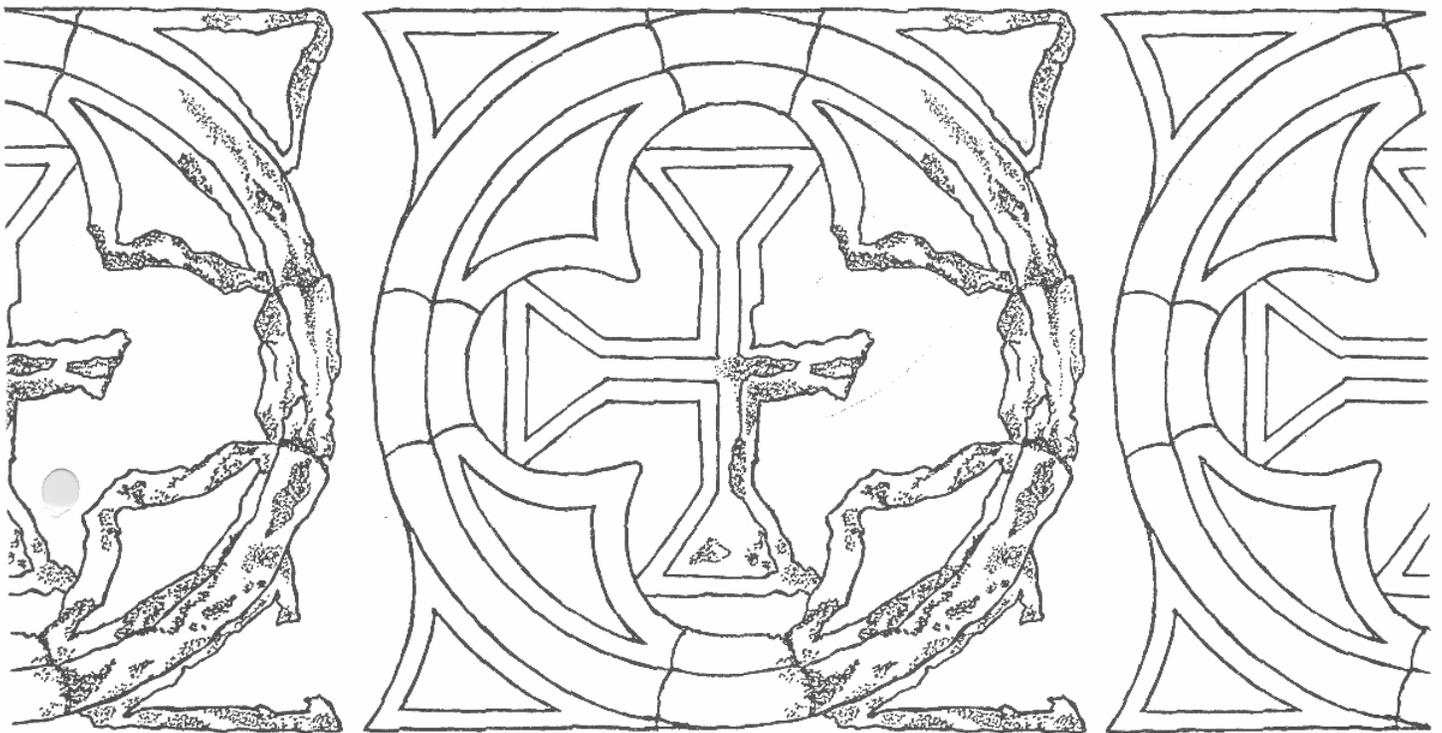


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WEATHERING OF THE NYDEGG BRIDGE IN BERNE, SWITZERLAND

Altération du pont du Nydegg à Berne, Suisse

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SUMMARY

Before starting the actual restauration of the Nydegg bridge in Berne, careful investigations, including mapping of weathering phenomena and the analysis of salt efflorescences, were carried out. The bridge contained considerable amounts of soluble salts from different sources, such as dry deposition of air pollutants, salts out of concrete and especially thawing salts. These salts made it hazardous to use hydrophobing and/or consolidating products, and therefore the use of such products was renounced. To avoid any additional input of salts, all the materials (e.g. plasters) that were used for the restauration, were analysed on their water soluble sodium and potassium content.

RÉSUMÉ

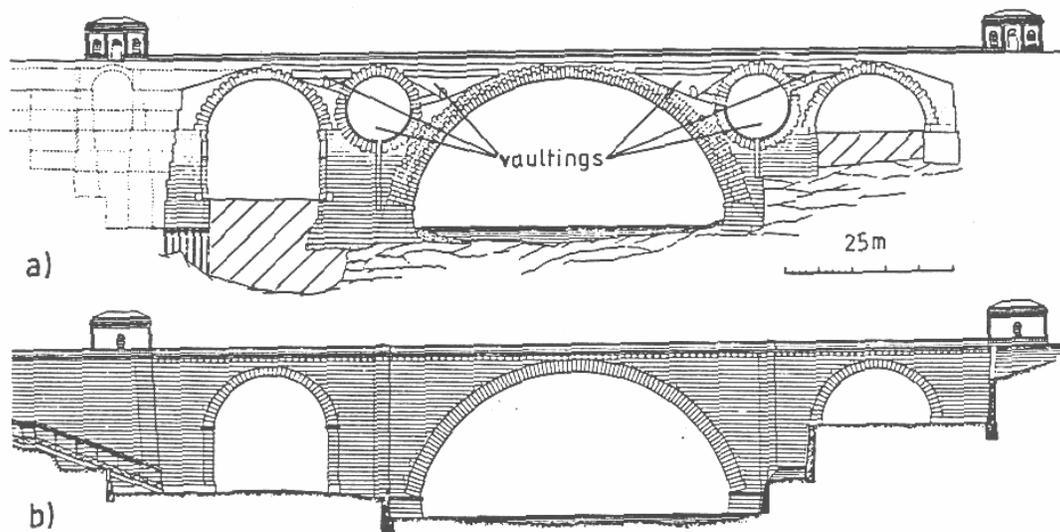
Avant de commencer les travaux de rénovation, le pont du Nydegg à Berne a été étudié en détail. Une carte des phénomènes d'altération a été faite et les efflorescences de sels solubles ont été analysées. Le pont contenait de grandes quantités de sels solubles provenant de sources variables, telles que la pollution atmosphérique, le ciment portland et surtout les sels de dégivrage. Tous ces sels rendaient hasardeux l'utilisation des produits de consolidation et/ou des hydrofuges. On a décidé de ne pas les utiliser. Pour éviter des apports supplémentaires de sels, on a déterminé les teneurs solubles en sodium et potassium dans les matériaux utilisés pour les mortiers de réaggréage.

1. INTRODUCTION

The Nydegg Bridge in Berne was built in the years 1840 until 1844 by the engineer K. E. Müller [10]. In 1941 the pavement was replaced and a concrete block containing a telegraphic conduit going all along the bridge was built in. In winter 1982, after a big piece of stone dropping from the western arch, it was decided to investigate the static and weathering condition of the bridge. Until then the roadway had been drained through the vaultings in the piers (figure 1a). For nearly 140 years all the water hitting the bridge did trickle into and through the construction. With this water e.g. faeces from draught animals and deicing salts were transported into the stones. Hence the first step of restauration was the installation of a proper drainage system in 1983.

Detailed investigations on the static and weathering situation begun in winter 1988 with the aim of finding a restauration concept. The restauration of the bridge begun in 1989 and it was finished in 1991. This paper reports on the investigations about surface weathering phenomena, the distribution of salts in the stones. The processes that led to the deterioration of the stones are discussed. Furthermore the contributions of these investigations to the development of the restauration concept are shown.

Figure 1: Side views of the Nydegg bridge, from [9] (slightly modified). a) cross cut West-East; b) South face



2. PRACTICAL APPROACH

The investigations were done in the following steps:

- 1.) Mapping of the surface weathering phenomena, sampling and analysis of salt efflorescences and crusts.
- 2.) Mapping of the condition of the stones in depth, mainly done by percussing them with a hammer. (During the restauration works it could be seen that this "archaic" method was quite efficient in finding the stones that needed to be replaced.)
- 3.) Steps 1 and 2 did show, that it was necessary to know more about the distribution in depth and the genesis of the salts, and about the static properties of some stones. Based on the surface mappings representative places for the drilling of cores were chosen,

- on which the compressive strength and/or the quantitative salt contents were measured.
- 4.) The evaluation of the results of the mapping and of the laboratory analyses led to the restauration concept.
 - 5.) During the restauration the concept was constantly reconsidered and whenever necessary somewhat adapted.

3. MATERIALS

The main parts of the bridge were built of Bernese Molasse sandstones (see table 1).

Table 1: Some important physical, chemical and mineralogical properties of Bernese sandstones (after [5], [6] and [8])

calcareous cement	7 - 12.5 wt%
total porosity	17 - 21 vol%
water suction through capillarity	0.038 - 0.10 (cm/sec ^{1/2})
compressive strength when dry	250 - 400 (kg/cm ²)
compressive strength when wet	100 - 200 (kg/cm ²)
main weathering phenomena	granular disintegration

Alpine granite was used for the surface stones of the middle arch, for the keystones and the edgestones of the side arches and for the balustrades. The granites, which were taken from erratic blocks [10], are light-green, very homogeneous, with an average grain size of about 0.5 cm, and contain only little porosity.

Müller [10] gives detailed descriptions of the mortars used, however, as he uses many product names of that time, it was not possible to reproduce these materials.

4. MAPPING OF THE WEATHERING PHENOMENA

Because of the dimensions of the bridge (length = 122m, height above the river Aare = 22m) it is not possible to reproduce here all the maps that were done. As an example figures 2 and 3 show the maps of the weathering phenomena of the western arch.

The northern side (figure 2a) is partially covered by thin crusts which are grey at the top and become black in the lower parts. Underneath the crust-covered parts are some areas with exfoliation; further down the stones show granular disintegration. The north side of the bridge is very rarely hit by rain, and hence is largely covered by crusts. The black areas look very much like the zone C [1] in walls that are in contact with ground moisture, where the highly hygroscopic salts are accumulated.

The weathering of the south face (figure 2b) is dominated by granular disintegration with only few parts being covered with dark crusts. In the upper parts some ashlar can be observed, that have been destroyed in an earlier time by granular disintegration, which later on were covered by a dark crust. It is not possible to tell when this change of weathering processes took place: maybe the situation changed whenever the drainage was built in 1983. However, there do not exist any documents giving evidence on this.

The differences in the weathering appearance between the two Sides are probably due to the different climatic conditions, i.e. the south side is more often hit by sun and rain than the north side.

On both faces the joints in the mouldings underneath the balustrade were open, and the water running off led to longish areas on the stones underneath, showing granular disintegration.

The western half of the underside of the arch differs from the eastern half especially in the central parts, where the first is covered by a black crust and the latter shows granular disintegration (figure 3). This is probably due to the fact, that the western side is in direct contact to penetrating ground moisture, while the eastern side forms the outer wall of a pier.

In contrast to the Bernese sandstones the granites show little damages. The under side of the central arch (granite) was widely covered by sinter crusts and frequent halite efflorescences.

Figure 2: Side views of the surface weathering phenomena on the western arch; a) North face; b) South face

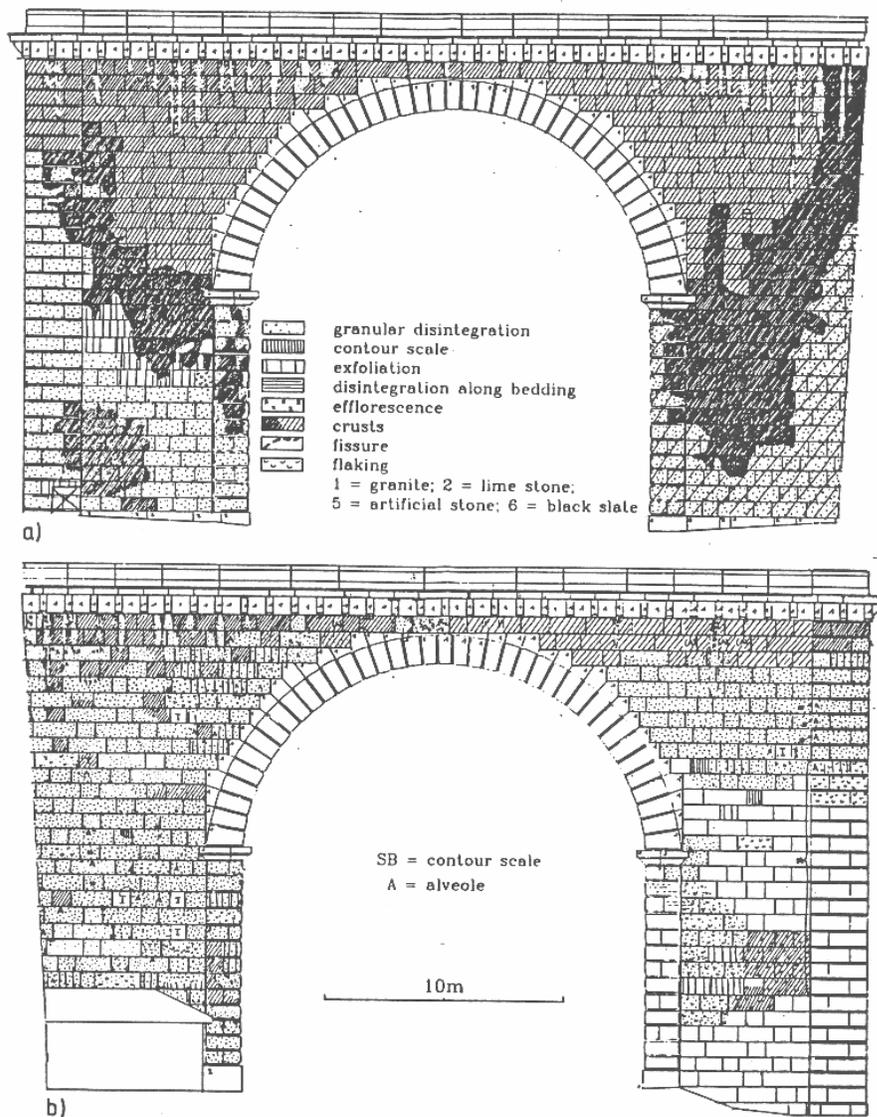
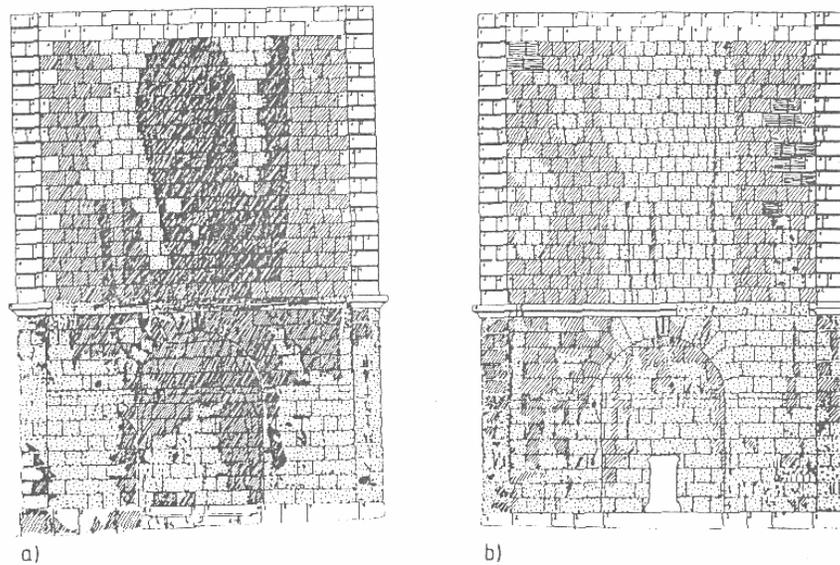


Figure 3: Surface weathering phenomena on the underside of the western arch; a) Eastern half; b) Western half (legend see figure 2)



5. SALTS

5.1 Salt efflorescences and crusts

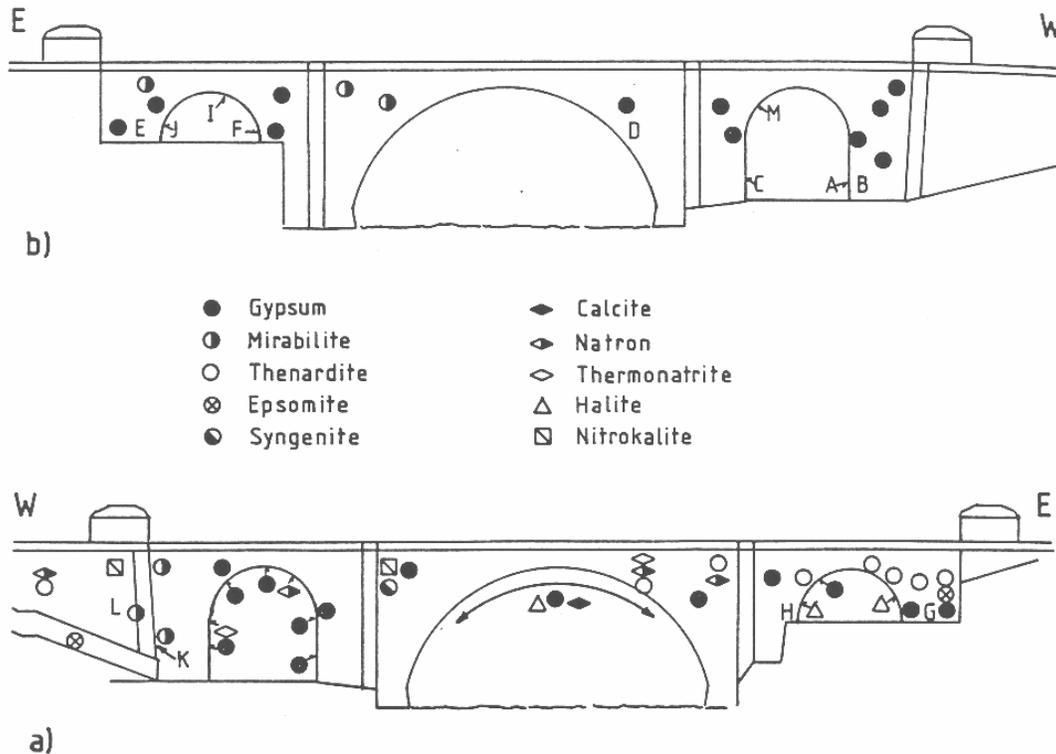
Most of the observed weathering phenomena are related to the activation of salts, therefore 75 samples of salt efflorescences, 32 of gray and black and 2 of hard white crusts were analyzed using the methods described in [2] (table 2). All the dark crusts contained gypsum and all the sinter crusts consisted of calcite.

Table 2: Minerals and ions in the salt crusts and in efflorescences. (Total number of samples analyzed = 109; freq. number of samples containing the mineral or ion)

Mineral	chem. formula	freq.	Ion	freq.
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	43	Na^+	85
Mirabilite	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	11	K^+	12
Halite	NaCl	11	Ca^{2+}	84
Thenardite	Na_2SO_4	9	Mg^{2+}	11
Natron	$\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	6	Cl^-	57
Thermonatrite	$\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$	5	NO_3^-	62
Nitrokalite	KNO_3	3	SO_4^{2-}	99
Calcite	CaCO_3	2	CO_3^{2-}	17
Epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	2		
Syngenite	$\text{K}_2\text{Ca}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}$	1		

Microchemical tests showed that the grey crusts only rarely contained other ions than Ca^{2+} and SO_4^{2-} , whereas all the black crusts contained great amounts of Cl^- and NO_3^- , forming rather hygroscopic mixtures. This supports the idea that the black crusts have grown in contact with the ground moisture (zone C, [1]).

Figure 4: Distribution of the salt efflorescences a) South side; b) North side; (A ... M location of drill cores).



One triggering factor for the growth effloresces is the relative humidity of the surrounding air [3,4]. The northern side of the bridge has got a rather humid and constant climate, whereas on the southern side and on the under sides changes of humidity due to e.g. sun, rain and draught must be frequent. This explains why at the northern side only a few mirabilite efflorescences were observed, whereas on the southern face and on the undersides many different minerals could be found (figure 4), although the drill cores of the different places did contain similar amounts of salt. Sodium carbonates did only appear in the upper half of the bridge.

5.2 Soluble salt content in drill core samples

The drill cores (figure 4) reached a depth of between 15 and 26 cm, and they were all drilled dryly. Two to three samples from different depth of each core were analyzed for their content of water-soluble salts, by means of ion chromatography (table 3).

High sulfate concentrations were only found in the surface samples (figure 5), whereas chlorides and nitrates are elevated even in some deep samples (e.g. C3). The total salt concentrations are usually higher in the cores from the north face and undersides, than in the cores from the south side.

There is a clear correlation between the water-soluble sodium and -the chloride content (figure 6), which is in good agreement with the fact, that halite was one of the most often observed efflorescence salts (table 2 and figure 4). An even better correlation can be seen between calcium plus sodium concentrations On the one hand, and chloride plus nitrate concentrations on the other (figure 7).

Table 3: Content of water-soluble salts in samples of drill cores. (A,B,C ... = names of the individual drill cores; BE = salt content of fresh Bernese Sandstones, after [6])

sample nr	depth [cm]	Cl- [ppm]	NO3- [ppm]	SO42- [ppm]	Na+ [ppm]	K+ [ppm]	Mg2+ [ppm]	Ca2+ [ppm]	total [ppm]
A1	0-1	5672	5270	279	5012	313	97	240	16883
A2	4-5	3191	1860	52	2966	274	49	281	8673
A3	20-21	181	87	18	322	117	97	441	1263
B1	0-1	3935	335	211	1862	195	170	922	7630
B2	4,5-5,5	312	22	39	483	195	24	321	1396
B3	19,5-22	39	12	10	115	78	73	441	768
C1	0-1	8119	477	49	3425	391	49	1443	13953
C2	5-6	3687	198	13	1747	117	122	1002	6886
C3	19,5-21	1312	53	8	920	78	97	441	2909
D1	0-1	3900	180	173	1839	156	73	1002	7323
D2	5,5-6,5	135	10	14	322	117	24	401	1023
D3	19-21	46	24	12	207	117	49	321	776
E1	0-1	2588	273	259	2391	117	24	361	6013
E2	6-7	340	38	14	759	78	0	240	1469
E3	21-23	82	7	10	299	78	49	401	926
F1	0-1	5460	155	144	3885	78	0	240	9962
F2	6-7	1383	25	22	1724	78	0	200	3432
F3	17,5-19	85	9	13	552	78	0	160	897
Gi	0-1	390	242	125	506	78	49	401	1791
G2	5-6,5	149	74	17	230	78	49	441	1038
G3	13-15	46	24	11	138	78	24	441	762
Hi	0-1	3333	291	144	2184	39	0	601	6592
H2	4-5	1844	180	16	1035	78	49	521	3723
H3	13-15	277	112	12	322	117	24	441	1305
K1	0-1,5	298	2108	2497	506	78	194	1603	7284
K2	4,5-5,5	167	955	63	322	78	73	601	2259
K3	10-17	23	113	57	115	39	73	561	981
L1	0-1	11	40	3746	69	78	73	1603	5620
L2	4-5	43	155	115	115	39	49	481	997
L3	16-17,5	23	68	6	23	39	49	481	689
M1	0-2	19	19	12	138	117	24	481	810
M3	25-26	19	11	0	138	156	49	401	774
BE	7-17	0-5	8-85	6-43	16-173	55-137	249-642	<1100	

Figure 5: Total water-soluble salt content in comparison to the depth (sample identification see table 3)

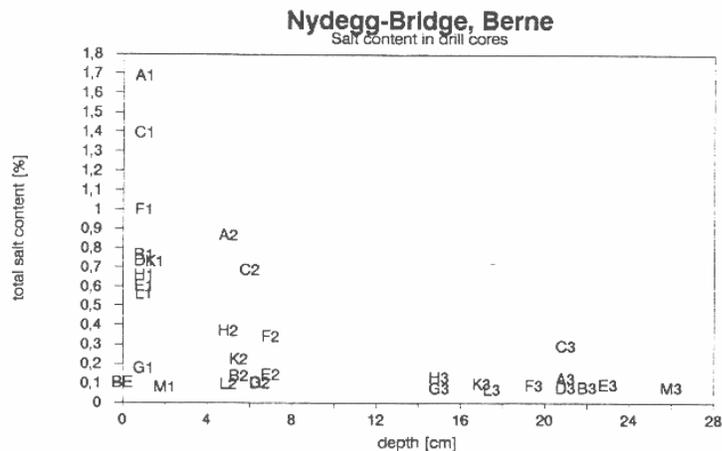


Figure 6: Content of water-soluble sodium versus water-soluble chloride (sample identification see table 3)

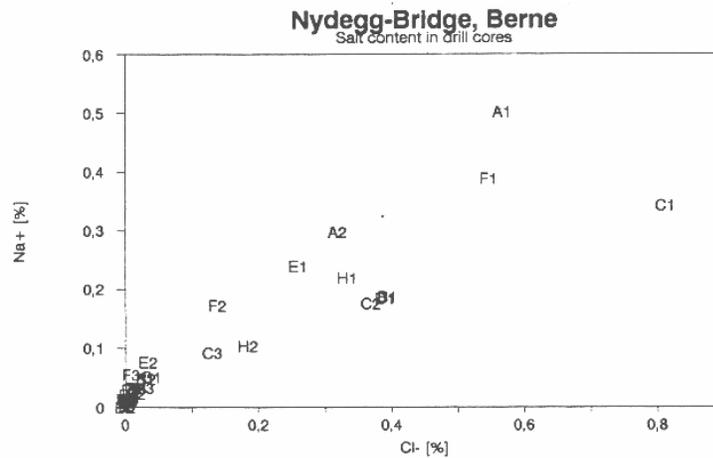
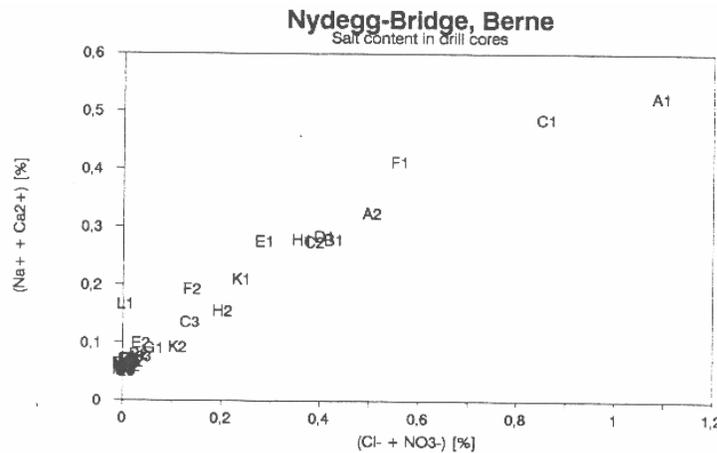


Figure 7: Calcium plus sodium concentrations versus chloride plus nitrate (sample identification see table 3)



5.3

Interpretation

In the following discussion salt concentrations exceeding the concentrations of freshly quarried Bernese sandstones ([6] and BE in table 3) will be considered elevated.

Gypsum crusts only develop in places that are protected from the rain, and gypsum never occurs in the depth, therefore it can be considered to be the product of the dry deposition. Today's deposition rate of sulfur on Bernese sandstone in Bern is 0.92 g Sulfur per m² and per year [7]. This deposition rate could lead to a crust of 0.2 mm depth in 100 years with the assumption, that the crust contains only gypsum and no porosity nor dust particles.

High concentrations of salt were found in places with microclimatic conditions that only seldom allow the growth of efflorescences (north side and undersides), where hygroscopic salt mixtures did form, giving the rock a dark, wet appearance. In the other places (south side) many salt efflorescences were found, that led to a loosening of grains of the stone (granular disintegration), which by falling of did take along at least some of the salts (the only core from the south side with very high salt concentrations was core H, whose surface was formed by a contour scale).

The sources for the chlorides are mainly thawing salts that have been used in large quantities since the fifties. Until 1983 all the surface water of the bridge containing salts was drained through the vaultings (figure 1) from where it could easily penetrate the stones by capillarity. The salts get concentrated near the surface of the stones because that is where the water evaporates leaving the salts behind.

Nitrate salts are the product of biological activity. They can penetrate with the ground moisture. Another source could have been the faeces from draught animals in earlier times and nowadays since carriage rides for tourists lead again over the bridge.

A few years ago a telegraphic conduit was implanted all along the bridges upper side by means of concrete. This concrete is believed to be the source for the sodium carbonates, that have been found exclusively in the upper parts of the bridge (figure 4). Furthermore concrete is the probable source of the sinter crusts, and of at least some of the sodium sulphates, because sodium carbonate can react with gypsum to form calcite and sodium sulphate [4].

6. IMPLICATIONS FOR THE RESTAURATION

Investigations of the engineer showed, that many parts of the bridge had to be repaired as they were no longer statically safe. In relation to that it was necessary to evaluate, what were the reasons for the damages and what could be done to either stop or to slow down the deterioration processes. As soluble salts played a major role in the deterioration processes, a further question was, whether it would be possible to remove the salts or the sources of the salts and if not, what implication the high salt concentrations would have for the restauration works.

The main reasons for the observed deterioration phenomena were, the lacking of a proper drainage system until 1983, furthermore the penetration of ground moisture in some parts of the bridge, the dry deposition of air pollutants on the surfaces of the stones and the built-in concrete as a source of alkaline salts.

With the installation of a drainage system in 1983 one of the major sources of water and salts was stopped. Other sources for the water were open joints, which could lead rain water into the construction, and therefore had to be closed. The effort to isolate the bridge against the ground moisture was considered to be in no relation to what it could bring, as the salts that were already in the stones would not have been removed by this.

To our knowledge, there does not exist a promising methode to remove important amounts of salts from a such a big building with an acceptable effort. This made it impossible to clean the bridge's surface by floating it with water, which is a frequently used method in Bern, as the pass of the resulting salt solution would be unpredictable. The surface was then cleaned mechanically with as little water as possible. The mortars and palsters used at the bridge were preliminarily tested for their water-soluble contents of sodium and potassium, to reduce any additional input of salts.

Because of the large amounts of salt there was no consolidation product that could safely be recommended. Hence it was decided, that the stones that were not considered to be statically save enough anymore should be replaced by freshly quarried Bernese sandstones. Small missing parts of stones were replaced by a specially developped alkalifree mortar. As the rain water does not seem to be a major reason for the observed deterioration it was decided to renounce all hydrophobing treatments.

7. CONCLUSIONS

The careful investigations before starting the restauration work did lead to know the major reasons for the deterioration. This helped to make a distinction between the weathering processes that are possible to slow down or even to stop, and the ones that lie within the structure, and therefore have to be accepted as weathering factors even in future. In addition to that the investigations were especially useful when, during restauration, unpredicted events happened and decisions had to be taken rapidly.

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REFERENCES

1. ARNOLD, A. (1982): Rising damp and saline minerals. - 4th Int. Congr. Deterior. Preserv. of Stone Objects, Louisville, Kentucky, 7.-9. July, 11-28.
2. ARNOLD, A. (1984): Determination of mineral salts from monuments. -Studies in Conservation, 29, 129-138.
3. ARNOLD, A., ZEHNDER, K. (1985): Crystallization and habits of salt efflorescences on walls II. Conditions of crystallization. - 5th Int. Congr. Deterior. Conserv. of Stone, Lausanne, 25.-27.Sept., 269-277.
4. ARNOLD, A., ZEHNDER, K. (1990): Salt weathering on monuments. -Advanced workshop on anal. methodologies for the invest. of damaged stones, Pavia, Italy, 14.-21. Sept.
5. BLÄUER, C. (1985): Weathering of Bernese sandstone. - 5th Int. Congr. Deterior. Conserv. of Stone, Lausanne, 25.-27. Sept., 381-390.
6. BLÄUER, C. (1987): Verwitterung der Berner Sandsteine. - unpubl. Diss. Univ. Bern.
7. FURLAN, V. and GIRARDET, F. (1988): Vitesse a' accumulation des composés atmosphériques du soufre sur diverses natures de pierre. -Proc. VIth Int. Congr. Deterior. Conserv. of stone, 12.-14.9., Torun, Poland, 187-196.
8. GERBER, M. (1982): Geologie der Berner Sandsteine. (Das Burdigalien zwischen Sense und Langete, Kanton Bern). - unpubl. Diss. Univ. Bern.
9. HOFER, P. (1952): Kunstdenkmäler der Schweiz Bd. 28, Verlag Birkhäuser, Basel.
10. MOLLER, K. E. (1848): Geschichte der Erbauung der Nydeckbrücke in Bern in den Jahren 1840 bis 1844. - Verlag Friedrich Schulthess, Zürich.