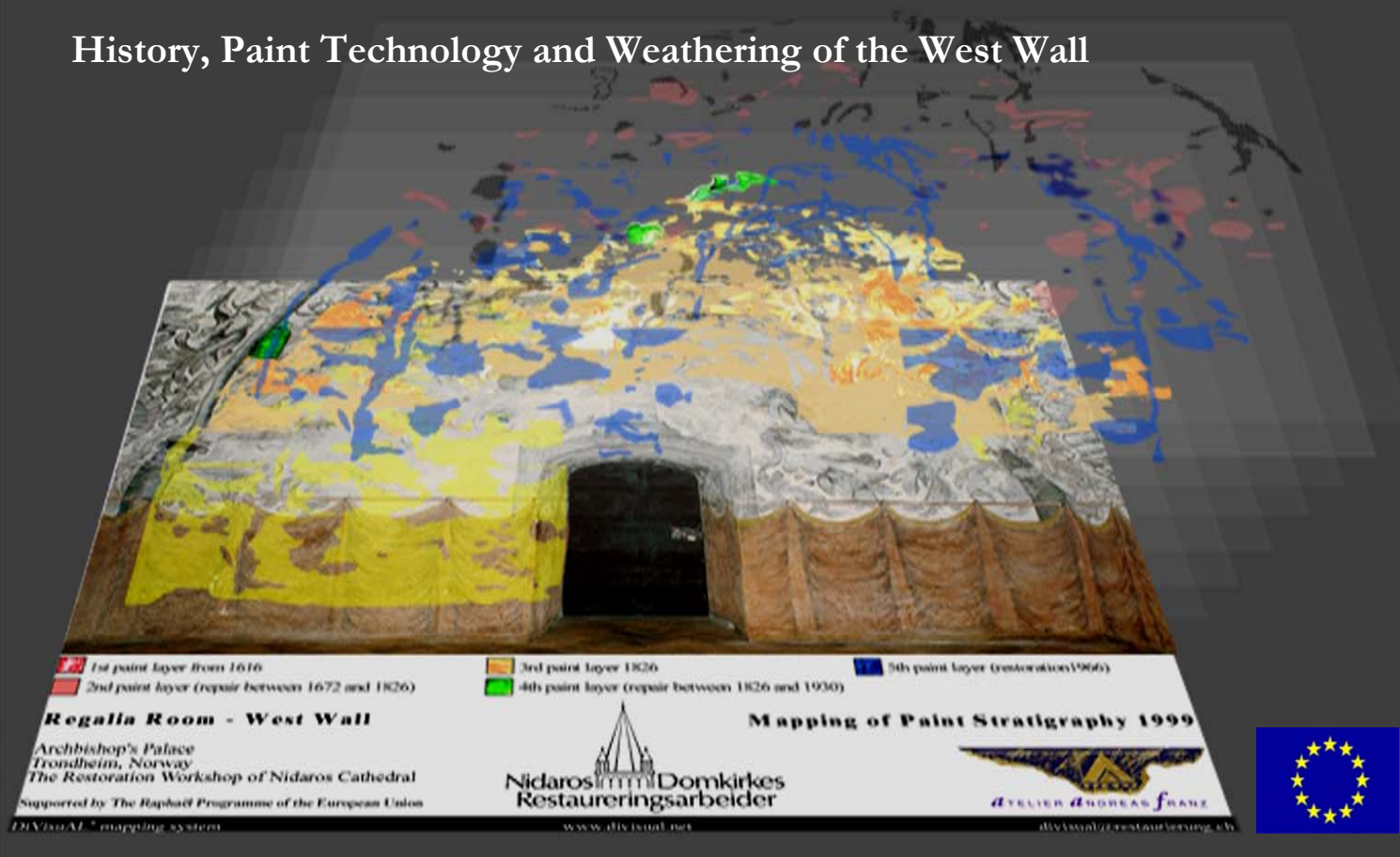


Andreas Franz and Per Storemyr

The 17th Century Mural Paintings in the Regalia Room, Archbishop's Palace, Trondheim, Norway

History, Paint Technology and Weathering of the West Wall



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Layout by Per Storemyr

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The Restoration Workshop of Nidaros Cathedral
P.O. Box 4447 Hospitalsløkkan
N-7418 Trondheim

Tel: 73 89 08 00
Fax: 73 89 08 08
E-mail: nidarosdomen@kirken.no
<http://www.nidarosdomen.no>

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Authors: Andreas Franz and Per Storemyr

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This is a special CD-ROM edition of a printed report with the same title and content.

The objective of the investigations reported in this work is to lay a sound basis for conservation of the 17th century mural paintings in the Regalia room, Archbishop's palace, Trondheim, Norway. Since the west wall of the room is by far the most damaged, the studies have been concentrated on this wall.

Mapping of stratigraphy, restoration phases and weathering forms were done digitally on-site by DiVisuAL, a system based on Adobe Photoshop. Results of the mapping campaign were interpreted in the light of building history, use of materials, structural problems, exposure conditions and indoor climate.

It is shown that the severe weathering can be explained by:

- Several known and formerly unknown harmful human interventions
- Former and perhaps still active structural problems leading to cracks and loosening of plaster
- Exposure conditions giving rise to water leaks
- Former heating creating a very hot indoor climate
- Salt crystallisation. Main salts are sodium nitrate and sodium chloride of unknown origin, and sodium sulphate originating from concrete used for masonry restoration (1962-75)

Urgent and long-term conservation measures are proposed on the basis of the results. The most urgent measure concerns fixing of very loose flakes of limewash and paint about to fall from the wall.

Preface

If the mural paintings on the west wall of the Regalia room are to be saved, an urgent conservation action has to be undertaken. This is perhaps the main practical conclusion of the present work.

Supported by the EC Raphaël Programme under the project "European Laboratories for the Heritage"/"Nidaros Cathedral Restoration", the work has been a co-operation mainly between Atelier Andreas Franz (CH) and The Restoration Workshop of Nidaros Cathedral (RWNC). Fieldwork was undertaken during three campaigns in Trondheim in 1999. All paint analyses were undertaken by Andreas Küng of the Swiss Federal Institute of Technology (ETH), Institute for Preservation of Historical Monuments and Sites (CH). Thanks a lot!

We also wish to thank the following persons for help during the work: Øystein Ekroll (RWNC) and Alf Tore Hommedal (NIKU) for building archaeological advice, Birgitta Odén (*Trøndelag Folkemuseum*) for art historical advice, Ola Grefstad (*Trøndelag Folkemuseum*) for comments on the last restoration (1966) in which he participated as assistant, the company Termokontroll (Trondheim) for undertaking thermography, Kjartan P. Hauglid for photographing the murals and Andreas Arnold (ETH) for a discussion on salt sources. Thanks also to many people in the workshop for help with all practical details necessary to carry out the project.

Zurich, 31. January 2000
Per Storemyr and Andreas Franz

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The weathered west wall of the Regalia room in the spring of 1999 (Photo: Kjartan Proven Hauglid)

Introduction

The so-called Regalia room in the Archbishop's Palace in Trondheim exhibits perhaps the finest example of secular mural paintings in Norway. Covering all the walls and the barrel vault of a medieval room in the palace, the murals were painted in the early 17th century when the Danish lord Claus Daa undertook a major renovation and made the room part of his private quarters. The current name, the Regalia room, derives from its use as storeroom for the Norwegian crown regalia in a short period after 1826.

The Regalia room is located on the first floor of the 13th century west house in the north wing of the Archbishop's Palace. It exhibits typical renaissance murals, composed of painted architectural elements, hunting scenes, other figurative motifs and tendrils. As the murals appear today, after centuries of weathering and several restoration phases, large parts look like *grisaille* paintings, monochromatic paintings in shades of grey. However, investigations have revealed that the paintings were originally very colourful. For example, the current greyish tendrils were painted in shades of green, grey and yellow.

Although the paint has faded and there are quite a few other damages, the murals are generally in relatively good shape. The great exception is the west wall, which is a gable wall and the only wall of the room heavily exposed to the weather. This wall has been in a very bad condition for at least 15 years,

even after having been extensively restored in the 1960s. Thus, as the damages are critical and reappearing after the last restoration, the current conservation project mainly deals with the west wall.



The Regalia room seen towards east
(Photo: RWNC - The Restoration Workshop of Nidaros Cathedral)

OBJECTIVES OF THE CONSERVATION PROJECT

The current conservation project was launched in the beginning of 1999 as a co-operation between the Restoration Workshop of Nidaros Cathedral, which is the responsible authority, and Atelier Andreas Franz in Switzerland. Institute for Preservation of Historical Monuments and Sites at The Swiss Federal Institute of Technology, (ETH), Zurich, has also been involved,



The west house of the Archbishop's Palace seen from the south. The Regalia room is situated in the upper left corner.

mainly in studies of pigments. Before the investigations reported in this work began, the history of the murals in the Regalia room, as well as in the nearby Drapery room and *Herresal*, were studied by art historian Birgitta Odén (Odén 1999). The murals were also photographically documented by Kjartan Hauglid in the spring of 1999.

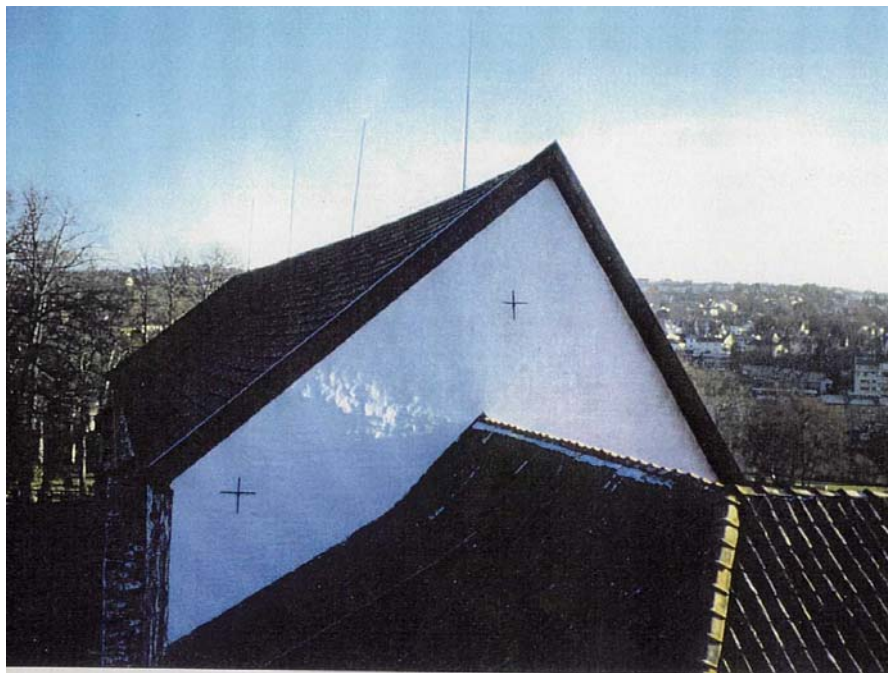
Efforts to reduce the weathering rate started, however, already in the early 1990s. At that time the very damaging floor heating installed in the 1960s was turned off, and the exterior part of the gable wall repaired by means of applying new plaster, a work led by restoration technician Geir Magnussen (Magnussen 1996). Since 1996 the room climate, as well as material fallen



The northwest corner of the palace. The Regalia room is situated below the gable wall. The vault of the room lies on the level of the roof of the west wing. (Photo: RWNC c. 1950)

from the west wall, have been recorded. In order to keep the room climate fairly constant, only very small groups of visitors are allowed entry with a guide twice a day in the summer season. Otherwise the room is closed to the public.

Since repeated surveys of the wall have shown that the weathering is very active and that there are no simple causes of the decay, the current project was designed as an *applied research* study, and not only a short-term investigation in order to draw up a practical conservation plan. The main objective is thus to lay a sound basis for long-term protection, maintenance and conservation, including necessary follow-up work of a scientific nature.



The gable wall above the Regalia room after plastering and whitewashing in 1993-95.

(Photo: Geir Magnussen)

Being part of the project "Nidaros Cathedral Restoration" within the Raphaël programme of the European Community (1999-2001), the mural painting project has an additional, more general objective; to explore the possibilities of state-of-the-art digital graphic documentation. The reason why this aim has been included is that Nidaros Cathedral, the closest neighbour to the Archbishop's Palace, is about to be surveyed by means of digital photogrammetry. Thus, the Restoration Workshop clearly sees the need to start working with digital systems for the subsequent *in-situ* mapping of themes like building history, materials and decay forms, and for drawing up conservation plans.

Since using AutoCad is the "standard" way of doing such work (for instance by means of Skart developed in Germany), and probably also will be applied for the majority of future survey work at the cathedral, it was decided to do something else in the present project. This project involves very delicate two-dimensional decorations, which are best represented by high-quality photographs. Moreover, as the standard way of digitally manipulating photos is by using Adobe Photoshop, we adopted the method called DiVisuAL[®], which is based on Adobe Photoshop. This method might become a handy tool also for the documentation of decorations at parts of the cathedral.

MAPPING METHOD: DiVISUAL[®] MAPPING SYSTEM

Following the digital revolution, in recent years there have been numerous attempts at developing digital documentation systems for use in conservation work (see for instance GraDoc seminar report 1999). One of these methods is the *DiVisuAL[®] mapping system*, which has been developed over the past five years. It has been tested on many locations in Switzerland. Mapping work made with DiVisuAL[®] ranges from mural paintings of 10 m² to whole buildings with a total surface area of 650 m².

DiVisuAL[®] is an abbreviation for *Digital Visual Analyses through Layers* and works very much like the traditional way of manual mapping on transparent media placed above a photograph or for instance a photogrammetric recording. The main drawback of the traditional method is that one quickly obtains an overwhelming number of different layers when trying to separate every distinguishable phenomenon. Moreover, it is difficult and expensive to reduce large formats for printing (reports, books).

After a long period of evaluation, Adobe Photoshop was selected as the most appropriate software. Photoshop was originally developed for the needs of the graphic industry, and its advantage over CAD programs is its ability to handle large, high-resolution images, as well as its superb compatibility

between Windows, Unix and MacOS (no need for converting). In addition, Photoshop is a fairly inexpensive program, relatively easy to operate, and in widespread use throughout the world.

Unlike in traditional survey work with pencil and paper, it does not matter how many layers that are put in use. It is possible to switch layers on and off as necessary, connect single layers to groups, and vary the degree of transparency, for instance in order to highlight important phenomena.

Another advantage over traditional methods is that one can zoom into the image as much the chosen resolution allows. This means that one can easily locate very small phenomena on the digital image, which is an important feature when mapping for instance mural paintings. Since the system is flexible enough to be used on laptop computers, one can use DiVisuAL[®] mapping system in the field (this was done in the Regalia room), comparing the image on the screen with the actual condition of the mural or monument. The excellent drawing tools in Photoshop makes it, moreover, fairly easy to create maps which "looks like" manual drawings.

DiVisuAL[®] can also be used for other tasks than mapping. Photogrammetric recordings can be used to rectify photos used as basis maps for surveying, and it is possible to include scaled historic images, UV photos, thermography images etc. Thus, one can create a complete collection of related data in one file. This is a great advantage in conservation work where it is often necessary to compare different images. In the same way it is possible to include new images, new survey maps and for instance undertaken conservation measures. Used in this way, DiVisuAL[®] mapping system is a continuous form of documentation.

All maps and many other images in this report have been made with DiVisuAL[®]. To fit the format of this report, most images had to be scaled down. The format of the actual work is much larger and can be seen on the attached CD-ROM.

Building History and Paint Technology

THE WEST HOUSE OF THE ARCHBISHOP'S PALACE

Situated close to Nidaros Cathedral and at the highest point in the centre of Trondheim, the Archbishop's Palace lays about 15 m above sea level on a fluvial/glaciofluvial delta. The foundations rest on a compact, one metre thick layer of clay originating from an avalanche in prehistoric time. This layer is known to be stable as long as it is kept relatively dry (cf. Storemyr 1997). The ground-water table lies about 6 m below the ground - and well below the foundations.

The so-called west house of the north wing is divided in two storeys and four rooms. On the ground floor there are two vaulted rooms (pointed vaults made of stone slabs), which have been used mainly for various storage purposes since they were built in the 13th century. Today the western room is empty, while the eastern one recently has been put in use as a simple chapel. Both rooms are equipped with wooden floors situated right above the ground.

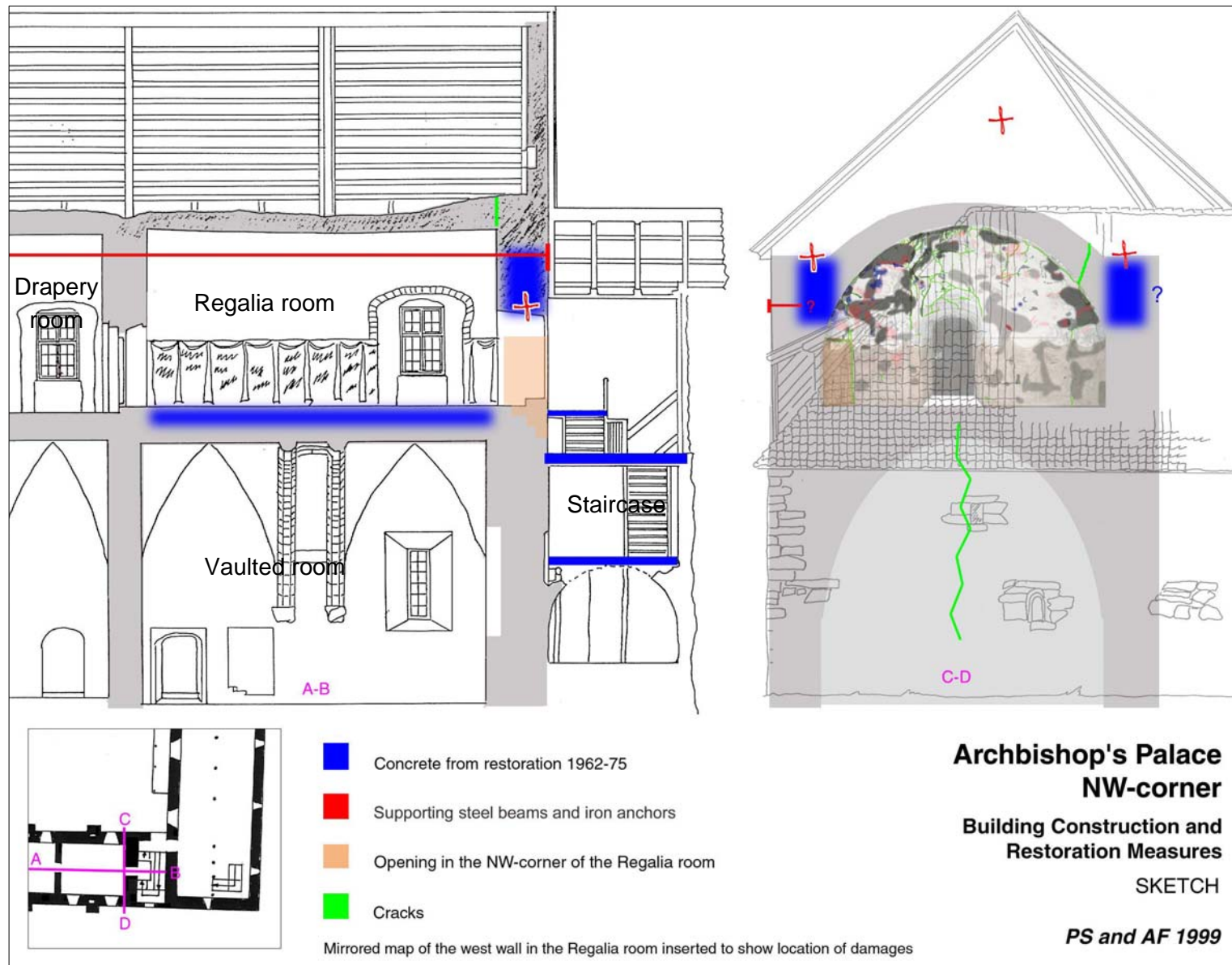
On the first floor, c. 7,6 m above the ground, are the Regalia room and the so-called Drapery room. Both rooms are maximum c. 4,4 m high, and belonged to the private quarters of the Archbishops before the reformation (1537) and of the Danish lords afterwards. They are designed in much the same way, with a half metre thick barrel vaults made from stone slabs. Both rooms are painted, but while the Regalia room has murals on all surfaces, the Drapery room only exhibits painted draperies along the lower parts of the walls. The Regalia room has three windows, two on the north side and one on the south.

The masonry of the west house is generally made of coursed rubble (local gneiss, greenstone etc.) with rubble filled cores. On the ground floor the masonry is some 1,6 m thick, thinning somewhat out to 1,4 m on the first floor. The western gable wall of the west house/Regalia room is considerably thinner. Except for measures carried out during the last restoration, in which Portland cement mortar was used, the whole masonry was made using lime mortar. Lime mortar was also used on the former plastered surfaces of the west house (outside as well as on the walls inside the vaulted rooms on the ground floor). Almost all plaster was removed during the last restoration, implying that the western gable wall is the only plastered wall at present.

Entrance to the first floor is either via the eastern part of the north wing, or through a heavily restored (1962-75) indoor staircase between the north and west wings of the palace. The roof of this staircase lies on the level of the vault of the Regalia room, implying that it is actually only the upper part of the west wall that is exposed on the outside.

HISTORICAL OVERVIEW

The long and complex history of the Regalia room has been worked out by Odén (1999). Below is an overview of her study, supplemented by our own findings and other detail. Very important events/measures are highlighted:



*Sketch showing the building
construction and various
restoration measures*



*The east wall of the Regalia room with the original paintings from 1616
(Photo: Kjartan Proven Hauglid)*



The Archbishop's Palace as a military depot c. 1910 (Photo: RWNC)

- Middle Ages The building of the Archbishop's Palace started after the establishment of the Archbishop's See in Trondheim 1152-53. The west house, including the Regalia room, was supposedly built around 1250 as part of the Archbishop's residential quarters. The Regalia room was probably painted already in the Middle Ages (*new discovery, see later section*). The vaulted room below may have been used as kitchen. A chimney-like structure seems to have been standing in the middle of the vaulted room, cutting through the floor and vault of the Regalia room. There are marks in the vault of the Regalia room that seem to confirm this theory (*new discovery*).
- 1532 The Palace burnt (1537: The Reformation)

- 1550s Restoration work began and the Palace was put in use as residence for the Danish lords (*lensherre*)
- 1614-1616 The Palace was thoroughly renovated under lord Claus Daa. **The Regalia room was painted by *Bjørn Maler* ("Bjørn the Painter") with *polychrome* architectural elements, draperies, hunting scenes, other figurative motifs and tendrils. At this stage the room had an opening in the west wall (door or window), a fireplace/oven with chimney at the west wall (*new discovery, see later section*), and probably a niche in the north west corner (*new discovery, see later section*). The older/medieval door opening here was thus closed.** The vaulted rooms below were used for storage of food etc.

- | | |
|--|--|
| <p>1686 The Palace was altered to a military depot and storehouse and remained so for the next 300 years. The Regalia room was used as arsenal until 1826. The vaulted rooms below were used as gunpowder stores (also until 1826).</p> <p>1672-1826 The fireplace/oven in the Regalia room was removed, probably between 1672 and 1708 when the Palace burnt once more. The area where the chimney had been was plastered, whitewashed and probably painted. Other repairs were probably also undertaken.</p> <p>1826 The Regalia room was put in use as storeroom for the Norwegian crown regalia (until 1837). The door opening in the west wall was enlarged, the niche/door in the north west corner was closed and the whole west wall was more or less completely overpainted, mirroring the paintings on the intact east wall of the room. A roofed staircase between the north and west wings was built to give access to the Regalia room. The gun powder stores in the vaulted rooms below were moved</p> <p>1927 Investigations undertaken by Domenico Erdmann. The west wall was described as very damaged.</p> <p>1930 The Palace was restored, but there are no indications of work done in the Regalia room, except for some "general" cleaning. The room was used as a showcase and for exhibitions in connection with the 900 anniversary of the death of St. Olav in 1030.</p> <p>1952 Investigations undertaken by Finn Krafft. The west wall was described as damaged, but there were no sign of water infiltration in spite of "large cracks".</p> <p>1954-1966 Investigations now and then undertaken by Ola Seter. The W. wall described as damaged and with deposits of "smoke and dust"(?)</p> | <p>1962-1975 The last large restoration of the Archbishop's Palace. The following building measures were of importance for the west wall:</p> <ul style="list-style-type: none"> • The wall, which was out of plumb, was connected by supporting steel beams with masonry in the eastern part of the building, on the loft above the vaults. The beam on the north side was fixed in reinforced concrete inserted directly above the vault close the north corner of the west wall. It has not been verified whether concrete was also used on the south side. • The wooden floor was removed and replaced by tiles on a layer of concrete (probably) • Electrical floor heating was installed • Plaster on the exterior walls, except on the gable wall, was removed. Joints were repaired with cement mortars • The fire-damaged exterior west wall (below the roof) was repaired (replacement of stone by brick, filling in of joints with cement etc.). The outermost frame of the door opening was repaired with cement. <p>1966 Restoration of the murals in the Regalia room was undertaken by Ola Seter and his assistant Ola Grefstad. The measures are described in Seter's restoration reports, of which a summary can be found in the next section.</p> <p>1983 Wooden buildings in the Archbishop's Palace burnt. A sprinkler system was installed in the palace afterwards, also on the loft above the vault in the Regalia room.</p> <p>1988 Investigations undertaken by Jon Brønne. Damages related to salt weathering, fissures and cracks, and gypsum repair mortars were described. The main reasons for the damages were supposed to be settlements in the building, water infiltration from the west wall and the high temperature in the room (at times 25°C).</p> |
|--|--|

- c. 1990 **The floor heating was turned off.** After then the Regalia room has had no heating.
- 1993- **The exterior west wall was plastered** with a mixture of lime and
1995 hydraulic lime and subsequently limewashed. Other small repairs were also undertaken. The wall was in bad condition before the repairs. Since then there has not been *observable* water leaks.
- 1996- The current investigations in the Regalia room started.
- 1999 The exterior west wall was maintained by a new layer of limewash.



*The west wall of the Regalia room under restoration in 1966. Note grey cement repairs
(Photo: Archives of the Directorate for Cultural Heritage, Oslo)*

STRATIGRAPHY, PAINT TECHNOLOGY AND RESTORATION PHASES







The investigation of stratigraphy was undertaken by comparing surface texture, brush marks, location of paint layers, styles and colours. In addition, pigments and binders were analysed (see appendix 2). Samples of mortar and limewash were also investigated using stereo microscopy. A simple stereo microscope was applied during the investigations on site.

The overall stratigraphy on the west wall can be summarised like this:

1. Probable medieval plaster (with remains of limewash and paint)
2. Various plaster before or in 1616
3. 1st limewash 1616
4. 1st paint layer 1616
5. Plaster in chimney area - between 1672 and 1826
6. 2nd limewash - between 1672 and 1826
7. 2nd paint layer - between 1672 and 1826
8. Plaster in door area 1826
9. 3rd limewash 1826
10. 3rd paint layer 1826
11. 4th paint layer - between 1826 and 1930
12. Gypsum/lime repair 1966
13. Cement repair 1966
14. 5th paint layer 1966
15. Glazing 1966

At present it is impossible to state how the room looked like in the Middle Ages, or before it was painted in 1616. This is because there are not enough places where earlier plaster/limewash/paint can be observed. However, at one place in Q1 (quadrant 1, upper left part of the west wall) there is some ochre on plaster/limewash which is definitely older than 1616.



- | | | |
|--|--|---|
|  Probable medieval plaster |  Plaster in chimney area (after 1672 - before 1826) |  Portland cement (1966) |
|  Various plasters (before or in 1616) |  Plaster in door area (1826) |  Gypsum / lime repair (1966) |

Regalia Room - West Wall

Archbishop's Palace
Trondheim, Norway
The Restoration Workshop of Nidaros Cathedral

Supported by The Raphaël Programme of the European Union

DiVisuAL® mapping system



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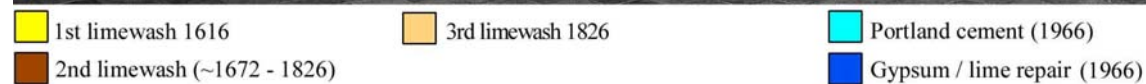
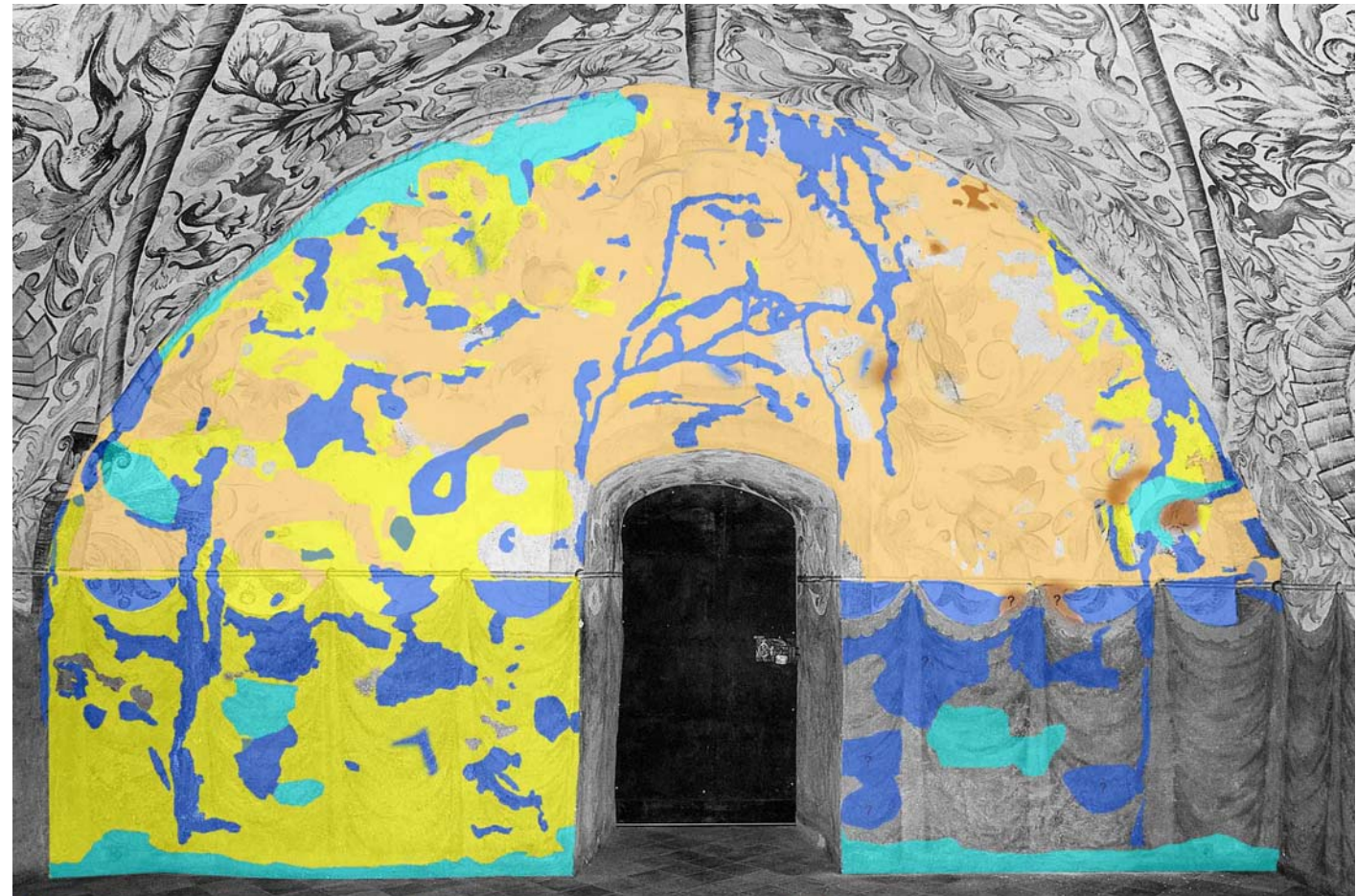
Mapping of Plaster Stratigraphy 1999



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Plaster stratigraphy on the west wall. The pictures show the fine-grained plaster in the chimney area (above) and exfoliating gypsum repairs from 1966 (below)



Limewash stratigraphy on the west wall. The picture shows the difference between the 1st (left) and the 3rd limewash (right). The 1st is characterised by its coarse, soft structure, while the 3rd has a "sandy" surface and closely-spaced brush marks

Regalia Room - West Wall

Archbishop's Palace
Trondheim, Norway
The Restoration Workshop of Nidaros Cathedral

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Mapping of Limewash Stratigraphy 1999


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The general painting technique both with regard to the "original" painting from 1616 and subsequent repair phases (1672-1826, 1826) was the "secco"-technique, painting on dry mortar: On a layer of plaster, a finer limewash was applied as ground for the paint. The binders used for the paint seem to be lime only, perhaps with some addition of animal glue (traces have been found). This animal glue could also stem from various restoration phases and not necessarily belong to the original paintings. During the restoration in 1966, oil and perhaps glue and casein were also used as binders, and oil may have been used in the drapery area (green drapery) in 1826.

Plasters applied *well* before 1616 are difficult to distinguish from those applied *immediately* before the west wall was painted in 1616. Compared to the present appearance, the wall must have looked very different in 1616, not least because of the large fireplace or oven (with chimney) which covered much of the northern part of the wall. Other features which made the wall look different include the niche in the north-west corner and the door/window in the middle which was lower, but not less wide than the present door opening. Observations indicate that the niche was not painted in 1616. It is, on the other hand, not possible to state whether the fireplace/oven and chimney was painted in 1616.

The removal of the fireplace/oven and chimney between 1672 and 1826 (probably before 1708 - the fireplace in the Drapery room was removed before 1708, see Odén 1999), led to a re-plastering of the area and probably also a re-painting. The remains of paint on this plaster are so fragmented that one cannot state for certain that it was painted the same way as the original in 1616. The presently blocked opening (with bricks) of the chimney can be observed both on the overside and underside of the vault.

In 1826 parts of the wall were re-plastered (repaired) and, apparently except for the drapery area, completely covered with new limewash before the application of paintings which mirrored the paintings on the east wall. The need for a solid iron door to protect the crown regalia, which were to be

stored in the room, led to a vertical enlargement of the main door opening. On the south edge of the opening one can still observe older plaster, indicating that the opening was not widened in 1826. New plaster was applied especially in the area affected by the enlargement, as well as on new masonry used to close the niche in the northwest corner. The drapery was painted green.

The wall must have been very damaged before 1826; otherwise there would have been no need to completely renew the paintings. It may be suggested that the fire in 1708, which might have strongly influenced the rear/outer part of the west wall, was responsible for a lot of the damages. The outer wall is extremely fire-damaged, but it is, on the other hand, not known whether these damages were introduced earlier than 1708 (for instance during the fire in 1532). If the fire in 1708 did not directly harm the paintings, it may be suggested that they were indirectly affected due to a weakened construction and subsequent water infiltration.

Between 1826 and 1966 it is possible to observe only one repair measure. It concerns just a few parts of the wall; the turkey in Q1 and parts of the leafs in Q2. These areas seem to have been overpainted by a *very* inexperienced painter.

The extensive restoration by Ola Seter in 1966 is described in his restoration reports. The following measures of importance for the west wall are supplemented by our own findings:

- The green drapery from 1826 was removed and replaced by the "original" red colour. "Strong chemicals" were used for the removal of the green drapery. According to Seter's assistant, Ola Grefstad (pers. comm. 1999), the chemicals might have been *Reprin* (paint stripping agent containing dimethyl-chlorid as active agent) or *Salmiakke* (probably ammonium hydroxide).
- Surface deposits were removed/cleaned by clay packs



1st paint layer from 1616
2nd paint layer (repair between 1672 and 1826)

3rd paint layer 1826
4th paint layer (repair between 1826 and 1930)

5th paint layer (restoration 1966)

Regalia Room - West Wall

Archbishop's Palace
Trondheim, Norway
The Restoration Workshop of Nidaros Cathedral

Supported by The Raphaël Programme of the European Union

DiVisuAL® mapping system

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Mapping of Paint Stratigraphy 1999

ATELIER ANDREAS FRANZ

divisual@restaurierung.ch

Paint stratigraphy on the west wall. The pictures show the 1st paint layer (above - tulip in Q1) and the 3rd paint layer (below - tendrils in Q2)

- Limewash in damaged areas was often knocked off and replaced by gypsum or cement
- Cement mortar was used to consolidate badly damaged areas and fix loose plaster
- Gypsum mortar was used to fix smaller cracks and exfoliated areas
- Large parts of the murals, especially the drapery, was overpainted, but relatively few reconstruction measures were undertaken (see also Odén 1999)
- Steel brushes were used to give patina to many overpainted areas



The west wall under restoration in 1966. Note all the white fields; many of these are gypsum repairs. (Photo: Archives of the Directorate for Cultural Heritage, Oslo)

DETAILS OF THE STRATIGRAPHY ON THE WEST WALL

Q1-Q4 refers to the "quadrants" of the wall - Q1 is the upper left quadrant, whereas Q4 is the lower right one.

Probable medieval plaster with remains of whitewash.

This is a relatively "smooth" lime plaster with remains of yellowish limewash above. The plaster is relatively "fat", homogeneous and porous with aggregates (Ø max. 1-2 mm) of quartz, feldspar, greenstone, schist and some fossils (beach sand?). Small pieces/fibres of wood can also be found.

Can be observed in Q1, Q2 and Q3. The best places to see it is in Q1

Various plaster before or in 1616

These are various plasters, which cannot be distinguished clearly. Their application before or in 1616 is indicated by the fact that the (1st) limewash above seem to have covered the whole west wall (and the rest of the room). The plasters are in general relatively "fat" and porous with less homogeneous aggregate size (Ø max. 2-4 mm) than the supposed medieval plaster. Some may also have larger aggregates. Aggregates consist of quartz, feldspar, greenstone and many heavily cracked transparent grains. Some fossils, small black flakes (schist?) and a few fibres of wood (?) can also be observed.

Q1 - Q4, mostly in Q1 and Q3

1st limewash 1616

This limewash has a soft, "wavy" surface texture because of the coarse ductus of the brush tool it was applied with. It seems that it is covered with a layer of **chalk**, but this may also be part of the paint layer above.

Q1, Q2 and Q3 but not in Q4. Also on all the other walls and the vault.

1st paint layer 1616

This is the "original" painting. It is still preserved on large parts of the east wall and the vault. Unfortunately, almost 99% of this layer are destroyed on the west wall. The few remains left were mostly uncovered by Seter in 1966.

It is a typical lime paint (perhaps with some animal glue added). Pigments found include **carbon black** and various types of **ochre**. Bright red colours, as found in the tulip in Q1, consist of **cinnabar** and some **charcoal black**.

Mostly in Q1

Plaster in chimney area between 1672 and 1826

This plaster was applied to close the gap when the fireplace/oven and chimney was removed. It differs from other plasters in its fine aggregates (0.2 -1 mm) and somehow "foamy" or very porous appearance. There are also some white, very fine-grained lime aggregates (German: "Kalkspatzen") which cannot be found in any of the other plasters investigated. Moreover, no fossils and no wooden fibres have been detected.

Q2 and Q4

2nd limewash between 1672 and 1826

This limewash is difficult to observe, but can be found above the plaster in the chimney area. Its appearance is similar to the 1st limewash, but a little more yellowish.

Q2 and Q4

2nd paint layer between 1672 and 1826

This paint layer is difficult to observe since there are only small traces left (red spot in the upper part of Q2). It must be assumed that this paint layer belongs to the repair undertaken just after the chimney was removed.

Q2

Plaster in door area 1826

This plaster apparently was applied to the area above the main door opening after its enlargement. It may also have been used on the new masonry inserted in order to close the niche in the northwest corner (at this place it cannot be seen directly). The plaster is less "fat" than the older plasters, coarse and with aggregate sizes varying from 0,5 to 7 mm.

Q1, Q2 and Q3

3rd limewash 1826

This limewash, with aggregate sizes up to 1 mm, was applied on the whole upper half of the wall, but interestingly, not in the drapery area. It can be easily identified by its coarse, sandy surface texture and sharp brush marks (much sharper than the 1st limewash). Its poor adhesion to the wall suggests that the ground was not pre-moistened before painting.

Q1 and Q2



Typical appearance of the 3rd (1826 - red berry) and 1st (1616 - grey lines) paintlayers in Q1



*The turkey in Q1 was probably overpainted by an inexperienced painter after 1826
(4th paint layer)*

3rd paint layer 1826

This is a mirrored copy of the painting on the east wall. The ornaments seem somewhat stiff and lifeless, indicating that the painter was much less a master than his predecessor. The paintings appear very powdery and opaque, and with the following identified pigments: **carbon black**, **bone black**, **red** and **yellow ochre**. It seems that the paint layer rests on a c. 0,5 mm thick layer of **chalk** with numerous microfossils. Chalk is also part of the paint. The green drapery, which was painted at this time, has not yet been properly analysed.

The actual layer seems, however, to contain glue, but also oil as binder (because of its appearance and because it had to be removed with "strong chemicals" in 1966), and a **dark blue** pigment (in addition to black and ochre). Seter indicated in 1966 that the green drapery had been *repaired* by paint with oil as binder.

Q1 and Q2

4th paint layer between 1826 and 1930

This is a poorly made repair, which can be identified by the "smeary" way it was painted. There is no indication of the date of the repair, but it can be seen on a photo from c. 1930. It can be difficult to distinguish this repair from the 3rd paint layer, also because the paint technique seems to be similar. One sample of grey consisted of very fine-grained **chalk** with microfossils, as well as very fine-grained **carbon black**.

Q1 and some in Q2

Cement repair 1966

Portland cement mortar was used by Ola Seter to close larger cracks and to fill the space after removed plaster. It is also possible that cement was used as injection material to fix hollow areas. Cement can especially be found along the border between the wall and the vault (this border is characterised by a large crack, which can be easily observed on the loft above the vault), as well as between the wall and the floor. Unpainted, dark grey cement mortar in the outermost frame of the main door opening must have been applied later than 1966 (Ola Grefstad, pers. comm. 1999)

Q1 - Q4

Gypsum/lime repair 1966

Thin gypsum plaster without or with very little aggregates was used to cover open cracks and to smooth irregular parts of the wall. The plaster originally covered relatively large areas, but due to its tendency to scale off, much has been lost since 1966. The plaster consists of gypsum with calcite or dolomite,

anhydrite and quartz (these are natural constituents in gypsum). "Grains" of a dark, rounded material have also been detected, possibly an organic component. Traces of animal glue have been found during binder analyses.

Q1 - Q4

5th paint layer 1966

The 5th paint layer can be found all over Seter's cement- and gypsum repairs, as well as on a few other parts of the wall. Seter mainly used two different types of binders:

- 1) On cement repairs the main paint seems to be **titanium dioxide white** in oil (linseed oil?) with a carbonate as filler. On the surface this layer is pigmented with **bone black, red and yellow ochre** and possibly **cobalt blue**.
- 2) On gypsum repairs, as well as on other parts, the binder has not been found yet. It may be lime, but very probably mixed with glue or casein. Pigments on grey coloured gypsum repairs include **bone black, cobalt blue, and red and yellow ochre**.

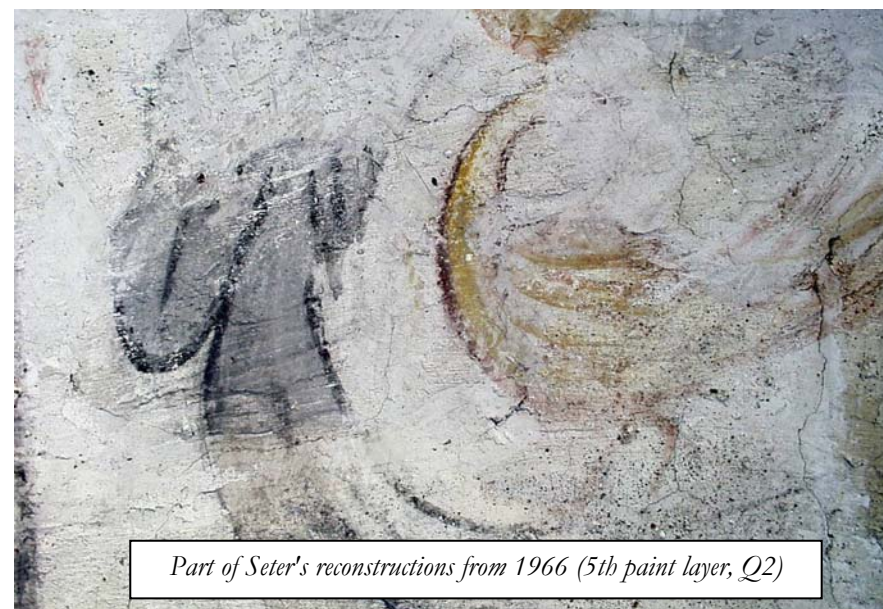
At a few places, especially on top of the column above the door, there are pencil strokes, which may have been drawn by Seter or his assistant (cf. Odén 1999).

Q1 - Q4

Glazing 1966

The red drapery painted in 1966 has a finish with a glazing. It has not yet been possible to discover what kind of glazing this really is, except that it contains red ochre, and that it has been given a patina by using brushes after application. The glazing has a strong tendency to exfoliate or scale off, indicating that an organic binder which develops strong surface tension may have been used.

Q3 and Q4



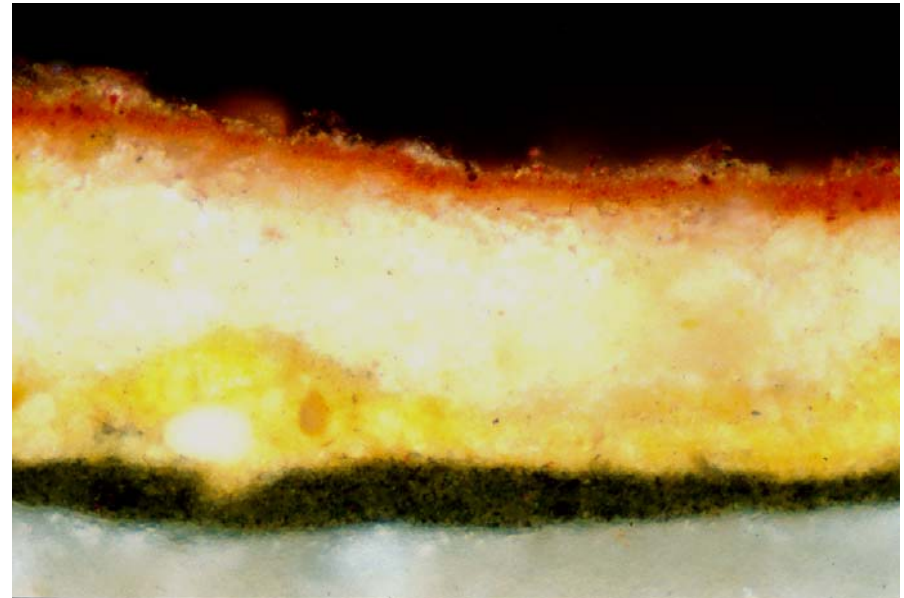
Part of Seter's reconstructions from 1966 (5th paint layer, Q2)



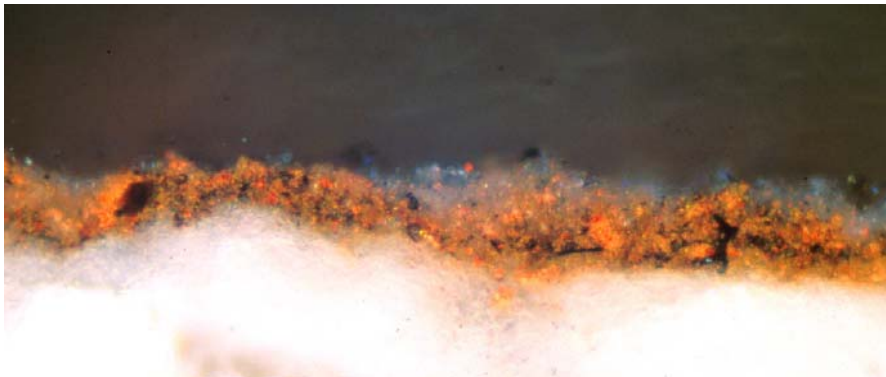
Exfoliating glazing from 1966 (Q3)



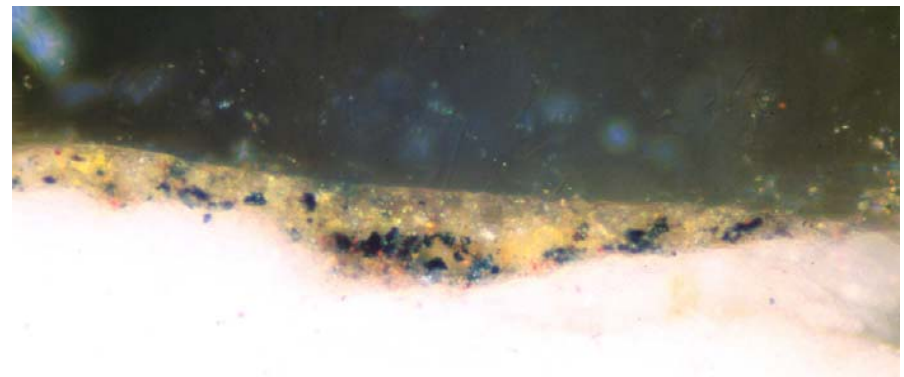
Mechanical damage at the south edge of the main door opening. On the "bottom" it is possible to observe a plaster from before 1616. The uppermost paint stratigraphy can be seen on the picture to the right.



Microphoto of the uppermost part of the stratigraphy in the damaged area to the left. From the bottom: white lime mortar/limewash, green/dark paint from 1826, a light brown/-yellow layer (unknown date), a light gypsum repair (1966) and the red paint/glazing from 1966. Sample P15, see appendix 1 for details. Width of field c. 0,8 mm



The original paint layer from 1616 on a bird in Q1. Red ochre and charcoal black. Sample P8, see appendix 1 for details. Width of field c. 0,8 mm

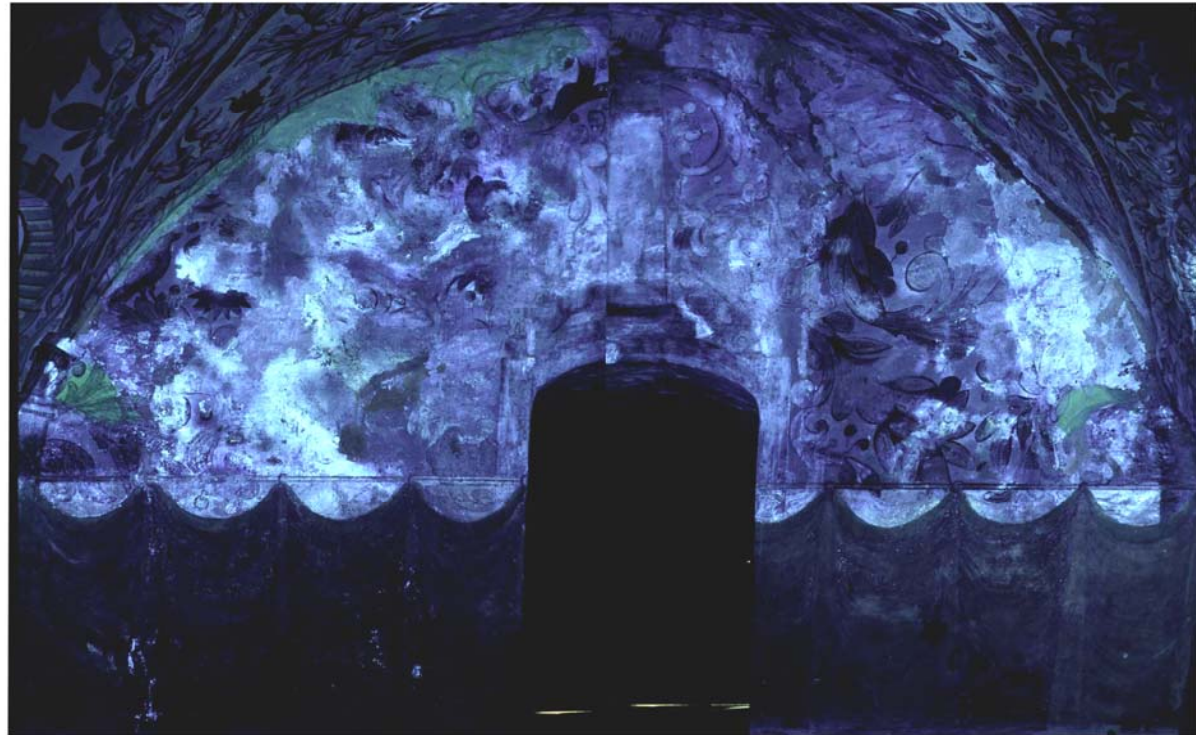


Yellow paint layer from 1826 in Q2. Yellow ochre, bone black and a little red ochre. Sample P11, see appendix 1 for details. Width of field c. 0,8 mm

RESULTS OF UV- PHOTOGRAPHY

UV-photography was performed in order to collect information about phenomena that cannot be seen in normal light. Unfortunately, the UV-recordings did not provide additional information, other than making it a bit easier to interpret phenomena that already had been surveyed. Such phenomena include:

- Plasters without limewash and paint often appear very light
- The 1616 and 1826 paintings are mostly bluish or dark
- The borders of the "chimney plaster" appear rather distinctively
- Cement repairs undertaken in 1966 are easily distinguished due to the dark yellowish colour (due to the oil-painted surface and pigments used)
- It is also very easy to see the borders of Seter's painting in the arch of the main door opening.



Regalia Room - West Wall

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UV Fluorescence Photography 1999


aTELIER aNDREAS fRANZ

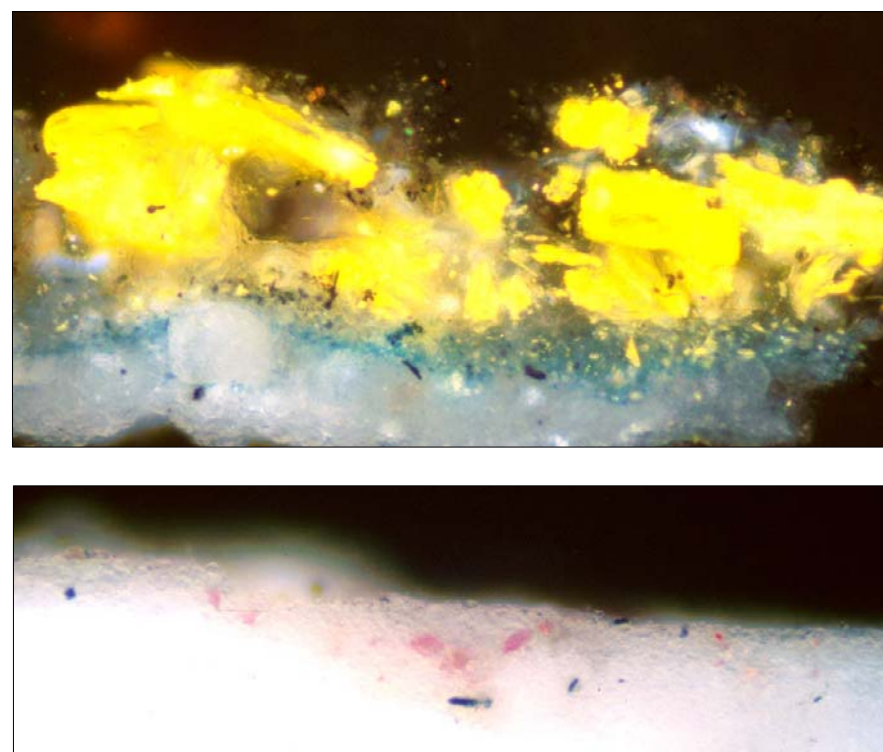
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The 1616 paintings on the east wall are relatively little affected by later restoration measures. The picture shows "vital" tendrils with faded-away polychromy. But it is still possible to see green and yellow colours with the naked eye.

A BRIEF NOTE ON THE PAINTINGS ON THE EAST WALL

In order to confirm earlier suggestions (especially by Erdmann 1927) that the original tendrils (presently looking like greyish *grisaille* painting) might have been polychrome, samples of the 1616 paintings on the east wall were analysed. During the collection of samples, undertaken by using stereo microscope, bright green, yellow and red/pink colours could be identified.



Paint samples from the east wall. Above: Yellow orpiment and indigo blue with some charcoal black and red ochre (sample P18). Below: Chalk with pink madder lake (sample P17). See appendix 1 for details. Width of field c. 0,8 mm.

The results of the pigment analyses confirmed the *in-situ* observations. The yellow and greenish colours, today fading into shades of grey, are mainly composed of **orpiment**, a poisonous arsenic sulphide, mixed with various quantities of **indigo blue**, red **ochre** and **charcoal black**. Domenico Erdmann already in 1927 indicated that indigo might have been used. He also suggested that the fading of the greenish colours could be

traced back to the use of indigo - his theory seems in other words to have been confirmed by these new analyses.

Pink colours, especially found on berries, are usually made of **madder lake** (German: "Krapprot") and **charcoal black** on **chalk** as substrate. Bright red colours, as in the 1616 tulip on the west wall, consist of **cinnabar** and **charcoal black**.

Orpiment, cinnabar and indigo blue were very precious pigments at the time they were applied. Especially orpiment is rarely used on mural paintings. As an anecdote it may be mentioned that Botticelli used a lot of orpiment during his commission in the Sistine Chapel (Neue Zürcher Zeitung, 8/9 January 2000, p. 65)

MORTAR AND LIMEWASH IN THE CLOSED OPENING IN THE NW-CORNER

The rear of the presently closed opening in the north-west corner of the west wall was briefly investigated in order to evaluate the former theory stating that it was completely open until 1826 (cf. Odén 1999). Our findings indicate that the opening was closed already in 1616, but used as a niche until 1826. The reason for this theory is that there is a remaining "piece" of masonry in the middle of the opening, which must have formerly blocked the whole passage. Towards the Regalia room, this "piece" of masonry has an upper layer of smooth limewash which is more or less identical to the limewash used as ground for the 1st paint layer (1616). There is no trace of weathered-away limewash above this smooth limewash. Perhaps the niche was used for

Views of the niche at the rear of the north-west corner of the west wall. Right: Overview showing the masonry at the rear of the blocked door that may formerly have led to a "toilet". Inserted: The backside of the "piece" of masonry in the middle has limewash which seems identical to the 1616-limewash in the Regalia room.



firewood before the fireplace/oven was dismantled?

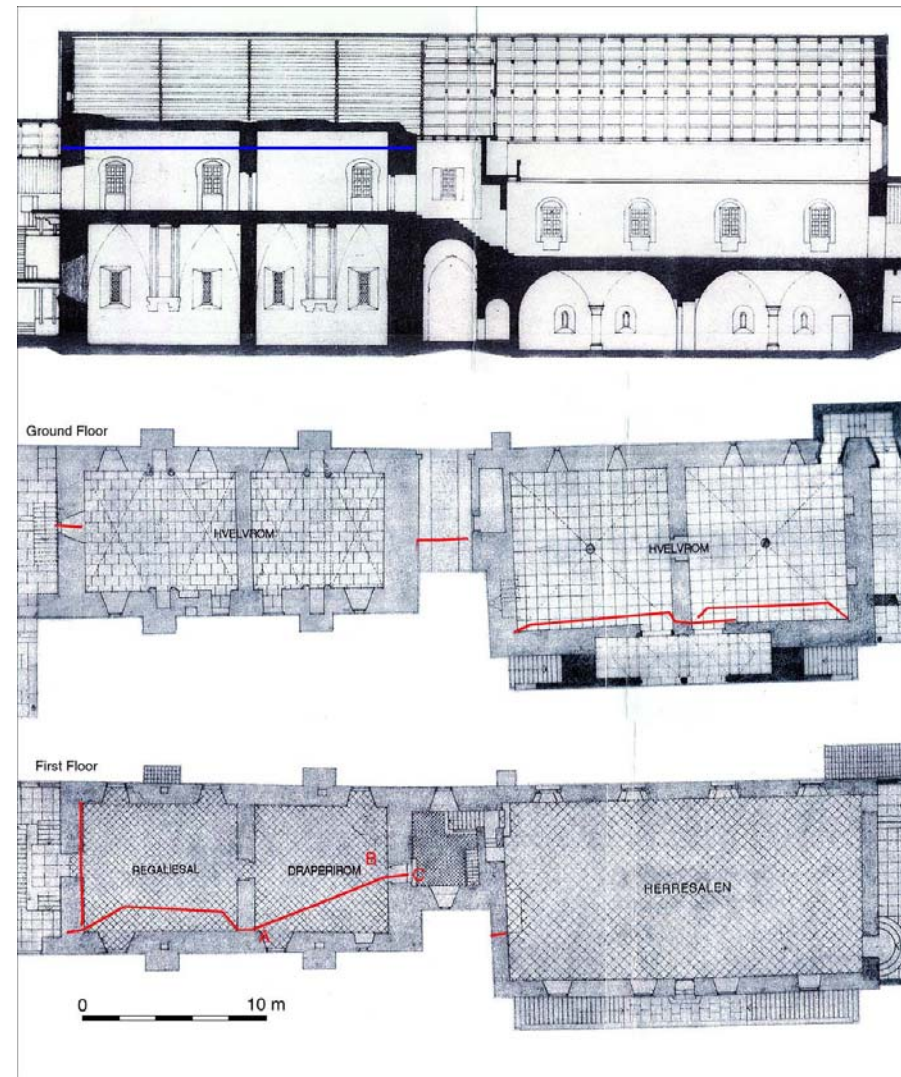
Otherwise, the rear of the closed opening has many different stones, bricks, joint mortars and plasters - indicating a complex history. In a later section will be described the weathering phenomena observed in the opening. These phenomena provide important clues for understanding the weathering of the paintings on the west wall. It should be noted, moreover, that the opening is a perfect place for in-depth building archaeological studies. Such studies could bring new light on the medieval history of the west house of the Archbishop's Palace.

Structural Problems in the North Wing of the Palace

Before turning to the present state of the west wall and the evolution of the weathering, possible structural problems in the north wing of the palace will be addressed. There are at least two different phenomena to be discussed. First, there are longitudinal cracks all along the north wing, and, second, there are transversal cracks close to the west wall of the Regalia room.

LONGITUDINAL CRACKS

The longitudinal cracks were discovered before the last restoration (Krafft 1952), but they apparently widened during and after all the interventions between 1962 and 1975. The cracks run in the southern part of the vaults and walls in the east house, continue through masonry in the tower room, and become especially wide in the vault of the Drapery room. In the Regalia room they are difficult to observe, but there is nevertheless a distinctive crack pattern in the south side of the vault. Obviously these features have caused some loosening of plaster and paint in this area - also close to the west wall.



Plans and section showing the location of cracks in the Archbishop's Palace (straight red lines), as well as supporting steel beams (blue)

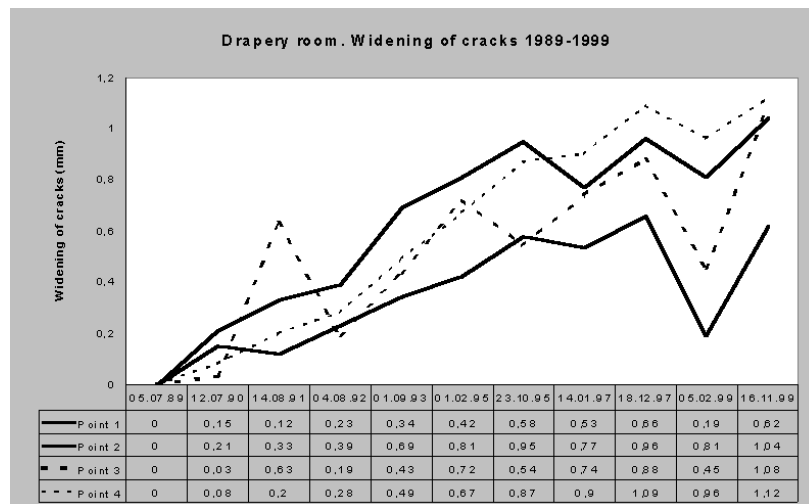


Diagram showing the widening of cracks in the Drapery room 1989-99

Since 1989 the cracks have widened between 0,5 and 2 mm. In the Drapery room where we have the closest measuring points to the Regalia room, the widening has been as low as 1 mm. Until 1997-98 the general tendency was a widening at all measuring points, but in the winter of 1999 the crack-widths suddenly decreased temporarily. This might have been because of a temporarily higher ground water table due to heavy rain for weeks. Measurements in November 1999 showed that the decrease really was of a temporary nature.

No one has yet made any serious attempts at interpreting the cracks. Two main hypotheses may however be put forward: First, the building of the large double porch/staircase on the south side of the east house just before 1975 might have pulled the south wall of this part outwards/downwards. Second, extensive archaeological excavations in the area might have changed the ground conditions to such a degree that the foundations temporarily became unstable. If this is right, we have to assume that the building is in the process

of finding its new structural equilibrium. A structural analysis should of course be made in the near future. Such an analysis should also consider the cracks in the middle of the west wall. In the room below the Regalia room there is a relatively wide crack from the ground and up to the vault. However, whether the cracks above the main door opening in the Regalia room itself belongs to the same pattern is unclear. These cracks might have evolved due to the enlargement of the opening in 1826.

TRANSVERSAL CRACKS

The transversal cracks affect the west wall of the Regalia room more directly. On the loft, between the vault and the western gable wall, there is an opening as wide as up to 10 cm (!). Although no measurements have been done, this opening/crack luckily seems to be rather stable at the moment. However, it seems clear that there must be a relationship between the crack and the heavy loosening of plaster just below the vault in the Regalia room. Some of this loosening also seems to have taken place after the restoration of Seter in 1966. Seter did a lot of work in this area; he especially fixed smaller cracks and loose plaster by cement. Although no documentation has been found, the transversal cracks were obviously the reason for installing the supporting steel beams above the vault during the last restoration, and to prevent the west wall from leaning more outward than it already is (50 cm?). Whether these beams have had any effect is unclear.

The cause of the crack pattern and its evolution is unclear. But it is possible to speculate about the cause. The gable wall might have become unstable during the catastrophic fires of 1532 and 1708, which destroyed the whole west wing of the Archbishop's palace. Furthermore, the introduction of supporting concrete beams in the staircase between the north wing and the west wing (1962-75) might have contributed to a further very small pulling outward of the gable wall. These speculations should certainly be analysed.

Exposure Conditions and Indoor Climate

EXPOSURE CONDITIONS

Situated on the southern shores of the wide Trondheim fjord, 50 km east of the Atlantic Ocean, Trondheim may be regarded as something between a coastal and an inland city. Like most coastal or near-coastal parts of Norway, the city has a maritime temperate climate with mild to rather cold winters and cool summers (cf. Storemyr 1997). The annual precipitation is about 900 mm, and as most of it falls during westerly winds, the west wall of the Regalia room is the only wall of the room affected by rain. Over the last years, since the wall was repaired 1992-95, leaks have never been observed. It is, however, to be supposed that smaller leaks, or at least water seepage, might have caused parts of the interior west wall to become moister than the rest of the room before the repair.

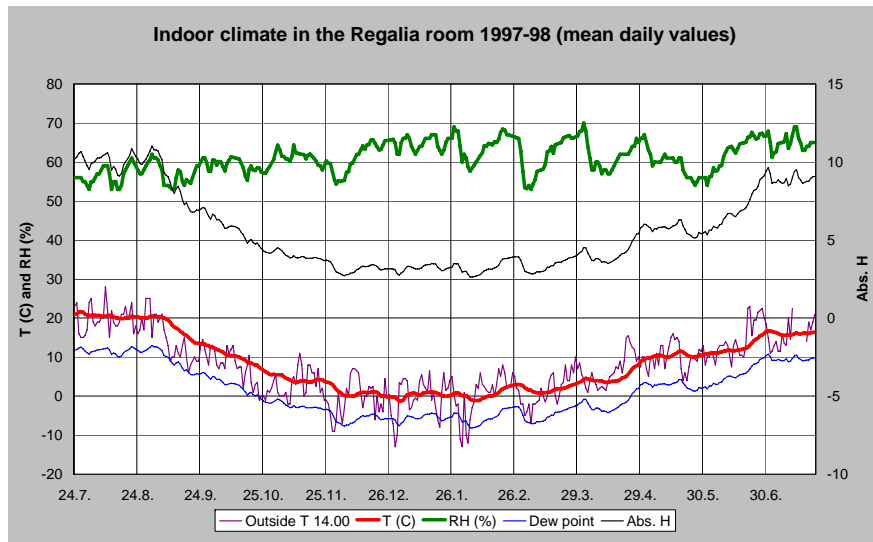
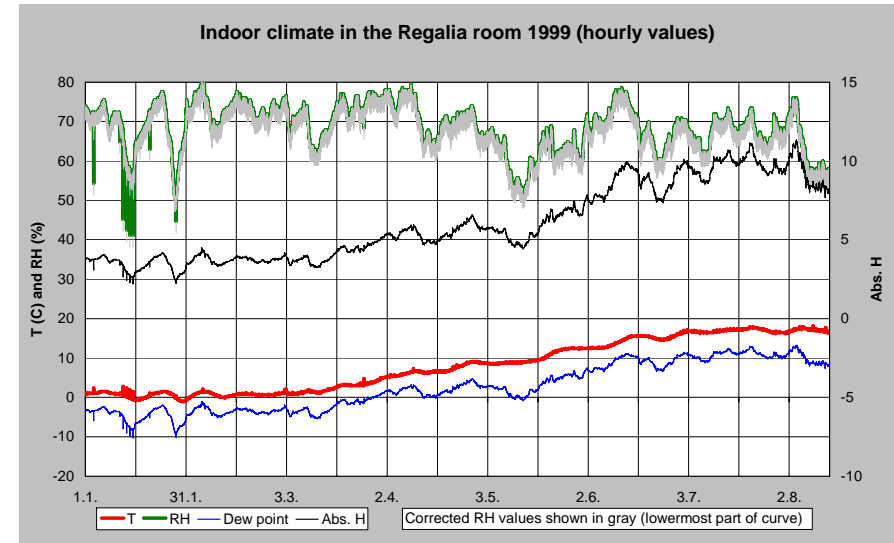
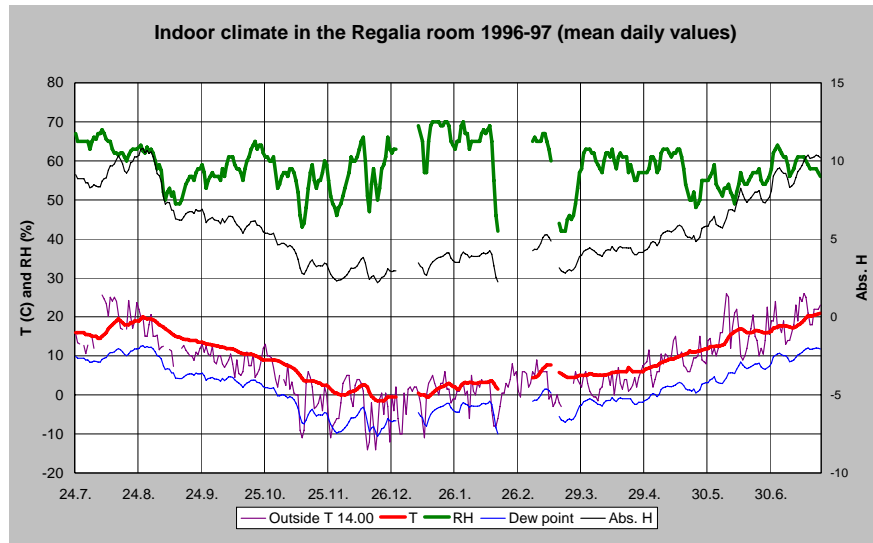
Snow is another important part of the Trondheim climate. Winters may be mild with only rain and sleet, but also relatively cold with large amounts of snow. Snow may in fact be of some importance for the west wall, since the

upper northern half of the wall is situated more or less on the same level as the roof of the staircase between the west and north wings of the palace. Snow may collect for longer periods of time on the roof, especially since there is a bay (probably built in 1826) with a relatively flat roof in the area. Upon thawing, snow may perhaps provide enough water to really moisten the wall. It is at least very interesting to observe that the presently most damaged areas on the west wall can be found at the rear of this place.

INDOOR CLIMATE

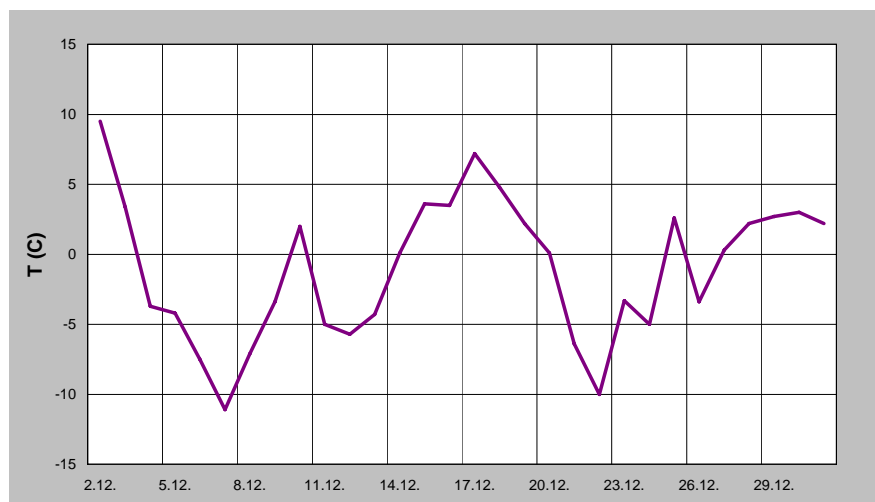
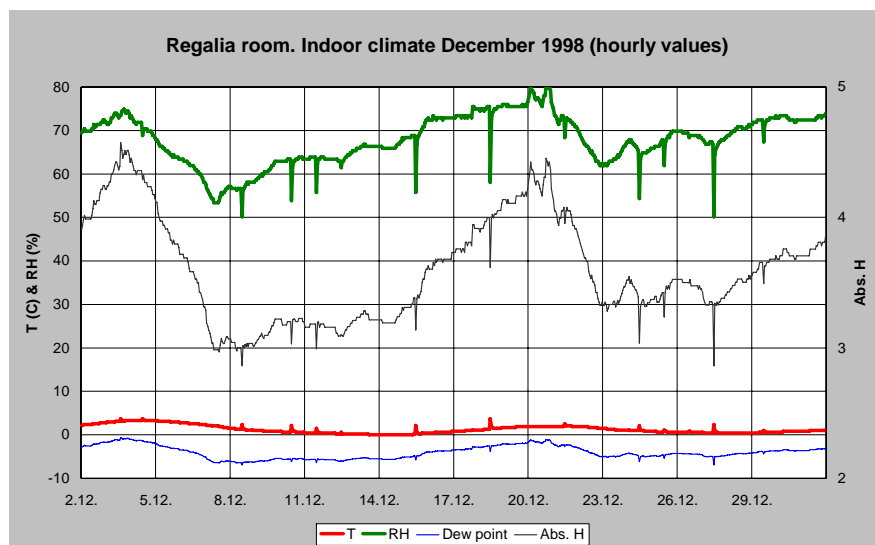
After the floor heating from the 1960s was turned off in the beginning of the 1990s, the climate in the Regalia room (and the Drapery room) has been a moderated outdoor one. The room is situated relatively far from other heated areas of the north wing. The nearest room is the *Herresal*, which has a background temperature of 8-15°C in the cold season (September/October-May), but which is heated to more than 20°C during occasional events. In the cold season it seems that the general air movement pattern in the north wing is from west to east, implying that cold air from the Regalia and Drapery rooms sinks down to the *Herresal*. Such observations have been made numerous times over several years, but it is of course possible that specific weather conditions may occasionally alter this pattern. A couple of years ago, electrical radiators were installed in the room below the Drapery room, but the room is so infrequently heated, and only to very moderate temperatures, that this hardly has any influence on the Regalia room. In conclusion it may be stated that the Regalia room is hardly influenced by indoor heating, except for the general very slight warming up of the masonry due to heating in adjacent parts of the palace.

The indoor climate of the Regalia room has been measured since 1996. The measuring devices have changed over the years, and unfortunately there has not been undertaken complete, relevant measurements of the outside



Diagrams showing the indoor climate in the Regalia room 1996-99.

The above section of the north wing of the Archbishop's Palace shows heated areas (red), unheated areas (blue) and rooms with only occasional heating (violet)



Indoor climate in the Regalia room in Dec. 1998 showing rapid changes at midday.

Below: Compare with outside temperature at Værnes (30 km east of Trondheim)

climate in the same period. This implies that it is not possible to properly interpret air exchange between the room and the exterior. An outside climate station has been installed only very recently.

The measuring devices have always been located in the northwest corner of the Regalia room. In 1996-97 a thermohygrograph working on a weekly basis was used, while in 1997-98 a monthly thermohygrograph took over. From the paper output, mean daily values of T and RH were calculated. Since December 1998 electronic devices measuring T and RH every hour have been used. The devices are called Tinytag and has an accuracy (as stated by the provider) of $\pm 1^\circ\text{C}$ and $\pm 2-3\%$ RH. In August 1999 an extensive test showed that the Tinytag instruments gave temperatures and relative humidities laying $+0,4^\circ\text{C}$ and c. $+3\%$ above the real values, respectively.

The various measuring techniques explain some of the differences in T and RH over the last few years: The monthly thermohygrograph (1997-98) is not able to pick up rapid changes in the room climate, thus giving a "smoother" RH curve than the weekly thermohygrograph (1996-97). Moreover, since the Tinytag instruments were placed close to the floor from December 1998, they seem to give a little lower T and higher RH than the thermohygrographs, which were placed on a table at the same location.

As can be seen from the diagrams, the indoor temperature varies between just below 0°C in the deepest winter to about 20°C in high summer (average $8-9^\circ\text{C}$). RH varies from c. 40% during cold winter periods to more than 70% in mild winter periods, as well as during humid summer days (average c. 60%). As expected, the indoor RH is extremely dependent on the outside temperature: Rapid temperature changes outside are very quickly reflected in the indoor RH.

The indoor T and RH are also dependent on sunshine in the winter time when the sun is so low that it shines through the south window, causing a rapid temperature increase of $2-5^\circ\text{C}$ and a RH decrease of up to 20% at noon time. Whether these rapid changes have much influence on the weathering is

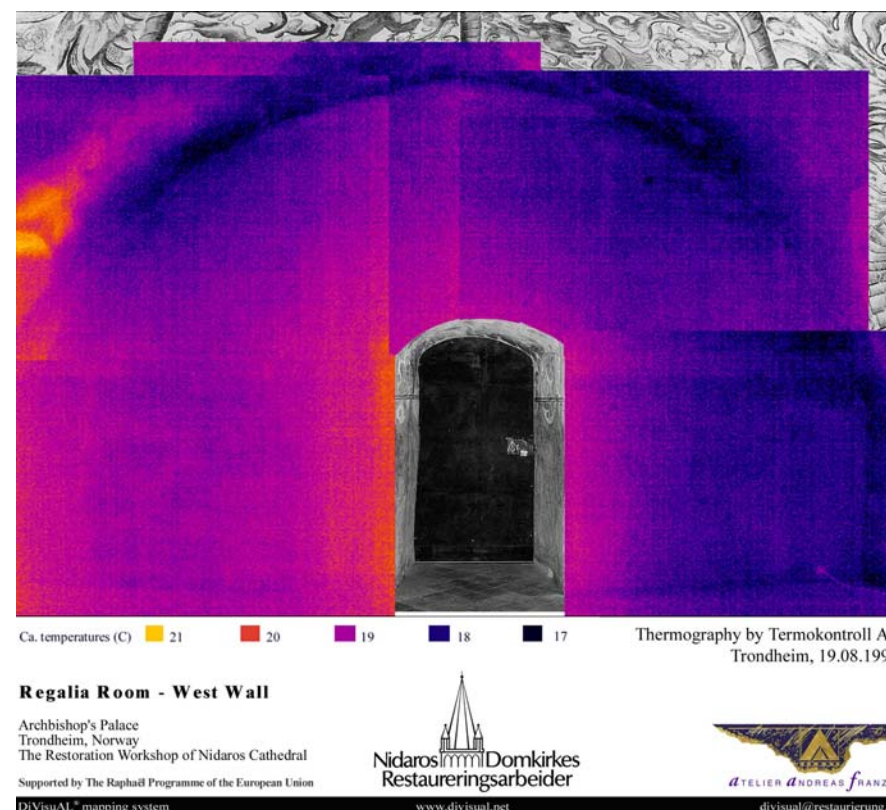
unclear. However, the bright sunshine entering the room at noon in winter might lead to a more rapid fading of colours on the murals. In order to solve this potential problem, the simple solution is to put up curtains or Venetian blinds.

Condensation does not seem to be a great problem in the Regalia room. The dew point is generally 3-10°C below the room temperature, indicating that only *extreme* temperature increases outside during the wintertime, or *extremely* humid late summer days, might lead to condensation. Occasional measurements have also shown that the surface temperature on the west wall generally differs only little from the room temperature (+/-1-2°C).

THERMOGRAPHY IN AUGUST 1999

In August 1999, during a fine weather period (T max. c. 25°C), thermography recordings were undertaken in order to detect cold corners and other temperature phenomena on the west wall. The recordings show that the temperature is rather even (some 18-19°C; room temperature c. 18°C), but that the border between the wall and the vault is some 1-2°C colder. The blocked opening for the former chimney can be spotted clearly on the recordings, as can the upper part of the blocked niche in the northwest corner. There are, moreover, a few cold spots on the northern half of the wall that cannot be explained properly. Perhaps they are connected with iron or concrete (from the last restoration) within the masonry? New thermography recordings will be undertaken during a typical winter situation also.

Although we have a fairly good picture of the room climate, we need more measurements in the Regalia room itself, in adjacent rooms, as well as of the outside climate, in order to be able to control the climate properly.



Weathering Phenomena

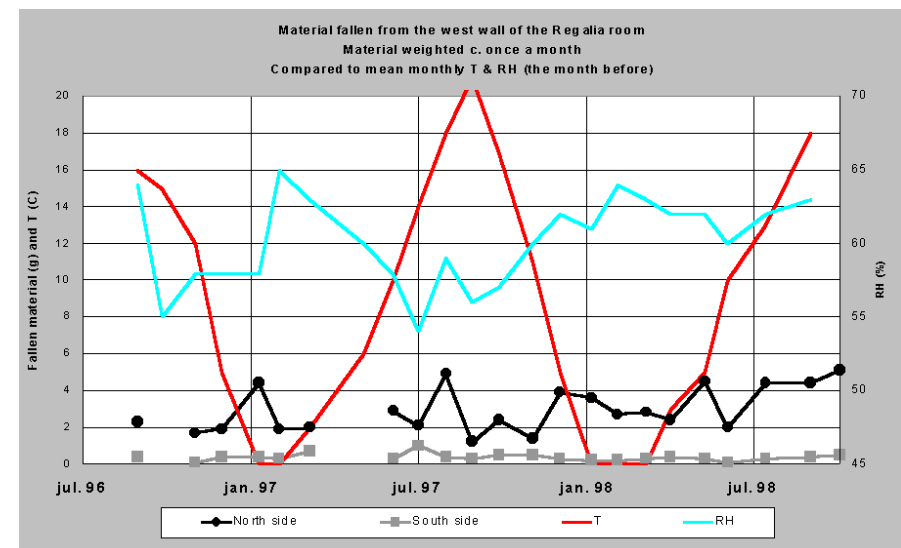
The north side of the wall (north of the main door opening) weathers much more actively than the south side. This can be seen from the amount of material that tends to fall from this side. Between July 1996 and October 1998, about 100 g fell from the north side, while only 10 g fell from the south side. It is difficult to observe any seasonal difference in the amount of fallen material, but it may seem that more material fall after the autumn and after the spring/early summer (north side). Generally, these are periods with the strongest temperature and RH gradients. It should be strongly underlined that parts of the murals are so fragile that the lightest touch will cause flakes to fall. This is the reason why more material tends to fall during investigations of the wall. Therefore, periods in which investigations have been undertaken have been omitted from the diagram to the right. This certainly complicates the interpretation above. Very much of the fallen material consists of flakes from Seter's gypsum repairs (1966), some of it is flakes from the 1826 painting, and the rest is powdery material and sand from disintegrating plaster and whitewash. There is much salt in the fallen material, mostly nitrates and chlorides (see appendix 2).

In the following is described how the weathering on the west wall and other relevant parts of the west house appears.

WEATHERING FORMS ON THE WEST WALL

Weathering forms have been classified according to the following scheme:

- Hollow areas
- Cracks
- Granular disintegration of plaster
- Exfoliation of limewash (and paint)
- Pitting
- Exfoliation of gypsum
- Exfoliation of glazing
- Powdering of paint
- Biological phenomena
- Mechanical damage



Material fallen from the west wall between July 1996 and October 1998, compared with the indoor climate (mean monthly values)



 Hollow areas	 Mechanical damage	 Granular disintegration of plaster	 Exfoliation of gypsum/lime
 Cracks	 Pitting	 Exfoliation of limewash	

Regalia Room - West Wall

Archbishop's Palace
Trondheim, Norway
The Restoration Workshop of Nidaros Cathedral

Supported by The Raphaël Programme of the European Union

DiVisuAL® mapping system



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Mapping of Damages 1999



divisual@restaurierung.ch



*Mapped weathering forms on the west wall.
The small picture shows the widespread
distribution of areas with powdering of
paint (or granular disintegration of paint)*

Many of these weathering forms occur together and it may sometimes be difficult to clearly distinguish between each form. Below, each form is nevertheless described separately, but with reference to other forms when appropriate. For example, salt efflorescences are mentioned in connection with the weathering phenomena they seem to influence.

Hollow areas

Hollow areas (German: *Hohlstellen*, Norwegian: *Bom*) mean areas where there is no or little adhesion between the uppermost plaster and underlying masonry (and/or older plasters). Such areas have been manually detected by careful knocking. They are very widespread, but many seem not to be very dangerous. The most problematic ones can be found along the border between the wall and the vault, and in connection with the plaster in the chimney area. In both cases it is possible that they are mainly caused by (earlier) stability problems, such as the outward drift of the wall (represented by transversal cracking), and vibrations when the main door opening was enlarged in 1826. However, especially parts of the "chimney plaster" still seem to move, and it is obvious that the hollow areas here influence on the strong exfoliation of limewash/paint above (see below). Most of the cement repairs undertaken in 1966 also have a hollow area underneath, but except for small exfoliation-like damages at the periphery, the cement layers themselves look rather stable.

Cracks and fissures

There are at least five types of cracks and fissures:

1. The large transversal crack between the wall and the vault. This has been mentioned earlier, and seems, as described, to be one of the causes for the hollow areas here.
2. The longitudinal crack patterns in the southern part of the barrel vault, which influences the west wall on the border between the vault and the wall. Also this crack has been mentioned earlier. It is reasonable to

suggest that some of Seter's cement repairs in 1966 were undertaken in order to stabilise areas affected by this crack pattern.

3. The extensive crack pattern above the main door opening. This seems to be a combination of shrinkage fissures in the plaster, and "real" cracks caused by either vibrations when the opening was enlarged or other kinds of stability problems in the west house (these cracks may continue in the west wall of the vaulted room below the Regalia room).
4. Cracks along the border between the wall and masonry inserted in order to block the niche in the northwest corner. These cracks are not dangerous.
5. Shrinkage fissures in the plaster, especially above the main door opening. Some of these fissures have caused the plaster to become unstable and should be repaired.

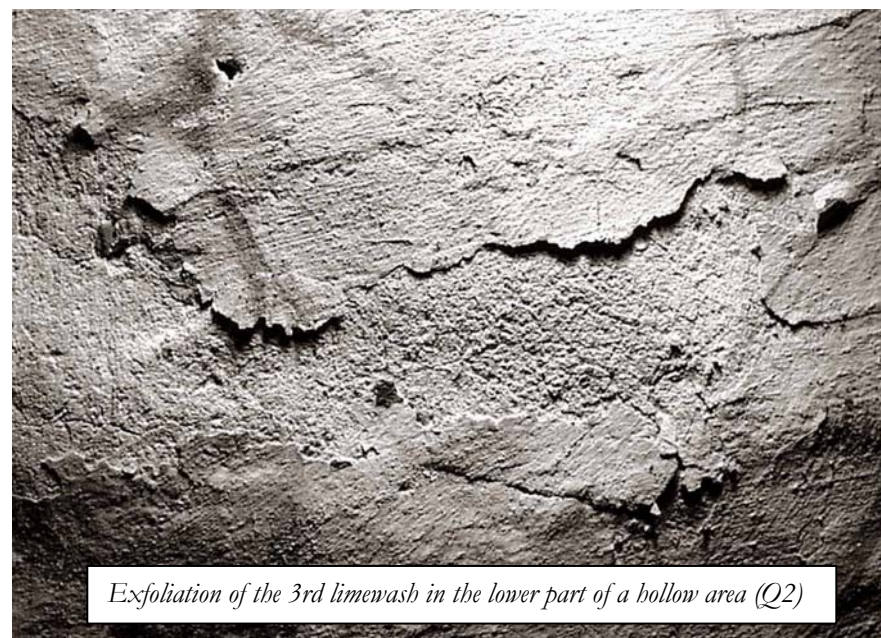


Crack pattern in the area above the door (type 3)



Granular disintegration of plaster

Intensive granular disintegration of plaster is mainly found on the northwestern part of the wall, but several other areas are affected as well. In the northwestern part both "various plasters" and the "chimney plaster" exhibit strong damages, and usually there is only "sand" left of the uppermost plaster surface. It is almost impossible to observe salt efflorescences, but analyses show that there are large amounts of nitrate, chloride, sulphate and sodium in the disintegrated areas. On other parts of the wall the damages are less severe and often connected to slight loss of adhesion in the mortar matrix, as well as disintegration of specific aggregates. These aggregate grains are mainly greenstone and various schists. Analysed disintegrated aggregates all have much salt (like those mentioned above). Limewash and paint in areas with disintegrated plaster usually exhibit slight to strong granular disintegration or "powdering" as well.



Exfoliation of limewash (and paint)

Exfoliation of limewash (and paint above) is very often concentrated along the borders of hollow areas. It seems that the deformation in the plaster creates tension causing the limewash to lose the adhesion to the ground. It should be noted that *severe* exfoliation mainly takes place in relation to the plaster in the chimney area, indicating that the adhesion between this plaster and the limewash applied in 1826 was rather poor from the beginning. It should also be noted that powdery salt efflorescences, especially thenardite, sometimes can be observed below exfoliated areas (mainly in the lower part of Q1).

Pitting

Pitting is a specific weathering form that mainly occurs underneath the arch in the main door opening. It takes the form of small "volcanic craters", or

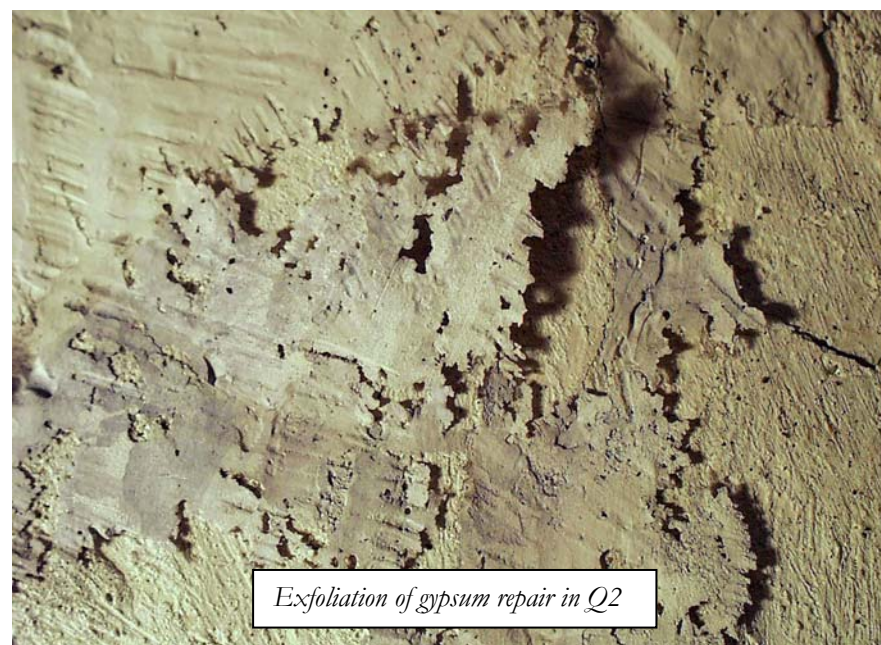


Pitting followed by epsomite in the arch of the main door opening

crater-like pits, cutting through paint and limewash. The "craters" often, but not always, originate on "top" of aggregates in the plaster. There is usually much salt along the "rim" of the "crater", mostly powdery efflorescences of epsomite. Clearly, the occurrence of epsomite points to salt as the main weathering agent, but the reason for the specific appearance of the weathering form remains unclear. Damages on the upper part of the glazing in Q4 have also been classified as pitting, although the weathering form might look like exfoliation. Powdery salt efflorescences in this area are mainly thenardite.

Exfoliation of gypsum repairs

Exfoliating gypsum repairs from 1966 is probably the most *apparent* weathering phenomenon on the west wall. One reason is that gypsum repairs are very widespread, another is that large proportions of the repairs are



Exfoliation of gypsum repair in Q2

damaged. Most of the exfoliation takes place where the gypsum has been used to fix cracks and fissures, or the boundaries between exfoliating limewash/paint and sound surfaces. There are often salts below exfoliating gypsum layers on the northwestern part of the wall, mostly powdery efflorescences of thenardite. Thus, there must be multiple causes for the severe exfoliation. In addition to *salts* and the *location* of gypsum repairs in areas with very active weathering, the material properties of the repairs themselves must be considered. Gypsum often shows high *thermal dilatation*, implying that temperature differences in the room might affect the weathering. Also *hygric dilatation* should be considered. Moreover, possible organic additives (animal glue) in the gypsum mixture might increase the extent/rate of swelling/shrinking of the repairs. A very important reason why all *exfoliating* gypsum repairs should be removed is that during



swelling/shrinking gypsum tends to destroy underlying limewash/paint. An additional reason is that during eventual condensation events, gypsum might dissolve/recrystallise, and add to the salt weathering problems on the wall

Exfoliation of glazing

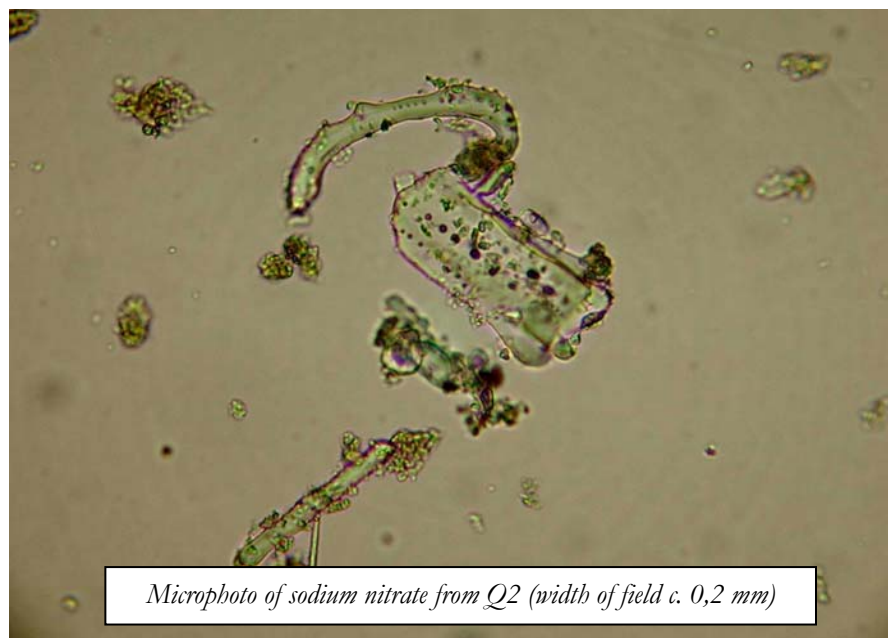
Exfoliation of glazing on the drapery is very widespread on the east wall of the Regalia room. On the west wall it is confined to a few areas with other damages as well. The glazing's tendency to flake is probably related to the unknown organic binder creating surface tension (casein, glue or modern lacquer/varnish?). There are also salt efflorescences in the area (sulphates and nitrates), and analyses with "test strips" have given strong *nitrite* reactions. At presents the origin of nitrite is unclear, but as it is confined to the drapery area (also on the east wall), it may be suggested that it stems from the glazing.



An important question is whether the glazing seals the surface, preventing moisture to pass through, and thus creating unknown problems behind. This would possibly also have a damaging effect on the moisture balance of the whole wall. At the moment this question cannot be answered.

Powdering of paint

Powdering (or granular disintegration) of paint is extremely widespread and represents perhaps the most serious weathering problem. It is, after all, the paint that is the most important feature of a mural painting! "Fading" of colours has earlier repeatedly been described as a problem in the Regalia room, and the main reason for this is probably the slow loosening of pigments, or powdering of the paint. It seems that tiny crystals and whiskers of sodium nitrate and halite are strongly involved in the weathering process.



These salts can hardly be observed by the naked eye, but under the microscope it becomes clear that there are large amounts present. Moreover, the paint technique used for the 3rd paint layer (1826) could have an influence as well. This layer appears very "powdery" and opaque, with little adhesion in the matrix. Thus, it might be an easy "victim" for salt weathering.

The occurrence of such large amounts of salts on the surface of the paintings makes it clear that the salt weathering mechanisms have to be properly understood before conservation measures like for instance desalination are undertaken. Theoretically, both halite and sodium nitrate have equilibrium relative humidities of c. 75% - a value that is infrequently passed in the room. Are the salts regularly dissolving and recrystallising? This will be the subject of a later section.



Biological phenomena

The walls of the room appear very "dry", but the relative humidity is sometimes so high that the presence of algae could have been expected. However, neither algae nor other kinds of organic growth have been observed with the naked eye. Furthermore, no analyses have been made in order to detect possible microorganisms. It has, on the other hand been observed a few beetle-like creatures, measuring some 3 mm. These creatures seem to be dead, but remains in several weathered-out small holes in plaster and limewash. They have not yet been determined, and whether they have played an active part in the weathering of the wall remains unclear. The occurrence of these creatures indicates that, at least earlier, the wall must have provided desirable living conditions (moisture and nourishment). Hence, the "beetles" should be analysed carefully. In this connection it should be pointed



*Another weathering form: Granular disintegration of aggregates (greenstone) in mortar.
Width of field c. 10 mm*

out that during recent archaeological investigations in the vaulted room below the Regalia room, many so-called "flour beetles" have been found. It seems that they "colonised" the room when it was used for food storage (Alf Tore Hommedal, pers. comm. 1999).

Since the wall at least earlier must have provided relevant conditions for beetle-like creatures, it is very reasonable to suggest that other organisms have been present as well. Thus, various organisms may have played a vital role in the production of the large amounts of nitrates that have been found on the wall.

Mechanical damages

A couple of places on the west wall show signs of mechanical damage, or small areas obviously affected during for instance building of scaffoldings. One area on the south edge of the main door opening is especially "valuable" because the whole stratigraphy (several layers of paint and whitewash) lies open here (see earlier).

WEATHERING OF THE EXTERIOR WEST WALL AND THE OPENING IN THE NW-CORNER

The fire damages on the exterior west wall facing the staircase between the north and the west wings of the palace can still be easily observed, despite extensive restoration measures in the 1960s. These restoration measures included patching the wall up with bricks and Portland cement mortar, as well as repairing the frame and installing a wooden door in the blocked opening in the northwest corner.

Masonry inside the blocked door opening is rather weathered, with granular disintegration as the main weathering form. There are also quite a lot of salts, of which powdery efflorescences of thenardite are most easily observed. Thenardite is probably derived from Portland cement mortars and concrete used during the restoration (sodium carbonate which have reacted with sulphate). Taking a closer look on the "ceiling" of the blocked opening, it can be seen that reinforced concrete was used to consolidate the wall and provide a hold for iron anchors and steel beams (see earlier section). It can also be observed that the reinforcement is rusting, indicating occasional rather moist conditions (for instance condensation). For unknown reasons, a wooden beam (with signs of fungi) has also been inserted in the wall close to the concrete. It should be remembered that these materials are situated probably less than a metre away from the most damaged parts of the mural paintings (!)

Even if thenardite is the most easily observed salt, there are lots of other salts in the masonry of the blocked opening. Samples of disintegrated bricks, stone and mortar all contain high amounts of chloride, nitrate and sodium, as well as some sulphate, magnesium and a little potassium. It is probable that this more or less represents the "bulk" saline chemistry of the wall. If this is the case, it is possible to conclude that nitrates and chlorides, which are also found in great amounts on the paintings, have been present in the wall for a very long time - they cannot have been introduced for instance during Seter's restoration of the murals in 1966.

As mentioned above, the origin of nitrates and chlorides will be discussed later. At this point it should however be noted that the former door opening in the north-west corner may have led to an exterior wooden toilet (in the Middle Ages, cf. Odén 1999). Although such toilets traditionally were situated on the outside of the masonry, salts may *theoretically* have been provided from the use of such a construction.

Above the staircase between the two wings of the palace, and below the western gable wall of the west house, is a small loft. A quick survey of this rather inaccessible place showed that masonry and wooden constructions were well preserved. There were no signs of moisture-related damages, indicating that there are no leaks at the moment.

WEATHERING IN THE VAULTED ROOM BELOW THE REGALIA ROOM

The vaulted room below the Regalia room is now empty, but was formerly used as gunpowder storage (1686-1826) and for storing food. It is not known what the room was used for in the Middle Ages. The room was formerly plastered, but the plaster was knocked off relatively recently.

The condition of the room is relatively good, but upon closer examination one can observe *large* amounts of salt efflorescences (whiskers, needles,



Two places where clues to the weathering in the Regalia room can be found. Left:: (Rusting) reinforced concrete inserted during the last restoration in the upper part of the opening at the rear of the northwest corner of the west wall. Right: The west wall of the vaulted room below the Regalia room. This room was used as gun powder store until 1826. Today there are massive amounts of alkaline salts of unknown origin on the walls

powdery efflorescences), especially in the western part of the room, as well as granular disintegration of mortar joints and of some stone types. Surprisingly, the salts mainly consist of trona and natrite/thermonatrite, which are alkaline salts usually originating from Portland cement or other alkaline building materials in the Trondheim region (Storemyr 1997). In this case it is uncertain whether Portland cement really is the main source of the salts. It seems that relatively little Portland cement was used for restoring the masonry of the

room during the last restoration (1962-75) - too little to account for the large amounts of alkaline salts. Thus, an additional source might be alkaline salts used for preserving and/or preparing food, for instance dried codfish prepared in lye (Norwegian: *Lutefiske*). It is also possible that lye was simply stored in the room.

Other salts include sodium nitrate, which must originate from the time when the room was used as a gun powder store. Since the Regalia room is situated more than seven metres above the ground, it is rather unlikely that rising damp could have transported nitrate all the way up. This theory is supported by the fact that "massive" rising damp never has been a great problem in the nearby cathedral or in other buildings close to the Regalia room.

Analyses of salts in the vaulted room have only included efflorescences. The bulk saline chemistry of the masonry has not been investigated. Thus, it is not yet possible to give a full interpretation of the salt system and its evolution. It is for instance very likely that the walls contain much more nitrate than the relatively limited amounts seen on the surface. This is because the room is rather humid, implying that salts like sodium nitrate (and also halite) will be in a dissolved state most of the time (EQRH c. 75%). Halite is to be expected in the masonry because it is a most important agent for food preservation.

WEATHERING OF THE EAST WALL OF THE REGALIA ROOM

The east wall of the Regalia room is in a *very* much better condition than the west wall. Although there are signs of limited repairs (cf. Odén 1999), most of the paintings, except the drapery, seem to be the original ones from 1616. Main reasons for the good condition, when compared to the west wall, are:

- The east wall is entirely within the building. This means only minor temperature- and humidity gradients through the wall. Moreover, it is unlikely that water leaks have had any big influence.
- The masonry has not been weakened by fire, or by transverse cracks along the border between the wall and the vault.
- There has been no oven/fireplace/chimney at the east wall, and therefore no need to undertake repairs after dismantling.
- There have been no doors in any of the corners
- No interventions during the last restoration, for instance repairs involving concrete, were undertaken in masonry close to the wall.
- The east wall is a little less subjected to light than the west wall.

As can be seen, the east wall has escaped the damaging effects of the outside weather, catastrophic fire events and human interventions. Hence, the active weathering agents have mainly been changes in temperature and relative humidity, and light. Moreover, the stability problems of the west house have affected the southeast corner of the wall (cracks etc.).

Despite escaping many damaging events and processes, the east wall certainly has a few minor problems. These are mostly related to fading of colours (or powdering of paint), small exfoliations, and scaling of the glazing in the drapery area. Preliminary analyses of salts on the wall show that there is relatively much chloride, a little less nitrate, and also nitrite in the drapery area. The occurrence of chloride and nitrate is difficult to explain as on the west wall.

Even though there are salts on the east wall, they appear not to have done as much damage to the paint layers as they may have done on the west wall. One reason might of course be that the amount of salts is much lower, another might be that the salts are much more active when they are affected, in addition to changes in temperature and relative humidity, by water seepage/water leaks as well.

Evolution of the Weathering Since 1826

The first known photo of the west wall was taken around 1930, another was taken around 1960 and from 1966 there are a few images showing Seter's work. All these photos are very valuable because they make it possible to follow the weathering and determine its rate.

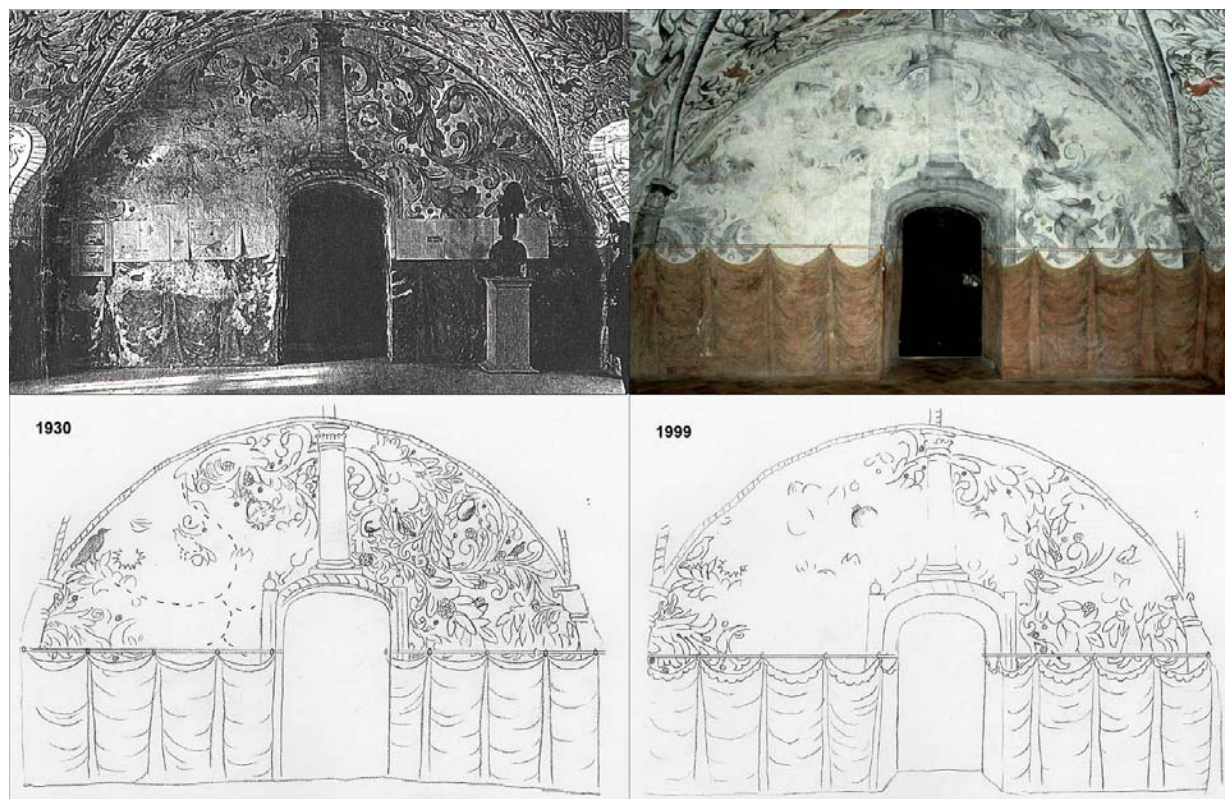
In 1930 the south part of the wall appears very weathered (almost like today), while the north part seems rather stable. It is impossible to state when the weathering on the south part was most active, but it must have been between 1826 and 1930, because the whole wall was painted in 1826. The main reasons for the damages on the south part are unknown, but we may presume that they were perhaps mainly connected with water leaks - southwest corners of buildings in the Trondheim region are usually the most exposed, and often the most easily damaged (cf. Storemyr 1997). On a photo from c. 1910 it can be observed that the exterior southwest corner has lost most of the plaster, while the rest of the north wing of the palace seems to have rather intact plaster. Possible stability problems leading to cracks and hollow areas, especially close to the vault where Seter in 1966 inserted a lot of cement, as well as salts (chloride, nitrate), may have led to some of the damages on the south side as well. Why the north part managed quite well

until after 1930 is difficult to explain. One would have expected that eventual leaks and other weathering agents should have been just as active as on the south part, but this does not seem to be the case.

From 1960 there is only one photo of the north part of the wall. It is not known whether this photo was taken before or after the extensive restoration of the exterior face of the west wall, and before concrete and iron beams/anchors were installed. It is, however, probable that these interventions were undertaken before the photo was taken, otherwise it is difficult to explain the fact that the weathering pattern in the northwest corner appears just like today, although less extensive. In this interpretation it is assumed that the mentioned interventions are at least partly responsible for



The north-west corner of the Regalia room 1960 (Photo: Schröder)



Comparison of the state of the west wall in 1930 and today. Drawings by Birgitta Odén, left photo from Schröder, right photo by Kjartan Proven Hanglid

the rapid weathering in the north-west corner: Concrete and iron may have changed the moisture balance or provided more moisture to the area by condensation, and concrete may have provided alkaline salts which have reacted with available sulphate to produce sodium sulphate (thenardite) found in the area. Another possibility is of course that water seepage from

the roof started to become active only after 1930.

The crack that can be seen in the upper part of Q2 does not seem to have changed very much between 1930 and 1960.

Studying the photos, it may seem that the weathering on the north part of the west wall was more active between 1930 and 1960, than

between 1960 and today. However, it should be remembered that Seter in 1966 partly reconstructed some of the paintings, and added materials such as gypsum and cement (with paint), implying that it would have taken some time to "weather away" his measures, before the older layers once more were heavily attacked by the weathering. It seems at least that the present general weathering *pattern* is just like the one observed on the photo from 1960. Put in another way: The areas that weather most actively at present are also those most heavily restored by Seter (in Q2). In this connection it should be recalled that especially Seter's gypsum repairs have fallen from the wall over the last years.

As a conclusion to the historical evolution of the weathering, it may be stated that the areas weathering most actively have changed over the years: In the 19th century the south part of the wall weathered most actively, while in the 20th century it was the north part that became most damaged.

Summary and Interpretation of Active Weathering Processes

In the following, a summary and interpretation of the active weathering processes on the west wall will be given

STABILITY PROBLEMS AND CRACKS AFFECTING HOLLOW AREAS AND EXFOLIATION

It is not yet known whether the west house is really stable. The longitudinal cracks still seem to widen a bit (as measured in the Drapery room), but it is unlikely that this has much effect on the west wall at present. The transversal crack between the vault and the west wall may also seem rather stable, but it is nevertheless possible that this crack has some influence on the hollow areas, especially in the higher part of the "chimney plaster". It seems as if the vault slowly "presses" the "chimney plaster" downward, leading to the largest hollow area just below, as well as resulting exfoliation of limewash and paint

where the plaster buckles the most. It should be pointed out that eventual movements in this area are very small. It is also possible that the evolution of this particular hollow area (in the higher part of the "chimney plaster") is rather caused by the blocked opening for the chimney. Perhaps there are some movements in the brick masonry used to block the opening? Moreover, the buckling of plaster may of course also be *influenced* by hygric and thermal movements. But since the hollow areas are generally distributed along known cracks, it is unlikely that such movements are the primary cause.

Other cracks in the west wall include those right above the main door opening. It is difficult to state whether the cracks are the primary reason for the heavy exfoliation of gypsum repairs in this area, or if thermal/hygric movement of the gypsum itself contributes the most. From a conservation perspective it does not really matter what is the primary cause, since the gypsum repairs will have to be removed in any case. However, one has to be careful when removing gypsum repairs because paint attached underneath might follow in the process.

POSSIBLE SOURCES OF MOISTURE AND SALT

In addition to the humidity of the air, moisture may *potentially* be provided by water seepage from the roof above the staircase area, and from condensation. It is also likely that concrete and iron installed during the last restoration enhance the risk of condensation inside the wall close to the areas that weather most actively. In this connection it should be mentioned that the risk of condensation increases when water leaks are active.

Since the Regalia room is situated at such an elevated level, it seems that the probability of former rising damp is low. The difficult question is then from where the large quantities of nitrates and chlorides found on the west wall originate. This question has also been posed in other cases of excessive amounts of nitrates and chlorides at elevated levels, but no definite answers



S = Sulphates N = Nitrates C = Chlorides

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Supported by The Raphael Programme of the European Union

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Summary of salt analyses 1999

ATELIER ANDREAS FRANZ

divisual@restaurierung.ch

Overview of salts on the west wall. Note that only salts that have actually been analysed are included. There are tiny whiskers and other forms of salts (probably sodium nitrate/chloride) also on other parts.

have been found yet (for instance in the monastery of Saint-Savin close to Poitiers in France, Andreas Arnold, pers. comm. 2000)

Generally, nitrates and chlorides are found together in masonry affected by human and animal habitation and/or activities (food, garbage, excrements). The salts are largely produced through biological metabolism. In

this connection it has to be recalled that the west wall once must have been rather moist (due to the observation of presently dead beetle-like creatures on the wall). If the supposed toilet outside the west wall was situated partly within the wall, this could perhaps explain the origin of the salts. The amount of salts is, on the other hand, so large that it is difficult to imagine the toilet as the sole source. Another possibility is that the room for the present staircase between the north and west wings of the palace once was used as a stable or barn, or for food preservation/storage.

Speaking against the "toilet theory" is the fact that nitrates and chlorides also have been found on the east wall. With regard to this wall, it is very difficult to imagine any other source of the salts than rising damp. Again, the elevated level of the Regalia room (almost) rules out this theory. It could of course be that the salts have been introduced with building materials and/or during restoration measures (through biological metabolism), but this is rather unlikely, considering the large amounts of salts.

Thus, a possible scenario is that a biological origin of the salts is less likely than an origin from gun powder and/or food preservation agents. It may be that not only the vaulted rooms at ground level, but also the Regalia and Drapery rooms themselves were used for gun powder and/or food storage in specific periods (before 1616). It has to be admitted that this explanation seems strange. Alternatively, storage within the vaulted rooms below might have been organised in such a way that gun powder etc. came into contact with the moist walls at very high levels. Furthermore, nitrates and chlorides could have been transported by means of capillarity from the points of contact. Another possibility is that nitrates and chlorides were provided through water seepage from the loft. Although there are no traces to be observed, the loft may have been a habitat for birds and bats.

None of these theories are very convincing. Moreover, the occurrence of other salts - notably nitrite on the drapery and sodium carbonates in the vaulted room below - have not been taken into account. Actual chemical

reaction systems have neither been considered. Gunpowder is for instance mainly made from potassium nitrate (and sulphate/charcoal), while in the Regalia room sodium nitrate is the sole nitrate found. In the presence of sodium chloride this is easily explained, but where did all the potassium go?

Perhaps one has to widen the perspective and carefully study the whole history of the west house with a view to salts in order to find convincing explanations of their sources. This could also bring new light to the history and use of the west house as such. For instance, and as far as we know, no good explanations of the "chimney-like" structures in the vaulted room below the Regalia room have yet been presented. Could it be that the vaulted rooms served as some kind of production facilities giving rise to fumes? It is known that the Archbishop's Palace produced large amounts of various commodities in the Middle Ages and later; there has for instance been found pits below the east house which appear to originate from saltpetre production for minting and gun powder manufacturing (Nordeide 1995).

Luckily, it is no so difficult to explain the occurrence of sodium sulphate (thenardite), magnesium sulphate (epsomite) and gypsum on the west wall. These salts are more or less confined to areas where water seepage/condensation through concrete and original building materials must have played a role.

Although we cannot at this stage explain the occurrence of nitrate and chloride, this should not have any large influence on the actual weathering processes at the moment. This is because the sources of these salts must have been removed.

ACTIVE SALT WEATHERING PROCESSES

It seems that all the thenardite in the northwest corner cannot represent a very active weathering agent unless moisture is provided regularly. The main reason is that we have never observed any other form of thenardite than

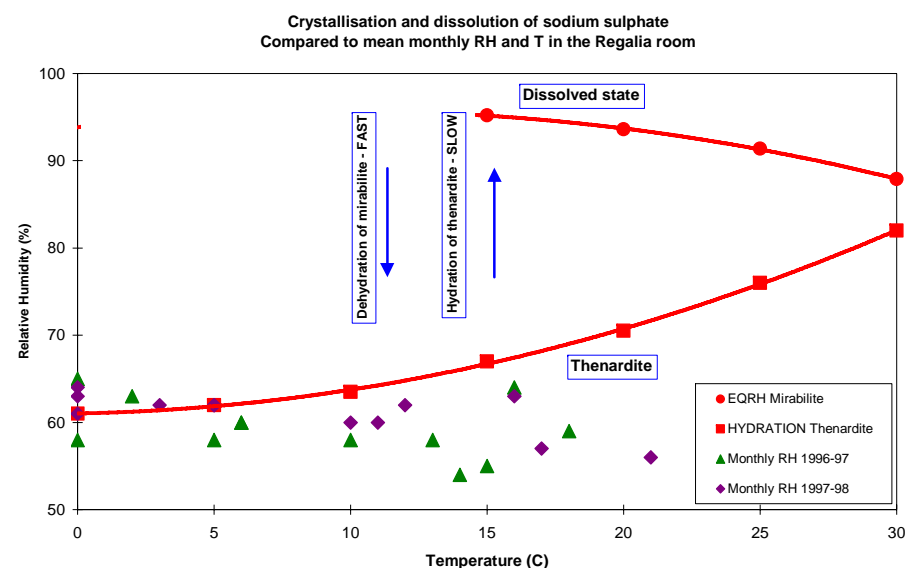


Diagram showing theoretical EQRH/hydration curve of two forms of sodium sulphate (thenardite and mirabilite) and mean monthly T and RH in the Regalia room 96-98

powdery efflorescences, obviously formed by dehydration of mirabilite. This again points to what is generally known about sodium sulphate in the Trondheim environment (Storemyr 1997): Whiskers and needles of mirabilite form after leaks, subsequently dehydrating to powdery efflorescences of thenardite when the leaks stop and the climate becomes drier. Unless more water or very humid conditions are provided, little will happen to the powdery efflorescences of thenardite. This is because hydration of thenardite to form mirabilite is a very slow process under "normal" circumstances, and, as it seems, can *theoretically* only happen during winter time in the Regalia room (see figure above). The ambient relative humidity seems to be too low for thenardite to pick up water molecules from the air and form mirabilite in other seasons. It should be underlined that these considerations are theoretical. In reality, the west wall of the Regalia room represents a complex

saline system with several salt species present, which may alter the theoretical picture. Thus, the best indication we have is observations showing that the powdery efflorescences of thenardite seem to be rather stable at the moment.

Salt weathering processes in relation to the Carolingian and Romanesque mural paintings in Müstair, Switzerland, give an idea of the difference between *theoretical* and *real* equilibrium relative humidity (EQRH) values. A simple system of sodium nitrate theoretically has an EQRH of some 75% at 20°C. In Müstair comprehensive observation has shown that the actual EQRH is about 61%, which may be explained for instance by other salts affecting the crystallisation and dissolution behaviour of sodium nitrate (Arnold et al 1991).

These findings are of importance also with regard to the Regalia room. As can be recalled, sodium nitrate and halite seem to be responsible for powdering of paint, and probably for other weathering processes giving rise to granular disintegration of materials as well. If the *real* EQRH is as low as c. 60% for sodium nitrate (and/or halite with a theoretical EQRH of about 75%), these salts may be regarded as potentially very harmful. This is because 60% is very frequently passed in the room, regardless of season. Although dissolution/recrystallisation of sodium nitrate and halite are relatively rapid processes, it should be noted that it will take some time (days/weeks) for the respective salts to form from a solution.

It would of course have been the best if such considerations could be confirmed by *in-situ* observations. The trouble in the Regalia room is that the minute whiskers, needles and crystals of sodium nitrate and halite are so small that it is impossible to see them properly without the use of microscope. Thus, good test fields should be established in order to follow the actions of the salts, which is necessary for controlling the indoor climate in the future.

Good test fields should also involve the other salts present on the wall. Luckily, both thenardite and epsomite can be seen with the naked eye. Observations until now show that epsomite, which is only present in the arch

of the main door opening, behave very much like thenardite. However, as the risk of condensation might be higher close to the door, it is possible that epsomite is more active than thenardite. Gypsum can also be found in the northwest corner of the wall. However, in order to contribute to damages, gypsum needs much more moisture than the other salts present on the wall. Gypsum is in other words usually harmful only when crystallising from a solution. This picture is, however, somewhat different when other hygroscopic salts are present.

OTHER ACTIVE WEATHERING PROCESSES

Although gypsum repairs as well as the glazing in the drapery area seem to be affected by salts, it is unlikely that salts cannot be the primary cause for the exfoliation observed. It seems that thermal and hygric dilatation are more active processes.

Light is another agent probably affecting the less light-durable pigments on the walls of the Regalia room. Indigo blue has been discussed earlier; there might also be other pigments that fade through time. Light could also affect both salt weathering and thermal/hygric dilatation processes. This is because the temperature rapidly rises 2-5°C, while the relative humidity simultaneously drops up to 20%, at midday in fine winter weather when the sun shines through the south window.

At last it should be mentioned that Man represents a very active weathering agent at present. The west wall is in such an unstable condition with regard to smaller and larger scales about to fall that the smallest touch will actually cause them to do so. Therefore, the first measure that has to be undertaken is to stabilise flakes etc. in order to be able to work with further conservation measures on the wall.

Conservation Concept

The primary aim for conservation measures in the Regalia room should be to *minimise the risks of further weathering*. This should be done by applying the concept of minimum intervention, or by undertaking small, "corrigible" conservation measures followed by monitoring over a long period of time (several years). Since one of the best measures of success or failure is the amount of material falling from the west wall, regular control of this material should be continued.

The Regalia room cannot be completely opened for visitors before it is absolutely certain that such an impact on the indoor climate will not be harmful. This means that the doors to the room should be kept closed in order to avoid large variations in temperature and relative humidity. However, guided tours for small groups of visitors should still be allowed. This is because such small groups appear not to significantly alter the indoor climate, as shown by measurements.

Practical measures related to the west wall include:

- Direct conservation measures
- Protective measures
- Indoor climate control
- Building restoration measures and structural interventions
- Various scientific investigations

In addition, investigations and conservation measures concerning the rest of the Regalia room should be considered. It is very important to note that further investigations in the rest of the room could bring new light to the findings reported in this work. This also holds for the rest of the west house of the palace.

DIRECT CONSERVATION MEASURES

Urgent measures

Urgent measures applicable to the west wall include fixing loose material and removing many gypsum repairs, as well as fixing the most unstable hollow areas related to the "chimney plaster". These, and other urgent measures, are described later.

Long-term measures

In addition to fixing other hollow areas, an important part of the long-term measures should be to develop a practical direct conservation strategy. Once the urgent measures have been undertaken, one should have a much better idea of further work needed. A practical conservation strategy should also include themes like conservation ethics (should for instance missing parts be reconstructed? Should all cement repairs be removed?) and necessary research on conservation methods.

PROTECTIVE MEASURES

Protective measures are mainly related to minimising the risk of water leaks. The following measures should be undertaken:

- Check the covering between the exterior west wall/gable wall and the roof and repair if necessary.

- Avoid large amounts of snow on the roof. This can be done by regular maintenance and/or by covering the roof by metal/copper instead of ceramic tiles.
- The outside corners/quoins of the Regalia room should be plastered (only lime mortar) in order to be absolutely certain that water leaks cannot enter the masonry. This should be seen in relation to plans for plastering the whole Archbishop's Palace.
- Undertake regular whitewashing and repair of the gable wall every second year or so.

Moreover, the risk of uncontrolled release of water from the sprinkler installation on the loft should be minimised. This can be done by installing a protective roof above the vault.

INDOOR CLIMATE CONTROL

Urgent measures

- Avoid sun - install curtains or Venetian blinds
- Establish test fields for monitoring of salt crystallisation (with microscope)
- Establish outdoor climate station and T/RH measurement stations in nearby rooms.
- Interpret results after one year of monitoring - suggest measures

Possible long-term measures

The indoor climate is rather stable, but it should be possible to make it even more stable. The important question is at which level the average relative humidity and temperature should lie. This question can only be answered after monitoring of salt crystallisation periods.

Otherwise there are many ways of controlling the indoor climate:

- Secure the windows in order to avoid draught
- Install wooden floor above the present ceramic tiles (which was the situation before the restoration in the 1960s). This will help buffer the indoor climate
- If a little more humid climate is needed, concrete below the ceramic tiles could be removed. This will probably lead to a better humidity exchange with the vaulted room below.
- Install extra air-tight doors outside the main door opening in the west wall and outside the door between the Drapery room and the Herresal/Tower room

BUILDING RESTORATION MEASURES AND STRUCTURAL INTERVENTIONS

Since there are many signs of cracks and structural instability, the west house should be properly investigated with regard to these issues. Such an investigation would include:

- Undertaking a proper survey (mapping of cracks etc.)
- Monitoring cracks over several years (add more measurement points to the current programme)
- Monitoring eventual settlements over several years
- Interpretation with the help of an expert on stability of old masonry buildings

The investigations have to be done before one can think of removing concrete and iron anchors/beams in the west wall. These installations might be harmful to the mural paintings (condensation, salts etc.), but they may also

be necessary for keeping the west wall structurally stable. Removing them might thus not only be a large and difficult intervention, but also a risky one.

VARIOUS SCIENTIFIC INVESTIGATIONS

In order to determine the source of the salts (especially nitrate, nitrite and chloride) on the west wall, a complete investigation of salts in the masonry of the west house should be considered. Such an investigation should also include measurements of moisture in the masonry. It can be undertaken by drilling holes in the joints of the exterior part of the west wall (ground and first floors) in order to establish a salt/moisture profile. Such an investigation will aid the further interpretation of the weathering as well as eventual decisions regarding desalination. It will also aid further building archaeological studies, especially related to the use of the west house throughout the centuries.

As can be recalled, small beetle-like creatures were observed on the west wall. These creatures are probably dead, but should be determined in order to interpret their possible damaging effect (earlier) and the former indoor climate of the Regalia room. Determination of these creatures should be seen in relation to similar studies that have been undertaken in the vaulted room below the Regalia room. Simultaneously, eventual microbiological activity should be investigated.

Certain investigations related to the materials on the west wall should also be considered. These investigations include properties of the glazing used in 1966 and traces of animal glue and other organic components in the paint layers. Better knowledge of possible organic additives is needed in order to design long-term direct conservation measures.

At last, thermography recordings undertaken in the summer of 1999 should be repeated in order to show a typical winter situation (January-February).

INVESTIGATION OF THE REST OF THE REGALIA ROOM

The west wall is only a small part of the Regalia room. Although the other walls and the vault are in a much better condition than the west wall, there are enough signs of active damages to justify a complete investigation of the whole room. As with the west wall, the first measure ought to be a comprehensive survey/mapping. With the experience collected on the west wall, such a survey will be relatively simple to perform, but rather time-consuming (perhaps 2-5 months).

Given that the necessary funding is granted, work in the Regalia room will continue for years. Thus, one should think of good ways of informing the public and visitors. One idea would be to use the Drapery room for a small exhibition explaining the work. Some of the graphic material presented in this report could be used for such a purpose.



 Hollow areas	 Mechanical damage	 Granular disintegration of plaster	 Exfoliation of gypsum/lime
 Cement	 Pitting	 Exfoliation of limewash	

Regalia Room - West Wall

Archbishop's Palace
Trondheim, Norway
The Restoration Workshop of Nidaros Cathedral

Supported by The Raphaël Programme of the European Union



Proposal for Conservation Measures 2000



DiVisuAL® mapping system

www.divisual.net

divisual@restaurierung.ch

Highlighted areas show which parts are considered in urgent need for direct conservation measures

Proposal for Urgent Direct Conservation Measures

The primary strategy for the urgent conservation measures is to first stabilise the surfaces (exfoliation, granular disintegration etc.) and then fix the most unstable hollow area under the "chimney plaster". Unless the surfaces are stabilised first, there is a great risk of loosing much of the limewash/paint layers upon fixing the hollow areas. Since current knowledge indicates that lime is the only binder on large parts of the mural paintings (only traces of organic binders have been detected), lime should also be applied during the conservation. However, in certain cases it might be necessary to apply other mineralic materials, such as ethyl silicate.

Considered measures include:

For granularly disintegrating plaster

The most heavily disintegrating plasters should be preliminary consolidated in order to prevent a further distribution of such areas. From a short-term perspective the most effective method for this purpose is probably ethyl silicate, but one should first try with limewater.

For exfoliating limewash (and paint above)

Loose scales of limewash (and paint above) should be fixed to the underlying plaster surface by means a suitable lime mortar. As above, ethyl silicate should be avoided if possible.

For exfoliating gypsum repairs

Where possible, exfoliating gypsum repairs should be removed. Great care should be exercised when removing gypsum, because there will always be a risk of loosing material attached to the underside. Where gypsum repairs seems stable, nothing should be done. If certain repairs cannot be removed, they should eventually be refixed to the surface. One has to find a proper material for this purpose.

For powdering paint

Only areas with very active powdering should be fixed. In practice this means borders between areas exhibiting also other damages and paint surfaces that are in a relatively good condition. In August 1999 both limewater and ethyl silicate were tested for the purpose of consolidating powdering paint layers. After a couple of weeks, it could be observed that both methods had some effect. Therefore, limewater sprayed on the surface should be the preferred method. Until more is known about the actual salt weathering processes obviously damaging the paint layers, one should not try to desalinate.

For visible salt efflorescences

Until more is known about the salt weathering processes, visible efflorescences (in practice thenardite and epsomite) should be brushed away only.

For hollow areas related to the "chimney plaster"

Most of the hollow areas might be fixed by filling in with a suitable lime mortar. However, in the upper part of the "chimney plaster" area, there is a need to first release the stress caused by the fact that the plaster continues around the corner to the vault. Releasing the stress might be done by simply

cutting a small trench. This has to be done very carefully, and with proper security measures, otherwise there will be a great risk of losing large parts of the plaster.

For removal of cement repairs

It is necessary to remove only one cement repair as part of the urgent measures. This repair can be found in the lower part of Q2. Carefully applying chisels for the operation seems to be the only way out. Also in this case one has to apply proper security measures. The "hole" should be filled with lime mortar (eventually pigmented).

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Appendix 1: Paint Analyses

Undertaken by Andreas Küng, Swiss Federal Institute of Technology, Institute for Preservation of Historical Monuments and Sites, Zurich

Sample no.	Location	Layer	Description	Befund und offene Fragen
P3	Q2	1616?	<p>Ground for the first paint layer</p> <ul style="list-style-type: none"> • Binder: Lime, a few fine aggregate grains • Sinter crust: Yes, very distinctive • Surface texture: distinctive texture of a rather coarse brush; characteristic brush-ductus (can also be seen on most of the vault and east wall - an indication of the 1616-painting) 	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> • Reste von Kalkputz mit Sand bis max. 1mm, der ecken- und kantengerundet ist; Zuschlag: plattige schwarze und dunkelgrüne Körner (Schiefer); farbloser-milchiggrauer-blassgelber Quarz; einzelne Glimmer (dunkel, wie Biotit); verholzte Pflanzenfasern (vermutlich Holz) • ca. 1mm dicke weisse poröse Kalkschicht mit wenig Sand; die Unterseite sieht wie ein Abdruck aus • Reste von Schwarz auf Weiss: Pflanzenschwarz mit wenig rotem und gelbem Ocker auf Kalk • Die vermeintliche Sinterkruste ist ein dichter Salzrasen, bestehend aus Nitronatrit (NaNO_3) und Halit (NaCl)
P4	Q2	1826?	<p>Ground for the third paint layer (probably)</p> <ul style="list-style-type: none"> • Binder: Lime, a few fine aggregate grains • Aggregates: Much more than in the ground from 1616 (P2 and P3); most aggregates are rather angular • Sinter crust: No, or not very distinctive; surface looks "dry" (perhaps the wall was not pre-moistened before application of the ground?) • Surface texture: distinctive texture of a fine brush - finer than P2 and P3 (the brush has left closely spaced lines) 	<p>zweilagige Kalkschicht mit eckigem Sand bis max. 1mm; einzelne verholzte Pflanzenfasern</p>

P7	Q1	1616	First paint layer - grey	Das Hellgrau / Dunkelgrau liegt direkt auf dem Kalkputz und besteht aus Kalk mit einem sehr feinkörnigen Kohlenstoffschwarz. Wurde die Oberfläche gewaschen oder handelt es sich um den charakteristischen Pinselduktus von 1616? Ist das Grau wirklich von 1616 oder ev. von 1826?
P8	Q1	1616	First paint layer on a bird - brownish	Auch an diesen Malschichtsplittern sieht die Oberfläche wie abgewaschen aus (vgl. P7). Das Dunkelbraun (= vollständige Farbschicht) bis Hellbraun (Farbreste) besteht aus Kreide (= Kalk mit zahlreichen Coccolithen u.a. Mikrofossilien) mit Pflanzenschwarz und rotem Ocker .
P9	Q2	1826	Third paint layer on a dark contour line	Auf der ca. 0.4mm dicken Kalkschicht mit Sand $\leq 0.5\text{mm}$ liegt ein sehr feinkörniges Kohlenstoffschwarz , dass aussieht wie Russschwarz. Auf der Oberfläche der Malschichtsplitter hat es Salzausblühungen von Halit (Nadeln) und Nitronatrit (rundliche Körner).
P10	Q1	1826	Third paint layer on a berry, reddish	von unten (älter) nach oben (jünger): <ul style="list-style-type: none"> ca. 0.5mm dicke Kreideschicht, die aus zwei Lagen besteht: Unten Kreide (zahlreiche Mikrofossilien) ?ohne Sand, oben Kreide mit wenig Sand $\leq 0.5\text{mm}$ Auf der Oberfläche, die wie gebürstet aussieht, liegt ein sehr feinkörniges Kohlenstoffschwarz (wie an P9) und ein Rot aus rotem Ocker.
P11	Q2	1826	Probably third paint layer on a berry, yellowish	Auf der Kalkschicht mit Sand bis etwa 0.5mm liegt ein schmutziges Gelb, bestehend aus gelbem Ocker , Beinschwarz und rotem Ocker .
P12	Q1	1826-1930	Fourth paint layer, dark (probably overpainting)	Die Probe besteht aus durchgehend grau gefärbten Malschichtsplittern, die beim Berühren pulverig zerfallen. Diese bestehen aus Kreide (CaCO_3) mit Körnern von meist etwa 1 - 4 μm , wovon zahlreiche Mikrofossilien sind, und einem beigemischten, sehr feinkörnigen Kohlenstoffschwarz (wie an P9 und P10).
P13	Q2	1960s	Gypsum with paint (1960s)	von unten (älter) nach oben (jünger): <ul style="list-style-type: none"> Die Unterseite der Splitter sieht wie gebürstet aus (= Abdruck der darunterliegenden Schicht) und weist Reste von anhaftendem, sehr feinkörnigem Kohlenstoffschwarz (wie an P9, P10, P12) in Kreide auf. Die ca. 0.3mm dicke Schicht besteht aus Gips ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) mit Karbonat (Calcit u./o. Dolomit), Quarz, Anhydrit u.a. Mineralkörnern (= natürliche

				<p>Verunreinigungen in Gipsgesteinen).</p> <ul style="list-style-type: none"> Die plane Gipsoberfläche trägt ein Grau, bestehend aus Beinschwarz, Kobaltblau ($\text{CoO} \cdot \text{Al}_2\text{O}_3$) und wenig rotem und gelbem Ocker.
P14	Q1	1960s	Paint on Portland cement mortar (1960s)	<p>Auf dem Zementmörtel liegt eine weisse Farbschicht aus ölgebundenem Titanweiss (TiO_2). Sie enthält einen nicht näher bestimmten karbonatischen Füllstoff, der sich in verdünnten Mineralsäuren löst. Das Titanweiss ist oberflächlich pigmentiert mit Beinschwarz, wenig rotem und gelbem Ocker und Spuren von einem nicht näher bestimmten Blau.</p>
P15	Q4	1826-1960s	Chip with paint on the "door" in the NW-corner; all paint layers; drapery	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> Kalkputz mit ecken- und kantengerundetem Sand bis ca. 2mm Ø; Zuschlag: farbloser und milchiggrauer Quarz; dunkelgrüne und schwarze Körner, oft plattig (Schiefer); Bindemittel: sehr feinkristalliner Kalk; die Putzoberfläche besteht aus einer weissen Kalkschicht durchgehende dicke schwarze Schicht aus einem sehr feinkörnigen Kohlenstoffschwarz mit gelbem und wenig rotem Ocker Hellbraun mit gelbem Ocker (an einer Stelle ein Olivgrün, das ein alkali- und säurebeständiges, tiefblau bis opak erscheinendes Pigment enthält, das vermutlich auf einem Substrat niedergeschlagen ist; bei diesem Olivgrün handelt es sich wahrscheinlich um einen Farbspritzer) weisse Schicht aus Calciumsulfat (verhält sich mikroskopisch wie das Halbhydrat, $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$) mit grösseren Calcit- und wenig Anhydritkörnern. roter Ocker auf der Oberfläche, die wie abgewaschen aussieht (einzelne Sandkörner "schauen heraus")
P16	East wall	1616	Green paint on a leaf with also grey and yellow	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> Kreide (mit zahlreichen Mikrofossilien) Blau aus natürlichem Indigo und Pflanzenschwarz Grün: Pflanzenschwarz + Auripigment + roter Ocker
P17	East wall	1616	Pink paint on a berry	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> Kalkputz Rosa: Kreide (CaCO_3) mit Pflanzenschwarz und Krapprot (-lack) (niedergeschlagen auf der Kreide)

P18	East wall	1616	Yellow paint on a leaf with also grey and green	<ul style="list-style-type: none"> • Kreide • Blau: Indigo + Pflanzenschwarz • Gelb: Auripigment + Pflanzenschwarz + roter Ocker
P19	Q1	1826	Third paint layer; grey paint on a leaf - is it green/yellow also here?	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> • Reste von anhaftendem Pflanzenschwarz • ca. 0.7mm dicke Schicht aus Kreide, 2lagig: untere Lage ?ohne Sand, obere mit Sand (Quarz) von ca. 0.2 - 0.3mm Ø • Beinschwarz auf der Oberfläche, die wie gewaschen aussieht (Sandkörner liegen bloss)
P20	Q1	1616	First paint layer; red paint in tulip	<p>von unten (älter) nach oben (jünger):</p> <ul style="list-style-type: none"> • weisse Schicht: Kreide mit wenig Sand • Rot: Zinnober mit Pflanzenschwarz
<p><u>Befund:</u> Die Ergebnisse beziehen sich nur auf das untersuchte Probenmaterial.</p> <p><u>Untersuchungsmethoden:</u> Die Proben wurden mikroskopisch (im Durchlicht, im Auflicht auch unter UV-Licht) und mikrochemisch (div. Nachweismethoden) untersucht. Für die Bindemittelanalyse wurden zusätzlich histochemische Anfärbemethoden verwendet. Dabei wurde für den Nachweis auf Proteine mit Amidoschwarz AB 3 (= Naphtholblauschwarz) und für den Nachweis auf getrocknete Öle mit Sudanschwarz B angefärbt.</p>				<p><u>Englische Bezeichnungen der Bindemittel, Pigmente etc.:</u></p> <ul style="list-style-type: none"> • Kalk = lime • Kreide = chalk • Titanweiss = titanium Dioxide White • Pflanzenschwarz = charcoal black • Beinschwarz = bone black • Kohlensoffschwarz = carbon black • Russschwarz = lamp black (bistre) • roter Ocker = red ochre • Krapprot (-lack) = madder lake • Zinnober = cinnabar • gelber Ocker = yellow ochre • Auripigment = orpiment • natürlicher Indigo (Waid, Färberwaid) = indigo (woad, wood) • Kobaltblau = cobalt blue

Email correspondence about paint analyses

Lieber Res,

thank you very much for the paint analyses. Many interesting things have turned up! Too bad, however, that it was not possible to say something more about the binders. We will of course have to follow this point up in order not to do any stupid things during the practical conservation work. My question to you now is simply if you have seen something regarding binders that you perhaps not included in the report? Another thing is whether you could recommend some of the samples you looked at for binder analyses? There are at least two important questions: Is there glue (Leim) in some of the layers and what is the glazing (Lasur) from the 1960s composed of. Regarding the glazing, we have found that it must contain nitrite in one way or another. So: did they work for instance with nitro cellulose?

Hoping that you can give some indications!

With very best regards from Per

Per Storemyr
The Restoration Workshop of Nidaros Cathedral
P.O.Box 4447 Hospitalslokkan
N-7418 Trondheim - Norway
Tel: +47-73 89 08 00/73 89 08 04
Fax: +47-73 89 08 08
Mobile: +47-93 46 80 23
Email: per.storemyr@kirken.no

Lieber Per,

1. zu den Bindemitteln:

Ich habe nochmals Bindemittel-Anfärbungen an den Proben P3,4,7,8,9,10,11,13,14,15,16,17,18 gemacht. Dabei habe ich "Ponceau-S-Rot" für Proteine und "Oil Red O" für getrocknete Öle genommen. Auch diese Anfärbemittel lieferten keine klaren Ergebnisse. Das heisst: Sowohl die früher durchgeführte Anfärbung mit Amidoschwarz AB 3 als auch jene mit Ponceau-S-Rot führten an einzelnen Proben (P3, P10) zu einer schwachen und unregelmässigen Anfärbung der Kalk- resp. Kreideschichten und könnten ein Hinweis auf tierischen Leim sein. Auch die Gipsschichten (an den Proben P13 und P15) aus den 1960er Jahren enthalten eventuell tierischen Leim. Hingegen lieferten die Anfärbungen mit Sudanschwarz B und Oil Red O keinerlei Hinweise auf getrocknete Öle (ausser beim Titanweiss an P14). Geeignete Proben für weiterführende Bindemittelanalysen sind: P3, P10 (und/oder P19), P15. Es ist noch genügend Material vorhanden.

2. zur "Lasur" (glazing) aus den 1960er Jahren:

An den Proben P13, P14 und P15 mit Schichten aus den 1960er Jahren konnte ich keine Lasur oder etwas Ähnliches erkennen. Vielleicht kannst Du mir Probenmaterial mit dieser Lasur zur Untersuchung nachliefern? zum Nitrit: Wie habt Ihr Nitrit bestimmt? Es gilt zu bedenken, dass auf der Wandmalerei Nitrat-Ausblühungen vorhanden sind und zu Nitrit reduziert werden können (unter Mithilfe von Mikroorganismen).

Ich hoffe, dass Dir und Andreas diese Angaben etwas weiterhelfen werden und wünsche Euch noch eine gute Zeit.

Mit herzlichen Grüssen, Res

Kueng Andreas
Institut fuer Denkmalpflege ETH
Forschungsstelle Technologie und Konservierung
Hardturmstrasse 181
CH-8005 Zuerich

E-mail: kueng@arch.ethz.ch
Phone: ++41 1 272 18 74
Fax: ++41 1 272 19 65

[Click on link by each sample to see sample location](#)

Appendix 2: Salt Analyses

Undertaken by Per Storemyr by means of optical microscopy, analytical test strips and micro chemistry. Location of samples in other places can be found on attached CD-ROM

Explanations:

DN: Door opening (in the rear of the north-west corner of the west wall)

Q1-Q4: Quadrant 1 (upper S) to Quadrant 4 (lower N) on the west wall

DE: Main door opening/entrance

VR: Vaulted room below the Regaliaroom, west wall

EW: East wall of the Regalia room

Sample no.	Location	Description/optical analyses/comments	Chemistry	
M10	DN	<i>Joint mortar between medieval bricks in the old door niche in the staircase</i>	pH SO ₄ Cl NO ₃ Na Mg	- No Much Yes - -
M11	DN	<i>Plaster above M10 (north side of the door niche)</i>	pH SO ₄ Cl NO ₃ Na Mg	- No Much Yes - -
S1	DN	<i>Powdery efflorescences. Dehydrated structure. Mostly thenardite</i>	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes No - - -

S2	DN	<i>Powdery efflorescences</i> Dehydrated structure. Mostly thenardite	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes No - Yes No
S3	DN	<i>Powder and fragments from a weathered brick</i> The sample may represent the bulk saline chemistry of the wall. Important to note that chloride and nitrate are both present. This may indicate that these anions were present in the wall before the restoration in the 1960s.	pH SO ₄ Cl NO ₃ Na K Mg	6-7 Yes Yes Yes Yes No Traces
S4	Q2	<i>Powdery material on second limewash, along a fissure which was earlier covered with gypsum repair mortar (1960s).</i> Mostly gypsum , also a sulphate, perhaps thenardite , and crystals with high int. col., probably a nitrate	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes Little Little - -
S5	Q2	<i>Powdery material on a gypsum repair.</i> Mostly gypsum , very little sulphate (thenardite or epsomite), some needles of a nitrate and halite	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes Yes - Traces Traces
S6	Q2	<i>Completely weathered aggregate grain in small "hole" in the plaster</i>	pH SO ₄ Cl NO ₃ Na Mg	6-7 Very little Very little Yes - -
S7	Q2	<i>Salt on and in between layers of exfoliated granite in a hole in the plaster. Much salt seems to continue under the plaster.</i> Mostly thenardite	pH SO ₄ Cl NO ₃ Na Mg	- - - - Yes -

S8	Q2	Powdery material behind the second limewash.	pH SO ₄ Cl NO ₃ Na Mg	6-7 Very little Yes Yes
S9	Q2	Crust-like efflorescences on the second limewash. Whiskers and crust of large halite crystals	pH SO ₄ Cl NO ₃ Na Mg	- - Yes - - -
S10	Q2	Crust-like or whisker-like efflorescences on the second limewash like S9. Whiskers of halite	pH SO ₄ Cl NO ₃ Na Mg	- - - - - -
S11	Q2	Brushed-away powder on relatively sound third paintlayer. Some needle-like structures can with difficulty be observed Large amounts of halite whiskers (and dust)	pH SO ₄ Cl NO ₃ Na Mg	- - - - Yes -
S12	Q2	Like S11 Large amounts of nitronatrite whiskers (optically determined).	pH SO ₄ Cl NO ₃ Na K Mg	6-7 Very little No Yes Yes (Traces) No
S13	Q2	Powdery material on a weathered area where only plaster is left.	pH SO ₄ Cl NO ₃ Na Mg	6-7 No Yes Yes - -
S14	Q2	Like S13	pH SO ₄ Cl NO ₃ Na Mg	6-7 No Yes Yes - -

S16	Q1	Powdery material, probably lime, in chiselmark holes from Seter's uncovering tests in the 1960s Only lime observed	pH SO ₄ Cl NO ₃ Na Mg	- - - - - -
S17	Q1	Paint and perhaps salts on weathered (exfoliated) area on painted cement Great amount of halite whiskers	pH SO ₄ Cl NO ₃ Na Mg	- - - - - -
S18	Q1	Powdery material and perhaps salts in a weathered-out hole in the plaster. Some nitrate-like grains observed	pH SO ₄ Cl NO ₃ Na Mg	6-7 No No Very little - -
S19	Q1	Powdery material and perhaps salts on gypsum repair. Much thenardite , a few nitrate-like grains (looks like Mg-nitrate)	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes No Yes - -
S20	Q2	Powdery efflorescences and paint fragments in a pitting/-exfoliation area on where glazing was applied in the 1960s Thenardite and a little gypsum Note: Strong nitrite reaction. Why?	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes No Yes - -
S21	DE	Salt efflorescences in pitting area Epsomite and a little gypsum	pH SO ₄ Cl NO ₃ Na Mg	- - - - - -
S22	DE	Salt efflorescences in pitting area Epsomite	pH SO ₄ Cl NO ₃ Na K Mg	6-7 Yes No Very little No No Yes

Click on link by each sample to see sample location

Appendix 2: Salt Analyses

S23	DE	Salt efflorescences in pitting area Epsomite and a little gypsum	pH SO ₄ Cl NO ₃ Na Mg	6-7 Yes No Very little -
S24	DE	Salt efflorescences in pitting area Epsomite and a little gypsum	pH SO ₄ Cl NO ₃ Na Mg	- - - - - -
S25	VR	Powdery efflorescences about five metres up from the ground. Trona.	pH SO ₄ Cl NO ₃ Na Mg	9-10 - - - - -
S26	VR	Large whiskers and powdery efflorescences about half a metre up from the ground. Trona and a dehydrated salt with relict whisker structure (natrite-thermonatrite)	pH SO ₄ Cl NO ₃ Na Mg	9-10 No No No - -
VH 270996/ 1	VR	Sample from the vaulted room below the Regalia room taken in 1996 Trona, natrite/thermonatrite, some aphthitalite		
VH 270996/ 2	VR	Sample from the vaulted room below the Regalia room taken in 1996 As above		
VH 270996/ 4	VR	Sample from the vaulted room below the Regalia room taken in 1996 Trona, natrite/thermonatrite, nitrate (sodium nitrate?)		

VH 270996/ 5	VR	Sample from the vaulted room below the Regalia room taken in 1996 As above		
VF 270996/ 6	VR	Sample from the vaulted room below the Regalia room taken in 1996 Trona		
Koni 1	Q4	Powdery material from the floor (fallen from the wall). Sample taken and analysed by Konrad Zehnder in June 1999 Water-extract analyses done	pH SO ₄ Cl NO ₃ Na Mg	6-7 Traces Yes Yes Yes Yes
EW1	EW	Powdery material in the drapery area. NB! Strong nitrite reaction	pH SO ₄ Cl NO ₃ Na Mg	- Yes Yes Yes - -
EW2	EW	Powdery material in the drapery area. NB! Strong nitrite reaction	pH SO ₄ Cl NO ₃ Na Mg	- Yes Traces Yes - -
EW3	EW	Powdery material above drapery area. NB! No nitrite reaction	pH SO ₄ Cl NO ₃ Na Mg	- No Traces Traces - -
EW4	EW	Powdery material above drapery area. NB! No nitrite reaction	pH SO ₄ Cl NO ₃ Na Mg	- No Much Traces - -