

# Weathering of soapstone in a historical perspective

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## Abstract

Soapstone is a main material used in Norwegian medieval stone architecture. It is a metamorphic, dense and durable stone, but like other stones, it is occasionally subject to severe weathering. This paper gives an overview of the core issues related to outdoor soapstone weathering in Norway and shows how the weathering has changed over time. First, objects that evidently weathered quite strongly during the Little Ice Age (14th–19th century), especially in the countryside, have now been relatively stable for a hundred years or more. Although a multitude of weathering processes might have been active, this could point to a higher frequency of damaging frost events in the Little Ice Age than at present. In the case of former ruins, the present stable condition might also be related to good roofing and less moisture in the masonry. Second, the weathering was in complex ways, often governed by changes in architectural design, influenced by air pollution in the cities from the late 19th century until the recent drastic reductions in SO<sub>2</sub> emissions. Third, alkaline salts from Portland cement, sulfate from air pollution and some stones, as well as chloride from acid cleaning, greatly enhanced the salt load at many monuments in the 19th and 20th centuries, giving rise to severe weathering, especially at places where water leaks and damaging run-off have prevailed. This situation obviously continues to be problematic.

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## 1. Introduction

Soapstone has been quarried, used and appreciated since the dawn of civilization. This talc-rich, metamorphic rock is very soft, heat resistant and dense—properties that made it a perfect material for vessels,

cooking pots and all kinds of small utensils and sculpture, and for fireplaces and stoves. In some countries, soapstone was 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 [1]. The best example is Nidaros cathedral in Trondheim, built between the 11th and the 14th centuries and heavily restored between 1869 and 1969. Although generally a durable material, soapstone at Nidaros cathedral and many

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other old buildings in the country exhibit serious weathering problems. Why is it so?

Weathering of stone at monuments is, to a large extent, determined by environmental conditions and the petrographical and petrophysical properties of the stone. In many cases, the weathering processes can be readily explained by reference to such properties and conditions alone, but more often, a satisfactory understanding of the weathering phenomena requires additional, in-depth studies and monitoring of actual exposure conditions (“microclimate”) and the structures and material assemblages in which the stone is situated [2].

The environmental conditions are not constant. Rather, they constantly change, on the one hand, over very long time spans and with regard to air pollution and, on the other hand, according to daily and seasonal weather/climate cycles and the occurrence of hardly predictable events, such as catastrophic fires, hurricanes and heavy condensation [2]. How the monument is actually exposed may also change significantly during its lifetime, e.g., according to more or less dramatic architectural design changes, various uses of the monument (e.g., changes in indoor climate) or alteration of the surrounding infrastructure. The stone itself may also undergo changes, which may alter its susceptibility towards weathering. Paint and plaster may be stripped off, and it may be conserved and consolidated with various means and materials.

Such changes imply that other weathering processes may have been active in the past than those we perceive at present and those that might determine the future fate of a monument and its stones. To understand properly the weathering processes at present and in the future, we have the possibility of directly monitoring the evolution. For the understanding of what has actually led to the present condition and the rate of weathering until today, there is no other way than using the much overlooked historical records of the monument and its surroundings, to undertake what we may call “retrospective monitoring”.

Retrospective monitoring is the primary method used in this paper, in which the intention is to (1) show the historical and climatic context in which soapstone weathering occurs, (2) review the current knowledge on soapstone properties and typical weathering phenomena, and (3) show the complex historical evolution of important weathering phenomena by

selected cases. The general aim is to track significant changes in outdoor weathering phenomena since the late Middle Ages, through the Little Ice Age, until the 19th century, and during the modern period of industrialization and the modern restoration wave from the 19th century onwards. Case studies carried out over the last 10 years form the basis of the paper.

## **2. A brief history of medieval soapstone monuments and their restoration**

About 270 stone churches and monasteries and a number of secular stone buildings were erected in the medieval period in Norway [3]. In many parts of the country, local and regional soapstone was used for decorative purposes at these buildings, and a few structures were even built using finely hewn soapstone as the primary construction material, together with local hard stone (e.g., Nidaros and Stavanger cathedrals and several churches in Bergen). In the 14th century, Norway was severely hit by the Black Death and later came under Danish rule for almost 400 years (until 1814). Together with the fact that Romanesque and Gothic buildings went out of use or became unfashionable in the post-Reformation period, this implied that a large number of them suffered from financial shortcomings and neglect and sometimes fell into ruin, if not being heavily rebuilt according to the style of the Renaissance and Baroque times [3]. In the post-Reformation period, very little finely hewn natural stone was used for building purposes in the country, although we have examples of fine soapstone portals from that time. It was not until the middle and late parts of the 19th century that stone again became important as a building material, now as part of nation building and associated reconstruction and restoration of medieval edifices, as elsewhere in Europe [1,3]. The demand for soapstone thus strongly increased, and many medieval quarries were reopened. As they ran out of stone, new ones were opened nationwide and worked until the “concrete age” was introduced in the first half of the 20th century. In addition to fireplaces and stoves, soapstone is presently only used for minor restoration purposes, especially at Nidaros cathedral.

From a weathering perspective, the 400-year long “decay period” and the large restorations in the 19th

and 20th centuries are particularly important. The reason why many structures fell into ruin or suffered heavy weathering was probably often connected to fires, natural hazards such as storms and, of course, the inevitable water leaks, biological growth and heavy frost damage following the loss of roofing. When not falling into complete ruin, many churches were, however, adequately repaired and refurbished [3], sometimes by using supporting buttresses for structurally damaged parts and lime plaster for the walls. Moreover, roofs were often well made, with projecting eaves that protected walls and decorations.

An important task at the largest buildings during the first phases of the restoration campaigns from the late 19th century onward was connected to structural repair. In addition, much reconstruction took place on the basis of assumptions of how the buildings might have looked like in the Middle Ages. In this way, especially at Nidaros cathedral, 16th–18th century roofs were often sacrificed and replaced by less protective Neogothic ones. Massive stone replacement using good and, at times, poor quality soapstone containing much sulfide was a major activity, as was the removal of lime plasters and paint to show the old, “natural” stonewalls. Such removal was often done using a combination of mechanical and chemical means, of which the latter included hydrochloric acid and lye. A major activity was also the redressing of weathered stone [4].

One of the greatest advances in the building industry of the 19th century was the introduction of Portland cement, which increasingly replaced traditional lime mortars and plasters. Until Norway acquired its first factory in 1892, Portland cement was imported from Britain and Germany and put in massive use for restoration purposes, especially in Trondheim, as early as the 1860s and 1870s [4]. It continued to be used for the repair and conservation of Norwegian stone buildings until quite recently, but as cracks, moisture and alkaline salt problems became increasingly evident, lime mortars also began to be used again in Norway.

### 3. Climate history since the Middle Ages

Norwegian stone monuments are mostly situated relatively close to the coast or along fjords, where the

ambient climate is generally maritime temperate, with cold to mild winters and cool to warm summers. There are large geographical variations in temperature and precipitation, though. Whereas the Bergen district receives as much as 2300 mm and more precipitation annually, Stavanger picks up a moderate 1200 mm, Trondheim about 900 mm and Oslo less than 800 mm. Snow is frequent in Oslo and Trondheim and much less common, in some winters even rare, in Bergen and Stavanger. Annual temperatures are lowest (5–6 °C) and vary most in Oslo and Trondheim, whereas those in Stavanger and Bergen are mild (7–8 °C) and buffered because of proximity to the Atlantic Ocean [5]. Over the last 3 years, Trondheim has experienced circa 50 freeze–thaw cycles (one cycle is defined by “mild to cold to mild”) annually, of which some 20 included drops to less than –4 °C or lower. This figure does not include cycles governed by sunshine at the south sides of monuments. Storms are common in autumn and winter, especially along the west coast, and westerly winds bring most precipitation, also extreme rainfall events (and sea salts), thus, the “weather side” of buildings is usually the southwest to northwest facade. Spring is usually the driest season in the country and the main period in which salt crystallization occurs. Condensation and white frost on exterior facades are not uncommon in autumn and winter.

The majority of monuments built from soapstone in Norway were constructed during the warm medieval period, which lasted until the 14th century. Although still debated, in this period, the average temperature may have been in the range of what we have experienced over the last 10–15 years [6]. After circa 1400, as the Little Ice Age began, it appears to have become colder, with temperatures generally 1–2 °C lower than today. Historic sources indicate a relatively high frequency of storms, floods, glacier advances and landslides (and famines) in this period, which lasted until the middle of the 19th century. However, the general precipitation pattern in this period seems to be less known. The temperature in the 20th century has gradually increased, especially over the last decade. Although fiercely debated, this phenomenon is generally attributed to manmade global warming. These general trends are followed by large variations over shorter time spans: There were exceptionally cold and very warm decades in the

warm medieval period and the Little Ice Age, respectively [6,7]. The regional climate prognoses for the next 50 years indicate that the minimum winter temperature and winter precipitation, especially along the west coast, may increase significantly and be followed by more storms [7]. Generally, this could imply less snow and frost, but more intense rainfall. However, in specific regions, this may also imply more snow and more frequent temperature variations around the freezing point.

The possible impact of climate change on stone weathering processes at monuments is hardly known because little research has been carried out so far. It is, of course, tempting to speculate on generally more frequent frost and moisture damage in the Little Ice Age than today, as Peter Brimblecombe does for Britain [8], especially because this long period was characterized by frequent problematic sociocultural circumstances in Norway. Repairs to monuments may have generally not been carried out immediately after, for instance, storm damage to roofs, and thus, subsequent moisture, frost and biological growth may have contributed to more intense stone weathering than otherwise would have been the case. In Britain, it has been shown that the actual number of freeze–thaw cycles were higher in the Little Ice Age than today [8], but no such data are yet available in Norway. With the complex Norwegian geography in mind, it is even possible that many places experienced fewer, but stronger, freeze–thaw cycles in the Little Ice Age, as compared with the present situation.

Whether higher temperatures and more intense winter precipitation in the near future will have drastic consequences is, as in the Little Ice Age, strongly dependent on how maintenance is organized and carried out.

#### 4. The history of air pollution

Compared with the UK and places on the European Continent [8], local air pollution came late to Norway and has rarely reached extreme concentrations. The history of air pollution in, for instance, Trondheim started in the early 19th century, when heating with coal commenced and small industrial enterprises were established.  $\text{SO}_2$  concentrations increased towards 1900, and on the basis of population increase, heating fuel statistics, industrial development and observations of black crust development on facades (from photographs, see Fig. 11), it has been estimated that average concentrations in the cold season barely exceeded  $40 \mu\text{g}/\text{m}^3$  between 1920 and the late 1970s [4]. Since then, there has been a drastic decrease to  $5 \mu\text{g}/\text{m}^3$  or below at present (Fig. 1a). Emission of  $\text{NO}_x$  and suspended particulate matter from traffic has increased during the last decades, and the concentration of  $\text{NO}_x$  is, at present, in the range of  $40\text{--}60 \mu\text{g}/\text{m}^3$  in the cold season [9]. Nevertheless, Trondheim is and has been a relatively “clean” city. Moreover, it has hardly been affected by acid rain from the European Continent and the UK, implying that dry deposition of

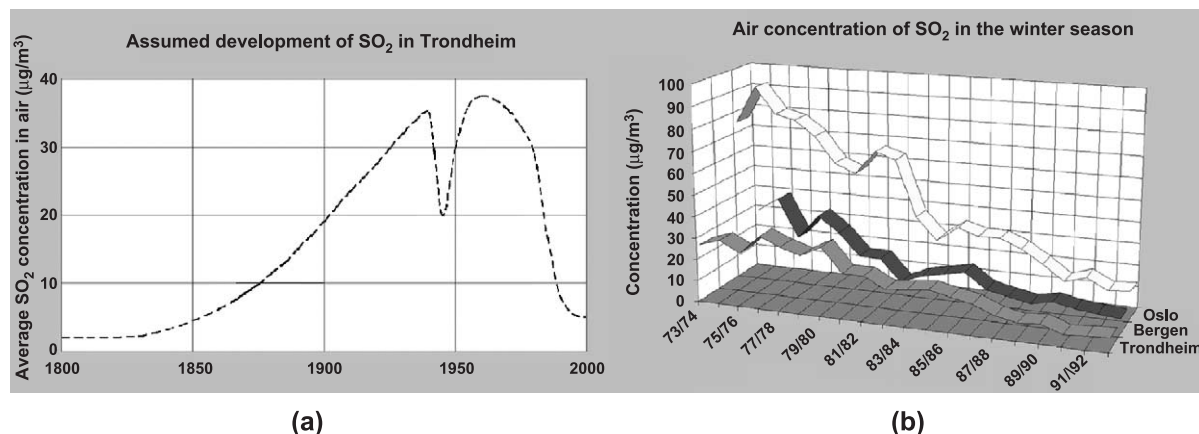


Fig. 1. Development of average  $\text{SO}_2$  concentration in the winter season. (a) Estimate for Trondheim since 1800 [4]. (b) Measurements since 1973 [9].

locally produced pollutants has had the major impact on buildings. Situated in the south of Norway, both Stavanger and Oslo have been affected by acid rain. Generally, these cities, as well as Bergen on the west coast, have been more polluted also with regard to local air pollution (Fig. 1b) [9].

## 5. Geology, petrography and autochthonous salt content of soapstone deposits

The term “soapstone” is derived from the “soapy” or “fatty” surface of the stone and is probably also related to the fact that the stone is so easy to carve. When talc takes a massive form and its content in soapstone approaches 100%, one often uses the term “steatite” or simply “talc”. “Soapstone” is also used for other kinds of soft rocks, like talc schist and serpentinite with high talc content [1]. Moreover, soft chlorite schist with low talc content, often derived from the tectonic transformation of basalt, has been called soapstone in Norway. Such stone has slightly different properties from soapstone but is treated in this paper because it is an important stone,

occurring together with soapstone in medieval monuments [10].

Soapstone originates from metamorphic alteration of various magnesium-rich rocks, such as peridotites and dolomitic carbonates. The softness of soapstone is determined by soft, flaky minerals, of which talc is the most important constituent. Other common minerals are chlorite and carbonates (calcite, dolomite and magnesite-breunnerite), while amphiboles, such as tremolite-actinolite, as well as small amounts of mica, occur in some deposits. Common opaque minerals include magnetite, pyrite and pyrrhotite. In deposits where the transition from olivine, pyroxene and serpentine is incomplete, relics of these minerals may be found [1].

Soapstone is found at a large number of locations in Norway (Fig. 2). It occurs essentially in the marginal part of ultramafic (peridotite) bodies and/or in shear-zones in the internal parts of such bodies and is of both Precambrian and Caledonian age. Some primary sources may have been eroded in Middle Ordovician time, forming deposits of serpentine conglomerate and sandstone, which later have been partly or completely transformed to soapstone. Thus,

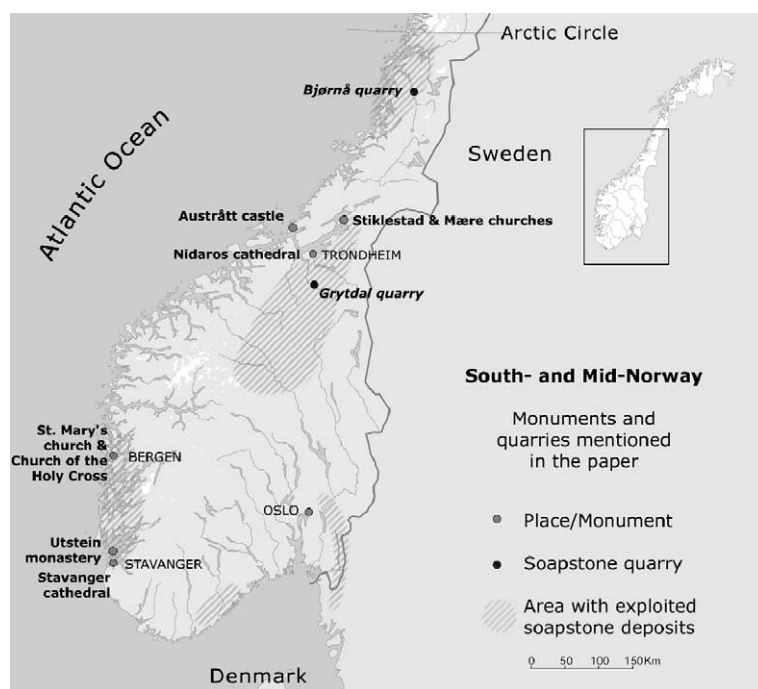


Fig. 2. Map of Norway with places mentioned in the paper.



in a number of soapstone deposits, especially in the Gudbrandsdalen area (eastern part of Norway), sedimentary structures can be recognized. Only one deposit derived from dolomite is yet known in Norway [1]. In addition to the primary rock source, the characteristics of soapstone deposits are strongly influenced by metamorphic grade and deformation history. The mineralogy and grain size vary with metamorphic grade, and deformation contribute to varying degrees of foliation, shear zones and cracks (Fig. 3).

Studies in ancient Norwegian quarries indicate that the main autochthonous salts produced by weathering are gypsum and various magnesium sulfates. This is mainly due to the oxidation of sulfides. In some Norwegian soapstone deposits, soluble magnesium carbonates forms [11], and sodium carbonates have been observed in deposits in Italy (Chiavenna). Sodium carbonates are, however, not stable in the presence of sulfates and have not been encountered in Norway.

Because it has been so important at Nidaros cathedral, the notorious, so-called Grytdal soapstone, which may contain as much as 10% pyrrhotite, deserves special attention. An unstable iron sulfide mineral, pyrrhotite readily oxidizes to form iron

hydroxides, jarosite, gypsum and some magnesium sulfates, which give rise to massive damage to the stonework [4]. Grytdal was the most commonly used soapstone at the cathedral between 1869 and 1892, in which period the majority of the best-preserved medieval parts were restored. These parts also have the most widespread occurrence of black gypsum crusts, which is normally attributed to the dry deposition of air pollutants ( $\text{SO}_2$  and particulate matter). However, because the Grytdal stone is so commonly used here, one cannot readily blame the formation of black gypsum crusts on air pollution alone. It has been estimated that, given the right exposure conditions, a medium large ashlar with 5% pyrrhotite is able to produce more than 100 g of gypsum. In a moderately polluted atmosphere (like Trondheim earlier), with an estimated dry deposition rate of  $1 \text{ g/m}^2$  per year (as sulfate), given the unlikely situation that all sulfur react to form gypsum, it would take 100 years to produce the same amount of gypsum at the same ashlar [4]. Clearly, without isotope data, which can help trace the source of sulfate, one cannot properly judge the relative importance of air pollution and Grytdal stone as contributors to black crusts, but the estimate shows that the stone cannot be overlooked in this regard.

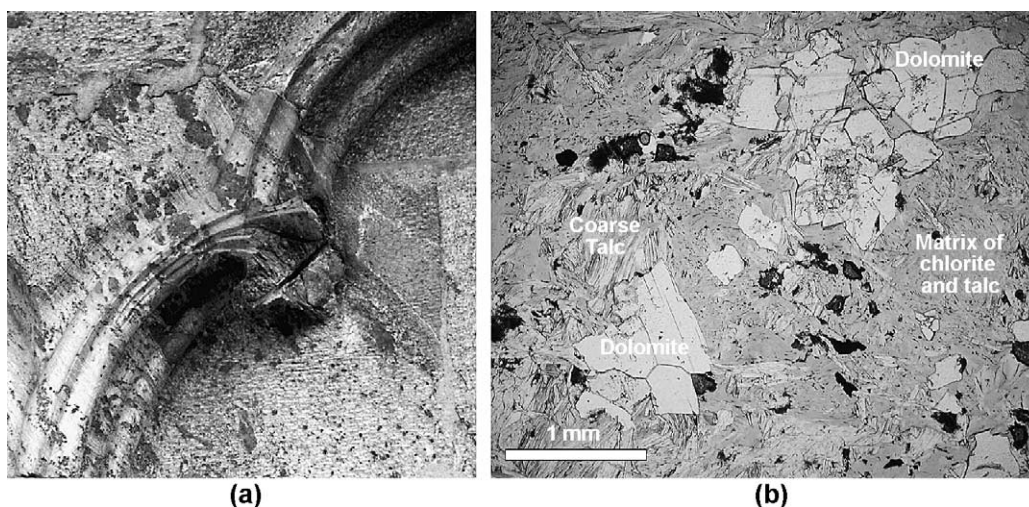


Fig. 3. Typical appearance of Caledonian, foliated soapstone (at Stavanger Cathedral). (a) Light grey areas are rich in talc and chlorite (matrix), dark grey, rich in chlorite and dark veins, are dolomite with a superficial layer of iron hydroxide, probably developed due to the leaching and oxidation of small amounts of iron in the dolomite structure. The ornament has been lost due to a rusting dowel from the 19th century. (b) Photomicrograph in normal light. Dark areas are mostly opaque minerals (magnetite, some pyrite).

## 6. Petrophysical and structural properties of soapstone

Due to strong variations in mineralogy and structure, it is difficult to consistently measure the petrophysical properties of soapstone. Below, an attempt at a brief summary of the most important petrophysical properties, as investigated on 7–8 different soapstones (derived from primary ultramafics) used at Nidaros cathedral, is presented and interpreted in the light of structural characteristics [4,12–14].

The maximum water-accessible porosity is in the range of 0.5–1.0 vol.%, whereas mercury porometry shows that there are usually no distinct pore classes in soapstone. This implies that the porosity is mostly confined to the microfissures of various thicknesses along the foliation. In less foliated soapstone, bimodal pore size distributions may occur, but also, in such cases, intergranular microfissures probably represent the main pore spaces. All stones contain pores also in the range below 0.1  $\mu\text{m}$ , i.e., in the range where capillary condensation can take place. Capillary water absorption is usually slow (in the order of 0.01–0.05  $\text{kg}/\text{m}^2\text{h}^{1/2}$ ), and desorption is mostly slower than absorption. Moreover, water is generally more rapidly absorbed/desorbed parallel to foliation. Water vapor diffusion studies show that, compared with sandstones, the diffusion resistance is particularly high in moist soapstone. However, because the actual uptake of water during rain is low, even less than sandstone treated with water repellents, soapstone usually dries up very quickly after a moderate rainfall. Despite their low water uptake, soapstone shows hygric swelling rates of 200 to more than 1000  $\mu\text{m}/\text{m}$  (higher perpendicular than parallel to foliation). Values around 1000  $\mu\text{m}/\text{m}$  are similar to many types of sandstone with a much higher water uptake. However, due to the low capillary water uptake of soapstone, such values may rarely be reached in real situations. Because of its metamorphic structure and large amount of (soft) phyllosilicate (flaky) minerals, soapstone has a high biaxial flexural strength (10–30 MPa); it is a “tough” stone. The compressive strength is of course relatively low, usually 30–60 MPa. A range of salt crystallization tests show that various types of soapstone may behave quite differently. Generally, the more porous types and those with a

relatively fast desorption are most vulnerable to salt crystallization damage.

## 7. Weathering forms and mechanisms

The typical weathering forms on soapstone are strongly dependent on exposure conditions and do not differ essentially from those of other stone [4]. Spalling and cracking involving loss of smaller and larger pieces usually occur at places strongly exposed to precipitation (rain, snow, and ice), such as cornices and capstones, as well as at exposed ornaments and sculpture. This weathering form is clearly related to soapstone structure, usually following the foliation or thin talc and carbonate veins. Strongly foliated stone may show delamination at exposed places, implying that the stone structure opens along the foliation, but that loss of pieces is not necessarily involved. This weathering form also occurs in transition zones between rain-exposed and sheltered parts of the walls, especially where salt and black crusts can accumulate. At moderately exposed places and in transition zones, flaking, meaning the development of tiny fissures parallel to the stone surface, and subsequent loss of millimeter- to centimeter-large “flat” pieces tend to occur. This weathering form may sometimes develop into contour scaling. Granular disintegration, implying the loosening of individual (flaky) mineral grains, occurs almost exclusively in rather sheltered locations and is normally followed by various types of salt. Extremely few soapstones (to date only three types out of several dozen investigated) show this weathering form at places exposed to rain, snow and ice, thus, it is a form strongly indicating salt weathering processes. When exposed to rain, soapstone always shows slight dissolution of carbonate veins and aggregates, usually followed by the oxidation of traces of iron in the carbonate structure. As a result of complex exposure conditions and varying stone properties, combinations of the typical weathering forms occur at most monuments.

Except for various kinds of salt weathering and dissolution processes, the physical, chemical and biological mechanisms leading to soapstone weathering are not yet properly understood. It has, for instance, not been possible to judge appropriately the relative importance of frost and hygric/thermal dila-



Fig. 4. Icicles and snow at the S. transept of Nidaros cathedral. The stringcourses made from Bjørnå stone have lost their moldings along the pronounced foliation in the stone. This stone has a lifetime of only 30–60 years when used at such places.

tation. This is related to the fact that, unlike salt weathering, frost and dilatation mechanisms cannot easily be observed phenomenologically. However, indications of frost as the more important mechanism have been found at Nidaros cathedral, where some 50 smaller and larger pieces have fallen from greatly exposed places (e.g., moldings at capstones and cornices) over the last 10–12 years (Fig. 4). Although this has happened predominantly in wet periods with rapid temperature changes around 0 °C, heavy rainfall on warm summer days also seems to further this type of weathering. This might imply that hygric swelling, possibly combined with thermal effects, plays a significant role as well [4].

### 8. “Old and worn” soapstone—weathering in the Little Ice Age

Many medieval and post-Reformation monuments in Norway have soapstone looking “old and worn”, especially at exposed places and in the countryside, but also in cities. These stones have frequently lost carved detail and show fissures and cracks and dissolved carbonate veins. However, the most typical feature is not the weathering form, but that the surfaces are now sound and stable despite their weathered appearance. Why is it so? When did the

damage happen? Why did the weathering processes come to a (temporary) halt?

A good place to study such phenomena is at the High Gothic west front of Nidaros cathedral (Figs. 5 and 6), which has countless destroyed medieval ornaments and sculpture made from foliated but generally durable Trondheim soapstone. It can be confirmed by the study of old photographs that the damage was there already by 1870 (Fig. 6) and that it has not significantly changed since then. To understand why the damage evolved, we have to return to 1531 and the devastating fire that ruined the west front.

Because the nave in periods was used as a stone quarry, only the two lower stories remained (Fig. 5) when the structure was put under a good roof in 1739 [15]. This means that the very delicate Gothic stonework was without protection for more than 200 years. The restoration of the west front was started by 1900. First, the old masonry was dismantled and the two lower stories rebuilt, primarily using the old and weathered decorative stones and generally refraining from reconstruction. The core of the two lower stories was strengthened and thus used as a “foundation” for the new west front, which was erected on top (Figs. 5 and 6). The building of the new west front continued with new stone until its completion in 1969 [16].





Fig. 5. The remaining two lower stories of the High Gothic west front of Nidaros cathedral by 1870. (Photograph: The Restoration Workshop of Nidaros Cathedral).

The damage to the stonework may have happened before the fire in 1531, but more likely during and after this event and continued until the two lower stories came under roof in 1739. There are rarely fire marks on the stones, so it is obvious that they have mainly been damaged indirectly by the fire, hit by, for instance, falling material. This could, however, only have happened to distinctly projecting stonework. Some mechanical damage may have happened upon the dismantling and rebuilding of the two lower stories, but photographs taken before and after this measure show only small changes. Boyish pranks may also have destroyed a few ornaments: They were allegedly favorite targets for stone throwing in the 19th century.

In conclusion, the 200 years without roofing appears to have been disastrous for the sensitive Gothic stonework. Although this period coincided with the coldest phase of the Little Ice Age, it is not possible to conclude that frost was the major cause of the damage. Other weathering agents may also

have been active (e.g., hygric/thermal dilatation, as shown above). Moreover, it cannot be ruled out that the weathering quite rapidly came to a halt because the most pronounced weaknesses (e.g., fissures) would have been the first ones affected by frost, water and temperature changes. As there were no major weaknesses left, this generally durable stone may simply not have been very vulnerable to weathering anymore.

Another example of old and worn soapstone can be found at the Gothic west portal of Utstein monastery church on an island close to Stavanger in southwest Norway (Fig. 7). Partly featuring lichen growth, the exposed flanks of the portal have numerous smaller damaged areas ranging from open joints and lost details to a rough and pitted surface, which is presently rather stable. Below the exposed and damaged, but stable, part of the arch is an inner, sheltered part, which is heavily disintegrating (Fig. 8), evidently due to salts [17]. Why do we observe this difference?

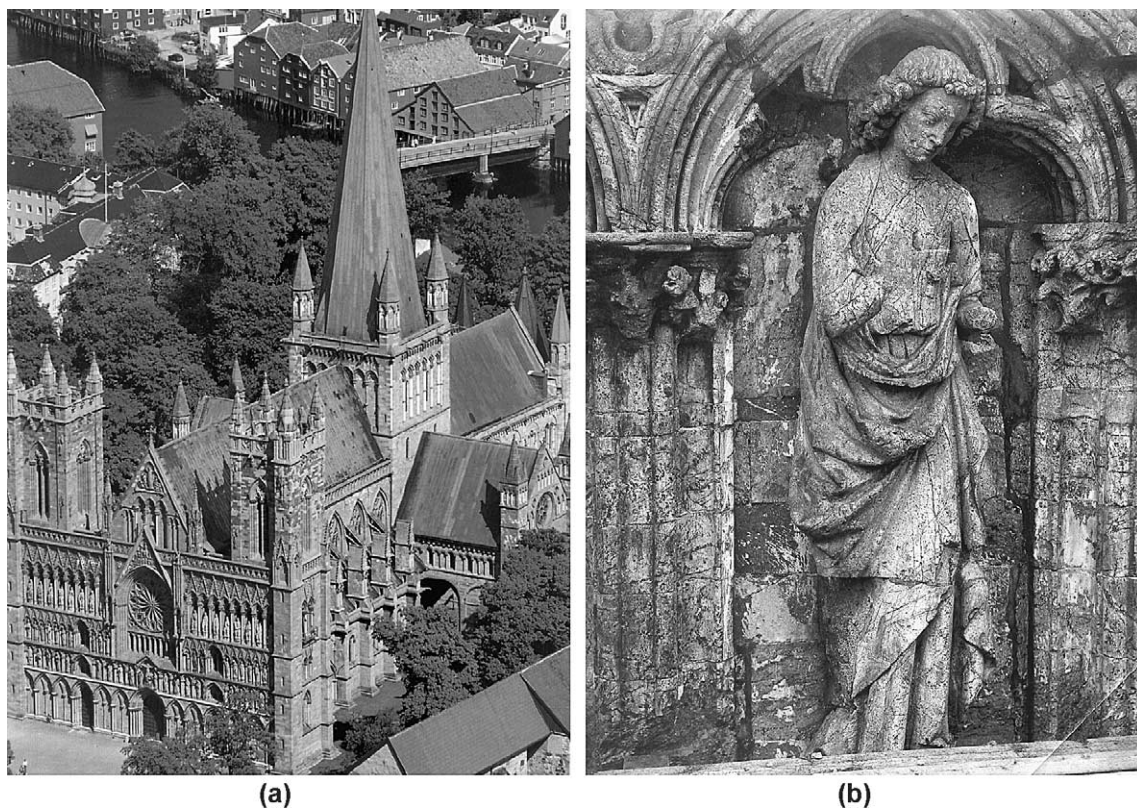


Fig. 6. (a) Nidaros cathedral today after a century of restoration. (b) St. John, one of the five remaining medieval sculptures at the west front by 1870. Note all damaged ornaments. (Photograph: The Restoration Workshop of Nidaros Cathedral).

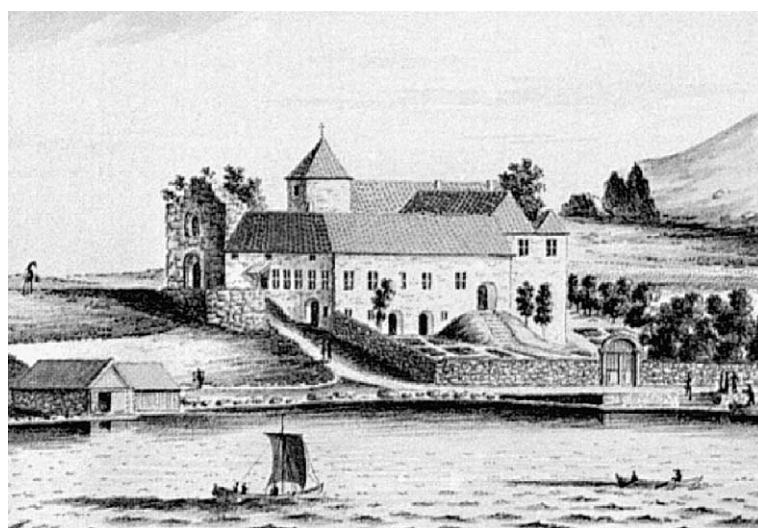


Fig. 7. Utstein monastery. The Gothic west portal is situated to the left in the ruined gable wall of the church. (Painting by Dreyer, 1822).





Fig. 8. The west portal of the Utstein monastery church (a) before 1965 (photograph from Ref. [19]) and (b) in 2001. Note many small damaged areas and that these damaged areas have hardly evolved.

The main reason is that, also, Utstein church fell into ruin after the Middle Ages (Fig. 7). It was sacked in the 16th century, and the wall heads were not covered until 1865. This preliminary protection remained another 100 years, and in 1965, the church was partially reconstructed and put under permanent roofing [18,19]. The portal was, to some extent, repaired (mainly the joints), and it still is one of the most authentic Gothic portals in Norway.

These circumstances imply that the portal was, more or less, completely exposed to the weather for more than 400 years. In this period, water infiltration and growth of bushes and moss must have played essential roles, especially in dissolving and destroying the joint system in the masonry. It is entirely possible that salt was transported to the sheltered part of the arch in this period. Gypsum is the primary salt in the arch, probably derived mainly from the building materials. Traces of chloride may stem from sea spray. Gypsum prevails in the arch until today because it cannot be washed away. It may, however, frequently dissolve and recrystallize because of condensation and minor water seepage [17].

Some exposed elements have clearly been destroyed by rusting iron dowels and cramps, some

of them associated with the door. Because the church was not in use in the post-Reformation period, it does not seem that the portal was covered with plaster or whitewash. This was generally a very frequent measure at fine portals after the Reformation and, at many places, gave rise to mechanical damage upon removal during the restorations in the 19th and 20th centuries. Thus, given that the removal of whitewash probably can be ruled out, and because there are no traces of fire or theft of ornaments, weathering having taken place during the Little Ice Age is probably the best explanation of the majority of the observed damage. We can be very certain that the masonry was moister before the church came under roof, but we can, of course, only assume that frost played an essential role in the weathering. Several reasons for the absence of new damage since 1965 may be indicated: less moisture in the masonry, rising annual temperatures at the southwest coast and generally higher wall temperatures because the church is now in use [17].

Similar old and worn, but presently relatively stable, surfaces of soapstone can be found at a range of portals in, e.g., the middle part of Norway. These include medieval portals at the Stiklestad and Mære

churches, as well as the portal from 1656 at the castle of Austrått, all situated in the countryside. In the latter case, the only significant damage that has taken place over the last 50 years was allegedly related to poor execution of plaster casts, which destroyed a coat-of-arms [20]. In the case of the Mære church, it is known from old sketches that, in the 18th century, the portals were protected by wooden porches. This shows that the old damage cannot readily be attributed to frost; a multitude of processes might have been active, which can only be explained by a proper historic investigation.

### 9. The advent of Portland cement

Portland cement damages masonry in many different ways. For instance, its inflexibility, “hardness” and dense texture are properties usually not compatible with old and “weak” masonry with natural stone and lime mortar. Regarding its direct damaging effects on soapstone, there are two major issues: weathering due to alkaline salts leached from the cement [21] and various types of damage along repointed joints.

The Nidaros cathedral is probably the medieval monument in Norway most heavily affected by

Portland cement (Fig. 9). Cement was introduced as the modern restoration started in 1869, first as a hydraulic additive to lime mortars, later as the “universal” mortar for large reconstruction works. Portland cement mortars have been used virtually everywhere—in strengthened foundations, along widened and repointed medieval joints, on top of wall heads and as grouts and “soups” injected in old and weak walls [4]. From old photos, it can be seen that calcite crusts (stalactites “stuck to the wall”) were not present before the restoration—they only turned up some years after various buildings parts were successively restored. This is a very good indicator of the use of Portland cement and the presence of water leaks. Upon the dissolution of calcium hydroxide present in Portland cement, calcite will form as the solution enters the surface (Fig. 9). The water leaks originate from poorly insulated parapet walks, from undersized water discharge systems and from fissures between joints in exposed building elements. The record for the choir, for example, shows 13 periods of major leaks, mostly occurring in the wintertime, between 1920 and 1995 [4].

Calcite crusts are not the only mineral deposits to have formed due to water leaks through Portland cement mortar. Alkaline salts, mainly various sodium

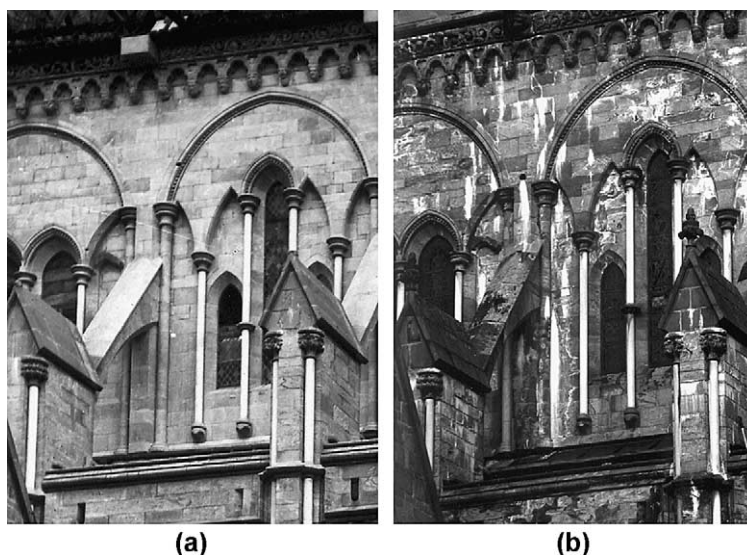


Fig. 9. (a) The choir at Nidaros cathedral was reconstructed using much Portland cement and stone rich in sulfide (Grytdal) in the 1880s. (Photograph: The Restoration Workshop of Nidaros Cathedral.) (b) One hundred years of water leaks through the masonry have produced massive calcite crusts and extreme salt weathering problems.



carbonates, will inevitably follow and form at places where they cannot be washed away. Thus, the main concentrations are found not only inside the cathedral, but also at dozens of sheltered locations outside. Moreover, because both the building materials and local air pollution contribute sulfate (primarily gypsum) to the walls, the sodium carbonates will frequently react to form sodium sulfate, which is known as one of the more damaging salts. Several other salts are produced as well (as determined by microscopy, microchemistry and X-ray diffraction), e.g., apthitalite, a sodium–potassium sulfate. The occurrence of this salt may partly explain where the potassium originating from the alkaline components in Portland cement escapes. Damage caused by excessive amounts of alkaline salt in masonry are well known [21], and soapstone forms no exception from the general rules.

Another damage category is represented by old masonry repointed with Portland cement mortars and later subjected to moisture. Because Portland cement mortars are dense and frequently strongly adherent to adjacent, structurally rather weak soapstone, two problems result (simplified [4]): First, moisture is concentrated behind the pointing mortar, contributing to the destruction of the old lime mortar; second, the pointing mortar gives way, perhaps due to frost, and often by forming fissures in the adjacent soapstone, along the joint. Alternatively, when much salt is present, weathering in the form of granular disintegration and flaking will form along the joint system. Because soapstone is so dense, moisture and, thereby, weathering phenomena commonly concentrate along the joint system, regardless of the mortar used. Compared with the weak, salt-free and easily repairable lime mortar joints, the problems only become much more serious when Portland cement has been in use.

## 10. Black crusts through 120 years and changes in architectural design

In the 1970s, the effects of decades and centuries of air pollution and development of black (gypsum) crusts at monuments in urban centres in Europe became increasingly evident. However, in Norway, as elsewhere, black crust formation cannot be seen in

isolation from other damaging phenomena at monuments. Two examples from Bergen and Trondheim will illustrate the intimate relationship between black crust formation due to mainly local emissions of SO<sub>2</sub> (dry deposition), moisture and run-off patterns due to changes in architectural design, salt from other sources and damage.

The north portal of the Church of the Holy Cross in Bergen was built in 1632. It is perhaps the finest renaissance portal in Norway and the only one so far at which traces of original polychrome painting have been documented. This masterpiece was soon in trouble, but nevertheless appears to have survived no less than three fires until 1746. Subsequently, a porch was built in front of the portal, perhaps to protect it or perhaps to conceal the damage (Fig. 10). The porch remained for a hundred years until the portal was restored in 1856–1857. It is likely that the polychromy was finally removed at this time, possibly by acid and/or lye [22]. The most important measure was not directly related to the portal, though, but to the fact that a large circular window was inserted just above it. By collecting rain and draining it directly onto the portal, this window has played a vital role in the weathering over the last 140 years. Already by 1900, the portal and the wall around had much black crust, which expanded greatly during the 1940s and 1950s. In the 1970s and 1980s, the extent had been slightly reduced, but this was mainly due to the fact that pieces had started to fall from the most damaged parts, which are essentially the somewhat sheltered areas below the upper arch and between the three architraves. Since the late 1980s, no great changes have been recorded [22].

The reasons why so much black crust could form at the portal is connected to relatively high atmospheric concentrations of SO<sub>2</sub> and particulate matter from heating and combustion processes over a long period, as well as the generally sheltered position of the north wall. The locations of the worst damage are also governed by rain and run-off from the window, which make these areas thoroughly moist, but not completely wet, like other more exposed but less damaged areas of the portal. The worst damage is located in a transition zone between dry, moist and wet—a zone in which damage related to black crusts is generally known to concentrate (valid for dense stones; [23]). In addition, gypsum in black crusts is not the only salt in

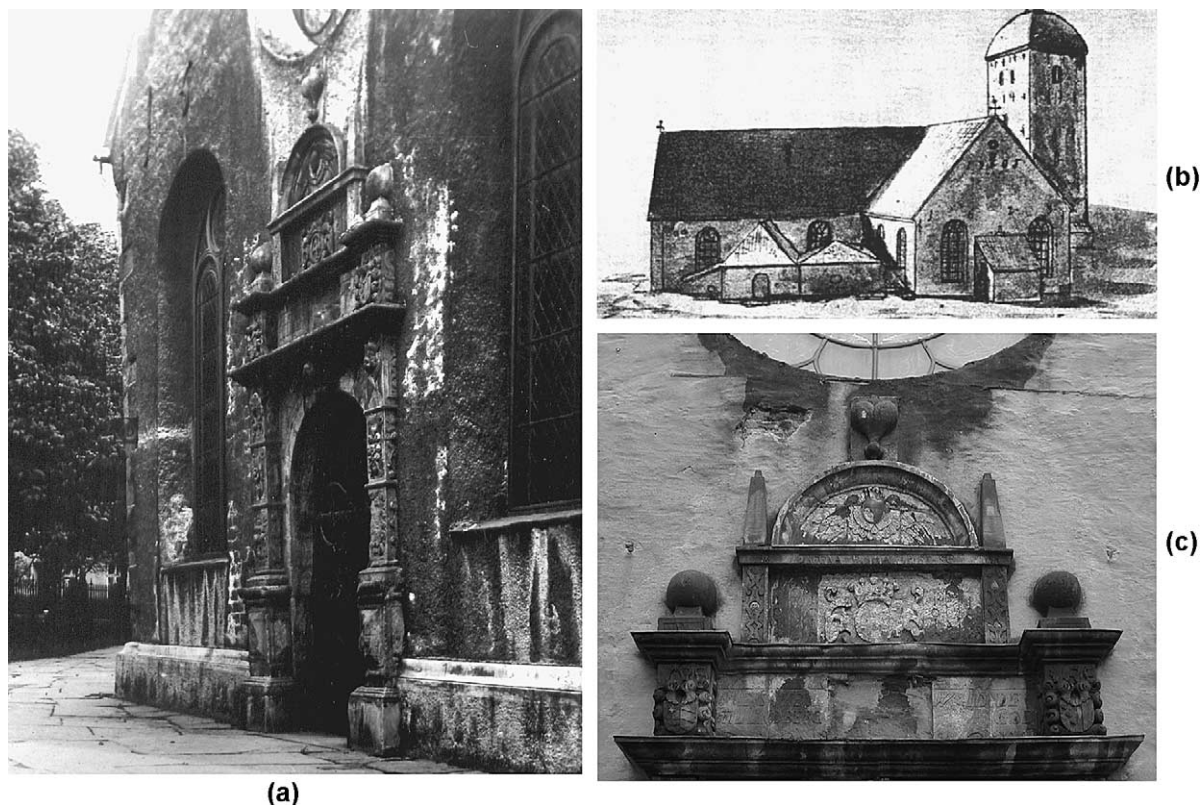


Fig. 10. Church of the Holy Cross. (a) The north portal, with much black crust by 1900. (Photograph: Directorate for Cultural Heritage.). (b) A porch in front of the portal in 1839. (Drawing by F. Bøe). (c) The upper part of the portal in 1999, showing damage where crusts formerly prevailed.

the damaged area—there is a range of other species present as well, of which halite is the most important. Halite may stem from sea spray, but perhaps more likely from acid cleaning in the 19th century. Furthermore, the foliated soapstone in the damaged area is edge bedded, a feature that makes it delaminate easily and lose the outer parts. Thus, air pollution and black crusts cannot, alone, be held responsible for the damage, but rather, a range of unfortunate circumstances starting with the “weakening” of the portal due to fires and the insertion of the circular window above the portal in the 19th century. This knowledge has important consequences for the conservation: A protective roof should be built above the portal.

Another example illustrating the importance of understanding former changes in architectural design can be found at the Nidaros cathedral, at the mixed Romanesque and Gothic north porch of the cathedral (Fig. 11). Probably after the fifth and last fire at the

cathedral in 1719, the porch acquired a good, traditional roof with projecting eaves, which protected the valuable Romanesque corbel heads in the cornice (Fig. 11b). A similar roof may have prevailed also before the fire. The corbels are made from chlorite schist with talc, and, according to old photos, they were in good condition before the modern restoration of the porch in the early 1880s. This restoration did not involve the corbels, which remained, more or less, untouched, but concentrated primarily on the roof, which was restored to what it might have looked like in the 13th century. A raised gable was constructed, the eaves were cut back, lead (later copper) plates were used as roofing material, and gutters and downpipes were added. Moreover, new Grytdal stone with a high content of pyrrhotite was applied in the beam directly above the corbels [4].

Towards the 1950s and 1960s, the condition of the outermost corbels at the west side of the porch was

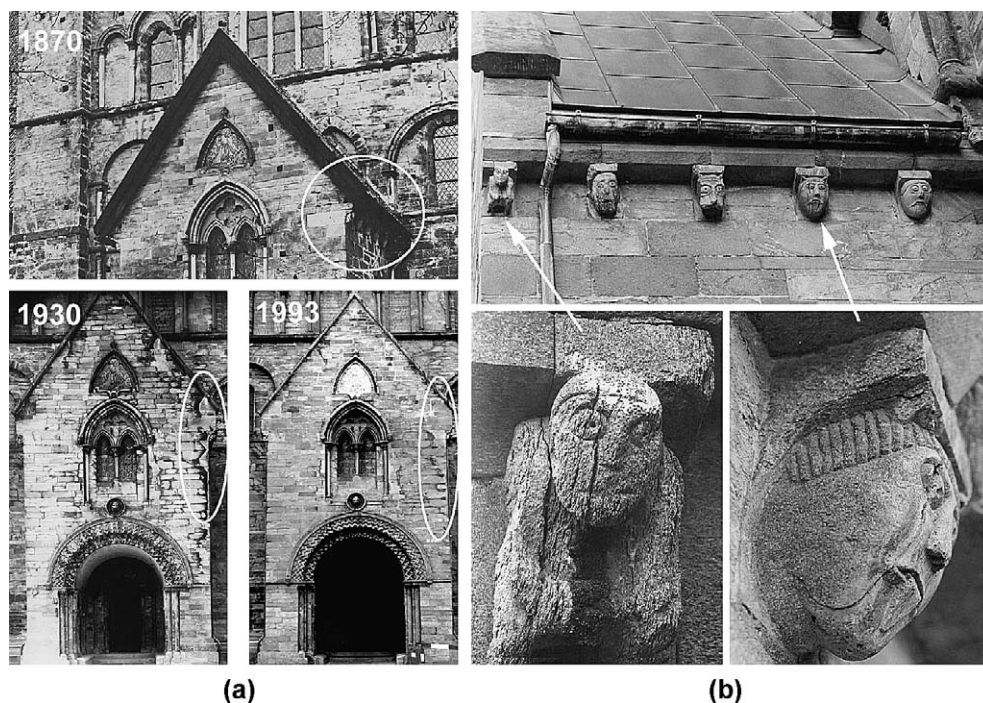


Fig. 11. The north porch at Nidaros cathedral. (a) Before and after the restoration in 1880; note the new roof and the development of black crusts. These were more widespread in 1930 than in 1993. (b) The corbel heads at the west side of the porch. (Historic photographs: The Restoration Workshop of Nidaros Cathedral).

drastically deteriorated. The chlorite schist delaminated, and there were clear signs of black crusts in the more sheltered areas (Fig. 11). But does this mean that air pollution was responsible for the damage? There is probably no doubt that the formation of black crusts and gypsum plays a role in the weathering, but it appears to be more important that the reconstructed roof is not able to protect the corbels properly. The outermost corbel, for instance, is only half protected (cf. weathering in the transition zone between wet, moist and dry at the portal of the Church of the Holy Cross in Bergen) and influenced by water leaks and run-off from the architecturally complex 1880 cornice and the occasionally overflowing gutter. Thus, frost may be an important weathering agent as well. Moreover, gypsum from the Grytdal stones above can easily be transported to the corbels [4].

Whatever the exact weathering mechanisms at the corbel heads are, the example shows a very normal historical development at many churches and cathedrals in Europe. During the restoration waves in the 19th and 20th centuries, thousands of sculptures and

ornaments were subjected to repairs in their surroundings, which drastically altered the exposure conditions. Whether such changes were for the better or the worse can only be determined by systematic studies of the restoration history, subsequently combining the findings with other relevant investigations.

Preservation dilemmas become very pronounced by roof changes. Our Romanesque corbel heads would definitely have had a much higher life expectancy if they had been protected by a good roof. But what is more important, to preserve the sculptures in situ or the reconstructed roof? Are we allowed to dismantle and alter the roof, giving it, for instance, the appearance it had in the 18th century, or is there no other option than transferring the corbels to a museum?

## 11. Conclusions

In this paper, the focus has been on tracking outdoor soapstone weathering phenomena through



history. Many other examples could have been given to back up the findings described, for instance, related to corroding iron dowels and cramps, which is so important at Stavanger cathedral [24], to a century of water leaks at the Romanesque portal of St. Mary's Church in Bergen [25], to the numerous fires that hit medieval buildings and to the rare negative effects of lichen growth on soapstone. Examples of soapstone as a very durable material could also have been given, for instance, 200- to 300-year-old gravestones in the dry part of east Norway with no apparent weathering forms, except for a fantastic lichen flora. The detrimental effect that indoor heating may have on the evolution of weathering within buildings and its influence on outdoor weathering could also have been shown.

However, the examples chosen should have given an impression of the core issues related to outdoor soapstone weathering in Norway and how the weathering has changed. First, objects that evidently weathered quite strongly during the Little Ice Age (14th–19th century), especially at the countryside, have now been relatively stable for a hundred years or more. Although a multitude of weathering processes might have been active, this could point to a higher frequency of damaging frost events in the Little Ice Age than at present. In the case of former ruins, the stable condition is also related to good roofing and less moisture in the masonry. Second, the weathering was in complex ways and often governed by changes in architectural design, influenced by air pollution in the cities from the late 19th century until the recent drastic reductions in SO<sub>2</sub> emissions. Third, alkaline salts from Portland cement, sulfate from air pollution and some stones, as well as chloride from acid cleaning greatly enhanced the salt load at many monuments in the 19th and 20th centuries, giving rise to severe weathering, especially at places where water leaks and run-off have prevailed.

Interpreting weathering phenomena in the historical context elucidate the great variety of options that we have for conservation measures. It should also enable us to undertake the best measures possible; in other words, to react on the most important causes (see also Ref. [26]). When it is known that a roof from the 1880s presents a greater problem than, for instance, air pollution, one should be able to better discuss efficient conservation options than what

would have been the case without this historical knowledge. And, if it is known that the condition of a monument has not changed much in 100 years, there will often be no need to intervene at all.

As the climate now seemingly becomes warmer and stormier, and as air pollutants other than SO<sub>2</sub> become more important, the historical knowledge may help us build scenarios for future weathering problems and conservation options at soapstone monuments. At some few places, a warmer weather may, for instance, give rise to more temperature changes around the freezing point, and with more precipitation, the risk of frost damage may increase. Moreover, the large amount of salt introduced from a great variety of sources since the 19th century appears to become an important issue; with more precipitation, there will also be a higher risk of water leaks and, thus, more water to mobilize and transport these salts. Thus, protection against water leaks and damaging run-off would be the appropriate reaction. This is nothing new and nothing spectacular, but it usually helps against weathering!

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