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by

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WEATHERING OF MOLASSE SANDSTONES ON MONUMENTS AND NATURAL OUTCROPS

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1. INTRODUCTION

Molasse sandstones are the main traditional building stones in a large part of Switzerland. The study of their characteristic weathering phenomena in different environments may contribute to a better understanding of their decay mechanisms and lead to some directions in building conservation.

This study is restricted to the most frequent types of molasse sandstones in the area of Zürich, the «Granitic sandstone» and the «Platten sandstone». The typical weathering phenomena occuring on buildings in urban area and comparatively in natural outcrops are described and analysed. The study is part of a thesis.

Both sandstones are located in the northern Prealps of Switzerland, together forming a 100 km long and less than 5 km wide strip from St. Margrethen in the East to Luzern in the West (de Quervain [19]). Geologically, they belong to the Tertiary subalpine molasse trough: The Granitic sandstone is a fresh water sediment of Aquitanian age (upper Oligocene) which is overlain by the Platten sandstone, a marine sediment from the Burdigalian (lower Miocene). Petrographically they are characterized as arkoses.

The Granitic sandstone (this term refers to its granite like appearance and composition) contains about 30-50% quartz, 25-40% feldspars, 5-15% rock fragments (chert, granite, dolomite, calcite, etc.) and accessory minerals such as mica and chlorite. The calcite cement is scarce (microscopically invisible) to about 10%. The Platten sandstone (this term refers to the good cleavage along the bedding planes) contains about 40-50% quartz, 15-20% feldspars, 15-20% rock fragments (magmatites, calcite, dolomite, etc.), 10-15% calcite cement and accessory minerals such as chlorite, glauconite, and mica (de Quervain [19] and Zehnder [23]).

The building stones of these types used in Zürich originate mainly from the area around the upper lake of Zürich (de Quervain [18], [19] and [20]).

2. WEATHERING PHENOMENA ON BUILDINGS

2.1. Introduction

In a natural outcrop, the stone is in contact with the original rock and exposed by a naturally formed erosion surface. In a building, the stone among other materials is part of an architectural structure. The transfer from its original to a man made environment (an early author dealing with this problem is Kaiser [10]) gives rise to a manifold set of processes we finally realize as weathering phenomena.

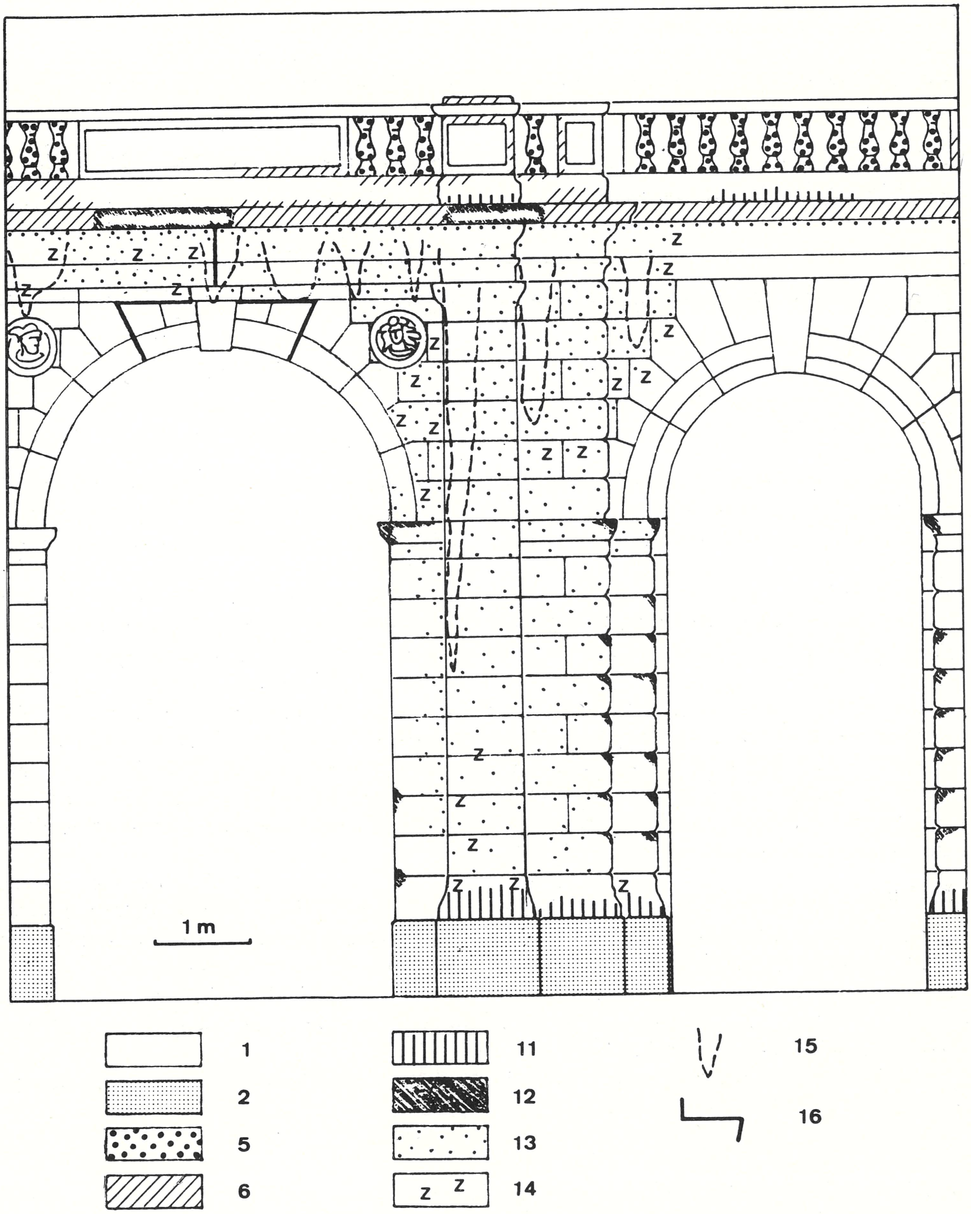

Fig. 1 – Main railway station of Zürich, section of the east façade. Sketch after the documentation which was performed during the present restoration (Arnold [3]). *Legend*: 1. Granitic sandstone, 2. St. Triphon limestone, 5. artificial stone, 6. mortar replacement, 11. Contour scaling, 12. spalling, 13. crust formation, 14. efflorescences, 15. area wetted by periodical water leakage, 16. settlement cracks.

Some important aspects of the stone's exposure on a building are:
— two weathered surfaces (inside and outside of a building);
— variable temperature and moisture in the interior;
— physical and chemical influences from surrounding materials;
— complicated artificial surface. It is delicate, and little changes from a known contour are conspicuous;
— in addition, buildings are concentrated in urban areas where air pollution is relatively high. In the centre of Zürich, the sulfur immissions are at least 2-3 times higher than in rural area (see page 102).

In the urban area of Zürich, the weathering phenomena are observed and documented on a large number of buildings.

Moreover, some buildings have been chosen for systematic study combined with sampling for laboratory investigations. Such an example is the main railway station of Zürich which was built during 1865 to 1871. Later modifications and repairs date from 1886-1901 and 1929-33, however, little information about the exact work done is available. During the present restoration, a detailed documentation of stones and deterioration on the building was performed in conjunction with the architects (Arnold [3]).

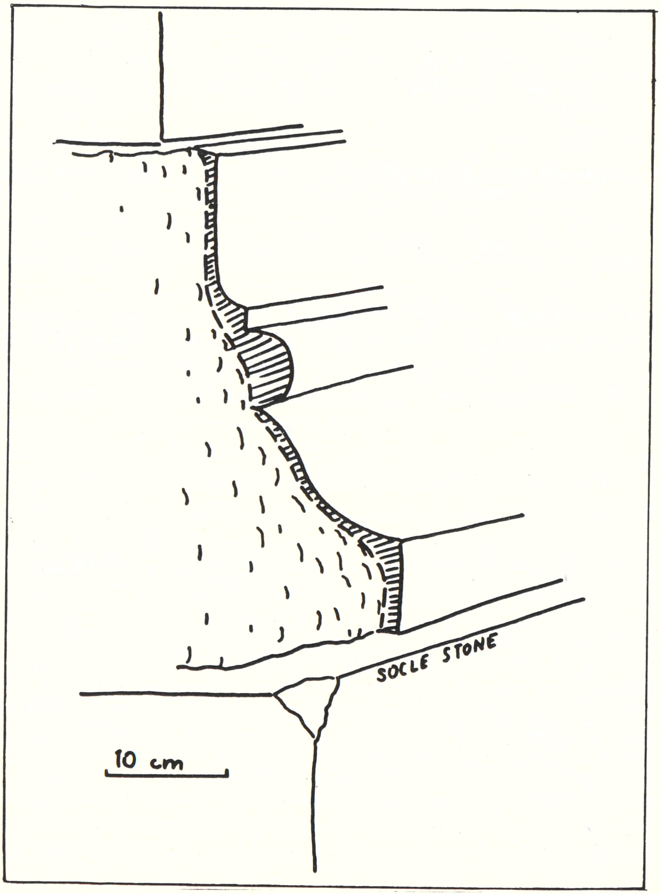

Fig. 2 – Detail from the central pillar in figure 1. Base from Granitic sandstone is affected by contour scaling (schematically).

The main parts of the station such as the façades and the towers are built from Granitic sandstone [1]. Supplementary construction stones are the St. Triphon limestone [2] for the socles, the Platten sandstone [3] for sills, the Bernese sandstone [4] for panels below the upper balustrade, and an artificial stone [5] for the balusters. Mortar replacements [6] are frequent on edges and faces of ashlars but predominant on cornices and on lower parts of balustrades. (Numbers refer to legend in figure 1). It is uncertains if the artificial stone for the balusters date from the original construction or a later restoration (Arnold [3]).

Figure 1 shows a portion of the projected groundfloor facing to the east. It should be emphasized that figure 1 illustrates a particular situation which of course is not representative for the whole building. There is a faulty gutter in the interior of the central pillar causing an intense deterioration on the surface. However, some of the typical weathering phenomena are well developed, others not. In the following we shall look at the building as a whole by giving a short description of some of the characteristic phenomena.

2.2. The weathering phenomena

Contour scaling is distinguished by the formation of a crumbling zone in depth from less than 1 mm to about 20 mm beneath the apparently unhurt stone surface. The loosening of an outer layer from the stone's interior progresses until the coherence is lost and a scale may fall off (figure 2). Typical contour scaling forms on all surfaces independently from the bedding and cleavage (from de Quervain [17], who called the phenomenon «Schalenbildung»). Similar phenomena are described for example from the cathedral of Cologne (Efes and Luckat [6]) and the cathedral of Strasbourg (Gross [9]). Contour scaling forms most characteristically on Granitic sandstones but is also common on the other molasse sandstones. A medium scale is 1-1.5 cm thick. The crumbling zone underneath ranges from a few millimeters to 1 cm thickness and consists of sand and flakes which often are dotted with little white bunches of gypsum. The phenomenon gives rise to the most severe damages not only at the main station but generally throughout Zürich. The formation is clearly controlled by the stone's exposure, it dominates the south and west façades which are the weather sides in Zürich. On some parts, for example on the upper south façade of the reception hall, it has affected more than 50% of the masonry. On east and north façades, it is restricted to small areas such as the bases of pillars, ledges and zones above cornices (figure 1). These parts as well are distinguished by exposure to the rain. It has been observed that the thickness of a scale varies with the stone's exposure in many cases. For example, on the parapet (Granitic sandstone) topping the south façade, 1-2 cm thick scales have formed on the south side, whereas they are only 2-3 mm thick on the upper and north sides (figure 3).

A discussion of the conditions favouring contour scaling and their influence to the shape of the scale is planned for a following more comprehensive study.

Spalling is the disintegration of the stone into compact fragments (= spalls, definition by de Quervain [17]). According to de Quervain [17], typical spalling occurs on massive limestones where irregular fissures give rise to more or less isometric spalls. On molasse sandstones, it is commonly a disintegration into thin flakes, their diameter ranging from millimeters to more than 1 cm. Spalling may fluently pass into granular disaggregation, as well there is no clear limit between large spalls and contour scales.

On Granitic sandstones at the station, spalling affects preferentially the projected corners and edges on east and north façades, as shown in figure 1. In some places, dropping rain water is observed to hit the stone where the spalls form – here the phenomenon approaches contour scales – but this is not a rule.

Spalling is generally associated with granular disaggregation and crust formation: Corners and edges spall off between surfaces which are affected by the latter two.

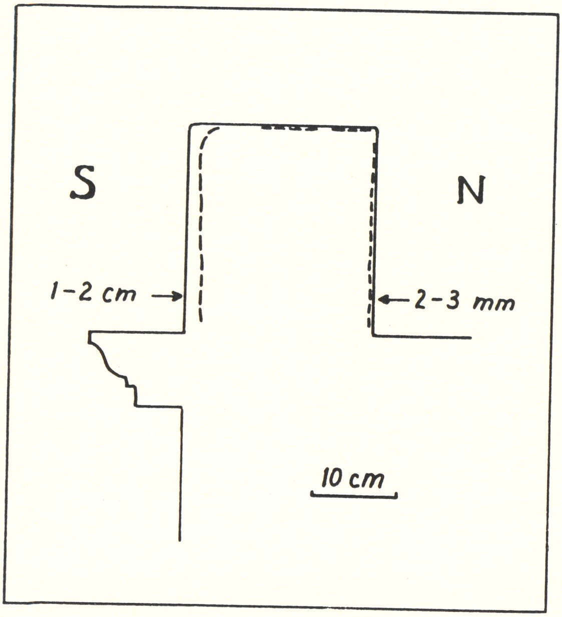

Fig. 3 – Cross-section through the parapet topping the south façade of the main station, Zürich. Different thickness of contour scales is related with different exposures of the stone surface (schematically).

Exfoliation is the disintegration of the stone into sheets parallel to the bedding and cleavage planes. At the station, this phenomenon is absent on Granitic sandstone but common on the sills from Platten sandstone.

Granular disaggregation is the disintegration of the stone into single grains (de Quervain [17]). It may affect only the outermost grains, or may loosen the stone to a depth of more than 1 cm causing crumbling into sand and flakes. Such a deep disintegration is typical on Bernese molasse sandstone and also common on Platten sandstone. On the Granitic sandstone, this form is restricted to strongly affected areas. Granular disaggregation may lead to a rounding of corners and edges if the whole surface is equally affected. If not, it may excavate even surfaces (alveolation) which is generally related to local concentration of soluble salts. (Alveolation is considered as a special case of granular disaggregation, see page 99).

The phenomenon is widespread in sheltered areas, hence prevailing on east and north façades. Favoured parts are below cornices, at the border of water leakage and on surfaces moistened by percolating waters. The same areas are distinguished by crust formation and periodically appearing efflorescences of Na_2SO_4.

Crust formation is primarily the covering of the stone surface with a crust which is commonly black and mainly composed of gypsum mixed with soot particles. We may include in this term the blistering and peeling off of the crust, causing a disintegration of the stone surface.

«Crusts» are known to be the most widespread phenomenon in urban areas and therefore mentioned by many authors. A detailed description is given by Kieslinger [11] who distinguished an «inner» from an «outer» crust. Since the gypsum cover (= outer crust) is adherent to the stone surface, it detaches the outermost stone layer (= inner crust) when it blisters. Moreover, Kieslinger uses the term «crust» also for phenomena comparable to contour scales («Diffusionsschalen»). In modern literature, the usage of the term is still inconsistent.

On molasse sandstones, less than 1 mm thick crusts may adhere on tight stones, but in most cases they blister easily, especially when getting thicker. With increasing thickness – exceptions of more than 1 cm have been observed – their surface develops to bumpy and branching forms (figure 4). The adherent stone material on their inside varies from a few grains to spalls, and the revealed stone surface may disaggregate granularly or spall off to a depth of more than 1 cm. De Quervain [17] ascribes the breakdown beneath crusts to an action of soluble salts which have concentrated there rather than to an effect of the crusts themselves.

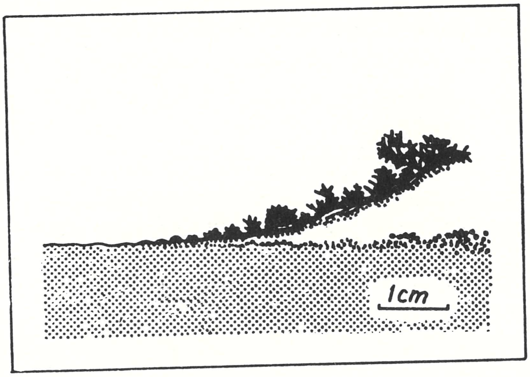

Fig. 4 – Cross-section through stone surface affected by crust formation. Schematical representation of a developing gypsum crust from left to right.

As it is well known, crusts generally form on sheltered surfaces of a wall, especially in recesses below cornices and ledges. The stones of the window-ledges on the west façade, for example, are affected by contour scaling on their upper and front sides but by intense crust formation on their bottom sides. This illustrates the preferred crust formation at the border of wetted zones and on surfaces which are moistened by percolating water. On the masonry shown in figure 1, crusts which are associated with spalling, granular disaggregation and efflorescences, have formed around areas which are wetted by water running through the open joints from the above cornice where gullies are obstructed. In this case, the crusts are very extensive in a lower part of the pillar as well. A faulty gutter in its interior, giving rise to percolating water and an extended moistening of the surface, is considered to be the cause.

Efflorescences are loose aggregates of soluble salts at or in the outermost zone of the stone surface (de Quervain [17]. Winkler [22] uses the term «subflorescence» for salts crystallizing beneath a skin of weathered rock). They periodically appear and disappear, thus they are very mobile. In the urban area of Zürich, the main soluble salt on molasse sandstones as well as on a great variety of other stones and mortars is Na_2SO_4. $MgSO_4$ is found occasionally, Na_2CO_3 rarely and is clearly related to recent cement mortars. (All the salts occur in their common hydrates. No obvious correlation is observed between the salt's nature and the type of stone in this area).

Except for traces of nitrates, only Na_2SO_4 has been found at the station.

Efflorescences generally occur in sheltered areas where crust formation and granular disaggregation are observed. They are concentrated on surfaces reached by percolating waters and at the border of zones wetted by water leakage (figure 1). The following zonation is observed: gypsum crusts, crusts plus efflorescences and finally efflorescences. Intense granular disaggregation coincides with efflorescing streaks.

Arnold [1, 2] shows examples of periodically appearing salts and points out their possible action in stone weathering by crystallization based on the daily temperature and humidity changes. The cold season (about November – May) favoures the salts to effloresce, yet the particular climatic conditions for their appearance are not established.

In contrast to the above mentioned phenomena, some important damages on buildings are not specific to the stones on which they occur. For example, *rusting iron* causes fissures by expansion which is very common at the station as evidenced by the spalling of mortar replacements containing iron reinforcements. Moreover, some *cracks* are *due to settlement*. A further discussion of construction faults is omitted here.

3. WEATHERING PHENOMENA ON NATURAL OUTCROPS

3.1. Introduction

In comparing weathering on a building to weathering on a an outcrop, we must be aware of the differences which may influence the observed phenomena. Referring to the characteristics for a stone exposed on a building (page 91), we may specify analogously for an outcrop:

— One weathering surface (apart from a much slower «secular» weathering in the rock's interior);
— constant temperature and moisture in the rock's interior (apart from slow seasonal changes);
— physical and chemical influences from the geologic environment (swelling rocks, migrating pore waters);
— rough surface due to a natural network of joints and bedding plains. (This is partially true for a quarry where the pattern of natural joints may be blurred more or less extensively by artificial cuts). The rock's contour before weathering is commonly unknown, and alterations are not conspicuous.

However, since stones are exposed to the weather in both environments, it may be examined if they react in similar ways or not. The initial field investigations checked the full spectrum of weathering phenomena in Granitic and Platten sandstone outcrops. From this survey, it was obvious that some phenomena in particular places compare well to weathering on buildings. Such localities were chosen for systematic investigations. The ancient quarry «Martinsbrugg» (near St. Gallen, Eastern Switzerland) is picked up as an example for a detailed study (figure 5). Platten sandstone has been quarried there until the end of the last century. This well bedded rock yields a stone which is somewhat denser than Granitic sandstone (water absorption for Platten sandstone is 1-2.5%, and 2.5-3.5% for Granitic sandstone, de Quervain [19]. The petrographic description is on page 91). The quarry faces to the west and south, the strata dip 20° to the northwest. Its central and left part in figure 5 has probably been exposed for 80 years, to the lower right, the rock has been removed by blasting about 11 years ago because of a broadening of the adjoining road. In figure 5 b, the good building stone is distinguished from overlying marl beds which grade into soil. The pattern of weathering phenomena on the rock surface is sketched in a slightly simplified mode.

3.2. The weathering phenomena

Contour scaling occurs in the centre and to the left (northwest) of the outcrop (figure 5b). The rock surface there is unhurt but covered with algea. A sharp edged date, «1899», chiseled on one place confirms its durability. Scales are about 0.5-2 cm thick. Underneath, a crumbling zone consists of sand, spalls and flakes which are dotted with white gypsum spots towards the surface.

The contour scaling area coincides with the portions of the rock exposed to direct rain. Evidently, the shape and distribution of this phenomenon is similar to that observed on buildings.

Spalling in the form of loosened corners and edges, as described from Granitic sandstones at the

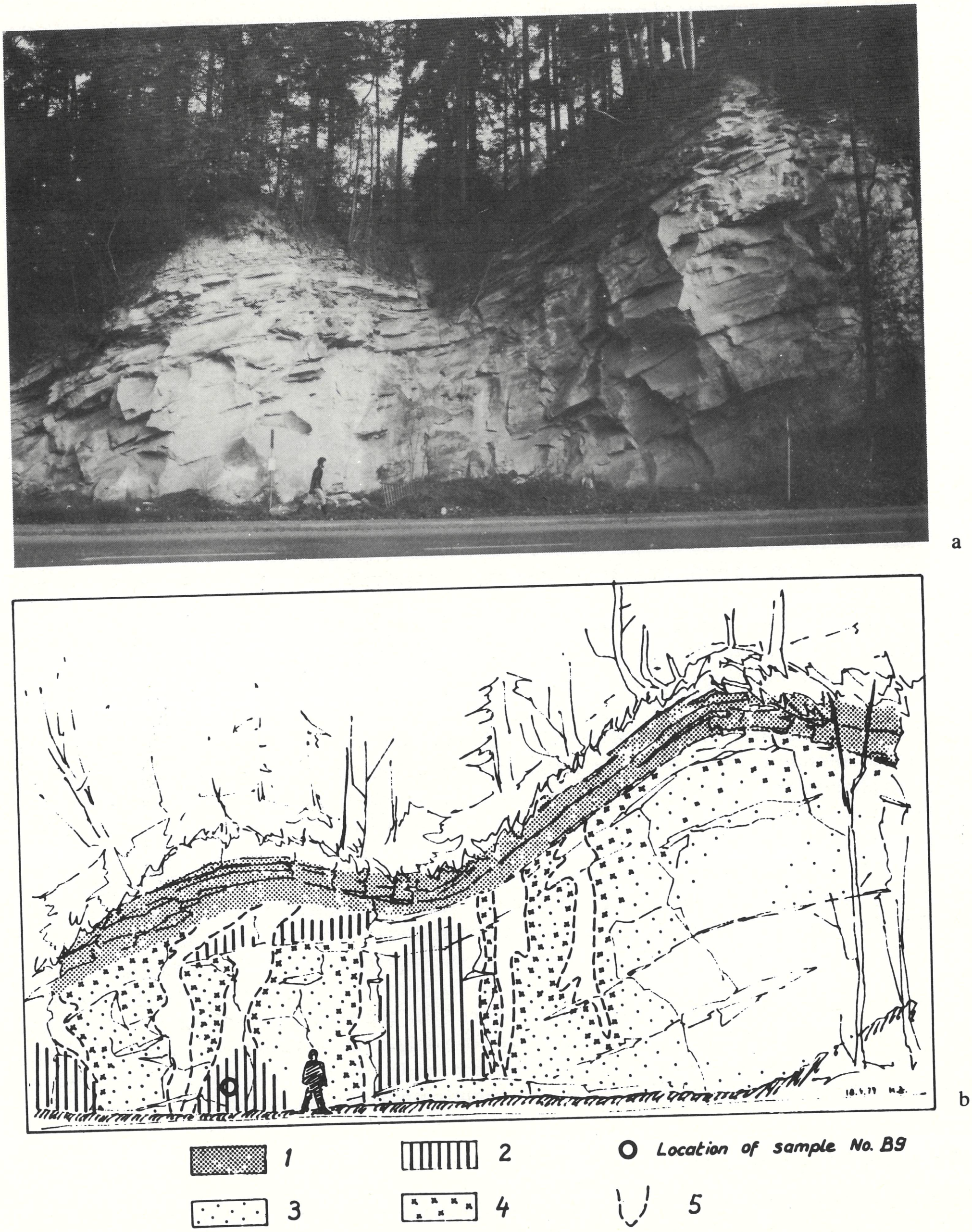

Fig. 5 – The ancient quarry «Martinsbrugg» (near St. Gallen, Eastern Switzerland) in Platten sandstone. a) Part of the quarry viewed from south west. b) Sketch after picture a) figuring the pattern of weathering phenomena on the rock (slightly simplified). *Legend*: 1. Marl beds overlying the quarried sandstone, 2. contour scaling, 3. peeling and granular disaggregation, 4. efflorescences, 5. area wetted by periodical water leakage.

station, is not as conspicuous here. This may partially be due to the rough rock surface which is difficult to survey, but also to the different type of sandstone and the different exposure. Spalling into flakes is very common but associated with a modified form we may call peeling.

Peeling is the superficial loosening of 0.5-1 mm thick stone sheets which tend to blister and fall off (figure 6 and 7). The process is distinguished by continuous repetition combined with granular disaggregation on sheets and underlying stone surface. It typically forms parallel to the stone surface which commonly is perpendicular to the bedding in this outcrop. Peeling may be influenced by the bedding where the surface is more or less parallel to it: the stone then tends to exfoliate (page 95. As well, the combined effect of peeling and exfoliation is most characteristic of Platten sandstones on buildings). Two to three sheets lying one upon another and blistering at the same time are common. The stone surface underneath the peeling sheets is covered with efflorescences (page 101).

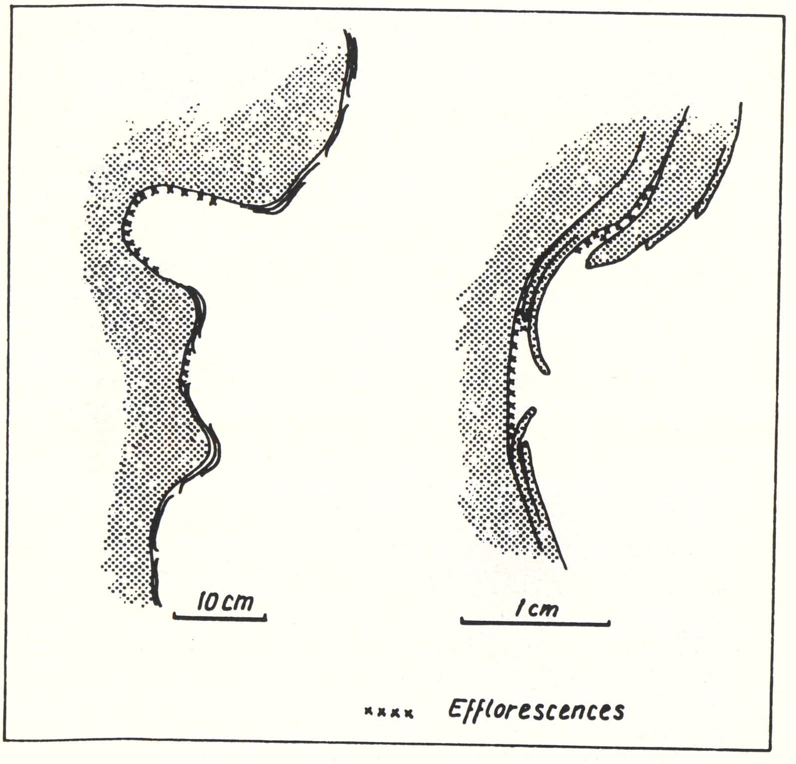

Fig. 6 – Cross-section through rock surface affected by peeling and granular disaggregation (schematically). Left: Alveolation in a peeling area. In an alveole, $MgSO_4$ efflorescences are associated with intense granular disaggregation. Projecting parts are accentuated as blistering stone sheets break off towards an edge. Right: Detail in a peeling area showing $MgSO_4$ efflorescences under blistering stone sheets.

Peeling generally develops in sheltered areas but is most intense where efflorescences concentrate. Projected portions resist disintegration longer even when they are strongly loosened. The blistering sheets consistently break off towards a ledge (figure 6 and 7). By this process, the relief is accentuated and amplified by intense peeling and granular disaggregation in adjoining recesses. Alveoles may represent a subsequent phase in this development.

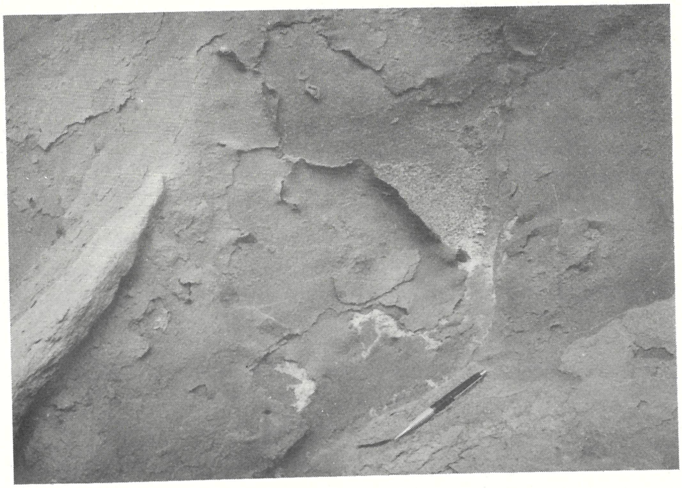

Fig. 7 – Detail in a peeling area. To the left, an edge resists disintegration. In the lower and right centre, peeling off stone sheets reveal $MgSO_4$ efflorescences which crystallize underneath.

Granular disaggregation (and alveolation) is mainly present in the same forms as described on buildings. By granular disaggregation, the formerly sharp-edged rock surface is rounded. An indication of the «erosion rate», gravels project up to 2 cm from the surface in a zone where the rock has been exposed by blasting about 11 years ago. The process is connected with superficial accumulations of $MgSO_4$. Alveolation is an excavation of the stone by locally intensified granular disaggregation. The resulting holes (alveoles) observed are from a few cm to some dm deep and approximately

Fig. 8 – Platten sandstone affected by alveolation (Martinstobel, south from bridge in Martinsbrugg). On the south facing rock, alveoles in the order of some dm to more than 1 m have formed in parts sheltered from direct rain.

as wide. (An ample literature on this phenomenon offers several terms such as shadow and cavernous weathering, tafonisation, honeycombing, etc., compiled by Evans [7]). In the outcrop shown in figure 5, a 20 cm deep alveole has formed among some blurred and smaller ones. On a neighbouring outcrop, a 100 m^2 large area is affected by alveolation. Large hollows in the order of some dm to more than 1 m can overlap a finemeshed pattern of a few cm large holes (figure 8).

Granular disaggregation dominates in the same areas as spalling, peeling and efflorescences occur and is generally associated with them. An alveolation tendency is conspicuous on the south to southwest facing surfaces which are sheltered from rain but well exposed to sun (figure 5 from centre to the left. Similar phenomena in association with $MgSO_4$, Na_2SO_4 and gypsum among other soluble salts are described by Schmölzer [21], Knetsch and Refai [12] and others. Pauly [14, 15] describes a modified type of alveolation associated mainly with NaCl).

Crust formation develops analogously as on buildings, but on outcrops the gypsum crusts are generally white and in most cases less than 1 mm thick. They tend to blister and are associated with granular disaggregation as well.

The formation is restricted to small streaks along zones of water leakage, beginning at the border of the wetted parts to a few cm outwards. The covered area disintegrates very slowly which compares well to the zones on a building where the crusts are as thin. Though the formation of gypsum crusts is subordinate in the considered outcrops, gypsum efflorescences are very common (see next section. Pauly [13] and de Beaucourt, Pauly and Jaton [4] describe a particular case of crust formation on rock where disintegration is related to concentrations of calcite, gypsum and Na_2SO_4 which form both crusts and efflorescences).

Efflorescences of gypsum form filmy white powdery covers. They concentrate in and immediately below the marl beds (marked in figure 5b) in sheltered areas which are reached periodically by ground waters from the marls. The efflorescences follow in cm to a few dm wide strips the borders of these wetted zones. In contrast to the periodically moving $MgSO_4$ efflorescences, gypsum efflorescences disappear only when wetted by superficial waters. The exact shape of wet zones may change from one rain period to the next but their rough pattern is stable. $MgSO_4$ efflorescences form either fluffy white aggregates up to 5 mm thick, or about 1 mm thick rigid sandloaden crusts. In this outcrop, $MgSO_4$ is the only soluble salt which has been found until now. (With a few exceptions of Na_2SO_4, $MgSO_4$ is prevailing in the considered natural outcrops on both Granitic sandstones and on Platten sandstones). $MgSO_4$ efflorescences concentrate besides the periodically wetted zones from the gypsum efflorescences to 0.1-1 m outwards in the sheltered areas. Peeling and granular disaggregation are most efficient in these streaks. In addition, $MgSO_4$ is spread over the rock surface in the area where peeling is observed, as peeling off sheets hide the soluble salt cristallizing underneath (figure 7). $MgSO_4$ efflorescences avoid projected edges but favour adjoining recesses, leading to an accentuation of the relief. In alveoles, $MgSO_4$ forms rigid sandloaden crusts which may peel off like stone sheets.

The observations are too fragmentary to specify the periods of $MgSO_4$ efflorescences in outcrops. Compared to buildings, a seasonal preference is less obvious in this outcrop, the salt seems to disappear only during wet periods (e.g. in March 1979). However, efflorescences are still at the surface in alveoles while disappeared on exposed parts. (A possibile explanation for a prevailing tendency to effloresce might be related to the constant moisture in the rock's interior).

The lower right part of the outcrop (figure 5) is *not affected by any apparent weathering*. This area is not exposed to direct rain, nor is it reached by waters seeping from above or beside.

4. ACCUMULATION OF SULFUR

On buildings as well as on the considered outcrops, most of the described weathering phenomena are somehow connected with concentrations of sulphates, that is gypsum, Na_2SO_4 and $MgSO_4$.

The origin of the sulfur in the outcrop studied is mainly related to the marl beds (marked in figure 5b) which contain up to 4% sulfur. Rust stains on the surface of the marls are often covered by a gypsum halo which indicates an oxidation of iron sulfides. The sandstone contains abundant dolomite which can react with the sulphate waters to form $MgSO_4$ and gypsum as stated by Pellerin [16].

On buildings, the origin of gypsum and Na_2SO_4 is less obvious. A reference to the effect of air pollution is given by analyses of rain and dust precipitations (modified bergerhoff-system, Deuber [5]). At the main station of Zürich, the amount of sulfur in solution is in the order of 1g SO_4/m^2. mounth which is 2-3 times more than in the considered rural area. However, these acid precipitations (average pH 4.0) contain too little Ca and Na (about 5% respectively 1% from SO_4) to saturate all of the SO_4 ions. It is assumed that the lacking cations are likely to originate from cement mortars, chemicals from previous restorations and possibly less important the building stones (Arnold [2]).

In order to get a closer insight to the distribution of sulphates in the stone, Na, K, Mg, Ca and S are analysed in the water extracts of weathering profiles.

Table 1
Concentrations of elements in water extracts from samples A (No. HB 38A) and B (No. B 9)

	Depth (cm)	Na	K	Mg	Ca	S
			(ppm from stone weight)			
A	0.2	70	160	70	225	20
	0.8	70	110	50	235	35
	1.3	110	110	80	(275)	545
	2	150	120	110	(650)	2480
	3	190	130	110	(710)	2230
	4	190	130	80	(700)	1990
	5	270	220	110	(280)	925
	6	310	240	110	(210)	695
	8	320	235	80	(160)	380
	10	360	220	70	(160)	205
	12	390	220	70	(190)	145
	14	340	125	50	(225)	100
	16	390	220	60	(190)	90
	18	340	175	60	(215)	90
					Total S	
	0.2					40
	2					2450
	18					160
B	0.2	40	220	120	(325)	80
	1	50	210	120	(295)	60
	1.8	40	165	110	(275)	60
	2.5	90	170	150	(1550)	3590
	3.2	180	160	160	(320)	605
	4	180	210	160	(235)	420
	5	190	215	160	(385)	780
	6	160	190	150	(345)	740
	8	150	210	150	(265)	525
	11	130	190	150	(235)	305
	14	140	190	170		355
	17	150	190	170		335
	20	140	220	160	(215)	395
	26	130	190	180	(185)	330
					Total S	
	20					565
	26					460

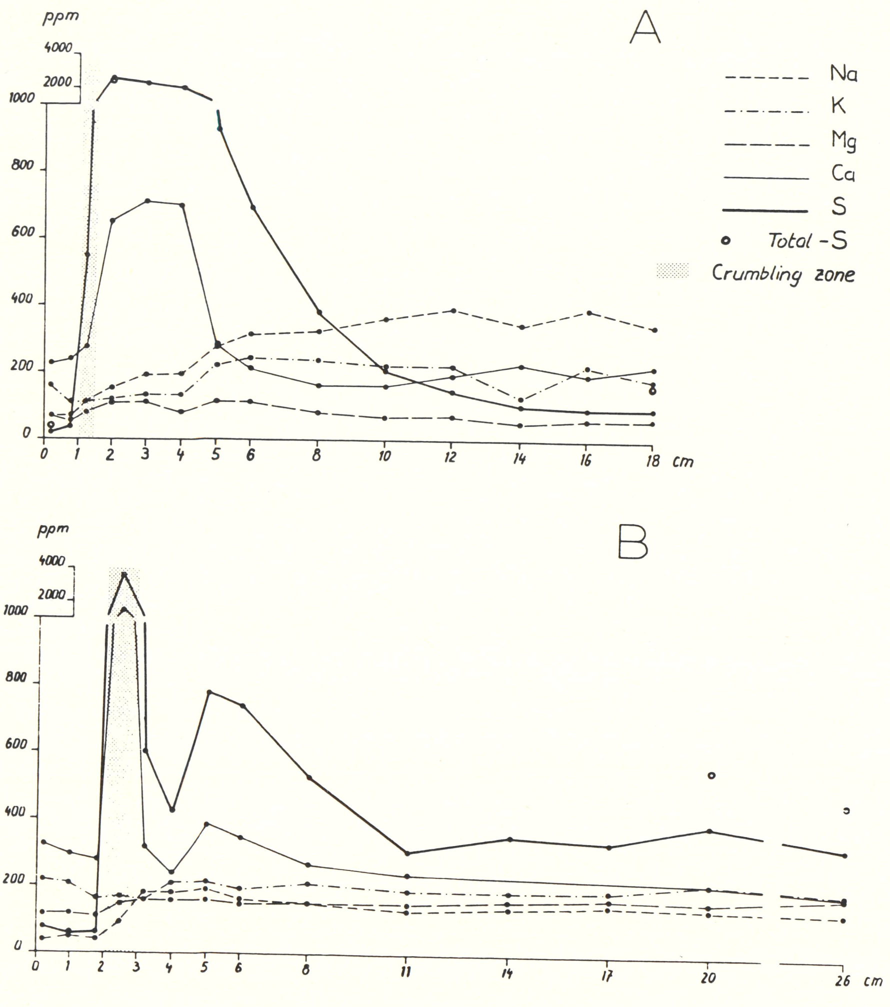

Fig. 9 – Analyses of water extracts from two profiles in contour scaling stones. Sample A (No. HB 38A) is from a south façade of the main station of Zürich, sample B (No. B 9) from the ancient quarry Martinsbrugg (figure 5). Concentrations (ppm from stone weight) are plotted versus depth (cm from surface). Data see in table I.

Cores are taken by dry drilling of the stones. Na, K, Mg, and Ca are analysed by atomic absorption spectroscopy, SO_4 as total S by an apparatus after Geilmann and Tölg [8]. The sulfur determination method has been chosen as it is accurate in the order of 0.1 μg S per ml solution respectively per 50 mg sample. A general inaccuracy of data, arising from the inhomogeneity of samples and determination methods, causes relative errors of ± 10%. Among a series of analysed weathering profiles, we choose two examples. Both are from a contour scaling area, and a crumbling zone has developed on both stones underneath a scale. Sample A (No. HB 38A) is from a south façade of the main station of Zürich, sample B (No. B9) from the outcrop Martinsbrugg (for exact location, see figure 5). The results of the water extract analyses are given in table 1 and figure 9. By comparing the element distributions from samples A and B, we notice:

S and Ca: The relative distributions of S and Ca are roughly the same in each profile from behind the scale to about 10 cm depth. This correlation indicates that gypsum is concentrated in this zone. Highest concentrations are in the crumbling zone in sample B, and/or behind it to a depth of about 7 cm in both samples. The significance of the double-peak in B is not yet clear. The deep penetration of S, and its relatively small maxima (except for the crumbling zone in sample B, they correspond to gypsum in the order of 0.1-1%) are striking. The total S in the interior of the stones is slightly higher than the water soluble S.

Na, K, Mg: In both profiles these elements show significantly different distributions from S and Ca in the zone 0-10 cm. Especially the low concentrations of Na in sample A and Mg in sample B are surprising because they form the main soluble salts in their environments.

Without going further into details, the rough pattern of the displayed diagrams is confirmed from other profiles in contour scaling stones. Conversely, profiles in granularly disaggregating stones yield significantly different distributions in the first 10 cm.

5. CONCLUSIONS

The following outline summarizes the present results, their further discussion is reserved for a more comprehensive study.

- Typical weathering phenomena on buildings in urban area are similar to phenomena in outcrops of the same stone types where sulfur is concentrated in the rock.
- On buildings and in outcrops, resembling phenomena are related to similar exposures to the weather and specific sulphate concentrations.
- Sulphate concentrations in weathering profiles generally form in the outermost 10 cm with a peak in or near the most altered zones.
- Black gypsum crusts are typical for urban areas. In natural outcrops, gypsum crusts form as well, they are white and very thin and associated with gypsum efflorescences.
- Na_2SO_4 is the prevailing soluble salt in the urban area of Zürich, whereas $MgSO_4$ predominates on the same stones in the considered rural areas.
- In the considered outcrop, alveolation is connected with $MgSO_4$ concentrations.
- The influence of frost action in the described phenomena is unknown.

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