Examples of weathering and deterioration of Tertiary building stones at St. Michael's Church in Cluj Napoca (Romania)

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ABSTRACT. St. Michael's Church is one of the oldest Gothic architectural monuments in Cluj, Romania, being built predominantly from Cenozoic (Eocene) limestones, locally known as the Cluj Limestone. These limestones are composed of different facies and microfacies types and were deposited on a shallow carbonate platform. The weathering features correspond to the microfacies types, to the position of the stones in the walls, and to the exposure (E, S, W, and N), which controls the moisture/dry cycles. This interrelationship is documented by macroscopic and microscopic examples of the decay of samples from the lower part of the walls. The general mechanisms of weathering, the migration of moisture, and the formation of crusts of varying mineralogy on the surface of building stones are documented. The macroscopic description of damage includes the decay into plates and flakes, the formation of crusts, the formation of fractures, and the growth of lichens and microorganisms. The microscopic analysis documents characteristic damage in detail: fractures parallel to the surface of the stone, internal cementation of fossil chambers, repeated formation of crusts in varying generations, fracturing in intensively lithified, rigid limestones, and settling of lichens in different positions. Briefly discussed are the behavior of the historical mortars and modern "concrete-mortars" in comparison to the adjacent limestones. Techniques of preservation and restoration are discussed with regards to the most recent methods used. The advantages and disadvantages of surface preservation by silica ester, by hydrophobic substances and by epoxy resin, as well as, acrylic total impregnation, lime slurry, biological lime slurry, and DIN-methods are presented.

Key words: weathering, deterioration, Tertiary building stones.

INTRODUCTION

Located in the heart of Transylvania, Cluj-Napoca (hun: Kolozsvár; ger: Klausenburg) also named "The Treasure City", contains treasures of ancient and modern architecture. Cluj-Napoca is approximately a thousand years old, which is reflected in the diverse cityscape and the monuments from past centuries.

Of all these architectural monuments, St. Michael's Church (Fig. 1) is one of the oldest and most highly esteemed Gothic-style churches and stands majestically in the heart of the Old Town.

The Church was built starting with the 14th century on the site of the older chapel of St. James. St. Michael's Church represents the second largest Gothic Church in Transylvania, after the Black Church in Braşov (hun.: Brassó; ger.: Kronstadt), which was built in the 14th century. The apse is 24 meters high and is the oldest section of the Church, dating back to 1390. The 80-meter-tall tower, including a 4 m high cross on top, was constructed from 1837-1859 in the Neo-Gothic style and was the last section of the Church to be built. The nave of the Church is 50 meters long and the walls 10 meters high.

Fig. 1. St. Michael's Church, main entrance, west side.

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Traces of medieval graffiti are seen on the external walls of the Church. The decoration of the main gate dates back to 1419 and contains three coats of arms from the reign of king Zsigmond: that of the Holy Roman Empire in the centre and those of the kingdoms of Hungaria and Bohemia to the right and left, respectively.

The goal of the present paper is to document characteristic damage occurring in the basal layers of dimension stones in St. Michael's Church. We discuss how their position in the building and their exposure (east, south, west, and north) are influenced by weather. Insolation and wet/dry-cycles (moisture content) are the most important parameters along with the properties the limestone inherited from their deposition (bedding, fossil content, particle size, porosity and clay content).

Several restoration projects have been carried out in the past on sections of the Church. Since then, the various features resulting from continued weathering can be observed, which are linked to the different preservation methods employed in the restoration. Furthermore, the different responses of new stones to weathering are apparent.

This paper could be the first step for an additional restoration of the church. It also takes into account the sedimentological characteristics of the limestones reflected by microfacies types after Flügel (2004). Detailed mapping of damage according to the scheme outlined by Fitzner and Kownatzki (1991) and by Fitzner et al. (1993) should be carried out to determine how information gained from the documented examples can be transferred to the entire outer wall of the Church.

LIMESTONES USED FOR CONSTRUCTION (CLASSIFICATION AND WEATHERING STABILITY)

St. Michael's Church is constructed mainly of Cenozoic (Eocene) limestones that were quarried around Cluj (Fig. 2A). The main quarry was in Baci, near Cluj (Fig. 2B), where the Upper Eocene limestones (Cluj Limestone) were excavated.

Fig. 2. (A) The sketch map of the Cluj area documents the occurrence of Eocene limestones near to Cluj. Legend: 1 = Metamorphic rocks; 2 = Upper Cretaceous deposits; 3 = Paleogene deposits; 4 = Miocene deposits; 5 = Quarry. (B) In the middle level of the Baci quarry a bed about 4 m thick occurs, composed of packstones and grainstones of good building stone quality.

The basal strata of the Cluj Limestone in the Baci quarry (Table 1) are composed predominantly of oolitic-bioclastic grainstone or packstone with well-developed ooids and superficial ooids. Foraminifera, miliolids, minor bivalves, and fragments of gastropods are common in this limestone. Corallinaceans fragments also occur locally throughout the limestone.

Table 1. Petrophysical and technical data of the Cluj Limestone from the Baci quarry (according to Maxim et al., 1959).

Density (g/cm ³)	2.55
bulk density (g/cm ³)	1.70 - 1.79
Porosity (vol.-%)	30.55 - 32.26
Water uptake (vol.-%)	5.11 - 6.38
Saturation index	0.55 - 0.79
Compression strength (kg/cm ²)	288.4 - 463.4
Shockproof (kg/cm ²)	8.4 - 35.4
Abrasion (g/cm ²)	0.79 - 1.03

As a result of the high porosity, large amounts of water can be easily stored within the limestone, making it softer and "easier shaped". After drying out, the limestone

increases markedly in hardness. Maxim et al. (1959) regard an infiltration of dissolved CaCO₃ from the overlying limestones when it is exposed as the main reason for this process.

The bioclastic and oolitic limestones were used predominantly in the construction of historical buildings. They reflect primary deposition on a shallow tropical carbonate platform established in the Transylvanian basin during the Cenozoic (Upper Eocene - Lower Oligocene). The environment of deposition was influenced by episodes of terrestrial (siliciclastic) input from the hinterland locality. Quartz, feldspar grains, and clay minerals were admixed to the carbonate sediment and are responsible for the white to yellowish color of the limestones, its technical characteristics, and different types and degrees of weathering. Clay minerals in particular strongly influence the weathering stability (Cichovski, 1990). The presence of finely dispersed swelling clay minerals in the micritic matrix of limestones (mudstones, wackestones, and packstones) makes these limestones highly sensitive to water uptake and

increased weathering. This effect can be commonly observed in geological young limestone such as the Tertiary limestones described here.

There are numerous examples of historical monuments and stones that demonstrate how weathering is controlled by these primary characteristics (Lorenz 1988a, b; Duttlinger and Knöfel, 1992; de Bario, 2000) and in terms of depositional environment, facies, and microfacies.

One of the first classifications of limestones was established by Folk (1959, 1962). Folk's classification, however, is very complex and includes genetic interpretations. Therefore, the Dunham classification (1962) enlarged by Embry and Klovan (1972) is used predominantly in technical fields (hydrocarbon reservoirs, building stone characteristics). It is more descriptive, easier to handle, and gives a first idea of porosity types and pore-geometry in a limestone. Porosity and permeability are responsible for the moisture transport in rocks and predominantly control the weathering stability. The porosity classification established by Choquette and Pray (1972) is commonly used.

The diagenetic development of limestones on the basis of the analysis of cements is summarized in many textbooks (e.g., Flügel, 2004), and in the classic paper by Longman (1980). Modern examples of the diagenetic development and of pore types in limestones are given by Friedman (1975), Enos and Sawatzki (1981), Fitzner and Snethlage (1982), Snethlage (1985), Fitzner (1988), Grimm (1990), May (1994), Koch et al. (1998, 1999), Koch and Sobott (2005), and Jost-Kovacs and Koch (2007). The most comprehensive book on porosity in sediments was published by v. Engelhard (1960). All the important parameters for deposition, diagenetic alterations, and fluid flow through different pore systems in sedimentary rocks are discussed there.

Three principal parameters are responsible for the decay of rocks in general and sedimentary rocks in particular. Most of the crystals that make up a rock are anisotropic (having physical properties that vary in different directions). One of these properties is the crystal expanding differently in crystallographic directions when the temperature is elevated (Fig. 3A). Calcite crystals show a remarkable anisotropy: when heated they expand parallel to the direction of the c-axes and contract in the direction perpendicular to it. This is the main cause for the characteristic decay of marble, if calcite crystals exhibit preferred orientation.

But thermal expansion can also occur in larger zones of the rock itself. The rock surface is more affected by insolation than the deeper part of the rock. Thus, thermal expansion depends on the orientation of exposure of a rock wall (south, west, north, and east). The heat absorption is stronger when black crusts occur, which are generally formed by a combined process of cementation and fixation of dust particles (soot from coal firing) introduced by air pollution (Krauss, 1988; Mirwald and Brüggerhof, 1995; Ettl and Schuh, 1996). Under such circumstances, swarms of fractures running parallel to the surface of the rock can be formed. Depending on the degree of internal cementation of the rock, the fractures will run around particles of a limestone or will traverse both particles and cements.

Chemical influences (Fig. 3B) by acids or by bases commonly result in dissolution of cementing agents and of single grains. Carbonate minerals such as calcite and

dolomite can be affected by dissolution. The concentration of these cations (Ca^{2+} , Mg^{2+}) will control the type of crust formed at the surface (Arnold, 1992; Ettl and Schuh, 1996). The anions for the crusts come from the air pollution produced by local industry. Carbon dioxide leads to the formation of carbonate crusts, SO_4^{2-} to gypsum crusts, and NO_3^- to the efflorescence of nitrates. The minerals formed have different hygroscopic characteristics and strongly influence the rate of decay of a rock (Snethlage, 1985; Fitzner and Kalde, 1991; Weiss, 1992).

The freezing of pore water and expansion of the ice (Fig. 3C) are most effective in the destruction of rocks. In general, a pore volume should not be saturated with more than 90% water, because the expansion forces of the ice may crack the surrounding rock. A comparable mechanism is valid for the crystallization pressure of salts (e.g., sulfates, halite) if precipitated within a rock from the pore solution (Snethlage, 1985; Fitzner and Kalde, 1991; Arnold, 1992; Weiss, 1992).

Fig. 3. Basic systems in weakening rock texture and in the weathering of rocks.

Biogenic degradation also has to be taken into account (Warscheid et al., 1989; Krumbein et al., 1992). Microorganisms and plants can live on the surface and/or penetrate into the rock. Two things can occur during these processes: physical degradation (growing force of the roots) where single grains (particles) decay, forming a sandy surface, or chemical decay by dissolution of cements and/or particles. Chemical influences depend on the pH of the metabolism-products of organisms, which can be either basic or acidic. Therefore, carbonates and silicates can be affected selectively depending on the pH of the pore water (Friedman, 1975).

The moisture transport within sedimentary rocks is mainly due to capillary forces (Hohl, 1981; Fitzner and Snethlage, 1982; Schön, 1983; Snethlage, 1985; Etris et al., 1988; Grimm, 1990; Koch and Sobott, 2005). Moisture is

usually provided by the surrounding ground water and rain and will migrate upwards due to capillary forces. The resulting amount of moisture (h in Fig. 4) depends on the capillary forces; the smaller the pore diameter, the higher the moisture can migrate. During this process, soluble cations can also be transported from inside the rock to the surface, where crusts are formed (cf. Figs. 4 and 5).

Fig. 4. Schematic picture of weathering due to moisture transport and formation of crusts (after Hohl, 1981). 1 = outer crust (salt and dust), 2 = inner crust (salt), 3 = zone of decay in grains due to dissolution of cements, 4 = original stone without alterations, h = height of capillary rise.

Fig. 5. Formation of crusts on the surface of a building stone due to moisture transport, internal dissolution, and precipitation of material on the surface.

Furthermore, the type and degree of internal cementation during varying stages of lithification in geological times (eogenetic, mesogenetic, and telogenetic, after Choquette and Pray, 1972) has a strong influence on the weathering stability of limestones.

Cementation and/or dissolution can occur as documented by Friedman (1975), because the solubility of limestone and carbonate minerals depends strongly on the carbonate balance (pH, CO_2 -partial pressure, temperature etc.) How the degree of cementation in bioclastic and oolitic

limestones influences the stability against freezing/thaw-cycles was recently documented by Dubelaar et al. (2003) from the Portlandian oolite of Southern England and by Jost-Kovacs and Koch (2007) from the Soskut-limestone, the most well-known Tertiary building stone of Budapest.

MACROSCOPIC ANALYSIS OF DAMAGE AT ST. MICHAEL'S CHURCH

The Cenozoic limestones used in St. Michael's Church are composed of different facies and microfacies types. The different weathering features depend mainly on microfacies types (including amount and composition of fossils), the degree of cementation (lithification), the amount of insoluble residue (non-carbonates, clay minerals), and the pore system (Vol.-%, interconnection and geometry of pores).

The main entrance on the west side (Fig. 1) shows evidence of a number of characteristic weathering features. Close to the entrance, the columns have a hard smooth surface caused by the formation of micro-crusts. They might, however, be augmented by the large numbers of people touching the surface of the limestone, leading to an invasion of sweat (Pl. I, Fig. 1 top). The lower part of some of these columns is composed of weakly cemented limestone and is weathering and decaying into fine sand-sized lime particles (Pl. I, Fig. 1 bottom).

The base of the pillar to the right of the entrance shows intensive formation of surface crusts and decay into sand-sized particles directly under the crust (Pl. I, Fig. 2b). Furthermore, different lichens settle on the surfaces of the limestones depending on the microfacies type of the limestone. Yellow lichens occur on stable limestone with sharp edges (Pl. I, Fig. 2a), whereas grey-black lichens settle on less stable, more porous limestone (Pl. I, Fig. 2c).

Limestones of different weathering stability are sometimes positioned directly beside each other (Pl. I, Figs. 3a and b). This results in different moisture transport and a more rapid decay of the less cemented limestone. Although the unweathered plate (Pl. I, Fig. 3a) was replaced just a few years ago, the difference in weathering is evident. Furthermore, it is not easy to understand why the heavily weathered limestone (Pl. I, Fig. 3b) has not been replaced simultaneously by material with a better stability.

Surfaces of pillars reveal vertical and surface parallel fractures (Pl. I, Fig. 4 arrows) caused by combined processes of thermal expansion (insolation) and formation of crusts. To a certain degree, the sculpturing of the surface of the pillar might be responsible for this damage. Surface treatment often results in micro-damage some mm to cm deeper in the rock due to shock absorption during sculpturing. This preconditioned damage will result in visible damage some years later after the rock becomes exposed.

Some limestones (Pl. I, Fig. 5; sample C.1) commonly reveal decay in fine flakes and single grains due to intensive surface weathering and formation of spotty areas covered by thin crusts. Moreover, these limestones have small areas, which are more resistant than the neighboring areas. Consequently, decay into small rock fragments of a few millimeters in size also occurs.

Decay in thin shells a few millimeters thick is often observed (Pl. I, Fig. 6; sample Cl.2). At these locations,

weathering has caused the shell to protrude a few millimeters to the front forming an open elongated pore space (little cavity) between the shell and the internal surface. This type of weathering is predominantly induced by intensive insolation resulting in thermal expansion and destruction of the limestone by numerous surface parallel fractures.

Nevertheless, the first shell with a smooth surface is commonly influenced by the cutting of the original dimension stone. Sawing a relatively soft limestone can result in the formation of surface parallel microfractures. Also, the formation of a surface of higher density (more resistance?) can occur due to fine powder (produced by sawing) invading the uppermost pores.

Thin paper-like crusts are observed (Pl. I, Fig. 7; sample Cl.4) on the surface of fine-grained oolitic limestones. These limestones commonly reveal boundaries or zones of moisture migration. White zones correspond to dry areas while darker zones correspond to wet areas and occur on both sides of the white zones.

On the northern side of the Church similar shells are often covered by numerous microorganisms and plants (lichens) due to the high amount of residual moisture over a long period of time (Pl. I, Fig. 8; sample Cl.6). Furthermore, it is observable that limestones with higher amounts of non-carbonate material (e.g., clay minerals) are more intensively overgrown by plants and lichens. This is due to the elements (K^+ , Na^+) being released from the limestone by local dissolution and used for the stabilization of cell membranes in the plants and lichens.

The moisture was derived from the mortar between the blocks. The direction of migration is indicated by the decreasing amount of black lichens from the joint between the blocks. The direction of migration can be observed by the downward movement of dark wet zones (Pl. II, Fig. 1). Limestones with irregular cementation show a slightly nodular fabric on their surface as the result of weathering (Pl. II, Fig. 2; sample Cl.10). Depending on the degree of local cementation and the matrix content, these limestones will decay into fragments or into a completely sandy surface structure (Pl. II, Fig. 2). If these limestones are adjacent to concrete mortars, the mortars will end up with a positive relief and the limestones will be completely weathered (Pl. II, Fig. 2 M).

The large interstices are commonly inhabited by insects, which contribute to a rapid decay of the limestones. Often the whole surface of a block is altered in this way (cf. Pl. II, Fig. 3) to such an extent that larger parts of the shell break off. Small limestone flakes occurring under the shells are detached by wind and rain and the shell forming process starts again. In some portions of the wall, newly restored blocks already reveal intensive formation of thin surface crusts. These crusts are caused by the preparation of the blocks in the quarry or in the factory (Pl. II, Fig. 3). Inadequate treatment (sawing, compression) of these soft Cenozoic limestones ultimately leads to the formation of thin surface crusts as described above. Under the crusts the decay of the limestones continues until the crust falls off. It is evident that only certain limestone facies are affected by the combination of irregular cementation and initial block preparation, whereas other limestone facies under the same conditions show almost no weathering.

More clayey limestones with a slightly nodular fabric due to irregular cementation show considerable surface

weathering if associated with mortar (Pl. II, Fig. 4) and influenced by moisture migrating downwards. The internal texture can then be recognized on the surface of the limestone due to differential weathering of particles, nodules, and matrix.

MICROSCOPIC ANALYSIS OF FACIES TYPES AND DAMAGE

The analysis of microfacies (Flügel, 2004) gives information on the internal texture, on the amount and composition of particles (abiogenic and biogenic), on the amount and distribution of matrix (micrite), and on the degree and spatial distribution of cementation. These parameters are finally reflected in the type, amount, and spatial distribution of porosity. Porosity has to be subdivided into effective and dead porosity, which both depend on the pore throat diameters connecting the pores.

Therefore, microfacies analysis is of the greatest value for understanding and interpreting parameters that influence weathering. Microfacies analysis with regard to primary environmental conditions (Enos and Sawatzki, 1981) presents basic data, which allow petrophysical and technical data to be correctly interpreted, as documented by May (1994), Koch et al. (1998, 1999), Koch and Sobott (2005), and Jost-Kovacs and Koch (2007).

The weathering features observed in the Cenozoic limestones used as building stones in St. Michael Church can be largely explained by microfacies analysis. Packstones with a micritic matrix and a distribution of well-cemented areas (Pl. II, Figs. 5 and 6) over larger areas show characteristic weathering features. Microfractures and enlarged fractures can occur at the boundaries between coarser-grained areas rich in sparry cement (grainstone areas) and areas rich in micrite (wackestone to packstone areas; Pl. II, Fig. 5; arrows). Pure micrite areas are rarely traversed by fractures. In contrast, areas that are intensively cemented by granular calcite may often be traversed by marked fractures. The direction of the fractures is not disturbed evenly by the occurrence of biomolds, due to the more rigid behavior of sparite in comparison to micrite. Biomolds and internal open pore spaces in larger fossils often contain coarse granular calcite cements (Pl. II, Fig. 6), which are the youngest of late diagenetic freshwater cements. These calcite cements were formed after the first marine cementation and the uplift of the Cenozoic sediments into the telogenetic zone with terrestrial freshwater influx.

The surface of this sample (Pl. II, Fig. 6) is covered by a dense micro-crust composed of crystalline micrite. This crust was formed by the transport of carbonate-rich pore water from inside the limestone towards the surface due to evaporation (driven by insolation), where the dissolved carbonate was reprecipitated as a crust. Thermal expansion and drying cycles resulted in the uplift of parts of the outer zones, especially in micritic areas. During this process small elongated cavities running parallel to the surface were formed. Consequently, the next dense surface crust was formed deeper in the rock as a new internal surface.

Intensively cemented packstones and grainstones (Pl. II, Fig. 7) reveal the formation of many surface-parallel fractures. These fractures were formed due to insolation and thermal expansion and occur predominantly in more rigid limestones, with abundant sparry calcite cement.

Primary sedimentary boundaries are marked by an alteration of layers between fine and coarse-grained particles (Pl. II, Fig. 7 lower part). These boundaries indicate anisotropy in the limestone. Consequently, fractures will occur predominantly at these boundaries. If such a limestone is exposed with the sedimentary surface parallel to the recent surface of the wall in a building, very thin layers, representing small primary sedimentary units, will be split off from the rock. Particles such as foraminifers, which reveal a complete cementation of the intraparticle porosity, form hard resistant grains ("mini-concretions") that fractures go around.

Lichens and plants commonly settle on the surface of the limestones, forming crusts < 0.1 mm to a few mm thick. On porous grainstones with moderate amounts of sparite almost no crusts are formed. In this situation, lichens just settle in small areas on a hard substrate, often in little depressions. The surface is not completely closed off by a crust and remains open. Lichens spread outside while they are growing and their root system becomes fixed in interparticle and intercrystalline pores. The damage caused by lichen growth commonly results in the decay of minor amounts of the surface and some particles or crystals will be detached from the surface. Roots of lichens can penetrate the grainstone to a depth of about 0.1 – 0.3 mm.

Moderately to well-sorted, very porous oolitic grainstones commonly show a relatively smooth uniform surface (Pl. II, Fig. 8). Certain types of lichens prefer to attach in small fractures parallel to the surface where they are sheltered against intensive sunlight (Pl. III, Fig. 1). The rock is cemented by isopacheous marine cement seams surrounding the calcite particles, which show moderate meteoric overprinting with scalenohedral terminations of some crystals. Due to this cementation, the rock has a homogeneous stability in all directions and reveals no anisotropy. If such a homogeneous well-cemented rock is compacted due to overburden by other large dimension stones, fractures show characteristic spatial distribution and morphology (Pl. III, Fig. 2). Many triple points develop from which the fractures run in three directions. Large clear calcite cements indicate a young freshwater influx along with the precipitation of blocky calcite.

Packstones with grainstone areas having a micritic matrix can be considered as a source of carbonate material that originates from their interior as a result of dissolution of highly soluble micrite (small particle size). The dissolved carbonate is transported by micro-evaporation to the surface of the limestone where it will be reprecipitated forming thin sinter crusts (Pl. III, Fig. 3). Where no carbonate is available in the outer surface (*e.g.*, on a quartz grain, (see Pl. III, Fig. 3) dissolved carbonate cannot be transported, therefore, no crust can form.

Dissolution of micrite continues under the crusts, as documented by the formation of numerous small dissolution cavities. Plants that are growing on these sinter crusts cannot penetrate deeply into the limestone. Only when the crusts are interrupted or broken can they invade. In this case, the continued growth of their roots induces further uplift of the crusts and decay of the sinter surface. Dissolution of matrix and fine-grained cements under the crusts can often be observed and results in the formation of elongated cavities (vugs, after Choquette and Pray, 1970).

Limestones composed of alternations of matrix-rich packstones and porous grainstones (Pl. III, Fig. 4) show

alternating weathering features on their surface within short distances. Lichens roots can invade the limestone depending on the amount of micrite and open porosity (Pl. III, Fig. 5). The more micritic matrix present, the more plants and lichens can remain on the surface. Drying out of lichens, results in vertical fractures, which run down towards the surface of the limestone block.

On the surface of porous, weakly cemented grainstones (Pl. III, Fig. 6), the base of different lichens might be fixed on single grains because no larger surface is available, such as in micritic limestones or on sinter crusts as described above. In these limestones, the dissolution of primarily aragonitic particles and the formation of biomolds are evident. Lichens on dense areas with smooth surfaces due to cements and sinter crusts grow vertically and form a fine interior network with a clear outer isotropic zone (Pl. III, Fig. 6 top left).

REMARKS ON MORTARS USED IN ST. MICHAEL CHURCH

Different historical mortars, mortars similar to historical mortars, and modern concrete mortars can be seen on the walls of St. Michael's Church. Much damage to the Church was caused by inadequate mortars.

Generally, mortars should have petrophysical and technical characteristics compatible with the stones they are binding together. The elasticity modulus (Young's modulus) is one of the most important parameters for characterizing mortars.

Mortars have to be attached to the surface of the building stones without microfractures occurring at these contacts (Pl. III, Fig. 7). The mortar should be elastic and able to absorb tension arising from thermal and hygric dilatation of the building stones. The historical mortars used in St. Michael's Church reflect these characteristics and reveal extremely good binding to the surface of the limestones, regardless of whether a packstone (Pl. III, Fig. 8) or a highly porous grainstone is the substratum.

By contrast, modern concrete mortars from one of the last restoration campaigns usually showed marked damage. The concrete mortars are too hard and weather less than the adjacent limestones (Pl. II, Fig. 2). Thus, marked parallel fractures are formed on both sides of the mortar at the contact with the limestone, due to different thermal expansion.

THE PRESERVATION AND RESTORATION OF WEATHERED BUILDING STONES

The history of preservation and/or restoration of building stones and important historical monuments are long and have seen many successes and failures. Modern techniques and examples of special stones and materials used in the preservation/restoration are described in books by architects, geologists, and chemists (Frank, 1983; Horie, 1987; Ashurst and Dimes, 1990; Snethlage and Wendler, 1996; Snethlage, 1997; Koch et al., 1998), as well as for special stones (Sattler, 1992; Jbach et al., 1999) and special materials (Jbach, 1981; Ettl and Schuh, 1989; Goretzki and Schmidt, 1991).

Generally, there are many ways of restoring or preserving a monument. There is no "golden rule" for

handling the matter. Architects, restorers, and natural scientists have to find an adequate solution for the monument under consideration. Among the many points to be considered are the material to be conserved, its state of decay, its size and location, etc. In one case, it is sufficient to copy the original monument and to store the original in a museum, in another, every effort must be made to restore original monument.

The basic question is whether or not a monument should remain exposed to the elements. This is of course, is not a question for large monuments, such as a city wall or a church; but it could be for parts of it. People can only recognize the historical techniques of stonemasons and become aware of stone decay if they can see a monument in its natural environment. Therefore, the basic question is to decide if a rock (monument, historical, especially valuable parts of a wall) should be accessible to the public. If possible, the monument should be kept in a museum if it is in a bad state that it cannot be preserved by modern restoration techniques.

If a stone monument has to be restored, different techniques are now available that have been developed over the last hundred years and are continually being improved by new methods and materials (Frank, 1983; Horie, 1987; Ashurst and Dimes, 1990; Winkler, 1994; Snethlage, 1997). One must take into account, however, that for each type of stone (facies type) the proper method of preservation/restoration has to be carefully selected (Sattler and Snethlage, 1988; Wendler and Sattler, 1989; Gerdes and Wittmann, 1999; Boos and Sattler, 2001).

This implies for the current example of the Tertiary limestones in St. Michael's Church, the limestones should be classified into microfacies types, which correspond to groups with characteristic uniform petrophysical parameters. Using this as a basis, large areas of the wall can be treated with the same restoration method or a combination of methods. Nevertheless, the adjacent stones have to be taken into account and it should be established that they have similar petrophysical characteristics.

Many companies practice a general surface preservation method by using silica ester and often apply hydrophobic materials in order to diminish the water uptake for a certain time span. Surface treatment often results in different behavior of the uppermost part of the treated rock compared to the untreated rock below. This often leads to more intensive damage directly under the conserved surface.

One should check to see if the material used in the preservation is bound to the surface of carbonate grains. Furthermore, pore spaces should remain open so that the water exchange is not hindered. The thermal expansion of the treated zone and the untreated rock should have the same order of magnitude in order to avoid tension between treated and untreated zones. This is also valid for the stabilization of surface zones when using epoxy resin. The epoxy resin binds loose particles well; however, its use often results in completely different thermal behavior of the treated zones.

The limestone surfaces are often preserved by treating them with lime slurry, which fits snugly into the contours of the limestone material. This "natural method" has to be renewed at certain time intervals, which must be taken into account in calculating the costs of a survey and for renewed treatment.

The method of full impregnation by acrylic acid is only possible for monuments or rocks that can be removed from

the building and brought into an autoclave where the treatment is carried out. Nevertheless, it must be noted that this method results in a large increase in the stability and other characteristics of the treated rock, allowing the preservation to last for much longer time (Goretzki and Schmidt, 1991; Jbach, 1981).

Even if only parts of dimension stones on a wall are replaced by artificial stone replacement material, it must be established that this corresponds to the characteristics of the rock. For this purpose, the most important technical and petrophysical parameters should be analyzed according to the DIN and EN norms (DIN 52100, 1992; DIN 52100-2, 2007; DIN 52102, 2006; EN 13755, 2002; EN 12371, 2002; DIN 52104-2, 1982; DIN 52106, 2004; EN 12370, 1999).

Further parameters which must be analyzed in order to find the adequate stone for the restoration should be the different types of porosity (Weiss and Schellhorn, 1989), the water uptake (Wendler and Snethlage, 1989) and saturation index, the permeability and the pore-throat diameter (Purcell, 1949; Metz and Knöfel 1991), and in certain cases also the specific surface (Brunauer et al., 1938).

The great problem of salt in limestones has to be taken into account. Salts have multiple influences on weathering and even on the preservation of the limestones. The various salts have different expanding forces, resulting in various degrees of damage to the limestone. Various hygric characteristics also prevent a rock from drying out. Furthermore, salts seriously hinder preservation, because fluids used to preserve the limestone cannot attach to the surfaces of grains (inner surface of a rock) if they are covered by salts.

Therefore, the analysis of damage in regard to the microfacies types of the limestones used in St. Michael's Church might be the first step towards the future restoration of the dimension stones and reliefs. In addition, the exposure, the moisture content, capillary movement, and possible influences by salt used on the roads in winter must be taken into account.

A detailed mapping of the damage, the different limestone types, and the actions to be carried out according to the analysis of the interrelationships between damage and microfacies types will be a sound basis for a realistic estimate of the costs of the restoration.

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PLATE I

Plate I. Macroscopic analysis of damages

Fig. 1. Formation of smooth microcrusts on the top part of small columns due to invasion of sweat from large numbers of people touching the limestone. The weakly cemented limestone at the bottom shows marked decay to fine sand-sized lime particles of.

Fig. 2. Intensive formation of surface crusts and decay in sand- sized particles directly under the crust (b). Yellow lichens settle on more horizontal parts of hard limestone (a) whereas gray-black lichens settle on less stable, more porous limestone (c).

Fig. 3. Limestones of different weathering stability (a) are positioned right next to each other, which results in more intensive decay of the less stable limestone (b).

Fig. 4. Surfaces of pillars reveal vertical (black arrows) and surface parallel fractures (red arrow), which are caused by combined processes of thermal expansion (insolation) and formation of crusts.

Fig. 5. Decay in fine flakes and single grains, due to intensive surface weathering and formation of spotty areas covered by thin crusts, can be observed locally.

Fig. 6. Decay in thin plates of some few millimeters thick can often be observed. Movement of the plates a few millimeters to the front creates open elongated pore spaces (small cavities) between the plate and the internal surface. The large interstices are commonly settled by insects, which also contribute to a more rapid decay of the limestones.

Fig. 7. Very thin paper-like crusts can be also observed on the surface of fine-grained oolitic limestones. Boundaries of moisture migration are documented as white zones, which correspond to the driest areas. Wet zones are darker and occur on both sides of the dry zones.

Fig. 8. On the northern side of the Church weathered surface plates are commonly covered by numerous microorganisms and plants (lichens) due to the large amount of moisture remaining in them over a long period of time.

PLATE II

Plate II. Macroscopic and microscopic analysis of damages

Fig. 1. Downward movement of dark wet zones can be commonly observed where moisture is transported along the slits between the blocks.

Fig. 2. Limestones with areas of less cemented or of intensively cemented areas show a slightly nodular fabric on their surface during weathering. If less cemented, the limestones can decay into a completely sandy surface. The mortars will end up with a positive relief (*M*) and the limestones will be completely weathered.

Fig. 3. In some parts of the wall newly restored blocks already reveal intensive formation of thin surface crusts, which seem to have been caused by the preparation of the blocks in the quarry or in the factory (sawing, compression).

Fig. 4. More clayey limestones with a slight nodular fabric due to internal areas of cementation show considerable surface weathering when associated with mortar.

Fig. 5. Packstones (sample Cl. 1) with micritic matrix and with a distribution of well cemented areas in larger areas show microfractures and enlarged fractures (arrows) occurring at the boundaries between coarser-grained areas rich in sparry cement (grainstone areas) and areas rich in micrite.

Fig. 6. Biomolds and internal open pore spaces in larger fossils often contain very coarse granular calcite cements, which are the youngest formations of late diagenetic freshwater cements (sample Cl. 1).

Fig. 7. Intensively cemented packstones and grainstones (sample Cl. 2) reveal marked formation of many surface-parallel fractures. They were formed due to insolation and thermal expansion and occur predominantly in more rigid limestones with abundant sparry calcite cement.

Fig. 8. Moderately to well sorted, very porous oolitic grainstones (sample Cl. 4) commonly show a relatively smooth uniform surface.

PLATE III

Plate III. Microscopic analysis of damages and mortars

Fig. 1. *Very porous oolitic grainstone. Special lichens have settled in small surface-parallel fractures where they are sheltered against intensive sunlight. The rock is cemented by isopacheous marine cement seams around particles, which show moderate meteoric overprinting with scalenohedral terminations of some crystals (sample Cl. 4).*

Fig. 2. *Porous, oolitic well-cemented grainstone (sample Cl. 5) compacted due to overburden by other large dimension stones. The pressure induces to the fracture-triple-points development causes fractures run in three directions.*

Fig. 3. *Dissolved carbonate from the inside of limestones is transported by micro-evaporation to the surface of the limestone where it forms thin sinter crusts (sample Cl. 6). On non-carbonate grains (quartz, top) through, which the dissolved carbonate cannot be transported, no crusts are formed.*

Fig. 4. *Limestones that are composed of alternations of matrix-rich packstones and porous grainstones (sample Cl. 7) show alternating weathering features on their surface within short distances.*

Fig. 5. *Roots of lichens can invade the limestone depending on the amount of micrite and open porosity. The more micritic matrix is present, the more plants and lichens remain on the surface (sample Cl. 7).*

Fig. 6. *On the surface of very porous weakly-cemented grainstones (sample Cl. 8) the base of different lichens might be fixed to single grains, because no larger surface is available such as in micritic limestones or on sinter crusts as described above.*

Fig. 7. *Good mortars (sample Cl. 10) are attached to the surface of the rocks without microfractures occurring at these contacts.*

Fig. 8. *The historical mortars reflect these characteristics and reveal extremely good binding to the surface of the limestones regardless of whether a packstone or a highly porous grainstone is the substratum (sample Cl. 10).*