Geolines 21: published by the Institute of Geology, Academy of Sciences of the Czech Republic.

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GeoLines
Volume 21

Sandstone Districts of the Bohemian Paradise: Emergence of a Romantic Landscape

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published in Prague,
December 2006
by the Institute of Geology,
Academy of Sciences of the Czech Republic

Introduction

In autumn 2005, the Bohemian Paradise area was included into the network of UNESCO Geoparks as the first object in the territory of the Czech Republic. This is already the second priority of the same area: the Bohemian Paradise also became the first Protected Landscape Area in former Czechoslovakia in 1955.

The aims of the central European nature conservationists basically copy the global efforts in nature protection. The establishment of the first protected areas in the mid 19th century was motivated by European romanticism and American transcendentalism. The values protected in these early times can be best characterized as “wilderness” or “sanctuaries of nature”. Such values were represented by the apparently pristine woodlands of the Boubín Forest and Žofín Forest in southern Bohemia.

The development after the year 1918 tended toward scientific nature conservation free from the romanticizing views typical for the 19th century. Majority of the first-established reserves were botanical ones, justified by complete lists of floral species. Only later, a similar tendency can be seen in the protection of zoologically important sites such as refuges of nesting birds.

Protection of geologically significant localities, especially key sections in stratified rocks and famous fossil sites, commenced only in the last decades. The first protected geosites were usually of small extent, represented by isolated natural monuments. This contrast can be explained by the general feeling of that time: rocks are so plentiful in the Earth that their special protection is not needed. Protection of a geosite was then plausible only in case the rocks were overgrown by valuable vegetation. It is only recently that the central European conservationists are becoming aware of the scarcity of pristine rocky valleys or untouched flood plains in a landscape that has been cultivated by humans for centuries. Many of the characteristic geological and geomorphic phenomena of different sizes are facing gradual destruction.

At present, all sandstone districts of the Bohemian Paradise lie within the limits of the Bohemian Paradise Protected Landscape Area. This area was established by Directive No. 261/1954, issued by the Ministry of Culture of the former Czechoslovakia on March 1, 1955. Its Administration has been seated in Turnov. Development of the area is governed by the Management Plan and community land-use plans. Core areas of the sandstone districts are, moreover, under a strict nature protection as nature reserves (limited access). The geopark in its present limits has a much larger extent.

The establishment of a geopark has no protective function in itself. Well-managed geoparks, however, have a great educational potential, hence also a great potential in the future development of geosciences. Providing hands-on understanding of geological processes in action, geoparks stimulate primary and secondary education in Earth Sciences and eventually motivate a number of enthusiastic young people for university studies. For the widest public, geoparks provide a possibility of a new form of sustainable tourism, combining textbook descriptions of geological processes with personal field experience from educational trails.

This volume of Geolines gives the basic characteristics of the individual sandstone districts of the Bohemian Paradise, accentuating the overwhelming diversity in features related to sandstone deposition, cementation, tectonic deformation and, finally, landform evolution. It is orientated at a universal geoscientist but its essentials should be understandable for everyone. For the very first time, presentation of these topics in the English language opens the discussion on geo-scientific and conservational issues in the Bohemian Paradise to a very wide public.

This volume not only summarizes the existing knowledge obtained from numerous older studies but also includes the latest results of ongoing or recently completed research projects. It will be surely followed by scientific papers dealing with the separate geological and geomorphological aspects in detail. Such papers should also coin terms for phenomena and processes newly reported in this issue. Some of the most interesting phenomena include sandstone ferruginization and silicification, and the origin of various microforms of sandstone relief.

As stated by A. Osborne (pers. comm. 2005), one of the major scientific problems of the Australian sandstone districts – covered by numerous guidebooks and photographic publications – is the frequent absence of elementary scientific papers to be used, for example, for further assessment of the scientific potential of the area. This volume is intended to fill a similar gap in the coverage of sandstone rocks cities in Bohemia.

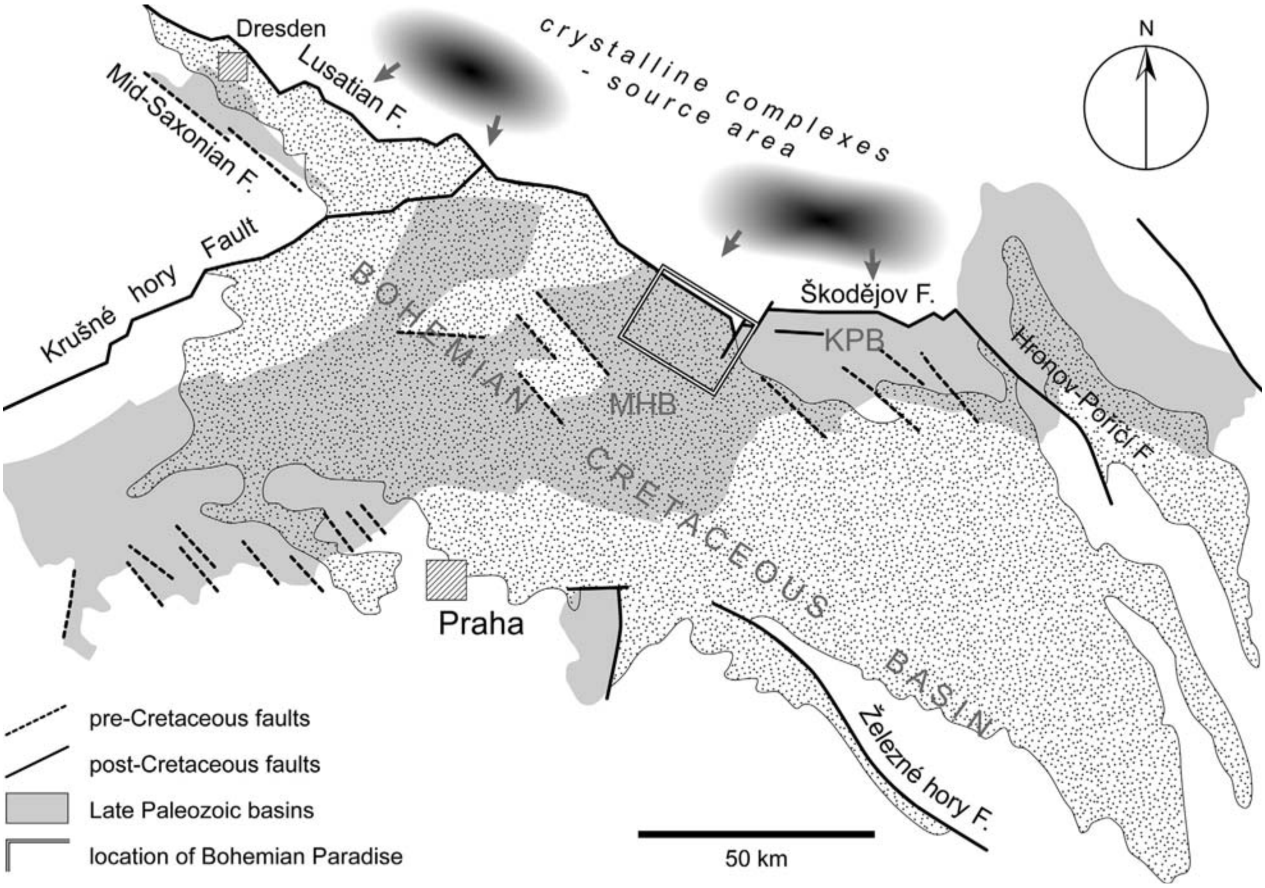
The main body of text refers on the geology of the Bohemian Paradise as a whole, and reviews geological and geomorphic features for each sandstone district separately. This document is an updated version of a study produced for the Administration of Protected Landscape Areas of the Czech Republic (Mikuláš et al. 2001), and is supplemented with photographic Plates 1–16. It was used as a justification for the implementation of the Bohemian Paradise in the UNESCO World Heritage List. The application for recognition as a World Heritage site was finally rejected in 2003, although the geodiversity of the area was highly acknowledged.

Other documents related to the presentation of the Bohemian Paradise sandstones to the international geological and geoconservational audience were included as self-sustained parts of the early version of the manuscript. In response to the recommendations of the reviewers, these documents were abbreviated and submitted in the form of Appendices. They are possibly of less academic significance, but of supreme importance for the discussion on eligibility of sandstone areas for inclusion in the UNESCO World Heritage List and the Network of European Geoparks of UNESCO. They illustrate the global scientific significance of the Bohemian Paradise, and the potential of the area for public education.

Some geological and geomorphological terms used in the text may not be understood unequivocally by wider geological public, as has been pointed out by the reviewers. Therefore, a glossary of terms was added to the original manuscript as Appendix 1. As for general terms, the nomenclature follows that of Nichols (2002) in sedimentology and stratigraphy, Tucker (2000) in sedimentary petrology, Vítek (1981), Rubín and Balatka eds. (1986) and Young and Young (1992) in sandstone landforms, and Wray (1997) in solutional weathering forms. Terminology related to honeycomb weathering follows Mikuláš (2001, 2006).

Appendix 2 is a set of tables created upon request of the IUCN evaluator, Mr. Stuart Chape, to illustrate the specificities of the Bohemian Paradise sandstone districts (Adamovič 2003).

Appendix 3 contains a proposal for geologically-orientated educational trails, featuring some of the outstanding geological and geomorphic processes and their products visible in the field



■ **Fig. 1.** A sketch-map illustrating the position of the Bohemian Paradise in the post-Variscan geology of the Bohemian Massif. The dotted area marks the extent of the Bohemian Cretaceous Basin. The extent of the Permo-Carboniferous basins underlying the Bohemian Cretaceous Basin is shown in grey, their names are given in abbreviated form. KPB – Krkonoše Piedmont Basin, MHB – Mnichovo Hradiště Basin.

(Adamovič and Mikuláš 2005). This proposal was prepared for the Ministry of the Environment of the Czech Republic which, together with the Administration of the Bohemian Paradise PLA and the Bohemian Paradise Museum in Turnov, coordinated the successful campaign for the inclusion of the Bohemian Paradise in the UNESCO Geoparks Programme.

Appendix 4 summarizes the regional geological and geomorphological literature so far published.

The presented set of documents tracks the five-years' effort devoted to the incorporation of this sandstone landscape within European and global geoconservation networks. As the Bohemian Paradise will by no means be the last geopark to be established in the central European realm, we believe that this study can be used as a tool for documenting other geologically valuable areas in the future.

1. Geological history of the Bohemian Paradise region

1.1 Pre-Cretaceous history

The Bohemian Paradise Protected Landscape Area (Bohemian Paradise PLA) is located in the Bohemian Massif, one of the exposures of the exhumed Variscan mountain belts in Europe. In this part of the Bohemian Massif, Variscan-consolidated crystalline rocks are overlain by a thick fill of the Late Paleozoic Mnichovo Hradiště Basin and a thinner sedimentary fill of the Bohemian Cretaceous Basin. The crystalline rocks are exposed to the northeast of the present PLA, in the Železný Brod area. The Železný Brod Crystalline Complex comprises the Lower Paleozoic sedimentary successions intercalated with basic volcanics and their tuffs, subjected to epizonal metamorphism in the Carboniferous. This process gave rise to chlorite-sericite phyllites, metadiabases and basic metatuffites. Limestone lenses were turned into marble. In the regional subdivision of the Bohemian Massif basement, the Bohemian Paradise largely belongs to the regional geological unit of Lugicum. Unmetamorphosed rocks of Upper Proterozoic age, pertaining to the Bohemicum, were encountered in boreholes approximately south of the line Sobotka – Jičín. Position of the Bohemian Paradise within the post-Variscan level of the Bohemian Massif is shown in Fig. 1.

The boundary between the Lugicum in the north and the Bohemicum in the south started to subside in the Late Carboniferous, and was gradually filled with Upper Carboniferous and Permian (Westphalian D to Autunian) continental sediments and volcanic effusions. This is referred to as the Mnichovo Hradiště Basin (Pešek ed. 2001). In the Bohemian Paradise region, the fill of this basin is max. 1800 m thick and directly underlies the Cretaceous sediments. It is composed of mudstones, sandstones and conglomerates in cyclic arrangement, and effusions of acidic volcanics (rhyolites) and intermediate volcanics – so-called melaphyres (andesites, latites). A stretch of Permo-Carboniferous rocks now lining the outcrops of Cretaceous sandstones on the NE edge of the Bohemian Paradise PLA is attributed to the neighbouring Krkonoše Piedmont Basin (Pešek ed. 2001, Ulrych et al. 2002). "Melaphyre" quarries at Bezděčín and on Kozákov Hill traditionally yield a rich paragenesis of void-filling minerals: different varieties of quartz (chalcedony, opal, amethyst), calcite and zeolites.

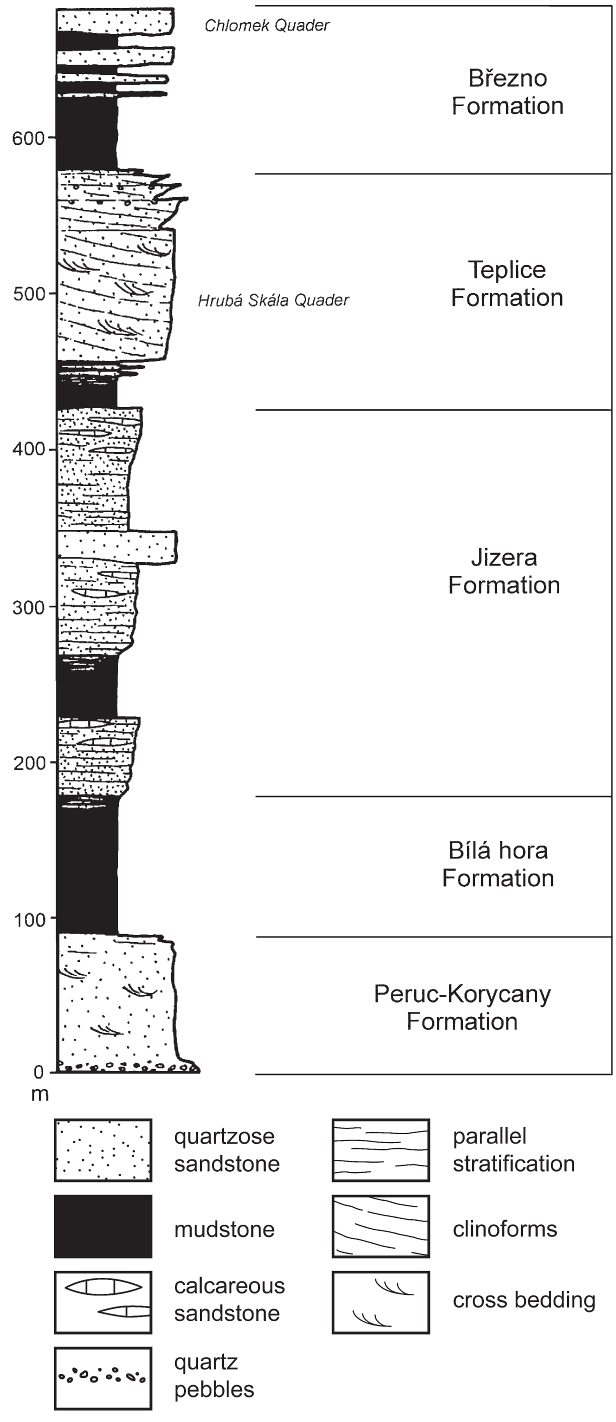
1.2 Late Cretaceous: sand deposition in a shallow sea

The surface of the Český ráj PLA and its surroundings is largely formed by sediments filling the Bohemian Cretaceous Basin. The first major subsidence of the basin floor occurred in the Middle Cenomanian, at approx. 94 Ma, when a sea penetrated into northern and eastern Bohemia along a fault-controlled depression of the Elbe Fault Zone (Skoček and Valečka 1983). The dominant tectonic style modifying the subsidence rate, distribution of depositional centres as well as the uplift of source areas beyond the northern basin margin, was a dextral transcurrent movement (Voigt 1994, Uličný 1997). In initial stages, shallow valleys were filled with rewashed Upper Paleozoic sediments. The character of the subsequent shallow marine sedimentation depended on relative sea-level fluctuations and the subsidence rate in separate subbasins. The youngest Cretaceous sediments in the Bohemian Paradise have been dated to the Upper Coniacian (87 Ma).

Boundaries between the individual lithostratigraphic units in the basin fill dip basinward, i.e., towards the southwest. These dips are tectonic in origin and their values increase towards the NE as far as to the faulted basin margin where the strata are turned upright or even overturned. This implies that the present erosional relief exposes progressively younger units in the direction from the NE to the SW. The vertical succession of Cretaceous strata is shown in Fig. 2.

In the present lithostratigraphic subdivision of the basin fill (Čech et al. 1980), the lowermost unit preserved in the Bohemian Paradise region is the Peruc–Korycany Formation (Cenomanian). Continental sediments were encountered only rarely, in boreholes, and the stratal succession generally starts with shallow marine, cross-bedded quartzose sandstones with a conglomerate bed, max. 2 m thick, at the base. This conglomerate bed is exposed at several sites in the Frýdštejn area, demonstrating a fault-free boundary between the Cretaceous and the Permian.

Deepening of the depositional area in the latest Cenomanian resulted in the deposition of deeper marine sediments: claystones and marlstones of the Bílá hora Formation (Lower to Middle Turonian). The Jizera Formation (Middle to Upper Turonian) is composed of 3–4 upward-coarsening cycles. Lower portions of the cycles are formed by silty calcareous fine-grained sandstones to siltstones, and their tops are formed by fine-grained, locally coarse-grained quartzose sandstones. The type section of the Jizera Formation is located on the periphery of the Bohemian Paradise PLA at Dolánky near Turnov (Čech et al. 1980). Relatively softer sediments of the Bílá hora Formation and the lowermost part of the Jizera Formation form depressions in the present relief, especially the NW–SE-elongated Hodkovický úval (Hodkovice Valley). Their outcrops are rather rare. Coarse-grained sandstones from the top of the 2nd cycle of the Jizera Formation are relatively well exposed in the Frýdštejn area, especially in the former sand pits at Smetí.



■ **Fig. 2.** Stratal succession of the sedimentary fill of the Bohemian Cretaceous Basin, Bohemian Paradise region. For lithological descriptions of the individual formations, see the text below.

The Late Turonian sea-level rise together with the basin-floor subsidence resulted in the deepening of the sea to ~150 m. The space thus created became progressively filled with sediments of the Teplice Formation (Upper Turonian to Lower Coniacian). Calcareous claystones to marlstones were deposited first; their preserved thicknesses rarely exceed 10 m in the northern part of the Bohemian Paradise but increase towards the SE and SW. This facies can be encountered in the Mnichovo Hradiště area and on the periphery of the Prachov District, where it passes into the overlying sandstones by rapid alternation of calcareous siltstone–sandstone and quartzose sandstone.

After the uplift of the source area beyond the northern basin margin, the proximal part of the basin was filled with an extensive body of subaquatic delta, aver. 80 m thick (Zahálka 1918, Uličný 2001). This body is known as the Hrubá Skála Quader (Krejčí 1870, Frič 1895). At its top, as a consequence of waning detrital influx and accelerating basin-floor subsidence, the sandstones grade upwards into the siltstones of the Březno Formation (Lower to Middle Coniacian). Occasional sharp-based intercalations of quartzose sandstone higher up in the siltstone succession thicken upwards and finally amalgamate into the so-called Chlomek Quader (ca. 30 m thick; Frič 1898) to the south from the Bohemian Paradise. In the PLA territory, a stratigraphic analog of this sandstone body was reached by a borehole near the top of Vyskeř Hill (Klein 1966).

The body of the Hrubá Skála Quader, belonging to the Teplice Formation, forms most of the sandstone districts in the Bohemian Paradise. Its base is either sharp, or defined by rapid alternation of siltstones and sandstones (Čech et al. 1995). Quartzose sandstones are medium-grained, locally fine-grained, with an admixture of coarse grains, no indications of a cyclic arrangement, and prominent clinoform surfaces (inclined at 5–15°) dipping to the south to southwest. These surfaces can be often traced across a thickness of several tens of metres and are interpreted as foresets of a delta body (Uličný 1998, 2001, Uličný et al. 2003). Lower-order surfaces such as foreset laminae of cross bedding (angles 15–34 °) are superimposed on the clinoform surfaces: they were formed by migration of dunes and sand waves across the seafloor. Cross-bedded sets may reach thicknesses between a few tens of centimetres and several metres (Adamovič 1992). The Hrubá Skála Quader is overlain by medium-grained, strongly bioturbated quartzose sandstones, 20–30 m thick in total, characterized by the arrangement of small upwards-coarsening cycles often topped by conglomerate beds. Despite the bioturbation, low-dipping clinoform surfaces (~4°) can be distinguished in each cycle. From the north to the south, i.e., from the Klokočí area (Klokočské skály) to the Plakánek Valley and Prachov area, these sandstones increase in thickness at the expense of the underlying Hrubá Skála Quader. This implies a lithological, and consequently also geomorphic, diversity of the Bohemian Paradise sandstone districts. The Rohatce Member (topmost part of the Teplice Formation), identified on the basis of its typical inoceramid fauna (Andert 1934, Čech et al. 1995), is represented by hematitic fine-grained sandstones and claystones at top of the sandstone body in the Prachov area. This facies, well marked by its reddish coloration, is best exposed in sand pits near Mladějov (Plate 1G). The overall thickness of the Teplice Formation sandstones generally decreases southwards from 160 m in the Sokol Hill area to 60 m in the Vyskeř area. South of the Žehrovka Stream, however, the thicknesses increase eastwards from 80 m to 140 m (Adamovič 1992). Further south, this body wedges out rapidly.

Cretaceous sandstones of the Bohemian Paradise yield relatively rich, although mostly poorly preserved, fossil remains of bryozoans, cephalopods and echinoderms (e.g., Soukup 1936, V. Ziegler 1977). They are not, however, concentrated into fossiliferous beds which could be displayed to the public as show sites.

1.3 Tertiary: tectonic deformations and volcanic activity

The sandstone landscapes of the Bohemian Paradise are limited in the north by the zone of the deep-seated Lusatian Fault, a segment of the Elbe Fault System of Scheck et al. (2002) now juxtaposing the high-grade metamorphosed rocks of the eastern Erzgebirge (Saxothuringicum) in the southwest and the low-grade metamorphosed Lower Paleozoic sediments of the Lugicum in the northeast. It accommodates maximum deformation within this system (DEKORP 1994). Activity of the Lusatian Fault until the Quaternary is suggested by the drainage pattern development and prominent fault-scarps, and by faulted Quaternary sediments in excavation trenches (Coubal et al. 1999).

On the present land surface, the Lusatian Fault separates the Permo-Carboniferous rocks and Cretaceous sediments in the SSW from the Železný Brod phyllites in the NNE along the line between Malá Skála and Kozákov Hill; farther southeast, the fault plane with the maximum displacement enters the Permo-Carboniferous fill of the Krkonoše Piedmont Basin. Fault planes of the zone dip to the NNE at medium angles and underwent a complex kinematic history with several phases from the latest Cretaceous to the latest Tertiary (Coubal 1990). The oldest, and the most significant reverse phase, correlated with the Laramide Orogeny in western Europe (P.A. Ziegler 1987, Adamovič and Coubal 1999), produced vertical displacement of about 1000 m. Rocks south of the main fault were subjected to fault-related ductile deformation (drag folding): sandstones of the Korycany Member are silicified, ferruginized and strongly fractured. Subparallel to the Lusatian Fault itself, the Rovensko Fault (Zahálka 1918, Andert 1934) lies 700 to 2000 m to the south. It shows a small vertical displacement but probably a major horizontal displacement; as revealed by boreholes and test trenches (Coubal et al. 1999), steep southwesterly dip angles change into subhorizontal southwest of this fault.

The same stress fields that activated the Lusatian Fault zone acted in its wide southern foreland, in the whole Bohemian Paradise region. Minor shear faults and deformation bands are common in the Klokočí Cliffs and in the Trosky Hill area. Subhorizontal thrust faults are presumed in the Klokočí Cliffs (Mertlík and Adamovič 2005). Yet farther south, the courses of the Libuňka and Žehrovka streams are controlled by faults parallel to the Lusatian Fault, and fracture zones with silicification of ferruginization. This way, brittle tectonics plays an important role in relief dynamics, groundwater and surface water circulation in the Bohemian Paradise.

Relatively common are intrusive bodies of young basaltic rocks (Plate 15), crosscutting the Cretaceous sediments and markedly contributing to the formation of the present relief. They concentrate into two areas: Mužský Hill–Vyskeř Hill area and Sobotka–Jičín area. Dykes, tens of centimetres to a few metres thick, and stocks are mostly composed of olivine-rich basanite and nephelinite (Shrbený 1992). The majority of the dykes strike ENE–WSW to E–W (Pacák 1947). The stocks, occasionally accompanied by intrusive breccia bodies, include the hills of Mužský, Vyskeř and Humprecht. Basanite from the intrusion at Střelečská hůra Hill yielded Late Oligocene K-Ar age (24.6 Ma, Wilson et al. 1994). An intrusive system consisting of a basanite stock, a dyke and a sill with a halo of ferruginous sandstone was recently exposed in the Střeleč sand pit (Adamovič 2001).

Much younger effusive bodies have been preserved northeast of Turnov: basanite lava flows dated to the Miocene–Pliocene (7 to 4 Ma), see Šibrava and Havlíček (1980), Ulrych and Pivec (1997). Relics of lava flows have been preserved in a broad strip between the hills of Sokol and Kozákov, which probably functioned as ascent paths. Basanite also forms the landmark of Trosky Hill – a dyke with a relic of a spatter cone (V. Cajz, pers.comm.).

1.4 Quaternary history

In the latest Tertiary, in Pliocene times, the central part of the Bohemian Paradise had the character of a relatively continuous table formed by the Teplice Formation sandstones, gently dipping to the south. This table was pierced by elevated exhumed intrusive bodies lined by relicts of the overlying siltstones and claystones. This was the time of accumulation of the high gravel terraces of the former Jizera River, now preserved at the altitudes of ca. 400 m.

In the Pleistocene, the sandstone table was dissected due to the base-level incision and headward erosion of the Jizera River and its tributaries, and also the Cidlina River tributaries in the east. The different stages of destruction of the original sandstone table now observed in the individual sandstone districts, is a function of their position relative to the Jizera River and its tributaries as well as of the local lithology and tectonic deformation. In general, the forces of erosion accentuated the tectonically controlled orthogonal jointing in quartzose sandstones. Where incision reached the plastic claystones underlying the sandstone table, processes of mass movement became obvious: block gliding, rockfall and landslides. On the other hand, the processes of sediment accumulation produced sand and gravel terraces along the Jizera River and deposition of aeolian sediments – loess and loess loam – on eastern and southeastern slopes.

Slope sediments are most often of Upper Pleistocene to Holocene age. They are dominated either by sand, derived from the Teplice Formation sandstones, or by loam, derived from loess. Rock colluvia derived from the young volcanics or the Jizera Formation calcareous sandstones are of a limited areal extent. Holocene sediments most commonly met in the sandstone districts include sandy slope aprons lining cliff bases, fills of crevasses and caves, and calcareous tufas.

Regional orographic units in the region were postulated by Demek ed. (1987). The Ještědsko-kozákovský hřbet Unit, specifically the Kozákovský hřbet Subunit, forms a narrow belt along the Lusatian Fault marked by the northernmost outcrops of Cretaceous sandstones and outcrops of pre-Cretaceous rocks. The wide altitude range of 200–400 m of the Kozákovský hřbet Subunit and its high mean surface inclination of 8.18° (Balatka in Demek ed. 1987) result basically from young tectonic activity (Neogene to ?Quaternary). The rest of the Bohemian Paradise region, in the southern foreland of the Lusatian Fault, is ranked within the Jičínská pahorkatina Unit and its Turnovská pahorkatina Subunit with a much gentler surface (3.45°, Balatka in Demek ed. 1987).

2. Geological and geomorphological characteristics of sandstone districts

Among the sandstone areas of the Bohemian Paradise, twelve characteristic “sandstone districts” (areas of extensive sandstone exposure) were selected for the detailed geological and geomorphological description (Fig. 3). Their pertinence to orographic units is listed below (TPS – Turnovská pahorkatina Subunit, KHS – Kozákovský hřbet Subunit):

TPS, Vyskeřská vrchovina Area
- Hrubá Skála District
- Apolena District
- Příhrazy District
- Plakánek Valley District
- Kozlov District

TPS, Prachovská pahorkatina Area
- Prachov District (Prachovské skály)

TPS, Turnovská stupňovina Area
- Klokočí and Betlém Cliffs (Klokočské a Betlémské skály)
- Drábovna District near Malá Skála
- Sokol Hill District

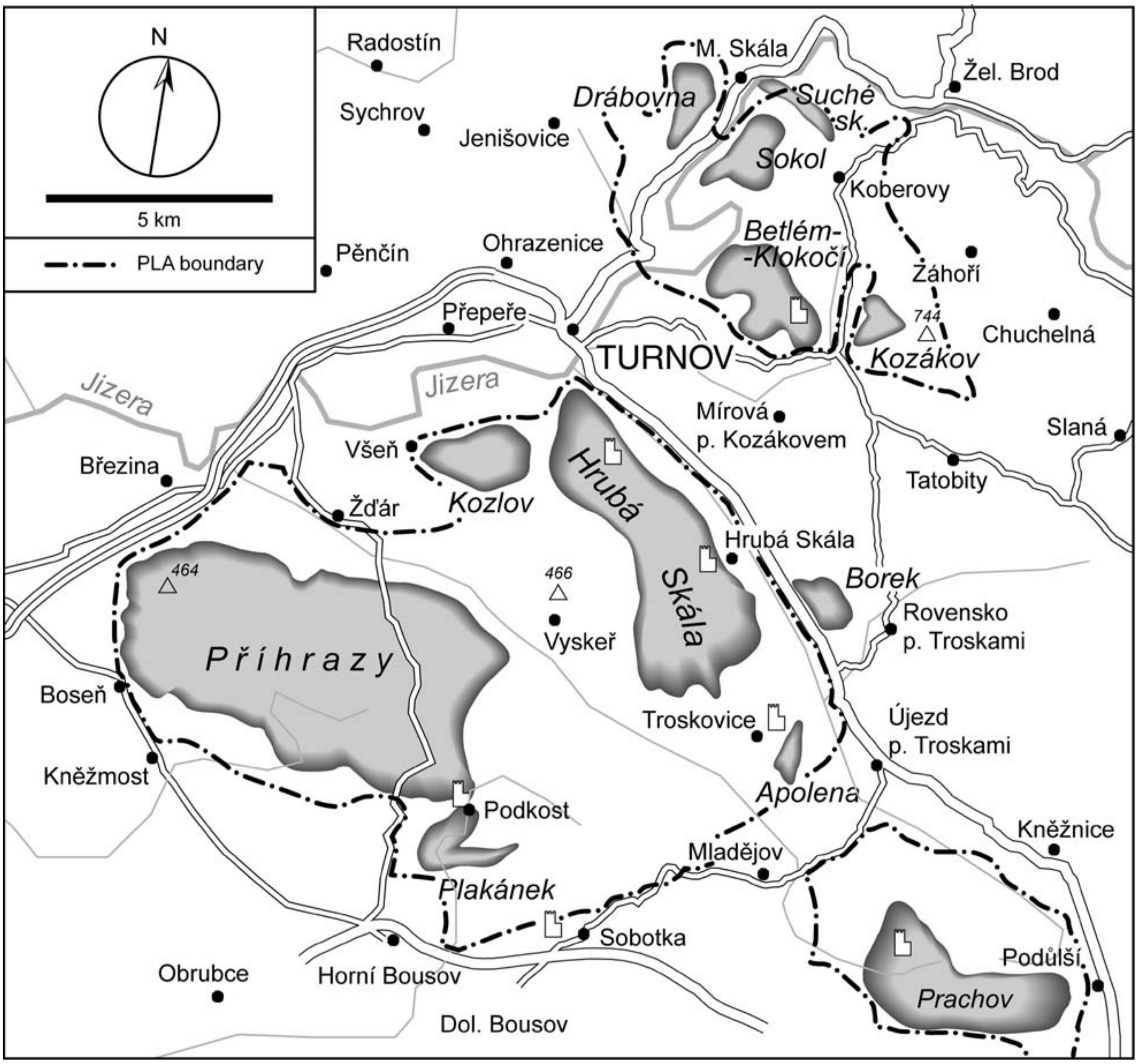
TPS, Libuňská brázda Area
- Borek District

KHS, Komárovský hřbet Area
- Suché skály Cliffs
- Kozákov Hill

2.1 Hrubá Skála

Geology

The cliffs are cut in weakly to moderately lithified, light grey quartzose sandstones of the Hrubá Skála Quader (Teplice Formation), with no signs of cyclic development. The sandstone body is approx. 120 m thick, with the individual cliffs reaching the height of 80 m max. Surfaces of four orders can be distinguished in the sedimentary succession. The areally most extensive are wavy erosion surfaces formed during collapses of the subaquatic delta front due to overloading with sediment, possibly related to seismic events. The erosion surfaces tend to scour clinoform surfaces dipping gently (4°) to the south to southeast. These were interpreted as delta foresets (Uličný 2001, Uličný et al. 2003). Third-order surfaces are the moderately-dipping foresets of giant-scale trough cross-bedded sets, up to several metres in thickness. These are products of migration of sand waves across the surface of the delta. Surfaces of the lowest rank are foreset laminae of planar or trough cross-bedded sets <25 cm in thickness, produced by dune migration. Calcareous claystones and marlstones under the sandstones are not per-



■ **Fig. 3.** A sketch-map of the Bohemian Paradise region with marked areas of vast sandstone exposure treated in this volume (grey areas).

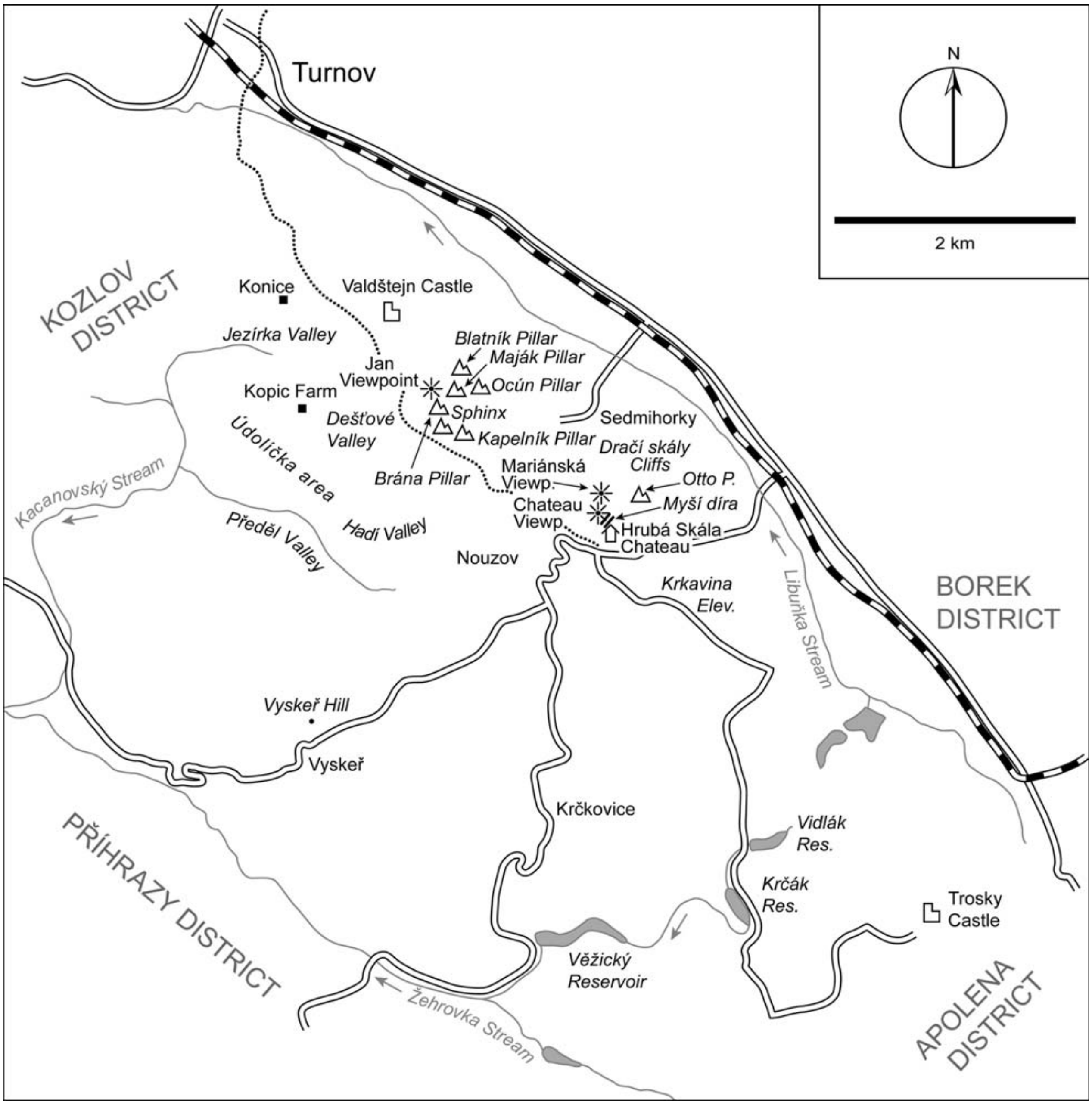
manently exposed but can be traced in the field due to their sealing effect on groundwater flow. A series of groundwater issues at this level is developed, for example, at Sedmihorky.

Variation in foreset dip directions of the giant-scale cross bedding indicates changes in prevailing directions of near-bottom currents and sand-wave migration during sand deposition in the Hrubá Skála area. Southerly dips prevail in the lower part of the sandstone body (near Sedmihorky) while southeasterly dips prevail near the top (Mariánská Viewpoint, Plate 1E), see Adamovič (1992).

The sandstone district lies in the tectonic Hrubá Skála Block limited by the fault of the Libuňka Stream in the NE, by the Kacanovský Stream in the W, by the Předěl Valley in the south and, finally, by the Vyskeř Hill massif formed by a basanite intrusion and a relict of the Březno Formation marlstones. The principal joint strikes are NW–SE and NE–SW. Joints of both these strikes are impregnated by iron compounds near Valdštejn and the former village of Nouzov, giving rise to joint fillings and tube-shaped concretions of ferruginous sandstone. Silicified sandstones were mined for building stone and millstone production at Konice. Young volcanic rocks have not been found in the Hrubá Skála District, with the exception of the nearby Vyskeř Hill. Pliocene fluvial gravels and sands have been preserved on top of the plateau around Hrubá Skála.

Large landforms

The Hrubá Skála District is an erosional relict of a plateau, the top of which lies at the mean altitude of 380 m, and its base at the altitude of 250 m. Closer to the Libuňka Stream, some parts of the plateau edge are incised by erosion to produce typical rock cities: groups of widely spaced pillars approximately rectangular in plan view. Their heights often exceed their widths by several times. The most prominent pillar groups forming separate, perfectly developed rock cities are (from west to east): Maják (Lighthouse) pil-



■ **Fig. 4.** A schematic map of the Hrubá Skála district. Principal tourist trails marked by dotted lines.

lar and its vicinity, Kapelník (Bandmaster) group – see Plate 8G, and Dračí skály (Dragon Cliffs) group, totalling tens of perfectly developed pillars. Other parts of the Hrubá Skála rock city have rather the character of a less dissected plateau relict: articulated plateau rims with short valleys, necks and pillars are developed farther to the northeast. The southwestern part of the Hrubá Skála plateau, called Údolíčka, is transected by three well-defined valleys (Jezírka, Děšťové údolí, Hadí údolí) having the character of broad canyons with sandstone outcrops ca. 20 m in height with sparse pillars below.

Sandstone mesorelief and microrelief

The pillars reach heights of 50 m measured from their up-slope bases and 90 m measured from the valley floors. Their tops are mostly rounded, with no soil cover, and occasional karren. Microrelief of steep cliff faces is dominated by elements derived from primary sedimentary structures in the sandstone: horizontal ledges accentuated by rows of arcuate honeycomb pits. Strata less resistant to weathering give rise to notable notches with cavities (Sphinx group). Case hardening is locally prominent (valley-facing side of the Kapelník Pillar, Otto pillars). Spherical or rhombic cavities tens of centimetres across are present, for example, in the vicinity of the Podmokly pillar. Simple vertical crevasses in the area of Dračí skály are occasionally vaulted to form false arches: Ocún (Autumn Crocus), Brána (Gate), Blatník (Mudguard). Microrelief typical of permanently moist outcrops (shallow horizontal ledges, imperfectly developed pitted surfaces) is commonly found in the Údolíčka area (Hadí údolí, Dešťové údolí).

■ **Fig. 5.** The church of St. John of Nepomuk was built in 1722 on ruins of the medieval Valdštejn Castle, in the NW part of the Hrubá Skála rock city. This post-card was published ca. 100 years ago by Rudolf Helikar, the owner of a former restaurant at the chateau.

Specifics within the Bohemian Paradise PLA

The Hrubá Skála District displays the most complete rock-city phenomenon in the Bohemian Paradise PLA, with the highest and most impressive rock pillars. At the same time, this sandstone district lies in one of the two large forested areas of the Bohemian Paradise as it is interconnected, across the Krkavina elevation, with the Věžický Reservoir and Trosky Hill in the southeast. A specific feature, resulting from both these facts, is the extremely high number of visitors to this area. The by far most frequented is the plateau-top tourist path interconnecting the Hrubá Skála Chateau and the Valdštejn Castle, which are the two major cultural attractions, lined with excellent viewpoints of the rock city (Fig. 5).

Outstanding geological and geomorphic features and their presentation

Considering the already enormous and hardly manageable load of visitor pressure, perhaps the only feature suitable for public presentation is the rock-city phenomenon by itself. Any ambitions for subsidiary presentation of other phenomena, such as sandstone microrelief or Quaternary sediment accumulations, would further aggravate the tight environmental conditions. The rock city can be appropriately observed from the existing viewpoints (Hrubá Skála Chateau, Mariánská Viewpoint, viewpoints over the Kapelník Pillar, Jan Viewpoint over the Maják Pillar group). Restricted access is, on the other hand, desirable in the Údolíčka area including the Kopic Farm site with rock carvings from the 1940s to 1970s, now overloaded by tourist activities.

2.2 Apolena

Geology

The Apolena District is formed by weakly lithified sandstones of the Teplice Formation, with some indications of cyclic arrangement near the top. The sandstones are mostly fine-grained, more rarely medium- to coarse-grained near the cliff bases. Tectonic controls on the weathering processes are expressed in a dense network of vertical joints striking WNW–ESE (with several-metres spacings) and orthogonal joints striking NNE–SSW (with tens-of-metres spacings). Well developed are subrecent sandy slope aprons and crevasse fills.

Large landforms

The Apolena District is basically a single continuous outcrop at the altitude of 350–370 m on the SE rim of the plateau topped by volcanic Trosky Hill with a medieval castle (488 m). The outcrop includes two short valleys trending N–S and NW–SE and stretches generally NNE–SSW for a distance of over 1000 m. The cliffs are max. 30 m high.

Sandstone mesorelief and microrelief

The mesoscale relief is dominated by necks and pillars of elongate, rectangular shapes in plan view, and by wall-shaped cliff faces. Numerous rock shelters (Plate 10B) and strata-bound caves, a perfectly developed arch (Plate 9G) and numerous rock windows are concentrated along cliff bases, especially in the southern part of the sandstone district. The pillars are notable for their rounded, convex tops, often completely free of vegetation. As judged by the rapid destruction of modern carvings on cliff tops, the weathering rates are very high, of the order of 10 cm per century. Crusts due to salt weathering are morphologically prominent in some places. Where developed, their remains contrast with the rapidly eroding smooth cliff surfaces. Inclined ledges are often developed low above cliff bases (Plate 11F). Being subparallel to the present soil surface, they most probably indicate former positions of slope apron surfaces or soil horizons (Mikuláš 2001b, 2006). Rhombic honeycomb pits are the dominant element on vertical cliff faces. Also very common are modern biogenic structures – nesting tunnels of solitary bees.

Specifics within the Bohemian Paradise PLA

This district differs from other sandstone areas of the Bohemian Paradise in its very weak lithification of the fine-grained sandstone, hence also greatly accelerated processes of meso- and microrelief formation. It is the only area in the Bohemian Paradise and in the Bohemian Massif in general, where rhombic honeycomb pits prevail, giving rise to structured systems covering whole cliff faces.

Outstanding geological and geomorphic features and their presentation

Instructive examples of all the above mentioned meso- and microrelief elements with the exception of rock pillars are contained in a small gorge near the southern end of the district (below the Svitačka campsite). The gorge is suffering from unrestricted access and illegal camping. The establishment and maintenance of trails in the future should permit the installation of information panels to inform the public without the risk of additional damage to the yet unaffected forest ecosystems and cliff surfaces.

Restricted access should also be recommended to the viewpoint of the Apollón Pillar (Apollo) in the central part of the district. Here, the origin of round pillar tops can be well observed and explained. This will give the visitor an idea of the rate of geological processes in this sandstone district.

The Apolena District provides the scientist with a unique opportunity to monitor natural changes in rock microrelief in real time. This research was started in 2001.

2.3 Příhrazy

Geology

Sandstone outcrops within the Příhrazy District (Příhrazské skály) lie in the Žehrov Block, bounded by fault zones in the NE (Žehrovka Stream fault zone), NW (Jizera River fault zone) and partly in the SE (Kněžmost – Přepeře line, Střehom Fault). In the SE, they pass to the Plakánek Valley, treated under a separate heading.

Cliffs in the Příhrazy District are cut in medium-grained, weakly to moderately lithified, weakly kaolinic sandstones of the Hrubá Skála Quader (Teplice Formation), with flat clinoform surfaces and in places well developed trough cross bedding. The uppermost quarter of the stratal succession is formed by upwards-coarsening cycles of bioturbated medium- to coarse-grained sandstone and topped with conglomerate beds. This topmost part also contains a separate set of flat, south-dipping clinoform surfaces in each cycle. In the Drábské Světničky area, the topmost sandstones show frequent sets of giant-scale cross bedding up to several metres thick (Plate 2B–C). Southwesterly dips of their foreset laminae indicate the prevailing flow direction at the time of sand deposition.

In the Neogene, the Příhrazy area sandstones were penetrated by intrusions of volcanic rocks: olivine nephelinites to basanites. The largest such body is the stock of Mužský Hill (463 m). It is surrounded by a sandstone plateau covered with an erosional relict of Upper Coniacian calcareous claystones and clayey limestones. Morphologically prominent is the WSW–ENE-striking dyke at Branžež and Zakopané, 2.5 km long and up to 3 m thick. In the Železné věže (Iron Towers) group, situated east of Mužský Hill, the tensional joints NW–SE in sandstone are filled with goethite and lined with tube-shaped ferruginous concretions (Plate7A–C). Their surfaces show prominent plume structures, arcuate ribs and hackle marks (Plate 4C). Joints striking E–W in the eastern part of the Příhrazy area are tight, with signs of shearing and associated silicification.

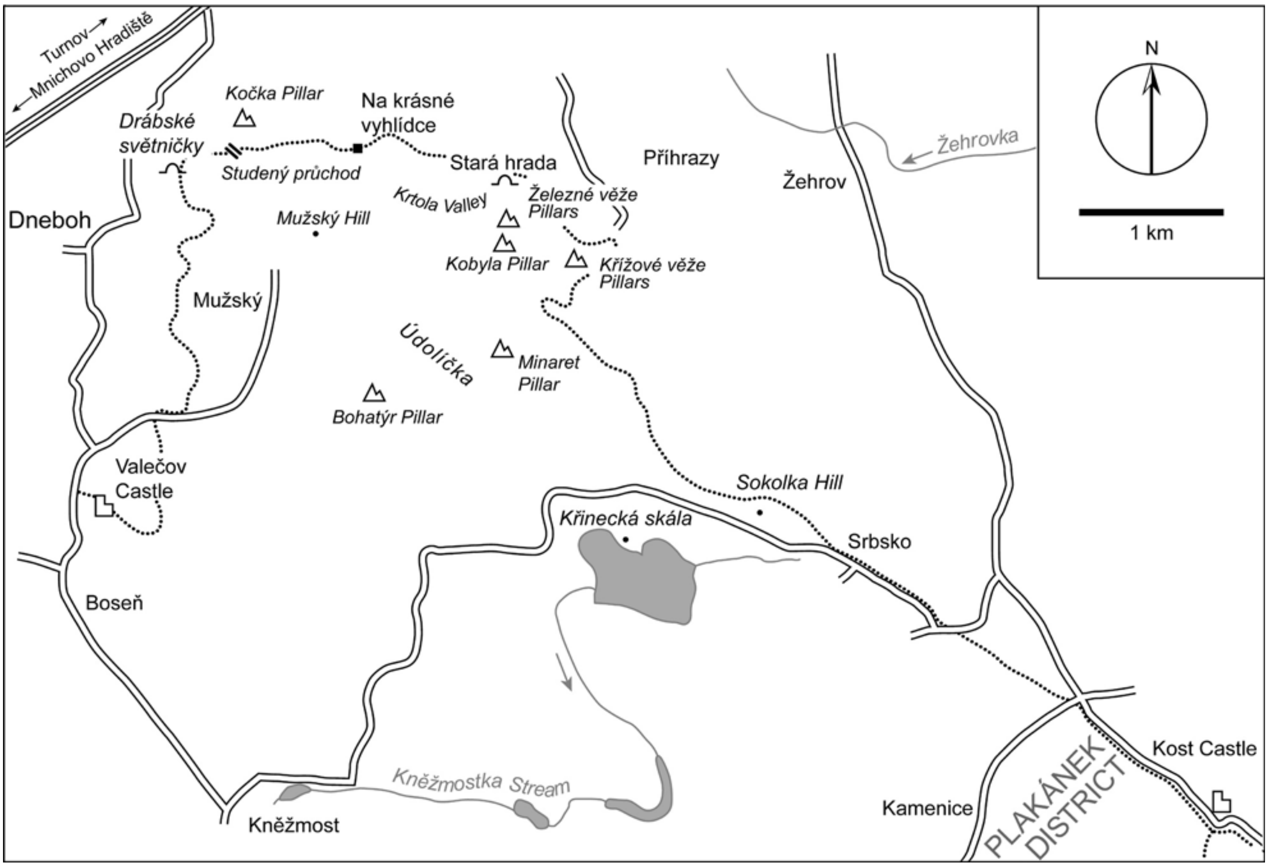
The sandstone package is underlain by marlstones and calcareous claystones of the lower part of the Teplice Formation. Gravitational loading and lateral bulging of inconsistent clays are the mechanisms of large-scale mass movement along the western rim of the Mužský Hill plateau. Slope deformations in this area are being monitored. Quaternary sediments include loess (Pleistocene), sandy slope aprons and colluvia (Holocene).

Large landforms

The plateau of Mužský Hill topped by a conical neovolcanic hill is the essential macrorelief element. It is further dissected, but no common pattern of relief formation can be found. Its northern rim between Příhrazy and Drábské Světničky has the character of a more or less continuous sandstone cliff face with narrow gorges, chimneys, numerous necks and pillars with low up-slope faces and high down-slope faces. Typical rock cities are not developed here. On the northwestern plateau rim, however, the pillars cluster into groups (e.g., the complex of Drábské Světničky), being separated by prominent NW–SE-trending valleys lined with cliffs with slope aprons and colluvia below. The southern side of the plateau is dissected by a dense network of canyons known as the "Příhrazská údolíčka". Their upper parts feature extremely complex sandstone outcrops with numerous necks, gorges, chimneys and concave and convex vertical edges. Towards the east, this type of relief passes into a network of E–W-elongated crests and valleys with less prominent outcrops. Two sandstone massifs having the character of small table mountains are located close to the SE edge of the Příhrazy area: Sokolka and Křinecká skála (also called Dráb – Catchpoll).

Sandstone mesorelief and microrelief

Mesorelief of the Příhrazy area is characterized by cliff faces dissected by narrow (often 1–2 m wide) gorges, chimneys and vertical edges. Pillars can be found either more-or-less isolated on the plateau rim (needle-shaped pillar of Kočka – Cat) or in small groups (Drábské Světničky, vicinity of the Kobyla – Mare Pillar), on necks where canyons branch (Bohatýr – Hero Pillar in the south) and below canyon edges (e.g., Minaret Pillar in the Údolíčka area). The heights of the cliff faces commonly range between 20 and 40 m. The complexity of mesorelief also explains the prevalence of certain microforms on specific sandstone blocks. For example, the southern faces of the Sokolka massif are



■ **Fig. 6.** A schematic map of the Příhrazy district. Principal tourist trails marked by dotted lines.

sculpted by prominent E–W shear joints. These faces also show high rates of case hardening with crusts covering vertical and overhanging, as well as sloping cliff faces (Plate 14E–F). A row of rock shelters at the southern foot of Sokolka Hill and numerous examples of insect dwelling and nesting structures are equally instructive (Mikuláš and Cílek 1998). The western cliff face of Sokolka is locally dominated by wavy notches and ledges accentuating syn-sedimentary deformation structures in sandstone. The top surface of Sokolka is rugged with karren of different shapes and sizes, and covered with rusty patches and cm-sized mammiform tubercles (minute goethite concretions) resulting from the redistribution of iron oxyhydroxides (Plate 6C–E).

The area of Údolíčka is characterized by cliff faces 15–20 m high with an extreme diversity of honeycomb pits of different types and spherical cavities (niches, small caves). Tensional joints in the Železné věže group on the NE edge of the Mužský Hill plateau are coated by ironstone and locally combine with dish-shaped surfaces on opposing joint planes indicative of joint dilation by tens of centimetres. Northern rim of the plateau, including Drábské Světničky, shows many examples of microrelief controlled by equal proportions of several factors: primary sedimentary structures (subhorizontal ledges) including bioturbated horizons (mushroom rocks, rock windows), evaporation of silica-rich solutions (rock crusts; Breiter 1976, Soukupová et al. 2002), gravity-induced movements (tensional joints) or a combined effect of complex erosion processes (honeycombs). Worth mentioning are the numerous sinkholes near the plateau rim, including one propagating into a shaft 22 m deep.

Specifics within the Bohemian Paradise PLA

The Příhrazy area displays probably the most diverse meso- and microrelief within the sandstone phenomenon of the Bohemian Paradise. Exceptional for the Bohemian Paradise are the solitary sandstone massifs having the appearance of small table mountains: Sokolka and Křinecká skála. Sandstone surfaces dominated by specific microrelief elements, such as rock crusts, tensional joints or vertical ironstone bodies, are also rare in other sandstone districts. The area between Mužský Hill and Vyskeř Hill also features a relatively high number of basaltic intrusions.

Outstanding geological and geomorphic features and their presentation

Apart from areas overcrowded by visitors, the less attended Příhrazy sandstones have a great potential for the presentation of various aspects of sandstone microrelief formation. This can be achieved, in our opinion, by an educational trail respecting the needs of nature conservation. Most of the geomorphic features worth to display are mentioned in the text above.

2.4 Plakánek Valley

Geology

The Plakánek Valley, also lying within the Žehrov Block, is incised in medium-grained, weakly lithified sandstones of the uppermost part of the Teplice Formation. Sandstone cliffs line both sides of the Klenice Stream flood plain and its tributaries. The dominant architectural element is the presence of clinoform surfaces dipping SSW (dip angles 0–10 °), interpreted as foresets of a prograding subaquatic delta body (Uličný 2001), Plate 1A–C. Several flooding surfaces near the tops of the cliffs result in progressive fining-upward and the presence of silty sandstone and siltstone. These flooding surfaces mark the transition to the Rohatce Member above. Younger marlstones and calcareous claystones of the Březno Formation are preserved on a plateau top above the valley. Dissolution of calcium carbonate at this level and its re-precipitation on the valley floor led to the origin of several tufa accumulations, rapidly aggrading in the recent years.

The axial Klenice Stream flood plain is about 50 m broad, filled with sand-dominated colluvio-fluvial sediments of Holocene age. Towards the south to southwest, the Plakánek Valley sandstones pass to the Mužský Hill plateau (Příhrazy, Žehrovský les) through areas with no prominent sandstone outcrops. In the south, sandstone outcrops are bounded by the WSW–ENE-striking Střehom Fault with relative subsidence of the southern block.

Large landforms

The Plakánek Valley is a typical canyon-like valley with a prominent flood plain filled with Holocene sediments. The main valley is 2 km long, while the side valleys have a total length of another 2000 m of sandstone outcrops.

Sandstone mesorelief and microrelief

Cliff faces are mostly 20–30 m in height. They start at the level of the flood plain or higher up on the slopes. Less common are rock pillars with prominent faces on the valley side and lower up-slope faces. The most common microforms are horizontal and subhorizontal ledges and honeycombs. Steep slopes affected by mass movements show gravitationally dilated joints and gliding blocks. A relatively large crevasse cave is situated in the central part of the valley. Case hardening is common (Soukupová et al. 2002) but does not occur on horizontal or, more exactly, subhorizontal, wavy ledges characteristic of permanently moist rock surfaces. Moisture on the rock surface permits the coverage of vertical cliff faces with vegetation (moss, lichens).

Specifics within the Bohemian Paradise PLA

The Plakánek Valley is the only sandstone district that has the character of a canyon with a permanent watercourse and a humid Holocene flood plain. Analogous valley segments can be also found on the Žehrovka Stream and in the Věžické Valley. Another specific feature is the presence of currently aggrading tufa accumulations.

Outstanding geological and geomorphic features and their presentation

The canyon-like character of the valley, the flood plain and the mesorelief can be well observed from the marked trail on the valley bottom between the Kost Castle and Rašovice. A set of information panels has been recently installed along this trail down the main valley and up the side valley leading to Vesec. From this trail, sedimentary architectures can be best viewed across the Timber Mill Reservoir (Pilský rybník or Obora), Fig. 7. However, no information is given on the tufa accumulations and on the examples of lateral stream erosion. From the viewpoint of the current research, this sandstone district is promising for a long-term monitoring of the vegetation–microrelief interaction.

■ **Fig. 7.** An old post-card with the scenery of the Timber Mill Reservoir (Pilský rybník), showing the clinoform surfaces gently inclined towards SSW. Photo by "J.L.Š".

2.5 Kozlov (Chlum)

Geology

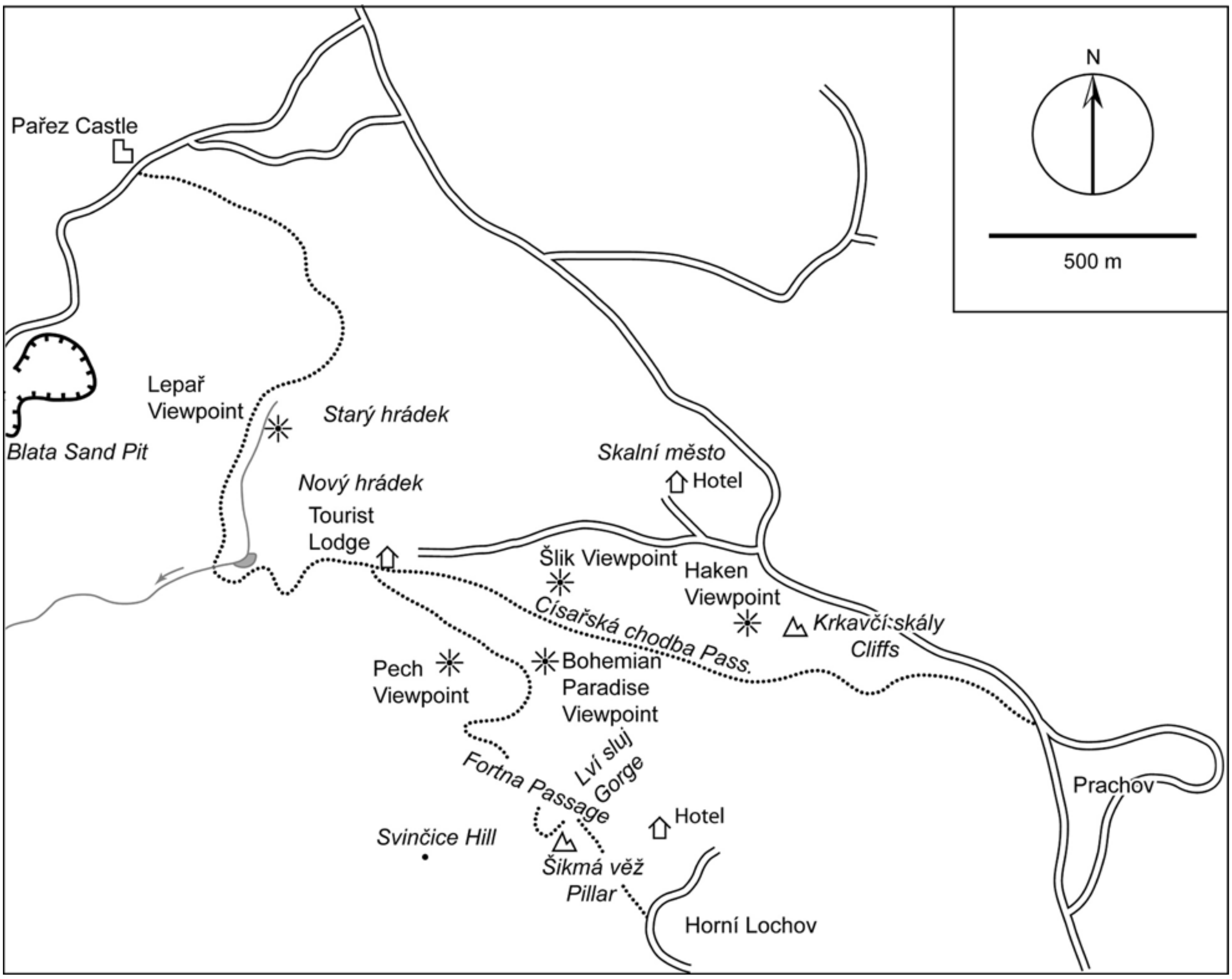
The Kozlov District is formed by medium-grained quartzose sandstones of the Hrubá Skála Quader (Teplice Formation). The tabular body of sandstone is only ca. 20 m thick, being underlain by marlstones (not in permanent outcrops) and possibly by other hidden, thinner sandstone bodies. The top of the plateau in the south is formed by marlstones of the overlying Březno Formation. The Kozlov District is an erosional relict of the western part of the Hrubá Skála Block.

Large landforms

A dominant elevation of the northern part of this sandstone area is the crest of Kozlov (also called Chlum) with a small but distinct rock city on its top. The crestline runs E–W, bending towards the SE. The southern part of the area is formed by a WNW–ESE-elongated plateau with the village of Pohoří. Sandstone outcrops are present mainly on the northern slope and do not have the character of a rock city: instead, they form a continuous cliff face and pillar-like sandstone blocks detached by gravitational gliding.

Sandstone mesorelief and microrelief

The area around the top of Kozlov Hill (358 m) is a unique example of a small, regularly arranged rock city. The sandstone blocks are rectangular in plan view and closely spaced (spacings of a few metres, max. tens of metres). On the northern slope, the sandstone outcrops on the upper edge pass into a landscape governed by block gliding, with some blocks transported as far as tens of metres from the clifflines. Down the slope, the blocks are mostly several metres in size; their microrelief (e.g., orientation of honeycomb pits) evidences repeated rotation and gliding during the last few centuries. Unique is the large, elongated crevasse cave at about mid-height on the northern slope: it is developed in a giant sand-



■ **Fig. 8.** A schematic map of the Prachov district. Principal tourist trails marked by dotted lines.

stone block whose bedding planes are now in vertical position (Mikuláš and Mertlík 2002b). Counterparts of fossil biogenic structures and tool marks on opposite cave walls document that these walls, now 2 m apart, once belonged to the same bedding plane. Blocky talus accumulation is so huge that the block containing the cave is not even exposed to the present surface.

Sandstone microrelief of the rock city and the blocky talus accumulation is largely derived from primary sedimentary structures, namely cross bedding. Honeycomb pits are only rarely arranged into compact “pitted surfaces” but are rather widely spaced (tens of centimetres to metres) and rare, as a result of block gliding.

Similar processes also operated on the northern slope of the Pohoří (also Pohoř) plateau. Several rows of gravitationally dismembered blocks ca. 10 × 10 × 10 m in size are present under the continuous sandstone outcrops of the plateau rim. Gliding of sandstone blocks was a more frequent feature than at the Kozlov crest. Typically, the movement of the bases of blocks was more rapid than that of their tops, which has produced rotated blocks, occasionally with their top parts leaning against the sandstone massif. Dilation of joints during this process gave rise to elongate caves. Microrelief of sandstones is similar to that of the Kozlov crest and includes excellent examples of inclined ledges that document former positions of the soil cover in crevasses between the blocks (Mikuláš 2001b).

Specifics within the Bohemian Paradise PLA

The area of Kozlov displays a concise set of features related to joint dilation, dismembering of sandstone blocks from the clifflines and block gliding. In other areas, these features are not so densely spaced and do not provide a full range of geomorphic expression.

Outstanding geological and geomorphic features and their presentation

Most of the above discussed phenomena can be displayed to visitors in the upper part of the Kozlov rock city and its close vicinity. Problematic is access to the infrequently visited plateau-rim sandstone outcrops north of Pohoří. In spite of this, an installation of a scenic educational trail showing the main geomorphic features should be possible without any adverse effects on the landscape as a whole. On the other hand, opening of the crevasse caves to the public is impossible: the space available in the cave interiors is usually very limited, and frequent visits would have a devastating effect on cave walls. Some elements of sandstone microrelief are remarkable from the viewpoint of the currently ongoing research: pitted (honeycomb) surfaces, inclined ledges, biogenic sedimentary structures.

2.6 Prachov (Prachovské skály)

Geology

The Prachov District is formed by weakly to moderately lithified quartzose sandstones of the Teplice Formation, mostly of medium grain size. The sandstones are arranged into upwards-coarsening cycles and contain cross-bedded sets tens of centimetres in thickness. Their foreset laminae dip generally south (Skoček and Valečka 1983). The exposed sandstone body is 100–140 m thick, and is underlain by marlstone. The present surface morphology evolved from a sandstone plateau slightly tilted by tectonic processes and intruded by numerous basaltic bodies like dykes and stocks (Svinčice, dykes at Blata). Orthogonal jointing favourable for the origin of a rock city comprises a dense network of vertical joints WNW–ESE (spacings in metres) and perpendicular joints NNE–SSW (spacings in tens of metres), see Plate 8A. Ferruginous cement in the sandstone concentrates to microconcretions along basaltic intrusions (Svinčice) and to tensional joints (Fortna), Mertlík et al. (2002).

Large landforms

The Prachov District represents a very complex erosional remnant of a sandstone plateau dissected by gullies, gorges and broader valleys. Segments of the original plateau now host a rock city dominated by narrow, tall pillars and blocks.

Sandstone mesorelief and microrelief

Sandstone necks, pillars with elongate-rectangular cross sections, and wall-shaped cliff faces are the most common. Microrelief of the rock city and blocky talus accumulations is largely derived from primary sedimentary structures: stratification and cross bedding. The honeycomb pits seldom group into pitted surfaces. Vertical crevasses, chimneys and concave and convex vertical edges are some of the most prominent features.

Specifics within the Bohemian Paradise PLA

The Prachov District, and its rock city in particular, exemplifies a very well-developed sandstone landscape with all characteristic features. Rock pillars are tall, usually markedly elongated in plan view (WNW–ESE), unlike those of the Hrubá Skála rock city. The extremely high visitor numbers to this area results from the long tradition of tourism and the relatively small area of the sandstone district.

Outstanding geological and geomorphic features and their presentation

Much like in the Hrubá Skála District, the enormous load of tourism is not favourable for the presentation of small-scale phenomena in sandstone. Illegal activities like rock carving, rock collecting, or digging for archeological artefacts would put such sites at risk. Preferably, the phenomenon of a rock city as such should be demonstrated from viewpoints. The current

■ **Fig. 9.** An old post-card with a photo of the Emperor Passage, published by the “Tržnice dopisnic” in Jičín in 1906.

network of marked trails and objects of tourist interest is very dense. Such objects include:

Americká sluj (American Grotto) – a wild, shaded, bouldery gorge in the Babinec labyrinth. Císařská chodba (Emperor Passage) – the largest gorge in the Prachov rock city, lined with vertical cliff faces (see Fig. 9 and Plate 8C, E). Fortna – a narrow passage among sandstone blocks in the southern part of Prachovské skály near the Šikmá věž (Leaning Pillar). Haken Viewpoint – an outlook point (ca. 460 m) in the central part of the rock city with a good look at the group of Krkavčí skály (Raven Cliffs). Lepař Viewpoint – an outlook (397 m) towards Nový hrádek and Krkaviny Cliffs in the northern part of the rock city, 1.5 km from the Skalní město Hotel. Lví sluj (Lion Grotto) – a short, bouldery gorge in the proximity of the Šikmá věž (Leaning Pillar). Pařez – remains of a castle partly carved in a sandstone block (360 m) on the NW margin of the rock city. Pech Viewpoint – a view of the rock city and forested slopes of Starý hrádek and Nový hrádek. Starý hrádek – an archaeological site of prime importance in the NW part of the rock city, 0.9 km west of the Skalní město Hotel, spread across a vast, forested sandstone plateau with steep, almost vertical cliff faces on all sides except for the eastern side accessible by a narrow neck. Svinčice – a basaltic elevation (451 m) in the southern part of the rock city with an abandoned quarry on its southern slope. Šlik Viewpoint – a cliff in the central part of the rock city (448 m) providing a good view of the central part of the rock city and the Míru and Bohemian Paradise viewpoints across the gorge. Bohemian Paradise Viewpoint – one of the best viewpoints in the central part (445 m) showing a panorama of pillar groups from the Císařská chodba (Emperor Passage) to the Tourist Lodge, and of the more distant hills of Trosky, Vyskeř, Mužský, Ještěd and Ralsko.

2.7 Klokočí and Betlém Cliffs (Klokočské a Betlémské skály)

Geology

The cliffs are cut in quartzose sandstones of the Hrubá Skála Quader (Teplice Formation), overlying the calcareous sandstones and sandy limestones of the Jizera Formation and basal calcareous claystones of the Teplice Formation, here reduced to only a few metres in thickness. Quartzose sandstones of the Hrubá Skála Quader are ca. 140 m thick. The dominant architectural elements are clinoform surfaces dipping SSW at an angle of 12–15°, of which about 5° can be ascribed to secondary tectonic dip (towards southwest) of the whole sandstone body. The clinoform surfaces represent slopes of a subaqueous delta (i.e., delta foresets). Superimposed on the clinoform surfaces, giant-scale cross bedding up to several metres thick documents a migration of sand waves (giant transverse bedforms) towards the north and the south. Bodies of young volcanic rocks have not been identified in this area yet. Jointing is a prominent feature in some places: joints are accompanied by silicification and are generally parallel to the Lusatian Fault (NW–SE). Ferruginization effects include tube-shaped goethite concretions and joint fillings that are concentrated in the NE edge of the sandstone district (Mertlík et al. 2002). This is probably defined by a fault zone or a dense fracture zone following the line Podloktuší – Klokočí – Podloučky. Tectonic stress related to movements on the nearby Lusatian Fault was released not only through minor faults but also swarms of deformation bands – zones of tectonic shearing (Main et al. 2001, Mertlík and Adamovič 2005), see Appendix 1 and Plate 5A–H. Strata-parallel thrust faults are indicated by flat-lying striated fault planes at several sites. In the southwestern part, the sandstone district is limited by the fault zone running along the Libuňka Stream and by the Stebenka Stream valley.

Large landforms

The Betlém Cliffs and the Klokočí Cliffs are two areas of vast sandstone exposure located on the Klokočí cuesta. The cuesta character is determined by the south-southwesterly dips of clinoform surfaces and the whole sandstone body. The Betlém Cliffs form a small rock city while the Klokočí Cliffs are characterized especially by the head of a cuesta with prominent cliff faces, although groups of pillars are also developed. Tectonic setting had a major effect on the formation of large landforms, namely the cuesta itself and the Zelený důl (Green Valley) canyon, but also mesoscale-landforms.

Sandstone mesorelief and microrelief

Among forms of mesorelief, rock pillars of various sizes with cliff face heights of 5–30 m are the most notable (Fig. 10). As a very peculiar mesorelief element, about 300 caves of all different types (crevasse caves, strata-bound caves, talus caves, rock shelters) are present on the Klokočí cuesta (Vítek 1987, Mertlík and Adamovič

■ **Fig. 10.** A post-card with a photo of the sandstone pillars, which supported the medieval Rotštejn Castle, in the SE part of the Klokočí Cliffs. Published by "Turistická a všeobecná poptavárna" in Turnov around 1910.

2005), see Plate 10C–F. The largest cave (Postojná) has a total length of 75 m and the area of 262 m^2 (Vítek 1987). The formation of caves may be connected with thrust faulting (Mertlík and Adamovič 2005). Several well-defined rock arches spanning max. 4 m including a double arch (Tripod – Trojnožka) are situated near Záholice in the Betlém Cliffs. Numerous false arches are formed by boulders that have fallen into broad crevasses (e.g., NE and E of Rozumov). Three dozen sinkholes are developed on top of the plateau, with the largest one 10 m in diameter.

Sandstone microrelief is exceptionally variegated. Ordinary elements include pitted surfaces with perfectly symmetrical patterns and an obvious "construction plan" governed by physical parameters of rock and the relevant environmental factors. Rock ledges and products of case hardening are also present. Honeycomb pits of various types are present (Mikuláš 2001a), see Plate 12G–H. Besides rillenkarren on tops of the pillars, thinner but straight wandkarren are developed on nearly vertical cliff faces by the action of dripping water (Plate 11D–E). A series of concave, striated cylindrical planes with subhorizontal axes near Rozumov represents a shear fault plane. Man-made traces resulting from millstone polishing have been preserved at a few sites (Mertlík and Mikuláš 2003), Plate 16E.

A less ordinary but very typical microrelief element on the Klokočí cuesta is the presence of vertical and inclined systems of grooves and ribs, often mutually intersecting. They are controlled by the courses of deformation bands (see Geology). On rock surface, the deformation bands are manifested by "veins" of sandstone of different colour intensity. These form either positive relief (where silicified) or negative relief. This phenomenon differs from common jointing in the absence of fissures as well as from wandkarren whose structures do not continue into the rock interior. The most instructive sites in the Klokočí Cliffs include the Koník Cliff (ca. 50 grooves on the cliff top 15 m broad, Plate 5D) and cliff faces beneath the Pětichlapka Cliff (about 30 intersecting bands on several square metres, Plate 5F–H). Very special microforms are formed at places with overstepping or bifurcating deformation bands, or where the whole system of deformation bands fringes out abruptly. On horizontal rock surfaces, the grooves are usually shallow (several cm) and U-shaped in cross section. Grooves on vertical cliff faces are up to 20 cm deep, with flat bottoms and straight or concave walls. Sets of closely spaced grooves with concave walls give rise to ridges between them, reminiscent of rails in their cross section and size.

Specifics within the Bohemian Paradise PLA

The Klokočí cuesta is a real "textbook of geomorphology". Almost all sandstone meso- and microforms so far described are present on an area of 3 km^2.

Outstanding geological and geomorphic features and their presentation

Caves are undoubtedly the most attractive geomorphic feature on the Klokočí cuesta. Their presentation to visitors is, however, problematic as greater visitor numbers would lead to their ultimate destruction and to the damage on their surroundings. The only exception is perhaps the Postojná Cave, which lies on a marked trail and is visited by thousands of tourists every year: here, a sensitive commercial operation should not be refused. The existing trails should be equipped with more detailed information on microrelief elements (karren, tectonic ribs, honeycomb pits) but opening of new trails cannot be recommended.

2.8 Drábovna near Malá Skála

Geology

The Drábovna District is formed by medium-grained, well-lithified quartzose sandstones of the Hrubá Skála Quader (Teplice Formation). These are underlain by claystones of the basal Teplice Formation only several metres thick, and by calcareous sandstones of the Jizera Formation. The district is a rugged erosional relict (466 m a.s.l.) of a formerly larger, elevated sandstone plateau (its limits are free of any faults). The most important ruptures are fracture zones striking NE–SW, which reflect waning strike-slip faults transverse to the Lusatian Fault zone (Adamovič in Budil et al. 1999). Much like in other sandstone districts in the Lusatian Fault proximity, the Drábovna shows systems of oblique joints and tectonic ribs controlled by the courses of deformation bands.

Large landforms

The plateau is dissected by shallow valleys of various cross section profiles (gradational to canyon-like) into segments lined with rock outcrops. Erosional processes resulted in the origin of small groups of isolated pillars – rock cities – in several areas. The cliff faces are usually about 10 m, exceptionally 20 m high (Hrádek Cliff).

Sandstone mesorelief and microrelief

Orthogonal jointing of the Drábovna sandstone plateau is not absolutely regular, with the more prominent, now dilated joints spaced at metres to tens of metres. The individual blocks are therefore characterized by different orientations of cliff faces and relatively large compact, often smooth surfaces ("smoothing" is contributed by the rapid formation of rock crusts, i.e., their slow destruction). Honeycombs, where present, are affected by the firmness of the crusts and secondary inhomogeneities of the sandstone: therefore, they often follow surfaces of tectonic grooves and ribs. The resulting microrelief does not differ much from that in the Betlém Cliffs.

The relatively small thickness of the sandstone body and its plastic footwall lead to gravitational dismembering of blocks at plateau rims. Deep rock shelters at cliff bases are common.

The relatively low permeability of the sandstone, caused by a certain proportion of quartz cement, has permitted the formation of solution basins on cliff tops. Elsewhere, the top portions of the cliffs are perforated in a complex manner. Morphologically prominent is a level of weakly cemented sandstone a few metres below cliff tops, giving rise to some of the best developed mushroom rocks in the Bohemian Paradise (Plate 9B, C).

Specifics within the Bohemian Paradise PLA

The combination of parameters responsible for the overall geomorphology of the Drábovna District – i.e., a relatively thin body of hard sandstone on an areally extensive plateau of amoeboid outline – is not paralleled elsewhere in the Bohemian Paradise. Sandstone microrelief is close to that of some portions on Sokol Hill and in the Betlém Cliffs.

Outstanding geological and geomorphic features and their presentation

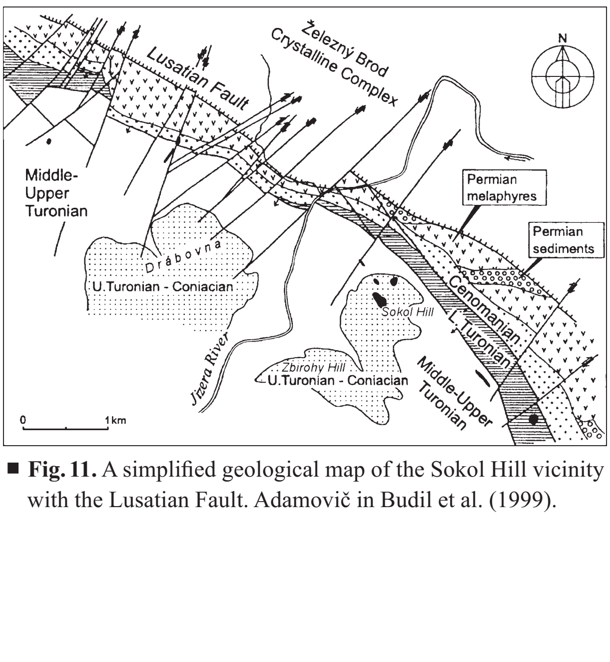
The Drábovna District is relatively frequently visited at present: it is transected by two marked trails, and the concentration of holiday homes in its neighbourhood is high. There is no need for the opening of new trails as landforms of meso- and microrelief of sufficient diversity can be displayed in the close proximity of the existing trails. These forms include cliff faces with diverse rock decorations around the Hrádek Cliff, perforations of pillar tops near trail crossing in the centre of the sandstone district, and deep rock shelters on its NE edge. With regard to current research, the Drábovna District is exceptional in its variety of landforms derived from tectonic structures: joints and deformation bands.

2.9 Sokol Hill

Geology

Outcrops on Sokol Hill can be classified as fine- to medium-grained quartzose sandstones of the Hrubá Skála Quader. The herein discussed area covers two enclaves of erosional relicts preserved in top parts of the hills of Sokol in the north and Zbirohy in the south. Tectonic dips of 5–10 ° to SSE are related to the Lusatian Fault zone running approx. 1 km to the northeast (Fig. 11). The sandstones are characterized by a high variability of sedimentary structures. The topmost parts of Sokol Hill display very good examples of giant-scale cross bedding over 7 m thick, with laminae dipping SSE (Adamovič 1992). The Chléviště rock city is rather dominated by planar and trough cross bedding 10–50 cm thick, occasionally arranged into herringbone bedding. The areas of Chléviště and Zbirohy Hill commonly display flat, wavy erosion surfaces with signs of hummocky cross-stratification, evidencing the effects of storm events below the fair-weather wave base. Rare ferruginized wood fragments were reported from the sandstone by Mikuláš and Mertlík (2002a).

The joint system shows a prevalence of strikes NNE–SSW and WNW–ESE. Sokol Hill is formed by a body of basaltic intrusive breccia near its top and other basaltic intrusions which probably represent some of the youngest volcanic rocks in northern Bohemia (Miocene to Pliocene). The sandstones at Chléviště and Zbirohy Hill enclose frequent spherical and tube-shaped ferruginous concretions: a thick bundle of ferruginous tubes elongated WNW–ESE marks the northern edge of the Zbirohy plateau (Mertlík et al. 2002). Holocene sandy slope aprons and blocky talus accumulations of quartzose as well as calcareous sandstone are common, especially on slopes leading down towards the Jizera River.



■ **Fig. 11.** A simplified geological map of the Sokol Hill vicinity with the Lusatian Fault. Adamovič in Budil et al. (1999).

The lateral extent of the sandstones is defined by an erosional boundary along the whole periphery of this sandstone area. To the west, the area is limited by the deeply incised, canyon-like valley of the Jizera River. Slopes above the Jizera River and below the base of the quartzose sandstones on the tops of Sokol and Zbirohy hills are lined with extensive outcrops of calcareous sandstones of the Jizera Formation.

Large landforms

Macrorelief of this sandstone area can be ranked among the most complex and variegated in the Bohemian Paradise. The southern part of the area – the separate elevation of Zbirohy (452 m) with a ruin of the Zbirohy Castle – forms an E–W-trending crest protruding westwards into a relatively narrow rocky spur. In the east, this elevation forms a narrow plateau rimmed by cliffs. The northwestern slope of Zbirohy Hill inclined towards the Jizera River shows two levels of cliff faces formed by calcareous sandstone and thick talus accumulations with blocks and boulders around their bases. The length of continuous sandstone outcrops is about 1000 m. In the northern part of the area, the outline of Sokol Hill is irregularly cupola-shaped to bell-shaped, controlled by the presence of basaltic bodies. Two prominent, isolated rock pillars are present near its top. A relatively small rock city of Chléviště is developed on the western slope of Sokol Hill, the Kalich rock city is located southwest of the top, and a small Besedice rock city lies south of the top of the hill.

Sandstone mesorelief and microrelief

The western part of the Zbirohy Hill crest provides disintegrated blocks of quartzose sandstone for talus accumulations, while the primary outcrops form only small necks and pillars on the crestline. Their surfaces are round and smooth or transected by ribs of deformation bands often accompanied by “chains” of honeycomb pits. Grooves on cliff edges, produced by mechanical abrasion by growing trees, are common. Less common are spherical cavities tens of centimetres in diameter and small solution basins. The eastern part of the same crest is articulated into numerous necks and small pillars. Features of sandstone microrelief include rock ledges controlled by primary sedimentary structures. Honeycombing is common on walls of rock shelters.

The Besedice rock city comprises rock pillars around 10 m in height, separated by fissures and small chimneys. Microrelief elements include horizontal or subhorizontal ledges (controlled by sedimentary structures), wavy ledges and honeycomb pits in rock-shelter interiors. Numerous tectonic ribs formed on deformation bands create several systems dipping at an angle of about 45°. The Kalich rock city is similar in its character and differs from the former only in the weaker sandstone lithification and a higher occurrence of rock niches and fallen blocks. The largest rock city in the Sokol area is the Chléviště, situated on the plateau rim above the Jizera River valley. Here, the cliff faces are max. 20 m high, scarred by grooves and ribs of deformation bands. Numerous “grottos” and narrow passages in the central part of the rock city are modified by fallen sandstone blocks.

The continuous outcrops of calcareous sandstone along the Jizera River are completely different in character. Minute (tens of cm) exfoliation scales parallel to the trend of cliff faces are the dominant microrelief element. Numerous crevasse caves correspond rather to corrosive karstic forms than to pseudokarst forms in their shapes. Thin, blister-shaped rock crusts occur occasionally, much like imperfectly developed arcuate honeycomb pits at other places. Several cliffs were shaped into vaulted rock shelters up to 5 m high. Conspicuous are the finds of fossils, e.g., *Pinna* bivalves preserved in life position. Some crevasses are very old: partial lithification of their sediment fills indicates their Tertiary age. Multi-phase dilation of the crevasses is evidenced by the presence of several generations of the fills.

Specifics within the Bohemian Paradise PLA

The Sokol Hill area provides the best outcrops of calcareous sandstones in the Bohemian Paradise PLA, displaying very specific and as yet not fully documented microrelief. The Chléviště and Kalich rock cities, much like the Kalich rock city, are characterized by the presence of “rock labyrinths”: networks of narrow passages between parted or fallen sandstone blocks. The western part of the Zbirohy Hill crest is typical in the prevalence of fallen blocks over primary sandstone outcrops.

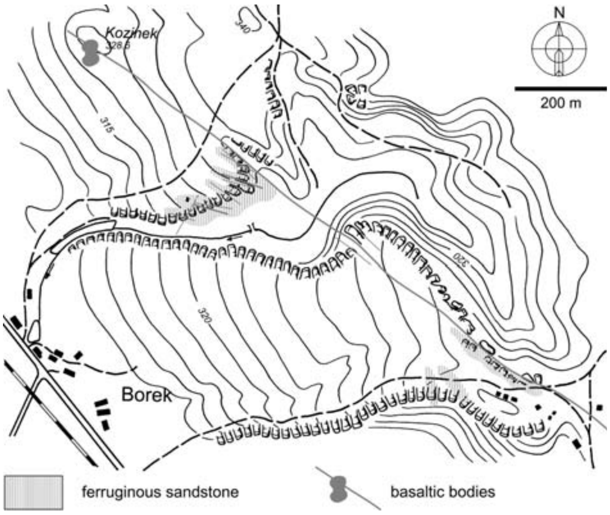
Outstanding geological and geomorphic features and their presentation

The rock cities of Chléviště and Kalich are made accessible through a marked loop trail, providing good views of most of the described phenomena. The same holds for the Besedice rock city. The potential presentation of the phenomena in the eastern part of the Zbirohy Hill crest (ironstones and other microrelief elements) and calcareous sandstones between Zbirohy Hill and the Jizera River is problematic because of the risk of falling from unconsolidated surfaces, blows by falling stones, damage to cliffs by collection of fossils, and damage to sedimentary fills of caves. It is therefore recommended that the present accessibility to the area is maintained.

2.10 Borek (Borecké skály)

Geology

This relatively small sandstone district is generally formed by medium- to coarse-grained, weakly lithified quartzose sandstones of the Hrubá Skála Quader (Teplice Formation). It is clearly affected by the proximity of the Lusatian Fault zone (ca. 1 km to the east): the whole sandstone body dips southwest at an angle of 5–10°. Sedimentary structures in the sandstones include horizontal stratification and cross bedding tens of centimetres thick. Specific ichnofabrics are developed in places (Plate 3F). Joints strike WSW–ENE and NW–SE. The topmost portion of the Borek Cliffs hosts a continuous but hidden basaltic dyke striking WNW–ESE, terminated by a complex of intrusive bodies at Kozinek Hill in the west (Mertlík et al. 2002), see Fig. 12. The southern contact of the dyke is lined with zones of ferruginous cement forming tube-shaped concretions and fills of subvertical joints (Plate 7E).



■ **Fig. 12.** A map of the Borek District showing the relationship between intrusive bodies of basaltic rocks and ferruginization. Heavy grey lines and areas – intrusive bodies, thin grey lines – joints, dashed areas – ferruginous sandstone. After Adamovič (2001).

Large landforms

Tectonic dips of the whole sandstone body are responsible for the existence of a rhomboidal cuesta, with its front striking NW–SE, dissected by transverse valleys drained towards the southwest.

Sandstone mesorelief and microrelief

Typical mesorelief elements are more-or-less straight cliff faces up to 30 m high, a sandstone neck transected by narrow gorges and chimneys, and a few pillars. Numerous short gorges and incipient rock pillars are developed on the cuesta front. Small elements of sandstone relief are locally dominated by case hardening and the destruction of rock crusts (Plate 14A), by pitted surfaces, but most typically by ledges following the original bedding planes. Loaf-shaped cavities (tafoni) up to several metres in diameter are ubiquitous.

Specifics within the Bohemian Paradise PLA

This area is protected as a nature reserve but lies just outside the PLA limits. Specific features within the Bohemian Paradise region is the relatively simple mesorelief and the large tafoni with unusual cliff-face sculptures (diffusely bounded rock crusts and beds impregnated with red iron oxyhydroxides) whose genesis has not been fully explained yet and is worth of further study. Instructive is the spatial relation of the basaltic dyke to the different forms of sandstone ferruginization.

Outstanding geological and geomorphic features and their presentation

The area provides good views to the centre of the Bohemian Paradise, and is therefore frequently visited. Moreover, holiday homes are scattered in its vicinity as well as in the sandstone district itself (on its periphery). In the southern part of the district, the above mentioned geomorphic peculiarities should be explained in more detail on information panels.

2.11 Suché skály

Geology

The crest of Suché skály Cliffs represents an exhumed belt of upturned quartzose sandstones of the Peruc–Korycany Formation (Cenomanian) along the WNW–ESE-striking Lusatian Fault. This belt is limited by andesites and latites of Permian age in the NNE and by marlstones of the Turonian Bílá hora Formation. These are very rarely exposed to the surface and are mostly hidden beneath thick talus accumulations of the sandstone. The sandstones are coarse-grained, passing to conglomerates, with cross-bedded sets several tens of centimetres thick. Bedding planes are subvertical, dragged in the proximity of the principal reverse fault of the Lusatian Fault zone. Three sets of ruptures determine the morphologies of the cliffs: 1. faults parallel to the rocky crest, both reverse and normal, with silicified fault planes with slickensides, often accompanied by a dense network of quartz veins; 2. faults and fracture zones perpendicular to the course of the rocky crest, with dilated ruptures only rarely showing strike-slip movement, rarely silicified but often ferruginized, and 3. faults striking E–W, activated as strike-slip faults, with silica cement and hence very resistant to erosion. The cliffs display tectonic zones of different orientations (strongly silicified tectonic ribs and less regular veins), see Plate 4B, D.

Large landforms

The upright-standing block of Cenomanian sandstone gave rise to a continuous rocky crest, which continues on the other bank of the Jizera River towards Frýdštejn under the name Vranovský hřeben Crest. The rocky crest is about 80 m broad at its base, ca. 1000 m long, with SSW cliff faces 40–80 m in height in its central part and NNE cliff faces 10–30 m in height. Farther to the ESE, the crest becomes less prominent, passing to isolated rocky outcrops and finally into a ridge without outcrops.

Sandstone mesorelief and microrelief

The rocky crest of Suché skály can be subdivided into four main "spires" and a number of isolated "tooth-like" cliffs both in their neighbourhood and within the "spires". The course of the crestline is controlled by the orientation of the silicified fault planes and sets of quartz veins resistant to erosion. Saddles between the individual crest segments are defined by the positions of transverse tectonic structures. Gently dipping faults of E–W strike give rise to prominent rock plates. Specific microrelief features include exhumed veins and tectonic ribs, locally developed honeycomb pits, and slickensides in the eastern half of the crest. Worth mentioning is an isolated sandstone pillar south of the rocky crest (Samotář – Recluse).

Specifics within the Bohemian Paradise PLA

The crest is exceptional for the PLA as well as all the Bohemian Massif sandstone landscapes as a relief sculpted in a vertical block of strongly lithified sandstone. This fact predetermines the essential macrorelief pattern; in addition, unique slickensides were formed by movement along fault planes.

Outstanding geological and geomorphic features and their presentation

The major attraction of the Suché skály Cliffs lies in its macrorelief, which can be viewed from a number of sites in the broader vicinity. The best view is obtained from Sokol Hill 1 km south of Suché skály. A series of viewpoints with explanatory texts should compensate for the limited access to the cliffs themselves, now suffering extensive damage from alpinists and other visitors. Establishment of a marked tourist trail leading from the north to the slickensides in the eastern face of the highest spire should be considered.

2.12 Kozákov Hill

Geology

The Kozákov District includes the Měsíční údolí (Moon Valley) and the high Drábovna block. Their geological setting is largely controlled by the proximity of the Lusatian Fault zone. Kozákov Hill is the area where the fault zone is left-laterally displaced by at least hundreds of metres. Blocks of Cenomanian sandstones (Peruc–Korycany Formation) on the western slopes of Kozákov Hill were uplifted, tilted and subsequently incised. Although continental sediments of the Peruc Member are also present (ancient galleries for coal prospection), the cliffs are formed by fine- to medium-grained quartzose sandstones of the Korycany Member. Tectonic dip of the strata is 15–30° to the SW. Orthogonal jointing is, however, subvertical (the same as in sandstone districts with horizontal dips of strata), giving rise to unusual rhomboidal shapes of pillars and cliffs in side view. Besides open, vertical joints, several systems of oblique joints (dip angles close to 45 °) are also developed, typically forming tables of more strongly silicified sandstone. At the hilltop, Permian andesitic volcanics are penetrated by bodies of Miocene–Pliocene basalt with olivine nodules (Medaris et al. 1999, Ulrych and Adamovič 2004).

Large landforms

The Kozákov District is developed in a partly destructed cuesta (Plate 4E). The unique configuration of tectonically tilted blocks gives rise to the canyon-like Měsíční údolí at a place where two rocky cuesta rims merge in downhill direction. The cliff faces are 15–20 m high in the upper parts of the valley and up to 30 m high in its lower part.

Sandstone mesorelief and microrelief

The prevailing vertical cliff faces bear numerous steep fissures and chimneys. Isolated pillars detached from the sandstone massif are rare but contribute considerably to the aesthetic value of the area. Sandstone in the lower parts of the cliff faces is only weakly lithified and prone to erosion. This gives rise to numerous niches and strata-bound caves at cliff bases. Case hardening, producing rock crusts, is a very rapid process in the lower parts of the cliff faces, and the crusts are equally rapidly destroyed. This explains the wide variety of unusual microforms, such as bowl-shaped crusts developed inside the honeycomb pits. Low arcuate honeycomb pits are also present (Plate 13A). Steeply dipping ribs are associated with systems of oblique joints and deformation bands. They become markedly more distinct towards the present cliff tops. Sandstone blocks on the plateau south of the upper end of the Měsíční údolí bear high numbers of closely-spaced ribs, thereby displaying the boxwork type of weathering. Cliffs north of the canyon-like Měsíční údolí host crooked veins of silicified sandstone of many different orientations.

Specifics within the Bohemian Paradise PLA

The southwestern slopes of Kozákov Hill represent the largest areal exposure of sandstones of the Peruc–Korycany Formation in the Bohemian Paradise. It is the only district in a markedly dipping sandstone body with prominent macrorelief (Měsíční údolí) and specific microrelief.

Outstanding geological and geomorphic features and their presentation

Large landforms in this area, i.e., the cuesta with superimposed smaller-size forms (cliff faces, fissures, pillars, niches) are the most instructive features to be presented to visitors. A frequented marked trail crosses the area of Drábovna. If other tourist trails are planned in the future, they should stay away from the Měsíční údolí. The only sites in the Měsíční údolí that can be made accessible for tourists are: 1. the lower end of the valley where the origin of rock niches and rock crusts is well documented, and possibly 2. the viewpoints above the southern part of the valley, currently not accessible for tourists but providing the best views of the tilted sandstone block (cuesta) and some good examples of tectonic ribs, hydrothermal silicification and Subrecent–Recent subaerial silicification of sandstone. These features should be explained on information panels.

3. The origin of sandstone landscapes – a review of processes

The evolution of the sandstone relief is a continuous process, depending on sandstone lithology and cementation, tectonic deformation before and after exhumation, much like on climate and its dynamics. Periods of only little change may alternate with periods of accelerated landscape degradation. Repeated episodes of rejuvenation may create extremely complex sandstone landscapes.

In spite of the complexity of sandstone landscapes evolution, a simplified model can be drawn, distinguishing separate stages in sandstone landscape development. The presented model, though somewhat schematic, is a traditional one. It was formulated in the pioneer papers of German and Czech geologists from the Saxonian Switzerland (Hettner 1887, Rast 1959) and other regions of the Bohemian Cretaceous Basin (Novák 1914, Vítek 1979, Balatka and Sládek 1984). It is presented here, with examples of specific sandstone areas, for further discussion.

3.1 Preparatory stage

In this stage, the sandstone body lies hidden beneath the surface and – with most of its volume also below the groundwater table. Groundwater circulation is mediated by pores in the whole volume of the sandstone body, but also by fractures and water influx in their close vicinity (tens of cm to 2 m). Observations from other areas, e.g., from the underground passages at Prosek near Prague, show that even in subsurface conditions the sandstone massif differentiates into more consolidated blocks (*Quader*) several metres in diameter, surrounded by soft sandstone or even loose sand. Some role of deep weathering under hot and wet conditions in the Tertiary is possible in this process.

When within the reach of erosion, such differentiated sandstone massif rapidly splits into solid cores that form the basis for an incipient rock city. The decisive role in the formation of such weakness zones can be attributed to frost action during glacial periods. Then, water-saturated fractures were subjected to freezing including the zones of water influx ca. 0.5–4 m broad, and to subsequent frost-induced loosening of the sandstone.

Cementation of sandstone has also a great bearing on the resulting landform types. In the Bohemian Paradise, first ruptures formed very early after the lithification of sand into sandstone in connection with the main reverse movements on the Lusatian Fault. Silica cement was derived from pressure solution of quartz grains and mostly precipitated on minor shear faults. This process was responsible for the origin of quartz and chalcedony veins in sandstone, that are highly resistant to erosion. Open ruptures and the ambient sandstone mass were filled with iron oxyhydroxides mobilized later, during episodes of volcanic/hydrothermal activity in the Tertiary. Various types of cementation are then responsible for the numerous deviations from the ordinary *Quadersandstein* geomorphic pattern.

3.2 Incipient stage

This stage is characterized by tectonic uplift and erosion of the weathered sandstone. It is typically exemplified by flat landscapes with sandstone gorges in central Bohemia. Further north, more mature forms of sandstone relief can be observed with the increasing rate of tectonic uplift. The individual stages in the evolution of sandstone landscapes in Bohemia can be thus traced along a line starting at Prosek or Vinoř in Prague, and continuing across the gorges of the Kokořín area and Skalsko plateau as far as to the rock cities of the Bohemian Paradise, Hradčanské stěny Cliffs and the Elbe River sandstones.

3.3 Maturity stage

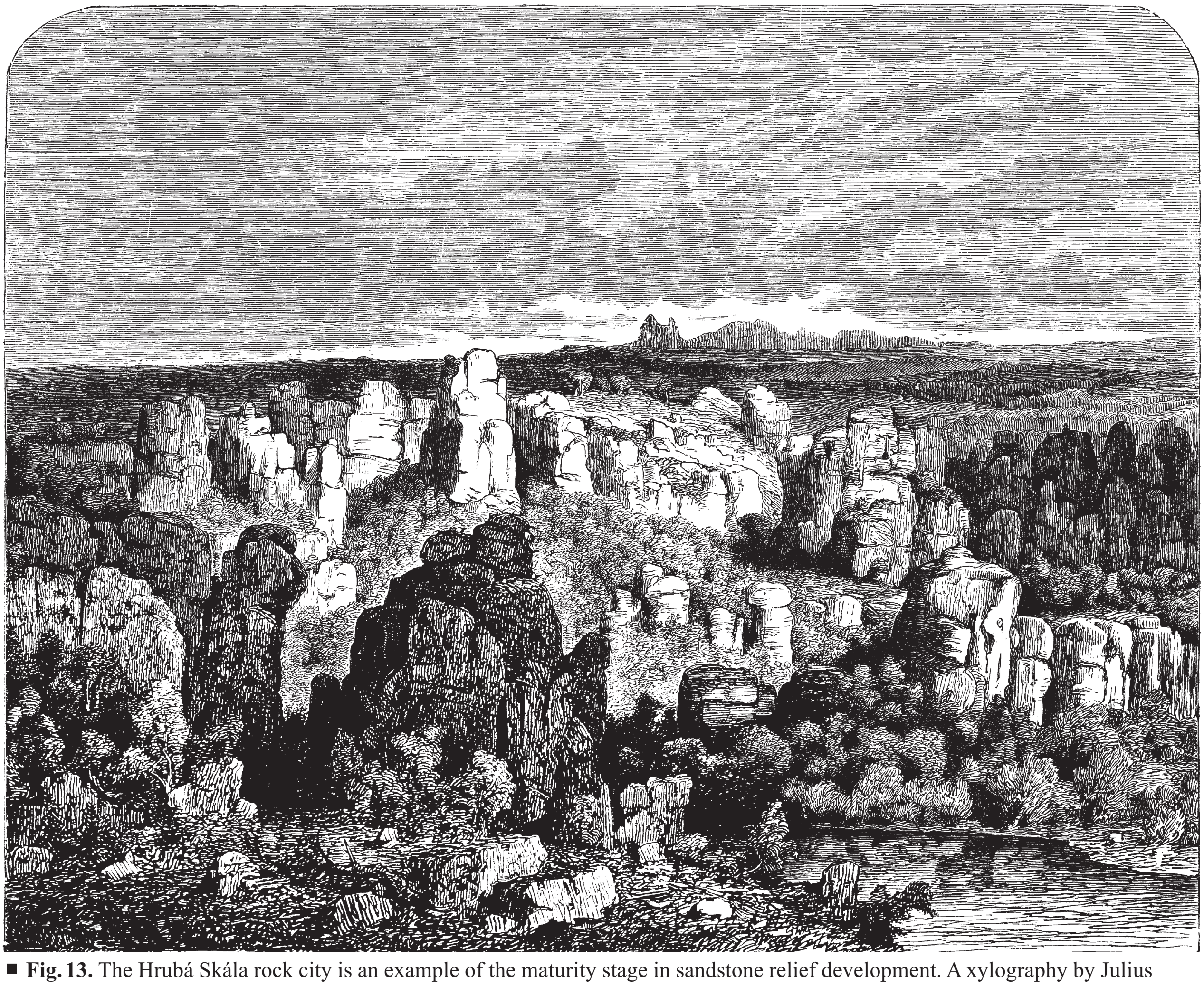
At a certain point in a sandstone landscape development, tectonic uplift and erosive exhumation of weathered zones are of very low or no effect. Instead, the surface is shaped by various types of weathering combined with the antagonistic process of protective rock crust formation. Eight years of excavation activities under sandstone rock shelters in central and northern Bohemia revealed an important fact: the Mesolithic layer repeatedly dated by ^{14}C method to 10–7 ka, tapers horizontally at a distance of only 3–15 cm from the present rock-shelter outline. This indicates that the rock shelters deepened by only about 10 cm during the whole of the Holocene. The bulk of this landform must therefore be attributed to periglacial effects, resulting from freezing and frost destruction of moister portions of the rock massif – for example, within the reach of rising capillary water – after multiple freeze-and-thaw cycles. It is also possible, however, that rock shelters relate to areas of inferior cementation during diagenesis.

Delamination of exfoliation scales is another very important mechanism of sandstone relief modification. Exfoliation scales are roughly tabular portions of the sandstone massif, 20–40 cm thick on average (max. >1 m), copying the contours of cliff faces. The spans of rock arches, for instance, often show fissures copying the arcuate stress trajectories (Young and Young 1992). Then, delamination of the bottom portions of the arch may take place (Skalní brána/Frauentor Arch in the Hradčanské stěny Cliffs). In rock shelters, delamination of the overhanging scales is a common feature. Nevertheless, delamination of lens-shaped scales also sometimes occurs on mushroom rocks; it has the character of typical, juvenile, concave-outwards ruptures.

Young scars on a sandstone surface become soon overprinted by a combined effect of several other types of weathering. These include particularly rain erosion, the intensity of which is probably controlled by kinetic energy of the falling raindrops. Also, the erosion of cliff faces by hail strikes should not be underestimated on a geological time scale. The role of vegetation is a more complex one: early-stage sandstone destruction by roots and anchoring fibres is later substituted by rock-surface protection against climatic effects. Salt weathering is an important process at sites protected from mechanical erosion, as in caves or rock-shelters. Halite crystallizing from relatively weakly oversaturated fluids that commonly occur under natural conditions, exerts pressures of about 60 kPa (equal to 600 atmospheres!). Crystallization pressures are around 30 kPa for gypsum and 5–30 kPa for most natural sulphates (Cílek 1998). Such pressures can disintegrate most of the common sedimentary rocks. A release of sulphur oxides due to sulphur-rich lignite combustion in 1950–1990 induced neutralization of acid rain by soil and rock substrates. This resulted in an enormous production of sulphates, attacking not only historical buildings and sandstone statues, but also the surfaces of sandstone cliffs. The fluids transporting the salts also contain dissolved silica, which is transported onto rock surfaces together with capillary waters. A mixture of salts and silica becomes precipitated after water vaporization. At protected sites, the destructive effect of salts gains prevalence. Where the salts become washed by rain, on the other hand, opal creates a crust resistant to weathering. Opal crusts provide armour to the rock surfaces and increase the life expectancy of features such as isolated rock pillars (Fig. 13).

3.4 Senility stage

In the arid zone, peneplanation leaves only isolated inselbergs in place, destroying any geomorphic diversity. In the temperate zone, headward erosion reaches deep into the original plateaus, outcrops along river valleys are destructed by lateral erosion and slope undercutting. As the erosional base reaches the less



■ **Fig. 13.** The Hrubá Skála rock city is an example of the maturity stage in sandstone relief development. A xylography by Julius Mařák. Reprinted from the journal Zlatá Praha I.,1884.

resistant or more plastic layer below the sandstone body, gravitational disintegration of the rock massif takes place quickly. This stage is characterized by a destruction of rock forms associated with mass movements, rockfall and deterioration of rock cities, as witnessed in some parts of the Elbe River sandstones or the Příhrazy area of the Bohemian Paradise.

Specific sandstone areas can be generally attributed to one of the above mentioned stages. Describing the detailed morphology of a certain locality, however, sandstone relief should be understood as a mosaic of surfaces of different ages: some surfaces may have formed as early as in the Tertiary and persisted owing to the protective function of rock crusts. Other surfaces are only several thousand or hundred years old, although having an ancient appearance due to weathering processes.

From the viewpoint of nature conservation and landscape formation, sandstone districts of the Bohemian Paradise lie intermediate between initial forms of the Kokořín area in the south and senile forms in the northern borderland of the Czech Republic. They represent the most complete and varied set of landscapes, providing characteristic examples of all the above stages of sandstone landscape evolution. All the above mentioned processes can be seen in action: mass movements and rockfall on the Mužský Hill plateau, salt weathering, selective removal of disintegrated sandstone from fissures in the Prachov rock city, armouring of rock surfaces with opal-indurated crusts (Hrubá Skála rock city) or secondary hardening of sandstone along active tectonic zones (Klokočí cuesta). Yet other instructive forms of relief mentioned in the text on the individual sandstone districts are well developed.

4. Sandstone phenomenon: definition of the term and history of usage

Sandstone phenomenon can be defined as a set of living and non-living natural components affected by Prehistoric, historical and contemporary interventions, and linked with a specific relief of sandstone districts and outcrops. It appears that sandstone areas are a category of landscape by themselves due to their specific substrate composition and distinct relief, thereby paralleling karst areas. In the recent years, this idea has gained favour not only in central Europe but also in Australia and elsewhere (Young and Young 1992, Robinson and Williams 2000).

The first published definition of the sandstone phenomenon is contained in the paper by Ložek (1995). Ložek also stated that the term "*Quadersandstein* phenomenon" would be a more appropriate one because only sandstones with orthogonal jointing (*Quadersandsteine*) are distinctly expressed in landscape morphology. The key parameters are the physical and chemical properties of the sandstones:

1. Because of their permeability and jointing, *Quadersandstein* sandstones give rise to a specific relief with streamless canyons and narrow gorges lined by cliff faces, and occasional rock cities.
2. They provide an acid substrate with low amounts of nutrients, not sufficient for the life of many plant and animal species with high requirements for bivalent bases in soil (Ca and Mg).
3. Their weathering produces sand-sized particles. Sand prevails in all sediments: residua, colluvia including slope aprons, as well as alluvial plains. The surface of the weathering outcrops is massive but delicately articulated in a closer detail (e.g., by honeycombs), see Mikuláš (2001a).
4. Sandstones and the products of their weathering are perfectly permeable for water. As a result, the areas built of sandstone typically lack surface waters.
5. The exceptional aesthetic values of sandstone landscapes attract visitors. The economic use of such landscapes is otherwise limited.

Sandstone landscape was referred to as "a mighty symphony with few notes" by Sádlo (2000). This parable points to the relative simplicity and transparency of processes in the living and non-living components of sandstone-dominated landscapes. As shown by the Bohemian sandstone phenomenon, however, even these "few notes" can produce innumerable combinations. As a result, each sandstone area has a specific meso- and microrelief. The list of factors contributing to the shaping of sandstone cliffs in Bohemia is by no means short.

Sand deposition in the shallow Late Cretaceous sea determined the size of sand grains at the given locality, the types of sedimentary architectures (cyclicity, clinoform surfaces) and structures (massive and bioturbated, horizontal stratification, planar and trough cross bedding, erosion surfaces etc.) and – to a certain degree – also the character of the matrix (calcareous, clayey). Different rates of basin-floor subsidence resulted in different thicknesses of the Teplice Formation sandstone body (a few metres to over 100 m). Tectonic movements during the Tertiary were responsible for uplifts and subsidence of blocks tens of square kilometres in areal extent, their tilting, fracturing and the typical vertical orthogonal jointing. From sand deposition to the present, sandstones are a lithology favourable for fluid migration due to their high porosity. The fluids transport common ions, especially calcium, sodium, sulphur, potassium, and iron. Fluids generated at times of elevated tectonic and volcanic activity in the Late Cretaceous and Tertiary were hot (hydrothermal). Specific processes take place on the present rock surface where the fluids evaporate. The evaporation produces a double effect: the surface layer is either hardened (if silica is involved) or salt efflorescences with destructive effect are precipitated (Cílek 1995). Both these effects are controlled by climate (climatic fluctuations within a decade, century, millennium) and microclimate (exposure to precipitations, wind, and insolation implying from variable configuration of rocks and vegetation). Hardening and disintegration of rock surfaces may proceed side by side in close proximity and, moreover, the two effects may alternate in time at the same place. This style of impregnation/erosion alternations gives rise to many other, seemingly illogical microrelief forms.

The role of vegetation is even more complex than the role of fluid evaporation from rock surfaces. It is either protective or destructive, depending on the type of vegetation (trees, moss, lichens etc.) and interaction with inorganic factors (cement removal vs. inhibition of salt erosion). Mechanical erosion (e.g., hail) and frost erosion are obvious factors, much like the uneven distribution of fluids in the rock massif (e.g., fluid migration along joints, rise of soil moisture).

Many of the above mentioned factors are influenced by the temperature and precipitation regimes not only at the given moment but, owing to the "memory of the system", also in the historical and geological past. With no ambition of providing a complete list, another two factors should be mentioned: animal bioerosion (e.g., nesting tunnels of solitary bees) and the effect of rock gravity (slumps and rockfall of sandstone blocks tend to be associated with microrelief reconstruction). Yet another factor, and a problem to be solved at the same time, is the presence of weathering products in rock cavities and crevasses: the intensity of morphogenetic processes under the weathering products has not been established, and the differences between the resulting landforms and subaerially-generated landforms have not yet been studied (Cílek and Langrová 1994, Cílek 1998, Cílek and Kopecký eds. 1998, Mikuláš and Cílek 1998, Mikuláš 2001a, b).

The definition by V. Ložek cited at the beginning of this chapter can therefore be countered by the argument that the term *Quadersandstein* is of limited use and difficult to understand in Anglo-Saxon literature. It would be more appropriate to speak of coarse-grained, porous sandstones forming thick bodies. Such rocks are almost exclusively subject to brittle deformation, and the presence of vertical joints subsequently contributes to the origin of numerous outcrops. The presence of carbonate cement in some sandstones does not alter their mechanical properties much and produces landscape of similar character, despite the different vegetation. Psammitic lithologies are also favourable for bioerosion, thus displaying a wide variety of strategies of biota in the colonization of sandstone substrates. This equally applies to the sandstone utilization by humans who carved rooms for dwelling or other purposes into weakly lithified outcrops.

Maps of climatic and vegetation zones, soil maps, geological maps and maps of zoogeographic provinces are available for different parts of the world. World maps of geobiological phenomena, however, have never yet been constructed with the exception of karst areas (speleologists closely collaborate on international scale). No attempts have been made to set up a definition of sandstone-related processes, extending beyond the individual continents or climatic belts either. Nevertheless, definitions of landscape types strongly dependent on specific substrate lithologies are scientifically advantageous, as illustrated by the wide use of the term “karst”.

However, global approaches to sandstone landscapes seem to be neglected. One of the reasons is probably the necessity of data synthesis from many different disciplines, which is difficult in one region and much more troublesome on a global scale. Another reason is the absence of sufficient practical motivation for such approach to the sandstone relief and vegetation. Sand and building stone are typically local materials, and bizarre cliff morphologies are understood as local tourist attractions rather than as a global theme. As a result, papers on sandstone relief tend to be scattered mostly in local journals. It is therefore reasonable to include the sandstone phenomenon – i.e., one of its type areas – into the UNESCO World Heritage List.

5. Comparison with other sandstone regions

Within the analysis of eligibility of the Bohemian Paradise sandstone districts for the inclusion in the UNESCO World Heritage List, these districts were compared with other sandstone regions in and outside the Czech Republic. The criteria taken into account encompassed the sandstone phenomenon as a whole. It is beyond the scope of this paper to give any detailed characteristics of the other sandstone regions or refer to any previous studies. All of them are specific in their geology, geomorphology and interactions with living organisms. Some of the facts are summarized in Appendix 2.

5.1 Comparison with sandstone phenomenon of the Czech Republic

Besides the Bohemian Paradise PLA, several other areas in the Czech Republic are partly or completely built of quartzose sandstones:
- Bohemian-Saxonian Switzerland National Park (Elbe sandstones)
- Lužické hory PLA
- Kokořínsko PLA
- area of the former Ralsko military training area
- Skuteč area
- Broumovsko PLA

This paper allows only a brief comparison of the Bohemian Paradise PLA with each of these areas.

5.1.1 Bohemian-Saxonian Switzerland National Park (Elbe sandstones)

Geomorphology of the whole region of Bohemian-Saxonian Switzerland, a borderland between northern Bohemia and Saxony, can be characterized by the following features:
- deep narrow gorges incised in sandstones of the Bílá hora and Jizera formations and hosting watercourses. These include the monumental Elbe River canyon 300 m deep;
- prominent sandstone table mountains in Saxony;
- generally very low altitudes of the lowermost storey of the sandstone landscape: the village of Hřensko is the lowest point of the Czech Republic (117 m a.s.l.);
- large areal extent of a continuous stretch of sandstone outcrops – a landscape modified by the sandstone phenomenon.

These characteristics produce what can be described as a three-storey landscape: the uppermost storey is formed by the table mountains (as relics of a once continuous plateau) and sandstone rock cities, the middle storey is formed by the presently existing plateaus, and the lower storey is represented by the network of gorges and valleys. This three-storey landscape architecture is the background for neovolcanic elevations. Besides the table mountains, the uppermost storey formed by Cretaceous sedimentary rocks includes also solitary outcrops of sandstone hardened by basaltic intrusions, such as that on Růžák Hill at an altitude of 480 m.

When compared to the Bohemian Paradise PLA, the Bohemian-Saxonian Switzerland NP shows a higher integrity of the landscape complex but less variation in the sedimentary cover composition. From cultural point of view, the Saxonian Switzerland and the Bohemian Switzerland belong among the areas which gave rise to the concept of central European romanticism and laid the foundations of tourism. Many large rock shelters in this region were inhabited since Prehistoric times. The biggest natural arch of Europe – Pravčická Arch – is located on the Bohemian side of the national park.

5.1.2 Lužické hory PLA

The Lužické hory Mountains (Lusatian Mountains) in northern Bohemia and Zittauer Gebirge Mountains in Saxony lie in the NE end of the Ohře Rift graben, south of the Lusatian Fault zone. Upper structural levels of the Lužické hory PLA are formed by Upper Cretaceous sandstones of the Jizera and Březno formations, which were penetrated by phonolitic, trachytic and basaltic intrusions in the Tertiary. Being more resistant to weathering than the ambient sandstone, these volcanic rocks were later exhumed by erosion. This gave the Lužické hory Mountains their characteristic relief with cupolaform volcanic hills and elongated sandstone crests controlled by faults and fracture zones. The sandstones are bonded against granitic rocks of the Lusatian massif by the Lusatian Fault, along which the older (Variscan and Cadomian) granites were thrust over the younger sandstones. In the Doubice area, narrow tectonic slices of Jurassic limestone were dragged to the surface. The Pleistocene period was dominated by erosion and produced huge talus accumulations on the slopes of volcanic hills. Sands and gravels deposited by a continental glacier, which came to the region from the north, have been preserved at Jítrava in the eastern part of the region.

The sandstone phenomenon of the Lužické hory Mountains is remarkable for the wide range of sandstone alteration effects (tectonic deformation, hydrothermal alteration and contact metamorphism), the most important of which are zones of sandstone silicification often associated with prismatic jointing of sandstone. Dykes of hydrothermally altered (ferruginized) volcanic rocks of the polzenite group, which harden the neighbouring sandstone and were historically exploited for iron smelting, have very few parallels in the Bohemian Paradise. True rock cities are, however, limited only to the area of Jonsdorf and Oybin in Saxony. The region as a whole rather provides a set of small interesting sites scattered over a relatively large area.

5.1.3 Kokořínsko PLA

The sandstone relief of the Kokořínsko area in central-north Bohemia is characterized by sandstone outcrops and isolated pillars developed on the edges of a dense network of valleys and canyons incised in the Jizera Formation sandstones. The flood plains of the two largest watercourses, the Liběchovka and Pšovka streams, are covered by moist grasslands with swamp communities. This relief permitted the emergence of a cultural landscape free of industrial facilities, with a balanced ratio between forested and unforested land.

In the south, the relief is largely determined by the interrelationship between two major landform groups: plateaus and deeply incised valleys with several cliff levels formed by stream erosion. Valleys form about ⅓ of the area. The best known geomorphic feature is the presence of mushroom rocks "Pokličky" in the 23 km-long Kokořínský důl Valley and its side valleys. Exhumed intrusions of volcanic rocks function as the main relief-forming element in the northern part of Kokořínsko PLA. They form prominent hills including the phonolitic Bezděz Hill in the NE, with a magnificent royal castle on its top.

As opposed to the Bohemian Paradise PLA, typical rock cities are missing, the sandstone outcrops are smaller, and outcrops of sediments other than quartzose sandstones are relatively rare. The southern part of the Kokořínsko PLA displays in particular, an incipient, valley-dominated sandstone relief rather than a fully developed sandstone phenomenon.

5.1.4 Former Ralsko military training area

The region of the former (until 1990) Ralsko military training area, situated NE of the Kokořínsko PLA and SE of the Lužické hory PLA, is a flat landscape with table mountains and conical volcanic hills lined by sandstone cliffs of the Jizera Formation. In contrast with the Bohemian Paradise, this region lacks typical rock cities, and the overall extent of the sandstone phenomenon is much smaller. On the other hand, the sandstone landscape is surrounded by extensive marshlands and archaeological sites, and is dominated by two landmark medieval castles: Bezděz and Ralsko. The natural, historical and cultural values of this region are rather scattered and are not concentrated into clearly defined complexes, as is the case of the Bohemian Paradise.

5.1.5 Skuteč area

Several valleys in quartzose sandstones of the Cenomanian Peruc–Korycany Formation are present in the area of Skuteč in eastern Bohemia. Their meso- and microrelief are relatively simple. Sedimentary architectures and structures are rather uniform and dominated by giant-scale cross bedding. The sandstone outcrops occur in a relatively small area with moderate geodiversity and no typically developed rock cities.

5.1.6 Broumovsko PLA

The extensive sandstone districts near Broumov in NE Bohemia, at the boundary with the Gory Stolowe National Park in Poland, are formed by quartzose sandstones and subarkoses of the Jizera Formation. Sandstone outcrops reach 100 m in height and form a dense network of canyons, narrow gorges and small valleys. The whole region comprises several areas of cliff faces of different heights, microrelief and exposures to geographic directions. When compared to the Bohemian Paradise PLA, the Broumovsko PLA displays a higher integrity of the landscape complex and a lower rate of human intervention, but less variation in sedimentary cover composition and a less varied meso- and microrelief. On the other hand, it has the best developed and most typical sandstone rock cities in the Czech Republic (Adršpach Cliffs, Teplice Cliffs).

5.1.7 Conclusions

Only two sandstone regions in the Czech Republic may pose an alternative to the inscription of the Bohemian Paradise sandstone districts in the UNESCO World Heritage List. It is especially the complex of the Elbe sandstones lying on both sides of the Czech/German border (Bohemian-Saxonian Switzerland) and the sandstone districts of the Broumov area and the Kłodzko area, namely the rock cities of Adršpach Cliffs, Teplice Cliffs and Broumov Cliffs in the Czech Republic, and the rock cities of Bledne Skaly and Szczeliniec Wielki (Gory Stolowe NP) in Poland. Both these sandstone regions are somewhat different from the Bohemian Paradise but represent highly valuable landscapes with well-developed sandstone phenomenon.

The nomination of the Elbe sandstones is hindered by two substantial facts:

- Valuable areas in the national park ore overloaded by tourist activities at present. The administrations of the protected areas therefore have no interest in further promotion of the region and consequent development of the region.

- The aim of completeness would require the inclusion of the Elbe River canyon in the set of localities (the only large river canyon in sandstones, and a European biocorridor). This canyon is not under nature protection at present due to conflicts of interests between riverine navigation, road and rail transportation, and recreational development.

The nomination of the sandstone districts in the Broumov area (Czech Republic) and Gory Stolowe Mts. (Poland) in the UNESCO World Heritage List is obstructed by the following facts:

- The administrations of protected areas in this region have not yet declared their interest in inclusion in the List yet.
- Although more monumental than those of the Bohemian Paradise, the sandstone landscapes are somewhat poorer in their geomorphic diversity, especially in sandstone microforms (slope and gravitational processes prevail), and in the variety of geological units exposed.
- Compared to the Bohemian Paradise, these sandstone regions cover a larger area that is more difficult to handle. In some cases, protection zones would be difficult to define because they pass into the surrounding agriculturally utilized land with abrupt terrain steps.

5.2 Comparison with sandstone phenomenon outside Czech Republic

The coverage of sandstone regions in the world by scientific literature is highly variable. Sandstone regions outside the Czech Republic, whose geology and geomorphology has been possibly best described, are 1. Saxonian Switzerland sandstone region in Germany, 2. Gory Stolowe in Poland, 3. Petit Suisse in Luxembourg, 4. the Fontainebleau sandstone in northern France, 5. Bulgaria (e.g., Belogradchik Cliffs), 6. the Pennine Gritstones of North Central England, 7. the Wealden Sandstones of SE England, 8. the New Red Sandstones of Cheshire and the Welsh Borders, 9. southern Algeria (Tassili), 10. Jordan, 11. Colorado Plateau, U.S.A., 12. Canaima, Venezuela. This list does not include conglomerate landscapes, although they often parallel the sandstone ones in their landforms (Meteora in Greece, Súľovské skály Cliffs in Slovakia). A more complete list of European sandstone regions with their brief characteristics has been completed and will be included in the monograph by Härtel et al. (2007 in print).

The above occurrences can be differentiated into sandstone phenomenon of temperate climatic zone (1–8), arid subtropical zone (9–11) and humid tropical zone (12). The differences result from the different rates of physical erosion and bioerosion and in the different proportions of mechanical and chemical processes in microrelief formation.

A strict comparison of sandstone regions in the temperate zone (1–7) with those in the tropical and subtropical zones is irrelevant with respect to the different environmental parameters. This implies a factual difference in geological processes and a different aesthetic impression on the visitors. In the temperate zone, the Bohemian Paradise shows the highest geodiversity and the most complete interactions between the biological, geological and anthropogenic components of landscape (see tables in Appendix 2).

The sandstone sites currently listed in the UNESCO World Heritage include Mesa Verde National Park (Colorado, USA), Grand Canyon National Park (Arizona, USA), Canaima National Park (Venezuela), Greater Blue Mountains (Australia), Dorset and East Devon Coast (England), Tassili n'Ajjer (Algeria), Wulingyuan Scenic and Historic Interest Area (China). Two of the sites from the temperate zone (Dorset and East Devon, Wulingyuan) can be hardly taken as analogues of the Bohemian Paradise. While the shores of southern England display mixed lithologies and are valued for their classical stratigraphy, the Wulingyuan rock city is sculpted in quartzite rather than sandstone. The only comparable site is thus the area of Greater Blue Mountains in the Sydney region of New South Wales, Australia. In view of global strategy, this site should be complemented by at least one other site from the temperate zone.

The Bohemian Paradise can be therefore considered a typical temperate-zone sandstone area, having the characteristics below:

- long tradition of nature conservation (it was the first large-scale protected area in the Czech Republic), support of local population,
- a manageable set of interconnected sites enclosed by an appropriate protection zone (after approval of PLA enlargement),
- position within Europe and the Czech Republic: it lies in the middle of central and western Europe in a geographic, climatic and altitudinal sense,
- exceptional diversity and completeness of geomorphic processes on various scales (high density of interesting phenomena),
- close links to the valuable, harmonic landscape around, with medieval castles and rural architecture,
- additional aspects of nature conservation like the presence of an important fern and lichen flora, historic sites and settlements of Prehistoric man, rock shelters with Prehistoric settlements and caves,
- a "national" landscape, which helped in the recognition of Bohemia and the nation in the 19th century, a landscape most commonly found on paintings.

6. Concluding remarks

Sandstone rock cities and sandstone outcrops in general give rise to a landscape with specific pedogenic, hydrological, microclimatic and biological histories, different from those of the surrounding areas. These specifics parallel those of the karst phenomenon, the value of which was recognized – owing to extensive cave research – as early as in the 19th century. Karstic landscapes are therefore adequately represented among all categories of protected sites and areas. In sandstone landscapes, it is only in the last decades that the extent and interrelationships of geological, biological and anthropogenic (particularly Prehistoric and Medieval colonization) processes have become unveiled and reflected in the appropriate conservational measures.

It is especially the interrelationship of geological, biological and climatic factors that gives the sandstone landscapes in different climatic zones a different appearance. The World Heritage List of UNESCO contains characteristic examples of the sandstone phenomenon from the arid zone (Mesa Verde on the Colorado Plateau with Anasazi pueblos, Tassili in northern Africa with a large set of rock carvings) and humid tropical zone (Canaima in Venezuela).

The Bohemian Paradise is a region with fully developed attributes of sandstone landscapes in the temperate zone, which is most favourable for the diversification of sandstone relief, especially its microforms. Geodiversity of the Bohemian Paradise is paralleled by a few other sandstone landscapes in the world like the Australian Blue Mountains, the Colorado Plateau or the South American *tepuis*, although it never concentrates to such a small area. On the other hand, the high concentration of instructive geosites makes the Bohemian Paradise even more vulnerable to environmental damage caused by its visitors.

The Bohemian Paradise is a relatively small and well protected area (the first Protected Landscape Area in the Czech territory). Its geographic position lies intermediate between incipient sandstone landscapes on the southern margin of the Bohemian Cretaceous Basin and senile sandstone landscapes in the north. Moreover, it is the region of numerous primaeval settlements (from the Paleolithic to the Slavonic tribes, archaeological finds pertaining to 18 Prehistoric cultures), Medieval castles and rich rural architecture in the buffer zone. Consequently, the conservational activities in the Bohemian Paradise cannot focus on a single crucial aspect – the geomorphic one – but should encompass a very wide range of geological, biological and anthropogenic features and processes. A mutual interaction of all these aspects is lumped under the collective term of "sandstone phenomenon".

The above reasons justified the inclusion of the Bohemian Paradise, after a several years' proceedings, into the international list of UNESCO Geoparks as the first area in the Czech Republic. We believe that this decision will enhance the interest in geology, e.g. by means of school excursions and family trips, and bring new, enthusiastic students to science classes.

7. Acknowledgments

This volume of Geolines is based on previous reports on geology and geomorphology of the sandstone districts of the Bohemian Paradise, financed by the Ministry of the Environment of the Czech Republic and the Administration of the Bohemian Paradise Protected Landscape Area. In this respect, Martina Pásková PhD. and RNDr. Lenka Šoltysová are thanked for their co-operation. Recent scientific achievements published in this volume benefit from field studies supported by Project A3013302 of the Grant Agency of the Academy of Sciences CR and from the Research Plan of the Institute of Geology AS CR AV0 Z 30130516.

The authors also wish to thank Jan Mertlík and Marie Nešporová for fruitful discussions and guidance in the field. Jan Mertlík also contributed with many unique photos to this volume. The company of Sklopísek Střeleč – Eximos and its chief-geologist Josef Ciprýn are acknowledged for providing access to the sand pit at Střeleč. Our colleague Jaromír Ulrych is thanked for providing post-cards from his collection. The maps were kindly drawn by Jana Rajlichová, and photographic plates were carefully arranged by Josef Brožek and Jaroslava Pavková (all Institute of Geology AS CR).

The manuscript was greatly improved owing to the thorough reviews by Jan Urban, Kraków, Poland, and D.A. Robinson, Brighton, England.

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Appendix 1

Glossary of terms (infrequently used terms are supplemented with literature citations)

Geomorphology

arrest lines: Concentric structures on →joint planes marking separate episodes of joint propagation. They are are circular or parabolic in shape, usually bound →hackle marks of →plume structures, and show a low relief on the joint plane.

clinoform surface: Gently inclined surface in sediment, traceable on a large scale and copying the ancient surface morphology. In shallow seas, clinoform surfaces form on the slopes of large subaqueous sand bodies, such as sand ridges, sand banks or sand-dominated deltas. Clinoform bedding indicates progradation of these sand bodies. In the Bohemian Paradise, clinoform surfaces represent →foresets of large subaqueous deltas, and dip generally south at angles of <15°.

HAMPSON G.J. and STORMS J.E.A., 2003. Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences. *Sedimentology*, 50, 4: 667-701.
ULIČNÝ D., 2001. Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. *Sedimentology*, 48, 3: 599-628.

convolute bedding: Disturbance of a soft, layered sand due to post-depositional deformation caused by, e.g., compaction and loading, slumping or water escape.

PETTIJOHN F.J., POTTER P.E. and SIEVER R., 1987. Sand and sandstone. Springer Verlag, New York, Heidelberg.

cross-bedding: Sedimentary structure characterized by a package of inclined →foreset laminae. It is formed by downstream migration of sand bedforms elongated transverse to the flow direction.

ASHLEY G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. *J. Sed. Petrol.*, 60: 160-172.
BLATT H., MIDDLETON G. and MURRAY R., 1980. Origin of sedimentary rocks. 2nd ed. Prentice-Hall Inc., Englewood Cliffs.

cross-bedding, giant-scale: Cross bedding produced by migration of →sand waves.

cross-bedding, large-scale: Cross bedding produced by migration of →dunes.

cross-bedding, planar: Cross bedding with planar →foreset laminae, produced by migration of sand bedforms with straight crests.
cross-bedding, trough: Cross bedding with trough-like, upstream-convex →foreset laminae and erosive bases, produced by migration of sand bedforms with sinuous crests.

deformation band: A planar zone in sandstone, usually 1–5 cm broad and tens of metres long, occasionally branching or braided, in which sand grains were reoriented or even silica-cemented due to tectonic shearing. Deformation bands are associated with no visible displacement but may or may not be associated with grain cataclasis. They are slightly lighter in colour than the ambient rock and their relief is positive (→tectonic ribs) or negative depending on the amount of quartz cement present. In the Bohemian Paradise, they are steep to vertical and run oblique to the course of the Lusatian Fault (E–W and NNW–SSE). Prominent deformation bands are observed in the Klokočí Cliffs and Betlém Cliffs.

ANTONELLINI M.A., AYDIN A. and POLLARD D.D., 1994. Microstructure of deformation bands in porous sandstones at Arches National Park, Utah. *J. Struct. Geol.*, 16: 941-959.
MAIN I., MAIR K., KWON O., ELPHICK S. and NGWENYA B., 2001. Experimental constraints on the mechanical and hydraulic properties of deformation bands in porous sandstone: a review. In: HOLDSWORTH R.E. et al. (Editors), The nature and tectonic significance of fault zone weakening. *Geol. Soc. London Spec. Publ.*, 186, pp. 43-63. London.
PARRY W.T., CHAN M.A. and BEITLER B., 2004. Chemical bleaching indicates episodes of fluid flow in deformation bands in sandstone. *AAPG Bull.*, 88: 175-191.

dune: A sand bedform elongated transverse to flow direction, <1 m in height. Dune migration produces →large-scale cross bedding.

fault: A tectonic rupture where a clear relative displacement of the blocks relative to each other is visible.

flooding surface: A relatively flat surface in the sedimentary succession, above which an abrupt deepening of depositional environment is observed.

foresets of a delta: Packages of sediment deposited on a delta front, dipping gently in the direction of sediment transport.

foreset laminae of cross bedding: Laminae inclined at an angle of <34° in a migrating bedform. They are formed by sand grains eroded from the up-current side of the bedform and deposited on the down-current side of the bedform by avalanching.

hackle mark: A low-relief ridge within a →plume structure, parallel to the direction of propagation of a tensile →joint.

McCONAUGHY D.T. and ENGELDER T., 2001. Joint initiation in bedded clastic rocks. *J. Struct. Geol.*, 23: 203-221.

herring-bone bedding: Directly superimposed sets of →cross-bedding whose →foreset laminae dip in opposite directions.

joint: A tectonic rupture where no slip can be detected alongside the two blocks, or the slip cannot be characterized more precisely from the outcrop. No slip movement occurs if the unidirectional compressive or tensional stress is oriented normal to the rupture plane.

plume structure: A ridge-like tracing on a joint plane reminiscent of a feather in its pattern. Plume structures are indicative of tensional stress.

*Quadersandstein***:** A term adopted from German, meaning "blocky-jointed" sandstone. In this paper, the term refers to such pattern of orthogonal jointing where subvertical joints intersect with no visible mutual displacement or butting relation. This jointing pattern may result from bedding-parallel tectonic slip in the footwall or hangingwall of the thick packages of massive sandstone. In the Bohemian Paradise, it is much more common than the "ladder-like" pattern.

sand wave: A giant sand bedform elongated transverse to flow direction, 1.5 to 20 m in height. Sand waves form at intermediate flow velocities but high flow thickness and typically migrate across tide-dominated shelves. Their migration produces →giant-scale cross bedding.

slickensides: Fault planes with prominent features of tectonic slip, such as striae parallel to slip direction and polished surfaces. These features result from pressure solution of quartz grains and minor silica redistribution due to tectonic shear stress.

COUBAL M., 1990. Compression along faults: example from the Bohemian Cretaceous Basin. *Miner. Slovaca*, 22: 139-144.

spatter cone: A surficial volcanic landform having the character of a low, steep-sided cone of spatter, mostly basaltic, formed above a fissure or a vent.

systems tract: In sequence stratigraphy, a linkage of contemporaneous depositional systems. It is represented by a sedimentary body bounded from bottom and top by unconformities and/or → flooding surfaces.

PLINT A.G., 1988. Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level. In Wilgus C.K. et al. (Editors), Sea-level changes: an integrated approach. *Society of Economic Paleontologists and Mineralogists Spec. Publ.*, 42, pp. 357-370.
POSAMENTIER H.W., JERVEY M.T. and VAIL P.R., 1988. Eustatic controls on clastic deposition I – conceptual framework. In: WILGUS C.K. et al. (Editors), Sea-level changes: an integrated approach. *Society of Economic Paleontologists and Mineralogists Spec. Publ.*, 42, pp. 155-182.
VAN WAGONER J.C., MITCHUM R.M., CAMPION K.M. and RAHMANIAN V.D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops. Amer. Assoc. Petroleum Geologists, 55 p. Tulsa, OK, USA.
WALKER R.G. and JAMES N.P., eds., 1992. Facies Models. Response to Sea Level Change. Geol. Assoc. Canada, 454 p. St. John's.

systems tract, falling-stage (FSST): A systems tract bounded by the first regressive surface of marine erosion below and the subaerial erosion surface above.

systems tract, lowstand (LST): A systems tract bounded by a subaerial erosion surface below and the first prominent transgressive surface above.

systems tract, transgressive (TST): A systems tract bounded by the first prominent transgressive surface below and the maximum →flooding surface above. The systems tract progressively deepens upward.

tool mark: A mark produced by the impact against a muddy bottom of a solid object driven by a current moving over the bed. It is usually preserved as a cast, seen on the base of a sand bed.

MIDDLETON G.V., 2003. Tool marks. In MIDDLETON G.V. et al. (Editors), Encyclopedia of sediments and sedimentary rocks. Kluwer Acad. Publ., p. 747. Dordrecht, Boston, London.

trace fossil: A sedimentary structure produced by vital activities of organisms. Trace fossils can be found on bedding planes (tracks, trails) or extending across one or several beds (burrows, tunnels).

Geomorphology

arch: A rock perforation whose bottom lies approximately at the level of the surrounding surface, 0.5 m to tens of metres across.

case hardening: A process by which the surface of a sandstone is impregnated with cement formed by evaporation of mineral-bearing pore water.

cave, crevasse: A cave bounded by joint planes, formed by gravitational dilation of joints. Heights of crevasse caves are usually higher than their widths.

cave, strata-bound: A cave formed by disintegration, removal and selective weathering of less resistant strata. Strata-bound caves are usually low and broad.

cave, talus: A cave represented by interconnected open spaces among large clasts in a talus accumulation or a block field. Talus caves have very irregular shapes.

chimney: A narrow vertical space between two cliff faces, between a cliff face and a pillar, or between two pillars. It is formed by progressive widening of a vertical joint or joints.

drainage runnels: A synonym for karren.

false arch: An arch formed by gravitationally rotated or fallen blocks.

grike: A joint in a quartzite or quartzose sandstone widened by solution as a result of channelized water flow.

honeycomb pit: A concave element (hollow) on rock surface, the size of which is at centimetre rather than decimetre scale.

honeycomb pits, arcuate: Pits with flat bottoms and spherical top parts on vertical or slightly overhanging sandstone walls. Their enlargement is probably caused by freezing of rainwater.

honeycomb pits, cellular: Closely spaced arcuate pits on the vaults of spherical or parabolic →rock shelters. As they have no bases, they form specific cellular patterns analogous to decorations on medieval (Gothic) vaults.

honeycomb pits, reticular: Closely spaced pits constituting matrix-type honeycombs with vertical ridges dominant over concave shapes.

honeycomb pits, rhombic: Rhombic pits, typically developed on inclined sandstone walls or on subvertical walls of very poorly lithified sandstone. They are also found on walls where the separation of clasts is influenced by shear stress.

honeycomb pits, spherical: Spherical pits, usually 1–10 cm in diameter, over large areas of vertical or, more often, overhanging sandstone walls. They form typical honeycombs.

inclined ledge: A →rock ledge with a worn edgeline, centimetres to a few tens of centimetres wide and several metres long. These ledges cross-cut primary sedimentary structures, lie low above the present soil surface, and are more or less parallel to this surface. This implies their relation to erosive processes (effect of humic acids?) linked with an older soil surface. Several inclined ledges may be present on the same cliff face.

MIKULÁŠ R., 2001. Poznámky ke vzniku některých prvků mikroreliéfu pískovcových skal. *Ochr. Přír.*, 56, 1, 19-21.

karren: Drainage channels, centimetres to tens of centimetres in depth, formed by a combination of mechanical and chemical erosion by meteoric waters. They are classified by their patterns and sites of origin.

mushroom rock: A mushroom-shaped rock mass, consisting of an upper layer of resistant rock underlain by a softer, partially eroded layer, thereby forming a thin "stem".

pillar: Morphologically prominent column of sandstone, exceeding 5 m in height.

pitted surface: A rock surface dominated by small-scale cavernous weathering, producing →honeycomb pits and →tafoni.

polygonal tesselation: Polygonal cracking of →rock crusts.

ROBINSON D.A. and WILLIAMS R.B.G., 1989. Polygonal cracking of sandstone at Fontainebleau, France. *Z. Geomorphol.*, 33, 59-72.

precipitation ledge: A wavy ledge on a vertical cliff face, around 1 cm thick, partially following lithological boundaries, but also deviating from them. It is formed by impregnation of particular portions of sandstone by silica.

rillenkarren: Karren on horizontal or gently inclined surfaces, with curved axes and more or less irregular pattern, often branching, formed by the direct action of sheetflow.

rock city: A group of isolated →pillars, typically formed on plateau edges or in heads of broad valleys.

rock crust: A layer of richly silica-cemented quartzose sandstone on subvertical cliff face, covering poorly cemented sandstone below. The crusts are usually 1–10 cm thick. They are produced by simple →case hardening. Detachment of rock crusts is caused mainly by salt weathering.

rock ledge: A narrow (centimetres to tens of centimetres) but continuous rock protrusion from the cliff face or a step in the cliff face. Horizontal ledges develop on more resistant beds in stratified sediments.

rock niche: A concave element (hollow) on rock surface. The size of rock niches is at decimetre to metre scale, and their width exceeds their depth.

rock perforation: Any perforation of sandstone wall. Large perforations include →arches and →rock windows. Smaller perforations formed by interconnection of neighbouring pits or joints give rise to rock sand-watches – residual sandstone columns a few decimetres tall.

rock shelter: A large loaf-shaped to horizontally elongated cavity in a cliff face, mostly at cliff base, providing a natural shelter.

rock window: A rock perforation whose bottom lies well above the cliff base, 0.1 m to tens of metres across.

sink: A circular or oval depression on a horizontal or gently sloping surface. Sinks include →sinkholes (analogues to those in limestone areas), potholes formed in valleys by eddying streams, and →solution basins.

sinkhole: A bowl- or funnel-shaped surface depression, usually elliptical in plan view and up to 20 m in width. Sinkholes in sandstone are generally formed by piping at sites of concentrated downward flow of meteoric water, such as at joint intersections. In the Bohemian Paradise, sinkholes typically form along gravitationally dilated joints near plateau edges.

solution basin: An oval depression on horizontal or gently incluined surface of quartzite or cemented quartzose sandstone, usually filled with rainwater, several centimetres to several metres in size. Solution basins are produced dominantly by the solution action of standing water.

tafone, *pl.* **tafoni:** A concave element (hollow) on rock surface, the size of which is at decimetre scale. True tafoni develop under a protective rock crust and widen towards the rock interior.

tectonic rib: A subvertical sheet-like body of sandstone, a few centimetres thick, showing positive relief over its surroundings. In the Bohemian Paradise, tectonic ribs are mostly formed by silica-cemented deformation bands or shear fault planes.

tree groove: A vertical groove on a steep cliff face formed by abrasion by swinging live trees.

wandkarren: Karren on steeply inclined surfaces, straight and long, formed by channelized water flow.

Appendix 2

Comparative tables and global significance

1. Geological diversity of sandstone districts of the Bohemian Paradise region

District	Formation[1]	Rock description	Tectonic dip	Surfaces formed during deposition[2]	Fossils and trace fossils	Jointing and faulting, volcanics[3]	Iron cementation	Quartz cementation
Hrubá Skála	Teplice Formation	Medium- to coarse-grained quartzose sandstone, scattered pebbles, with no grading, in upper part arranged to upwards-coarsening cycles topped by conglomerate beds.	Subhorizontal	Kilometre-scale erosive surfaces overlain by massive sandstone, clinoforms, giant-scale cross-bedding, large-scale cross bedding (foresets and backsets). Convolute bedding.	Two finds of stratigraphically important bivalve *Inoceramus*. Trace fossil *Ophiomorpha* on transgressive surfaces in upper part.	A fault in the NE. Orthogonal system of joints. No bodies of volcanic rocks known.	Iron compounds occasionally lining joint planes or forming subhorizontal tubes.	Locally developed weak quartz cementation.
Apolena	Teplice Formation	Medium-grained quartzose sandstone with no grading. Basaltic intrusion forming the landmark of Trosky Hill.	Subhorizontal	Clinoforms, giant-scale cross bedding.	Rare.	Poorly developed orthogonal joint system. Basaltic intrusion elongated E–W on top of plateau.	Insignificant.	None.
Příhrazské skály	Teplice Formation	Medium- to coarse-grained quartzose sandstone with no grading, in upper part arranged to upwards-coarsening cycles topped by conglomerate beds.	Subhorizontal	Clinoforms, large-scale cross bedding (foresets and backsets), often with scoured bases. Rare giant-scale cross bedding. Convolute bedding.	Trace fossils, e.g. *Ophiomorpha*, on transgressive surfaces in upper part.	Faults in NE and SW. Orthogonal joint system with numerous features of tension on joint surfaces (plume and bowl-shaped structures). Basaltic stock on top of plateau, basaltic dykes.	Very prominent in some areas, with iron compounds forming thick linings on joint planes and subhorizontal tubes.[4] Numerous small ferruginous concretions in the SE.	None.
Plakánek	Teplice Formation	Medium- to coarse-grained quartzose sandstone with no grading, in upper part arranged to upwards-coarsening cycles topped by conglomerate beds.	Subhorizontal	Steep clinoforms.	Trace fossils, e.g. *Ophiomorpha*, on transgressive surfaces in upper part.	A fault in the south. Orthogonal system of joints. No bodies of volcanic rocks known.	Present precipitation of iron in the flood plain.	None.
Kozlov (Chlum)	Teplice Formation	Medium- to coarse-grained quartzose sandstone with no grading.	Subhorizontal	Clinoforms, large-scale cross bedding. Convolute bedding.	Unique assemblage of trace fossils on bedding planes including crawling traces (*Cruziana*) and fish-resting traces (*Piscichnus*).[5]	Well developed orthogonal joint system. No bodies of volcanic rocks known.	Insignificant.	None.

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District	Formation[1]	Rock description	Tectonic dip	Surfaces formed during deposition[2]	Fossils and trace fossils	Jointing and faulting, volcanics[3]	Iron cementation	Quartz cementation
Prachovské skály	Teplice Formation	Medium-grained quartzose sandstone with no grading.	0–10° W	Clinoforms, giant-scale cross bedding.	Rare bivalve shells. Remains of ice-age mammals in caves. Trace fossils common.	Orthogonal joint system but E–W-striking joints clearly dominant, locally penetrated by basaltic magma (dykes, stocks).	Iron compounds lining joint planes.	None.
Klokočské skály	Teplice Formation	Medium- grained quartzose sandstone, no grading.	5–13° SSW	Clinoforms, giant-scale cross bedding.	Bivalve bed also containing stratigraphically important bivalve *Inoceramus*.[7] Trace fossils common, including rare *Megaplanolites* and *Gyrolithes*. Ferruginized wood fragments.	Fault bounding the district in the NE. Orthogonal system of joints of mostly compressional character. Sets of prominent deformation bands. Rare polished surfaces of minor fault planes. No bodies of volcanic rocks known.	Iron compounds lining joint planes or forming subhorizontal tubes.	Quartz cementation as a product of tectonic movement in deformation bands.
Drábovna	Teplice Formation	Fine- to medium-grained quartzose sandstone with no grading, in upper part arranged to upwards-coarsening cycles.	3–5° SW	Clinoforms, large-scale cross bedding.	Rare.	Poorly developed orthogonal joint system, dominated by structures transverse to the Lusatian Fault running 1 km to the NE. Deformation bands present.	Iron compounds occasionally lining joint planes.	Quartz cementation as a product of tectonic movement in deformation bands.
Sokol	Teplice Formation	Fine- to medium-grained quartzose sandstone with no grading.	5–10° S to SE	Wavy erosional surfaces and large-scale cross bedding. Giant-scale cross bedding near top. Occasional clinoforms.	Ferruginized wood fragments.	Orthogonal joint system linked with the Lusatian Fault 1 km to the NE. Deformation bands present. Several basaltic intrusive bodies.	Botryoidal clusters of ferruginous concretions. Iron compounds also forming subhorizontal tubes and locally prominent tube bundles.[4]	Quartz cementation as a product of tectonic movement in deformation bands.
	Jizera Formation	Fine-grained silty calcareous sandstone.	5–10° S to SE	Parallel stratification.	Common mollusc shells in life position, foraminifers. Numerous trace fossils.			
Borek	Teplice Formation	Medium- to coarse-grained quartzose sandstone arranged into upwards-coarsening cycles.	5–10° SW	Clinoforms, large-scale cross bedding.	Trace fossils common.	Orthogonal system of joints, with prevailing strike NW–SE. One such joint hosts a continuous basaltic dyke subparallel to cuesta edge.	Iron compounds concentrate to joint planes and subhorizontal tubes parallel to the basaltic dyke.[4]	

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Suché skály	Peruc-Korycany Formation	Medium- to coarse-grained quartzose sandstone with conglomerate beds.	Subvertical.	Parallel stratification and large-scale cross bedding.	Rare bivalve shells. Trace fossils on bedding planes.	Sandstone belt aligned parallel to the adjacent Lusatian Fault and dissected by several systems of joints and faults.[8] Common deformation bands, polished surfaces and slickensides. No bodies of volcanic rocks known.	Linings of iron compounds on joints transverse to the Lusatian Fault.	Quartz cementation culminating in zones of maximum shear (deformation bands).
Kozákov	Peruc-Korycany Formation	Medium- to coarse-grained quartzose sandstone underlain by coaly claystone.	24–45° WSW	Parallel stratification and large-scale cross bedding.	Rare bivalve and gastropod shells in sandstone. Bivalve shells and terrestrial plants in coaly claystone.	Orthogonal joint system linked with the adjacent Lusatian Fault and a transverse fault. Deformation bands and polished surfaces of fault planes present. Huge basaltic stock and lava flow beyond the E and N limits.	Iron compounds lining joint planes.[4]	Quartz cementation as a product of tectonic movement in deformation bands.

[1] All sandstones extensively exposed in the Bohemian Paradise are Upper Cretaceous in age. The Teplice Formation is Upper Turonian to Lower Coniacian in age, the Jizera Formation is Middle to Upper Turonian in age, and the Peruc-Korycany Formation is Middle to Upper Cenomanian in age, see Čech S., Klein V., Kříž J. and Valečka J. (1980): Revision of the Upper Cretaceous stratigraphy of the Bohemian Cretaceous Basin. *Věst. Ústř. Úst. geol.*, 55: 277-296.

[2] The term "clinoforms" refers to gently dipping surfaces interpreted as foresets of a subaquatic delta body, often traceable for tens of metres in vertical succession. Clinoforms are occasionally associated with horizontal bedding planes interpreted as delta topsets. Sets of giant-scale cross bedding reach thicknesses of 1–10 m, sets of large-scale cross bedding reach thicknesses of 0.1–0.4 m. The latter are often incorporated in the former and show not only foresets but also backsets. This concept follows the paper of Uličný D. (2001): Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. *Sedimentology*, 48, 3: 599-628.

[3] Orthogonal joint system is commonly met in all rock cities, giving rise to pillars with rectangular bases, as reflected by the German name *Quadersandstein*. In the proximity of major faults, "joints" of this system function as splay faults. Tensional and compressional joints are distinguished. Deformation bands are zones of maximum shearing (i.e., sliding of blocks parallel to their plane of contact) 1–20 cm wide, with grain crushing and cataclasis, and frequent quartz dissolution/reprecipitation phenomena.

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2. Geomorphic diversity of sandstone districts of the Bohemian Paradise region

District	Maturity[1]	Large forms of sandstone relief	Sinks	Caves and rock shelters	Rock perforations	Pitted surfaces, niches and tafone	Furrows[2]	Salt weathering and case hardening
Hrubá Skála	Mature	Dissected sandstone plateau. Tens of isolated pillars 40–80 m in height, especially on NE plateau rim. Narrow passages developed locally.	Numerous well developed sinkholes.	Tens of caves on bedding planes or joints. Prominent rock shelters.	A dozen arches, the largest 5.5 m in height and 7 m in span. Many false arches and rock windows.	Honeycomb pits common: arcuate, rhomboidal or spherical in shape. Tafone common, their inner surfaces with well-developed honeycombs.	Occasional karren on tops of pillars, tree grooves.	Crusts locally present, in stage of destruction.
Apolena	Incipient	Dissected edge of a sandstone plateau. Oblique ledges at pillar bases indicating ancient soil surfaces.	None.	Tens of caves developed on bedding planes. Cave 200 m long developed on a dilated joint.	Tens of arches and rock windows.	Honeycomb pits of rhombic shape dominant. Nesting pits of solitary bees.	None.	Crusts mostly destructed but morphologically prominent.
Příhrazské skály	Incipient to mature	Dissected edges of a sandstone plateau, with pillars and needles 50 m high in the west. Network of canyon-like valleys in the centre, with pillars 15–20 m high. Two table mountains in the SE. Oblique ledges at pillar bases indicating ancient soil surfaces.	Numerous sinkholes; one of them open to form an abyss 22 m deep. Solution basins present.	Tens of caves and rock shelters in the central and SE parts.	A dozen arches, the largest of which is 10 m in height and 7.5 m in span. Tens of false arches, tens of rock windows.	Honeycomb pits common, highly variable (arcuate, spherical, cellular). Specific microrelief linked with ferruginous linings and concretions (papillate surface). Nesting pits of solitary bees.	Karren common on tops of pillars and table mountains.	Crusts present, in various stages of destruction.
Plakánek	Incipient	Sandstone cliffs lining a valley with a stream and side valleys. Flood plain. Calcareous tufa cascades.	Potholes.	Caves formed by gravity-induced joint dilation or following bedding planes.	Rock windows occasionally present.	Honeycomb pits scarce, widely spaced.	None.	Crusts present.
Kozlov (Chlum)	Senile	Sandstone cliffs and pillars lining an E–W-trending ridge. Well developed oblique ledges at cliff bases indicating ancient soil surfaces. Rows of leaning pillars are a typical feature.	Prominent sinkholes, elongated in plan view.	Caves formed by gravity-induced joint dilation or among large fallen blocks in talus; the largest cave is 20 m long.	Several false arches present.	Prominent reorientated honeycomb pits on fallen blocks, often horizontally elongated.	None.	Crusts present.
Prachovské skály	Mature	Dissected sandstone plateau. Tens of pillars and needles 50–70 m in height, separated by narrow passages.	Numerous sinkholes.	A dozen caves developed on joints or among fallen blocks.	False arches present.	Honeycomb pits common, spherical in shape or vertically elongated.	Karren common on tops of pillars.	Crusts present.

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Klokočské skály	Mature	Dissected edge of a sandstone cuesta, with pillars 40 m high on the NE rim. Network of canyon-like valleys in the centre, with pillars 10–20 m high. Mushroom rocks present.	About 40 well developed sinkholes ca. 10 m in diameter. Potholes max. 1 m deep and solution basins present.	About 300 caves, mostly following bedding planes and subhorizontal fault planes, formed by tafone enlargement. The largest cave is 75 m long. Hundreds of rock shelters.	Tens of rock windows, the largest windows 3 m in diameter. Tens of arches up to 12 m high and several false arches near cuesta rim. Double arch 1.9 m in height and 6.8 m in span.	Tafone and niches common. Their merging produces tunnels up to 9.3 m long. Honeycomb pits common, spherical in shape or vertically elongated.	Occasional karren on tops of pillars. Series of vertical furrows on steep walls produced by dripping water or controlled by courses of deformation bands. Frequent tree grooves.	Crusts locally present, in stage of destruction.
Drábovna	Mature	Dissected sandstone plateau.	Solution basins common.	Tens of rock shelters.	Frequent perforations near tops of towers. Arch.	Honeycombs scarce.		Crusts present.
Sokol	Mature to senile	Dissected sandstone plateau with pillars up to 20 m high separated by narrow passages. Leaning or fallen pillars common.	Sinkholes and solution basins occasionally present.	Caves mostly formed among fallen sandstone blocks. Tens of rock shelters. Small dissolution caves formed in calcareous sandstone.	Rock windows present. Tens of false arches.	Honeycomb pits locally well developed, aligned along deformation bands. Smaller tafone and niches scarce.	Frequent tree grooves.	Crusts present.
Borek	Mature	Dissected edge of a sandstone cuesta and a network of canyon-like valleys in the centre.				Honeycombs present. Tafone and niches up to 1 m in diameter.		Crusts well developed, also present inside tafone.
Suché skály	Senile	Prominent sandstone ridge 80 m wide and 1000 m long, pillars and needles max. 80 m high. Fault-controlled subhorizontal ramps developed.	None.	Insignificant.	False arches present.	Honeycombs present but scarce.	Karren controlled by course of bedding planes.	None.
Kozákov	Incipient	Tilted sandstone block rimmed by sandstone cliffs.	None.	Tens of caves and large rock shelters formed along bedding planes.	Rock windows and false arches present.	Honeycombs locally well developed, pits horizontally elongated or filled with salt crusts.	Karren present.	Crusts mostly destructed but morphologically prominent on lower parts of cliffs.

[1] This feature relates to the stage in the evolution of the sandstone landscape. This does not depend on the real time for which erosion takes place but on the position of the sandstone area relative to the local base level (stream), its tectonic position (subsidence *vs.* uplift), footwall stability and rock resistance. "Incipient stage" refers to plateau edges dissected by a system of dilated joints, "mature stage" to fully developed rock cities with high pillars surrounding multiple relics of the original plateau, now deeply incised. The term "senile stage" describes sandstone areas dominated by boulders and fallen pillars, formed by complete destruction of the original plateau. Each of these stages is characterized by a different set of forms of sandstone relief. Suché skály Cliffs represent erosive relief on an uplifted block where a belt of resistant sandstone forms prominent relief.

[2] Furrows include different types of linear depressions in sandstone relief, usually tens of centimetres in size. They include drainage runnels (e.g., rillenkarren, wandkarren) and tree grooves produced on vertical rock surfaces by movement of living trees.

3. Geology and geomorphology of related sandstone regions of the world

Sandstone region	Climatic zone	Age, genesis	Rock description	Characteristic	Surfaces formed during deposition	Cementation	Tectonic deformation	Caves and rock shelters	Medium forms of relief	Small forms of relief	Salt weathering and case hardening
Bohemian Paradise, Czech Republic	Temperate.	Cretaceous, shallow marine.	Sandstone	Faulted and partly tilted plateau, often dissected to form rock cities.	Delta foresets, erosional surfaces, different types of cross bedding.	Ferruginous cement locally prominent. Quartz cement.	Faults, slickensides, deformation bands, joints. Intrusive bodies.	Different types of caves, rock shelters.	Arches and rock windows, sinkholes, potholes, solution basins. Rare tufa accumulations.	Karren and grooves, ledges, different types of well developed pitted surfaces (honeycombs, tafone).	Crusts present, locally prominent.
Bohemian/ Saxonian Switzerland NP, Czech Republic/ Germany[1,2]	Temperate.	Cretaceous, shallow marine.	Sandstone.	Faulted plateau, often dissected to form rock cities.	Different types of cross bedding, delta foresets.	Ferruginous cement locally prominent.	Faults, slickensides, deformation bands, joints. Intrusive bodies.	Different types of caves, rock shelters.	Arches and rock windows, mushroom rocks, potholes, solution basins.	Karren and grooves, ledges, different types of pitted surfaces.	Crusts present.
Wulingyuan Scenic and Historic Interest Area, China[3]	Temperate.	Cretaceous, shallow marine.	Quartzite, shale. Limestone.	Plateau margin dissected by the Suoxi Brook and its tributaries. Sets of isolated pillars and pinnacles, canyons, waterfalls.	Parallel stratification.	Quartz cement.	Vertical joints.	Large caves (but in lime-stones).	Arches and rock windows, natural bridges.	Insignificant.	None.
Greater Blue Mountains, Australia[4–6]	Temperate.	Triassic to Permian, fluvial and marine	Sandstone, shale with coal seams. Limestone.	Plateau dissected by canyons to form steep cliffs, ridges, pillars, pinnacles and pagodas.	Parallel stratification, cross bedding.	Different types of cement, especially ferruginous cement.	Faults, vertical joints. Intrusive and volcanic bodies.	Caves and rock shelters. Large caves in limestones.	Mushroom rocks.	Irregular pits, ledges.	Crusts present, locally prominent.
High Weald, England[7–8]	Temperate.	Cretaceous, shallow marine	Sandstone.	Cliffs along valley sides.	Parallel stratification, cross bedding.	None.	Joints.	Rock shelters.	Solution basins.	Karren, pitted surfaces (honeycombs), polygonal cracking.	Crusts well developed, important for outcrop preservation.
Meteora Group of Monasteries, Greece[9]	Subtropical, oceanic.	Tertiary, deltaic and alluvial fan.	Conglomerate, sandstone.	Eroded delta body forming isolated rock pillars.	Delta foresets, cross bedding.	Calcitic cement.	Vertical joints.	Large cavities and rock shelters.		Irregular pits, ledges.	Insignificant.
Tassili n´Ajjer, Algeria[10–11]	Subtropical, arid.	Ordovician and Devonian, shallow marine. Proterozoic.	Sandstone. Crystalline rocks.	Tilted plateau dissected by gorges to form rock cities and pillars.	Parallel stratification.	Ferruginous cement.	Faults and joints. Volcanic bodies.	Caves and rock shelters.	Arches and rock windows.	Ledges, eolian pits, faceted surfaces.	Crusts locally prominent. Desert varnish.

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Zion NP, USA[12–13]	Subtropical, arid.	Jurassic, eolian, fluvial and deltaic.	Sandstone, siltstone.	Plateau dissected by the Virgin River and its tributaries. Table mountains, steep walls, canyons.	Well-developed different types of cross bedding.	Different types of cement, especially ferruginous cement.	Vertical joints. Intrusive bodies.	Rock shelters common, often represented by imperfectly developed arches.	Mushroom rocks (hoodoos), arches and rock windows, potholes. Small tufa accumulations.	Tafone, relicts of pitted surfaces.	Desert varnish, opal and salt coatings, coatings of blue-green algae.
Arches NP, USA[13–15]	Subtropical, arid.	Jurassic, eolian, fluvial.	Sandstone	Edge of faulted and folded plateau eroded by tributaries of the Colorado River. Salt domes in footwall. Rock cities and isolated pillars.	Different types of cross bedding.	Different types of cement, especially ferruginous and quartz cement.	Faults with slickensides, deformation bands, prominent folds, cleavage planes, joints.	Rock shelters common, often represented by imperfectly developed arches.	Fins, perfectly developed arches and rock windows, potholes.	Tafone, relicts of pitted surfaces. Solution furrows.	Desert varnish, opal and salt coatings.
Canyonlands NP, USA[16]	Subtropical, arid.	Jurassic to Pennsylvanian, eolian, fluvial and shallow marine.	Sandstone, siltstone.	Plateau dissected by the Colorado and Green Rivers. Salt domes in footwall. Meteorite impact. Table mountains, deep canyons, rock cities and isolated pillars.	Different types of cross bedding.	No prominent cementation.	Faults, prominent folds, cleavage planes, joints.	Rock shelters common.	Fins, rock needles, mushroom rocks, arches and rock windows.	Tafone, relicts of pitted surfaces.	Desert varnish, opal and salt coatings.
Mesa Verde NP, USA[17]	Subtropical, arid.	Cretaceous, shallow marine and eolian.	Sandstone, shale, coal seams.	Plateau dissected by canyons with seasonal streams. Table mountains.	Cross bedding, parallel stratification.	No prominent cementation.	Joints.	Huge rock shelters.		Tafone, relicts of pitted surfaces.	Desert varnish.
Colorado NM, USA[17]	Subtropical, arid.	Triassic and Jurassic, eolian and shallow marine	Sandstone.	Plateau dissected by canyons with seasonal streams. Cliffs, domes, isolated pillars.	Cross bedding, ripples, parallel stratification.	No prominent cementation.	Joints.		Arches and rock windows, mushroom rocks.		Desert varnish.
Canaima NP, Venezuela[18–21]	Tropical, humid.	Proterozoic, shallow marine and lacustrine.	Sandstone, quartzite, quartz veins.	Plateau dissected by canyons with Río Venamo and Río Caroní rivers. Table mountains, waterfalls.	Different types of cross bedding, ripples, parallel stratification.	Quartz cement, rare ferruginous concretions.	Joints, intrusive bodies.	Caves hundreds of metres long formed by quartz dissolution. Rock shelters.	Sinkholes, arches and false arches, mushroom rocks, solution basins.	Grooves following joints, rarely developed pitted surfaces.	Silcrete.

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Sandstone region	Climatic zone	Age, genesis	Rock description	Characteristic	Surfaces formed during deposition	Cementation	Tectonic deformation	Caves and rock shelters	Medium forms of relief	Small forms of relief	Salt weathering and case hardening
Jameson Land, Greenland[22]	Arctic.	Jurassic, shallow marine.	Sandstone.	Rock walls, block accumulations and rare pillars on seashore and in glacial troughs.	Cross bedding, ripples, parallel stratification.	Quartz cement.	Joints.	Caves among fallen blocks.	False arches.	Ledges, rare pitted surfaces	None.

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4. Global significance

Significance of sandstone districts of the Bohemian Paradise, Czech Republic, for the understanding of major stages in Earth´s history and ongoing geological processes in landform evolution

Scientific importance of the Bohemian Paradise sandstone districts can be highlighted in three areas:

Sedimentology and stratigraphy

The lowermost 80–100 m of the sedimentary pile of the Teplice Formation (Upper Turonian to Lower Coniacian, Upper Cretaceous) exposed in the sandstone districts are formed by a basinward-prograding body of subaquatic delta with relatively steep foresets (Gilbert-type delta). Internal architecture of the delta body is clearly visible in outcrops. The presence and migration paths of shallow-sea bedforms (dunes with straight and sinuous crests, ripples, sand waves) are well documented by different sedimentary structures. The uppermost 20–30 m of the sedimentary pile evidence progradation of low-profile subaquatic delta bodies at constantly rising sea level. The whole sandstone body is a 3rd-order depositional sequence.

The sandstone districts thus document the style of deposition in a shallow Late Cretaceous sea in the foreland of the closing Tethys Ocean, which, in turn, reflects the global climate and sea-level changes. The Bohemian Paradise area provides the best outcrops of coarse detrital sediments of Late Cretaceous age in Europe. All outcrops are well accessible for study.

Relevant publications in universally recognized journals:

SKOČEK V. and VALEČKA J., (1983). Paleogeography of the Late Cretaceous Quadersandstein of central Europe. *Palaeogeogr., Palaeoclim., Palaeoecol.*, 44: 71-92.

ULIČNÝ D., (2001). Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. *Sedimentology*, 48, 3: 599-628.

ULIČNÝ D., ČECH S. and GRYGAR R., (2003). Tectonics and depositional systems of a shallow-marine, intra-continental strike-slip basin: Exposures of the Český ráj region, Bohemian Cretaceous Basin. *Geolines*, 16: 133-148.

Morphology of rock surfaces

The erosive landscape of uplifted and tilted blocks in proximity of a major fault zone combined with favourable rock resistance and favourable climatic conditions of temperate zone are the factors considerably enhancing geomorphological diversity of the sandstone districts of the Bohemian Paradise. The diversity of microforms of sandstone relief is not paralleled elsewhere in the world. Many features are specific to the Bohemian Paradise and have not been reported from other sandstone areas. These include, for example:

1. inclined ledges near bases of spires copying ancient earth surfaces (Plate 11F, G),
2. ferruginous (goethitic) linings of joints with morphologically manifest "flow lines" – paths of migration of iron-rich fluids (Plate 7A, B),
3. special forms resulting from the combination of honeycombs and salt crusts, like "wasp nests" and "bubbles" (Plate 12G, H),
4. subvertical grooves on steep walls formed by differential weathering of deformation bands (Plate 5D),
5. series of vertical grooves on steep walls formed by dripping water (Plate 11D).

These facts make the sandstone districts of the Bohemian Paradise the best area for the study of present geomorphic processes in sandstone and their products in global scale.

Relevant publications in universally recognized journals:

MIKULÁŠ R., (2001). Gravity and orientated pressure as factors controlling „honeycomb weathering“ of the Cretaceous castellated sandstones (northern Bohemia, Czech Republic). *Bull. Czech Geol. Surv.*, 76, 4, 217-226.

MERTLÍK J. and ADAMOVIČ J., (2005). Some significant geomorphic features of the Klokočí Cuesta, Czech Republic. *Ferrantia*, 44: 171-175.

Brittle tectonic structures

The Lusatian Fault, bounding the sandstone region of the Bohemian Paradise in the NE, is the most prominent structure of the tectonic Elbe Zone stretching over a major part of Europe. The block in the northeast was uplifted by ca. 1000 m relative to the block in the southwest in the latest Cretaceous and earliest Tertiary. Later evolution of the fault zone involved reverse, normal and strike-slip movements.

Many features visible in the sandstone districts of the Bohemian Paradise document the character of deformation, its intensity and superposition of movement: fault planes with slickensides (Suché skály – Plate 4D), polished surfaces and slickensides as well as different types of joints (tensional, compressional, shear). Deformation bands have been reported from the Arches NP, USA, but show higher variability in the Bohemian Paradise (Klokočí Cliffs, Suché skály Cliffs, Kozákov Hill), see Plate 5.

Analyses of brittle structures in the sandstone districts of the Bohemian Paradise permit the reconstruction of the succession of regional stress fields in northern Bohemia from the latest Cretaceous to the present. The identified succession was shown to copy the one previously reported from the Alpine–Carpathian mountain chain. This conclusion contributed to the recently acknowledged fact that stresses from collisional zones can be transferred far into their foreland.

Relevant publications in universally recognized journals:

BUDIL P., ŠTĚPÁNEK P., ADAMOVIČ J., COUBAL M., CHLUPÁČ I., OPLETAL M. and VALEČKA J., (1999). Examples of important geological localities in the Sudetes (Czech Republic). *Polish Geol. Inst. Spec. Pap.*, 2: 27-32.

COUBAL M., (1990). Compression along faults: example from the Bohemian Cretaceous Basin. *Miner. Slovaca*, 22: 139-144.

Appendix 3

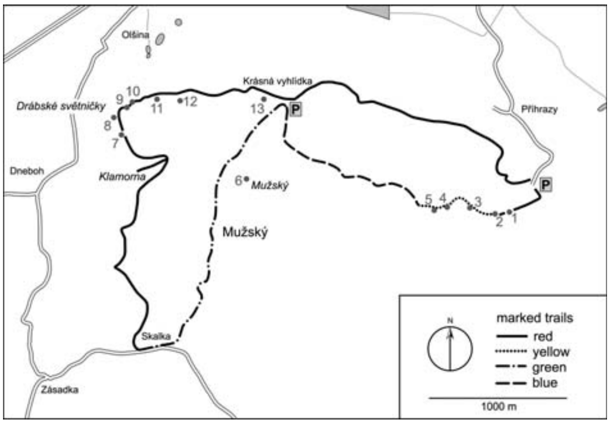
Geo-educational trails

1. Mužský Hill in the Příhrazy District

Sandstone plateau with a volcanic neck in the centre

ROUTE

Point	km	Marked trail from this point on
Příhrazy, parking lot	0	yellow
Hrázka (saddle)	1.3	blue
Krásná vyhlídka (restaurant)	2.8	green
Skalka (saddle)	5.5	red
Drábské světničky	8.5	red
Krásná vyhlídka (restaurant)	10	red
Příhrazy, parking lot	13	



■ **Fig. 14.** A map illustrating the course of the Mužský Hill trail.

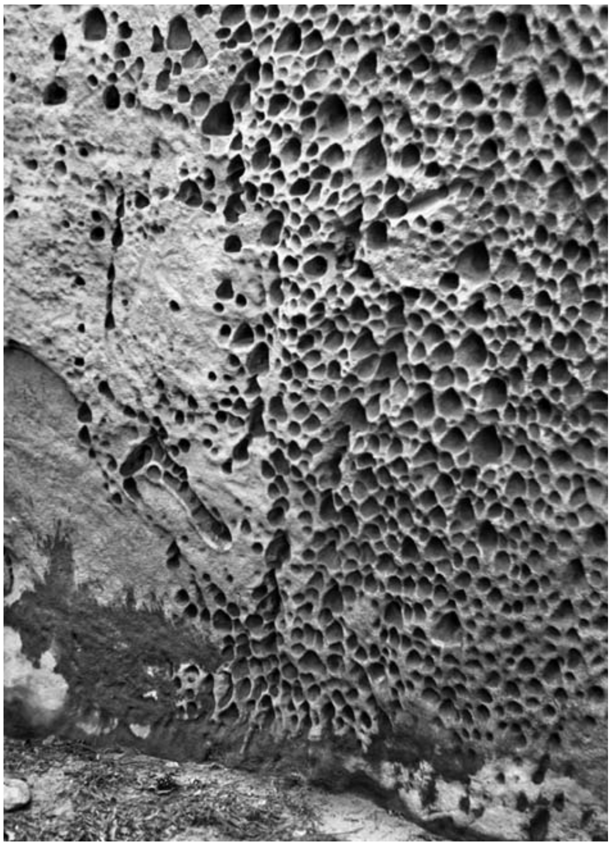
STOPS

1. pitted surface – honeycombs, 0.25 km
Teplice Formation (Hrubá Skála Quader)

A fallen block on the left shows many typical features of honeycomb "weathering": their distribution in strings following primary (?bioturbation) and secondary (irregular shear zones – no discernible fissures!) inhomogeneites of the rock (Fig. 15). Also, relations between secondarily hardened rock crusts and honeycomb pits can be demonstrated: pits are missing from places of fresh exfoliation of crusts, as well as from places which are so much hardened that they do not provide suitable substrate for salt weathering.

2. rock window, trough cross bedding, tree grooves, 0.4 km
Teplice Formation (Hrubá Skála Quader)

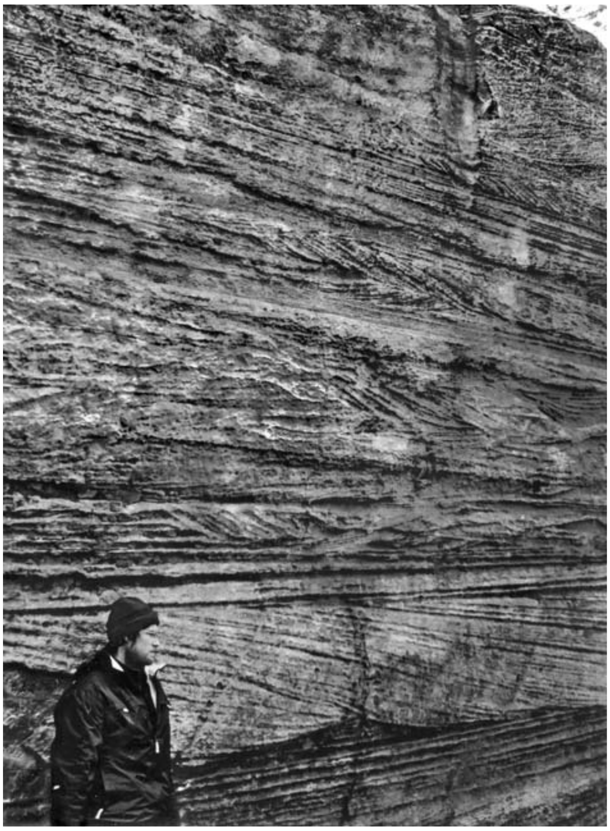
Sedimentary structures in the upper part of the Hrubá Skála Quader are characteristic for very shallow marine environment (parallel stratification, well-developed cross bedding with scoured base dipping WNW, Fig. 16). Good accessibility of the rock window (Plate 9F) causes prominent anthropogenic erosion of its bottom. The tree groove belongs to the rare cases of this phenomenon which can be approximately dated: thin rock crusts and small honeycomb pits on the surface modelled by the tree point to an age of several hundreds of years.



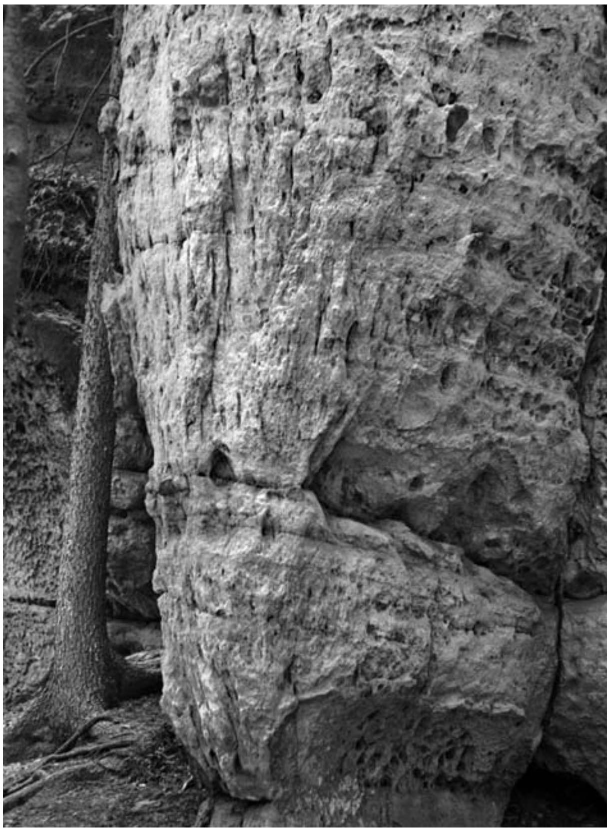
■ **Fig. 15.** Honeycomb weathering. Stop 1 on the Mužský Hill trail.

3. tafoni, rock shelters, 0.7 km
Teplice Formation (above the Hrubá Skála Quader)

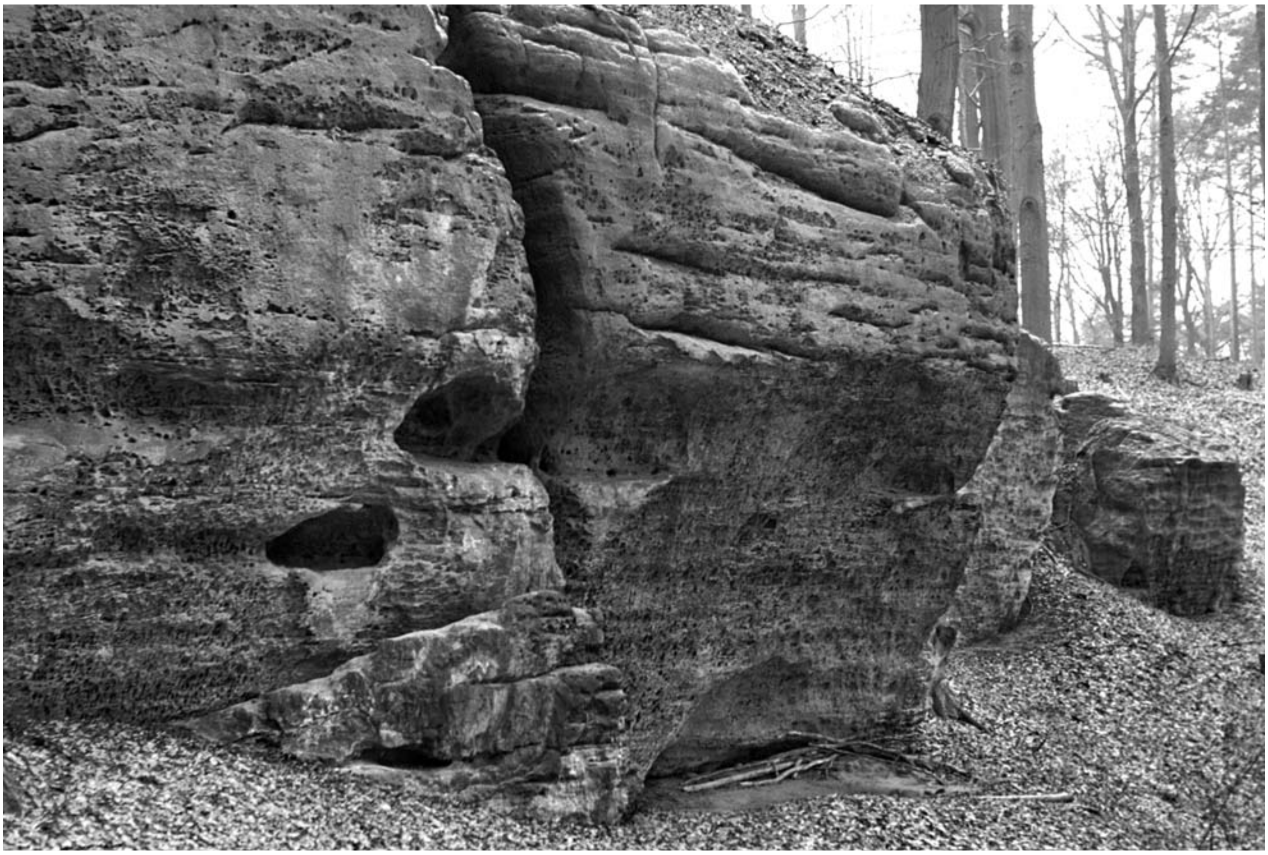
Sandstones above the Hrubá Skála Quader are generally coarser-grained and poorly sorted. Upwards shallowing (coarsening) is locally visible, interrupted by fourth-order flooding surfaces. Bedding planes are gently inclined, probably foresets of low-relief subaquatic deltas. Two principally different concave forms of the sandstone micro- to mesorelief are developed together on this part of the cliffs: rock shelters have flat sand-filled bottoms at the level of cliff foot, with the humidity responsible for weathering (frost, salt, capillarity) coming from the soil. Tafoni resemble large honeycomb pits (Fig. 17). Transitional forms between tafoni and small honeycomb pits can be occasionally observed. The water supply which augments the weathering comes from the rock massif along predisposed paths of percolation.



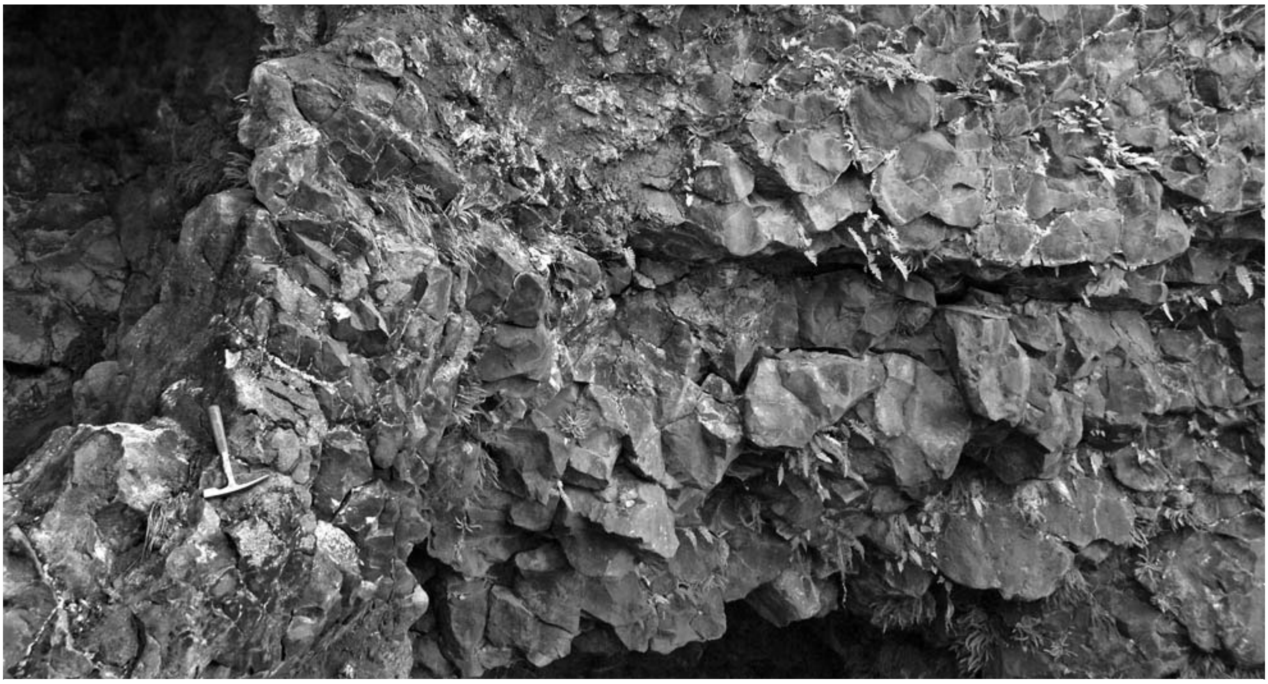
■ **Fig. 16.** Trough cross bedding. Stop 2 on the Mužský Hill trail.



■ **Fig. 18.** Stress-aligned microfractures. Stop 4 on the Mužský Hill trail.



■ **Fig. 17.** Cavities on a cliff face. Stop 3 on the Mužský Hill trail.



■ **Fig. 19.** Columnar jointing of olivine nephelinite. Stop 6 on the Mužský Hill trail.

4. rock crust, stress-aligned microfractures, 1 km
Teplice Formation (above the Hrubá Skála Quader)

The small rock pillar shows two notable features of the sandstone microrelief: (1) relatively hard vertical rock crusts weathering off from the poorly lithified sandstone; (2) incipient honeycomb pits, elongated in the direction of the orientated rock pressure (which is evidently different from the gravity vector around the perforation of the pillar). A network of subvertical microfractures results from stress reorientation due to local loading (Fig. 18).

5. elongated pits on abutment of a rock shelter, thrust plane, 1.15 km
Teplice Formation (above the Hrubá Skála Quader)

Another example of honeycomb pits elongated in the direction of the orientated rock pressure in the support structures of a rock shelter. The honeycombs are not affected by the network of joints dipping WNW at an angle of 27° in the rock shelter area. These joints are splay structures to a subhorizontal thrust plane some 50 cm above the rock shelter, and indicate E–W-orientated compressional stress field.

■ **Fig. 20.** A rock window at Stop 8 of the Mužský Hill trail.

6. an old quarry in basaltic neck, Mužský Hill, 3.35 km

Columnar-jointed dyke of olivine nephelinite is exposed in a quarry on top of Mužský Hill (463 m), Fig. 19.

Columnar jointing in sandstones near dyke contact, indicative of volume changes and fluid escape during dyke emplacement, was visible a few decades ago. Some samples are now displayed in the Turnov Museum.

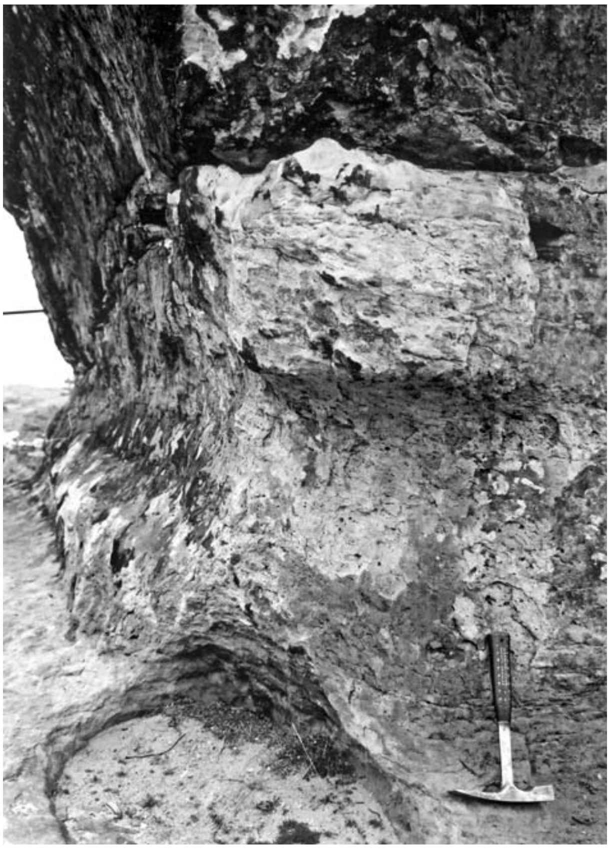
7. foresets of sand bedforms, 8.4 km
Teplice Formation (Hrubá Skála Quader)

The SE-dipping surfaces represent foresets of bedforms attributed to giant sand dunes or small deltas. Backsets locally preserved between individual foresets dip SE at low angles and possibly belong to antidunes migrating upslope the foresets (Plate 2C). The foresets are truncated by a flooding surface above, possibly the base of the TST. Sedimentary structures at top of the Hrubá Skála Quader indicate shallow marine conditions with progressively decreasing accommodation space.

8. a fortification carved in sandstone, mushroom rock and rock window, foresets, plume structures – Drábské světničky, 8.5 km
Teplice Formation (Hrubá Skála Quader)

Bioturbation structures in the poorly lithified sandstone bed, best visible on rock pillars with carved fortifications, are responsible for the origin of mushroom rocks and rock windows (Fig. 20). The trace fossils are simple tunnels, U-shaped burrows and branching patterns. The most prominent bioturbated horizon (Fig. 21) marks the flooding surface on top of the Hrubá Skála Quader.

Foresets of a migrating sand bedform above the wooden gate dip west and show scoured tops.



■ **Fig. 21.** A bioturbated horizon at Stop 8 of the Mužský Hill trail.

The whole rock massif at the edge of the plateau is deteriorating due to gravity-induced footwall bulging (plastic clays at the base of the Teplice Formation). Sandstone pillars are getting detached from the massif, sliding and collapsing. The process is documented by plume structures on joint planes, with vertical axes, opening downwards. One such structure is visible on a joint to the left from the wooden gate (Plate 4F). A series of plume structures is developed some 30 m higher up the slope (Fig. 22), immediately below the flooding surface on top of the Hrubá Skála Quader.

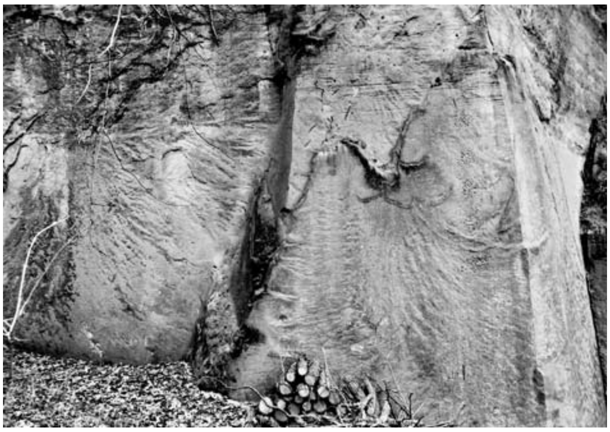
The place around the entrance to the fortification also displays honeycomb pits and rock crusts.

9. bioturbated bedding plane in a rock shelter, 9 km
Teplice Formation (above the Hrubá Skála Quader)

The low rock shelter displays the bottom of an interval in sandstone affected by the activity of marine invertebrates. During the existence of the Cretaceous sea, the invertebrates (especially decapods) excavated complex systems of tunnels relatively deep in the sandy substrate. At this site, the network (or, more accurately, boxwork) of tunnels, approx. 2 cm in diameter, is visualized owing to rusty pigmentation by iron oxyhydroxides.

10. a view of a landslide, 9.1 km

The presence of plastic clays at the base of the 80 m thick sandstone body makes the rock massif vulnerable to rockfall and



■ **Fig. 22.** Plume structures at Stop 8 on the Mužský Hill trail.

landsliding. Active slope deformations are evidenced by leaning fruit trees in orchards at cliff bases (Fig. 23). One of the largest landslides occurred in 1926, and destroyed several houses (Fig. 24). Gravitational movements of sandstone blocks are being monitored.

11. inclined ledge, 9.25 km
Teplice Formation (Hrubá Skála Quader)

The rock pillar on the right shows prominent gently dipping bedding planes – subaquatic delta foresets. Microforms of sandstone relief include numerous large honeycomb pits and small tafone-like forms. On its lower part adjacent to the steep narrow gorge, an inclined, moderately curved ledge shows the former level of the soil cover (Fig. 25). Honeycomb pits below the ledge are much smaller and generally different in patterns compared to those above the ledge; therefore, they have been developing for a much shorter time period. According to analogues from the Bohemian Paradise and other areas, 2000 years may be a reasonable estimation of the age of the exposure of the lower part of the pillar to salt weathering, which may coincide with one of the periods of ancient settlement on Mužský Hill.

12. dilated joint with giant plume structures – Studený průchod, 9.35 km
Teplice Formation (Hrubá Skála Quader)

Northern block of the Studený průchod (Cold Passage) shows features of soft-sediment deformation (Plate 2D), accentuated by honeycomb pits. The well developed arcuate honeycomb pits (Fig. 26) have their flat bottoms horizontal, despite the primary inhomogeneities of the sandstone. It proves the fact that the flat bottoms are controlled by the gravity vector, not by the bedding (as often interpreted). Also the neighbouring faces show nice and instructive honeycomb decoration.

These are "bubble-like", arcuate or cellular honeycomb pits arranged in clusters. Nice pits combined with generally horizontal precipitation ledges are developed on the cliff face to the left from the entrance to the passage.

The passage itself (Fig. 27) is a gravitationally dilated joint striking 60°. Tensional character of the joint is documented by large-

■ **Fig. 23.** A view of slope deformations from Stop 10 on the Mužský Hill trail.

■ **Fig. 24.** A historical photo of the landslide near Olšina (1926).

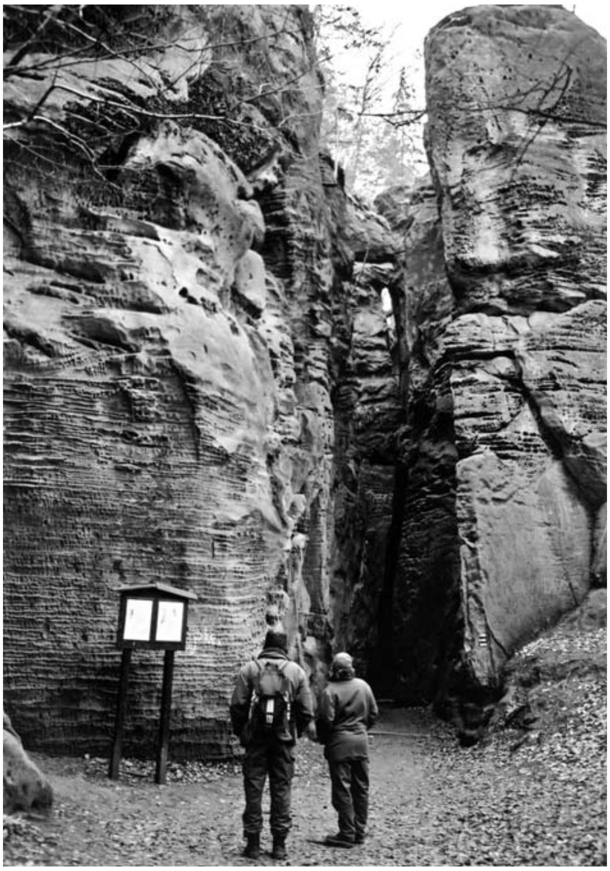
■ **Fig. 26.** Arcuate honeycomb pits. Stop 12 of the Mužský Hill trail.

■ **Fig. 25.** An inclined ledge. Stop 11 on the Mužský Hill trail.

shaped bowl structures and plume structures with vertical axes on its walls (Fig. 28). A borehole at the exit from the passage was drilled with the prospect of explaining the mass movement mechanism.

13. abyss-like dilated joint, 9.9 km

Walls of the joint are smooth, without at least initial forms of honeycomb pits. Upper parts of the joint walls are covered with continuous growths of mosses (Fig. 29). Clearly, relatively stable humidity and temperature protects the walls from salt weathering and other processes responsible for honeycombing.



■ **Fig. 27.** Gravitationally dilated joints of the Sudený průchod (Cold Passage). Stop 12 of the Mužský Hill trail.

■ **Fig. 28.** Bowl-shaped structures of arrest lines on plume structures. Stop 12 of the Mužský Hill trail.

14. bioturbated bedding plane, flooding surface – Stará hrada, 12 km

Teplice Formation (above the Hrubá Skála Quader)

A bioturbated interval in sandstones of the transgressive systems tract of the Teplice Formation. The well visible trace fossils represent nearly vertical to slightly inclined shafts of complex boxworks of invertebrate burrows (Plate 3A). Bioturbation structures are developed in poorly lithified sandstone, which is the home for nesting bees.

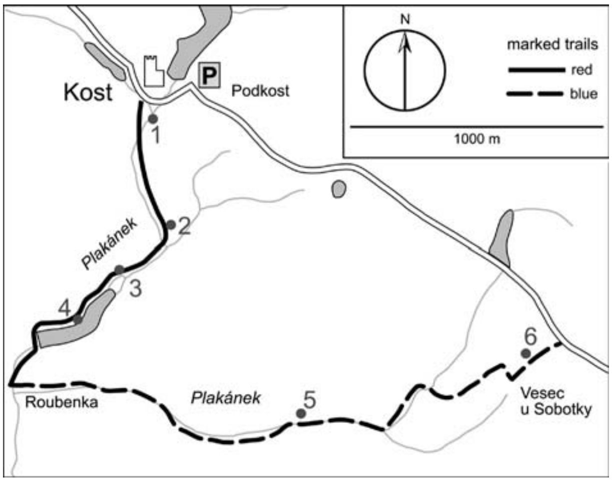
2. Plakánek Valley

Downdip a subaquatic delta

ROUTE

Point	km	Marked trail from this point on
Kost Castle, parking lot	0	red
Roubenka	2.3	blue
Vesec village	4.8	road
Kost Castle, parking lot	7	

■ **Fig. 29.** Abyss-like dilated joint. Stop 13 of the Mužský Hill trail.



■ **Fig. 30.** A map illustrating the course of the Plakánek Valley trail.

■ **Fig. 31.** Clinoforms representing delta foresets. Stop 2 on the Plakánek Valley trail.

STOPS

1. sedimentary architectures – Kost Castle, 0.3 km
Teplice Formation (Hrubá Skála Quader), TST in top parts of cliffs

The upper portion of the Hrubá Skála Quader in the area of this trail is occupied by a body of a large subaquatic delta, 55 m thick, prograding to the south. Delta foresets (strata gently inclined to the right in this view) form the pedestal for the medieval Kost Castle. The top of the delta and the Quader is marked by a prominent silt-dominated flooding surface, above which another delta with a lower relief (only a few metres thick) prograded in approximately the same direction (Plate 1A). The level at the flooding surface was enforced by cement by medieval masons to prevent undercutting and rockfall (Plate 1B).

2. delta foresets, 1 km
Teplice Formation (Hrubá Skála Quader)

The Šrámek Pillar is a place where delta foresets can be observed in close-up view (Fig. 31). In the Plakánek Valley, the delta front was reactivated by multiple episodes of such high frequency that no larger bedfoms like dunes could be preserved. This is why cross-bedded sets of only tens of centimetres thick are visible.

3. convex-up delta foresets, 1.4 km
At some places, the individual delta foresets show variations in their dips, thus forming convex-up surfaces.

4. sedimentary architectures, Timber Mill Reservoir (Pilský rybník), 1.8 km
Teplice Formation (Hrubá Skála Quader), TST in top parts of cliffs

The top of the Hrubá Skála Quader is well visible across the water reservoir. The flooding surface bounding the Quader lies a few metres below the upper edge of cliffs. In detail, the transgressive systems tract comprises (from bottom to top) a bed of sandy siltstone, a bed of bioturbated silty sandstone, a conglomerate bed and finally another delta body of medium-grained sand, of lower relief than the underlying delta, prograding in approximately the same direction – to the south (Plate 1C).

5. tufa cascade, 3.8 km
Late Pleistocene to Holocene

A terrace of calcareous tufa is developed close to the trail. The terrace is still aggrading, fed by calcium carbonate-rich water from the Coniacian calcareous claystones and Pleistocene loess deposits above.

6. use of sandstone blocks in traditional architecture – Vesec, 4.8 km

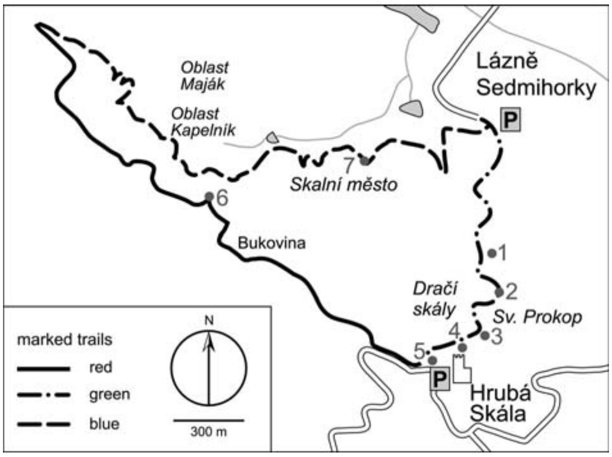
The traditional rural architecture in the Bohemian Paradise made a wide use for sandstone, exploited at many sites in the form of rectangular blocks. Many houses in the village of Vesec were built from sandstone exploited in the Plakánek Valley (e.g., quarries near Stop 6).

3. Hrubá Skála

Interior of a mature rock city

ROUTE

Point	km	Marked trail from this point on
Sedmihorky, parking lot	0	green
Hrubá Skála, parking lot	1.5	red
Přední Skalák	4	blue
Sedmihorky, parking lot	7.5	



■ **Fig. 32.** A map illustrating the course of the Hrubá Skála trail.

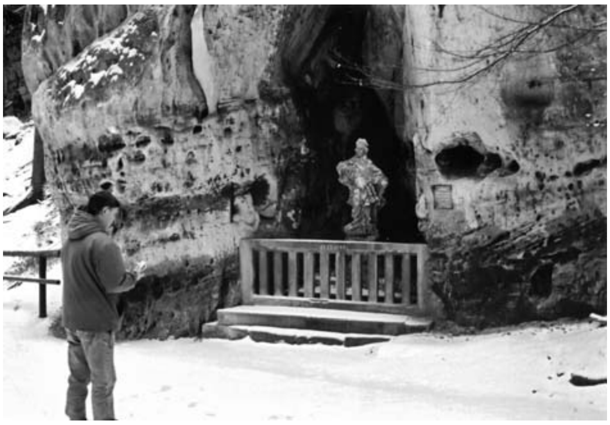
STOPS

1. delta foresets, tafone enlarged into a rock window, polygonal tessellation of a rock crust, 1 km

Teplice Formation (Hrubá Skála Quader)

Faces of the cliff to the left of the trail, called Osudová věž (Destiny Pillar), show well developed bedding planes gently inclined towards S to SSE (Fig. 33). They are interpreted as foresets of a subaquatic delta body similar to that in the Plakánek Valley and can be observed throughout the Hrubá Skála Quader. Only occasionally are they interrupted by large-scale syn-depositional erosion surfaces caused by collapse of the whole upper shoreface sand accumulation. The slightly overhanging lower part of the cliff face shows polygonal "flakes" of a rock crust,

■ **Fig. 33.** A rock crust developed on the Osudová věž Pillar. Stop 1 on the Hrubá Skála trail.



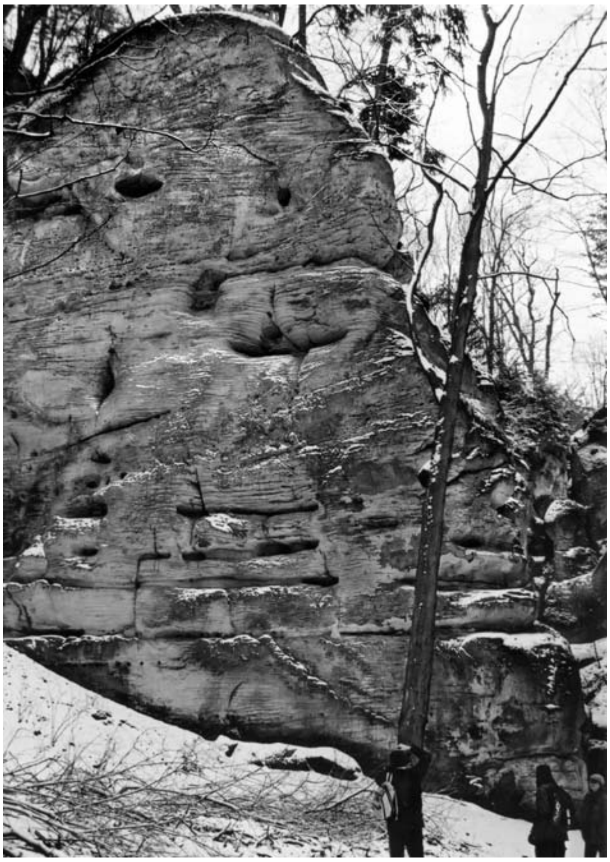
■ **Fig. 34.** Giant-scale cross bedding at the statue of St. Procopius. Stop 2 on the Hrubá Skála trail.

■ **Fig. 35.** Bránička Arch. Stop 3 on the Hrubá Skála trail.

i.e., the first stage of destruction of the originally coherent hard "envelope" of the rock pillar. On the left part of the pillar, three tafone-like concave forms contributed to the origin of a perforation and a rock column ("rock sand-watch").

2. giant-scale cross bedding, dilated joint – St. Procopius, 1.05 km
Teplice Formation (Hrubá Skála Quader)

The statue of St. Procopius was erected in a dilated joint in sandstone showing a combination of gently inclined delta foresets



■ **Fig. 36.** An inclined ledge at Stop 4 of the Hrubá Skála trail.

and giant-scale cross-bedding dipping towards SW at the base of the cliff (Fig. 34, Plate 16B). The joint is widened in its lower part due to the erosive effect of capillary water (cf. Stop 3 of the Mužský Hill trail).

3. sandstone arch 20 m from trail, 1.2 km
Teplice Formation (Hrubá Skála Quader)

The Bránička sandstone arch located on a small crest ca. 15 m to the left of the trail was formed by transverse perforation of a rock wall and is ca. 5 m high (Fig. 35). Its surface bears minute honeycombs and larger tafoni, and is covered by a thin rock crust.

4. bedding plane pigmentation, inclined ledge, 1.35 km
Teplice Formation (Hrubá Skála Quader)

This cliff face, ca. 30 m high, shows numerous interesting features of microrelief: (1) wavy laminae rich in ferruginous pigment, following and accentuating bedding planes, which in this case form mostly negative relief and separate rock ledges; (2) small systems of strata-bound caves developed in easily-weathering sandstone intervals; (3) tafoni, (4) an inclined ledge which indicates the past soil level on the base of the cliff (Fig. 36, Plate 11G).

The base of the cliff further down the trail, on the left, shows vertical undulating joints formed as a product of load-stress release, a phenomenon sometimes responsible for the formation of rock arches (Fig. 37). The trail then takes you through a NW–SE system of erosively enlarged joints called Myší díra (Mouse Hole).

■ **Fig. 37.** Curved joints at Stop 4 of the Hrubá Skála trail.

5. pitted surface on delta foresets, above the enlarged joint of Myší díra, 1.45 km

Teplice Formation (Hrubá Skála Quader)

Outcrops on both sides of the trail show several nice examples of sandstone microforms. Although the surfaces were adapted artificially in medieval times, by the present time they have developed initial to nearly mature forms of honeycomb decorations. This example shows that, under optimum conditions, honeycomb pits may form within several hundreds of years (Fig. 38, Plate 13F).

6. a view of the Kapelník (Bandmaster) group of pillars, 3 km

Teplice Formation (Hrubá Skála Quader)

One of the best views of the Hrubá Skála rock city (Plate 8G). The favourable factors for the development of a mature rock city were: 1) a thick body of relatively well sorted and lithified sandstone, 2) lack of fining- and coarsening-upwards trends and of conglomerate beds, 3) a network of orthogonal joint systems, one of which is parallel to the Lusatian Fault. Some of the isolated pillars are as much as 60 m tall.

7. spring area near Sedmihorky, 6.5 km

Issues of groundwater concentrate to the level of the basal sandstones of the Hrubá Skála Quader. The underlying calcareous claystones act as an aquitard. A spa was founded at Sedmihorky in 1841 and the water was used for the treatment of anemia.

4. Trosky Castle in the Apolena District

Basaltic spatter cone injected by a dyke

STOPS

1. spatter cone – pyroclastics with xenoliths, at castle entrance

Trosky Hill, the popular landmark of the Bohemian Paradise region, is an E–W-striking dyke of olivine nephelinite with plagioclase. It was emplaced in a spatter cone body of nephelinite rich in shallow-crustal xenoliths (mostly Cretaceous sediments, see Fig. 39). Subvertical contact of the intrusion striking NE–SW is exposed at the base of the Panna spire on the outer side of the castle. Volcanic products in this area are presumed to be Pliocene in age, as indicated by radiometric datings from the near basaltic effusions at Smrčí on the Lusatian Fault.

2. a view of the E–W dyke from the Baba spire at the castle

The two spires bear remains of a medieval castle. The taller one Panna (Virgin, Plate 15C) is 59 m high, and the shorter one Baba

■ **Fig. 38.** Arcuate pits in staircase arrangement on gently dipping clinoform surfaces. Stop 5 on the Hrubá Skála trail.

■ **Fig. 39.** A contact of a basaltic dyke (right) with the surrounding xenolith-laden spatter cone body (left). Stop 1 on the Trosky Castle trail.

(Old lady) is 49 m high and can be reached on a staircase. Castle palace was standing between the two spires.

5. Klokočí Cliffs

Tectonized cuesta rim

ROUTE

Point	km	Marked trail from this point on
Klokočí, parking lot	0	red
Nad Průchody	0.5	yellow
Postojná Cave and back (optional)	2.5	yellow
Rotštejn, parking lot	3.8	blue
Fialník	4.8	red
Klokočí, parking lot	5.5	

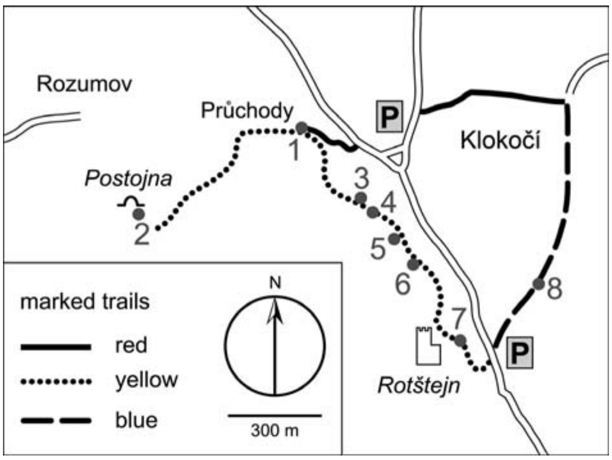
STOPS

1. a passage along dilated joint, false arch, sinkholes, 0.5 km
Teplice Formation (Hrubá Skála Quader)

The stop is located above a rock passage called Průchody (Passages), an erosively enlarged joint striking ESE–WNW, similar to Myší díra (Mouse Hole) at Hrubá Skála. Two sandstone blocks fallen into the corridor gave rise to a false arch. The near sinkhole is the southeasterly-most one of a group of 36 sinkholes distributed parallel to the cuesta rim, ca. 150 m from the edge. The sinkholes are slightly elongated in NW–SE direction and may exceed 10 m in diameter.

2. a cave formed by enlargement of serial tafoni – Postojná Cave, 1.5 km
Teplice Formation (Hrubá Skála Quader)

Caves are a very common feature in the Klokočí Cliffs, mostly concentrated in valleys draining the cuesta towards SW. Some of them were formed by tafoni enlargement while others follow



■ **Fig. 40.** A map illustrating the course of the Klokočí Cliffs trail.

weak zones along subhorizontal thrust planes, as indicated by polished and striated surfaces in the caves. The Postojná Cave is the largest of the local caves: it is elongated NW–SE, has the area of 262 m^2, and its rooms interconnected by passages have a total length of 75 m.

3. deformation bands on Radnice Cliff, 2.8 km
Teplice Formation (Hrubá Skála Quader)

The stop is located on the edge of the Klokočí cuesta, only ca. 1.5 km from the NW–SE-striking Lusatian Fault (Fig. 41). The tectonic dip is about 3° SW at this point but steepens to the NE, closer to the main fault. The proximity of the fault is manifested by numerous features of brittle tectonic deformations along this trail. Deformation bands cluster into steep swarms and produce negative relief.

4. sedimentary structures controlling tafoni formation, tree grooves, 2.9 km
Teplice Formation (Hrubá Skála Quader)

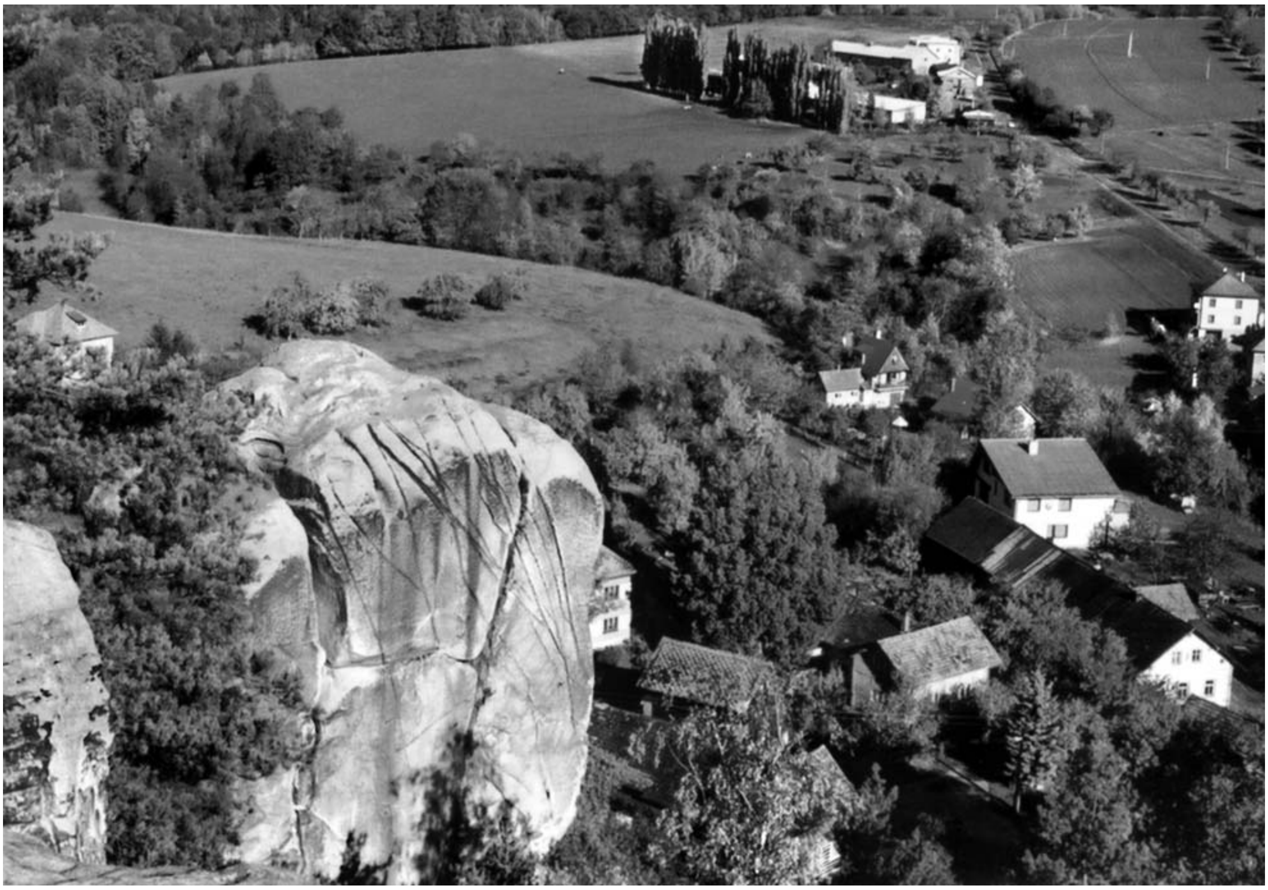
Cliffs to the right of the trail above the staircase display southerly-dipping bedding planes – foresets of a subaquatic delta – combined with trough cross bedding in their lower part and massive texture (slumped material due to shoreface collapse?) in their upper part. Besides primary sedimentary structures and ubiquitous deformation bands, the cliffs also display nice examples of tafoni. To the left of the pathway, a small birch is presently modelling a tree groove. It is notable that the origin of tree grooves is usually (as in this case) connected with large deformation of the tree trunk, which, however, does not lower the life expectancy of the tree.

5. deformation bands and polygonal tessellation on rock crusts on Džbán (Jug Cliff), strata-bound cave and ferruginous cement in joint filling, 3.05 km
Teplice Formation (Hrubá Skála Quader)

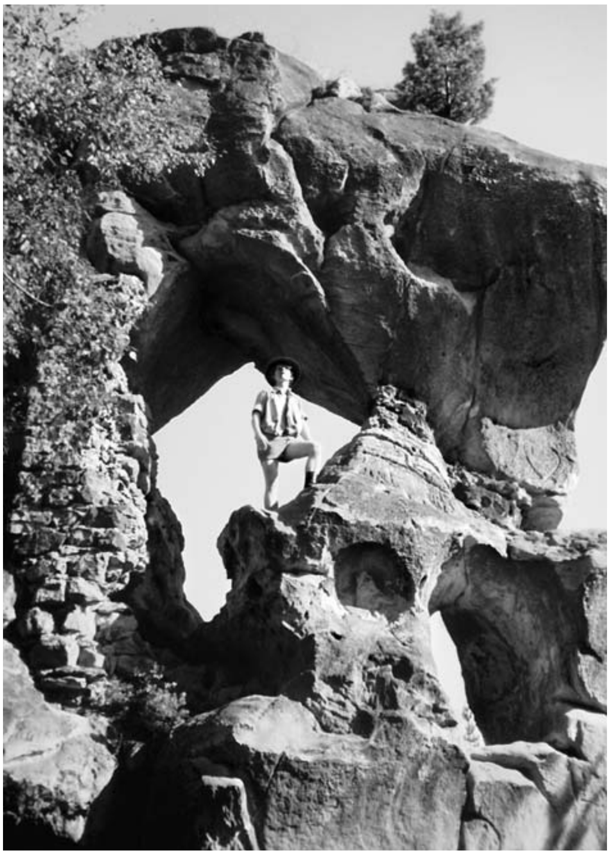
The vicinity of the Džbán (Jug Cliff) displays a number of mesoforms typical for the Klokočí Cliffs. The cliff itself (Plate 9A) is rugged by deeply weathered deformation bands, which morphologically clearly overprint the inclined bedding planes and cross bedding at the foot of the cliff. Well-developed is polygonal tessellation on rock crusts (if viewed from the east). The face of the cliff on the left (south of Džbán) is impregnated by a crust of iron oxyhydroxides; these crusts are related to syntectonic migration of hydrothermal fluids along joints. A strata-bound cave is developed in this cliff with its bottom dipping at 13° to the south.

6. siliceous rock crust, tree grooves, 3.3 km
Teplice Formation (Hrubá Skála Quader)

The cliff on the right, closely before the staircase, shows a good example of a rock crust, i.e., vertical, tabular body of well-cemented grey sandstone, which is sharply bounded against poorly lithified and easily eroded sandstone. This illustrates the importance of case hardening and resulting rock crusts for the persist-



■ **Fig. 41.** Radnice Cliff scarred by deformation bands. Stop 3 on the Klokočí Cliffs trail.



ency of outcrops built by weakly lithified sandstones. After the destruction of the crusts, the underlying sandstone gets rapidly eroded. Farther right, a pine tree is in convexo-concave contact with the cliff face, producing a tree groove. An older, partly erased tree groove is visible 50 cm to the right.

7. polygonal tessellation on rock crusts, use of sandstone morphology for castle construction – Rotštejn Castle, 3.6 km
Teplice Formation (Hrubá Skála Quader)

Rock crusts on sandstone faces beneath the Rotštejn Castle are developed on massive sandstone in the lower part of the section but are absent from the well stratified (delta foresets) sandstone above. Rock crusts are characterized by polygonal tessellation. Large rock windows are developed in a sandstone pillar dominating the castle (Fig. 42).

8. a view of the cuesta rim from a distance, outcrops of underlying marly sandstones to marlstones, 4.1 km
Jizera Formation

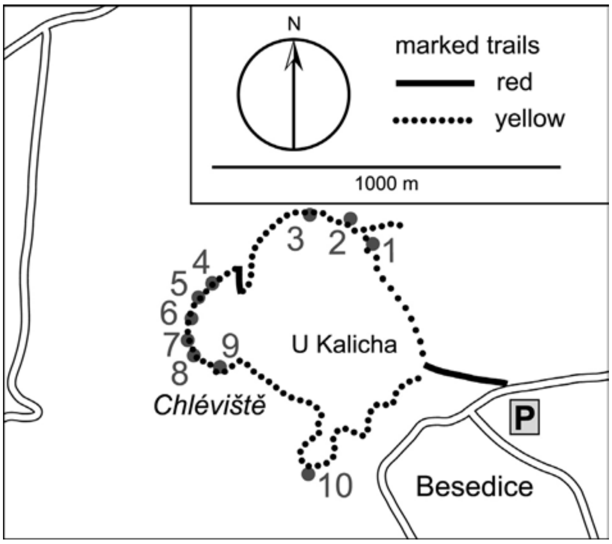
■ **Fig. 42.** A rock window at the Rotštejn Castle. Stop 7 on the Klokočí Cliffs trail.

6. Sokol Hill

Sandstone plateau with a volcanic neck in the centre

ROUTE

Point	km	Marked trail from this point on
Besedice, parking lot	0	red, blue
U Kalicha (restaurant)	0.3	yellow
Sokol Hill	1.1	yellow
view of Suché skály Cliffs and back (optional)	1.35	yellow
crossing with red trail	2	yellow
U Kalicha (restaurant)	5	red, blue
Besedice, parking lot	5.3	



■ **Fig. 43.** A map illustrating the course of the Sokol Hill trail.

STOPS

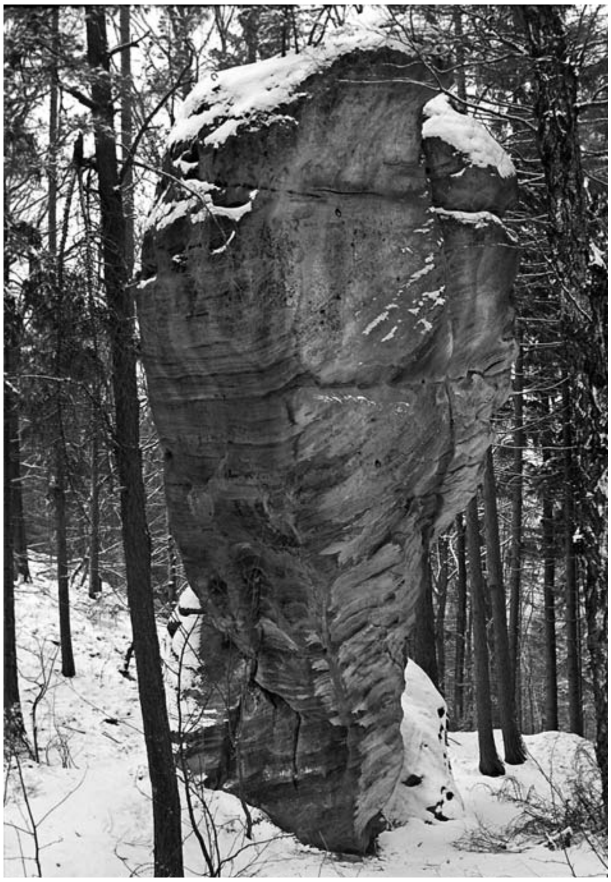
1. blocky talus, 0.9 km

Pleistocene talus accumulation formed during glacial periods on slopes of Sokol Hill

2. a view of Suché skály Cliffs (tectonic klippen), volcanic bodies, 1.1 – 1.35 km

Teplice Formation
Suché skály: Peruc–Korycany Formation

The top of Sokol Hill is formed by medium-grained sandstones of the Teplice Formation (see map in Fig. 11). Although this is an equivalent of the Hrubá Skála Quader, the sandstone body here is thicker (140 m) and lies closer to the basin margin, now only 1 km SW of the Lusatian Fault. Tectonic dip can be estimated at ca. 4° SW. Inclined bedding planes (delta foresets? accretion surfaces of bars?) observable on this trail dip gently (<13°) to the SSE or NNE. The cliff with the viewpoint also shows giant-scale cross bedding.



■ **Fig. 44.** The Sokolík Pillar at Stop 2 of the Sokol Hill trail.

The top of the hill offers a nice view of the tectonic northern margin of the Bohemian Cretaceous Basin, here represented by the Lusatian Fault. Cenomanian sandstones, lying across a valley formed by soft Lower Turonian marlstones, are tilted with their bedding planes to vertical position, intensively fractured and possibly horizontally transported for a distance of hundreds of metres. Silicification of the Cenomanian sandstones made them more resistant to weathering.

A small volcanic knob on the northeastern slope of the hill (marked trail) is formed by olivine basalt and functioned as a vent for lava flows which covered the area between Sokol Hill and Kozákov Hill in the Late Pliocene.

3. giant-scale cross bedding, two generations of honeycomb pits on fallen block, 1.45 km

Teplice Formation

Sets of giant-scale cross bedding were produced by migrating transverse sandy bedforms known as sand waves. They are typical for tidally influenced shelves and may reach heights of ~20 m. A prominent set of giant-scale cross bedding >7.5 m thick on the Tyrš Cliff and the neighbouring Sokolík Cliff (Fig. 44) is topped by a truncation surface with quartz pebbles and followed by an interval of finer massive sandstone, possibly a subaquatic slump. Foreset laminae of the cross bedding dip SSE at an angle of 32°. Cross-bedded sets 2.3 m above the top of the former set dip generally south. All these structures give evidence of the dynamic sedimentation on the bottom of a shallow sea.

A fallen sandstone block ca. 30 m east of the Tyrš Cliff has an instructive honeycomb decoration. Precipitation ledges are relatively steeply inclined (30 °). The spaces between them are filled with honeycomb pits. Most of them have horizontal flat bottoms despite the inclination of the ledges; some of them, however, have oblique subvertical axes; yet others have oblique bottoms. Such a picture of shapes and orientations of honeycomb pits is typical for fallen or slumping blocks; after the fall, some honeycomb pits become "re-built" according to the new gravity vector (Fig. 45). Some of them, however, may remain conserved in their original form. Also a completely new generation of honeycomb pits showing no "deformation" may be present; these are usually the smallest of all.

4. entrance to the rock city, bedding planes with iron pigmentation, rock maze, 2.2 km
Teplice Formation

The cliff face to the right from the entrance to the Chléviště rock city is nicely decorated with wavy laminae of ferruginous pigment, which (in contrast to those at Stop 4 at Hrubá Skála) form positive relief, i.e., undulating horizontal ledges (Fig. 46). Short after the entrance, the trail leads through a rock maze defined by a set of orthogonal joints striking 210° and 120°.

5. two false arches, talus field, 2.4 km
Teplice Formation

False arches are formed by leaning and fallen sandstone blocks. The blocks forming the roofs of the arches show interesting and prominent honeycombs: individual pits are interconnected to form a shallow, locally branching system of grooves (light) and ridges (dark). The structure resembles grikes but its origin is supposed to be quite different.

After this stop, the trail enters a block field typical for rock cities which have reached beyond the point of maturation.

6. laced pitted surfaces, false cave – below the Kde domov můj Viewpoint, Matěje Krocínovského Cave, 2.8 km
Teplice Formation

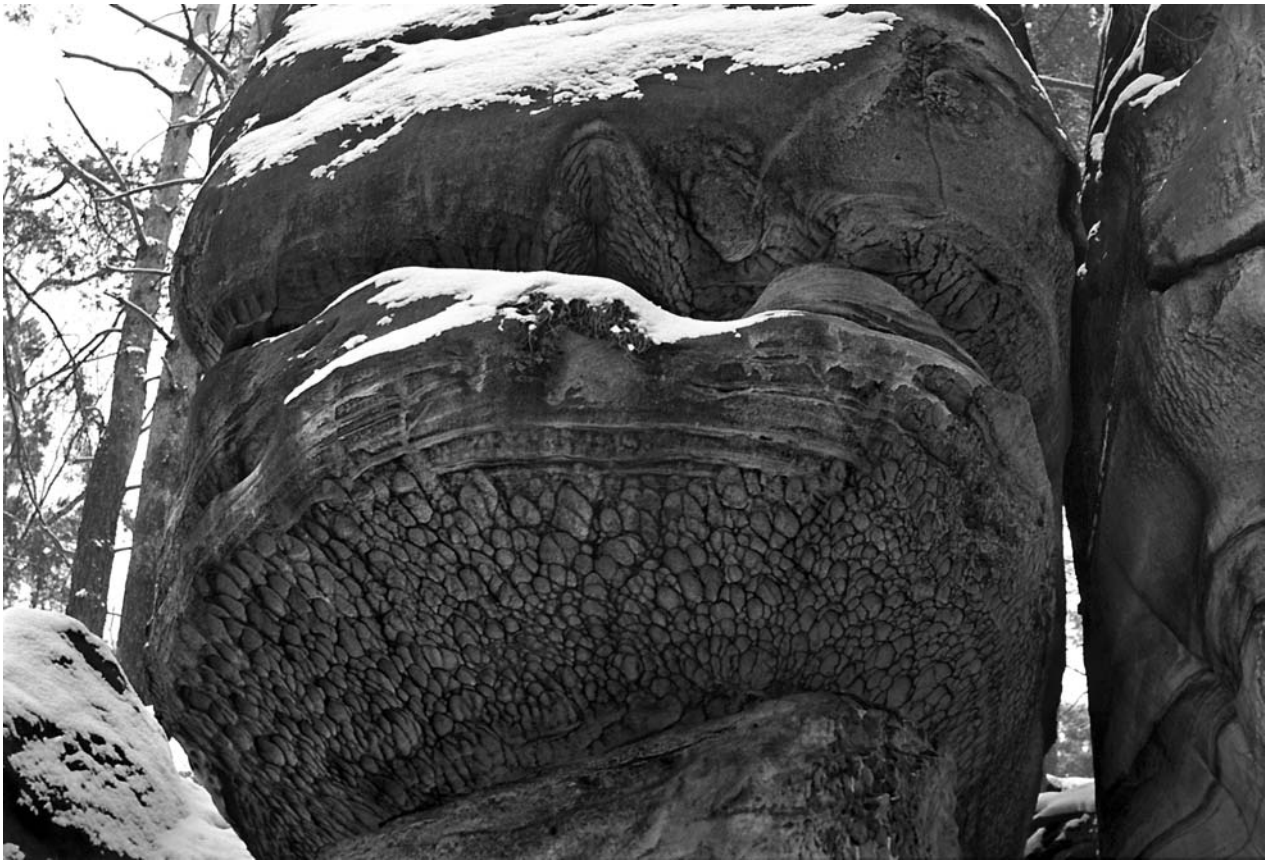
Most of the overhanging surfaces around the Kde domov můj Viewpoint are densely covered with cellular honeycomb pits (Fig. 47). Small ribs lining the pits are dark in colour (algae, dust) and contrast well with light internal area of the pits.

7. ferruginous tubes, deformation bands, polygonal tessellation on rock crusts – past the Václava Sadovského Cave, 3 km
Teplice Formation

A cliff face 10 m high, facing south, near the exit from the Václava Sadovského Cave shows a combination of typical features

■ **Fig. 45.** Re-oriented honeycombs at Stop 2 of the Sokol Hill trail.

■ **Fig. 46.** Undulating rock ledges controlled by ferruginous pigment in sandstone. Stop 4 on the Sokol Hill trail.



■ **Fig. 47.** Cellular honeycomb pits. Stop 6 on the Sokol Hill trail.

■ **Fig. 48.** A rock crust at Stop 7 on the Sokol Hill trail.

of the local sandstone microrelief. Deformation bands (formed by tectonic shearing) are less common than in the Klokočí Cliffs but still well visible: here, they are subvertical, marked by chains of uniform honeycomb pits, and combined with polygonal tessellation on rock crusts (Fig. 48). In the lower part of the face, the bands are transected by well-defined undulating and branching precipitation ledges parallel to bedding. A relict of a crust of ferruginous sandstone is present in the top part of the face.

8. polygonal tessellation on rock crusts, 3.05 km
Teplice Formation

A pillar on the right near the exit from the Chléviště rock city, supporting a false arch, shows a nice example of polygonal tessellation cracks, forming a turtle-shell pattern. Such cracks mark the initial stage of the destruction of a rock crust.

9. ferruginous tubes, 3.2 km
Teplice Formation

On the block on the left, bedding-parallel precipitation ledges of tube-like shapes supported by ferruginous cement (Fig. 49) pass into a continuous ferruginous rock crust copying the rock surface. Tube axes dip northwest at an angle of 35°. These features are to be distinguished from much older hydrothermal ferruginization related to tectonic and volcanic activity and following mostly dyke contacts and joints.

■ **Fig. 49.** Tube-shaped ferruginous concretions. Stop 9 on the Sokol Hill trail.

10. Kalich sanctuary, 4.3 km

Teplice Formation

This stop lies in the middle of another small rock city, Kalich, generally following an orthogonal joint plan. Kalich (Goblet) is a symbol of the Hussite revolution in the early 15th century. The site is believed to have functioned as a hidden sanctuary of supporters of the Catholic reformation in the 17th century.

The geo-trail continues to the notheast, back to the U Kalicha Restaurant at Besedice. The present trip will, however, follow the green and blue trails downhill to observe outcrops of the calcareous silty sandstones of the Jizera Formation at lower stratigraphic levels along the way. We will finish our walk at Vranové, a part of Malá Skála, a village lying precisely on the Lusatian Fault.

Photos to Appendix 3 were taken by Jiří Adamovič (16, 19-23, 25-28, 31, 33-38, 41, 48-49), Radek Mikuláš (15, 17-18, 29, 39, 44-47) and Miriam Adamovičová (42).

Appendix 4

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To avoid duplicity, this list does not include citations given in the References.

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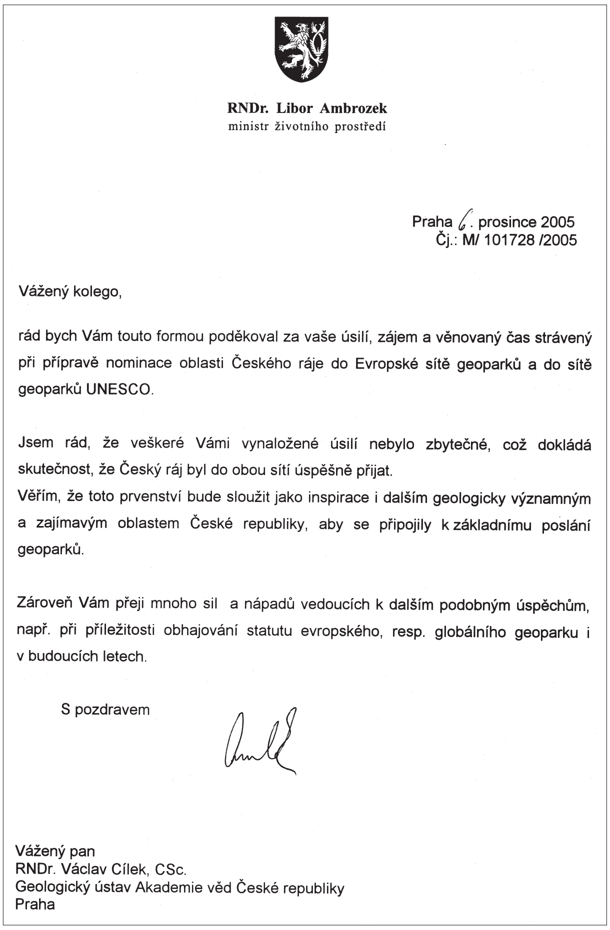
RNDr. Libor Ambrozek
ministr životního prostředí

Praha 6. prosince 2005
Čj.: M/ 101728 /2005

Vážený kolego,

rád bych Vám touto formou poděkoval za vaše úsilí, zájem a věnovaný čas strávený při přípravě nominace oblasti Českého ráje do Evropské sítě geoparků a do sítě geoparků UNESCO.

Jsem rád, že veškeré Vámi vynaložené úsilí nebylo zbytečné, což dokládá skutečnost, že Český ráj byl do obou sítí úspěšně přijat.
Věřím, že toto prvenství bude sloužit jako inspirace i dalším geologicky významným a zajímavým oblastem České republiky, aby se připojily k základnímu poslání geoparků.

Zároveň Vám přeji mnoho sil a nápadů vedoucích k dalším podobným úspěchům, např. při příležitosti obhajování statutu evropského, resp. globálního geoparku i v budoucích letech.

S pozdravem

Vážený pan
RNDr. Václav Cílek, CSc.
Geologický ústav Akademie věd České republiky
Praha

■ **Fig. 50.** A letter of acknowledgment from the Minister of the Environment of the Czech Republic.

Plates

published in Prague,
December 2006
by the Institute of Geology,
Academy of Sciences of the Czech Republic

Plate 1.
Sedimentary architectures

- **A.** The Plakánek Valley is cut in the top part of the Teplice Formation, built by a southward-shifting subaquatic delta body (gentle dips of clinoforms = delta foresets are marked by arrows). Flooding surfaces near cliff tops (dashed line), cutting the clinoforms, suggest that the top of the formation is a transgressive systems tract. Photo J. Adamovič.
- **B.** In the upper part of the Plakánek Valley, the lowermost flooding surface cutting the delta foresets lies 1.5 m below the top of the cliffs on a plateau of the medieval Kost Castle. Photo J. Adamovič.
- **C.** Medium-grained sandstone bodies with S-dipping clinoforms are best exposed in the central part of the Plakánek Valley. They are truncated by flooding surfaces near cliff tops (dashed line). Photo J. Adamovič.
- **D.** Giant-scale cross bedding up to 8 m thick is a common feature in the succession of delta foresets on the Mužský Plateau (Příhrazy area). This particular set of cross bedding on the northern rim (Janebova věž area) shows tangential toes of foreset laminae and an erosional top surface. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **E.** Internal architectures of the Hrubá Skála Quader (Teplice Formation) are best revealed in the Hrubá Skála rock city. Cliffs around the Mariánská Viewpoint show extensive erosion surfaces, packages of clinoforms (lower half of cliff), and SE-dipping foreset laminae of giant-scale cross bedding (upper half of cliff). Photo J. Adamovič.
- **F.** A sandstone cliff face near Zdenčina Viewpoint, Betlém Cliffs, is dominated by S-dipping clinoforms (delta foresets, marked by arrows) with superimposed trough cross-bedded sets ca. 1 m thick. In the uppermost few metres of the outcrop, parallel stratification with planar and trough cross bedding shows only low tectonic dips to the SW (dashed line). Upper part of the Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **G.** A sand pit near Blata on the W margin of the Prachov rock city shows the transgressive systems tract in the top part of the Teplice Formation. Medium-grained quartzose sandstones with clinoforms are separated from the overlying hematitized fine-grained sandstones (Rohatce Member) by a prominent flooding surface. Photo J. Adamovič.

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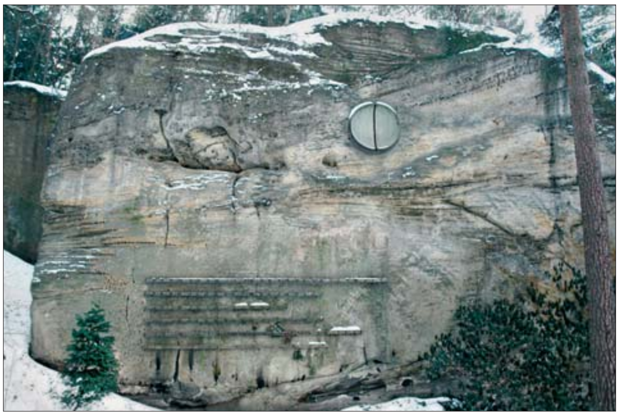

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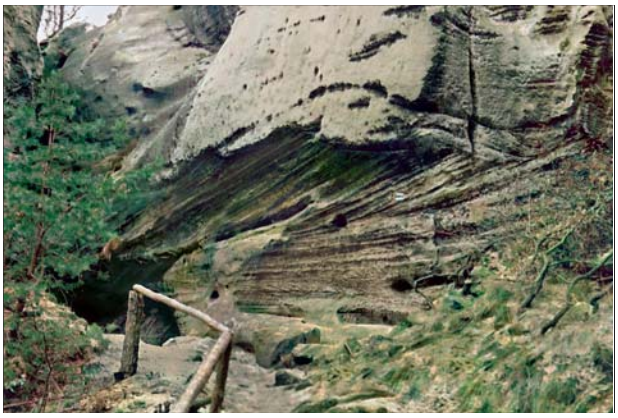
Plate 2.
Sedimentary structures

- **A.** Perfectly developed large-scale cross bedding in the Hrubá Skála Quader (Teplice Formation) SW of Příhrazy. Superimposed sets with homogeneous dip orientations of foreset laminae, much like the less frequent examples of herring-bone bedding, are indicative of tidally influenced sand deposition on sea bottom. Photo J. Mertlík.
- **B.** A cross-bedded set near the entrance to Drábské Světničky (Příhrazy area) with tangential toes of WNW-dipping foreset laminae. The erosional top surface is the base of a set of trough cross bedding. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **C.** A set of giant-scale cross bedding 4 m thick with SE-dipping foreset laminae near Drábské Světničky (Příhrazy area). Note the slightly diagonal reactivation surfaces and a 20 cm thick lens with foreset laminae dipping very gently SE in upper part of the photo (arrows). Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **D.** A cross-bedded set near Studený průchod (Příhrazy area) with a scoured base and overturned foreset laminae in its upper part, probably due to the shear stress exerted by the bedload transport in its hangingwall. Lines of individual honeycomb pits follow the foreset laminae, thereby accentuating the primary sedimentary structure. Vertical dimension ~3 m. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **E.** Several sets of trough cross bedding SW of Příhrazy. The thickest set clearly shows the relationship between base scouring and reactivation surface formation. Foreset laminae of the thickest set dip WNW. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.
- **F.** A channel with gravelly fill cut into sandstones of the Hrubá Skála Quader (Teplice Formation) in the Zelený důl Valley, Klokočí Cliffs. Channel width ~2 m. Photo J. Adamovič.
- **G.** Convolute bedding in fine-grained sandstone, probably caused by water escaping from the sediment during its burial. Western face of Sokolka Hill SE of Příhrazy. Hrubá Skála Quader, Teplice Formation. Photo R. Mikuláš.
- **H.** Gravitationally induced soft-sediment deformation in medium-grained, cross-bedded sandstone in the Zelený důl Valley, Klokočí Cliffs. The conglomerate bed at top left can be traced along an inclined erosional surface to the bottom right (base marked by a dashed line). The displacement magnitude is about 2 m. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.


A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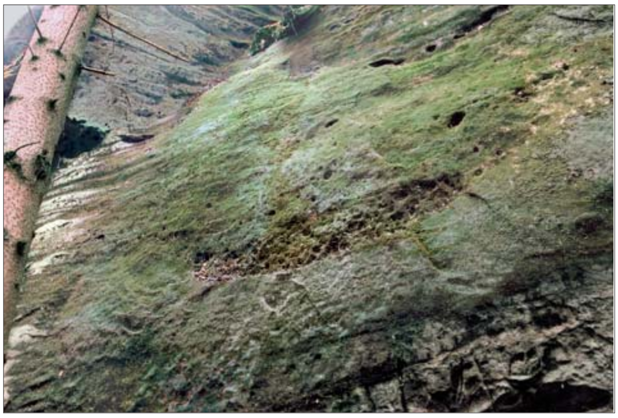
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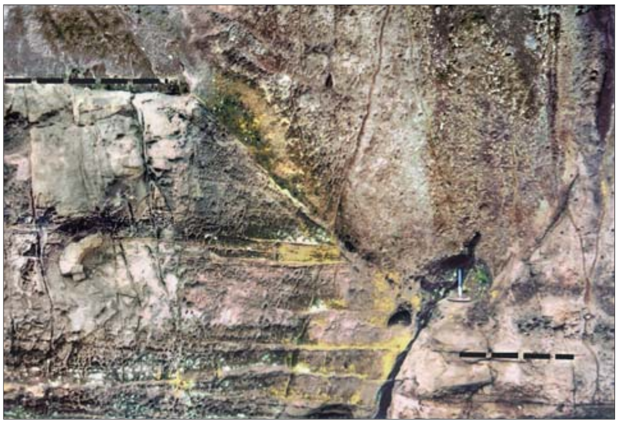
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Plate 3.
Biogenic sedimentary structures and fossils

- **A.** Large *Ophiomorpha–Thalassinoides* burrows in sandstones at Stará hrada near Příhrazy. Each of the several episodes of sea-level rise, which can be documented in the upper part of the Teplice Formation, was associated with a boom of organisms burrowing in the sea bottom. Small pits at top left are modern nesting tunnels literally bitten into the weakly consolidated sandstone by solitary bees. Photo J. Adamovič. For details see Mikuláš and Cílek (1998).
- **B.** Vertical burrows (mostly *Ophiomorpha*) decorating a flooding surface in the transgressive systems tract of the uppermost Teplice Formation near Vyskeř. Photo J. Adamovič.
- **C.** A view of the ceiling of a steep rock shelter showing the distribution of vertical shafts of the *Ophiomorpha* boxwork system. Lining of the shaft walls contain ferruginous pigment. Koník Cliff area, Betlém Cliffs. Teplice Formation. Photo R. Mikuláš.
- **D.** A near-vertical bedding plane with hematite pigment at Pantheon near Malá Skála, showing ichnofossils of *Planolites* isp. (straight to slightly curved tunnels, A) and a few fragments of the boxwork of *Thalassinoides* isp. (broad tunnels, B). Coin diameter 25 mm. Peruc–Korycany Formation. Photo J. Adamovič.
- **E.** A fossilized shell of the bivalve *Pinna* sp. in life position. Calcareous fine-grained sandstones of the Jizera Formation near Rakousy. Photo R. Mikuláš.
- **F.** Deep vertical to steeply inclined shaft of *Ophiomorpha* isp. Teplice Formation sandstones, Borek District. Scale bar is 5 cm. Photo L. Koptíková.

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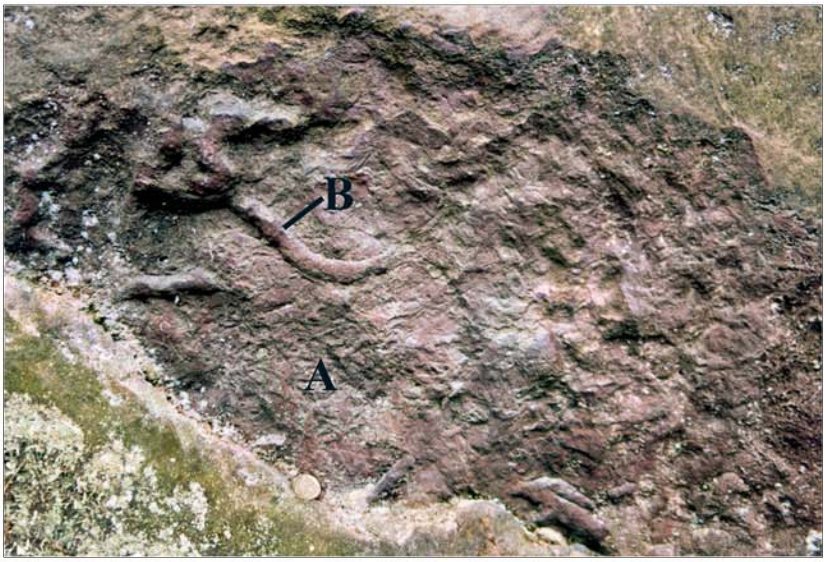

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Plate 4.
Tectonic features

- **A.** A belt of exposed Cenomanian sandstones stretches along the Lusatian Fault from NW to SE, forming a prominent crest in the Malá Skála area. Pantheon Cliffs (foreground) lie on the right bank of the Jizera River while the Suché skály Cliffs (background) lie on its left bank. The most prominent subvertical surfaces on the photo roughly correspond to bedding planes. Peruc–Korycany Formation. Photo J. Adamovič.
- **B.** Features of brittle deformation along the Lusatian Fault include transecting systems of deformation bands ("quartz veins", left) and zones of tectonic brecciation (centre). The origin of these phenomena was succeeded by massive silicification of sandstones near the fault. Suché skály Cliffs near Malá Skála, Peruc–Korycany Formation. Photo J. Adamovič.
- **C.** Sandstone massif west of Příhrazy dissected by an orthogonal system of tensional joints with prominent plume structures, arcuate ribs and hackle marks. Plume axes are mostly vertical, indicating progressive downward joint opening, but also horizontal. Železné věže (Iron Towers) site, Teplice Formation. Photo J. Adamovič.
- **D.** Fine, subhorizontal tectonic striae on a SE-dipping fault plane transverse to the course of the Lusatian Fault. They indicate largely lateral movement of blocks relative to each other. Suché skály Cliffs near Malá Skála, Peruc–Korycany Formation. Photo J. Adamovič.
- **E.** A block of Cenomanian (Peruc–Korycany Formation) sandstones on the SW slope of Kozákov Hill, in the proximity of the Lusatian Fault. Tectonic dip of the strata is ~20° to the SW. Photo R. Mikuláš.
- **F.** A well-developed plume structure on a joint at the entrance to Drábské Světničky (Příhrazy area). Curvature of arrest lines clearly indicates that the joint propagated in downward direction. Hrubá Skála Quader, Teplice Formation. Photo J. Adamovič.

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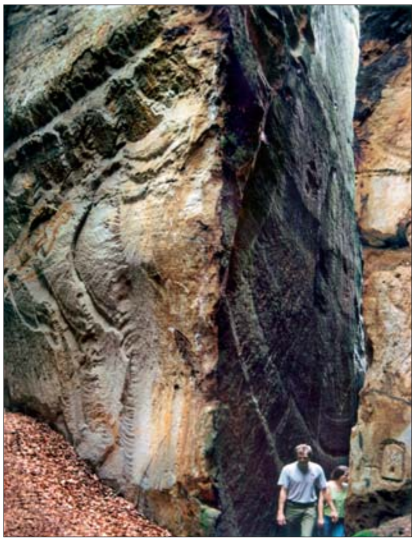

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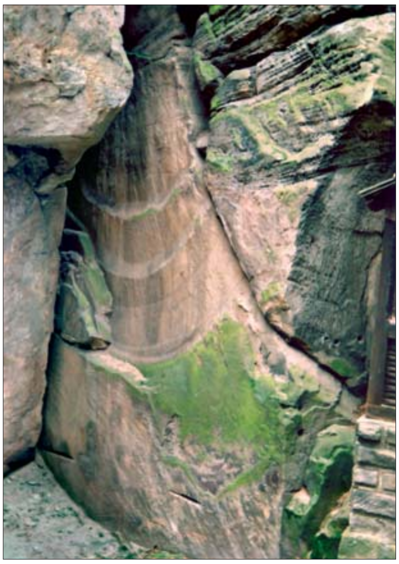

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Plate 5.
Deformation bands

- **A.** Broad deformation bands 2 m apart with less prominent splay deformation bands in *en échelon* arrangement and a dense network of short, transverse deformation bands. Zelený důl Valley in the Klokočí Cliffs, a view towards ESE. Photo J. Adamovič.
- **B.** A broad, NNW–SSE-striking deformation band on a horizontal rock surface. The accompanying pit karren are elongated parallel to incipient splay joints to the master structure. Betlém Cliffs. Photo J. Mertlík.
- **C.** A broad deformation band visible on a vertical cliff face. Note that honeycomb pits are practically missing on the surface of the broad band, although pit chains well accentuate other, minor deformation bands on the same cliff face. Zelený důl Valley in the Klokočí Cliffs. Photo J. Adamovič.
- **D.** A series of poorly cemented subparallel deformation bands gave rise to sharply incised wandkarren on a vertical cliff face. Koník Cliff area, Betlém Cliffs, a view towards SSE. Photo J. Adamovič.
- **E.** Branching, broad (3–5 cm) deformation bands on a horizontal rock surface. Betlém Cliffs, a view towards SSE. Photo J. Adamovič.
- **F.** Two intersecting systems of deformation bands below the Pětichlapka Pillar in the Zelený důl Valley, Klokočí Cliffs. Near-vertical bands dip NE, moderately inclined bands dip NNW. Note that the deformation bands are almost free of honeycomb pits. Photo J. Adamovič.
- **G.** A detail of the same cliff face showing the style of thinning-out of the deformation bands. Thinning of each band is associated with a micromorphological transition from a rib to a groove with a median keel, and finally to a groove with no continuous keel (bottom right). In the same direction, honeycombing becomes more prominent. Horizontal dimension 0.7 m. Photo J. Adamovič.
- **H.** A general view of the same site as in Photos F and G. In the area of the highest density of deformation bands, honeycombing is poorly developed, possibly as a result of stronger silica cementation. Coalesced, elongated pits form only in the zone where the deformation bands thin out and become imperceptible (bottom). Photo J. Adamovič.

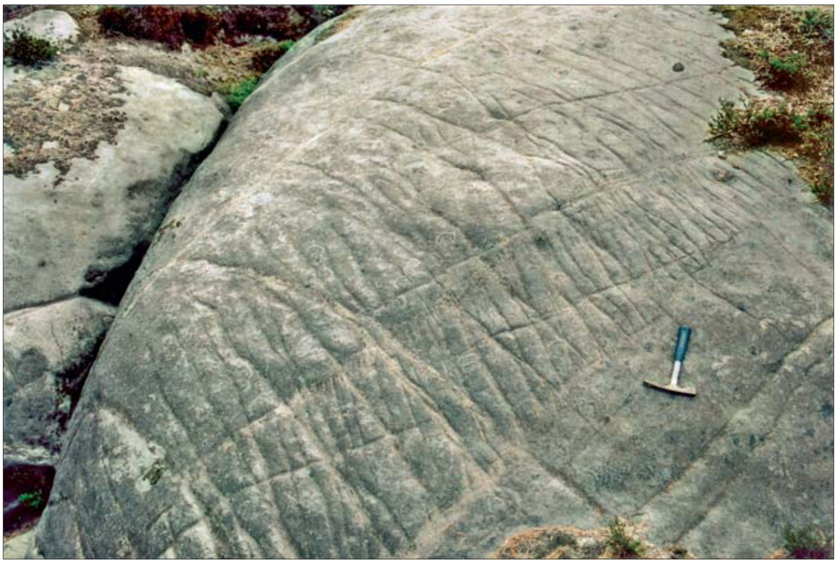

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Plate 6.
Sandstone cementation, concretions

- **A.** A rare example of clustered ellipsoidal ferruginous concretions in sandstones near the Král Cliff (King), Zbirohy rock city in the Sokol Hill District. Teplice Formation. Photo R. Mikuláš.
- **B.** A cross section of a large, elongated, multi-layered ferruginous concretion at Pantheon near Malá Skála. Peruc–Korycany Formation. Photo J. Adamovič.
- **C.** Patches of drab areas in sandstone with ferruginous pigment on top of the table mountain of Sokolka SE of Příhrazy. Teplice Formation. Photo J. Adamovič.
- **D.** The same effect as in Photo C but drab areas are of smaller extent. Iron oxyhydroxides removed from these areas accumulate on their edges, thereby forming simple concretions. Sokolka Hill, Teplice Formation. Photo J. Adamovič.
- **E.** A ferruginous concretion 45 mm in diameter. The drab centre of the concretion is poorer in iron than the host sandstone. Ferruginous concretions 10–20 mm in diameter, mostly lacking drab centres, are a typical feature in this area. Sokolka Hill, Teplice Formation. Photo J. Adamovič.
- **F.** Spherical calcareous concretions ca. 5 cm in diameter are developed in cliffs at Tachov near Trosky Hill. Calcium carbonate probably penetrated into the Teplice Formation sandstones from the overlying marlstones of the Březno Formation. Photo R. Mikuláš.
- **G.** A spherical cavity ca. 20 cm in size filled with friable sandstone probably formed from an earlier concretion by dissolution of carbonate or siliceous cement. A wall of a cave on a right tributary of the Zelený důl Valley, Klokočí Cliffs. Photo J. Mertlík.

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Plate 7.
Ferruginous cement in joint linings and laminae

- **A.** A NE–SW-striking joint filled with iron oxyhydroxides arranged into laminae several centimetres thick. Courses of the laminae document the flow direction of mineralizing fluids. Teplice Formation sandstones 1 km SW of Příhrazy. Photo J. Adamovič.
- **B.** A joint dipping SE with thick coating of iron oxyhydroxides passing downward into individual high-relief ferruginous laminae. Fluidal structure of the coating indicates the flow direction of mineralizing fluids. Same area as in Photo A. Photo J. Adamovič.
- **C.** An orthogonal system of tensional joints is developed in the area of Železné věže (Iron Towers) west of Příhrazy. Only joints striking NW–SE show rich ferruginous linings. A view towards WSW. Teplice Formation. Photo J. Adamovič.
- **D.** A photomicrograph of ferruginous sandstone of the Teplice Formation NW of Valdštejn, Hrubá Skála area. The pores in sandstone are almost completely filled with ferruginous cement, with isopachous arrangement of layers suggesting multiple episodes of fluid flow: pale bands are formed by goethite while darker bands are formed by goethite and kaolinite. Reflected light, the field in view is 0.2 mm long. Photo J. Adamovič.
- **E.** In the Borek District, ferruginous laminae can be observed on joint planes parallel to a basaltic dyke following the cuesta edge. Teplice Formation. Horizontal dimension ~2 m. Photo L. Koptíková.
- **F.** A WNW-dipping fault plane with a ferruginous coating up to 6 cm thick. Post-mineralization jointing produced a tile-like pattern on the crust (arrow). Peruc–Korycany Formation, Pantheon near Malá Skála. Photo J. Adamovič.

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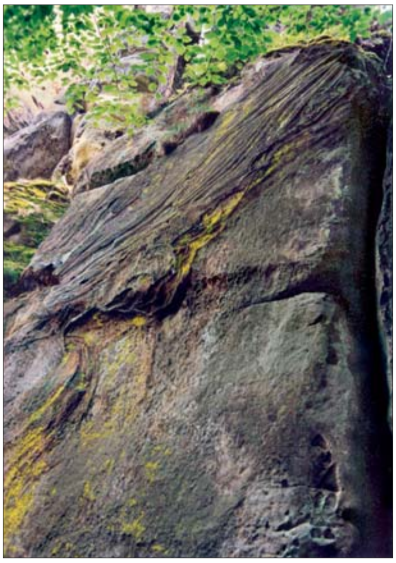

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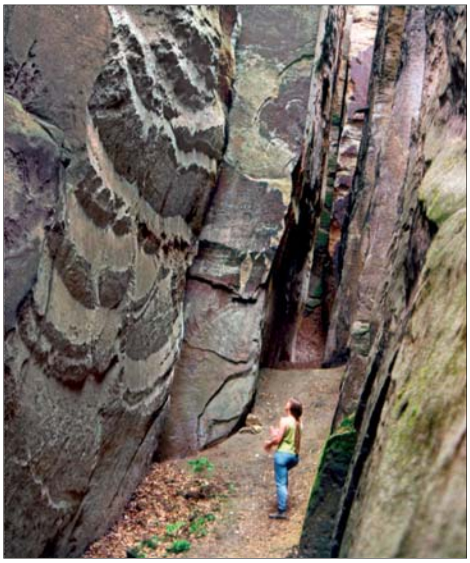

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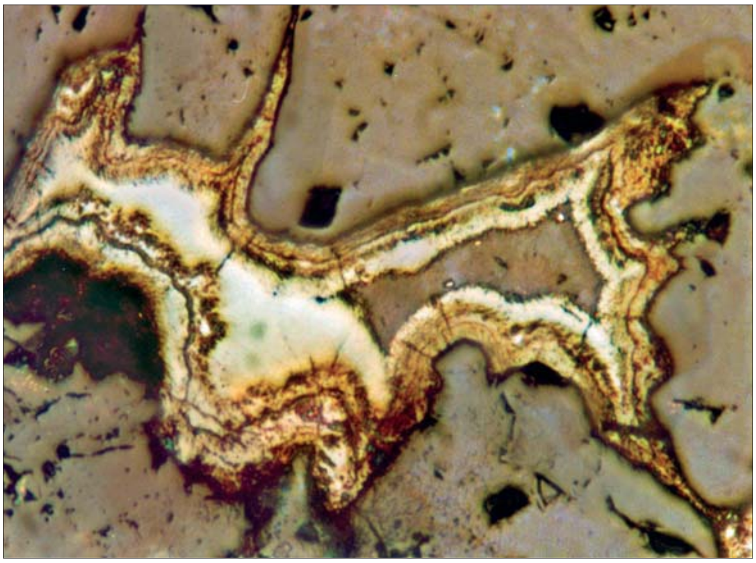

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Plate 8.
Rock cities, pillars

- **A.** The Prachov rock city is articulated by WNW–ESE-striking fracture zones giving rise to canyon-like valleys, and by transverse joints limiting the individual rock pillars. Another factor shaping rock microrelief is the horizontal stratification. A view from the Bohemian Paradise Viewpoint towards ENE. Teplice Formation. Photo J. Adamovič.
- **B.** The weak lithification of sandstones in the Apolena District produces rounded tops of rock pillars, free of vegetation. Honeycomb pits lined along bedding planes are the dominant microrelief element. Apollón (Apollo) Pillar in the central part of the rock city, Teplice Formation. Photo R. Mikuláš.
- **C.** A cliff face framing the gorge of Císařská chodba (Emperor Passage) in the Prachov rock city illustrates the elongation of the pillars in plan view and their shaping into a series of pinnacles in the top part. Photo J. Adamovič.
- **D.** Unlike those in the Prachov rock city, sandstone pillars in the Hrubá Skála rock city are regular in plan view. Dračí skály (Dragon Cliffs), viewed from the Chateau Viewpoint in this photo, are almost free of vegetation. The dominant microrelief elements are subhorizontal ledges and notches controlled by primary sedimentary structures. Teplice Formation. Photo J. Mertlík.
- **E.** The course of the Císařská chodba (Emperor Passage) in the Prachov rock city is controlled by a dense fracture zone striking WNW–ESE. Photo J. Adamovič.
- **F.** The steep Hlavní věž (Main Pillar) of the Suché skály Cliffs is formed by sandstones of the Peruc–Korycany Formation in a steeply tilted tectonic block near the Lusatian Fault. Sharp morphologies of the Suché skály are determined by strong lithification and silica cementation of the sandstones. Photo J. Adamovič.
- **G.** The Hrubá Skála rock city is an example of mature stage of sandstone relief development. Some of the pillars are completely isolated, other are detached from clifflines of buttes covered with vegetation. The Kapelník (Bandmaster) group 2 km NW of Hrubá Skála. Teplice Formation. Photo J. Adamovič.


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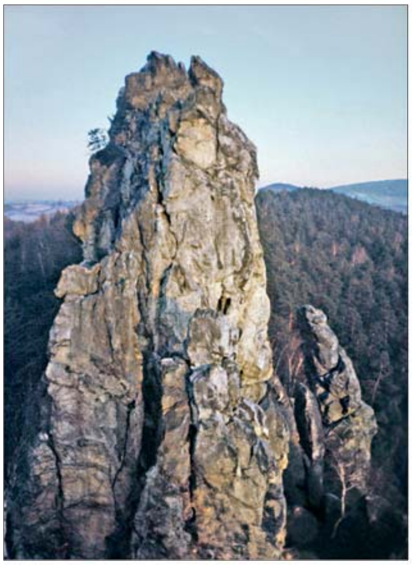
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Plate 9.
Mushroom rocks, rock windows and arches

- **A.** The base of the mushroom rock called Džbán (Jug) on the rim of the Klokočí Cuesta is developed at the level of closely spaced bedding planes (clinoforms). Teplice Formation. Photo R. Mikuláš.
- **B.** A mushroom rock 200 m north of the Drábovna Castle. Height 3.8 m. Teplice Formation, Drábovna District. Photo J. Adamovič.
- **C.** A mushroom rock on a crest 100 m west of the Drábovna Castle. Height 2 m. Stems of mushroom rocks in this area lie at a level of prominent cavernous weathering. Teplice Formation, Drábovna District. Photo J. Adamovič.
- **D.** An arch supported by three abutments in the upper reach of the Zelený důl Valley. Teplice Formation, Klokočí Cliffs. Photo J. Adamovič.
- **E.** A prominent false arch near Žehrov east of Příhrazy formed by slippage of a rock pillar from the cliff face. Teplice Formation. Photo J. Mertlík.
- **F.** A rock window near the plateau edge SW of Příhrazy cut in the Teplice Formation sandstones. Its position on a marked tourist path results in undesirable anthropogenic modelling of its floor. Photo J. Adamovič.
- **G.** Soft sandstones of the Apolena District are particularly prone to erosion, thus forming a variety of rock shelters, rock windows and arches. This arch is developed on the slope of one of the side valleys. Teplice Formation. Photo R. Mikuláš.

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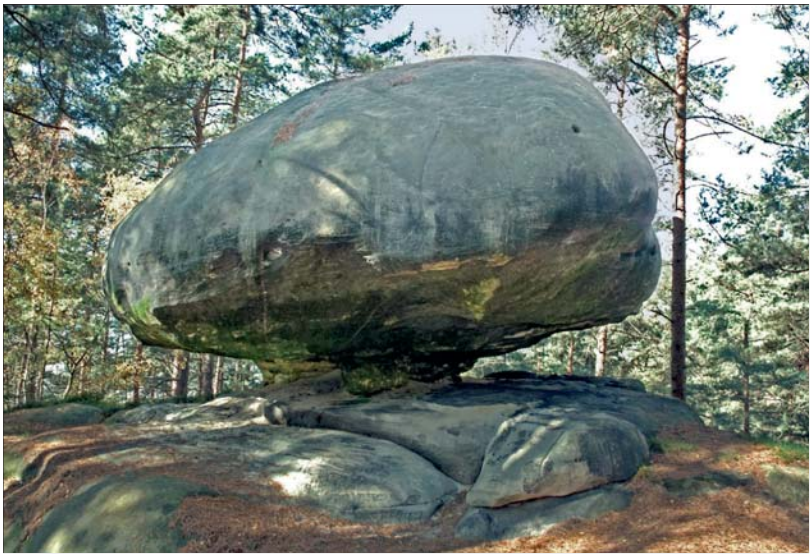

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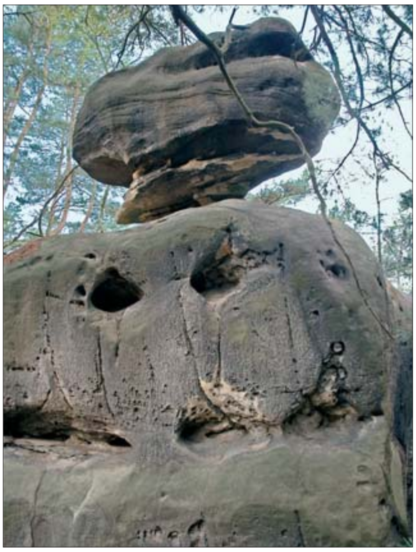

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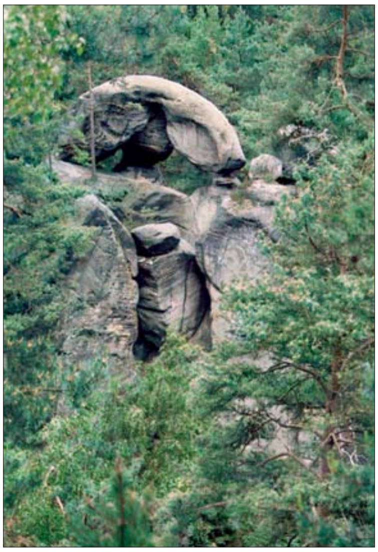

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Plate 10.
Caves and rock shelters

- **A.** A view through a horizontal passage of a strata-bound cave across a densely fractured zone. The circular end of the passage (centre) shows a vertical section across bedding planes accentuated by ferruginous pigment. Horizontal dimension 2 m. Betlém Cliffs, Teplice Formation. Photo J. Mertlík.
- **B.** A large rock shelter formed in the weakly lithified Teplice Formation sandstones in the Apolena District. Height of the rock shelter 2.5 m. Photo R. Mikuláš.
- **C.** On the Klokočí cuesta, caves often have circular entrances and concentrate to a level of ca. 15 m below the cuesta edge. The striated and polished surfaces in cave interiors may suggest the existence of a very flat thrust fault at this level (Mertlík and Adamovič 2005). Tunnel diameter 1.2 m. Right tributary of the Zelený důl Valley near Rozumov. Teplice Formation. Photo J. Mertlík.
- **D.** Interior of the largest cave in the Bohemian Paradise: the Postojná Cave. This strata-bound cave has a total length of 75 m and is the only large cave located on a marked tourist path. Height of ceiling 3 m. Klokočí Cliffs. Photo J. Mertlík.
- **E.** The entrance to the Svojsík Cave decorated by sets of radiating deformation bands. This strata-bound cave is about 20 m long and extends to the other side of a sandstone crest lying between two tributaries of the Zelený důl Valley. Teplice Formation, Klokočí Cliffs. Photo J. Adamovič.
- **F.** Entrance to a cave of a straight tunnel shape in the Zelený důl Valley. Its origin can be explained by dissolution of cement in the sandstone. Cave entrance 0.8 m in width. Teplice Formation, Klokočí Cliffs. Photo R. Mikuláš.

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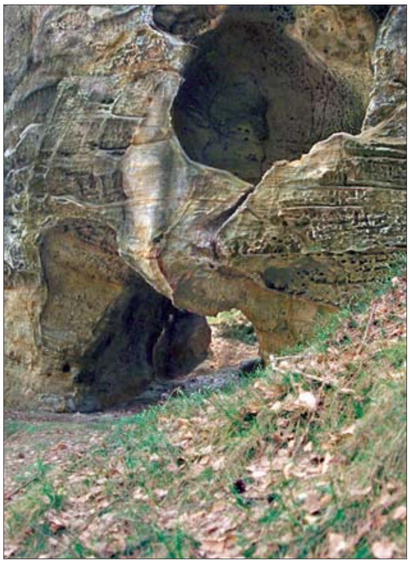

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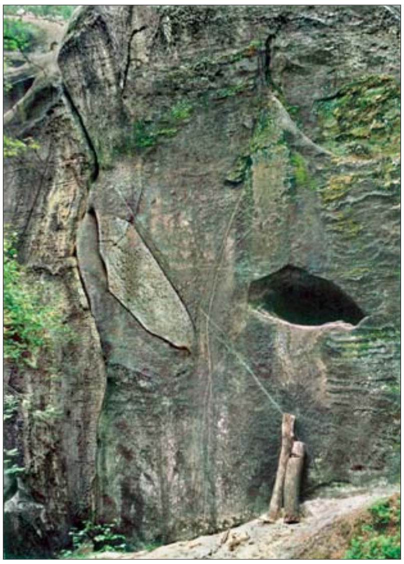

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Plate 11.
Karren, inclined ledges

- **A.** Irregular rillenkarren, max. 60 cm in height, on top of the sandstone elevation of Stará Hrada are similar to those in other sandstone areas in Bohemia. Teplice Formation, Příhrazy area. Photo J. Mertlík.
- **B.** A vertical groove produced by a once growing tree on Křížové věže (Cross Pillars) near Příhrazy. The absence of a rock crust on its walls indicates a very young age for the groove. Teplice Formation. Photo J. Mertlík.
- **C.** A system of closely spaced wandkarren on a vertical cliff face in the Apolena District near Svitačka. Honeycomb pits corresponding to karren width in their diameter are present at intersections with prominent bedding planes. Larger pits, several karren widths in diameter, were probably formed by fusion of neighbouring honeycomb pits. Teplice Formation. Photo R. Mikuláš.
- **D.** Incipient wandkarren on a steep face in the head of the Klokočí cuesta. The karren were shaped by water dripping from the overhanging rock above. Teplice Formation, Klokočí Cliffs. Photo J. Adamovič.
- **E.** Fully developed wandkarren formed by episodic downward movement of surface water and its evaporation. The concentration of circular honeycomb pits above the prominent subhorizontal notch is probably connected with permanently higher influx and evaporation of water. At this site, wandkarren combine with deeply incised grooves of deformation bands. Teplice Formation, Klokočí Cliffs. Horizontal dimension approx. 3 m. Photo R. Mikuláš.
- **F.** Inclined ledges form at places where soil borders on steep sandstone cliff faces unprotected by rock crusts. This is a process opposite to the formation of solution notches in limestones and granites. An incipient ledge (arrows) is currently developing at this site in the Svitačka area, Apolena District. Teplice Formation. Photo R. Mikuláš.
- **G.** A prominent inclined ledge beneath the Hrubá Skála Chateau. Teplice Formation. Photo R. Mikuláš.

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Plate 12.
Typology of honeycomb pits

- **A.** A honeycombed cliff face in weakly lithified Teplice Formation sandstones in the Apolena District. Series of honeycomb pits generally follow bedding planes. The pits are mostly rhombic in shape, with only rarely developed bottoms. Horizontal dimension 2 m. Photo R. Mikuláš.
- **B.** A blind arch developed in the Teplice Formation sandstones of the Betlém Cliffs. Large honeycomb pits, normally circular in shape, become ellipsoidal on the supporting abutments. Long axes of the ellipsoids are aligned parallel to stress trajectories. Horizontal dimension 3 m. Photo R. Mikuláš.
- **C.** A solitary spherical cavity 15 cm in diameter, probably produced by removal of the inner part of a concretion, contrasts with the ambient circular to arcuate honeycomb pits in various stages of degradation. Teplice Formation. Zbirohy rock city near the Král (King) Cliff, Sokol Hill District. Photo R. Mikuláš.
- **D.** Reticular honeycomb pits passing into cellular pits (top) and solitary arcuate pits (below). All honeycomb pits tend to form horizontal bottoms despite the inclined bedding planes. Teplice Formation sandstones near Studený průchod, Příhrazy area. Photo J. Adamovič.
- **E.** A vertical cliff face at a site where a fissure surface was recently exposed by rockfall (far right). The fissure surface was covered by a rock crust and lacks prominent microforms due to stable humidity and temperature and low evaporation. On the other hand, the rest of the face (centre and left) shows a network of irregular ribs as remains of the original honeycombs. Spherical and arcuate honeycomb pits are well preserved in the narrow transitional zone. Teplice Formation, Zelený důl Valley in the Klokočí Cliffs. Horizontal dimension approx. 0.5 m. Photo R. Mikuláš.
- **F.** A series of flat-bottomed arcuate honeycomb pits following a softer bed in sandstone. The dip of the bed is responsible for the staircase-like pattern. Teplice Formation, Betlém Cliffs. Size of the view ca. 0.4 × 0.5 m. Photo R. Mikuláš.
- **G.** Weathering of a cliff face formerly covered with a rock crust. Rock crusts lining the inner surfaces of honeycomb pits now form bubble- and ring-shaped forms. Teplice Formation, Klokočí Cliffs. Horizontal dimension ~0.6 m. Photo R. Mikuláš.
- **H.** Weathering of a spherical rock crust formed inside honeycomb pits, creating specific bubble-shaped forms. Teplice Formation sandstones below the Pětichlapka Pillar, Klokočí Cliffs. Horizontal dimension approx. 0.6 m. Photo R. Mikuláš.

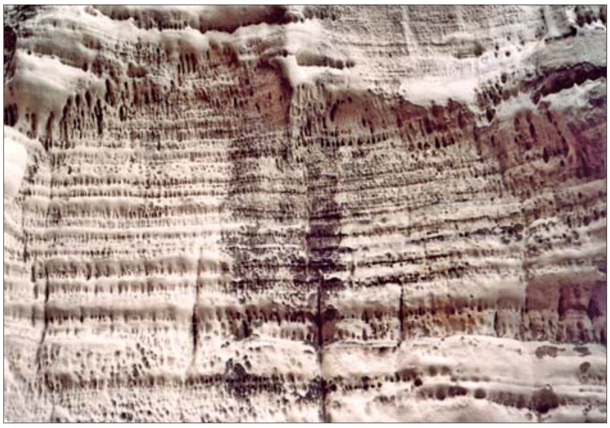
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Plate 13.
Pitted surfaces – distribution controls

- **A.** Flat-bottomed honeycomb pits with extremely low height/width ratios. On bedding planes, the pits occasionally coalesce to form subhorizontal notches on the cliff face. Vertical dimension ~0.8 m. Peruc–Korycany Formation, NW part of the Kozákov Hill District. Photo R. Mikuláš.
- **B.** Honeycombs are poorly developed on a sloping wall (lower part of cliff face) where salts are washed from the sediment and no salt weathering occurs. In contrast, dense honeycombing is developed on vertical walls. An incipient inclined ledge is present just above the cliff base (as in Plate 11F), documenting a recent sinking of the land surface. Teplice Formation, Apolena District near Svitačka. Photo R. Mikuláš.
- **C.** In the area SW of Příhrazy, the distribution of small circular honeycomb pits is normally controlled by primary sedimentary structures (left). In the brownish area on the right, a ferruginous coating prevents honeycomb formation, and inhomogeneities of rock surface related to oblique fluidal structures are the only microrelief elements. Where the ferruginous coating gets thinner (bottom), honeycomb pits are present, aligned parallel to the fluidal structures. Teplice Formation. Photo J. Adamovič.
- **D.** Type of honeycombing inside a cavity in sandstone. Long axes of the pits are deviated from vertical direction depending on the stress distribution pattern in peripheral parts of the cavity. The pits have no bottoms as they are developed on a strongly overhanging surface. Horizontal dimension ca. 1 m. Teplice Formation. Údolíčka, Příhrazy area. Photo J. Mertlík.
- **E.** Small, roughly circular honeycomb pits are strictly confined to deformation bands in otherwise strongly lithified Teplice Formation sandstone. Head of the cuesta, Klokočí Cliffs. Horizontal dimension approx. 0.4 m. Photo R. Mikuláš.
- **F.** The presence of honeycomb pits inside man-made niches (probably excavated in late medieval times) documents the relatively short time needed for their formation. The pits are generally aligned parallel to the dip of strata. Teplice Formation. Myší díra (Mousehole) near the Hrubá Skála Chateau. Horizontal dimension approx. 0.5 m. Photo R. Mikuláš.

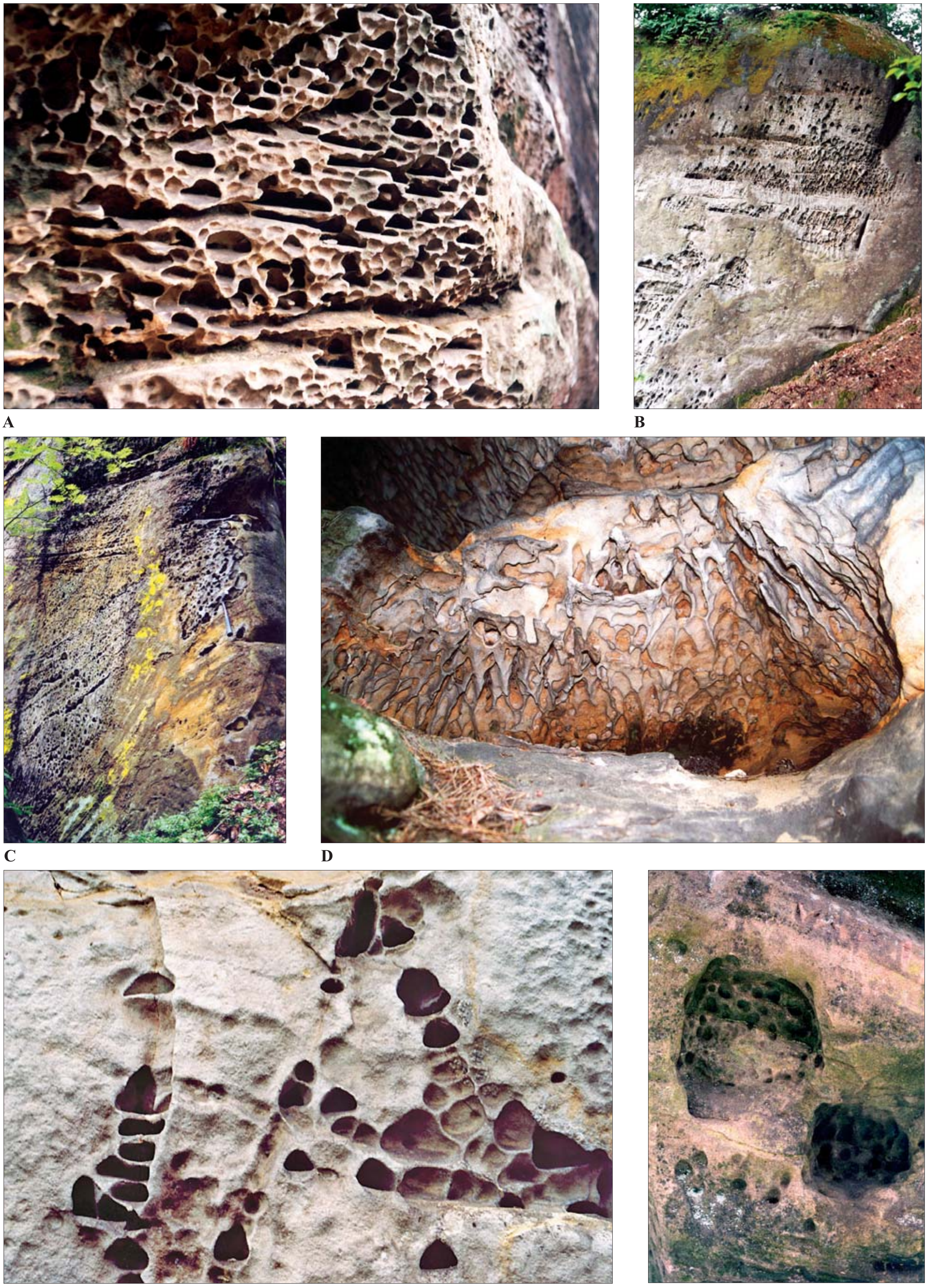

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Plate 14.
Surface hardening

- **A.** An almost completely destroyed rock crust, preserved only in the most distal parts of honeycomb pits. The crust relicts form isolated “ears”. Teplice Formation, Borek District. Horizontal dimension ca. 1 m. Photo R. Mikuláš.
- **B.** The rate of erosion is much slower on open cliff faces, if protected by rock crusts (top), than beneath the soil cover (bottom). This difference is well illustrated at this site, where accidental stripping of soil (tree uprooting) exposed a solution notch below the former land surface. Teplice Formation. Zelený důl Valley, Klokočí Cliffs. Vertical dimension approx. 1.2 m. Photo R. Mikuláš.
- **C.** These fractures in a rock crust in the Zelený důl Valley, Klokočí Cliffs, differ from the usual polygonal tessellation in their radial arrangement, and possibly represent a partly faded impact trace (blow by a falling tree?). Teplice Formation. Horizontal dimension ca. 1 m. Photo R. Mikuláš.
- **D.** Sporadic remains of a rock crust, now preserved mostly on the inner walls of honeycombs. Formation and destruction of rock crusts is a very rapid phenomenon (centuries for the whole cycle) on lower cliff portions in the Měsíční údolí (Moon Valley), Kozákov Hill District. Peruc–Korycany Formation. Horizontal dimension ca. 0.8 m. Photo R. Mikuláš.
- **E.** At least three generations of rock crusts have been preserved in a rock shelter on the southern foot of Sokolka Hill SE of Příhrazy. The oldest, platy crusts preceding rock-shelter formation are preserved in only small relicts on the outermost part of the cliff face. Teplice Formation. Horizontal dimension ca. 2 m. Photo J. Adamovič.
- **F.** A vertical cliff face at Sokolka Hill is covered by a continuous rock crust passing upwards into a patchy crust. The topmost patches of the crust lie only 1 m below the upper cliff edge. Note the presence of a drainage runnel for runoff water (arrow). Visible cliff height 5 m. Photo J. Adamovič.

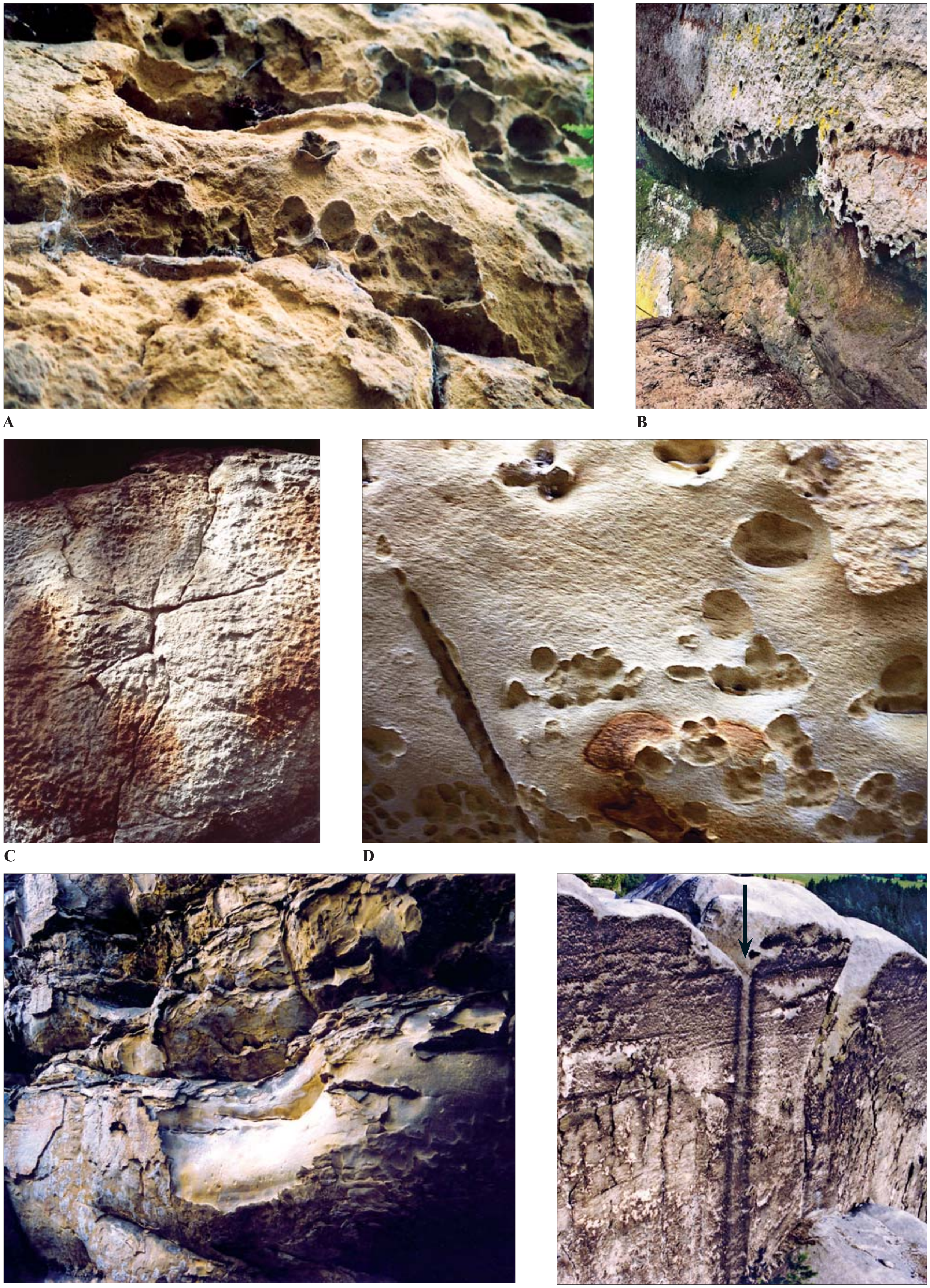

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Plate 15.
Volcanic bodies

- **A.** A colonnade of Pliocene basanite lava flow in a quarry at Smrčí. Northern slope of Kozákov Hill. Photo J. Adamovič.
- **B.** A NE–SW-elongated body of basaltic volcanic breccia is exposed in a small quarry 300 m south of the Frýdštejn Castle, in the Lusatian Fault zone. Note the abundant xenolithic material of Cretaceous claystones and marlstones. Photo J. Adamovič.
- **C.** Panna (Virgin) is one of the two basanite spires supporting the ruins of the medieval Trosky Castle. The two spires are separate stocks or remains of a subvertical dyke, with imperfectly developed columnar jointing. Flanks of the spires, on the other hand, show structures typical of spatter cones (V. Cajz, pers. comm.). Photo M. Adamovičová.
- **D.** A basanitic intrusive complex was exhumed in the Střeleč sand pit SE of Trosky Hill in 1999. It consists of an E–W-striking dyke, a discontinuous sill, and a stock ca. 15 m in diameter. All intrusive bodies are lined with iron oxyhydroxides. The site has been subjected to quarrying and reclamation since the photograph has been taken. Photo J. Adamovič, October 1999.
- **E.** A view of the basanitic stock exposed in the Střeleč sand pit in 1999. Lighter spots in the basanite are xenoliths of sandstone. Photo J. Adamovič.
- **F.** A detail of a sandstone xenolith in the basanite stock in Photo E. Note the columnar jointing produced by the effect of heating/cooling of the clast. Photo J. Adamovič.

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Plate 16.
Sandstone utilization

- **A.** The complex of seven sandstone pillars known as Drábské Světničky bears a number of artificially excavated chambers. These adaptations date to around 1430 when the pillars supported a timber-made castle. Northern rim of the Mužský Hill plateau near Příhrazy. Photo R. Mikuláš.
- **B.** The statue of St. Procopius in the valley north of the Hrubá Skála Chateau is an example of Baroque art spread outside human settlements. Photo V. Cílek.
- **C.** A relief with a horseshoe, a hammer and pliers carved in sandstone near Příhrazy, by an unknown person. The latter half of the 19th century witnessed rapidly developing tourism in the area. It was also the period when the designation "Bohemian Paradise" started to be used for the land between the Krkonoše Mts. and the Jizera River. Photo R. Mikuláš.
- **D.** Weakly lithified sandstones often become targets for rural-art sculptors. The photo shows one of the multiple carvings in sandstone in the vicinity of the Kopic Farm west of Hrubá Skála. They were made by Vojtěch Kopic, a former farm owner in the mid-20th century. Photo R. Mikuláš.
- **E.** Traces after millstone shaping (arrows) on cliffs at the head of the Klokočí cuesta. Klokočí Cliffs. Photo J. Adamovič.
- **F.** Sandstone used for Gothic masonry at the Kumburk Castle NE of Jičín. Note the surface hardening on the circumference of ashlars and honeycombing. Photo V. Cílek.

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