Environ Geol (2007) 52:353–367
DOI 10.1007/s00254-006-0463-2

ORIGINAL ARTICLE

Long-term monitoring of wall paintings affected by soluble salts

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Received: 18 June 2006 / Accepted: 7 August 2006 / Published online: 16 November 2006

Abstract Long-term monitoring of wall paintings in historical monuments aims at clarifying involved decay processes and at the same time controlling effects of interventions for conservation. Monitored decay processes relate to the crystallisation of various salts – particularly of nitronatrite and gypsum – from hygroscopic solutions accumulated in the zone of ground moisture. The salts crystallise in response to climatic variations and other environmental changes. Measures for conservation such as protection from water infiltration, reduction of heating temperature and reduction of surface salt accumulation cause a significant slow-down but not a stop of decay. The particular dynamics and causes of remaining slow decay processes are described on three sites in Switzerland: the convent church of Müstair, the crypt in the cathedral of Basel and the crypt in the Grossmünster church of Zürich.

Keywords Wall paintings · Salt crystallisation · Indoor climate · Long-term monitoring · Conservation

Introduction

Wall paintings are delicate coatings of walls and at the same time most valuable parts of historical buildings. Stresses affecting the wall will normally first affect its painted surface. Paintings transmit a message or decorate a space but they also act as a temporary protection of the underlying building material. Paintings were overpainted according to changing fashion or in order to renew their protective function. Today, historical paintings are considered as unique values and hence protected as they are. This evokes new demands for their conservation. Risks have to be faced and deterioration processes reduced as much as possible. The basic question at the beginning of this study was: how does salt weathering affect wall paintings? Knowing the answer is essential for knowing how deterioration can be slowed down. First answers to these questions, and actions taken since more than 20 years ago, caused new questions. By continuous monitoring and step by step, it was recognised that salt activities change in the long term. *How* they changed was at times unexpected. Questions to be dealt with in this paper are as follows:

- How are "slowly" deteriorating wall paintings monitored in the long run?
- How do salt crystallisation activities on wall paintings change in the long run?
- Which are the specific causes of monitored changes?
- What is a realistic perspective for long-term conservation of wall paintings?

This paper is based on and continues earlier results given by Arnold and Zehnder (1991). The first section deals with methodology focussing on fieldwork. Though there is more time spent in the laboratory with analyses etc., and even more with compiling and evaluating acquired data, fieldwork remains the essential part of monitoring. In the next section, case studies are presented where deterioration processes have been monitored during several years, e.g., in Müstair from 1982 to 2005. All examples are in the

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context of accelerated decay due to heating. The emphasis is on the results that show how and why damage processes changed during and after changing environmental conditions. The last section concludes with a practical outlook.

Methodology for monitoring wall paintings affected by salts

Investigations of deterioration processes on wall paintings have been done in various ways and with different purposes. Monitoring of weathering is particular and an intricate subject, because phenomena are blurry; they evolve slowly and usually look unimpressive. On the other hand, decay might happen abruptly and change unexpectedly. Long-term investigations are problematical as a matter of funding and of keeping the object accessible to scientific purposes. It does therefore not astonish that information giving concise results on deterioration processes on monuments and their effects in the long run are rare.

Though there is, in theory, a general consensus on how to monitor wall paintings, scientific literature shows that it is hard to apply in practice. Therefore it is advantageous to start with an aide-memoire (referring to Arnold 1997; Cather 2003a, b and others):

1. Collect information on topography, climate, and history etc. of the site and the local context of the object.
2. Recognise the wall painting in its architectural context. Identify its particular usage, its exposure to climate and other environmental factors.
3. Analyse the history of the painting in relation to its damage evolution and present condition.
4. Characterise the materials in their historical sequence (old compounds, later additions, products of restorations, etc.). Identify problematic interactions between old and new materials, and of materials in climatic response.
5. Redraw the scientific problem which may have changed since the beginning of investigations. Design a working hypothesis of apparently harmful processes to be monitored.
6. Carry out investigations not only to provide detailed data but also an overview of the damage situation as a whole. Diverse data from history, materials, salt analyses and environmental impacts must fit to the unique situation and help to understand what is going on there.
7. Verify or falsify provisional conclusions repeatedly on site. Draw a concept for conservation on the basis of thorough risk analysis. Discuss it with practitioners and those who know more in neighbouring disciplines.
8. Continue basic monitoring during and after interventions. React on significant changes in order to reduce damages and risks as much as possible or feasible.

When wall paintings affected by salts are monitored, the following specific methods and tools are indispensable:

Periodical visual inspection. This is done in a general way on the whole area affected. Raking light is preferable in order to detect efflorescence, loose particles and other peculiarities on the surface. On small but representative locations the processes are observed and monitored in detail. The width of such *reference fields* ranges from a few square centimetres to several decimetres according to the situation and particular needs. Overall and detailed information is complementary. The same holds for overview and detailed observation.

Documenting observed phenomena by mapping, text and photographs is self-evident. Nevertheless it remains the most challenging task despite increasingly skilful electronic tools. It is necessary to combine a sense for the whole and an ability to discern important from unimportant things with consistency in details and in the long term.

Samples of salt efflorescence are taken with various instruments: A soft brush (for watercolour painting) serves to collect loose deposits; a scalpel is needed to detach hard crusts. Experience proves that the more specific and pure a sampled material is, the easier it will be to analyse and to interpret the result. Therefore it is preferable to take small samples but from various locations than one from a mixed compound. This does not automatically mean more analytical work—as a series of samples can be treated more efficiently—but definitely clearer results. Dissolved salts in the form of droplets are sampled with tiny strips of blotting paper. In order to detect cyclic crystallisation, it is compulsory to collect samples on representative areas (e.g. on reference fields) and in appropriate time intervals. Samples are investigated first under the binocular, secondly with a polarising microscope and by chemical analyses. Binocular examination is necessary to survey the sample, to assess its composition, morphologies of salt efflorescence etc. and to separate particles that will be microscopically and chemically analysed. Samples can be weighed in order to evaluate qualitative and quantitative decay rates. The net weight of a sample is accurately determined down to a few milligrams if the empty bag is weighed before sampling. Only on a brushed and ‘‘clean’’ reference field it will be possible to distinguish a new growth of efflorescence from an earlier deposit. A detailed tutorial of sampling and analysing salt efflorescence is given by Bläuer Böhm (1994).

Climate (commonly temperature and humidity) is monitored on the basis of a climatic survey and according to the particular questions. The location of measuring instruments (data loggers) should of course be representative for the considered processes. A general rule holds also for climatic monitoring: make it as complex as necessary but as simple as possible.

In order to monitor a damage evolution over the years, a specific methodology should be consistently used from the beginning up to the end. This means first of all to observe and to document precisely. As memory is short and subjective, documentation is all that remains in the long run. Photographs have to be taken with high resolution (phenomena are very small!), of the same area, from the same point of view, with a similar illumination etc. The visual aspect of efflorescence may also change according to natural light and climatic conditions. Observations are greatly influenced by these variables. So much the worse there is a considerable risk that monitored processes stop on a reference field where they have been photographed but develop or continue just a few centimeters aside where no photographs had been taken. Such unpredictable behaviour of weathering in the micro scale can only be coped by an appropriate density of reference areas.

Another difficulty arises by the need of adapting to new aspects that become visible or increasingly significant. Consistent long-term monitoring restrains the liberty of changing previous and inventing new distinction criteria. System breaks of documentation must and can be avoided even in a continuously changing situation. The means is to recognise changes, to characterise them clearly and to link them to earlier stages of the same evolution. Last but not the least, change is also a subjective process. A situation looks different with time due to increasingly sharpened eyes. On the other hand, observers become indifferent and not alert when repeatedly faced to an unchanged visual aspect. Such problems were also encountered in the following case studies, though the focus will be on results.

Case studies

Damage evolution on wall paintings in the convent church of Müstair

The Carolingian and Romanesque wall paintings in the convent church of Müstair (Switzerland) are part of a UNESCO World Heritage site (Fig. 1). They have gained particular attention for conservation and care. The paintings date from about 800 and 1200, respectively. They were overpainted in 1609/25 and in 1878/79 and re-discovered in 1894 (historical data according to Goll and Emmenegger 2002). No information is available on the state of conservation when they were re-discovered. From their history, it can be induced that they suffered at least two fires (about 1080 and

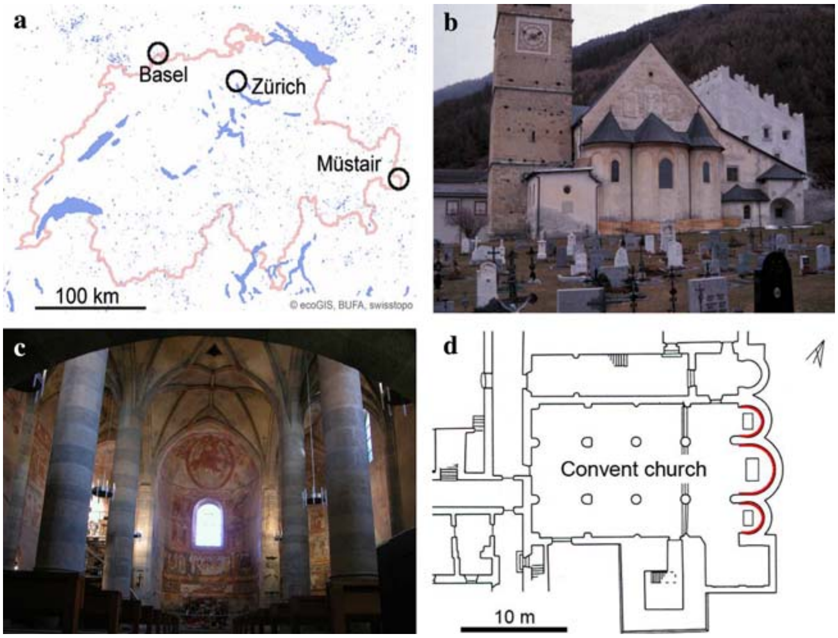


Fig. 1 **a** Map of Switzerland showing the location of studied sites. **b** Convent church of Müstair viewed from the east. The photograph was taken in wintertime, when wooden planks were mounted at the base of the walls of the three apses to protect them from water infiltrations by melting snow. **c** Interior of the church towards the east with the middle apse in the centre. The north and south apses are behind gothic pillars. **d** Ground plan of the church. The position of investigated paintings is marked in *red*

1500), crude constructional interventions by apertures of windows in a post-gothic period and in the nineteenth century, and the removal of overpaints. The fact that the Carolingian paintings are well preserved except for the zone of less than 1 m above floor level is impressionable. It suggests that among other things weathering conditions were generally favourable. The superimposed Romanesque painting may have behaved as a protective coating during many centuries.

The conservation history is briefly as follows: 1947/51 they were restored with the best technical skills and practices of that time. A drainage trench was constructed. The shingle roof was replaced by a copper roof with gargoyles. As an unexpected consequence, water wetted the walls in constricted areas more than before. More snow slipped from the roofs, accumulated and melted at the base of the walls. An electrical heating was installed in the formerly unheated church. New materials such as cement and gypsum mortars were used to repair lime plasters. Water glass was applied to consolidate the fresco paintings. Convinced of having done the necessary to prevent further damage to the precious paintings, another period of neglect followed. New damages were noticed in the 1960s. A poorly adhering partition of Romanesque paintings had to be detached. It was pushed off by nequehonite crusts which formed by reaction of water glass with magnesium ions in the salt solution of the wall (Arnold 1981). Excessive moisture combined with increased salt efflorescence initiated investigations and corrective interventions. They started in 1973 and lasted until 1990.

Such pattern of conservation history is typical for many medieval wall paintings in Switzerland and elsewhere in the twentieth century (e.g. Exner and Schädler-Saub 2002, Gowing and Heritage 2003). It is characterised by the following stages: (1) First-time exhaustive restoration involves profound constructional, material and climatic changes. New materials and technologies are added to, and old materials interfered with. (2) Assuming to have completed a long-lasting amelioration, another time of neglect follows. (3) New damages reveal deficiencies, errors and unexpected effects of the restoration. (4) The paintings are re-restored and corrective interventions undertaken.

First corrections at the convent church of Müstair were: to replace gargoyles by downpipes; to clean and adjust the drainage trench; to mount wooden planks at the base of the walls in wintertime in order to keep melting snow off (Fig. 1b). The heating which was disclosed to provoke intense salt damage was reduced and finally removed in 1988. The salts were wiped off and extracted with wet blotting paper and cellulose poultices from 1982 to 1986. Repairs and consolidation of the paintings have been carried out by conservators. For example, they replaced gypsum mortars by lime mortars as gypsum mortars were found to damage the paintings by swelling.

Interventions were a result of careful investigations. Monitoring started with a baseline assessment in 1982. It aimed at finding the causes of ongoing damages and at controlling the effects of interventions taken. The monitoring measures chosen were simple and sophisticated at the same time. They consisted of: (1) periodical visual inspections of salt efflorescence (about three visits per year); (2) periodical sampling and analyses of salts; and (3) continued climatic monitoring. The consistency of the measures was stressed rather than the sophistication of applied instruments. The findings were regularly communicated and discussed with concerned persons (architect, monuments conservation official, conservators and nuns).

The following decay processes have been detected and monitored (based on Arnold and Zehnder 1991; Arnold et al. 1991):

1. *Efflorescence of epsomite* ($MgSO_4 \cdot 7H_2O$) *and nitrokalite* (KNO_3) at the base of the wall (the so-called zone B, Fig. 2) stopped after improvements of the draining system. In 1982, the walls obviously had dried out in this zone, so epsomite and nitrokalite were no more active (Fig. 3).

2. *Efflorescence of nitronatrite* ($NaNO_3$) was very active in an upper zone of ground moisture (zone C, see Fig. 2) during dry periods in wintertime until 1988. This was a consequence of heating. It caused seasonal humidity variations which were undoubtedly stronger than ever before in this church. Intense periodical efflorescence of hygroscopic salts such as nitronatrite and even nitromagnesite was a most damage-resulting process. After cutting off the heating, seasonal humidity cycles smoothened, so that nitronatrite and nitromagnesite efflorescence was prevented. Figure 4 documents the climatic evolution from 1985 to 2005 and the significant changes before and after 1989. Reduction of salt content by cellulose poultices probably contributed to a reduced efflorescence from 1982 to 1986. However, this effect is considered to be subsidiary. Examples of seasonal crystallisation are shown in Figs. 5a, b and 6b, c.

3. *Efflorescence of nitrokalite* (KNO_3) formed together with nitronatrite in the same areas (zone C) but to a minor extent. From 1989, when nitronatrite was no more active in the unheated church, nitrokalite continued to effloresce in wintertime. This is explained by the decreasing solubility of nitrokalite at low temperature. The affected area was reduced to a few percents

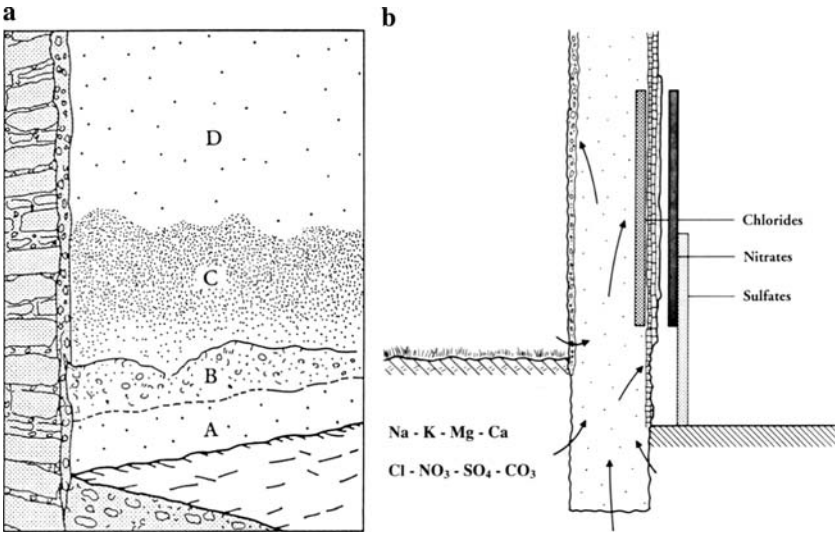


Fig. 2 Zones observed on a wall in the area of rising damp (**a**) and related model of salt accumulation (**b**) after Arnold 1982 and Arnold and Zehnder (1991). **a** *Zone A* just above ground level shows less damage than *zone B*. In *zone B*, most damages (granualar disaggregation, crumbling, scaling, etc.) and most salt efflorescences (mainly of sodium sulphate, magnesium sulphate, calcium sulphate, potassium nitrate and sodium carbonate) appear. *Zone C* generally appears dark and damp with less or no physical damage. It is particularly well developed on stables, churches and other historic buildings. **b** Model of the evolution of salt systems in a wall in the zone of ground of moisture. From a mixture of ions originating from different environmental sources (Na–K–Mg–Ca and Cl–NO$_3$–SO$_4$–CO$_3$) salts are precipitated from the evaporating solution in the following sequence. The less soluble compounds are precipitated first (e.g. calcium and magnesium carbonates, corresponding to *zone A*). Then, a group of moderately soluble and poorly hygroscopic salts is accumulated and precipitated (particularly sulphates and potassium nitrate, corresponding to *zone B*). It is followed by a remaining fraction of most soluble and hygroscopic salts which is normally dissolved (e.g. magnesium and calcium chlorides and nitrates, corresponding to *zone C*)

(less than 1 m^2 in total) of the former extent. An example is shown in Fig. 5d. Monitoring showed that the exact outlines of efflorescence changed during one crystallisation cycle as well as from one cycle to the next. For instance, the seasonal efflorescence started in December from a central location within a larger area that was normally affected. Then it spread more or less concentrically sideward during January and February, as air and wall temperatures decreased. In cold winter seasons (e.g. 1998/99), nitrokalite efflorescence was significantly stronger as compared to mild winter seasons. Such observations gave insights into the reaction of nitrokalite to environmental conditions, in particular to temperature changes. However, the precise distribution and chemical composition of accumulated salt solutions and their interactions with environmental conditions remain still unknown. In the last 5 years, a slight increase in nitrokalite efflorescence has been observed. Open questions are if- and why this trend continues. Is it due to a long-term re-distribution of solutions after wet salt extractions? Are there other changes in the wall and its environment?

4. *Efflorescence of gypsum* ($CaSO_4 \cdot 2H_2O$) was noticed first in 1982 after salt extraction with wet blotting paper. In the following years, gypsum veils and a related powdery decay of the paint surface increased until about 1990. At that time, the affected area roughly reached the outlines of nitronatrite efflorescence from 1982, as it can be seen in Fig. 5b, c (compare with Fig. 3). After 1990, gypsum veils have recessed again. Figure 7b, c shows one variety of observed gypsum efflorescence. Weighing of efflorescence samples showed that gypsum crystallises much slower and in smaller amounts than more soluble nitronatrite. Also, the amount of crystallised matter roughly correlates with the material loss it causes (Table 1). It is supposed but not yet established that gypsum efflorescence vanishes by partial recrystallisation, dissolution, falling off and occasionally by mechanical removal. Major problems with observing and documenting gypsum efflorescence were its inconspicuousness and the impression that its aspect changed inconsistently from season to season. This is attributed to varied natural illumination and possibly varied surface moisture rather than to changed properties of the efflorescence itself. The phenomenon of gypsum efflorescence from hygroscopic solutions in the upper zone of ground moisture has been described earlier (Zehnder 1993, 1996). However, it is not yet properly understood and remains a subject for further research.

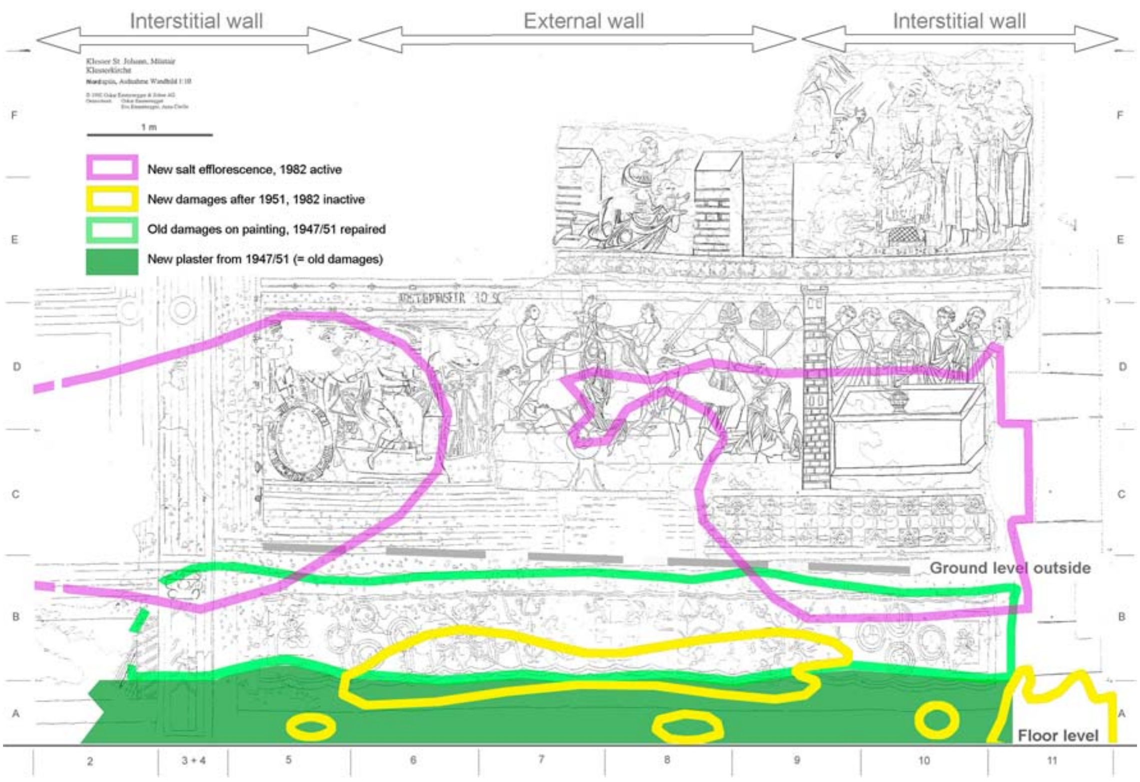


Fig. 3 Map of the paintings in the north apse of the convent church of Müstair (drawing by Oskar Emmenegger). A grid of 1-m^2 fields with co-ordinates marked at the margins provides orientation for sampling and monitoring purposes. Damages observed in 1982 are situated on different zones and are attributed to different periods of formation. Old and at the time no more active damages (*green* and *yellow*) are associated with efflorescence of epsomite and nitrokalite. New and active damages (*purple*) are associated to nitronatrite and nitrokalite efflorescence. The location of old damages corresponds to *zone B*, new damages to *zone C* in Fig. 2. It is interesting to note that old damages have formed in an approximately horizontal strip, whereas new damages concentrate on interstitial walls (compare Fig. 1d). Analogous patterns are observed in the middle and south apse. An explanation of this distribution could be as follows: In the lowest zone salts are activated and transported during periods of rain and melting snow. Accumulation of epsomite and nitrokalite in this zone represents a moisture distribution during "wet" phases. In contrast, hygroscopic salt mixtures are activated and mobile during wet and dry periods. They are accumulated on recessed zones which remain longest cool and damp

5. *Deficiencies of the drainage system* combined with icing gutters in the harsh winter of 1990/91 caused water leakage and infiltrations with subsequent damages within the next two years. Efflorescence of nitrokalite and epsomite developed also on paintings. Such an event highlights that failure is not entirely excluded even on well-maintained buildings. Traces of earlier water infiltrations have been noticed on various locations.

Figure 8 is a graphical attempt to visualise the intensity and duration of different salt damage processes which affected the paintings in the convent church of Müstair. Decay was reduced considerably, but it has continued and probably will do so in future. In the long run, salt damage is not the only threat to the paintings. A progressive detachment of the Romanesque from the Carolingian paintings (Arnold 2002; Emmenegger 2002) and fungal growth on the retouchings from 1951 (Raschle 2002) are further problems for conservation. They all require continued monitoring and coordinated actions.

Damage evolution on stones and wall paintings in the crypt of the cathedral in Basel

The Romanesque crypt in the cathedral of Basel dates from 1019 (Fig. 9). Building materials are two varieties of Triassic sandstones. Walls were originally painted. The crypt was for the first time extensively modified after its partial destruction during the earthquake in 1356. New vaults were painted on limewash. In post-medieval times various inscriptions were added. An overall restoration of the cathedral with profound constructional changes was performed in 1857. A heating was installed in 1890, with a newly excavated central heating room under the crypt and the coal

Fig. 4 Damage evolution on a section of the north apse in the convent church of Müstair, exemplified by four stages from 1983 to 2004. **a** Illustrates a seasonal cycle of nitronatrite efflorescence during the heating period of 1982/83. It started in the centre of an area that was affected by this salt earlier (Fig. 3), then it spread and retreated with irregular outlines. **b** In 1986, gypsum efflorescence developed associated with powdery decay of the paint surface. At the same time, nitronatrite efflorescence was reduced as a consequence of reduced heating temperature and salt extractions. **c** Ten years later, the area of powdery decay had spread, and spots of white dots of gypsum efflorescence had developed. No nitronatrite efflorescence was observed when the air humidity remained over 60% RH (Fig. 4). **d** In 20003/04, powdery decay has ceased and white dots of gypsum efflorescence largely disappeared. Nitrokalite efflorescence continued to appear on much reduced spots in wintertime

stockyard in the crypt. In the 1960s, an old exterior crypt to the east was excavated and integrated in a construction of concrete. In 1973, the crypt has been restored to its actual form. The hot-air heating in the cathedral was exchanged by a floor-heating powered by district heat. Archaeological excavations on the outside of the crypt established that its foundation walls were covered by adobe. It aimed at protecting the founda-

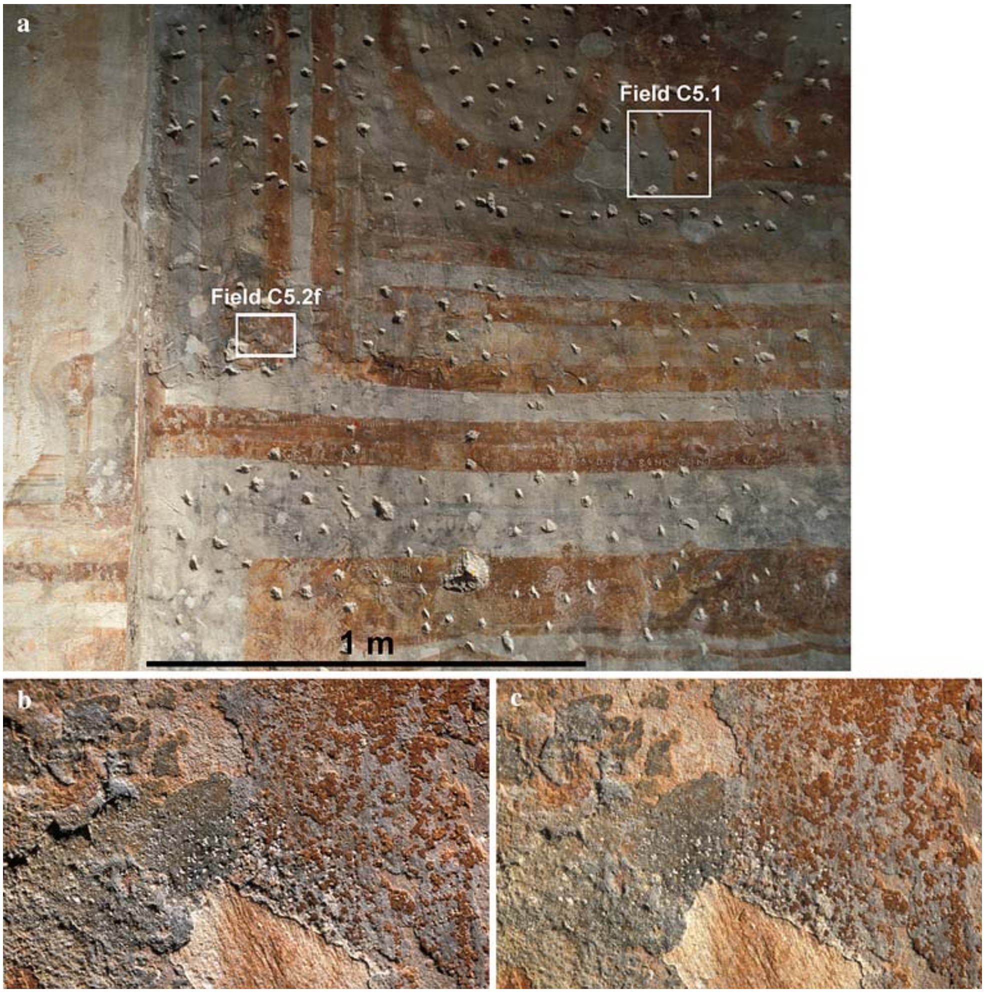


Fig. 5 Section of the Carolingian paintings in the north apse of the convent church of Müstair. **a** Overview of reference area C5 (21 January 1998). **b** Field C5.2f on 30 September 1994, showing an assemblage of white dots of gypsum efflorescence. The dots are 0.1–0.5 mm in diameter (width of image 5 cm). **c** The same detail on 21 January 1998 showing diminished efflorescence of gypsum. Some of the dots have disappeared, and others have persisted unchanged

tions from excessive ground moisture and assumedly dates from the nineteenth century.

Very scarce information is available on the condition of paintings and stone surfaces in 1973. This lack of documentation is contrasting with the painstakingness of restoration and conservation works that were carried out. After restoration, the crypt remained in a largely uncontrolled condition until 1991. The perception of dramatic decay associated with salt efflorescence provoked investigations, remedial interventions and monitoring of their effects. Investigations started in 1992 by a comprehensive damage assessment. An area of about 60 m^2 on external walls was affected by new damages (Fig. 10). This area is influenced by ground moisture. Figure 10 shows that new damage was partly superimposed to old damage from a period earlier than 1973.

Interventions started in 1993 by separating the crypt from the heated nave with a wooden barricade in wintertime. The objective was to keep humidity above 60% in the crypt and thus to prevent cyclical salt crystallisation (see below). However, the effect of this first measure was feeble (Fig. 11). Openings that let warm air into the crypt were detected later on and closed in 1997. These ‘‘passive’’ interventions caused a significant reduction of decay rates. In order to reduce salt crystallisation even more, a humidifier was installed in 2004. Due to suboptimal operation, it maintained the air humidity the first winter period at an undesiredly high level of about 70% RH (Fig. 11). That proves how delicate even simple measures can turn out in practice. The following works were carried out by conservators of the cathedral’s workshop. Restoration mortars contaminated by salts were replaced by salt-free lime mortars. Small defects on mortars, stones and paintings were repaired and consolidated. New efflorescence on stones was removed (hoovered) every year in spring. Surface salt accumulations were reduced by wet cellulose poultices in 1994–1996 (Fig. 10).

Monitoring of the damage evolution was performed by the workshop since 1993. At the beginning, it

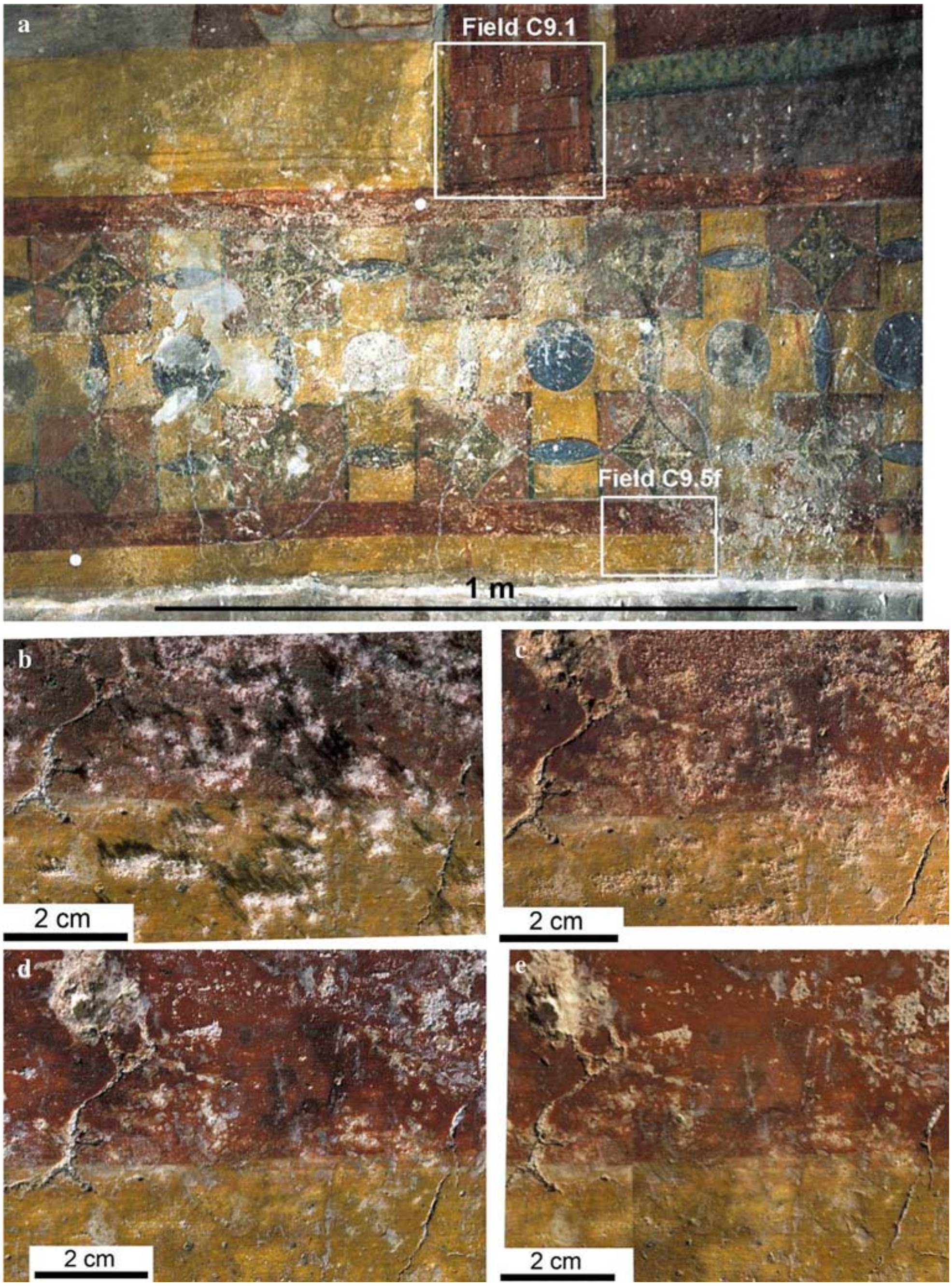


Fig. 6 Section of the Romanesque paintings in the north apse of the convent church of Müstair. **a** Overview on reference field C9 (7 April 1982). **b** Field C9.5f on 7 May 1982, showing fluffy efflorescence of nitronatrite. Clusters of salt crystals concentrate on lacunaes in the paint layer and on areas where the paint layer is reduced. **c** On 19 January 1984, new efflorescence of nitronatrite has formed within one month after wiping off efflorescence like the one in (**b**). **d** On 27 February 1992, a veil of gypsum efflorescence on the upper and upper right part of the reference area has formed. **e** On 21 January 1998, gypsum efflorescence has disappeared

consisted of two visual inspections per year: one in February/March assessed the main salt activity in wintertime, one in August the situation when ambient temperature and humidity were at the highest level of the year. After 1998, inspections were done only once a year in wintertime. They were accompanied by scientific investigations, particularly observing, sampling and analysing of salt efflorescence. The climatic evolution was monitored by means of mechanical thermohygrographs operated by the workshop. Results of visual inspections, scientific investigations and climatic evolution were evaluated, communicated and discussed in order to optimise actions for conservation.

The following salt species and related decay processes have been identified:

1. *Nitronatrite* ($NaNO_3$) and *halite* ($NaCl$) were the prevailing salts within the whole area of active decay in 1992. They caused the largest part of new damages. As for the case of Müstair, they crystallised during dry periods in wintertime as a consequence of heating (Fig. 11). Since 1997, nitronatrite and halite crystallisation has been reduced to a total area of about 15%

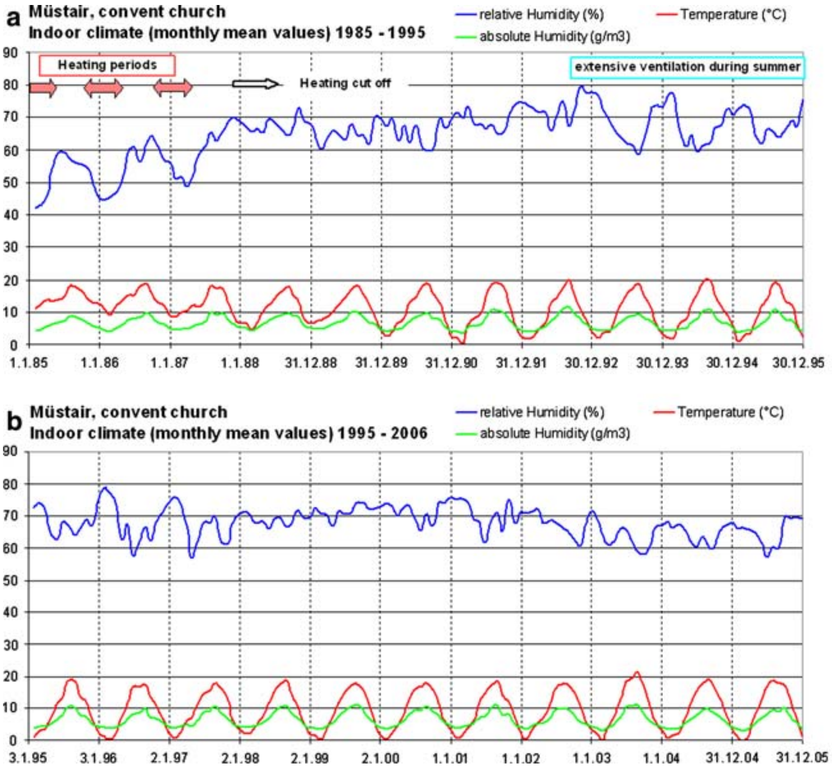


Fig. 7 Evolution of indoor climate (monthly mean values) in the convent church of Müstair from 1985 to 1995 (**a**) and from 1995 to 2005 (**b**). Air humidity was very low in wintertime from 1985 to 1987 due to heating, and relatively low in summertime (e.g. 1993 and 1994) due to long openings of the door when the weather was dry. The temperature variations from 1985 to 1989 reflect the gradually reduced heating temperature in the church. Apart from seasonal variations, air humidity varies irregularly in response to weather changes

Table 1 Decay associated to salt efflorescence on wall paintings in the convent church of Müstair (compilation of results from weighings and analyses of samples)

Weight of salt efflorescence	Composition and estimated portion of sample[a]			Weight of material loss
	Crystallised salt	Paint and/or mortar	Accessories (dust etc.)	
Nitronatrite and nitrokalite efflorescence: 1–100 (g/m^2) accumulated within one crystallisation cycle (i.e. some months)	70 to >90	<10–30	<<10	0.1–10 (g/m^2) within 1 year
Gypsum efflorescence: 0.1–10 (g/m^2) accumulated within several years	30–70	30–50	20–40	0.05–0.1 (g/m^2) within some years

[a] Estimation in percent of volume by visual examination under binocular and microscope

compared with the initial extent. This is mainly due to the changed climatic conditions but also due to surficial salt reductions.

2. *Epsomite* ($MgSO_4 \cdot 7H_2O$) *and nitrokalite* (KNO_3) were present in 1992 on a wide area but in a rather spotty distribution. They seem to be partially stable (as crusts), while they crystallise periodically in other parts (in the form of whiskers and fluffy efflorescence) mainly in wintertime and probably as a consequence of cooling. A gradual spreading and new affected areas have been noted since about 1998. The particular reaction of epsomite and nitrokalite to climatic and other environmental impacts is still not clearly elucidated in this site. This is due to scarce and rather inaccurate observations, and also to insufficient monitoring of all relevant environmental conditions. Climatic monitoring should in this case be complemented by monitoring of moisture changes inside the wall—which is in fact not trivial.

3. *Natrite* ($Na_2CO_3 \cdot 10H_2O$), *thermonatrite* ($Na_2CO_3 \cdot H_2O$), *mirabilite* ($Na_2SO_4 \cdot 10H_2O$) *and thenardite* (Na_2SO_4) are associated to cement mortar repairs. As for epsomite and nitrokalite, natrite and mirabilite crystallise in some places in wintertime (probably as a consequence of cooling) and recrystallise or dehydrate later on. In other places they seem to

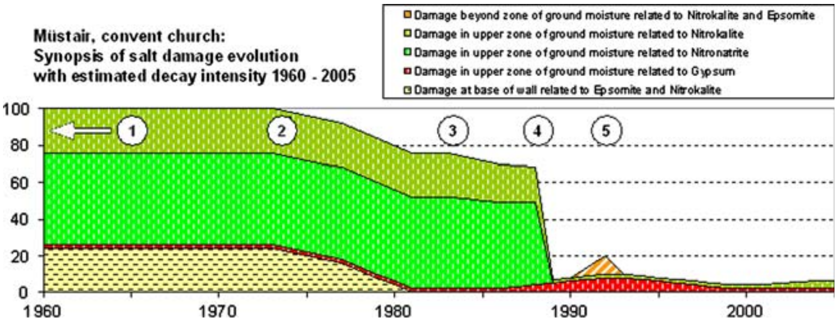
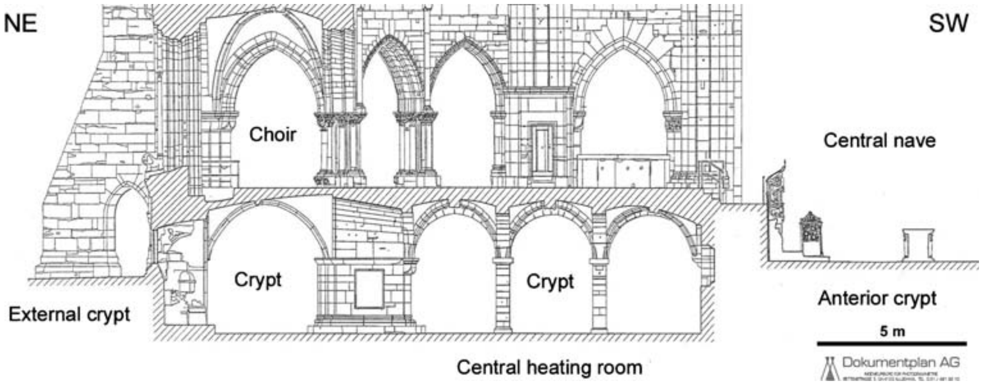


Fig. 8 Salt damage evolution in the convent church of Müstair. Numbers *1–5* indicate the following events which provoked major changes: *1* Restoration of 1947/50 caused new damages due to inappropriate constructions and the heating. *2* Corrections of the drainage system began in 1973 and continued until 1980 when the walls were protected from melting snow (Fig. 1b). *3* Surface salt reductions by dry removal of efflorescence and wet cellulose poultices were carried out from 1982 to 1986. Gradual reduction of heating temperature began in 1985. *4* Heating was cut off in the church in 1988. *5* In 1991, water infiltrated due to defects and icing of gutters

Fig. 9 Longitudinal section of the crypt in the cathedral of Basel



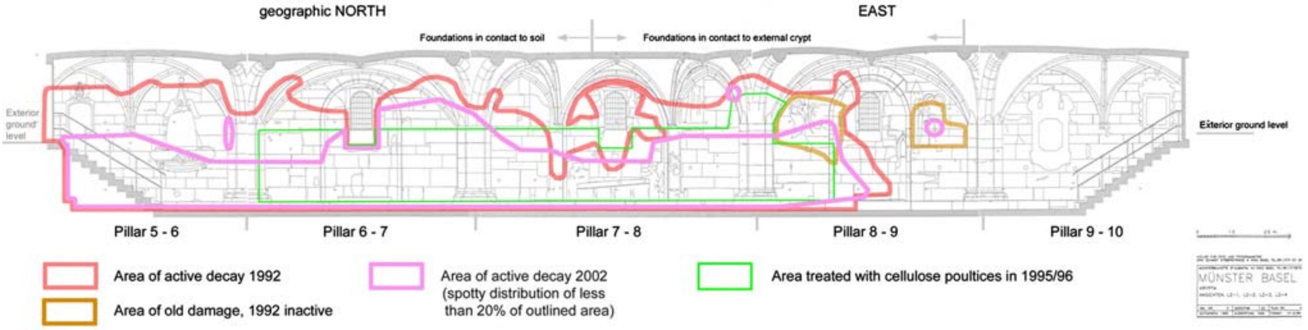


Fig. 10 True length projection of exterior walls of the crypt of the cathedral of Basel. Outlines of damages observed in 1992 (*red* and *brown*) and in 2002 (*pink*) as well as the area treated by cellulose poultices in 1995/96 (*green*) are shown

be stable (in the form of crusts). Thermonatrite and thenardite are apparently stable; i.e. no signs of hydration have been observed. Therefore, it is assumed that dehydrated salts originally crystallised by their hydrated phases.

4. *Gypsum* ($CaSO_4 \cdot 2H_2O$) is present in various forms: (1) Old and stable crusts are blackened by soot particles dating from the coal heating period. (2) Younger gypsum crusts containing no soot particles are almost stable as well. However, long-term monitoring has revealed that they are—at least partly—in a very slow progress. Painted surface and gypsum crusts expand to bulges and open up by a process that is schematically drawn in Fig. 12b. Fragments of paintings and crusts are breaking off from time to time. (3) Gypsum veils and tiny white dots are associated with

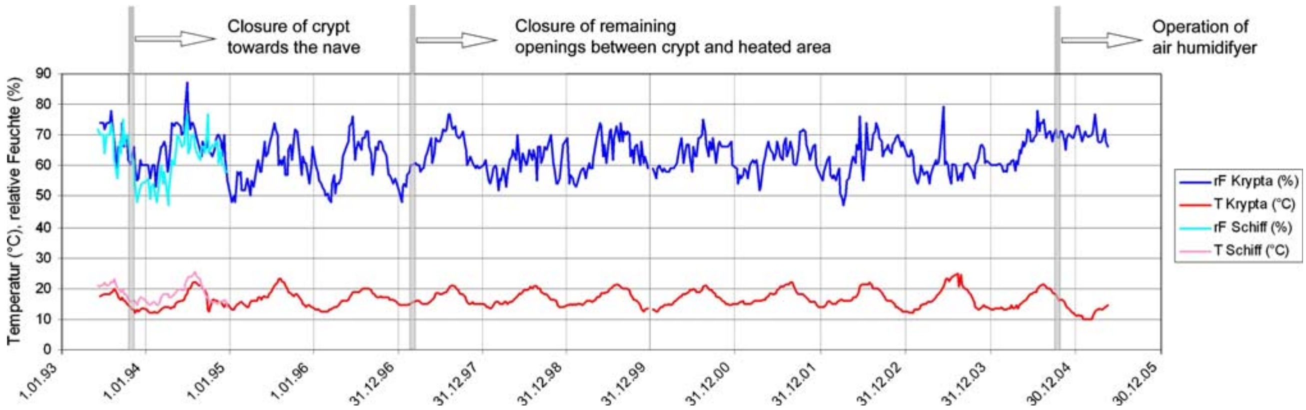


Fig. 11 Evolution of indoor climate in the crypt of the cathedral of Basel from 1993 to 2005 (weekly mean values). The climatic difference between actively heated nave and passively heated crypt is illustrated for the period 1993/94. Until 1997, air humidity dropped to values of about 50% RH in wintertime. Seasonal variations smoothened but not sufficiently from 1997 to 2004. In winter 2004/05, a humidifier was installed so that air humidity was kept at a high level. Apart from seasonal variations, air humidity varies irregularly in response to weather changes and uncontrolled ventilation

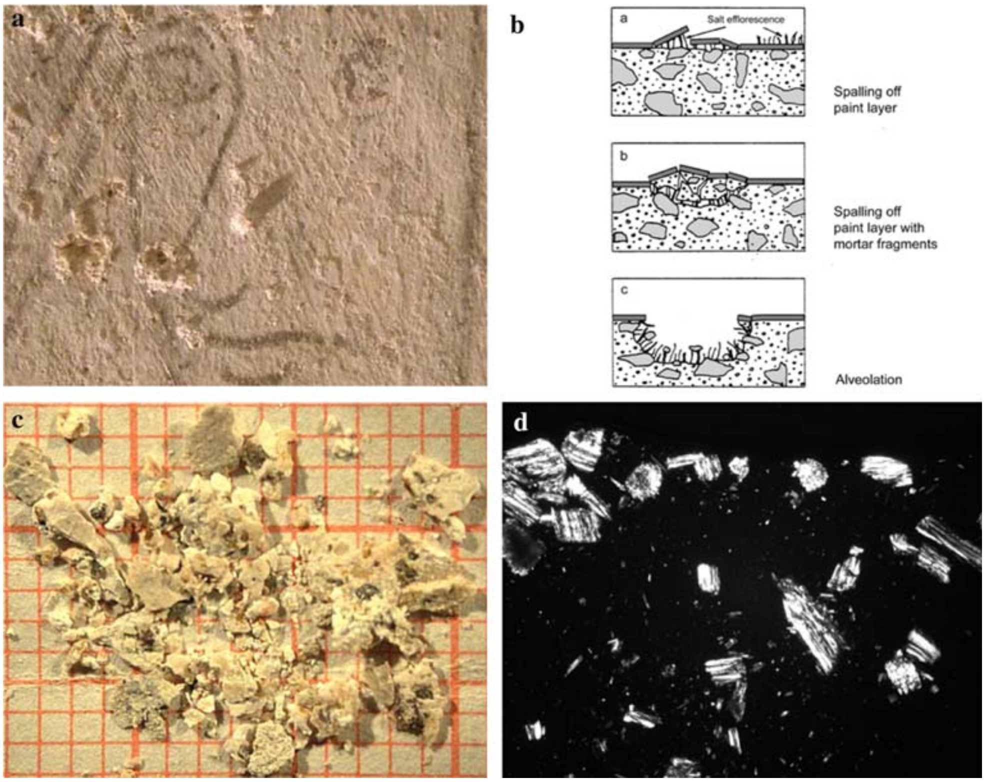


Fig. 12 Examples of decay caused by crystallisation of gypsum on wall paintings in the crypt of the Grossmünster church in Zürich. **a** Detail of the painting (grisaille technique on limewash) showing new alveoles in the lower left sector and pustules of gypsum in the centre in February 2003, width of image is 5 cm; light is from lower left. **b** Schematical drawing of decay process (after Zehnder et al. 1986). **c** Fragments of limewash and the supporting mortar collected with a soft brush on a reference field of 15 × 15 cm^2. The sample weighs 40 mg and the particles from the surface correspond to an area of 0.5–1 cm^2. **d** Microscopical aspect of gypsum efflorescence from a pustule showing fibrous aggregates of 100–300 μm in length; crossed polarisers, width of image 2 mm

powdery decay of stone and painted surface. This process is slowly active as well. (4) Gypsum has been admixed to nitronatrite and halite efflorescence (by a ratio of approximately 1% or even less). Analogously to the case of Müstair and other sites, it is supposed that these salts crystallise at the same time from a solution that is saturated with respect to all of the crystallising salts.

The salt system and crystallisation processes in the crypt of the cathedral of Basel have revealed to be complicated. The ways how climatic variations and supposed external moisture sources interfere are still poorly understood. The chosen monitoring and conservation concept has been capable to verify and eliminate harmful effects of the heating. But it is inadequate to elucidate further deterioration processes that persist. This remains a subject of extended research.

Damage evolution on wall paintings in the crypt of the Grossmünster church in Zürich

The crypt dates from 1107. After a changeful history, it was restored to the actual form in 1913/15. Damage evolution was monitored from 1982 to 2003 with interruptions from 1998 to 2000. Continued observation of salt activities, analyses of salts and climatic monitoring have established that the new salt damage was mainly caused by heating (Zehnder et al. 1986). Nitronatrite and halite crystallised intensely during dry periods in wintertime. A planned draining of the north wall—which stays in contact with the soil—was abandoned because such an enormous intervention would have very little effect. Instead, the following corrective measures were undertaken since 1984. The heating temperature was reduced from 20 to 15°C in the nave. Doors were installed between the crypt and the nave and sources of heat transfer to the crypt eliminated in order to keep the crypt in wintertime as humid as possible by ‘‘passive’’ interventions. Salt-contaminated mortars and plasters were replaced by lime mortars. Surface accumulation of salts was reduced by continued dry removal of fresh efflorescence and with cellulose poultices in 1988/89. In 1994, damage by crystallisation of *nitronatrite* and *halite* was reduced to a few percents of its initial extent. This is considered an overall effect of the measures taken, but essentially because of reducing the heating temperature. Efflorescence of nitronatrite continued to occur sporadically when the air humidity dropped significantly below 60% RH for at least for a couple of days. Crystallisation of *gypsum* associated to slowly growing alveoles and detaching paint particles was first noticed in 1985 (Fig. 12). This decay process continued and was still active at the end of monitoring. In addition to salt damage, growth of microorganisms was accelerated in 1992 as a consequence of insufficient ventilation in summertime. In order to prevent crystallisation of nitronatrite entirely, it was suggested to operate a humidifier. This option has been rejected. It was argued that the effort of maintenance and monitoring was exaggerated in comparison to an expected further reduction of decay.

The difficulty on this object was to monitor slow and much dispersed decay by crystallisation of gypsum. It was not managed to document a phenomenon accurately that appears on a few square centimetres somewhere within an area of about 20 m^2. The location of new damages was of course not predictable; and most of detaching particles were too small to be individually detected. In addition, the photographic documentation of reference areas from 1982 was not updated after completion of interventions for conservation in 1994 because decay seemed to be stopped. This of course should have been done in order to distinguish new damages since 1994 from earlier damages. It demonstrates that it is almost impossible to pursue a process unless it is visualised in its particular dynamics.

Open questions and practical issues

The described cases have many common characteristics. Decay was accelerated after restorations and during inappropriate conditions (mainly heating); and it slowed down after corrective measures. It seems obvious that a ‘‘slow’’ decay existed since long. It probably was hidden by an intense decay when monitoring started and emerged again when the latter was stopped. The three cases also show that slow and inconspicuous damage processes are hard to recognise, to monitor and to elucidate. They pose a scientific, and in the long run a practical problem for conservation. The following deficiencies in understanding slow processes of salt weathering can be identified:

- What are the mechanisms and conditions of gypsum crystallisation from hygroscopic solutions in zone of ground moisture on historical buildings?
- Are there short-term crystallisation/dissolution cycles e.g. of nitronatrite, gypsum and other salts that have been overlooked as monitoring is not accurate enough?
- How are accumulated hygroscopic salt solutions composed and distributed? How do they change in short and long time periods? First results to this subject have been presented by Sawdy and Price (2005) and by Bionda (2006).
- How is the moisture distribution in the zone of accumulated hygroscopic solutions and the surrounding wall? How does it change in time and space?
- Resolution of these questions demands fieldwork and monitoring rather than research in the laboratory.
- Regarding the practical issue, certain slow decay processes have to be accepted. Such decay may rightly be characterised as minimal when all necessary and reasonable conservation measures have been carried out and a thorough maintenance is ensured. Dealing with risk management, the questions are: Which value does the object in risk have?

Which effort for conservation is it worthy of? Which are the remaining risks? More specifically, which extent of damage will presumably develop within 50 or 100 years at a given rate of decay? What kind of monitoring, maintenance and documentation does the object need? Maintenance of sensitive cultural heritage requires the involvement of qualified and responsible professionals (e.g. Feilden and Jokilehto 1998) and includes a higher level of monitoring. This is often ignored mainly because of management and funding problems. In the presented cases, an efficient (and inexpensive) care has still to be implemented.

Conclusion

Long-term monitoring of decay processes on wall paintings was carried out for two aims. The first is to detect and clarify decay processes; the second to control the effects of conservation measures. Reactions of buildings to structural and environmental changes are often slow and long lasting. This makes long-term monitoring necessary. In the presented cases, it was a key element of a larger set of investigations. It has been shown that it requires a precise knowledge not only of the damage situation in general but also of the specific processes to be monitored. It revealed detailed insights into the dynamics of salt crystallisation processes and of the architectural structure in change. Fast decay at the beginning changed into slow decay processes at the end of long-term monitoring. First interventions had drastic effects. In subsequent years, deterioration slowed down but did not stop.

Sustainable care of wall paintings and other sensitive monuments in situ implies in many cases accepting a minimal decay. Its kind and level should be identified in order to get a realistic long-term perspective. As a general conclusion, the needs (‘‘living conditions’’) of a monument should be balanced by the demands of its users. The monument is reactive, thus users have to adapt their activities. Sustainable care is invisible but not cost-free. That is one of the reasons why it is so difficult to be funded opposite to spectacular restoration and conservation. Its invaluable benefit is authenticity.

Acknowledgments I am grateful to Andreas Arnold who has initiated this work. Investigations on sites were co-financed by ‘Pro Kloster St. Johann Müstair’ foundation, ‘Basler Münsterbauhütte’ foundation and the canton of Zürich. Many thanks to Christine Bläuer Böhm and Per Storemyr for continued interest and support, discussions and reading the manuscript.

References

Arnold A (1981) Nature and reactions of saline minerals in walls. In: The conservation of stone II, reprints of the contributions to the international symposium. Bologna, pp 13–23

Arnold A (1982) Rising damp and saline minerals. In: 4th International congress on the deterioration and preservation of stone objects, Louisville, pp 11–28

Arnold A (1997) Weathering and preservation of stone monuments. Methods of interdisciplinary approach. In: La pietra dei monumenti in ambiente fisico e culturale. Atti del 2° Corso Intensivo Europeo tenuto a Ravello e a Firenze dal 10 al 24 aprile 1994, pp 9–19

Arnold A (2002) Nachhaltige. In: Die mittelalterlichen Wandmalereien im Kloster Müstair, vol 22. Veröffentlichungen des Instituts für Denkmalpflege an der ETH Zürich, vdf Hochschulverlag, Zürich, pp 141–150

Arnold A, Zehnder K (1991) Monitoring wall paintings affected by soluble salts. The conservation of wall paintings. In: Proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13–16, 1987. The Getty Conservation Institute, pp 103–135

Arnold A, Zehnder K, Küng A, Emmenegger O (1991) Wandmalereizerfall, Salze und Raumklima in der Klosterkirche von Müstair. Zeitschrift für Kunsttechnologie und Konservierung, vol 5/2. pp 171–200

Bionda D (2006) Modelling indoor climate and salt behaviour in historical buildings: a case study. PhD thesis no. 16567, ETH, Zürich

Bläuer Böhm C (1994) Salzuntersuchungen an Baudenkmälern. Zeitschrift für Kunsttechnologie und Konservierung, vol 8. pp 86–103

Cather S (2003a) Assessing causes and mechanisms of detrimental change to wall paintings. In: Gowing R, Heritage A (eds) Conserving the painted past. Developing approaches to wall painting conservation. Post-prints of a conference organised by English Heritage, London, 2–4 December 1999, English Heritage, pp 64–74

Cather S (2003b) Aqueous extraction of soluble salts from porous materials: alternatives and contra-indications. Tagungsbeiträge zu ‘‘Mauersalze und Architekturoberflächen’’, HfBK Dresden, 1.–3.2.2002, pp 167–172

Emmenegger O (2002) Karolingische und romanische Wandmalerei in der Klosterkirche. In: Die mittelalterlichen Wandmalereien im Kloster Müstair, vol. 22. Veröffentlichungen des Instituts für Denkmalpflege an der ETH Zürich. vdf Hochschulverlag, Zürich, pp 77–140

Exner M, Schädler-Saub U (eds) (2002) Die Restaurierung der Restaurierung? Zum Umgang mit Wandmalereien und Architekturfassungen des Mittelalters im 19. und 20. Jahrhundert. ICOMOS Hefte des Deutschen Nationalkomitees, p 37

Feilden B, Jokilehto J (1998) Management guidelines for World Cultural Heritage sites. ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property), Rome

Goll J, Emmenegger O (2002) Katalog der Wandmalerei und Stuckausstattung im Kloster St. Johann. In: Die mittelalterlichen Wandmalereien im Kloster Müstair, vol 22. Veröffentlichungen des Instituts für Denkmalpflege an der ETH Zürich, vdf Hochschulverlag, Zürich, pp 31–48

Gowing R, Heritage A (eds) (2003) Conserving the painted past. Developing approaches to wall painting conservation. Post-prints of a conference organised by English Heritage, London, 2–4 December 1999, English Heritage

Raschle P (2002) Die Klosterkirche Müstair—Wandbilder und die Mikroorganismen. In: Die mittelalterlichen Wandmalereien im Kloster Müstair, vol 22. Veröffentlichungen des Instituts für Denkmalpflege an der ETH Zürich. vdf Hochschulverlag, Zürich, pp 151–154

Sawdy A, Price C (2005) Salt damage at Cleeve Abbey England. Part II: seasonal variability of salt distribution and implications for sampling strategies. J Cult Herit 6:361–367

Zehnder K (1993) New aspects of decay caused by crystallization of gypsum. In: Conservation of stone and other materials. Proceedings of the international RILEM congress, Paris, vol 1, pp 107–114

Zehnder K (1996) Gypsum efflorescence in the zone of rising damp. Monitoring of slow decay processes caused by crystallizing salts on wall paintings. In: 8th International Congress on deterioration and conservation of stone, Berlin, 1996. pp 1669–1678

Zehnder K, Arnold A, Spirig H (1986) Zerfall von Wandmalerei durch lösliche Salze. Eine Fallstudie am Beispiel der Krypta des Zürcher Grossmünsters. Maltechnik/Restauro 2/1986. Callwey, München, pp 9–33