problems are related to loss of carved detail along foliation planes at exposed places, and heavy crumbling when great amounts of soluble salts are present in sheltered or partly sheltered locations.

It has also been shown that there are major gaps in our understanding of soapstone weathering. The influence of petrography on weathering at places exposed to direct precipitation, frost and biological agents are not properly understood. Moreover, the relative importance of frost, crystallising salts and other agents, especially related to weathering at partly exposed places, should be investigated more carefully, as should the weathering mechanisms when soapstone is affected by alkaline salts.

In order to mitigate the evolution of weathering processes at stonework made of soapstone, the general rule applies: think in terms of preventive measures, such as avoiding water leaks and applying protective structures where possible and sensible. However, in order to avoid stone replacement programmes, one also has to think in terms of direct conservation measures, of which the most important ought to be various forms of desalination and cleaning procedures, filling in cracks and gaps with suitable materials and consolidating weathered structures. Since there is almost no experience with direct conservation of soapstone, basic research certainly has to be carried out first.

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**"Weathering and conservation of soapstone":
Report on the fieldwork at Nidaros cathedral, Trondheim (N),
15 - 19 June 1999**

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Introduction

This personal note on the object and the project is based on fieldwork undertaken together with Per Storemyr (project manager) and Eberhard Wendler (conservation specialist), in parts also by Tom Heldal and Maarten Broekmans (geologists from the Norwegian Geological Survey). The aims were to get familiar with the object and its conservation problems, and to discuss and draw up the specific items of the project. The project, which is a part of the EU Raphaël Programme, aims at introducing and providing an appropriate 'conservation strategy' for the cathedral (particularly of the medieval parts). Conservation means, strictly understood, to repair existent and prevent forthcoming damages on the monument. In a more general sense, it means to *preserve the monument as an integral and authentic historical structure* for a long term.

Remarks to the object and to the weathering situation

Our observations during the fieldwork went out from, and were related to the extensive work done by Per Storemyr and the insight he gave us to the object. A personal impression of the cathedral's weathering situation might be summarised by these two features:

1. The exceptional quality of soapstone. It is an extraordinary construction material with a peculiar appearance, workability and weathering resistance. Its preservation on the

cathedral ranges from very well preserved, weather beaten stones of the Middle ages, to badly weathered stones of the 19th and 20th centuries.

2. Water infiltrations combined with alkaline salts have produced the most evident and widespread stone damages. The salts stem from alkaline building materials which have been used in large quantities as portland cement mortars and concrete. They are activated by run-off water which enters through fissures and open joints (due to settlements), enhanced by insufficient drainage systems and poorly constructed roofs. Correspondingly there are numerous water leaks in the interior of the cathedral as well. Hence, the most important weathering processes are salt crystallisations (and recrystallisation) besides of the actions of wetting and frost. Of course, analogous situations are found on many other historical buildings, in particular as their construction history is as complex as is the case of the Nidaros cathedral.

Damage assessment - Risk assessment - Conservation strategy

At first glance one is tempted to explain the present deterioration of the cathedral as a result from a continuously ongoing or even accelerated process. However, weathering proceeds rhythmically, episodically, or by singular events. This is manifest e.g. in the case of water leaks. Weathering is activated by each water intrusion, and it slows down or stops subsequently. So weathering activities and weathering patterns may change with time according to the changed conditions. *What we see today on the weathered structure is the sum of all decay events* which occurred during a certain period (e.g. since the last restoration) at a certain place.

Therefore the *damage assessment* on the cathedral has to find out rigorously whether, and to what degree, decay is active or not, and to trace active decay back to its most important causes. This obliges the responsible persons to be aware of and to understand the relevant weathering processes.

In a further step, the *risk assessment* evaluates the most important present and potential future threats. This is the basis for the necessary preventive conservation measures. Interventions are indirect (influencing the conditions), or they are direct (influencing the affected materials themselves). This demands the knowledge of preventive conservation and materials repair techniques.

As a general proceeding in conservation it is recommended to

- 1) identify the materials and damages,
- 2) identify and characterize the damage processes,
- 3) evaluate the risks and
- 4) act in order to prevent further damages as much as possible.

Important issues for the Raphael project and the conservation strategy on the Nidaros cathedral are therefore:

1. Detect the causes of active decay. This needs some further research on the weathering situations, stone properties and weathering processes.
2. Eliminate the causes (sources) of active decay. This needs an appropriate maintenance such as "simple" practical interventions (e.g. on roof constructions and drainage systems), but also some further research on new, appropriate conservation materials and techniques. As an example, the cathedral's damage history illustrates the significance to avoid harmful

materials. This necessitates a profound knowledge and a sufficient caution on what is done on the object.

3. Prevent further decay as far as possible. Like issue 2, this is the task of an appropriate maintenance. Direct and indirect interventions may reduce the deterioration velocity, or reduce and eliminate specific threats. This means to manage the risks by continuous monitoring and, again, by cautious interventive actions.
4. Repair the effects of previous decay (the existent damages). This is strictly seen not only a conservation but also a restoration measure. It joins to issues 2 and 3.

It is stressed that the *specific risk assessment for each part and for the cathedral as a whole* is of primordial practical importance because it provides the tool to recognize the urgency of interventions on a particular part of the object, or in the case of doubtful situations and/or conservation methods, to evidence the need for doing strictly object-related research.

Conclusion

The outstanding importance and the unique character of the Nidaros cathedral obliges to undertake its conservation in an extremely conscientious and careful way. As there is almost no experience with conserving soapstone buildings, long term scientific research is needed to develop appropriate conservation measures, and to assist the workshop of the cathedral in order to sustain a continued and improved practical experience. This task of course supplements the indisputably maintenance practices.

Sustained care by minimal but appropriate interventions needs a differentiated understanding of the threats and a continued monitoring. However, it is the way to preserve the materials and structures authentic and to act economically.

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