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Cretaceous sandstones in Moravia and Silesia and their application as building and ornamental stones

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Abstract. Sandstone is the rock type most widely used for building and ornamental purposes in the Moravian and Silesian regions. Many types of Cretaceous sandstone have been used for construction throughout history, most of which come from numerous small quarries along the south-eastern margin of the Bohemian Cretaceous Basin and the Outer Carpathian nappes (Silesian Unit). However, production currently continues only at the Řeka locality (Outer Carpathians). The Bohemian Cretaceous sandstones that have been surveyed are quartzose with high proportions of SiO_2 and low alkalies. The Outer Carpathian sandstones are glauconitic, with local calcareous cement, and higher proportions of Al_2O_3 and alkalies. The Bohemian Cretaceous sandstones are the more mature of the two. Furthermore, the physical properties of the sandstones from these two regions differ significantly, with those of the Bohemian Cretaceous Basin showing lower bulk density, compressive strength and frost resistance, and higher porosity and water absorption than those of the Outer Carpathian, Silesian Unit. The thermal properties of these two sandstones differ as well, the Carpathian sandstone being a better heat conductor. Both types are suitable for construction purposes: the Carpathian sandstone as a dimensional/building stone (due to its lower degree of workability) and Bohemian Cretaceous sandstone as an ornamental stone. The current sources would be able to sustain future exploitation.

Key words: Cretaceous, sandstone, building stone, ornamental stone, petrology, Moravia, Silesia

Introduction

Sandstones have been used as construction material in Moravia and Silesia since ancient times. The center of the town of Olomouc provides a good example of the wide use of sandstones in many large, historical structures, such as the St. Wenceslas Church. The use of sandstones is also known from Moravian medieval castles such as Bouzov (Cenomanian quartzose sandstones of the Orlice-Žďár Unit), Hukvaldy (quartzose sandstones from the Silesian Unit of the Outer Carpathian nappes), and Buchlov (Tertiary quartzose sandstones from the Magura nappes of the Western Carpathians). The sandstones from the Magura nappes were also used in the city wall around the town of Kroměříž. Sandstones were appreciated for their easier extractability and workability compared to other rock types, as well as for their availability and easy transport within the Moravian and Silesian regions.

The application of sandstone as building and ornamental stone increased significantly during Renaissance and Baroque times. The development of sculpture during the Baroque period, in which many structures were decorated with statues, encouraged the quality assessment and further exploitation of this rock type. As a result, selected kinds of sandstones were used as ornamental stone, others for construction. Examples in the Moravian region include the Maletín (the Orlice-Žďár Unit of Czech Cretaceous Basin) and the Petřkovice quartzose sandstones (Lower Cretaceous, from the Hradiště Formation within the Western Carpathian Silesian Unit). In addition to these, glauconitic sandstones (Upper Cretaceous, from the Godula Formation in the Silesian Unit) have been widely used in a raw or roughly worked state. Devonian, Lower Carboniferous, and Permian sandstones have sometimes also been used in addition to those of the Cretaceous and Tertiary. Jahn (1917, 1931), Mrázek (1990), and Rybařík (1994) have described the applications of these sandstones with respect to their characteristics.

In the present article, sandstones used as building and/or ornamental stones are petrographically characterized and classified within their regional geological units. It will thus be possible to predict a sandstone behaviour and durability when exposed to the elements.

Methods

During the field survey, samples of Cretaceous sandstones were taken from the Bohemian Massif and the the Silesian Unit of the Outer Carpathians. Samples were collected from both quarries and building structures, and have been prepared for thin sections, chemical analyses, element distribution mapping, and physical tests. The Jenapol U polarizing microscope was used for petrographical study. Silicate analyses of the main rock-forming oxides were conducted in the chemical laboratory of the Department of Mineralogy, Petrology, and Geochemistry of Masaryk University. EDX analyses were conducted at the same institution. The physical properties of the samples were tested based on the formal standards of the Civil Engineering Faculty in Brno. For specific thermal tests, small tabular samples (40 × 40 mm, with thicknesses of 9, 12, and 24 mm) were used. Infrared radiation was produced using the Philips HP 3616 tungsten lamp, the parameters of which are shown in Fig. 1. Temperatures were measured by a Testo contact gauge, and the readings were stored in a Testo 171-6 data

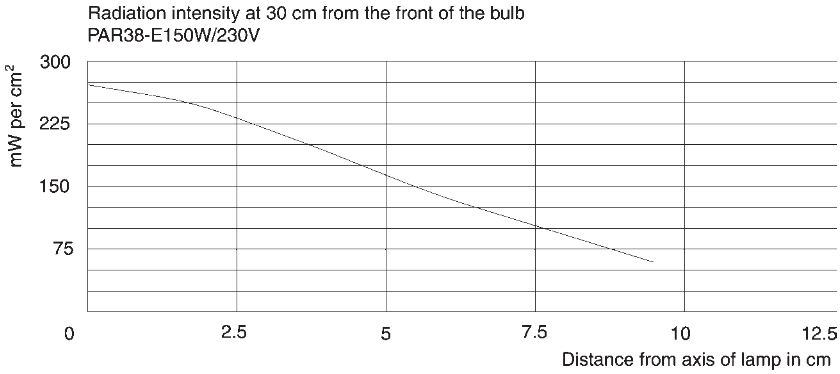

Figure 1. Intensity of infrared radiation: tungsten lamp PAR38-E (Philips).

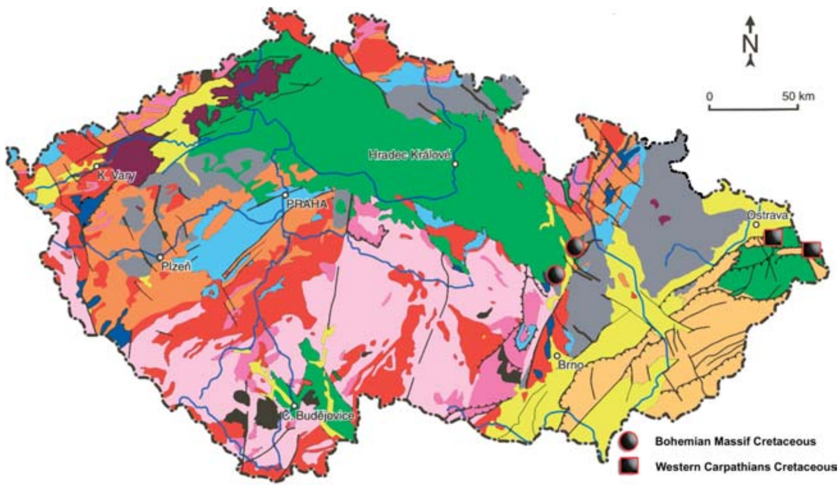

Figure 2. Schematic geological map showing the major regions of Cretaceous sandstone production in Moravia and Silesia (according to CGS).

logger. The heat lamp was axially centred 30 cm in front of the sample, and the temperature was measured from the back of the sample in dry and water saturated states, with exposure times of 30 minutes. The conditions for all measurements were identical.

Geological characteristics

The Cretaceous sandstones of the Bohemian Massif

Cretaceous sandstones occur in the Moravian and Silesian regions in two very different geological environments (Fig. 2). The southeastern part of the Bohemian Cretaceous Basin extends into northwest and central Moravia, and belongs to a system of epicontinental basins that were connected by the Cenomanian transgression (Přichystal et al. 1993). Sedimentation in this part of the basin began as separate depressions in freshwater conditions at the turn of Albian/Cenomanian. With the continuing subsidence of the entire area, transgression of the sea began during the Cenomanian, causing the onset of marine conditions. The oldest sediments form the Peruc-Korycany Formation, which is usually divided into the older Peruc Formation, with quartzose conglomerates and sandstones alternating with siltstones and claystones. These are lacustrine and alluvial sediments, with bed thickness ranging from tens of centimetres to metres. The total thickness of the Peruc Formation is up to 120 m. The Korycany Formation (overlying the Peruc Formation) represents a marine transgression that occurred in several phases. Its characteristic lithology is quartz-kaolinitic sandstone with an admixture of glauconite. The proportion of glauconite increases towards the top of the formation, as the colour of the stone changes to a characteristic green-grey shade. Sandstones often alternate with fine-grained conglomerates, sometimes with siltstones (Chlupáč et al. 2002). The ratio of sandstones to other rocks in Bohemian Cretaceous Basin is about 31%, according to Kukal (1985).

The Cretaceous Sandstones of the Western Carpathians

Cretaceous and Tertiary sediments that form nappes in the flysch of the Western Carpathian orogen extend into eastern Moravia and Silesia. They were deposited in a marginal sea of the Tethys Ocean. Cretaceous sediments are known from the Magura and Outer group of nappes. The complete sequence of Cretaceous sediments from the Berriasian to the Maastrichtian has been documented in the Silesian Unit of the Outer group of nappes only (Přichystal et al. 1993). Flysch sedimentation in the Silesian Unit, with the formation of the thick Těšín-Hradiště Formation, began in the Valanginian following the deposition of limestones at the turn of the Jurassic/Cretaceous. The development of sandstones in the lower part of the Hradiště Formation documents tectonic activity and the deposition of detrital material. The thicknesses of separate layers reaches tens of metres (Menčík et al. 1983). Sedimentation continued in the overlying beds, with the deposition of varied claystones from the Cenomanian to the Lower Turonian. The bed of the Ostravice sandstone replaces varied claystones in the Godula development. The major sedimentation change occurred in the Upper Turonian. The mobility of the flysch sedimentation areas was increased by the Austrian and Mediterranean orogenies, bringing an end to the period of unified sedimentation that characterises the Lower Cretaceous. The Godula Formation reaches up to 3000 m and is connected to subsidence of the sea bottom in this area. Its central part is formed by coarsely rhythmic flysch depositions, with a prevalence of glauconitic sandstone (which is the most widely used sandstone in northern Moravia and Silesia). The thicknesses of individual beds reaches up to several tens of metres (Menčík et al. 1983). The Istebná Formation overlies the Godula Formation, and has been quarried episodically up to the present. It is comprised mostly of arkose and greywacke sandstones with conglomerates, alternating with beds of black-grey claystones with thicknesses ranging from 40 to 200 m. The total thickness of the formation reaches 1200 m. Rocks of the Baška Formation (which covers Těšín, the Hradiště Formation) have also been used locally. It is a medium to coarsely rhythmic flysch formation, formed of calcareous sandstones (often with glauconite), sponge-spicule cherts, limestones, and calcareous claystones. The proportion of sandstone increases towards the overlying beds (Chlupáč et al. 2002).

Major localities of sandstone exploitation

Locations in the Bohemian Cretaceous Basin at which the quarrying of sandstone has been documented include Maletín, Mladějov, Březová nad Svitavou, Moravská Chrastová, Boskovice, Valchov, Skalice nad Svitavou, Rájec, Dolní Lhota, and Buková (Jahn 1917, 1931, Mrázek 1990, Rybařík 1994). Starý Maletín is the most significant of these sites. The quarrying of sandstone at this location resumed in 1994 (Morávek 1994). The quarry is situated approximately 2 km northwest of the Starý Maletín village (Figs 3 and 4), on the west slope of the Vysoký vrch Hill. The quarry is accessible by a rough driveway. This geological environment is part of the eastern margin of the Kyšperk Syncline. The Cretaceous beds in the Maletín area are gently inclined and oriented toward the west-southwest. Throughout their thickness, these Cretaceous sediments include alternating beds of claystones and grey-yellow, locally white-grey or rusty-brown, smudged to laminated quartzose sandstones (freshwater/brackish water). They formed during the Cenomanian, and have a thickness of 20 to 35 m. The fine-grained "Maletín" Sandstone occurs within this formation. This sandstone features block disintegration, and forms the upper parts of the Peruc Formation. Its granularity varies locally, and it alternates with conglomerate. These sandstones indicate an environment of shallow coastal lagoons. The Korycany Formation (white-grey to brown-grey, locally greenish glauconitic sandstones) overlies the Peruc Formation. Towards the top, the sequ-

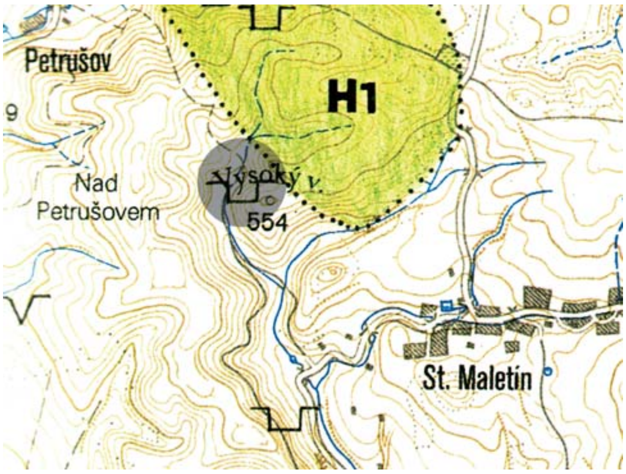

Figure 3. Detailed map showing the position of the quarry (scale 1 : 50 000 CGS).

Figure 5. Detailed map showing the position of the quarry (scale 1 : 50 000 CGS).

Figure 4. Overview of the quarry near Starý Maletín when active. The quarry wall is approximately 40 m long and 12 m high. Photo by P. Pospíšil.

Figure 6. Overview of the quarry near Řeka when active. The quarry wall is approximately 40 m long and 12 m high. Photo by P. Pospíšil.

ence of beds continues with sponge-spicule siltstones of the Lower Turonian. This quarry is of significance for palaeontological studies as well. The activity at this quarry has recently stopped, and it is currently abandoned.

Figure 7. Fresh fracture surface. Godula Sandstone, from the quarry near Řeka. Photo by P. Cikrle.

Figure 8. Clay shales above and beneath the Godula Sandstone bed at the quarry near Řeka. Photo by P. Cikrle.

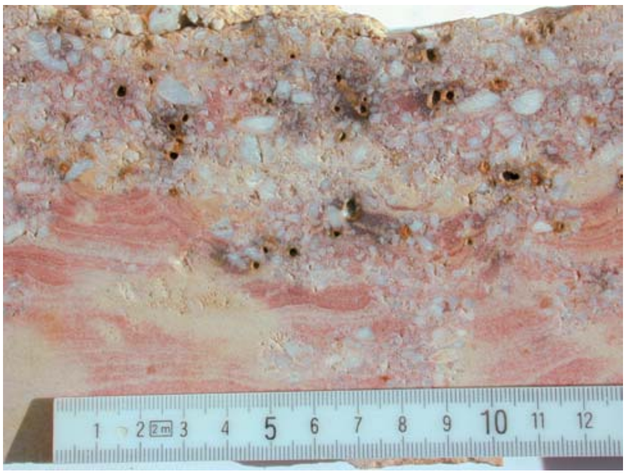

Figure 9. Red-violet streaks caused by Fe oxy-hydroxides and variations in granularity in the Maletín Sandstone. Photo by P. Pospíšil.

The following localities within the Moravskoslezské Beskydy Mountains are centres of historical sandstone production: Řeka, Petřkovice, Janovice, Zašová, Valašské Meziříčí, Prostřední Bečva, Horní Bečva, Trojanovice, Nový Jičín, Štramberk, Hukvaldy, Čeladná, Frýdlant nad Ostravicí, and Jablunkov (Jahn 1917, 1931, Menčík et al. 1983, Rybařík 1994). The most significant of these localities is Řeka, which has been registered in the database of Geofond mineral resources. Other quarries at which activity is intermittant include Trojanovice (Godula Formation), Hažovice, and Horní Bečva (Istebná Formation).

The quarry near Řeka is located on the northern margin of the village, on the left side of the Řeka-Střítež road, on the east slope of the Godula Hill (Figs 5–8). This deposit is exposed in a shale-sandstone formation in the middle of the Godula Formation. These sediments represent an area close to the front of the Godula nappe (Silesian Unit in the Outer Carpathian Flysch Zone). Sandstone prevails over clay shale within this deposit, with shales forming approximately 4% of total deposit volume (Marková 1961). The thickness of the sandstone beds varies from 0.3 to 4 m. Alternating dark grey to black clay shales, with thicknesses from 0.1 to 1 m, are usually removed from the sandstones during the quarrying. The size of the quarry is approximately 100 × 80 m. The orientation of beds is mostly horizontal. The beds are not tectonically jointed. Joints occur only locally in the N-S and E-W directions, with inclinations of 80 to 90 degrees.

Sandstone properties

Petrographical properties

The chemical, physical, and mechanical performance and durability of a sandstone can be predicted based on an accurate description of its mineralogy, texture, and microscopic features. Depending on the proposed application of a certain sandstone, other methods should be used in con-

Figure 10. Red-violet streaks (Fe oxy-hydroxides) in the Maletín Sandstone. Detail from a statue in the Botanical Garden at Kroměříž. Photo by P. Pospíšil.

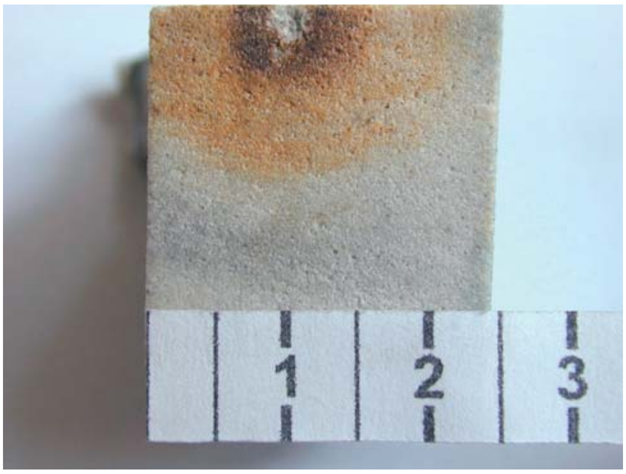

Figure 11. Macroscopic nodule in the Maletín Sandstone, formed by Fe oxy-hydroxides during pyrite weathering. Photo by P. Pospíšil.

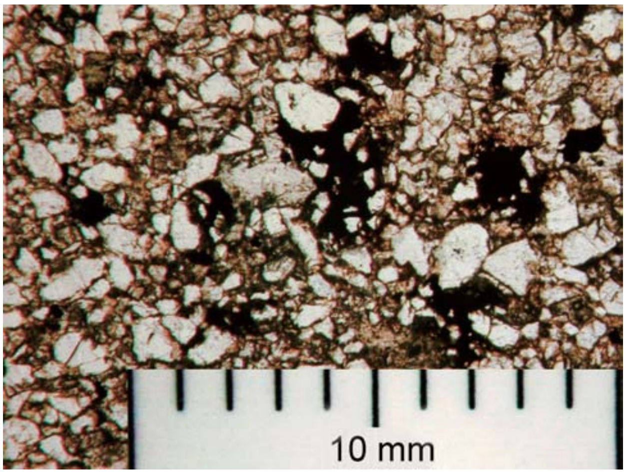

Figure 12. Fine-grained texture of the Maletín Sandstone. Locally formed Fe cement. II N. Photo by P. Pospíšil.
Microscopic description: Quartz grains are subangular to subround. Plagioclases are locally polysynthetically twinned and sericitized. K-feldspars are microperthitized. Neither feldspar is abundant. Micas are represented by muscovite and rarely by biotite. Rare, subangular rock fragments are of sericite schists. Accessory minerals include zircon, tourmaline, epidote, and rutile. Pyrite occurs rarely. Matrix is formed by clay minerals. Cement is mostly silicious (chalcedony), locally coloured by Fe oxy-hydroxides.

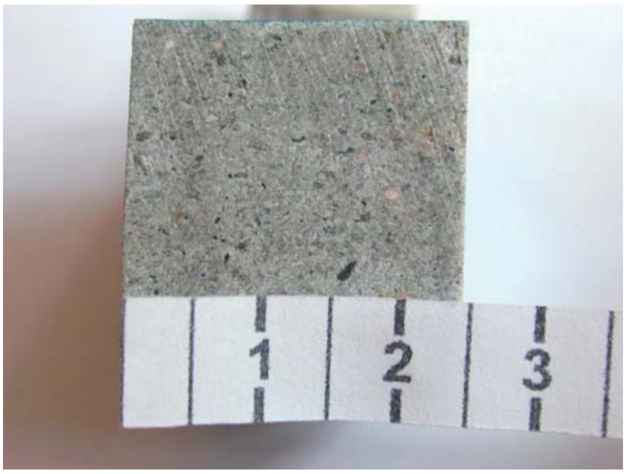

Figure 13. Sample of Godula Sandstone. Photo by P. Pospíšil.

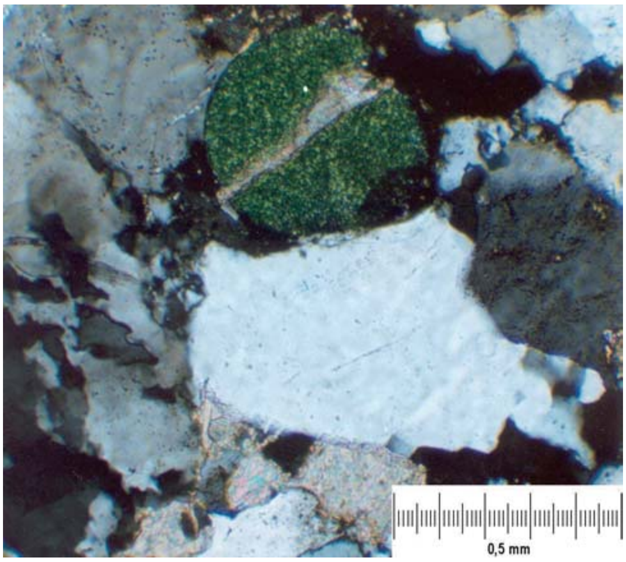

Figure 14. Carbonate cement replacing quartz and rounded glauconite within pores in the medium-grained Godula Sandstone. X N. Photo by P. Pospíšil.
Microscopic description: Quartz grains are subround, locally ruptured, with secondary crystallized quartz or calcite in fissures. Calcite cement locally replaces quartz grains. K-feldspars are ruptured, subrounded, and microclinized or perthitized in some places. Plagioclases, which occur less often than K-feldspar, are subangular to subround, and polysynthetically twinned. Both feldspars are kaolinized and sericitized. Scales of muscovite are rarely plastically deformed. Subround glauconite grains occur frequently. Fragments of rocks represent orthoquartzite, schist, volcanic rock, and bioclastic limestone. Accessory minerals include tourmaline, garnet, zircon and apatite. Carbonate cement forms recrystallized calcite and sparite.

junction with petrography for predicting the service time of the stone.

Cretaceous quartzose sandstone of the Peruc Formation, Bohemian Cretaceous Basin

This sandstone is white-grey in colour, with some yellow. It is mostly fine-grained, even though it locally alternates with conglomerates (Fig. 9). Some parts contain thin layers of small, red-violet coloured, orbicular aggregates of pyrite (Fig. 10). There are also brown secondary oxy-hydroxides of Fe (Figs 11, 12). The cement is mostly siliceous, though a ferrous cement occurs at some places. The crystallinity of the siliceous cement is similar to that of chalcedony or quartz. Isometric quartz grains often form a mosaic texture. The thin coating on the fissure walls is locally formed of white or bluish chalcedony. Foraminifera and sponge-spicules occur in these sandstones (Zimák and Pek 1996).

Cretaceous glauconitic sandstone from the middle part of Godula Formation, Godula development, Silesian Unit, Outer Flysch Carpathians

This sandstone is grey-blue, sometimes green-grey. It is fine- to medium-grained, with glauconite and locally developed calcite cement. The grain size varies within the interval 0.02–0.05 mm, sometimes up to 2 mm (Figs 13, 14).

Figure 15. Gradual weathering of the Maletín Sandstone caused by moisture and frost action in the basement of a seventeenth-century structure in the town of Olomouc. Photo by P. Pospíšil.

Figure 16. Exfoliation of the Godula Sandstone caused by a combination of moisture and frost. Basement of the Military Academy in Brno (20th century). Photo P. Pospíšil.

Figure 17. Detail of exfoliation on the margin of a tile of Godula Sandstone, approximately 50 years old. Military Academy in Brno. Photo by P. Pospíšil.

Figure 18. Exfoliation of Godula Sandstone in an approximately 5 years old basement wall in Třinec. Photo by P. Cikrle.

Physical properties

Among the physical properties of sandstone, it is important to study those that essentially affect its application to construction and ornamental purposes. The following properties have been examined in the present study: bulk density, water absorption under atmospheric pressure (closely related to open porosity), and compressive strength (according to valid standard approaches). Additionally, we have tested selected thermal properties that affect the durability of sandstones in an outside environment.

Sandstone usually has a higher ability to absorb water compared to other rock types, due to the presence of open pores. These pores are of an optimal size for capillary water migration. Water absorption plays an important role in the freezing/thawing cycle and the subsequent mechanical decay of a stone. Differences in the compressive strength among individual samples of the same type are apparent. The present study confirms the material heterogeneity and anisotropic behaviour of these sandstones. This behaviour complicates their applicability to construction. The service life in outside conditions is highly variable, and depends mostly on the nature of a sandstone matrix/cement (Brunjail et al. 1993, Winkler 1994).

Bulk density is an important factor for a sandstone applicability for construction purposes (for instance, in retaining walls). The Godula type sandstones of the Silesian Unit show $\rho = 2610$ kg . m^{-3}, while the Maletín Sandstone of the Bohemian Cretaceous Basin shows only $\rho = 2250$ kg . m^{-3}. The water absorption of the Godula Sandstone is $NV_{48} = 1.47$ wt%, while the same value for the Maletín Sandstone is $NV_{48} = 6.62$ wt%. Frost resistance is closely related to water absorption and significantly limits the application of sandstones. This property has been measured in our samples from 25 freezing/thawing cycles. The frost resistance is $KM_c = 0.95$ for the Godula Sandstone and $KM_c = 0.80$ for the Maletín Sandstone. Compressive strength is also important with respect to construction purposes. The compressive strength of the Godula Sandstone, $R_c = 130$ Mpa, is much higher that of the Maletín Sandstone, at $R_c = 75$ MPa. However, all of these values indicate that these sandstones are sufficient for construction purposes. Mechanical test results confirm that the Godula Sandstone is more diagenetically strengthened, and its workability is lower. Therefore, it is a suitable material for armour stone and other exterior applications. The Maletín Sandstone is not as strengthened, and can thus be used for sculptures and other artistic applications (though we recommend it be placed inside a building, or at least under a shelter). As both sandstones differ in their physical properties, we thus defined the specific aspects limiting their appropriate use. Note that the effects of moisture, frost, and insolation are very important in the climate of the Czech Republic (Figs 15–18).

The processes of physical and chemical degradation are affected by temperature variations. Therefore, the specific behaviour of our sandstone samples was experimentally tested. This experiment was based on the assumption that sandstones exposed to outdoor conditions receive solar radiation of varying intensity and length of time. The amount of absorbed heat energy depends on the object's azimuthal orientation and angle to the horizontal plane, the emissivity of its material, and its structure and/or colour (Fig. 19). Identical experimental conditions were established for all samples. The samples were irradiated for period of 30 min at an intensity of 2500 W . m^2. This condition is comparable to the maximum radiation intensity during the summer, which that is three times lower but of longer duration (Vaverka et al. 2000).

It appears that the total amounts of radiation energy to which sandstone objects are exposed in nature was approximately equal to that of the laboratory experiment. The results of these tests are shown in Figures 20 (dry state test) and 21 (water saturated state). Although both sandstones are given common values for heat transfer and heat capacity in the literature (Vaverka et al. 2000), their behaviour under identical conditions differs significantly. The surface temperature gradient that affects surface/subsurface chemical reactions in the rock can be derived from these diagrams. In a dry state, the temperature of the sample increases up to a stationary state of heat flow, even if the dependence on temperature or absorbed energy (representing various depths in stone ashlars in real structures) differs with sample thickness, as it does for the Maletín and the Godula sandstones. This fact is related to the differing emissivity and porosity of these sandstones. Sandstone emissivity was determined as 0.59 by Vaverka et al. (2000). There have also been found emissivity values for sandstones on the Internet which fall within the 0.60–0.83 range. The emissivity of the white-grey Maletín

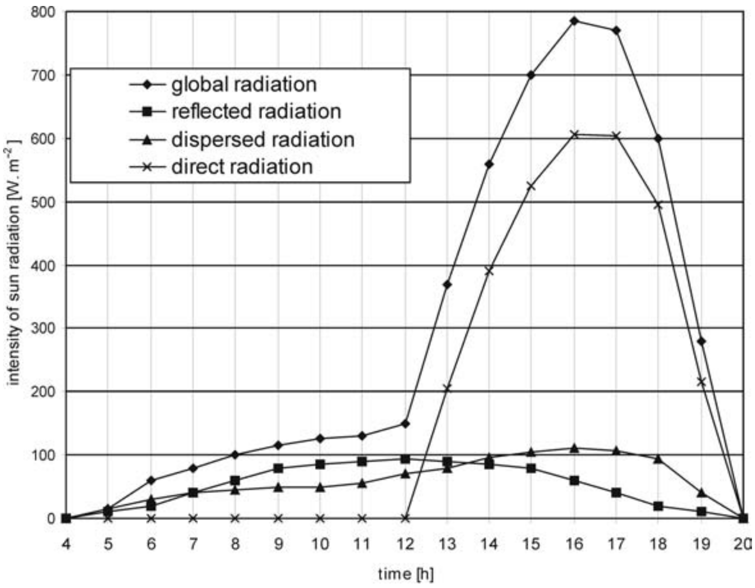

Figure 19. Intensity of solar radiation 15.7 at 52° north lattitude (Vaverka, Chybík, Mrlík 2000).

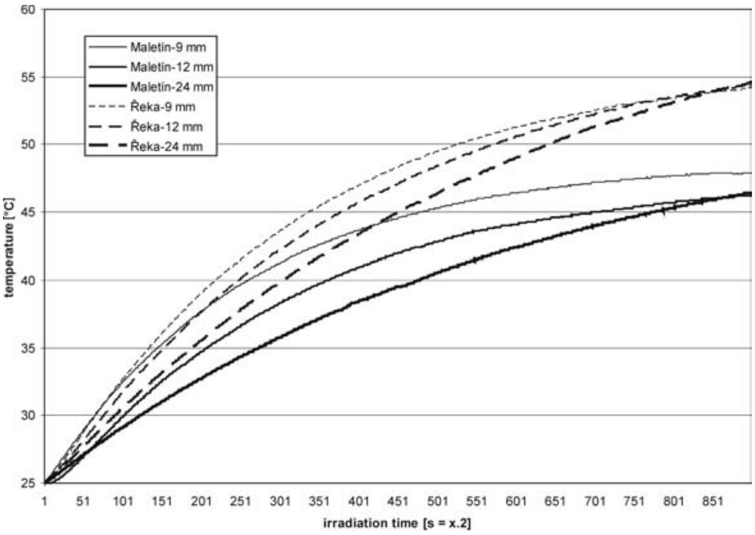

Figure 20. Temperature increase of samples in relation to irradiation time. Dry samples.

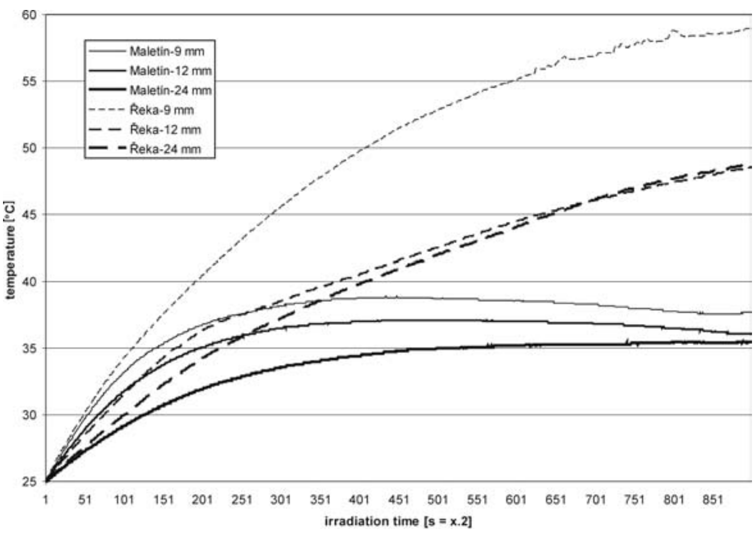

Figure 21. Temperature increase of samples in relation to irradiation time. Water saturated samples.

Table 1. Chemical analyses of the Maletín sandstone (Starý Maletín quarry) and the Godula Sandstone (Řeka quarry). Oxide proportions are presented in wt%. B1 and B2 – the Godula Sandstone used as building stone in the Brno area. O1 and O2 – the Maletín Sandstone used as building stone in the Olomouc area

	Řeka	B1	B2		Maletín	O1	O2
SiO_2	78.70	74.43	73.43	SiO_2	97.75	90.63	93.36
TiO_2	0.04	0.52	0.54	TiO_2	0.13	0.63	0.29
Al_2O_3	4.60	10.88	11.95	Al_2O_3	0.42	2.23	1.41
Fe_2O_3	0.04	1.06	0.85	Fe_2O_3	0.00	1.03	1.54
FeO	0.93	2.99	3.03	FeO	0.37	0.09	0.04
MnO	0.04	0.02	0.02	MnO	0.01	0.01	0.01
CaO	6.89	1.04	0.76	CaO	0.39	2.02	1.06
MgO	0.14	1.44	1.50	MgO	0.00	0.09	0.03
K_2O	1.78	2.46	2.75	K_2O	0.00	0.21	0.09
Na_2O	0.88	1.36	1.39	Na_2O	0.00	0.07	0.02
S	0.01	0.11	0.12	S	0.00	0.00	0.00
CO_2	4.93	0.58	0.33	CO_2	0.34	1.35	0.76
P_2O_5	0.04	0.17	0.20	P_2O_5	0.02	0.02	0.04
H_2O^-	0.11	0.37	0.30	H_2O^-	0.06	0.22	0.18
H_2O^+	0.04	2.28	2.51	H_2O^+	0.11	0.88	0.71
Σ	99.17	99.71	99.68	Σ	99.60	99.48	99.54

Sandstone is closer to 0.59, while that of the green-grey Godula Sandstone is closer to 0.83 (or even to the emissivity of concrete: 0.89). This has been derived from the colour and porosity of the material. The maximum surface temperature reached by the Maletín Sandstone was 48 °C, while that of the Godula Sandstone reached almost 55 °C. The surface temperature of the thinnest sample of the Godula sandstone in a water saturated state increased relative to the dry state. However, the maximum temperatures of the thicker samples were lower than those in a dry state. Specific values were recorded during the tests on the Maletín sandstones. Surface temperatures began to decrease even while the irradiation of the samples continued.

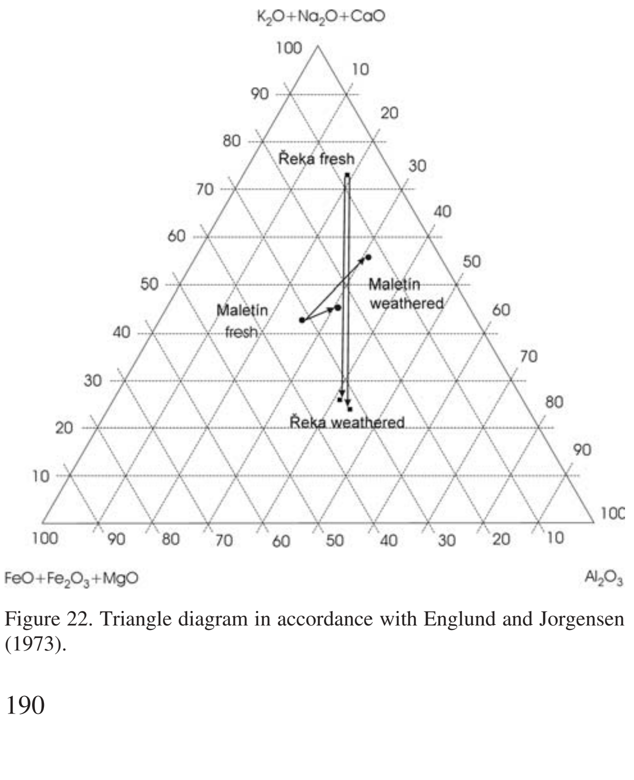

Figure 22. Triangle diagram in accordance with Englund and Jorgensen (1973).

The temperatures reached values in the 35 °C to 38 °C range in 30 min. This phenomenon can be explained by the absorption of part of the energy during the experiment, in connection with the evaporation of water in the pores of the sandstone sample, after which the vapour probably moves toward the irradiated surface of the sample. Moisture generally increases the heat transfer of the material. However, the specific structure of a material can effectively decrease the maximum temperature it reaches during irradiation (up to a specific radiation energy level).

Chemical Properties

The chemical properties of our samples were studied using silicate analyses (see Table 1).

Differences in chemical composition have been observed from analyses of fresh and weathered samples of the Godula and Maletín sandstones. The major difference concerns the proportion of SiO_2. The Maletín Sandstone shows SiO_2 values reaching 97.75 wt% (due to the higher proportion of quartz in the detrital material and the presence of siliceous cement). Major differences were also found for Al_2O_3 (higher in the Godula Sandstone). The higher values of CaO and CO_2 in the Godula Sandstone indicate the presence of calcareous minerals in the sandstone's cement. The Godula sandstones also contain higher K_2O and Na_2O, which is due to presence of feldspars. Fe oxides were found in amounts lower than 1 wt%. The chemical quotient values relative to Kukal (1985) are as follows:

Maletín locality, Bohemian Massif
$SiO_2/Al_2O_3 = 232.7$ Al_2O_3/Na_2O = N/A Na_2O/K_2O = N/A

Řeka locality, Outer Western Carpathians
$SiO_2/Al_2O_3 = 17.1$ $Al_2O_3/Na_2O = 5.2$ $Na_2O/K_2O = 0.49$

The higher maturity of the Maletín Sandstone clearly influences the factors listed above. Quotients of Al and Na oxides could not be calculated, as the amounts of K- and Na-oxides were below the detection limit.

A decrease of SiO_2 in both sandstone types was noticed during the study of weathered samples taken from objects exposed outdoors in the towns of Brno and Olomouc. In contrast, the stable oxides (TiO_2, Al_2O_3, Fe_2O_3, and FeO) show significantly increased values in these samples, while the remaining oxides (MgO, K_2O, and Na_2O) also show a slight increase. The proportion of sulphur only increased in the Godula Sandstone samples. The proportions of CaO and CO_2 were significantly decreased in the Godula Sandstone samples, but increased in those of the Maletín Sandstone. The decrease in CO_2 and CaO may depend on the amount of calcareous cement gradually leached during the weathering process. See the diagram in Figure 22 for the proportions of individual oxides recalculated into molar values, including changes during weathering.

X-ray mapping based on EDX analyses has confirmed substantial changes in chemical composition. In this experiment, Samples from the surface and the interior of the objects (3 mm deep) have been used in this experiment (Fig. 23).

The occurrence of Na and Cl on and beneath the surface confirms presence of NaCl within both levels. The Ca and S may combine to form $CaSO_4 . 2H_2O$. In this process, the sulphur originates in atmospheric sulphur oxide. The concentration of Ca decreases beneath the sample surface.

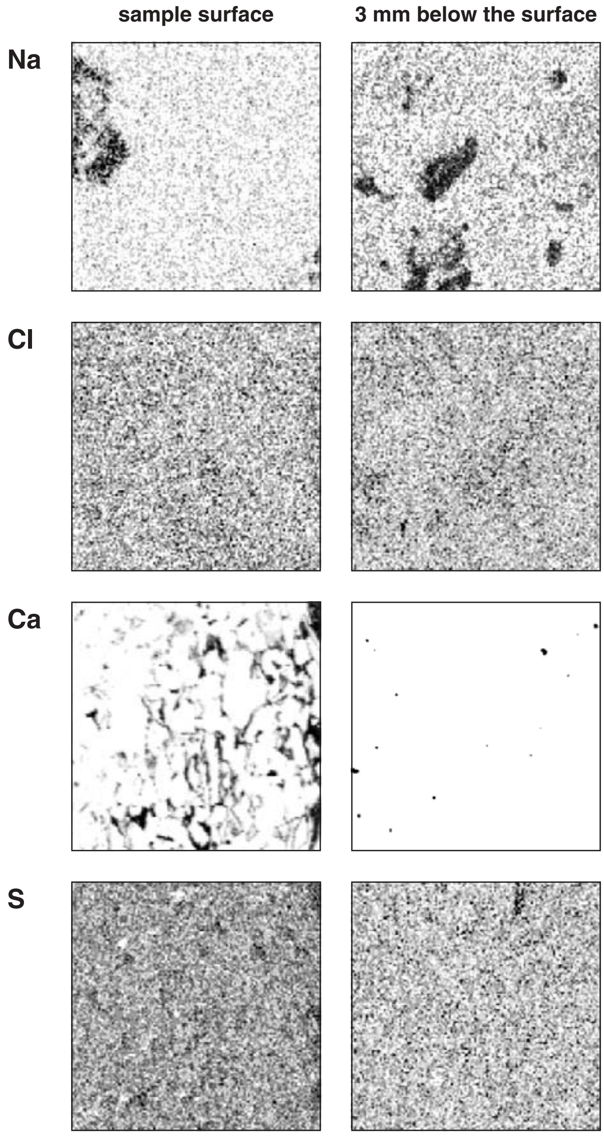

Figure 23. X-ray mapping of sample of weathered Godula Sandstone from the outer cladding of the Military Academy in Brno.

Graffiti

The main problem with sandstones used as building and ornamental stone is their high porosity, and their ability to absorb water and corrosive organic agents present in the nitrocellulose-based paints often used for graffiti.

By graffiti we mean unofficial illustrations, graphic marks, and signs painted on the surface of a structure (Fig. 24). The nitrocellulose-based spray paints used for graffiti contain a dyeing pigment that deeply penetrates porous matter. These paints can cause irreversible damage of the stone surface and subsurface.

Protection of the stone surface would seem to be the easiest way to prevent such damage. There exist special “antigraffiti”sealants just for this purpose, which prevent the peneration of liquids into the stone. For untreated stone surfaces, the degree to which it can absorb liquids such as paint becomes very important. The Maletín Sandstone irregularly absorbed nitrocellulose paint to a depth of 2 mm, while the surface of the Godula Sandstone was not penetrated by this substance (Fig. 25–28).

Based on our experiments, the Godula Sandstone is more appropriate for application within the exterior parts of buildings, such as basements and ground floor areas. Graffiti has been found to be removable from the surface of the Godula Sandstone, while the Maletín Sandstone is badly damaged by spray paints.

Figure 24. Graffiti on a facade constructed from Godula Sandstone, at the Military Academy in Brno.

Technical Properties

Sandstones show a wide variety of properties (Smith 1999). Both the Maletín and the Godula sandstones can be extracted in large blocks. The thickness of individual beds in both localities reaches up to several metres. The blocks lie in a horizontal or sub-horizontal position, and the amount of fissures is low. If some blocks of the Godula Sandstone remain exposed to weathering in the quarry, they begin to disintegrate along several bedding planes during the winter. This is surprising, as this sandstone shows low water absorption and high compressive strength. This behaviour may be connected to stresses within the rock massif that were originally (and perhaps continue to be) induced by orogenic/diagenetic factors. The high compressive strength of the Godula Sandstone results in low workability, and thus discourages its application for artistic or decorative purposes. It can best be used as dimensional stone and as tiles for cladding or pavement. The degree to which the Godula sandstones can be polished is a unique feature. The Maletín sandstones, on the contrary, are easy to work, and can thus be used for sculpture and decorative purposes (as in the doorways of historical buildings).

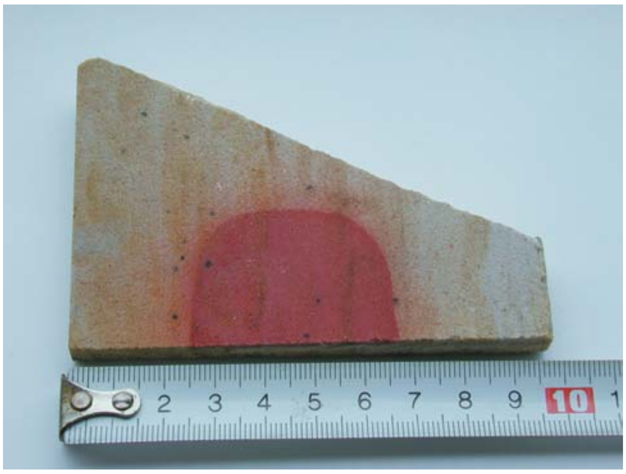

Figure 25. Absorption of nitrocellulose paint by the Maletín Sandstone.

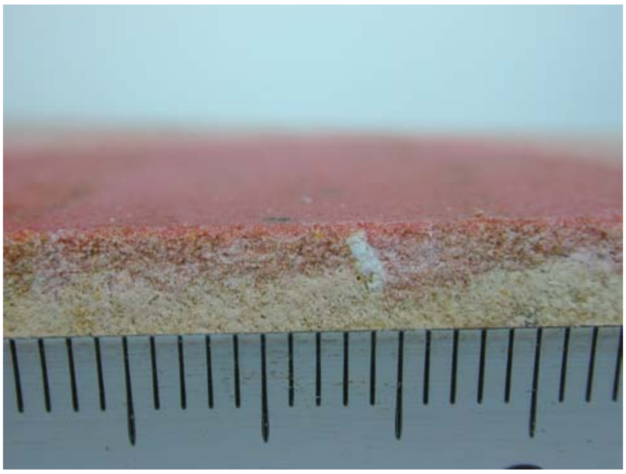

Figure 26. Detail of Fig. 25 in section.

Conclusions

Cretaceous sandstones are a common rock type in the northern Moravian/Silesian regions. Sandstones were more frequently used in the past, when they were extracted from multiple quarries in the Cretaceous of the Western Carpathians and the south-eastern edge of the Bohemian Cretaceous Basin. In recent times the quarrying has largely been stopped, and most sites remain abandoned. A catalogue of construction materials published in 1958 only included information on the Maletín and the Řeka localities. During the 1980s, only the Řeka quarry was continuously active. Although a historical quarry near Starý Maletín was reopened in the second half of the 1990s, it has since been abandoned again. Other quarries that have been episodically active during recent times include those near Trojanovice, Hažovice, and Horní Bečva. The quarrying at these sites produced dimensional stone, broken stone, and crushed stone. The petrographical, physical, chemical, and technical properties of these sandstones made them suitable for use as dimensional, building, and ornamental stones. The sandstones of the Bohemian Cretaceous Basin

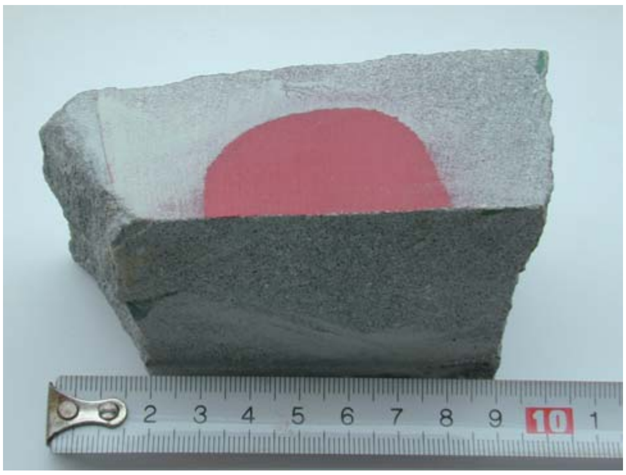

Figure 27. Absorption of nitrocellulose paint by the Godula Sandstone.

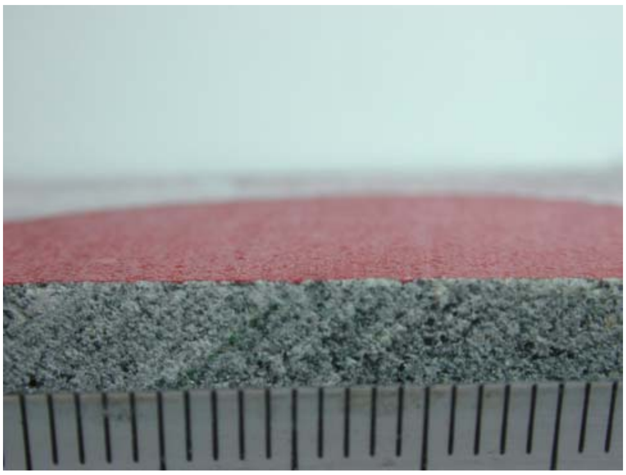

Figure 28. Detail of Fig. 27 in section.

show higher porosity and lower compressive strength. Therefore, they are suitable especially for ornamental purposes. The Godula Sandstone of the Outer Carpathians can be used as dimensional/building stone, and is highy polishable. The verified resources of these sandstones are sufficient for future long-term production.

Civil engineers frequently used both types of sandstone during the 1990s, mainly for reconstruction purposes. They have sometimes been used also for new structures, an example of which is the Godula sandstone used for the cladding of the Skoda Pavilion at the Autostadt near Wolfsburg, Germany.

The recent phenomenon of graffiti makes the modern application of sandstones more difficult. This is especially true for sandstones that show water absorption, such as the Cretaceous sandstones of the Bohemian Massif. This property may be countered by the use of special sealants applied to the stone surface.

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