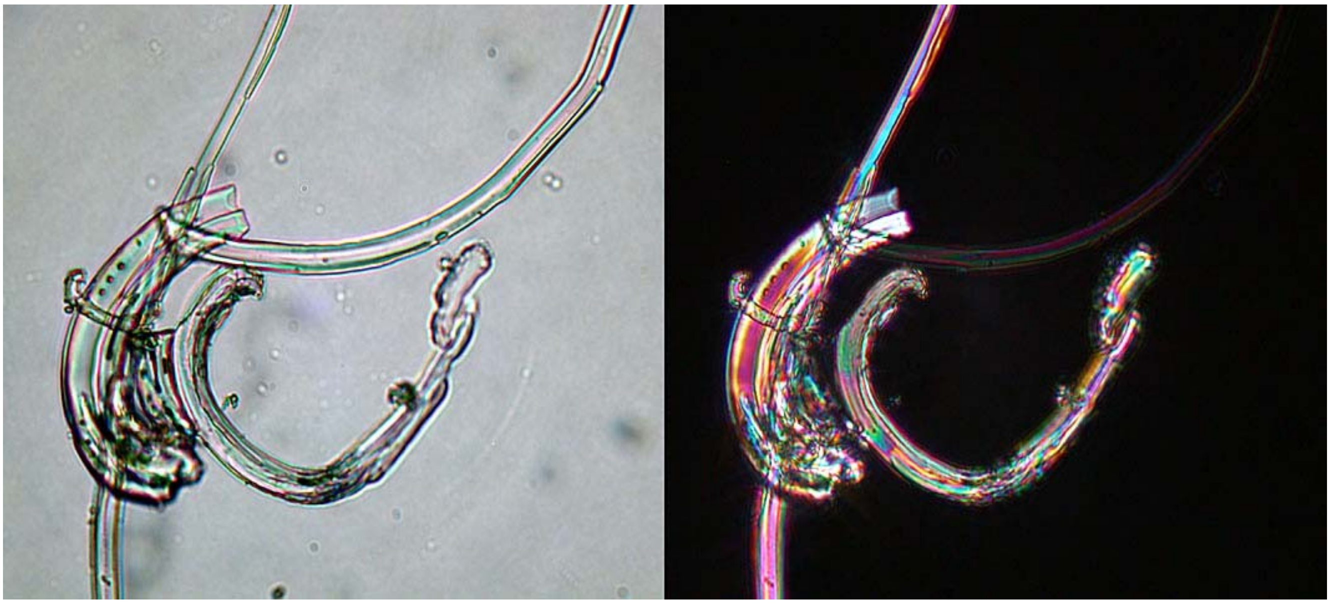
REPORT

The Regalia Room Mural
Paintings Conservation Project,
Trondheim, Norway

Conservation Measures and Monitoring of Salt Weathering 2001-2002

18.12.2002

In co-operation with Atelier Andreas Franz — Nidaros Domkirkes Restaureringsarbeider



REPORT

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Title *The Regalia Room Mural Paintings Conservation Project, Trondheim, Norway:* **Conservation Measures and Monitoring of Salt Weathering 2001-2002**

Client The Restoration Workshop of Nidaros Cathedral, Norway (www.nidarosdomen.no)

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Report no. 2002-051 **Date** 18.12.2002 **Distribution** See list behind

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ABSTRACT

The most important results of the 2001 conservation campaign in the Regalia room and the subsequent monitoring can briefly be summarised in this way:

- The emergency conservation in 2000 and the conservation in 2001 must be regarded as successful as the amount of material falling from the west wall has been reduced by 15-25 times to 0,2-0,4 g/month.
- The main future conservation challenge at the west wall is related to the development of a method capable of properly securing the brittle and strongly exfoliating 1826 limewash. Until now it has only been possible to secure the borders of this limewash.
- The indoor climate in the Regalia room has drastically improved after measures carried out in the winter of 2001. The relative humidity is now in the range of 60-75% year-round. According to observations and computer modelling, the lower limit of 60% is to low in order to avoid damaging salt crystallisation. It has to be raised to some 70% to be on the safe side.

The main recommendations for the west wall follow from the summary above:

- Laboratory- and in-situ experiments with various conservation methods in order to find a method to secure the exfoliating limewash.
- Continuation of careful monitoring of the west wall in order to get a proper basis on which to discuss permanent climate control measures.

The Regalia room conservation project also aims at conservation of the vault and all the other walls in the room. Comprehensive recommendations for the continuation of the project have been included in the report.

Cover photo: The salt nitratine (sodium nitrate) is a main weathering factor in the Regalia room, Microphotos. Left: normal light, right: polarised light. Width of field: c. 0,3 mm. (RE02_009)

Preface

Supported by the Restoration Workshop of the Nidaros cathedral this work-in-progress report is part of a co-operation between the Workshop, Expert-Center für Denkmalpflege and Atelier Andreas Franz.

I wish to thank all involved in the project for good work, especially many colleagues in the Workshop who have contributed with practical help during the project.

Zürich in December 2002
Per Storemyr

"The Bug"
...a brass beetle and our steady companion in the Regalia room

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1 Introduction

The so-called Regalia room in the north wing of 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 renaissance murals were painted in the early 17th century. The current name, the Regalia room, derives from its use as a storeroom for the Norwegian crown regalia in a short period after 1826.

Figure 1: From the 2001 conservation campaign at the west wall. Note the preliminary wooden floor – a measure undertaken in order to check its buffering capacity on the indoor climate

The weathered state of the murals, especially on the west wall, gave the impetus for the current conservation project, which was started in 1999. However, building conservation measures and monitoring related to the murals commenced already in the early 1990s.

In the course of the current conservation project documentation in the form of reports have been prepared after each main work phase. A list of the reports [1-7] can be found at the end of this report. Moreover, a project website has recently been established, at which background information, principles governing the conservation, as well as descriptions of the most important work and scientific results can be found. Most reports produced in the project can also be downloaded from the website. The address is: www.ecd.ethz.ch/regalia.

This *documentation* report, which does not aim at definite interpretation, describes the work undertaken since the main emergency conservation effort in the summer of 2000. It includes measures, investigations and analyses carried out until September 2002 and addresses the following themes:

- Conservation measures, conservation tests and photo documentation related to at the west wall in 2001
- Measures for climate control 2001
- Climate monitoring 2000-2002
- IR-Thermography in March 2002
- Monitoring of salt crystallisation and material downfall
- Computer modelling of the salt crystallisation phenomena
- Crack monitoring and various material analyses

2 Conservation of the west wall 2001

by conservator Andreas Franz

The conservation campaign was undertaken over two weeks in August 2001. It started by controlling the effect of the measures carried out in 2000 [4] and continued with mainly closing cracks and gaps with lime mortar at the west wall. Much time was used for experimentation with regard to the difficult task of fixing brittle, exfoliating limewash to the underlying, porous plaster.

Figure 2: Closing cracks with lime mortar on the west wall in August 2001

CONTROLLING THE EFFECT OF EARLIER MEASURES

In the beginning of the August 2001 work it seemed that the situation at the west wall had stabilised following the emergency measures in 2001 [4]. There was much less material downfall on the floor than previously (see also chapter 6). Although in an apparently stable condition after having been stabilised along their borders, many exfoliating limewash layers were still in a critical state.

In 2000 it was decided to test whether the use of limewater could have a consolidating effect on the "powdering" or disintegrating paint layers [4]. The use of limewater is controversial, some conservators claim that positive effects have been obtained, whereas most scientists discards its use due to the low solubility of calcium hydroxide. Our initial philosophy was that it couldn't harm using limewater instead of pure water, since large parts of the wall nevertheless had to be moistened before other conservation treatments. At the same time we were aware of the risk of bringing much limewater into the heavily salt-laden west wall.

The result of the limewater treatment, as controlled in 2001, was negative. We could not prove any consolidating effect upon carefully brushing selected areas with soft brushes and gently pressing soft paper onto disintegrating paint layers. Although the most important reason for the method's ineffectiveness probably is the low solubility of calcium hydroxide, one should not rule out the possibility that the porous plaster simply "sucked" up all the moisture and left the lime to crystallise far into the structure. Observations with regard to salt crystallisation after the limewater treatment are summarised in chapter 6.

Conservation measures carried out in August 2001

The actual conservation work carried out in August 2001 involved mainly closing cracks and gaps, which borders had been secured in 2000, by various types of lime mortars. The final finishing of the mortar repairs (toning etc.) was not undertaken (fig. 3-7).

Prior to some of the repairs, gypsum and cement mortars from the restoration in 1966, and not removed in 2000, were taken away (fig. 3). Originally, it was intended to remove much more cement, but as its removal in many cases poses a larger strain to the wall than leaving it, it was decided to refrain from treatment in most cases.

As a result of the conservation, the west wall can now be considered in a semi-stable state, in which there are two major problems yet to be solved: The "final" fixing of brittle limewash (see next section) and controlling the salt weathering processes (see chapter 6).

The mortars used for the restoration are shown in table 1 and the actual measures undertaken in figure 9. Since the map of the measures carried out in 2000 contained some mistakes, a corrected version is reproduced in this report (fig. 8).

Table 1: Mortars used to close cracks (volume parts)

Use	Lime (Rödvig lime putty – mixed before use)	Sand 0-1mm	Quartz powder < 300my
Ground mortar (to fill deeper cracks)	1	4	0
Fine mortar 1	1	2	2
Fine mortar 2	1	1	3

Figure 3: After removal of cement mortar from the 1966 restoration. NW-corner.

Figure 4: Same area as in fig.3 after application of new lime mortar

Figure 5: After application of lime mortar repair in the NW-corner

Figure 6: After removal of gypsum from 1966 and application of lime mortar repairs just above the west door

Figure 7: After removal of gypsum from 1966 and application of lime mortar repairs in a crack on the south side

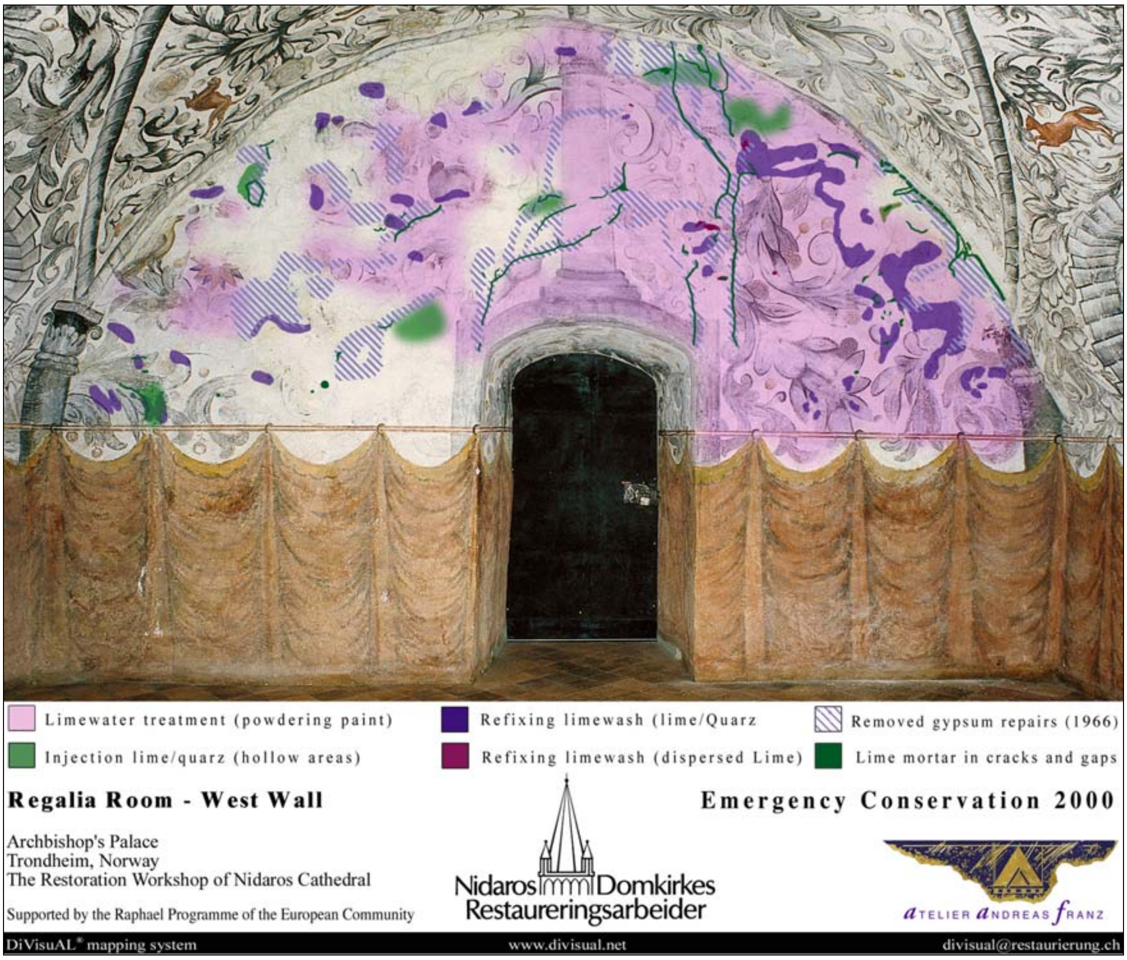

Figure 8: Emergency conservation measures 2000. Updated map.

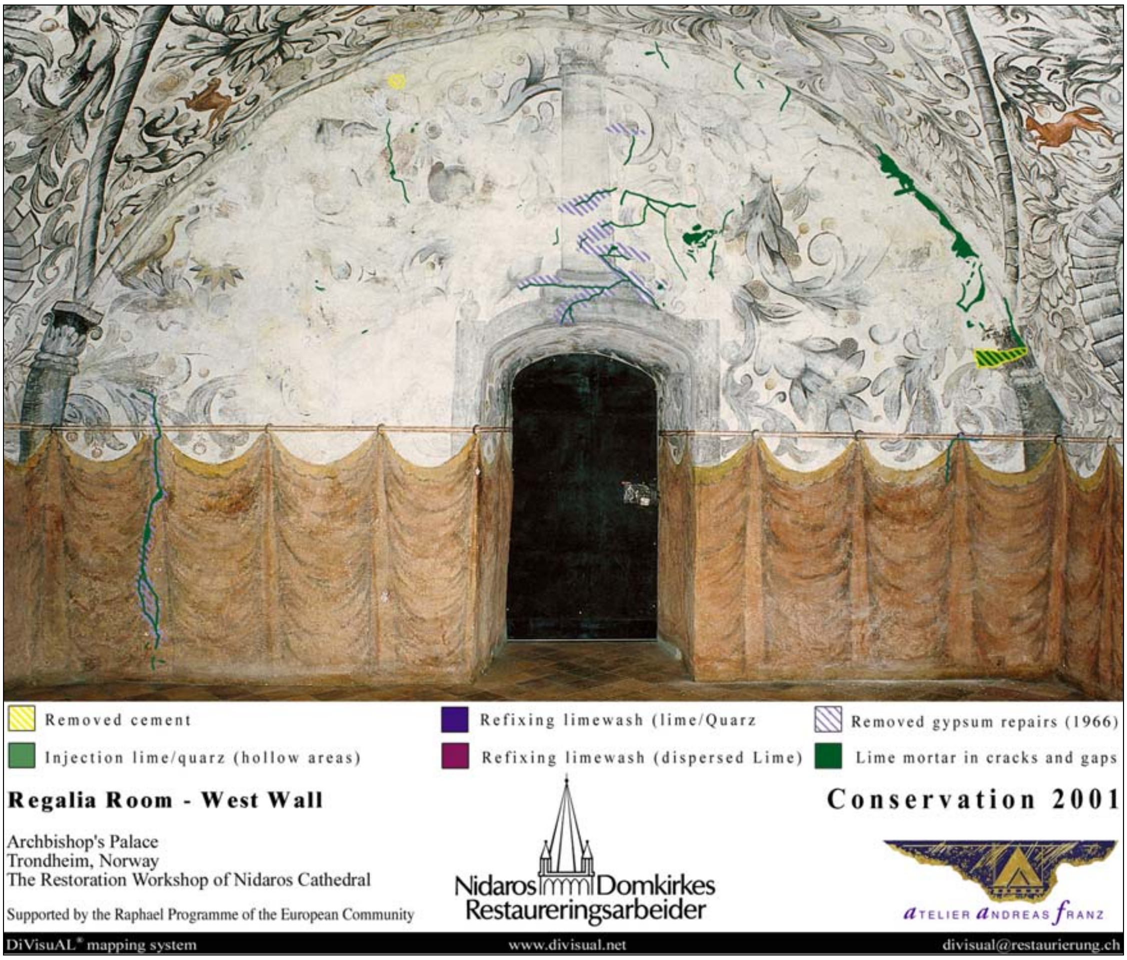

Figure 9: Measures carried out during the 2002 work

SIMPLE EXPERIMENTS ON FIXING EXFOLIATING LIMEWASH

On large part of the west wall, especially connected to the porous, so-called "chimney plaster" on the north side, the brittle limewash applied in 1826 strongly exfoliates. One reason for its poor adhesion might be that the limewash was applied on dry plaster [2,4]. The borders of most exfoliating limewash was secured by fine lime mortars mixed at high speed in 2000 [5]. However, at that time it was not possible to properly bring in very fine lime mortars / lime injection mortars behind the brittle flakes and thus securing them more permanently. The fine lime injection mortars were usually too viscous, thus not being able to enter the narrow space between limewash and plaster. Another problem was that, if the plaster was too dry, the finest injection mortar dried out too quickly upon injection.

In order to deal with this problem, limewater was applied in order to try to properly moisten small, selected test areas (fig. 10). Subsequently, "lime paint" (very liquid injection mortars as described in [4]) were injected behind the exfoliating limewash / flakes. Even though several hundred millilitres of limewater was used, it was not possible to properly saturate the underlying porous plaster and thus the injection mortars were unfortunately absorbed by the plaster or dried out too quickly. In other tests pre-hydrolysed ethyl silicate were injected after properly moistening the test areas with limewater. The alkaline limewater was used in order to quickly start the gel-forming reaction of ethyl silicate. Flakes were gently pressed to the plaster after the procedure. Unfortunately, this procedure was also unsuccessful. It would seem that the gel-forming reaction took place very quickly, but the plaster nevertheless absorbed the consolidating agent. Thus, the flakes of limewash loosened from the plaster after the drying of the liquid.

Obviously, further experiments with various consolidants will have to be carried out in order to find a good method for fixing the brittle, exfoliating limewash to the porous plaster.

Figure 10: Applying drops of limewater over a longer period of time with an injection needle in order to moisten the plaster before application of consolidants.

Photo documentation

After the August 2001 conservation campaign, the west wall was photo documented in sections, roughly following the grid shown in fig. 11. A digital camera (Nikon Coolpix 950) and direct flash light was selected in order to easily and quickly be able to compare with future photos taken in a similar manner. Three areas (fig. 12) were also selected for in-depth documentation. All photos are digitally stored in the archives of Expert-Center für Denkmalpflege.

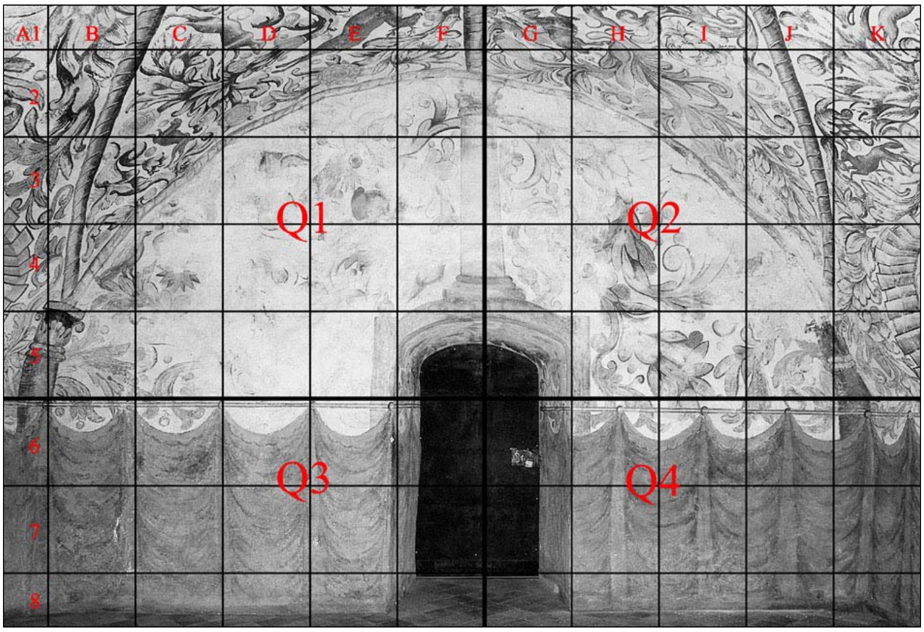

Figure 11: Grid for photo documentation of the west wall after the August 2001 conservation campaign

Figure 12: Areas for in-depth photo documentation: Top left: PM1 (Grid I-J4), top right: PM2 (H4), bottom left: PM3 (C3-4). All areas have 4 simple register marks for future comparisons. Camera data:
Nikon Coolpix 950
Auto mode
Originally jpg, compression fine
Original file size 620-725 kB
Image size: 1600x1200 pixels
Original image resolution: 300x300 dpi
Speed light: On
Shutter: 1:60
F number: 3,3 - 3,4

3 Measures for climate control

During the course of the conservation project it was recognised that the indoor climate in the unheated Regalia room was heavily influenced by draughts through the old iron door in the west wall. The door, which cannot be properly closed, leads to the heated staircase between the north- and west wings of the Archbishop's Palace. The heating in the staircase leads to a slight reduction of the general relative humidity in the Regalia room, as shown by climate recordings (appendix 1), but first of all to large *variations* in relative humidity; between 40 and 85% in 2000, before measures for climate control were undertaken.

The most important measure was the installation of a temporary (reversible), extra door in the west wall (fig. 13,14). This was undertaken in February 2001, and simultaneously wooden planks (untreated spruce) were laid on the floor in order to buffer the indoor climate as much as possible (fig. 14). Moreover, the door leading from the courtyard of the Archbishop's Palace to the staircase was insulated. The results of these measures can be seen on the climate diagrams in chapter 4 and appendix 1. The relative humidity drastically stabilised after February 2001, and has generally been in the range of 60 to 75% in the Regalia room since then. This is a very significant improvement. However, as the relative humidity drops to 60% over long periods of time, this still causes problems with salt crystallisation (se chapter 6).

Figure 13: Temporary (reversible) door installed in the door-opening in the west wall of the Regalia room in February 2001

Figure 14: The temporary door as seen from the Regalia room. Note the wooden planks on the floor. A permanent door should be installed as soon as the effect of the temporary one is properly confirmed.

4 Climate monitoring

After the establishment of the climate control measures described in chapter 3 (February 2001), it can be seen that the stable indoor climate roughly follows the outside variations in temperature with a general delay of less than ca. 1 week (fig. 15, see also appendix 1). The indoor climate is strongly dependent on the outside temperature, but also the outside relative humidity plays a great role. For instance, the cold May in 2001 (arrow, fig 15) was followed by a low indoor relative humidity because the weather was

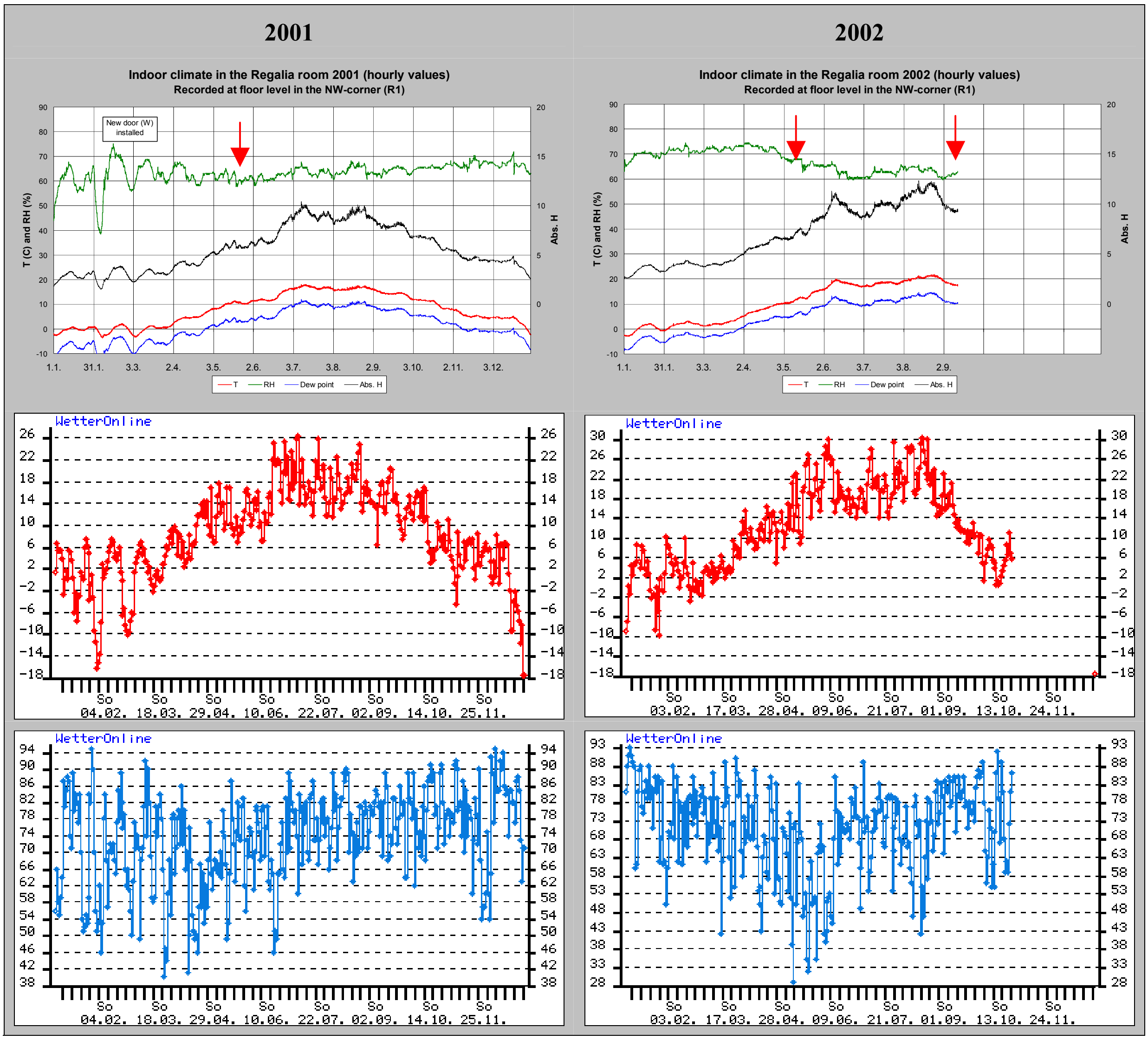

Figure 15: Excerpt from the climate diagrams in appendix 1. Top: Indoor climate in the Regalia room 2001-2002 (T, RH, abs. humidity, dewpoint; daily values). Middle: Daily temperature maxima in Trondheim 2001-2002. Bottom: Mean daily relative humidity values in Trondheim 2001-2002. Note that the outdoor diagrams have different scales. Outdoor diagrams from www.wetteronline.de

very dry. Likewise, the extremely warm and dry 2002 summer (2 arrows, fig. 15) – the warmest in Trondheim since measurements started in 1866 (www.met.no) – gave a stable relative humidity at 60-65% for nearly 4 months. The temperature in the same period rose to well above 20ºC, which is almost 5ºC higher than what has been generally measured over the last few years.

After the climate control measurements were carried out in the winter of 2001, the fluctuations in the heated staircase by the Regalia room have also been reduced. Before the measurement, the relative humidity could drop to 20% in cold winter periods; afterwards values have rarely dropped below 40% (appendix 1).

5 IR-Thermography 9-10 March 2002

IR-Thermography was undertaken 9-10 March 2002 as a follow-up of similar measurements in August 1999 [2] (fig. 16). In addition to the west wall of the Regalia room, several other walls were recorded (fig. 17-20). The weather in the winter of 2002 was a little milder than normal, with two distinct cold periods in December and late February. In March the temperature was in the range –5ºC to +5ºC. Methodology for the IR-recording is described in [8].

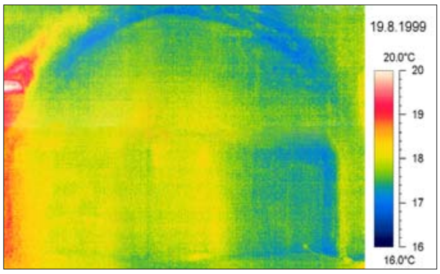

Figure 16: IR-Thermography of the west wall from August 1999 (cf. [2]). Note the cold spots (c. 17ºC) along the border to the vault and in the NW-corner. Room temperature c. 18ºC

The most important findings from the IR-recordings in March 2002 were:

1. The floor in the staircase (by the entrance) has electric heating, which is the reason why the staircase is relatively warm (fig. 17).

2. There are no great temperature gradients on the west wall in the room, except for the door, which is influenced by the heated staircase (fig. 18). The border between the wall and the vault had a temperature of c. 1ºC, the rest of the wall was 1 to 1.5ºC warmer by a room temperature of 1.5-2.0ºC. The largest cold area is in the NW-corner, like in the summer time (fig. 16). The east wall of the room was also recorded; temperature gradients could hardly be found here (general temperature of c. 2ºC)

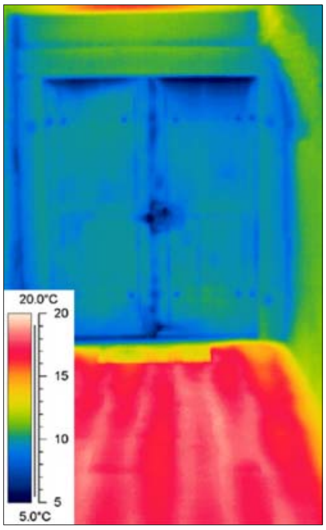

Figure 17: IR-Thermography, entrance to staircase from the outside.

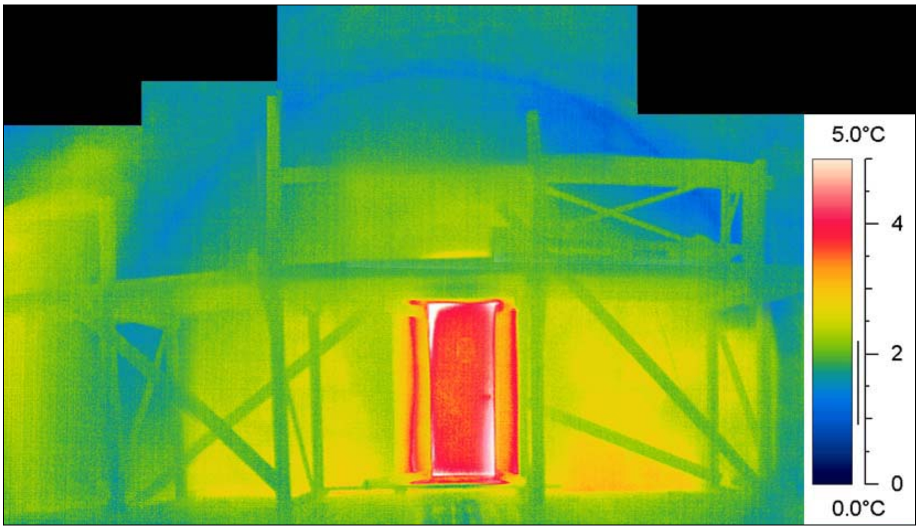

Figure 18: IR-Thermography recordings from the west wall of the Regalia room.

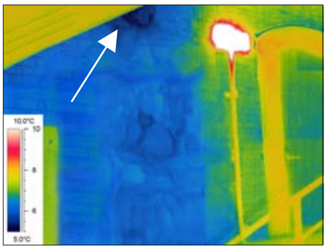

Figure 19: IR-Thermography on the rear of the west wall in the staircase. The white spot is a lamp.

The cold border between the wall and the vault can be explained by the fact that the only part of the wall that is directly exposed from the outside is located here (cf. fig. 20). Moreover, there is an old, large crack between the vault and the wall, enabling cold air to enter. It is also possible that the many hollow areas along the border play a role [2].

3. There was a cold spot just below the ceiling in the rubble masonry beside the entrance to the Regalia room (on the rear side of the west wall, in the staircase, fig. 19, arrow). This cold spot might indicate very minor water seepage, or it could alternatively be connected to iron in the wall or cement or granite creating a cold bridge. The temperature difference is small: 1-2ºC as compared to the immediate surroundings. Otherwise, the rear of the west wall had a general temperature of 5-7ºC, by a room temperature of 8-9ºC, as compared to the wall temperatures of 1-2.5ºC in the Regalia room.

4. IR-Thermography was also undertaken on the exterior facades of the Archbishop's palace. The images in fig. 20 do not reveal anything new, but the differences between heated and unheated building parts can clearly be seen (compare fig. 20 and 21). The south façade had temperatures between 3ºC (unheated) and c. 6ºC (heated), whereas the north facades showed values below the freezing point (minimum –2ºC). The ambient temperature was in the range between –4ºC to +4ºC in the actual period (overcast weather).

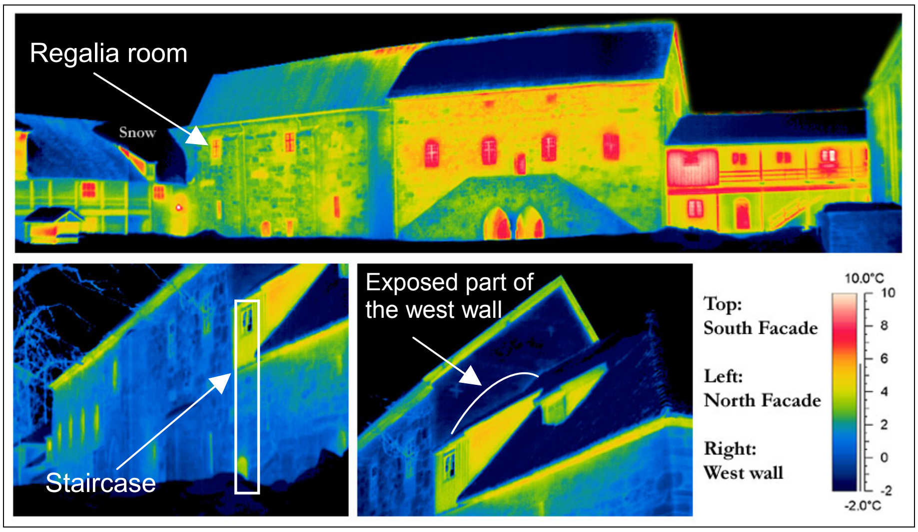

Figure 20: IR-Thermography on outside facades of the Archbishop's Palace. Top: South façade. Bottom: North façade.

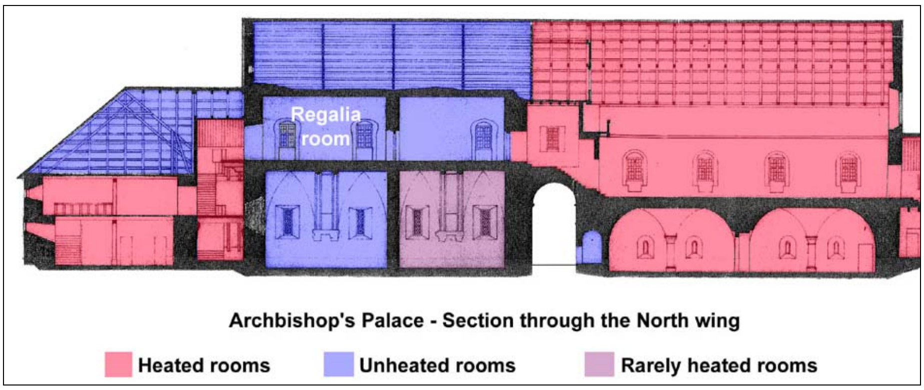

Figure 21: Heated and unheated rooms in the Archbishop's Palace. North wing, as seen from the south.

6 Salt crystallisation and material downfall monitoring

In order to be able to monitor the effect of the direct conservation and climate control measures, salt crystallisation periods and material downfall from the west wall are recorded on a regular basis. Salt crystallisation monitoring has been undertaken by the author, whereas Rasmus Woldmo of the Restoration Workshop of Nidaros Cathedral has been responsible for collecting material downfall.

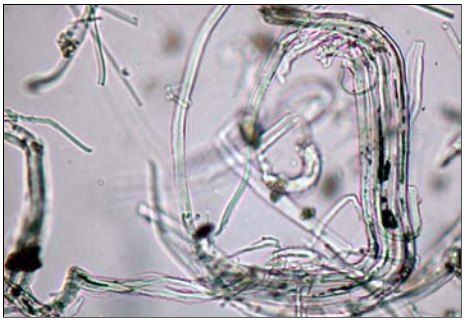

Figure 22: Halite (sodium chloride) whiskers on the west wall in September 2002. Sample RE130903_4, microphoto, width of field c. 0.5 mm

MONITORING OF MATERIAL DOWNFALL FROM THE WEST WALL

Material downfall from the west wall was also recorded in the period 1996-1998, before the emergency conservation measures were undertaken in the summer of 2000 [4]. At that time the downfall was in the range of 2,5-4,5 g/month at the badly deteriorating north side of the wall and 0,2-0,4 g/month at the south side (fig. 23).[1] It was at that time difficult to establish relationships between the downfall, variations in the indoor climate and salt crystallisation periods. A main reason was the extremely fragile state of large amounts of exfoliating gypsum repairs from 1966 and old limewash, which implied that a few large, fallen flake could completely obscure the picture. However, it would seem that most downfall occurred in spring and autumn, during periods with the largest temperature and humidity gradients [2].

After removal of most of the exfoliating gypsum repairs and preliminarily securing most of the fragile limewash flakes, the downfall has been drastically reduced. Between October 2001 and August 2002, it has been in the range of 0,1-0,3 g/month (north side) and 0,1-0,2 g/month (south side) (fig. 24). For the north side this is a reduction of 15-25 times.

At the north side fragments of limewash is the most common material that tends to fall, whereas on the south side such fragments are mixed with larger

[1] The north and the south side of the west wall have roughly the same area (about 12-13 m^2)

aggregate grains from underlying plaster. This is probably because there is more "open" plaster on the south side.

Whether the climate control measures have had any influence on the positive downfall statistics is still hard to state. The amount of downfall is small and, like before the conservation measures, extremely dependent on whether a few large, fallen fragments obscure the picture. However, it is a fact that the general room climate was drier and much more variable in the period from 1996 until the installation of the preliminary door in February 2001. Recording of downfall will continue in the hope that a clearer picture will emerge after a few years.

It is important to note that downfall was not recorded in 1999-2000. This was because frequent conservation measures in this period obscured the reliability of such recordings.

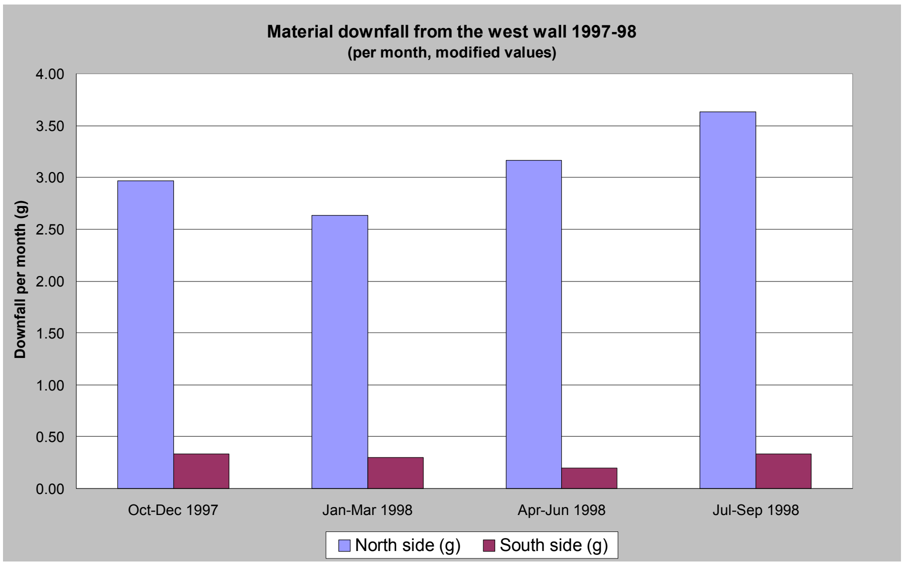

Figure 23: Material downfall from the west wall 1997-1998

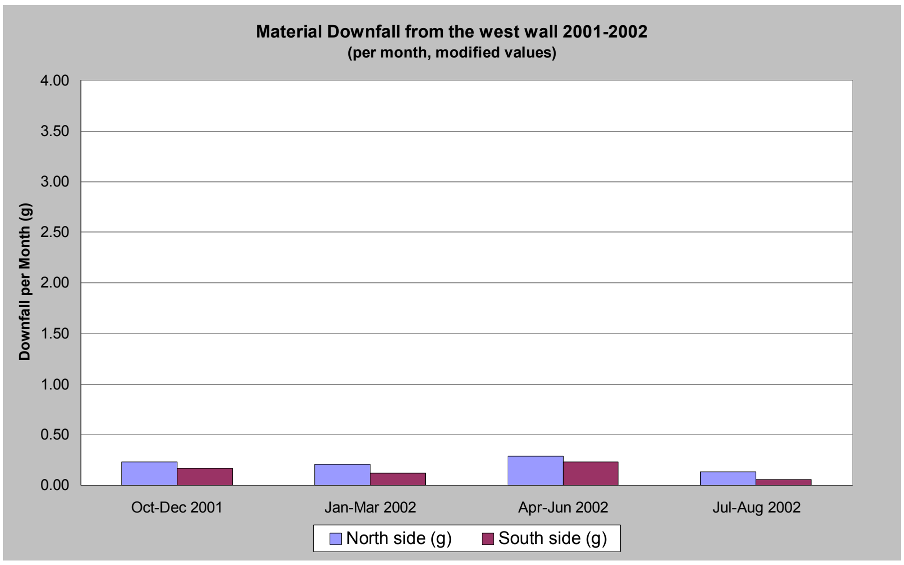

Figure 24: Material downfall from the west wall 2001-2002

MONITORING OF SALT CRYSTALLISATION PERIODS

The west wall has much salt – up to nearly 3% by weight in some samples analysed ([6], see also [2] and [4]). Monitoring of salt crystallisation periods has therefore been carried out since 2000 and was intensified after the emergency conservation in 2001. The general problem is that the salts are very hard to see by the naked eye, thus it is also hard to determine under which circumstances (temperature, relative humidity) they crystallise. In order to deal with this problem, special observation spots (O.1-O.4) have been established [4], from where samples are collected by brushing with small, soft paintbrushes and subsequently analysed by microscopy and, when necessary, microchemistry. In this way it's possible to determine whether salts are present, and, if they are, which types are concerned and in what approximate amount. All analyses undertaken over the last two years can be found in appendix 2.

Sampling of salts was undertaken 14.2.2001, 10.6.2001, 5.7.2001, 15-17.8.2001, 9.3.2002 and 13.9.2002. The general results can be seen in fig. 25: Medium amounts of the most important salt species (halite and nitratine) could be found in February and June 2001, they subsequently almost disappeared in July and August and were also more or less absent in March 2002. In September 2002, however, after the extremely warm and dry summer, the amount of salt nearly exploded. By then it was for the first time possible to very easily see the salts, present as whiskers and cotton-like bundles of needles, with the naked eye (fig. 26-28).

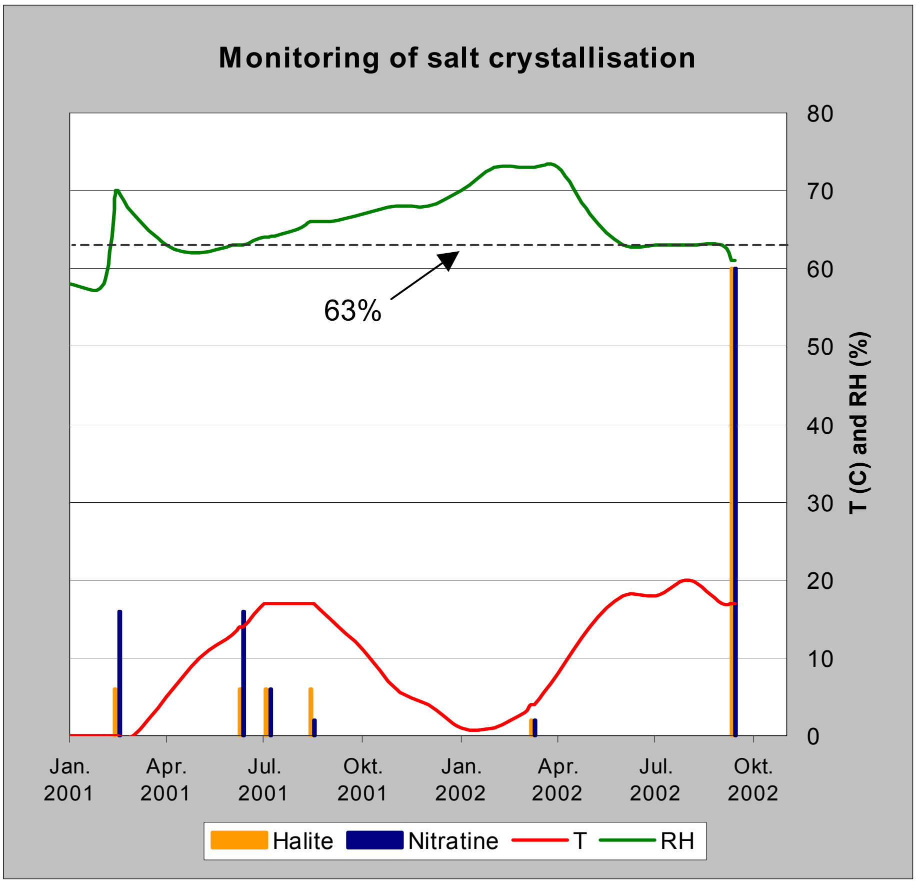

Figure 25: Presence of halite (sodium chloride) and nitratine (sodium nitrate) at the time of observation as compared with the mean monthly relative humidity and temperature. The relative amount of salt is indicated by the bars. The amount of salt was roughly estimated from analyses of several samples at each time of observation.

Figure 26: Salt whiskers on a new lime mortar repair. Salt has a tendency to effloresce on such material because of its finer pores, which keeps moisture longer, as compared to the adjacent old lime plaster. The area was not sampled in order to be able to follow the evolution of the whiskers in the future. Width of photo c. 5 cm. Photo no. RE02_002.

Figure 27: Long needles and whiskers of mainly halite and a little nitratine (sodium nitrate) forming cotton-like bundles. Width of photo: c. 8 cm. Photo no. RE02_003, sample no. RE130902_04. Microphoto no. RE02_010 (see fig. 22)

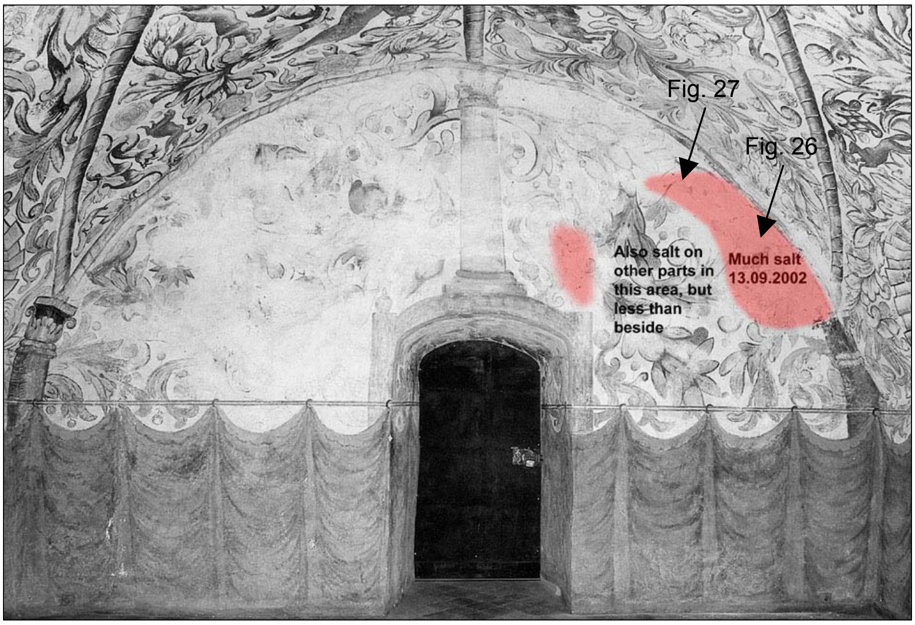

Figure 28: Areas with much salt in the middle of September 2002. Salts included mainly halite and nitratine.

It is still too early to draw final conclusions on the relationship between salt crystallisation periods and ambient temperature and relative humidity. However, from fig. 25 it would seem that the Equilibrium Relative Humidity (EQRH) of the actual salt mixture in the wall is in the range 63-67%. This does, however, not mean that the salts are always present below and absent above 63-67% relative humidity, as the kinetics of the salt crystallisation processes also must be considered. For instance, it would seem that the "salt explosion" in the late summer 2002 was related to the fact that the relative humidity had been stable around 63% for nearly 4 months, thus enabling the salts to build up larger whiskers and needles. It can of course not be ruled out that supply of moisture from minor water leaks also plays a role, but this is unlikely, since the summer of 2002 was so dry (see appendix 1).

A further reason might be the relationship between the indoor climate in the Regalia room and the staircase at the rear of the wall (see appendix 1). Although the absolute humidity in the Regalia room and the staircase is practically the same (winter and summer), it could be that small differences facilitate moisture transport through the wall. However, in order to find out about this, very careful modelling on the basis of the climate recordings would be necessary. This has not been undertaken yet.

Although the exact mechanisms for the strong salt crystallisation can only be supposed at the moment, it becomes clear from fig. 25 that the relative humidity in the Regalia room is too low, thus enabling salts to crystallise. From the figure it would seem that the *safe lower limit* of the relative humidity has to be raised to about 70% (year-round) in order to avoid crystallisation. Whether this can be done by "low-tech" means or if one has to install humidifiers in certain dry periods remains an important open question. It should, however, not be forgotten that the summer of 2002 was exceptional – and on the other hand: exceptional climatic events appear to become more frequent.

SALTS ON THE EAST WALL

Although no salts could be seen by the naked eye on the east wall of the Regalia room in September 2002 (like in former years), a sample was nevertheless taken near the SW-corner, c. 2 m above the floor, by gently brushing with a small, soft paintbrush (sample RE130902_12). The analysis showed that quite a lot of halite whiskers were present, thus confirming that not only the west wall is contaminated by salts.

7 Computer modelling of salt crystallisation phenomena

The response to changing relative humidity and temperature of the salts on the west wall has been simulated using the thermodynamic model of ECOS [10] and the new computer program RUNSALT [9]. Given that quantitative salt analyses are available, these computer tools make it possible to predict under which conditions complex mixtures of salts crystallise and dissolve. A major drawback with the tools is that the presence of alkaline carbonates, and to some extent gypsum, cannot be included. However, in the Regalia room this is probably not of great significance, since no alkaline salts have been found. However, analyses have shown that water extracts from west wall samples are slightly alkaline ([6], see also chapter 8). More thorough information on the application of ECOS/RUNSALT to practical situations can be found in [11].

The quantitative analyses (see [6]) of the following samples were used for the computer modelling:

- RE140201/07: Mortar sample from the border between the wall and the vault in the NW-corner.
- RE140201/08: Grey plaster sample from the north side of the closed niche in the NW-corner of the west wall.

Table 2: Salt content in samples selected for simulation

	RE140201/07 [mg/g]	RE140201/08 [mg/g]
Na^+	7.40	0.49
K^+	0.74	0.20
Ca^{2+}	0.90	0.60
Mg^{2+}	0.26	0.09
Cl^-	4.90	0.91
NO^{3-}	11.10	0.37
SO_4^{2-}	1.59	0.11

Results from the computer simulation can be found in appendix 3 and fig. 29. Depending on how the “gypsum-problem” is solved, either by removing calcium or sulphate from the simulation, the results are slightly different for each simulated sample. However, the general tendencies are the following:

- In the winter (0ºC): Most salts should be in solution above 68-71% relative humidity. However, in the presence of sulphate, low temperatures can favour the formation of mirabilite at higher relative humidity.
- In the spring/autumn (10ºC): All salts should be in solution above 67-70% relative humidity.
- In the summer (20ºC): All salts should be in solution above 66-70% relative humidity.

As can be seen, these results correspond roughly with the observations in the Regalia room (chapter 6), although the observed Equilibrium Relative Humidity (EQRH) might be slightly lower (towards 63-67% rather than 67-70%). A most important feature is also that in summertime the EQRH of the salt mixture is slightly reduced. However, the summer of 2002 was still dry enough for the salts to strongly crystallise in the Regalia room (lower part of fig. 29). In the wintertime, however, even if the EQRH is raised to some 70%, the relative humidity in the Regalia room was high enough for the salts to generally stay in solution in 2001-2002 (upper part of fig. 29).

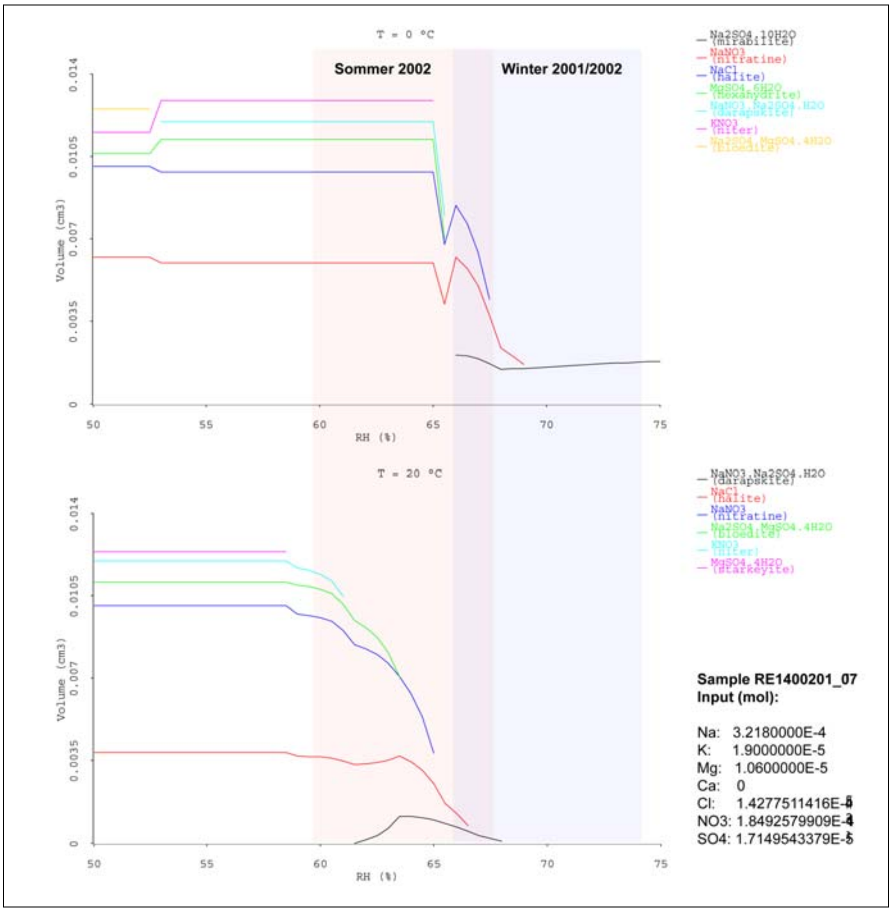

Figure 29: Computer modelling of sample RE140201_07 with removal of calcium to facilitate the analysis. Upper part: Graph by 0ºC. Lower part: Graph by 20ºC. The pink and light blue fields show the relative humidity range in the summer of 2002 and the winter of 2001-2002, respectively.

8 Crack monitoring

Crack monitoring in the north wing of the Archbishop's Palace has been carried out since 1989 and is thoroughly described in [4]. The most recent measurements, undertaken in the spring of 2002 by Kristin Bjørlykke of the Restoration Workshop of Nidaros Cathedral, in the Drapery room just to the east of the Regalia room showed very small changes since 2001. Although it might seem that the cracks are not significantly widening at the moment, one should bear in mind that their behaviour is probably dependent on ground water level changes, as shown by the measurements in 1999 when the cracks contracted after an extremely wet period (fig. 30).

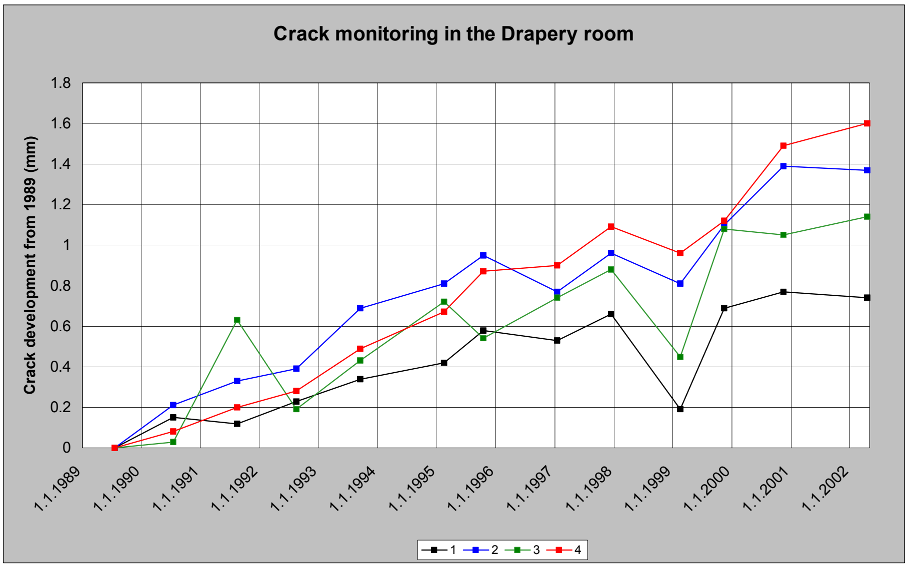

Figure 30: Crack monitoring in the Drapery room to the east of the Regalia room. 1-4 means various measurement spots as described in [7].

9 Various investigations and observations

Two reports made by sub-contractors to the project were prepared in 2001. One report concerns quantitative salt analyses and sorption of mortar samples taken [6]; the other analyses of old injection mortars on the west wall [7]. Morover, a few observations pertaining to the stratigraphy of the paint layers of the west wall have been made.

QUANTITATIVE SALT ANALYSES AND SORPTION OF MORTARS

This work, undertaken by Konrad Zehnder, showed that the salt content in samples taken from the west wall and in the closed niche in the NW-corner of the wall was in the range of 0,3-2,7% by weight. The most important ions were sodium, some magnesium, calcium, chloride, nitrate and some sulphate. This ionic composition corresponds to the observed salts species on the west wall (mainly halite and nitratine with some epsomite, gypsum and mirabilite/thenardite [2,4]. An important observation is the alkalinity (pH 9-9,5) of the water extracts from the samples. This might imply that there are minor sources of hydroxide, possible from lime mortars/plasters not having completely carbonated, or, alternatively, sources of alkaline salts (sodium or potassium carbonates). The latter explanation is probably the best one, as it is known that concrete and cement mortars have been used in or in the vicinity of the west wall [2,4]. The reason why we have never found for instance sodium carbonates in crystalline form on the wall might be related to reactions between sodium carbonate and available sulphate forming sodium sulphates (mirabilite/thenardite).

The sorption and desorption characteristics of the samples taken appear to be more or less completely dependent on their actual salt content (fig. 31). As the relative humidity rises above 60-70%, the samples quickly starts to pick up moisture; the higher the salt content (e.g. sample RE140201_07), the higher the absorbed moisture.

INVESTIGATION OF MORTAR TYPES

Investigation of three mortars from the west wall was undertaken by Thorborg von Konow. Samples were taken from the closed niche in the NW-corner of the west wall (RE 140201_12), from a cement mortar on the west

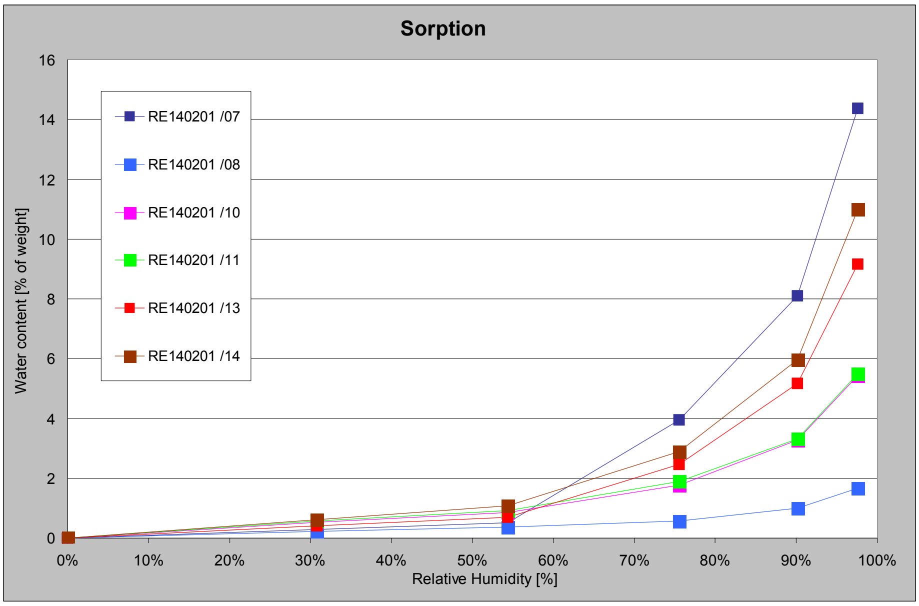

Figure 31: Sorption curves for the mortar samples at 20ºC. Diagram from [6]. Sample RE140201_07 has the highest amount of salts (2.7%); sample RE140201_14 the lowest (0,3%).

wall (RE 140201_06) and from a grey injection mortar found behind plasters on the west wall (RE 140201_05). The investigations showed the following:

RE 140201_12: Surprisingly, the grey mortar is not a typical, old lime mortar, but contains in the range of 10-15% (weight) hydraulic components and has a rather high aggregate content. The nature of the hydraulic components is not known.

RE 140201_06: This is, as expected, a repair mortar with c. 20% cement and c. 15% calcite, which indicates a very cement-rich mortar. This is in line with observations.

RE 140201_05: It has not yet been possible to determine whether the grey, soft and often completely pulverised injection mortar used at large parts of the west wall [4], is a cement-bound or clay-bound mortar. Thermogravimetry indicated that the sample contained chlorite and vermiculite, and thus is a clay-mortar, but this result is uncertain. The peculiar feature about the injection mortar is its pulverised state, thus it would seem that it does not contain cement. However, it is also possible that the availability of moisture upon setting was too low to make the cement properly bind. Microscopy of similar samples (RE130902_10 and 11) indicated that the samples contained much well-defined quartz grains and a murky mass of very fine grained powder with 1st order interference colours. This is hardly representing clay particles, but on the other hand no hydraulic clinker grains were observed. Thus, further analyses have to be undertaken in order to determine the nature of this enigmatic mortar. It is for instance possible that the mortar contained the salts that are so common on the wall today?

OBSERVATIONS ON STRATIGRAPHY

Upon removing 1966 gypsum repairs from the “coloumn” above the door (fig. 9), it was possible to get a new view of the stratigraphy of the limewash and paint layers of the wall. Surprisingly, a formerly unknown layer (no. 2, fig. 32) turned up between the original grey paint from 1616 (no. 1) and the 1826 limewash (no. 3). It is possible that this layer corresponds to the what has been called the 2nd limewash/paint, supposedly applied in the periods between 1672 and 1826 and earlier found on the north side of the wall. However, only tiny fragments have been found earlier [2].

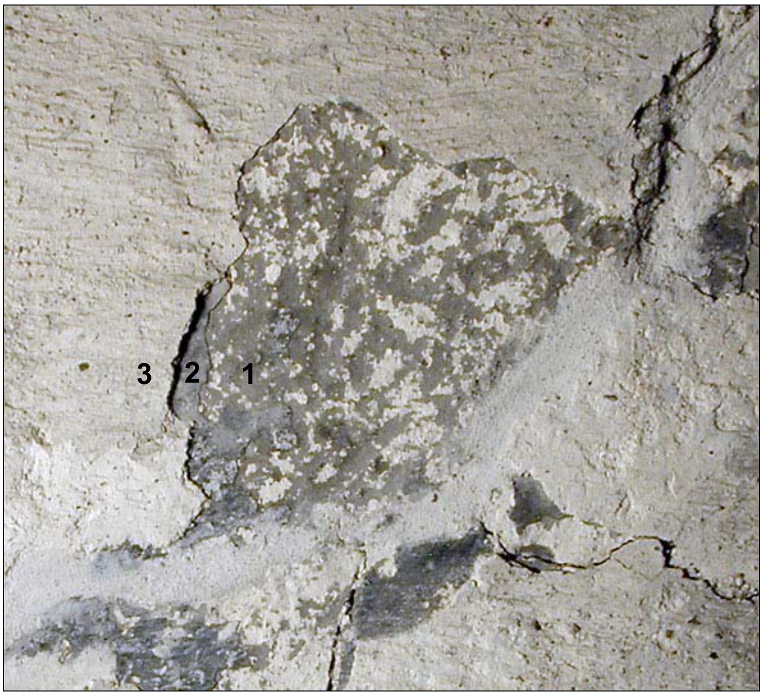

Figure 32: Layer of paint (2) found between the 1616 paint (1) and 1826 limewash (3)on the “column” right above the door opening.

10 Summary and recommendations

SUMMARY

The most important results of the 2001 conservation campaign and the subsequent monitoring can briefly be summarised in this way:

- The emergency conservation in 2000 and the conservation in 2001 must be regarded as successful as the amount of material falling from the west wall has been reduced by 15-25 times to 0,2-0,4 g/month (north side of the west wall).
- The main future conservation challenge at the west wall is related to the development of a method capable of properly securing the brittle and strongly exfoliating 1826 limewash. Until now it has only been possible to secure the borders of this limewash.
- The indoor climate in the Regalia room has drastically improved after measures carried out in the winter of 2001 (e.g. a new, preliminary door). The relative humidity is now in the range of 60-75% year-round. However, according to observations and computer modelling, the lower limit of 60% is still to low in order to avoid damaging salt crystallisation. This limit has to be raised to some 70% to be on the safe side. It has not yet been possible to find out how this can be achieved.

The main recommendations for the west wall follow from the summary above:

- Laboratory- and in-situ experiments with various conservation methods should be undertaken in order to find a method to secure the exfoliating limewash.
- Careful monitoring of material downfall from the west wall, salt crystallisation periods and indoor climate should be continued at least another c. two years in order to get a proper basis on which to discuss permanent climate control measures. This is because the outside weather strongly influences the indoor climate – and the weather is at the moment hard to predict, as shown by the hot 2002 summer.

RECOMMENDATIONS

The Regalia room conservation project also aims at conservation of the vault and all the other walls in the room. In an interim report to the Restoration Workshop of Nidaros Cathedral by Per Storemyr and Andreas Franz, dated

21. August 2001, the following work has been proposed (not including work recommended above, and slightly modified):

<u>2003 (proposed for 2002, but not undertaken then)</u>

- Conservation experiments for the west wall
- Photographing the vault and all walls to get a basis for documentation and conservation
- Measured survey of the Regalia room and the whole West house of the Archbishop's Palace (for stability investigations and documentation purposes)
- Stability investigation of the West house
- Further research on salt weathering in order to find the sources of the salts in the Regalia room.
- Starting the mapping of all paintings in the room, including scientific analyses, like the mapping of the west wall in 1999 [2].
- Discussing and dealing with the major risks and problems related to the preservation of the paintings in the whole room (water leaks from the gable, fire, unwanted release of the sprinkler system at the loft, how to deal with visitors etc.).

<u>2004</u>

- Continue and finalise the conservation of the west wall with refined conservation methods
- Finalise the mapping of the rest of the room
- Undertake decisions with regard to major risks and climate control
- Monitoring

<u>2005</u>

- Conservation of the rest of the room
- Undertake measures with regard to major risks and climate control
- Monitoring

<u>2006</u>

- Closing of the conservation work
- Visitor control programme and monitoring (also later)
- Publication (web and book)

The years given are meant as a suggestion only, showing the necessary phases that will have to be included in the conservation project, as well as the approximate time needed to carry out the project.

It is also recommended to organise a seminar with national and international participation in order to discuss and find the best possible measures for the conservation.

References / reports from the conservation project

[1] Odén, B. (1999): Kunsthistorisk analyse av kalkmaleriene i Erkebispegården i Trondheim. *NDR Report* no. 9901, 67 p, 13 figures in report, 117 attached figures on CD, with English abstract: Art Historical Analysis of Mural Paintings in the Archbishop’s Palace in Trondheim

[2] Franz, A. & Storemyr, P. (2000): The 17th Century Mural Paintings in the Regalia Room, Archbishop's Palace, Trondheim, Norway. History, Paint Technology and Weathering of the West Wall. *NDR-report*, no. 0001, 66 p.

[3] Storemyr, P. & Franz, A. (2000): Experiences from the use of Adobe Photoshop® and DiVisuAL® for digital graphic documentation of mural paintings and exterior stone facades. In: The Raphael Programme, Nidaros Cathedral Restoration. Report Raphael I (to the European Commission) (*NDR-report* no. 1/2000), pp. 91-98.

[4] Franz, A. & Storemyr, P (2001): Conservation of Mural Paintings in the Regalia Room, Archbishop's Palace, Trondheim, Norway 1999-2005: Emergency Conservation of the West Wall and Scientific Investigations 2000. *NDR-report*, no. 1/2001, 41 p.

[5] Storemyr, P. & Franz, A. (2001): Summary of Research and Conservation Work on Mural Paintings in the Regalia Room, Archbishop's Palace, Trondheim, Norway. In: Lunde, Ø. & Gunnarsjaa, A.: Report Raphael II Nidaros Cathedral Restoration Trondheim Norway 2000. The Restoration Workshop of Nidaros Cathedral, Trondheim. *NDR-report*, no. 2/2001

[6] Zehnder, K. (2001): Trondheim (N), Archbishop’s Palace, Regalia Room: Salt content and sorption of mortars. *Report* (RE140201)from ETH Zürich, Institut für Denkmalpflege, 6.9.2001

[7] von Konow, T. (2001): Projekt – Nidarosdomen. Rapport Brukanalyser. *Report* from Tureida, Helsinki, Finland 31.8.2001

(NDR-Report: report from The Restoration Workshop of Nidaros Cathedral)

Other references

[8] Storemyr, P. (2002): Nidaros Cathedral, Trondheim, Norway. Infrared thermography March 2002. *Bericht*, No. 2002.019, Expert-Center für Denkmalpflege, Zürich, 12 p.

[9] Bionda, D. (2002): RUNSALT computer program. Unpublished.

[10] Price, C. A. (ed.) (2000): An expert chemical model for determining the environmental conditions needed to prevent salt damage in porous materials, European Commission Research Report No 11, (Protection and Conservation of European Cultural Heritage). Archetype Publications, London.

[11] Bionda, D. & Storemyr, P. (2002): Modelling the behaviour of salt mixtures in walls: a case study from the Tenaille von Fersen building, Suomenlinna, Finland. In: von Konow, T. (ed.): *The Study of Salt Deterioration Mechanisms. Decay of Brick Walls Influenced by Interior Climate Changes. European Heritage Laboratories – Raphaël 1999*. Helsinki: The Governing Body of Suomenlinna, pp. 95-101.

Distribution of the report

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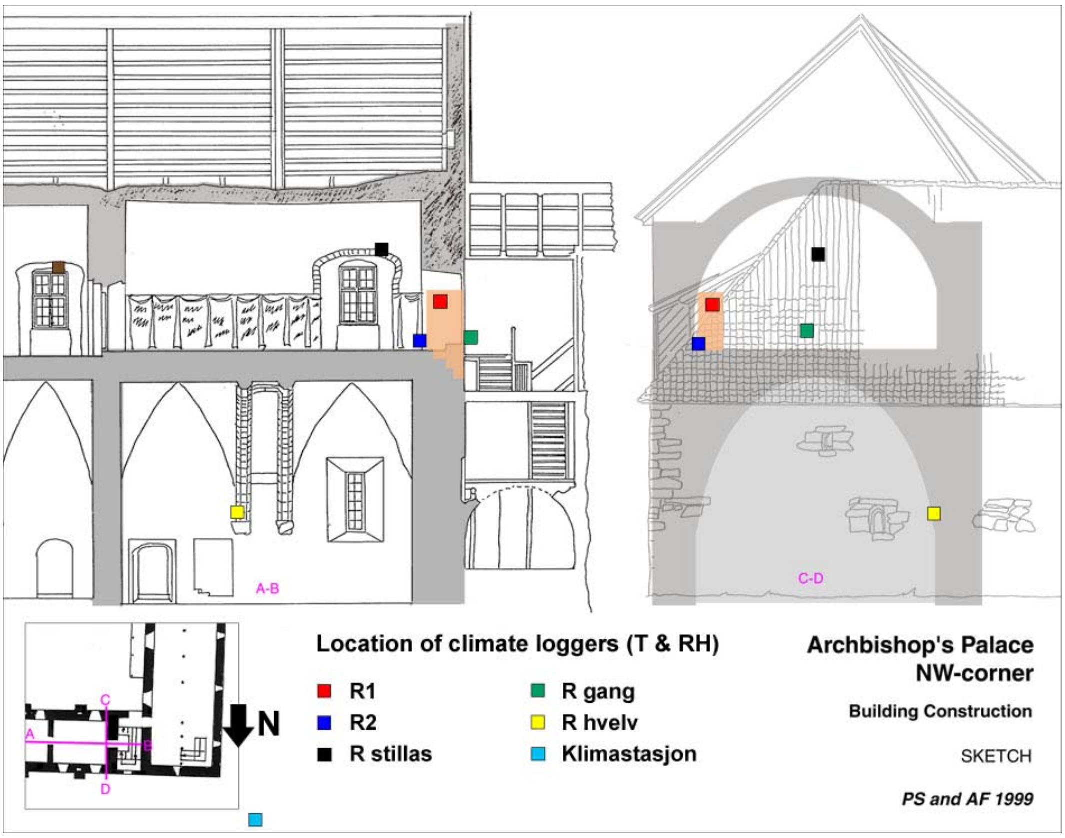
In addition, the report will be available for download at the project website www.ecd.ethz.ch/regalia

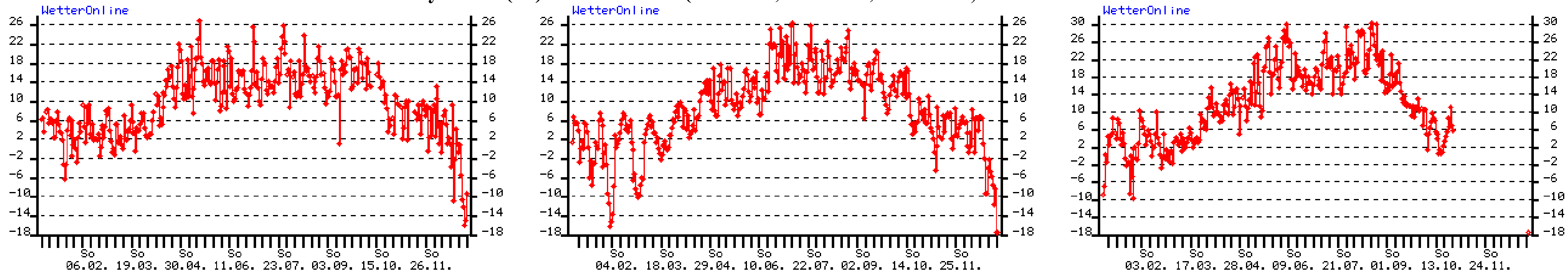
Appendix 1: Indoor climate



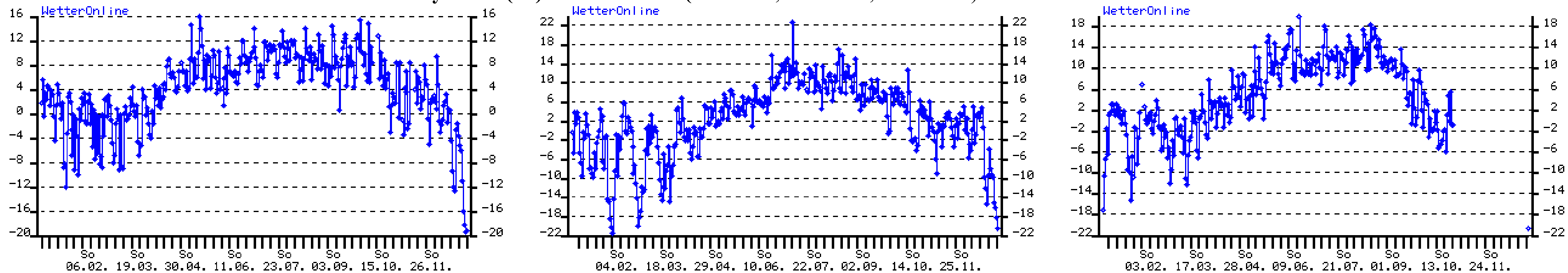
Location of climate loggers

On the next three pages the indoor climate from all stations, except the station in the Drapery room to the east of the Regalia room and the outdoor climate station ("Klimastasjon") between 1.1.2000 and September 2002 can be found. All measurements are done with various types of Tinytag loggers. For the outdoor climate, data from www.wetteronline.de have been included. Also, observations of the crystallisation of soluble salts can be found below.

Daily Tmax (ºC) in Trondheim (10° 56' O, 63° 28' N, 17 m.a.s.l.) **from wetteronline.de**

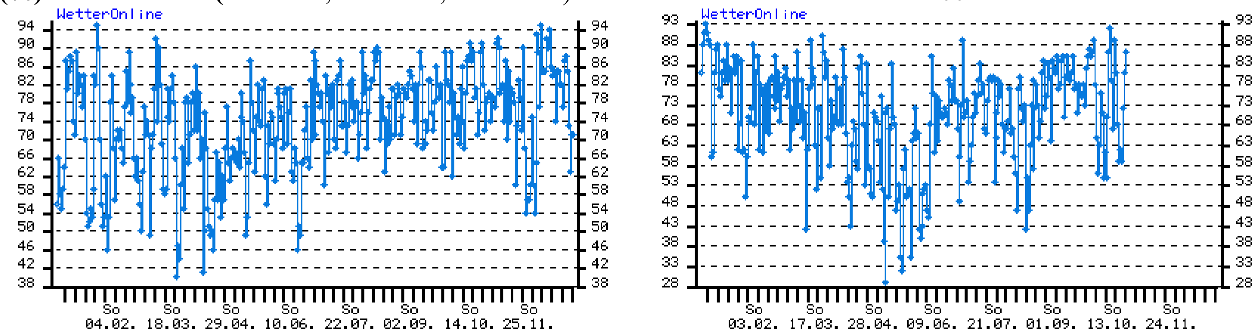


2000 **Daily Tmin (ºC) in Trondheim** (10° 56' O, 63° 28' N, 17 m.a.s.l.) **from wetteronline.de** **2002**

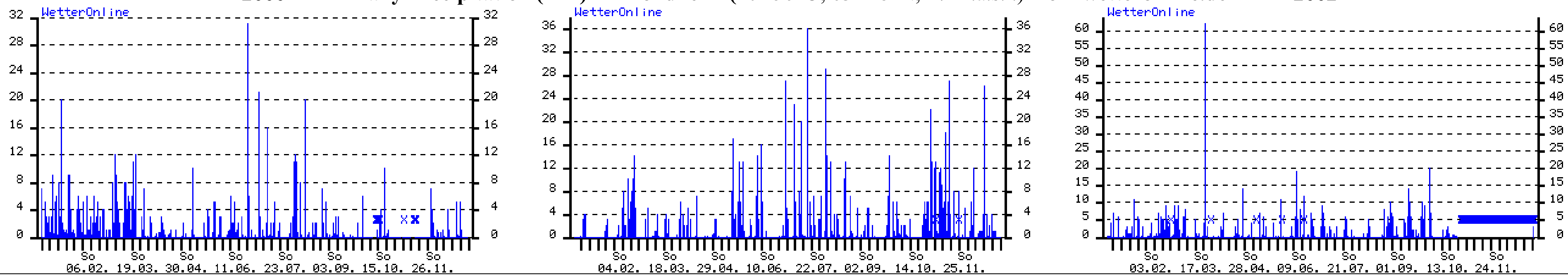


2000 **Mean daily RH (%) in Trondheim** (10° 56' O, 63° 28' N, 17 m.a.s.l.) **from wetteronline.de** **2002**

(Not available)



2000 **Daily Precipitation (mm) in Trondheim** (10° 56' O, 63° 28' N, 17 m.a.s.l.) **from wetteronline.de** **2002**



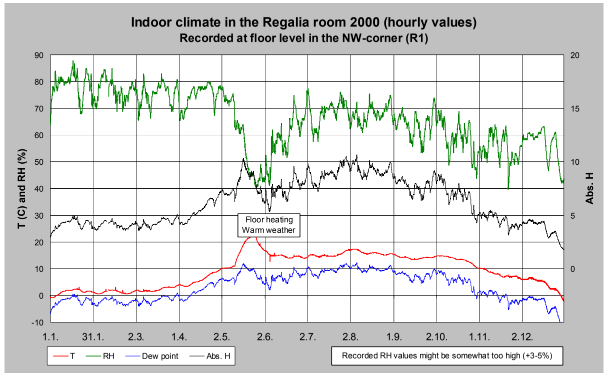
Observations of salts on the west wall in the Regalia room (mostly nitratine and halite)

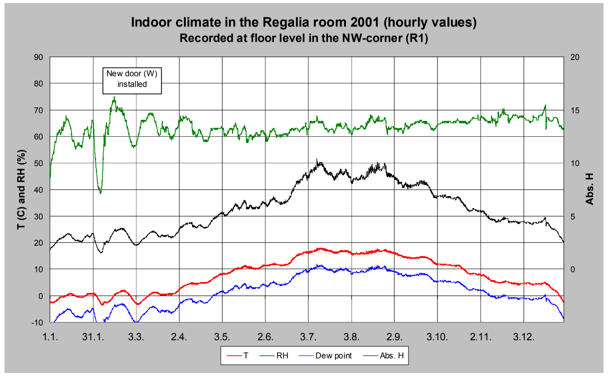
++= much, +=present, +/-=very little, -= hardly present

2000		2001					2002	
+	(No observations)	+	+	-	+/-	(No observations)	-	+ +

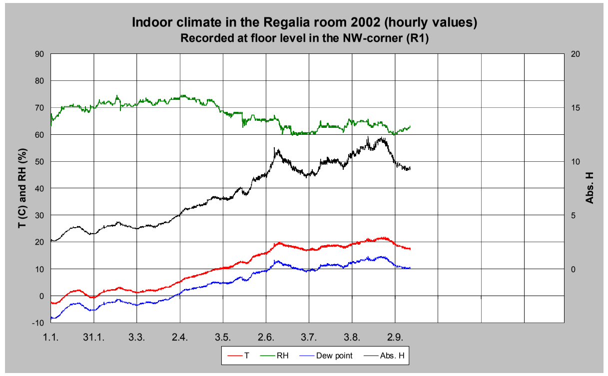
Regalia room, floor level, NW-corner (R1)

2000



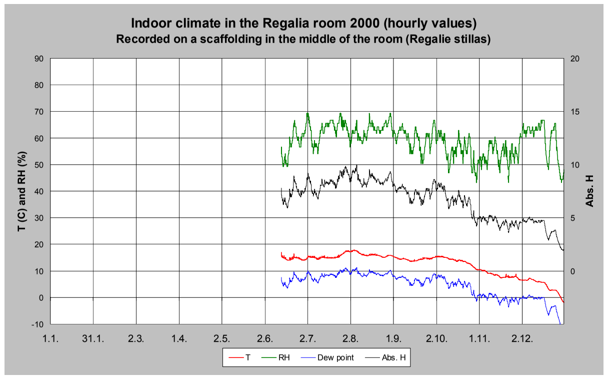


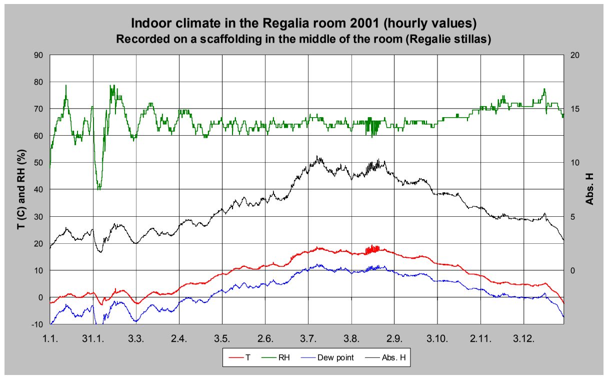
2002



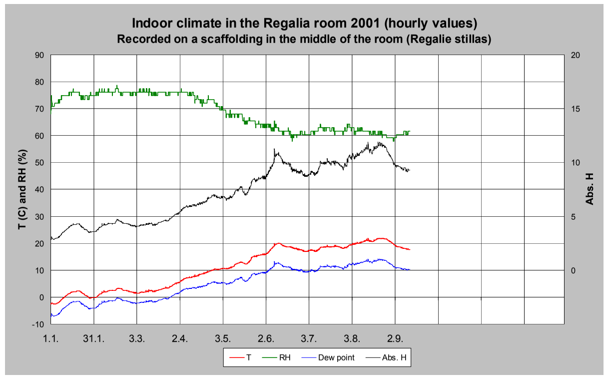
Regalia room, middle (Regalie stillas)

2000

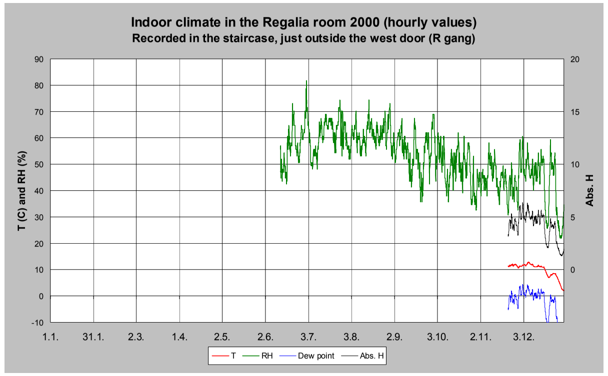




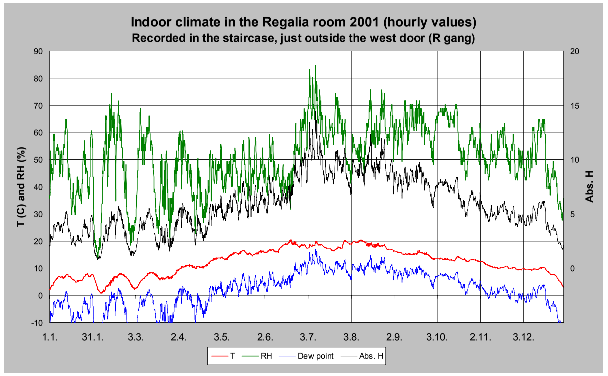
2002



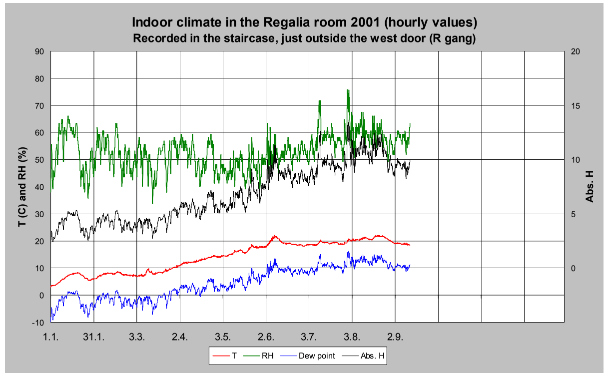
2000



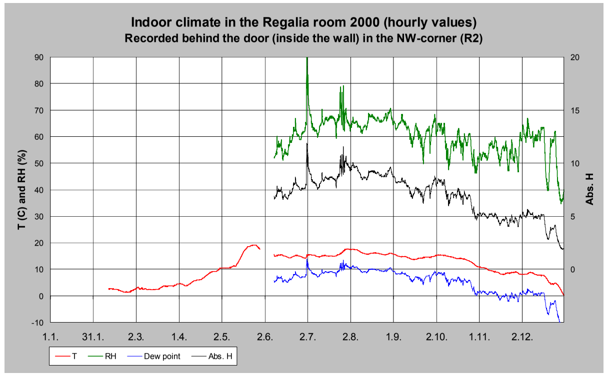
Staircase, outside the Regalia room (R gang)



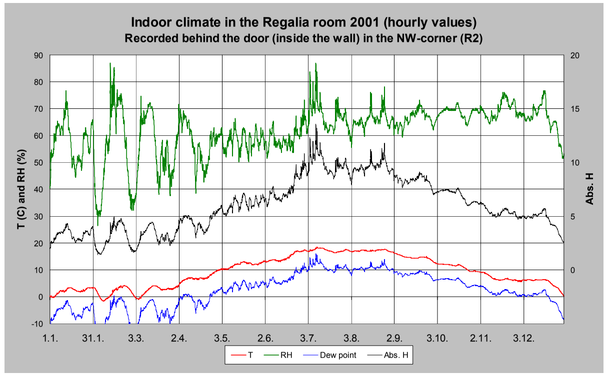
2002



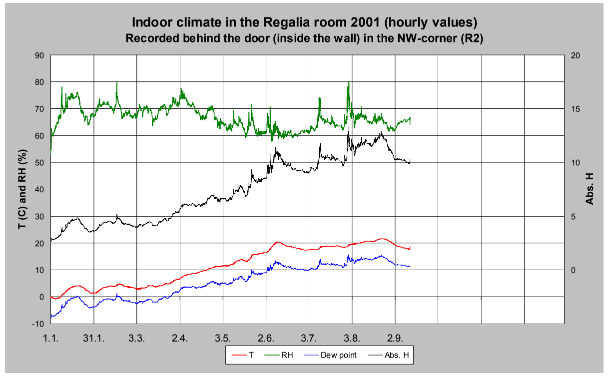
2000



Closed niche, “inside” W-wall Regalia room (R2)



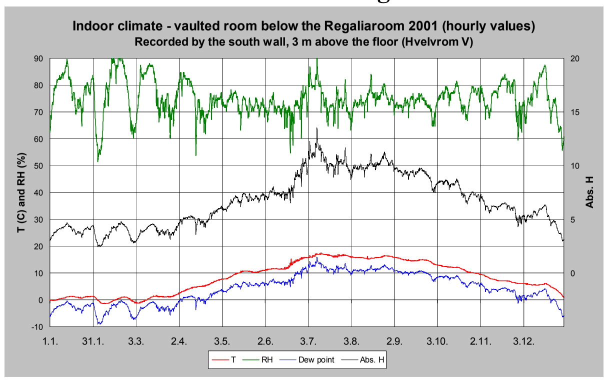
2002



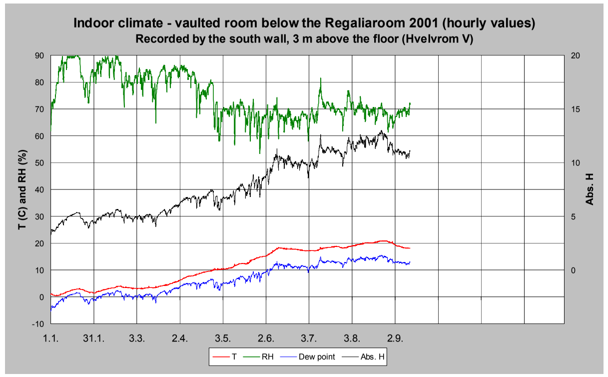
2000

(No recordings in 2000)

Vaulted room below Regalia room



2002



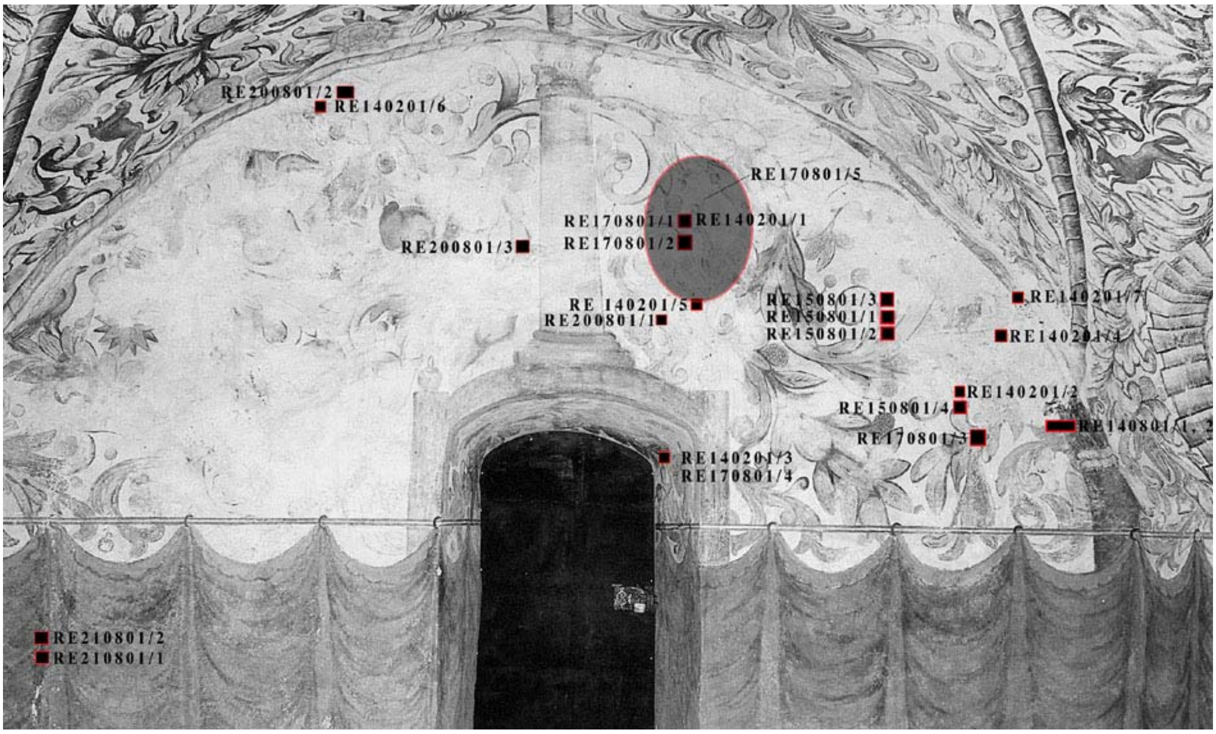
Appendix 2: Material analyses

Salts analysed by microscopy and microchemistry by Per Storemyr
Location: Q1-Q4: Quadrant 1 (upper S) to Quadrant 4 (lower N) on the west wall.
O.1-O.4 mean "observation spots". For accurate location; see maps behind.

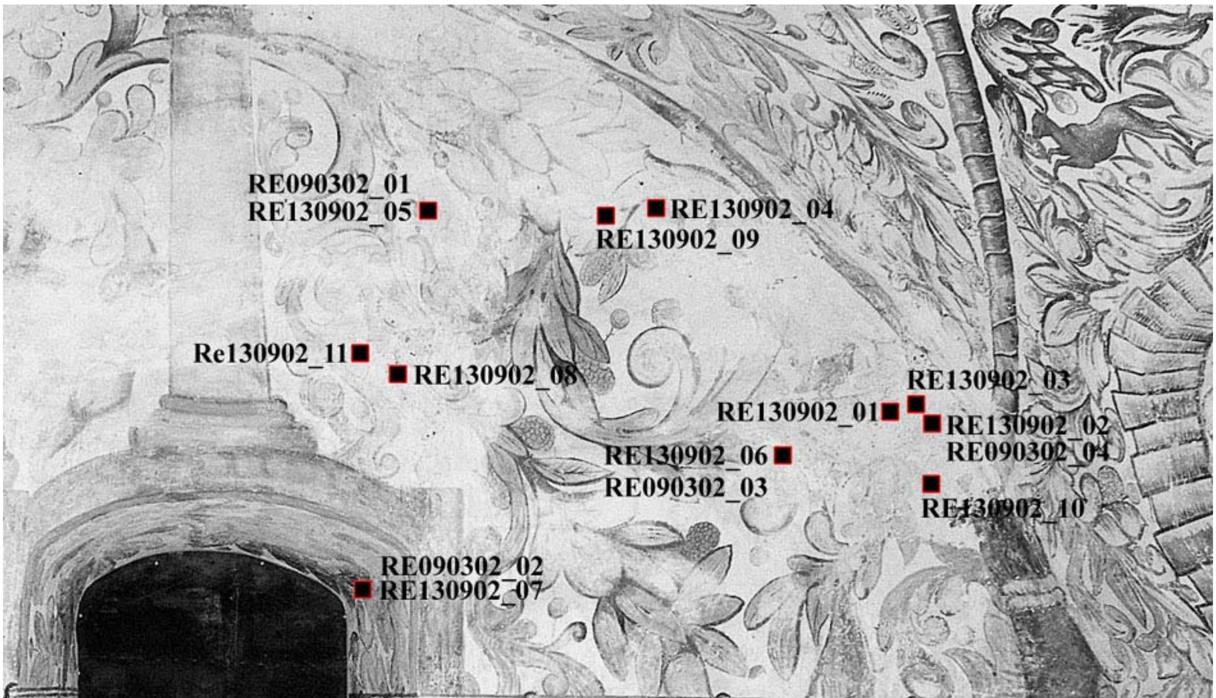
Sample no	**Location**	**Sample type**	**Description**	**Analyses**
RE140201/01	O.1	Salt	Powder brushed from the area around O.1. Little powder, no visible sign of salts	Very much sodium nitrate; whiskers, rounded particles, needles. The salt looks "fresh". Much more salt than after the limewater treatment in the summer of 2000, but almost the same amount as before treatment. Also some gypsum, some few halite grains and a pink salt with low relief. Photo no. RE01_01 (width of field c. 1 mm). Maybe the salt came during the cold period in Jan/Feb 2001?
RE140201/02	O.2	Salt	Powder brushed from O.2. Little powder, no visible sign of salts. Note that the area was covered by lime mortar in 2000	Some very few, small halite needles, otherwise nothing.
RE140201/03	O.3	Salt	Powder brushed from O.3. Some cotton-like efflorescences. These must have developed since the summer of 2000 since the spot was brushed "clean" at that time	Much epsomite, looks "fresh" (not partly dehydrated), a couple of halite needles. Photo no. RE01_02 (width of field c. 0,5 mm)
RE140201/04	Q2	Mortar	Gray powder from hole for injection mortar. Some lime from around came also into the sample. For mortar analyses	Not analysed
RE140201/05	Q2	Mortar	Gray powder from hole for injection mortar. Some lime from around came also into the sample. For mortar analyses	Analysis by Tureida/Thorborg von Konow, see report dated 31.8.2001. No definite result was achieved, but it is suggested that the mortar might be a lime-clay mortar. However, it cannot be ruled out that it is a lime-cement mortar that did not harden due to lack of water/humidity. Further analyses pending
RE140201/06	Q1	Mortar	Cement repair from 1966 (for comparison with the two samples above)	Analysis by Tureida/Thorborg von Konow, see report dated 31.8.2001. According to thermogravimetry the cement content is about 20%, whereas the lime content is some 15%. This means that the cement content is very high. There are also signs of an organic component, but this probably belongs to an organic paint used on the cement.
RE140201/07	Q2	Mortar	Mortar sample from the border between the wall and the vault (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich
RE140201/08	Closed niche	Mortar	Gray plaster/mortar sample from the north side (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich
RE140201/09	Closed niche	Mortar	Gray mortar sample from the south side. Used between bricks	Not analysed
RE140201/10	Closed niche	Mortar	Mortar sample from the south side (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich
RE140201/11	Closed niche	Mortar	Mortar sample from the south side (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich
RE140201/12	Closed niche	Mortar	Gray mortar sample from the south side (Note: It has always been supposed that the gray, relatively soft mortar in the closed niche at the rear of the west wall is an old lime-containing mortar.)	Analysis by Tureida/Thorborg von Konow, see report dated 31.8.2001. Summary: The cement content is quite high, 10-15% by weight, the binder has mostly not carbonatised. Inhomogeneous mortar, many small lime lumps. Further analyses pending
RE140201/13	Closed niche	Mortar	Mortar sample from the south side (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich
RE140201/14	Closed niche	Limewash	Limewash sample from the south side (for absorption isotherms)	See results in report RE140201 from Institut für Denkmalpflege, ETH Zürich

Sample no	Location	Sample type	Description	Analyses
RE210601/01	O.1	Salt	Powder brushed from O.1.	Large amounts of "fresh" whiskers of sodium nitrate
RE210601/02	O.2	Salt	Powder brushed from O.2. No visible salts	A few fine halite whiskers. NB! No thenardite
RE210601/03	O.3	Salt	Powder brushed from O.3. Only few salts visible by sampling	Many quite fine epsomite crystals. More rounded grains than whiskers.
RE050701/01	O.1	Salt	Powder brushed from O.1	Very little sodium nitrate. Moist period before sampling. Is this the reason why there is so little salt, or did the salt not return after sampling in june?
RE050701/02	O.2	Salt	Powder brushed from O.2	A few small halite crystals. Looks partly dissolved. A little epsomite?
RE050701/03	O.3	Salt	Powder brushed from O.3	Very little epsomite, but there is still epsomite in the area around. It seems that the epsomite does not really return quickly after having been brushed away.
RE140801/01	Q2	Loose material in joints etc.	Sand from wall appearing upon removing some of the cement repairs by the painted capital. Beware of possible slag in the material. Also observed some whiskers under the stereo microscope.	Studied the sample closer in the stereomicroscope: "Slag" looks black, shiny and with irregular forms. Under the pol. microscope it could be seen that the "slag" is carbonate with black spots in it - quite large spots. What is this? A bit nitrate, very small traces of chloride and a bit sulphate in the sample (Mercoquant test strips). Further analyses pending
RE140801/02	Q2	Mortar	Probably medieval joint mortar from the same spot as sample above.	Not analysed
RE140801/03	Q2	Mortar	Cement repair and various mortar removed from same spot as above.	Not analysed
RE150801/01	Q2	Salt	Powder brushed from plaster area that was soaked with water (150 ml) in order to provocate salt efflorescences. No salts observed visually.	No salts observed under the microscope, only lime and rock fragments/minerals. With Merckoquant teststrips minor amounts of nitrate and chloride.
RE150801/02	Q2	Salt	Powder brushed from plaster/limewash/paint area that was soaked with water (100 ml) in order to provocate salt efflorescences. No salts observed visually.	No salts observed under the microscope, only lime and rock fragments/minerals and black colour. With Merckoquant teststrips minor amounts of nitrate and chloride.
RE150801/03	Q2	Salt	Powder brushed from ABOVE plaster area that was soaked with water in order to provocate salt efflorescences. No salts observed visually, neither in unsoaked area, nor in soaked area	Possibly very small traces of halite observed under the microscope, otherwise only lime and rock fragments/minerals. With Merckoquant teststrips major amounts of nitrate and chloride.
RE150801/04	Q2	Salt	Powder tapped out from below exfoliating limewash. No salts observed visually.	Possibly very small traces of halite and gypsum observed under the microscope, otherwise only lime and rock fragments/minerals. With Merckoquant teststrips major amounts of nitrate and chloride, as well as very small traces of sulphate
RE170801/01	O.1	Salt	Powder brushed from testfield O.1. No salts visible	Very few traces of halite (perhaps). Perhaps some gypsum. But generally very little salt, if any.
RE170801/02	O.1	Salt	Powder brushed from just below testfield O.1. No salts visible. This area was chosen because it has not been brushed earlier this year.	Some few traces of sodium nitrate whiskers. A couple of grains with possible sodium chloride. Generally very little salt
RE170801/03	O.2	Salt	Powder brushed from testfield O.2. No salts visible.	Some few traces of sodium chloride - rounded grains and small "rods" rounded at the ends. Very little salt.
RE170801/04	O.3	Salt	Powder brushed from testfield O.3. No salts visible, but much epsomite in the area around the testfield. This means that the epsomite does not come back quickly after having been brushed away (last time in june 2001)	Some few traces of epsomite and perhaps a little gypsum.
RE170801/05	O.1	Salt	Powder brushed from around testfield O.1, radius c. 30 cm. No salts visible. The aim was to se whether there is more salt around than within the much brushed testfield itself.	Relatively much halite whiskers, very few traces of sodium nitrate. This could mean that sodium nitrate dissolves before halite. And it means that at brushed areas it takes a long time before the salts return (since there are extremely few salts in the O.1-testfield itself)

Sample no	Location	Sample type	Description	Analyses
RE200801/01	Q2	Mortar	Powder from injection mortar	Not analysed
RE200801/02	Q1	Mortar	Cement mortar repair 1966	Not analysed
RE200801/03	Q1	Mortar	Powder from injection mortar	Not analysed
RE210801/01	Q3	Mortar	Mortar from crack in which gypsum was removed. Probably medieval	Not analysed
RE210801/02	Q3	Mortar	Probably brick dust from crack in which gypsum was removed.	Not analysed
RE090302_01	O.1	Salt	Powder brushed away. No salts could be observed by the naked eye	Microscopy: One proper sodium nitrate whisker, otherwise few salts. Some small halite needles and possibly a little epsomite
RE090302_02	O.3	Salt	Not exactly by O.3, but beside where much salt could be seen. Powder brushed away.	Microscopy: Much "fresh" epsomite
RE090302_03	O.2	Salt	Powder brushed away	Microscopy: Quite a lot of gypsum, as "verfilzte" needles. Also some few halite needles and regular crystals. No "fresh" needles or whiskers. Perhaps some epsomite looking "old"
RE090302_04	Q2	Salt	Powder brushed away just beside the bird in Q2. Quite a few needles could be seen by the naked eye.	Microscopy: Much "verfilzte" gypsum needles. These are possible what can be seen by the naked eye. Some halite, as short needles and more regular crystals.
RE130902_01	Q4	Salt	Powder brushed away just beside the bird in Q2. Much needles and cotton-like efflorescences could be seen by the naked eye.	Fine, fresh whiskers of sodium nitrate. Much salt (Photo: RE02_009)
RE130902_02	Q2	Salt	Powder brushed away on new mortar repair. Much cotton-like efflorescences	Fine, frsh whiskers and parts of crusts, sodium nitrate and some halite
RE130902_03	Q2	Salt	Powder brushed away on new mortar repair (crack repair and beside). Much cotton-like efflorescences	Fine, frsh whiskers and parts of crusts, sodium nitrate and some halite
RE130902_04	Q2	Salt	Powder brushed away by flaking limewash. Much - really much - cotton-like efflorescences, also behind flake that was about to be liftet up. Brusched more or less all away, including a small flake.	Long needles and whiskers of mainly halite. A few sodium nitrate whiskers. Photo no. RE02_010
RE130902_05	O.1	Salt	Powder brushed away by observation spot 1. No salts could be seen by the naked eye	Little sample material. Some halite, a tiny amount of gypsum?
RE130902_06	O.2	Salt	Powder brushed away by observation spot 2. No or few salts could be seen by the naked eye	Much quartzgrains from the new mortar, otherwise: Halite!
RE130902_07	O.3	Salt	Powder brushed away by observation spot 3. Less salt in the area than normal	Epsomite, but also some longish grains, 1. order int. colours, <1,515.
RE130902_08	Q2	Salt	Powder brushed away on "disintegrated area". Needles could be observed.	Much halite, broken, thick whiskers
RE130902_09	Q2	Salt	Cotton-like efflorescencees and flakes brushed away. The area was very loose - from the recent salt-crystallisation??	Much halite, whiskers and needles, much lime mortar grains.
RE130902_10	Q2	Injection mortar	Gray-green powder in hole - perhaps injection mortar. Look for not hydrated cement phases	Could not find hydrated cement phases. Much small, rounded quartz grains. Otherwise murky mass of fine grains with 1. order int. col. Probably not clay, rather cement?
RE130902_11	Q2	Injection mortar	Gray-green powder in hole - perhaps injection mortar. Look for not hydrated cement phases	Could not find hydrated cement phases. Much small, rounded quartz grains. Otherwise murky mass of fine grains with 1. order int. col. Probably not clay, rather cement?
RE130902_12	East wall	Salt	Brushed away powder in the SE-corner. Look for salts.	Quite a lot of halite whiskers. Otherwise opaque grains from paint (pigments) and lime.

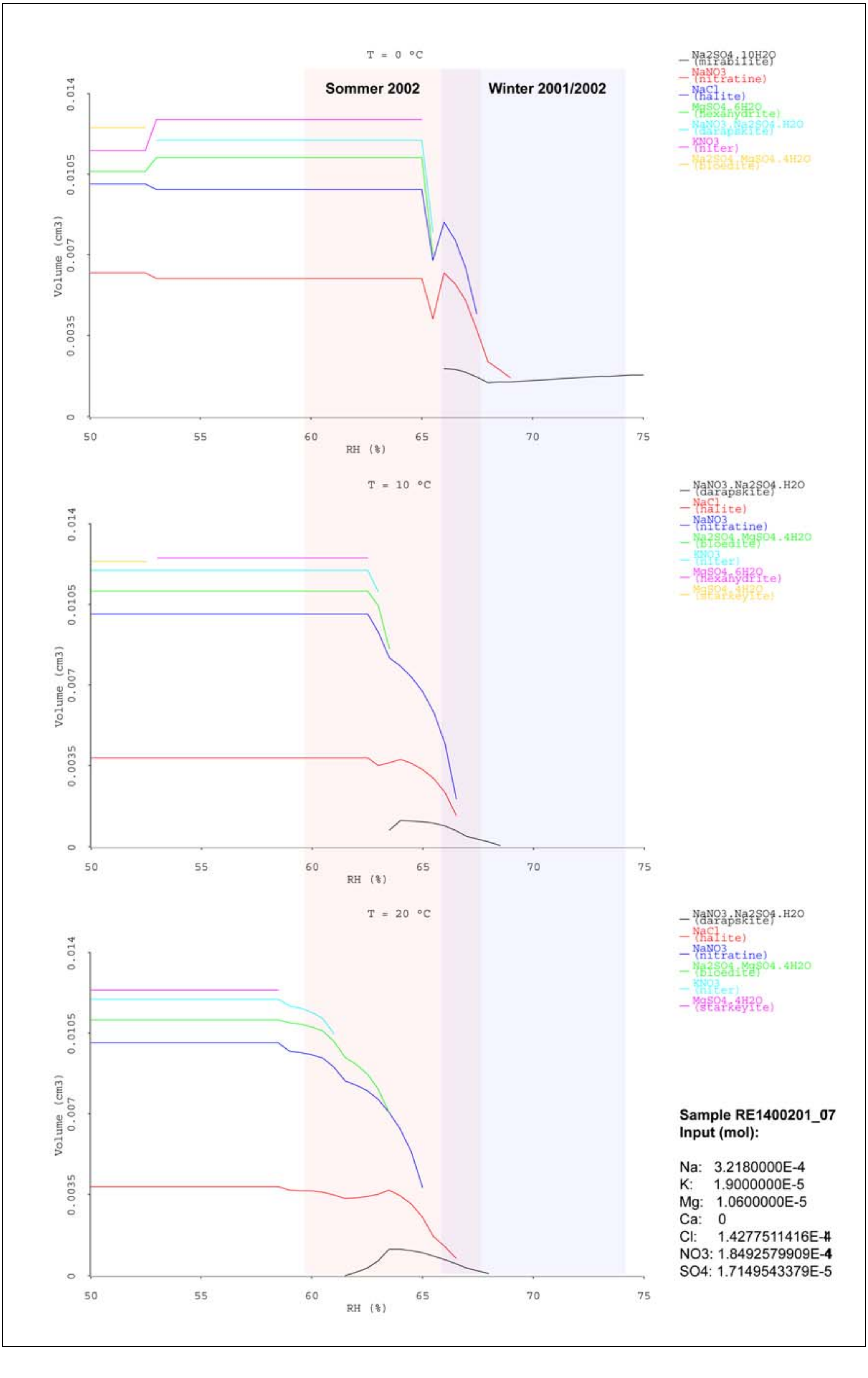


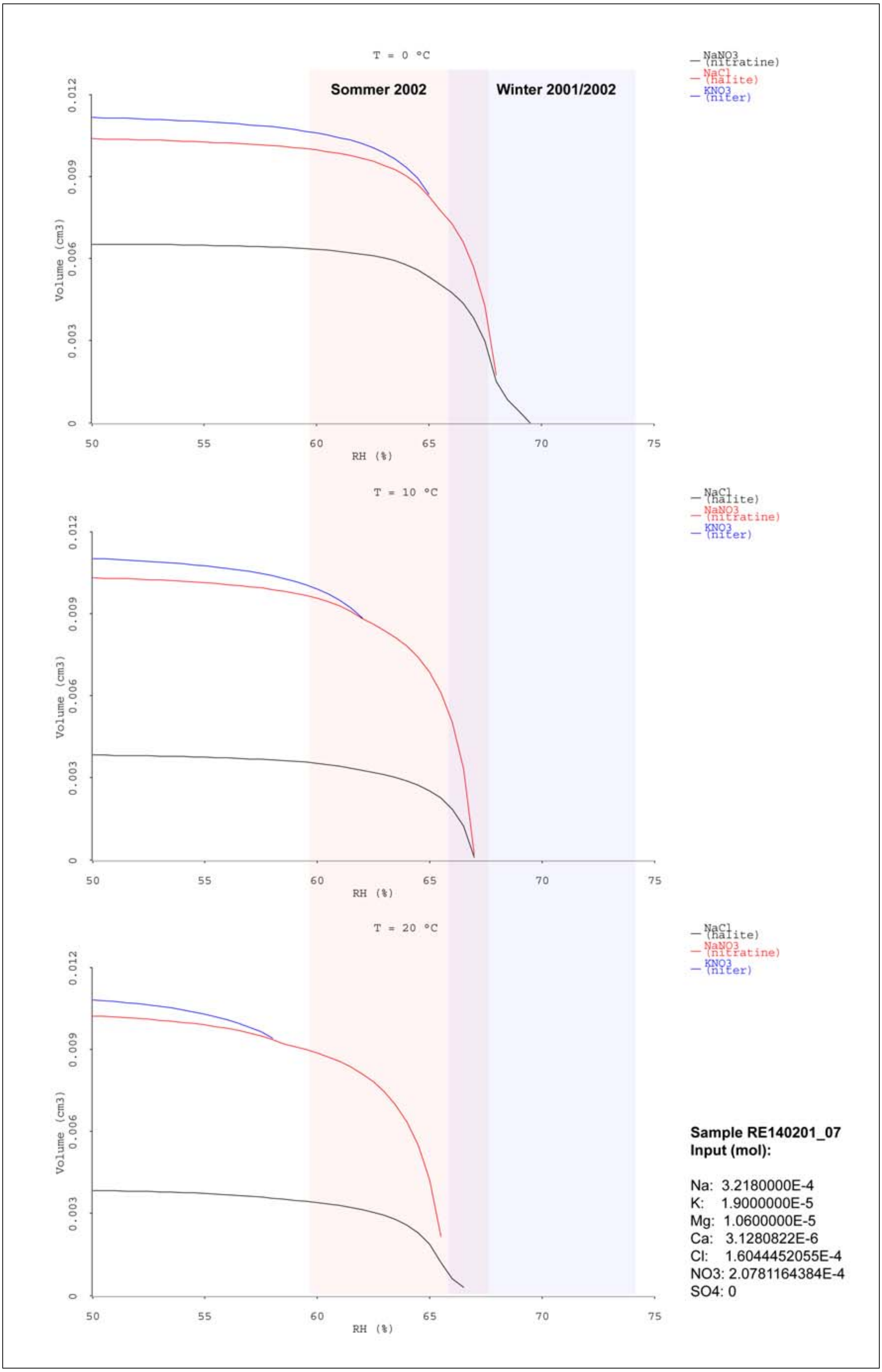
Location of samples taken in 2001

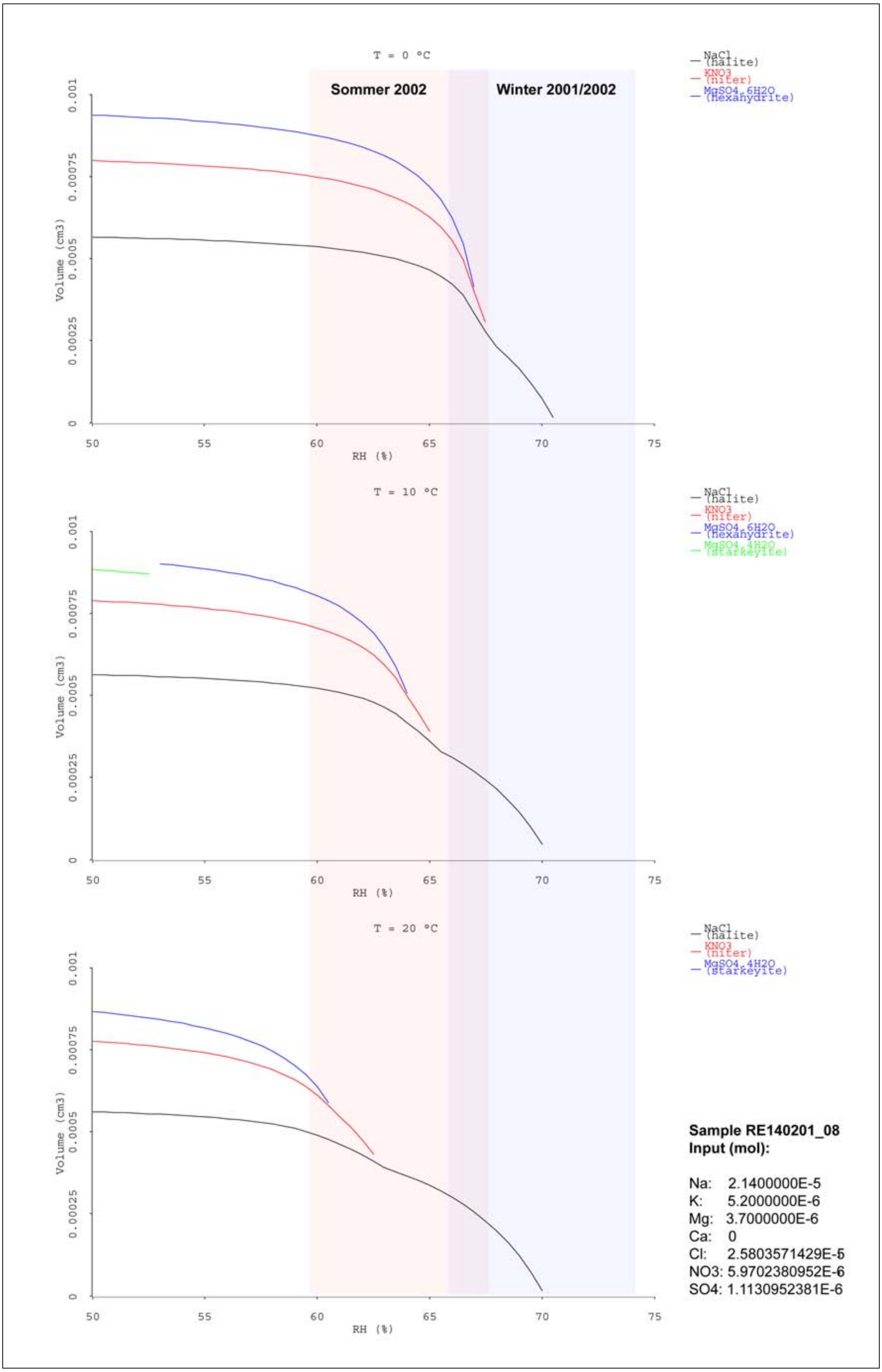


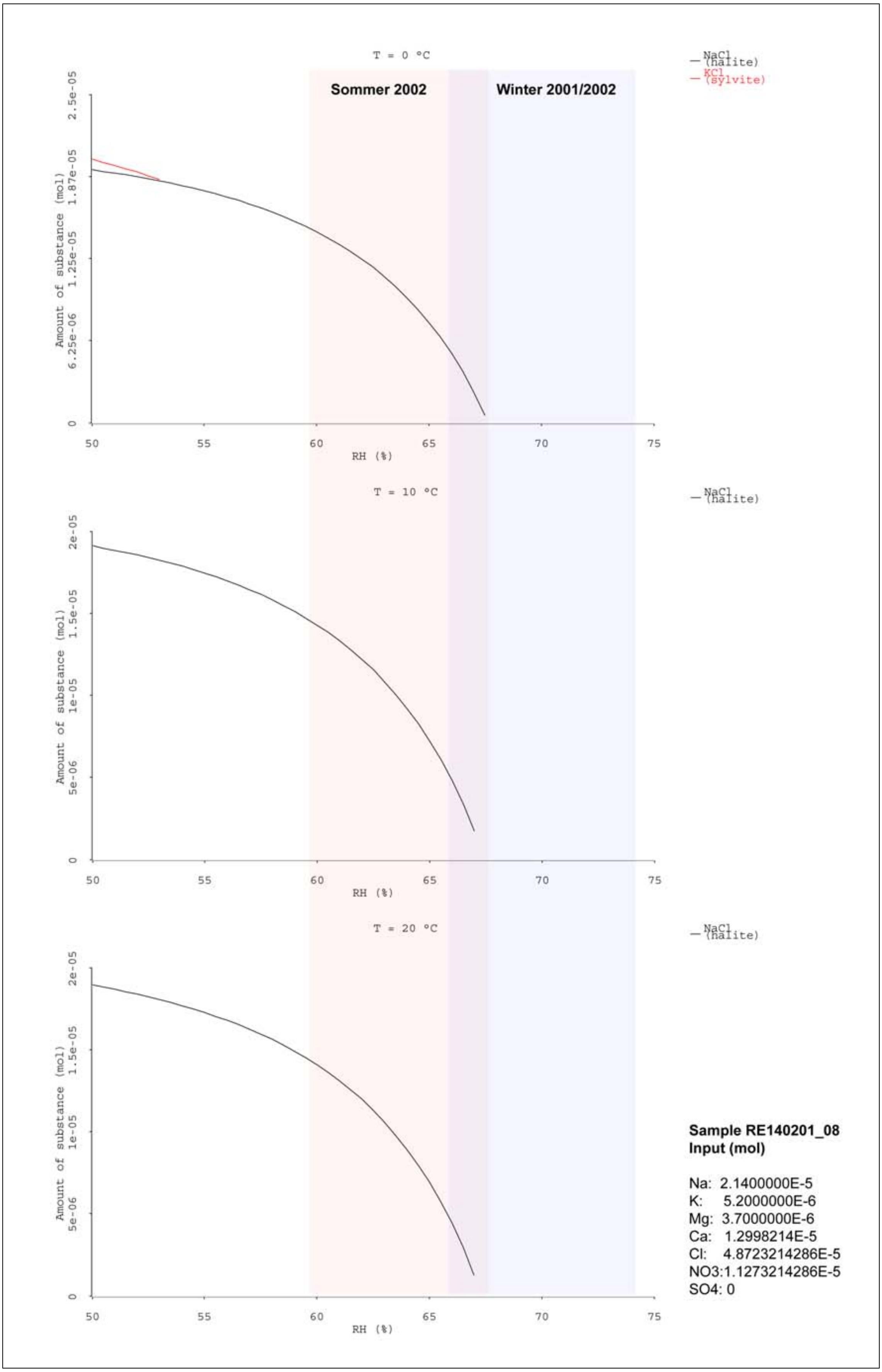
Location of samples taken in 2002

Appendix 3: Computer modelling of salt crystallisation




T = 0 °C
Sommer 2002
Winter 2001/2002
NaNO3 (nitratine)
NaCl (halite)
KNO3 (niter)
Volume (cm3)
RH (%)
T = 10 °C
NaCl (halite)
NaNO3 (nitratine)
KNO3 (niter)
Volume (cm3)
RH (%)
T = 20 °C
NaCl (halite)
NaNO3 (nitratine)
KNO3 (niter)
Volume (cm3)
RH (%)
Sample RE140201_07
Input (mol):
Na: 3.2180000E-4
K: 1.9000000E-5
Mg: 1.0600000E-5
Ca: 3.1280822E-6
Cl: 1.6044452055E-4
NO3: 2.0781164384E-4
SO4: 0


T = 0 °C
Sommer 2002
Winter 2001/2002
NaCl (halite)
KNO3 (niter)
MgSO4.6H2O (hexahydrite)
Volume (cm3)
0
0.00025
0.0005
0.00075
0.001
50
55
60
65
70
75
RH (%)
T = 10 °C
NaCl (halite)
KNO3 (niter)
MgSO4.6H2O (hexahydrite)
MgSO4.4H2O (starkeyite)
Volume (cm3)
RH (%)
T = 20 °C
NaCl (halite)
KNO3 (niter)
MgSO4.4H2O (starkeyite)
Volume (cm3)
RH (%)
Sample RE140201_08
Input (mol):
Na: 2.1400000E-5
K: 5.2000000E-6
Mg: 3.7000000E-6
Ca: 0
Cl: 2.5803571429E-5
NO3: 5.9702380952E-6
SO4: 1.1130952381E-6


T = 0 °C
Sommer 2002
Winter 2001/2002
NaCl (halite)
KCl (sylvite)
Amount of substance (mol)
0
6.25e-06
1.25e-05
1.87e-05
2.5e-05
50
55
60
65
70
75
RH (%)
T = 10 °C
NaCl (halite)
Amount of substance (mol)
0
5e-06
1e-05
1.5e-05
2e-05
50
55
60
65
70
75
RH (%)
T = 20 °C
NaCl (halite)
Amount of substance (mol)
0
5e-06
1e-05
1.5e-05
2e-05
50
55
60
65
70
75
RH (%)
Sample RE140201_08
Input (mol)
Na: 2.1400000E-5
K: 5.2000000E-6
Mg: 3.7000000E-6
Ca: 1.2998214E-5
Cl: 4.8723214286E-5
NO3:1.1273214286E-5
SO4: 0