The Kokořín Area: Sandstone Landforms Controlled by Hydrothermal Ferruginization

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Abstract

The area between the Jizera and Elbe rivers in north-central Bohemia features a southerly dipping package of sedimentary rocks of Cretaceous age, subjected to modest uplift throughout the Quaternary. The Kokořín sandstone (Middle to Upper Turonian) comprises five superimposed bodies with generally high permeability and low-to-medium resistance to weathering. Most valleys are dry, shaped by occasional flash floods and gravitational processes. Disintegration of vertical cliff faces is dominated by salt weathering. Specific landforms develop on sandstones cemented by iron oxyhydroxides of hydrothermal origin. These form thin (centimetres to metres), sheet-like bodies, either subvertical or bedding-parallel, and give rise to structural plateaus and mesas, steep erosional ridges and mushroom rocks. The variety of small-scale relief forms on ferruginous sandstone is unique at a global scale. The highest elevations in the landscape are formed by exhumed subvolcanic bodies. The Kokořín Area is a perfect example of a sandstone-dominated erosional landscape whose high relief complexity is largely due to the contrasting resistance of rocks to weathering.

Keywords

Kokořín area • Cretaceous sandstones • Landforms • Hydrothermal activity • Ferruginization

13.1 Introduction

Kokořínsko (Kokořín area) is the area of excellent sandstone exposure between the towns of Mělník and Česká Lípa to the north of Prague. Its name is derived from the name of the Kokořín Castle, a historical landmark founded above the stream of Pšovka in the thirteenth century. The extent of the Kokořín area tends to be synonymized with the limits of the Kokořínsko Protected Landscape Area (PLA), established in 1976 with the aim of conservation of unique geomorphological features, flora and fauna. The Kokořín area covered by this contribution is best characterized as the Kokořínsko PLA area before its 2014 expansion to the northeast. South of Dubá, it includes the basins of the southerly flowing streams of Pšovka and Liběchovka. In the north, areas of vast sandstone exposure form a divide between the Obrtka flowing to the Elbe River (=Labe in Czech) and the Robečský potok flowing north, to the river of Ploučnice. Most of the valleys are dry, lying well above the present groundwater table. In the geomorphological subdivision of Bohemia, the whole Kokořín area belongs to the unit of the Ralská pahorkatina, subunit of the Dokeská pahorkatina and the district of the Polomené hory (Balatka and Kalvoda 2006). In the southeast, the rugged relief passes to the flat, gently sloping unit of the Jizerská tabule Table. The altitudes range between 160 m in the Liběchovka valley and 614 m at Vlhošť Hill (Balatka and Sládek 1981), the average annual temperatures are 7–8.5 °C, and the annual precipitations are 480–680 mm (Mikuláš et al. 2007).

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The Kokořín area lies in the central part of the Bohemian Cretaceous Basin, the sedimentary fill of which has been subjected to several episodes of tectonic deformation, emplacement of volcanic rocks, and hydrothermal activity. In quartzose sandstones, circulation of hydrothermal fluids resulted in a localized dissolution of quartz grains and re-precipitation of silica in the inter-granular space, known as *silicification*. Even more notable are the effects of *ferruginization*: introduction of ferrous iron by fluids from deep-reaching convective cells and its precipitation in the form of iron oxyhydroxides. The importance of ferruginization and silicification of Cretaceous sandstones for the landscape evolution in the Kokořín area has been recognized already by Bruno Müller who published a classical paper on this subject almost 90 years ago (Müller 1928).

13.2 Geological Background

13.2.1 Cretaceous Sandstones

The floor of the Bohemian Cretaceous Basin actively subsided in the Cenomanian to Santonian (ca. 97–84 Ma) to allow deposition of a sediment pile >1000 m in thickness, mostly in a shallow marine setting (e.g., Uličný et al. 2009). Coarse detrital material was supplied to the basin from the north, where crustal blocks dominated by granitic plutons were constantly rising along faults of the Elbe Zone. This paleotectonic situation produced a series of sand-dominated wedges reaching from the northern basin margin to its axial part. Geometries of these wedges were controlled primarily by sea-level fluctuations of either eustatic or tectonic origin.

The Kokořín sandstone, outcropping in the wide region between the Jizera and Elbe rivers in north-central Bohemia, occupies a distal part of a clastic wedge protruding towards the southeast along the axis between Blíževedly and Mšeno (Fig. 13.1). This wedge is ranked within the basin-wide Jizera Formation sensu Čech et al. (1980) whose age is Middle to Upper Turonian based on fossil fauna (ca. 92–89 Ma). The Kokořín sandstone consists of five superimposed sandstone bodies generally coarsening from base to top, each of them 30–80 m thick (Fig. 13.2). The bases of the bodies consist of fine-grained silty sandstone, mostly bioturbated, deposited in lower shoreface conditions (depths 30–40 m). Middle and upper parts of the bodies consist of medium- to coarse-grained sandstones with trough cross-bedding and other sedimentary structures indicative of deposition in upper shoreface conditions (depths 5–30 m). Beds of gravelly sandstone and conglomerate, deposited on gravelly beaches, form the very tops of the bodies but may equally occur on tops of lower-order upward-coarsening cycles within each body (Adamovič 1994). Over 90–95 % of the sandstone is composed of quartz, 1–3 % is feldspar, <1 % is glauconite. The sandstone also contains a variable amount of kaolinite. No pervasive mineral cement is usually present, and the strength of the sandstone is rendered by the packing of quartz grains due to sediment compaction, and by poor quartz cement at points of mutual grain contact. The overall thickness of the Kokořín sandstone package is 230 m in its axial part.

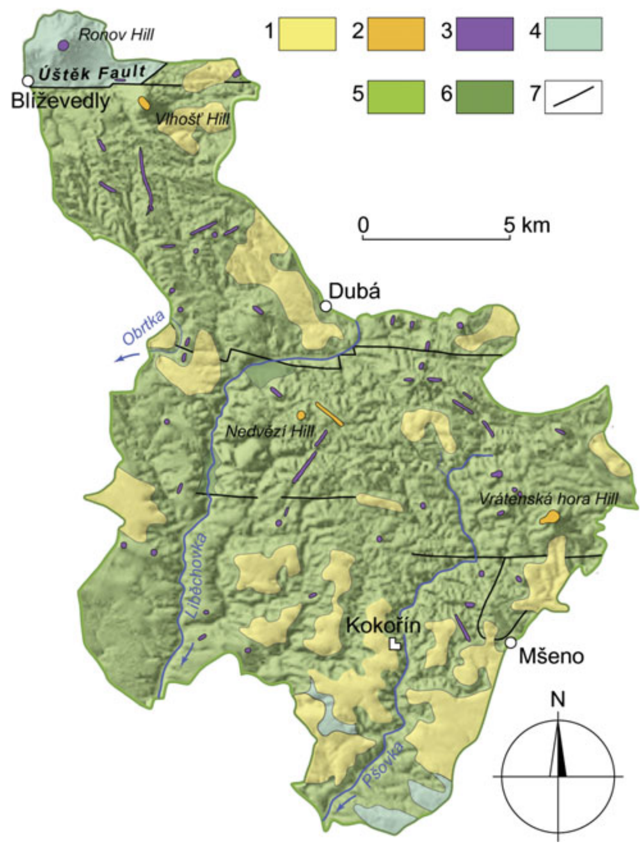

Fig. 13.1 Geology of the Kokořín area on a shaded relief map. Quaternary: *1* loess and loess loam; Tertiary: *2* trachyte and phonolite, *3* basalt; Mesozoic, Upper Cretaceous: *4* marlstone (Upper Turonian to Coniacian), *5* sandstone (Middle to Upper Turonian), *6* calcareous siltstone (Lower to Middle Turonian); *7* prominent faults. Shaded relief: Czech Institute of Geodesy and Cadastre, www.cuzk.cz

13.2.2 Tertiary Volcanics

Magmatic activity in the Kokořín area was related with crustal relaxation and formation of the Ohře Rift graben in the Late Eocene to Early Miocene (ca. 35–20 Ma; Adamovič and Coubal 1999; Ulrych et al. 2011). Phonolitic and basaltic magmas were emplaced almost simultaneously, as suggested by sparse radiometric data. Phonolites typically form laccoliths (Vrátenská hora) or plugs (Nedvězí and Vlhošť hills), surrounded by smaller basaltic dykes. Two basaltic intrusive centres with a number of plugs, dykes and

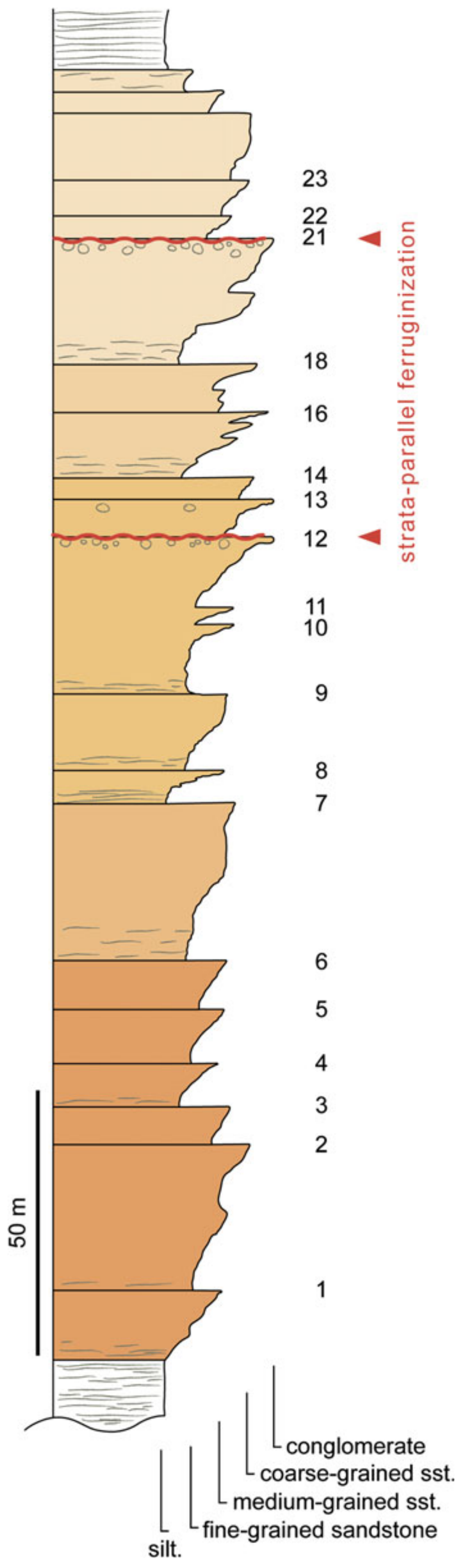

Fig. 13.2 Vertical section of the Jizera Formation in the axial part of the Kokořín sandstone body NW of Kokořín, showing the most complete succession of superimposed sandstone units. Numbers 1–23 denote the upward-coarsening cycles, each of the five sandstone units (higher-order cycles) are marked in different colours. Positions of beds usually cemented by iron oxyhydroxides are marked by arrows

bodies of intrusive breccia lie to the SE of Dubá (Houska and Beškov) but thinner (<1 m) basaltic dykes are scattered throughout the whole area. No superficial volcanic products have been reported from the Kokořín area yet.

Smaller intrusive bodies became subjected to hydrothermal alteration (kaolinization) immediately following their emplacement and produce no prominent landforms. On the other hand, large bodies are responsible for the origin of basaltic necks with more-or-less circular bases, rising 30–120 m above the surrounding sandstone plateaus. The most important of these hills are Lipový kopec (471 m), Kuželík (482 m) and Zámecký vrch (432 m) SE of Blatce, Velký Beškovský kopec (474 m) and Korecký vrch (465 m) SE of Dubá, and Ronov (552 m). Basaltic dyke swarms typically give rise to elongated hills and ridges like Supí hora (434 m), Dubová hora (397 m) and Kostelec (433 m). Phonolitic bodies tend to produce large, symmetrical cupola-form hills with radial valley patterns independent of the local tectonic setting: Vrátenská hora (508 m), Nedvězí (458 m), and Vlhošť (614 m)—the highest peak in the area. For the locations of the hills, see Figs. 13.1, 13.7 and 13.8.

The interaction between alkaline magma and water-saturated porous host rock is generally associated with a number of phenomena, most of which are well documented in outcrops in the Kokořín area. These include various thermal effects associated with the origin of columnar jointing in host sandstone (Fig. 13.3), deformation bands due to shear stress produced by penetrating magma, chemical corrosion of quartz grains and subsequent silica re-precipitation in inter-granular spaces. Especially, the redistribution of silica has a great impact on the development of sandstone macro- and microrelief at a local scale. Even more important in this respect are the processes of syn-magmatic and early post-magmatic ferruginization, covered in Sect. 13.3.

13.2.3 Tectonic Setting

Since its deposition, sedimentary fill of the Bohemian Cretaceous Basin has been affected by several paleostress fields of compressive or tensional character (Coubal et al. 2015). By effect of these stresses, the body of the Kokořín sandstone became segmented into separate tectonic blocks, and magma ascent was permitted along tensional fractures. Tectonic dips of strata of 2–3° towards the south are observed in the northern part of the area; these are interpreted as a result of the oldest stage of ductile deformation which took place in the latest Cretaceous times (Coubal and Klein 1992). Analogous dips of ca. 1° towards the south-southwest are common in the southern part of the area, although these may locally reach as much as 4° due to subsequent strike-slip movement along faults NNE–SSW and NW–SE and the related rotation of

Fig. 13.3 Columnar-jointed sandstone in the proximity of a basaltic dyke at Čířhill SW of Dřevčice (*Photo* J. Adamovič)

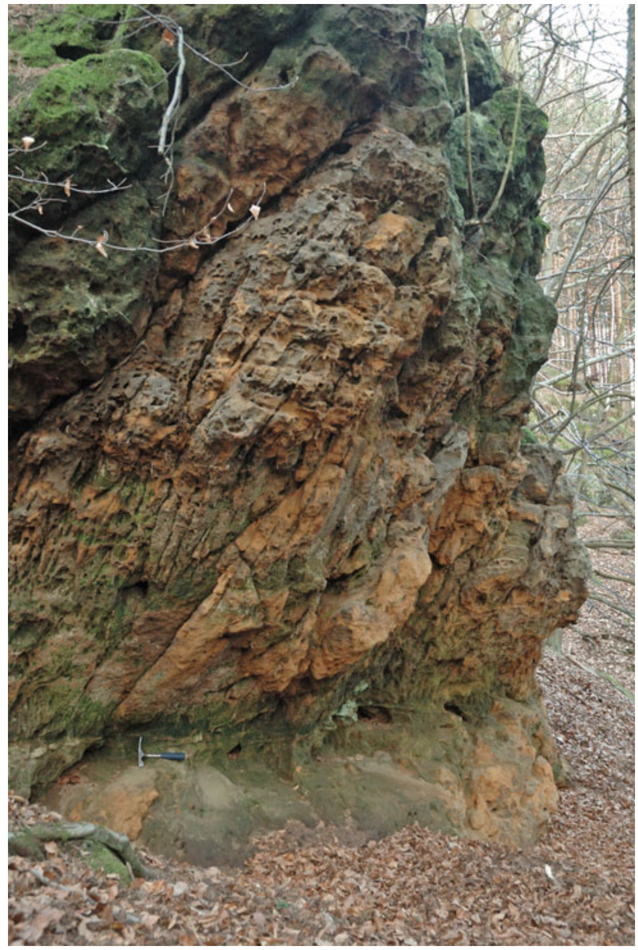

Fig. 13.4 A dense fracture zone accompanying a bedding-plane slip fault in Černý důl Valley W of Vrátenská hora (*Photo* J. Adamovič)

smaller (ca. 1.5 by 1.5 km) tectonic blocks. Steeply and moderately dipping dense fracture zones are very typical for sandstones in the Kokořín area (Fig. 13.4); they accompany minor thrust faults and bedding-plane slip faults (Adamovič and Coubal 2012).

The most intensive faulting in the Kokořín area took place during the period of crustal relaxation and rifting in the Late Eocene to Early Miocene. The southern marginal fault of the Ohře Rift graben, locally called the Úštěk Fault, transects the northernmost part of the Kokořín area. The subsided northern block with Ronov Hill (a throw of ca. 400 m) exposes Upper Turonian to Coniacian siltstones with thin sandstone intercalations, building a flat landscape completely different from that in most of the Kokořín area. Minor shear faults of the Úštěk Fault zone cut the Kokořín sandstone in the slopes of Vlhošť Hill and display silicified, polished and striated fault planes.

13.3 Ferruginization Process

In bodies of ferruginous sandstone, cement fills all voids in the rock. It is composed mostly of goethite (α-FeOOH), less commonly with some proportion of lepidocrocite (γ-FeOOH) or hematite (α-Fe_2O_3). Three different morphological types of bodies of ferruginous sandstone are distinguished in the Kokořín area (Fig. 13.5):

- Subvertical planar bodies, mostly developed as fillings of open joints and faults. As revealed by geological survey, such fractures almost invariably intersect a body of volcanic rock further along their strike in the Kokořín area (Adamovič et al. 2001). Where developed at the very contact with a basaltic dyke, the layer of ferruginous sandstone passes directly to a layer of hard, ferruginized basaltic rock.

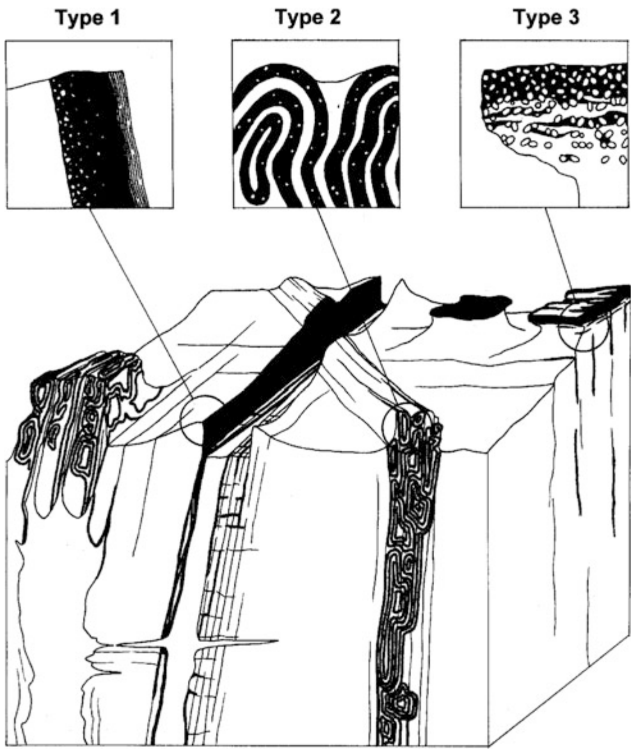

Fig. 13.5 A schematic block-diagram showing the different macromorphological types of ferruginization in relation to dykes and pipes of volcanic rocks and fracturing of the host sediment in the Kokořín area. *Type 1* subvertical planar bodies lining contacts of basaltic dykes or filling joints and faults; *Type 2* undulating ferruginous crusts; *Type 3* strata-bound subhorizontal bodies. After Adamovič et al. (2001)

- Thin, undulating crusts, often tube- and sheath-like in shape, clustered within subvertical zones several metres or first tens of metres wide in sandstone. Characteristic morphotypes are single-layered tubes and their bundles, or multi-layered tubes with low plunge angles, trending parallel or somewhat oblique to the strike of the zone. This pattern occasionally becomes rather distorted, with locally developed crusts of vermiform, rose-like or cauliflower-like appearance with variable trends of axes of tubes. Some of these zones stretch at a distance of several kilometres. Their genesis is explained by the Liesegang phenomenon describing periodical precipitation structures formed by diffusion (e.g. Ortoleva 1994). Its application to the precipitation of iron compounds in the Kokořín sandstone was first pointed out by Graber (1904). The Liesegang phenomenon explains the formation of ferruginous rings and spherical concretions by diffusion in static-fluid conditions, i.e. in open joints and in water-saturated sandstone, and the formation of tube-like crusts by diffusion in sandstone with a steady fluid flow.
- Strata-bound subhorizontal bodies with ferruginous cement, which follow subhorizontal zones of higher permeability in sandstones, such as conglomerate beds or major unconformities. Some of these bodies reach several km^2 in area (Močidla Gorge) and a thickness of 1 m or more (max. 6 m thick). Ferruginous cement is massive or composed of a number of undulating laminae.

The origin of ferruginous cement has been interpreted in different ways in the past (see review in Adamovič 2002b). Watzel (1862) suggested that iron was produced by the heat effect of magma emplacement. His "contact theory" has been soon abandoned and the role of groundwater circulation along intrusions of basaltic rocks has been adopted for the origin of morphological types 1 and 2 (Müller 1914, 1928; Zima 1950). Strata-bound bodies of ferruginous sandstone have been, however, long considered products of precipitation of iron from groundwater, reflecting its successive levels during a progressively lowering base level during the Quaternary (e.g. Müller 1928; Zima 1950). Iron was believed to have been released from weathered volcanic rocks or from iron-bearing detrital and authigenic minerals contained in the sandstone (glauconite, pyrite). Later studies (Adamovič 1988; Adamovič et al. 2001) found a close spatial relationship between the distribution of ferruginous cement in type-3 ferruginization and basaltic bodies, suggesting a hydrothermal origin of iron-bearing fluids and their ascent along dyke contacts simultaneous with, or slightly post-dating, the dyke emplacement. In this process, types 1 and 2 functioned as feeders for type-3 strata-bound bodies. The source of iron for all types of ferruginization is provided by basaltic rocks, with a contribution from granitic rocks in the basement, as suggested by trace element contents in the goethite cement.

Association of massive type-3 ferruginization with high-permeability sediments is well illustrated by the Močidla Gorge NW of Mšeno. Here, ferruginization is best developed below the top of a conglomerate bed overlain by less permeable fine-grained sandstones, in the axial part of a flat anticlinal structure (Adamovič 1988). Large bodies of intrusive breccia to the east of the gorge are interconnected with the body of ferruginous conglomerate by joints striking NW–SE and NE–SW, some of which contain thin basaltic dykes. Many of them show linings of iron oxyhydroxides and are interpreted as additional ascent paths for iron-bearing fluids (Fig. 13.6).

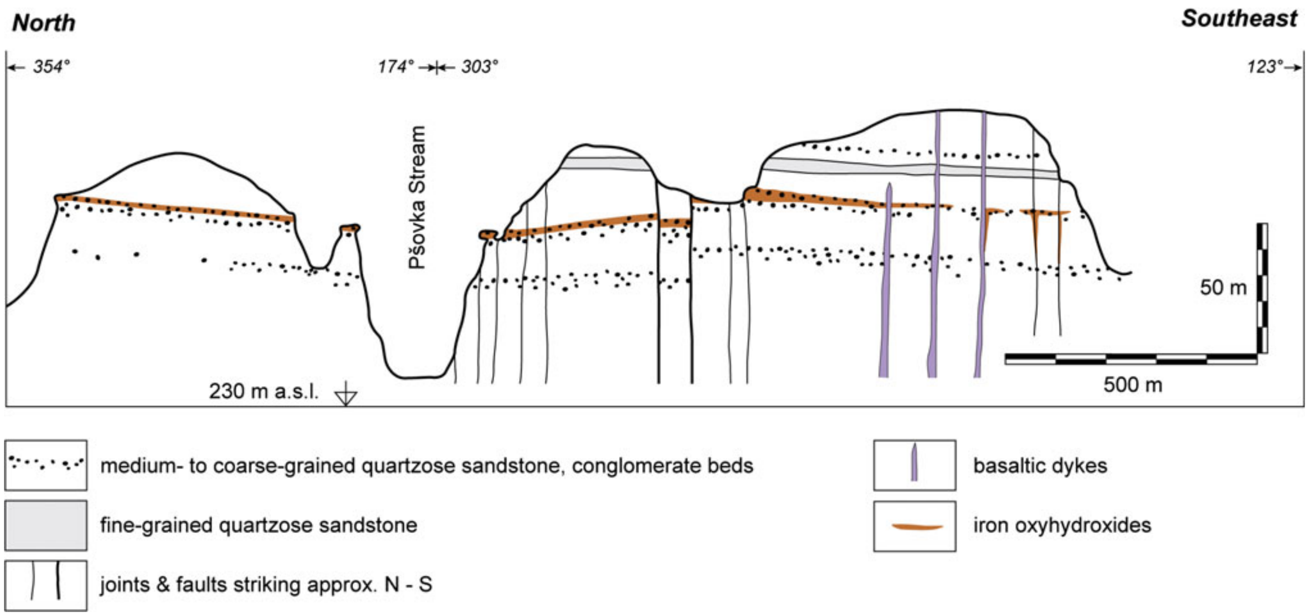

Fig. 13.6 A longitudinal section of the Močidla Gorge NW of Mšeno. Iron oxyhydroxides precipitated in the form of pervasive cement in a flat-lying conglomerate bed. Ferruginous conglomerate is cut by two N–S-striking faults, clearly post-dating the hydrothermal mineralization. Iron-bearing fluids were supplied from a large body of intrusive basaltic breccia at the eastern end of the Močidla Gorge

13.4 Landforms Due to Ferruginization

13.4.1 Structural Plateaus and Ridges

Ferruginous sandstones and conglomerates show a higher strength and a higher resistance to weathering compared to uncemented sandstone (Figs. 13.7 and 13.8). Almost horizontal strata-bound bodies of ferruginous sandstone (type 3) therefore tend to produce flat surfaces. Two principal beds of ferruginous conglomerate can be distinguished in the Kokořín sandstone between Mšeno and Dubá. Although showing an uneven areal distribution of ferruginous cement depending on the location of the sources of iron-rich fluids, each of these two beds was responsible for the origin of flat-topped hills—structural plateaus (Fig. 13.7). Tops of hills developed on the stratigraphically lower bed can be traced from the Močidla Gorge area in the SE (300 m a.s.l.) in northwesterly direction as far as to Supí hora (ca. 370 m a.s.l.) and northerly-lying Rač hills (380–390 m a.s.l., Fig. 13.9a). Those on the stratigraphically upper bed include flat surfaces at Zadní Žluč (408 m a.s.l.) and Nedvězí hills (ca. 400 m a.s.l.). Tops of the hills formed by ferruginous conglomerate are inclined very gently (1–3°) south to south-southwest, following the regional tectonic dip.

Structural ridges controlled by the courses of vertical zones of ferruginization are very common throughout the Kokořín area. They rise ca. 10–50 m above their surroundings, being topped by a straight line of cliffs, isolated pillars and walls of ferruginous sandstone up to 15 m high (e.g. Houska SE of Blatce, Čap Hill—Fig. 13.9c). Slopes of some of the ridges are covered with blocky talus (Kamenný vrch). The role of structural ridges is most notable in the northern part of the Kokořín area between Dubá and Vlhošť Hill (Fig. 13.8).

13.4.2 Pillars and Mushroom Rocks

Ridges dissected by a regular network of vertical joints are sites favourable for the origin of "rock cities" in which groups of pillars separated by grikes were formed by erosion due to the lowering of base level. Although smaller in area (max. 200 by 200 m) than those in other sandstone regions in Bohemia, some of the "rock cities" are perfect labyrinths providing shelters and hideouts (e.g. Kobylka and Pastuší gorges NW of Mšeno, several sites in the valley of Planý důl, Rač plateau). Free-standing pillars, separated from the main rock mass by deeply eroded fracture zones, are common. Where the tops of the ridges and hills are flat, formed by a resistant ferruginous layer, pillars on their rims tend to produce mushroom-shaped forms. Their stipes of gravelly quartzose sandstone become thinner due to the combined effect of salt and frost weathering, while their caps of ferruginous conglomerate show a higher resistance to weathering. Occasionally, perforations beneath the caprock have the character of rock arches and rock windows.

The best example of mushrooms rocks is present at the mouth of the Močidla gorge (Fig. 13.9d) where the pillars

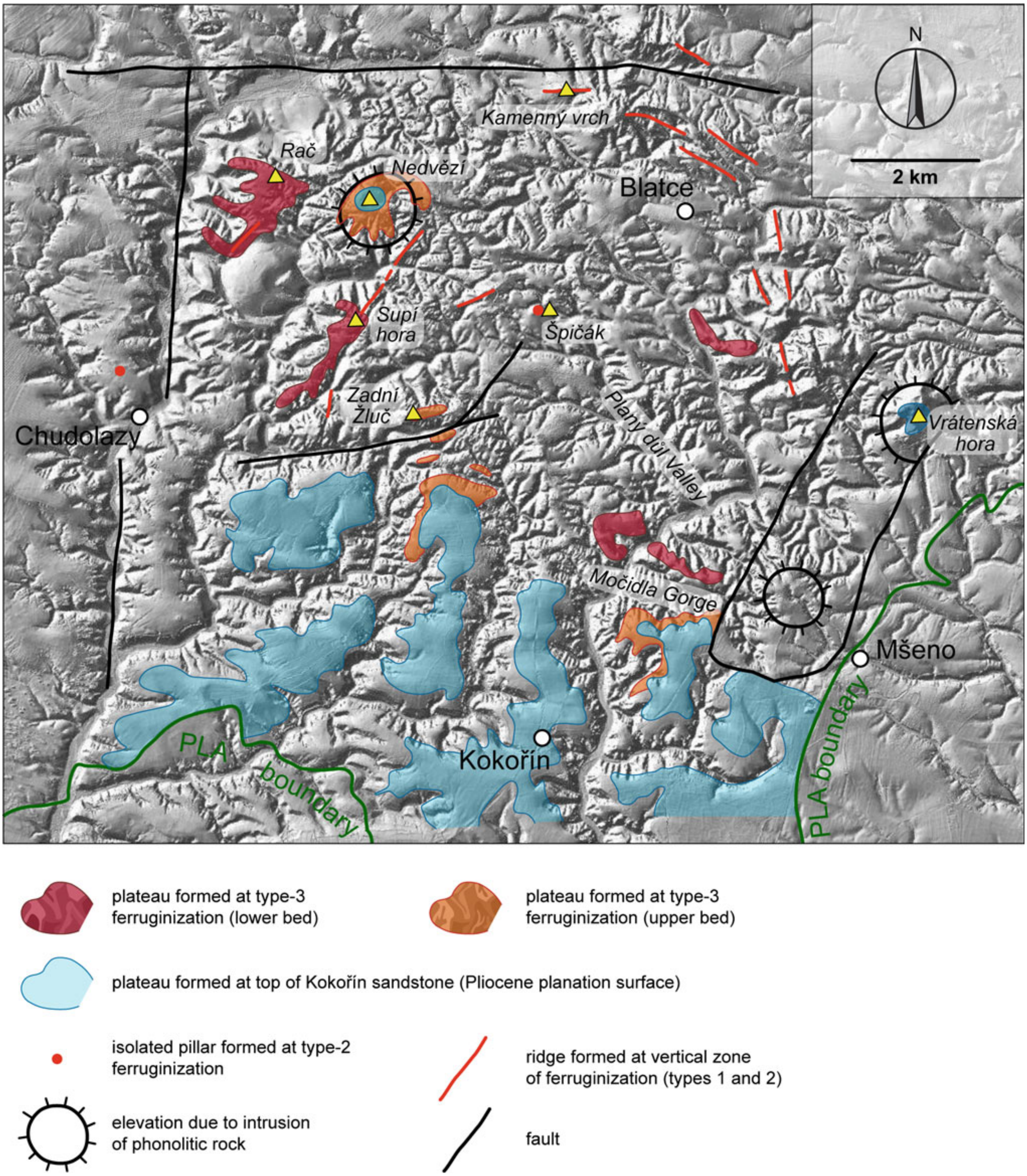

Fig. 13.7 A shaded relief map of the southern part of the Kokořín area between Kokořín and Dubá showing the main structural plateaus and ridges due to ferruginization (*red* and *orange red*) and relicts of the Pliocene planation surface (*blue*). Shaded relief: Czech Institute of Geodesy and Cadastre, www.cuzk.cz

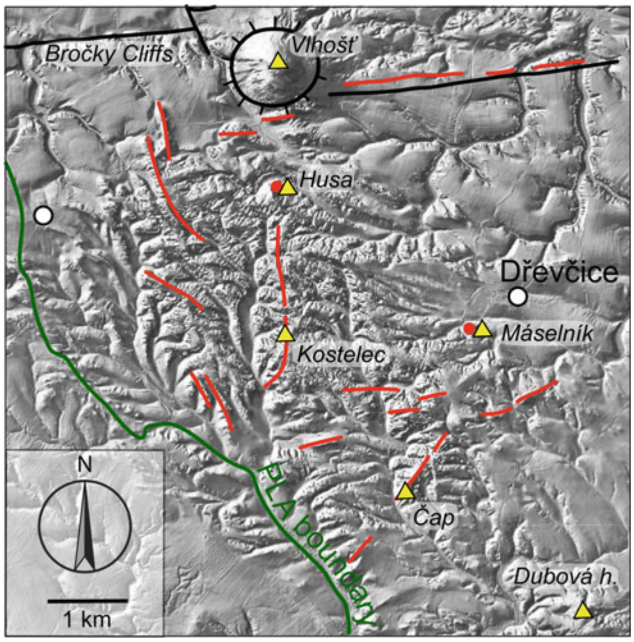

Fig. 13.8 A shaded relief map of the northern part of the Kokořín area between Dubá and Vlhošť hill. Some of the ridges are clearly connected with the courses of vertical zones of ferruginization. Shaded relief: Czech Institute of Geodesy and Cadastre, www.cuzk.cz

are 12–15 m high and their tops lie 60 m above the bottom of the Pšovka valley (Balatka and Sládek 1981). Mushroom rocks at the same level of ferruginous conglomerate lie only 1 km farther north, in the Vojtěšský důl. Mushroom rocks of the same type commonly appear along the circumference of relict plateaus topped by the upper layer of ferruginous conglomerate, such as Zadní Žluč, Supí hora and Rač hills.

Prominent rocky crests and hilltops, occasionally dissected into separate pillars, form at occurrences of ferruginous sandstone of morphological type 2. The most notable examples in the southern part of the Kokořín area are the hills of Špičák near Střezivojice and Kamenný vrch near Dubá (Figs. 13.7 and 13.9; Adamovič et al. 2001; Adamovič 2002a). Mushroom rocks and pinnacles at sites of type-2 ferruginization represent prominent landmarks in the northern part of the Kokořín area (Figs. 13.8 and 13.9), e.g. at Čap, Husa, and Vlhošť hills, and in the Bročky Cliffs east of Blíževedly.

13.4.3 Microforms

The variety of small-scale relief forms specific to ferruginous sandstone observed in the Kokořín area can be hardly paralleled elsewhere. This is largely due to the wide variety of forms of type-1 and type-2 ferruginization in sandstones now exposed at the surface (Fig. 13.9). These structurally controlled microforms include:

- systems of concentric rings of positive relief on steep or vertical surfaces of ferruginized joint planes;
- mammillary surfaces on sandstones with scattered iron-rich enclaves, such as spherical ferruginous concretions or ferruginized bivalve shells;
- “wrinkled” surfaces consisting of parallel ridges formed by mm- to cm-thick laminae of ferruginous sandstone: wavy, subspherical or contorted, very complex patterns. Irregular concentric patterns have been previously often referred to as “rock roses” (Balatka and Sládek 1981), e.g. Špičák and Kamenný vrch hills (Fig. 13.9g). Bowl-shaped depressions max. 2 m in diameter, resembling weathering pits, may form on horizontal surfaces in the centres of the concentric structures (Husa Hill, Fig. 13.9e);
- tubes and their bundles with straight, parallel axes. Tube walls are formed by mm- to cm-thick laminae of ferruginous sandstone. The tubes are max. 0.5 m across and 5 m in length, producing positive relief with their outer surfaces, and negative relief with their interiors (east of Vlhošť, Fig. 13.9i).

13.5 Geomorphic Evolution in the Quaternary

The highest structural plateaus in the Kokořín area follow the top of the Kokořín sandstone and are probably Pliocene in age (Balatka and Sládek 1981). Their distribution (Fig. 13.7) suggests that they were originally interconnected to form a more-or-less continuous planation surface extending from the Elbe River in the south to the Úštěk Fault in the north, now completely destructed in the northern part

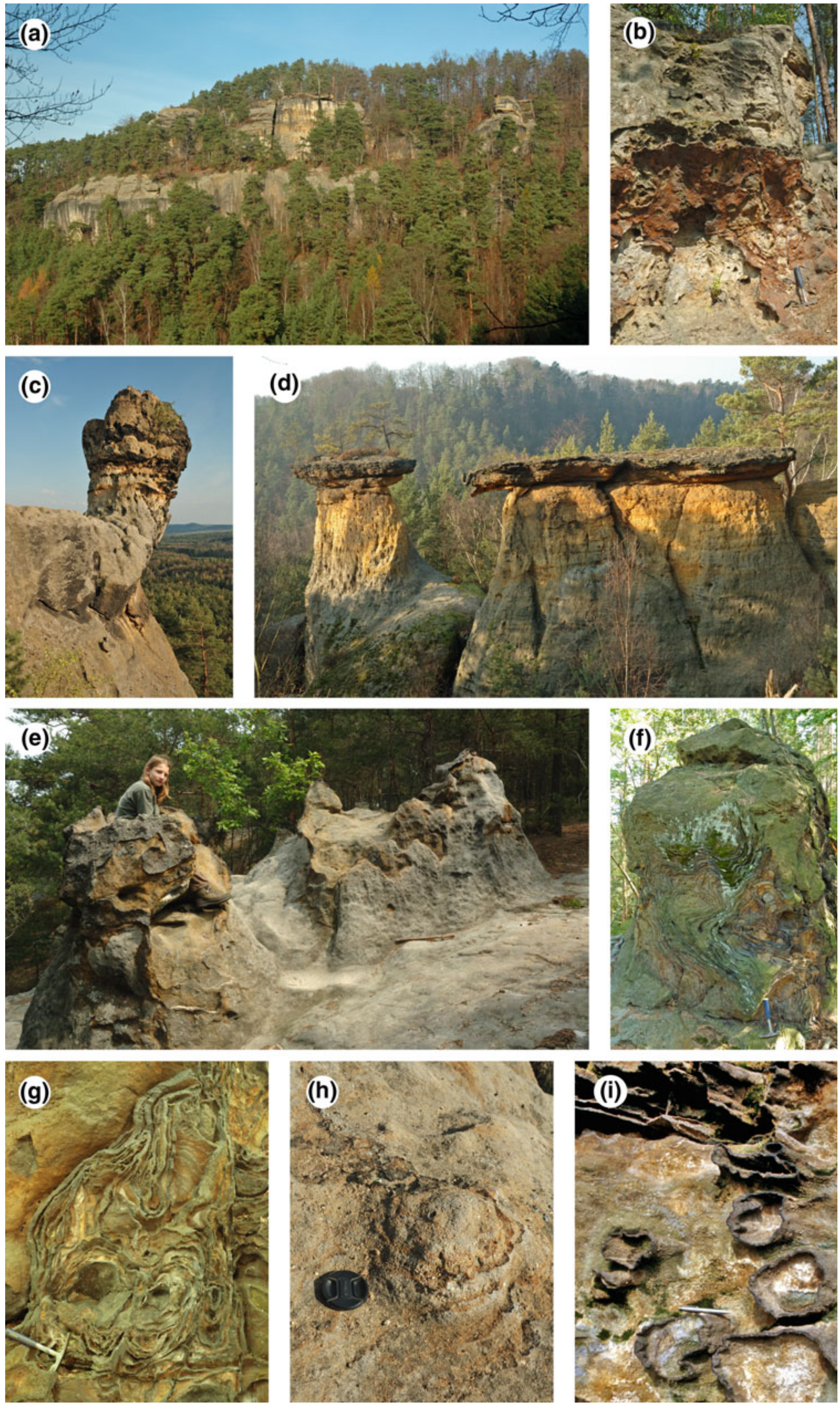

Fig. 13.9 Landforms on ferruginous sandstone/conglomerate in the Kokořín area. **a** The Rač plateau topped by a bed of ferruginous conglomerate; **b** An uneven layer of ferruginous sandstone lining a basaltic dyke–Laka valley N of Mšeno; **c** An isolated pillar of ferruginous sandstone near a basaltic dyke–Čap Hill; **d** Mushroom rocks topped by a bed of ferruginous conglomerate—"Pokličky" at the mouth of Močidla Gorge; **e** Bowl-shaped depressions at vertical columns of ferruginous sandstone (also called "geyser stalagmites" in literature)—Husa Hill; **f** "Wrinkled" surface due to parallel laminae of ferruginous sandstone—Strážný vrch NW of Mšeno; **g** Parallel laminae of ferruginous sandstone constituting large concretionary forms—Kamenný vrch; **h** Subtle elevations on top rock surface due to thin bedding-parallel laminae of ferruginous sandstone; **i** Tube-shaped forms with parallel axes at extremely elongated single-layered concretions of ferruginous sandstone—Švábský důl east of Vlhošť Hill (*Photo* J. Adamovič)

of the area. The only elevations reaching above this surface were those formed by exhumed Oligocene to Miocene subvolcanic bodies.

In the Pleistocene, a network of valleys was incised in the Kokořín sandstone as a result of base level lowering. During the last 2.6 My, the valley of the Vltava River around Prague deepened by 125 m with the highest estimated incision rate in the Mid Pleistocene (3–10 cm/100 years; Balatka and Kalvoda 2006). Further downstream, the valley of the Elbe River near Děčín deepened by 180–200 m during the same time interval (Kalvoda and Balatka 1995). This suggests that the incision of major river valleys in northern Bohemia was at least partly driven by tectonic uplift whose intensity increased towards the north; this also explains the higher degree of destruction of the Pliocene surface in the northern Kokořín area. In the Kokořín area, incision of major valleys by 120–200 m can be observed, with two to four levels of cliffs, each representing one of the superimposed bodies of the Kokořín sandstone (see Sect. 13.2.1).

The general southerly inclination (SSW to SE) of the Pliocene planation surface was responsible for the early south-directed drainage of the Kokořín area, mediated by the Pšovka, Liběchovka and Obrtka streams. Apparent offsets of the courses of the Liběchovka and Obrtka streams along the E–W line south of Dubá were explained by piracy inflicted on the hypothetical westerly flowing “Dubá River” in Mid Pleistocene by Müller (1939) but may equally result from the progressive destruction of a Pliocene fault scarp along the E–W-striking fault (see Fig. 13.1 for a general view). Alluvial plains of the Pšovka and Liběchovka streams lie at the level of the groundwater table within the Kokořín sandstone, being fed by valley springs. In contrast, floors of their tributary valleys lie well above the groundwater table and host no permanent streams. They deepen during periodical flash floods while their slopes are modelled by a steady gravitational redeposition of weathering products.

Initial valleys, broad and shallow, were possibly formed by stream erosion in the Early Pleistocene, at a higher groundwater table and a slow uplift rate. The main valley incision occurred in the Mid Pleistocene, based on parallelism with the Elbe River valley (Balatka and Sládek 1964). The tributary valleys could not keep pace with the increasing rate of stream erosion in the main valleys and their broad transverse profiles changed into narrow ones. Slot canyons tens of metres deep were locally formed, following fractures and fracture zones and often showing zig-zag courses depending on tectonic offsets of the master fracture. In the Late Pleistocene, loess was deposited on the plateaus and on right-hand slopes of the south-directed valleys, thereby pushing their courses somewhat to the east and giving them asymmetrical transverse profiles (Balatka and Sládek 1964; 1981). Higher erosion rates in the main valleys at the Pleistocene/Holocene transition can be inferred from the presence of hanging valleys with almost 10 m drops in the valley floor at their mouths.

Directions of the uppermost reaches of valleys and gorges conform to the strikes of fractures. In contrast, courses of middle and lower reaches of the valleys are largely controlled by the orientation of tectonic dips. This is well demonstrated by radial patterns of valleys around phonolitic intrusions associated with periclinal dips of strata in the host sandstone (Na Rovinách elevation NW of Mšeno, Vrátenská hora, Fig. 13.7).

Deepening of valleys within the Kokořín sandstone was uneven due to the presence of harder, cemented layers several metres thick in the sedimentary succession. This is demonstrated by stepped longitudinal profiles of upper and middle reaches of valleys (Balatka and Sládek 1964) where waterfalls up to 6 m high develop after torrential rains. Hydrothermal hardening of sandstone, i.e. ferruginization and silicification related to volcanic processes in the Tertiary, had a profound inhibitory effect on the progress of headward erosion. Structural plateaus were formed at levels of areally extensive beds of ferruginous sandstone (type-3 ferruginization), and ridges and necks similar to those on sub-volcanic bodies were formed at type-1 and type-2 bodies of ferruginous sandstone. In the northern part of the Kokořín area, the distribution of volcanic rocks and ferruginous cement seems to be the most effective factor controlling the valley network pattern (Fig. 13.8).

13.6 Geological Heritage and Human Impacts

Throughout the history, the dense network of deep, cliff-lined valleys in the Kokořín area provided shelters for prehistoric hunters, places of solitude for hermits, hideouts for outlaws but—most of all—refuges for local villagers during wartime. The cliff dwellers left behind a number of inscriptions and carvings on vertical rock faces. Sandstone clifftops and tops of volcanic necks were perfect sites for the construction of fortifications.

Elevations of ferruginous sandstone were used as observation points in the Mesolithic (Strážník Cliff near Dřevčice) and sites for timber-made castles (Čap and Rač hills) in the Middle Ages (Gabriel and Panáček 2000). In the northern Kokořín area, fragments of ferruginous sandstone were used by Mesolithic hunters and foragers in their dwellings under rock shelters: as boiling stones in fireplaces and as heat-accumulation stones (Svoboda 2003, V. Cílek, pers.-comm.). Silicified sandstone was extensively used for the production of millstones in the eighteenth–nineteenth centuries (e.g. Kostelec and Supí hora hills).

In the mid-nineteenth century, the Kokořín area became renowned as a Romantic landscape—an attitude supported

Fig. 13.10 The incised valley of the Pšovka stream with three levels of sandstone cliffs has been mentioned in the writings of the famous poet Karel Hynek Mácha. The Kokořín Castle (*left*) was reconstructed in the early twentieth century in a style enhancing the Romantic spirit of the valley (*Photo* J. Adamovič)

especially by the journeys and writings of the famous Romantic poet Karel Hynek Mácha (1810–1836). Two of his masterpieces were situated in this area: the poem *Máj* (May) and the novel *Cikáni* (Gypsies). The rugged, densely forested country started to be visited by pilgrims of all sorts, and legends appeared on mysterious knights, hidden treasures, robbers and magic creatures. The ruin of the Kokořín Castle—the central point of Mácha's experience—was purchased by the Špaček family and reconstructed in a Romantic style in 1911–1918 (Fig. 13.10).

Tourist activities in the southern part of the Kokořín area flourished after World War I, being supported by the Czech Tourist Club. Sandstone country around Dubá, then known under its Romantic name "Dubá Switzerland" (*Daubaer Schweiz*) became increasingly visited by members of the German tourist club *Nordböhmisches Excursions-Club* after its foundation in Česká Lípa in 1877. Much like in the south, a boom of tourism around Dubá is linked with the signposting of tourist paths after World War I. Rock climbing activities in the Kokořín area started in the same period: the earliest ascents date to the year 1909. They culminated in the 1980s, and over 1000 pillars are registered by climbers today.

13.7 Conclusion

Among the many sandstone areas in the Bohemian Cretaceous Basin, the area between Kokořín and Česká Lípa displays the widest variety of products of hydrothermal ferruginization. It equally provides a number of good outcrops documenting the close link between the distribution of ferruginous cement and the origin of landforms of all different sizes. Such a textbook of "hydrothermal geomorphology" can be hardly paralleled at a global scale. Geosites related to hydrothermal sandstone alteration therefore deserve due attention. Conservation of geomorphic features and living nature has been rendered since the establishment of the Kokořínsko Protected Landscape Area in 1976: the most valuable landforms are protected within the status of nature monuments; others lie in areas protected within the category of nature reserves.

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