Geological Quarterly, 2024, 68, 42
DOI: http://dx.doi.org/10.7306/gq.1770

Pennsylvanian–Permian deposits in northern Bohemia: a correlation with neighbouring basins and discussion of their formation and demise within the "Elbe Zone System"

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Nádaskay, R., Valečka, J., Opluštil, S., Mlčoch, B., Skácelová, Z., Horna, F., 2024. Pennsylvanian–Permian deposits in northern Bohemia: a correlation with neighbouring basins and discussion of their formation and demise within the "Elbe Zone System". Geological Quarterly, 68, 41; https://doi.org/10.7306/gq.1770

The crustal-scale shear-zones of the Bohemian Massif were recurrently active during the Late Paleozoic, as inferred from the depositional record of numerous penecontemporaneous basins distributed along NW–SE faults. This paper focuses on the correlation of sedimentary basins associated with Late Paleozoic reactivation of the NW–SE-trending Elbe Zone System, based on subsurface data from Permian outliers preserved along the Lusatian Fault in northern Bohemia. Comparison of the lithofacies development together with recently published geochronological data facilitates possible correlation to the Weißig and Döhlen basins, and Bohemian basins, respectively. Stratigraphic dating and mutual correlation of the Late Paleozoic basins within the Elbe Zone allow comparison of their development and subsequent demise as a result of polyphase tectonic evolution of the northern Bohemian Massif. The Late Mississippian–Middle Pennsylvanian (~330–310/305 Ma) late orogenic strike-slip tectonic movements were followed by extension related to orogenic collapse. This process was overtaken by intraplate extension by ~306/305 Ma at the latest. It has been suggested that the NW–SE faults (incl. Elbe Zone System) were reactivated in a strike-slipe regime during the Middle Pennsylvanian–early Permian (Moscovian–early Asselian; ~310–300/298 Ma), i.e., concurrently with the intra-plate extension. Further strike-slip reactivation of the NW–SE faults occurred during the early Permian (late Asselian–early Kungurian; ~297–283 Ma).

Key words: Late Paleozoic, Permian, Lusatian Fault, Elbe Zone, Bohemian Massif, basin tectonics.

INTRODUCTION

The Elbe Zone and the Lusatian Fault in Saxony and northern Bohemia are among the most prominent tectonic features of the northern part of the Bohemian Massif. They represent parts of the wider Elbe Zone System (*sensu* Scheck et al., 2002) which belongs to the group of NW–SE trending shear zones that truncated the NE–SW trending Variscan zones (Fig. 1A; Arthaud and Matte, 1977; Edel and Weber, 1995; Mazur et al., 2020). These faults formed during the Mississippian and were reactivated during the Pennsylvanian–Permian (e.g., Mattern, 2001; Edel et al., 2018). Individual NW–SE-trending faults belonging both to the Elbe Zone System or to a parallel group of so-called 'Sudetic' faults may have been further reactivated during Mesozoic times (e.g., Solecki, 1994, 2011; Voigt, 2009; Kowalski, 2017, 2020; Nádaskay et al., 2019b; Käßner et al., 2020; Kowalski and Pacanowski, 2024). Despite the well-documented complex evolution of these faults since the latest Cretaceous (e.g., Coubal et al., 2015; Tietz and Büchner, 2015), the pre-Cretaceous tectonic history of the Elbe Zone System is relatively poorly constrained, apart from a few studies (e.g., Pitra et al., 1994, 1999; Mattern, 1996; Wenzel et al., 1997; Verner et al., 2009; Vondrovic et al., 2011; Tomek et al., 2019; Machek et al., 2021). However, the depositional record of the Permian, Jurassic and Upper Cretaceous distributed along the individual faults of the Elbe Zone System indicates that at least some of these faults played an active role in basin creation and subsequent inversion (e.g., Uličný et al., 2009a, b; Hofmann et al., 2018; Nádaskay et al., 2019a, b).

The association of Permian sedimentary basins with NW–SE-trending fault zones has been widely studied in different parts of the Bohemian Massif – e.g., Pfahl-Danube system in Bavaria (Schröder, 1988; Schröder et al., 1997) and Thuringia (e.g., Andreas, 1988), Elbe Fault Zone (Möbus, 1966; Absolon, 1979; Reichel, 1985) or Sudetic Fault System (Holub

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Received: August 16, 2024; accepted: November 6, 2024; first published online: December 16, 2024

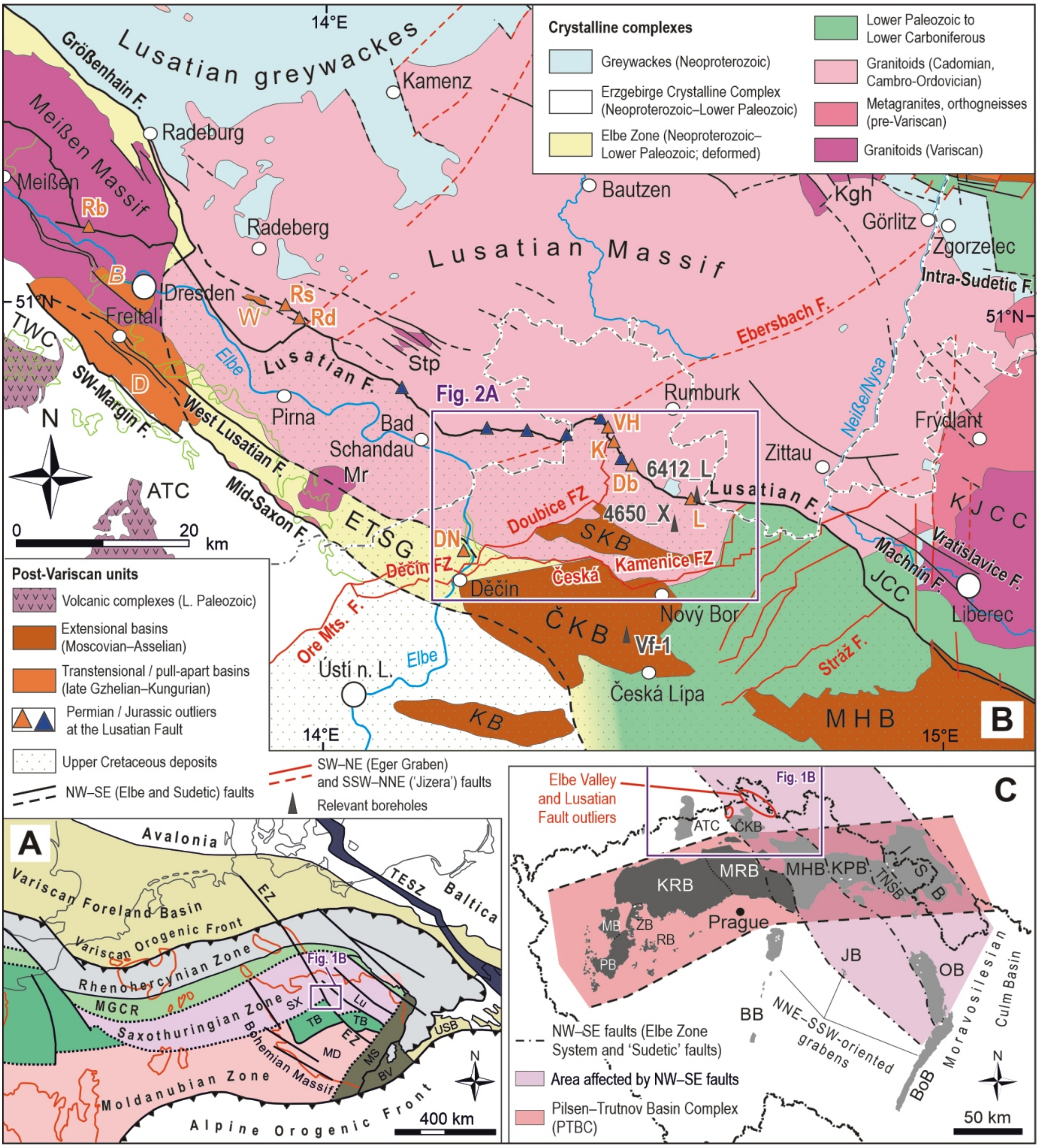


Fig. 1A – overview map of Variscan Europe: heavily modified after Zagórska et al. (2020) and references therein; abbreviations: BV – Brunovistulian; EZ – Elbe Zone; Lu – Lugian; MGCR – Mid-German Crystalline Rise; MS – Moravosilesian; TB – Teplá–Barrandian Unit; TESZ – Trans-European Suture Zone; USB – Upper Silesia Basin; VS – Variscan suture. B – outline of the broader area of interest in the northern Bohemian Massif showing the Permian outliers studied: Db – Doubice; DN – north of Děčín; K – Kyjov; L – Lesné (with borehole 6412_L); Rb – Radebeul; Rd – Rossendorf; Rs – Rosinendörfchen; VH – Vlčí Hora; abbreviations: ATC – Altenberg–Teplice Caldera ČKB – Česká Kamenice Basin (*K* – Kravaře sub-basin; *SKB* – Srbská Kamenice sub-basin); D – Döhlen Basin (*B* – Briesnitz sub-basin); W – Weißig Basin; ETSG – Elbe schist belt; JCC – Ještěd Crystalline Complex; KgH – Königshain Massif; KJCC – Krkonoše–Jizera Crystalline Complex; MHB – Mnichovo Hradiště Basin; Mr – Markersbach massif; NSB – North Sudetic Basin; TWC – Tharandt Wald Caldera. Geology of the German and Polish territories adapted after Brause (1972) and Kozdrój et al. (2001). C – Late Paleozoic continental basins in the Czech territory (Opluštil et al., 2013, amended); abbreviations: ATC – Altenberg–Teplice Caldera, BB – Blanice Graben, BoB – Boskovice Graben, ČKB – Česká Kamenice Basin, ISB – Intra-Sudetic Basin, JB – Jihlava Graben, KRB – Kladno–Rakovník Basin, MB – Manětín Basin, MHB – Mnichovo Hradiště Basin, MRB – Mšeno–Roudnice Basin, OB – Orlice Basin, PB – Pilsen Basin, RB – Radnice Basin, TNSB – Trutnov-Náchod sub-basin, ŽB – Žihle Basin

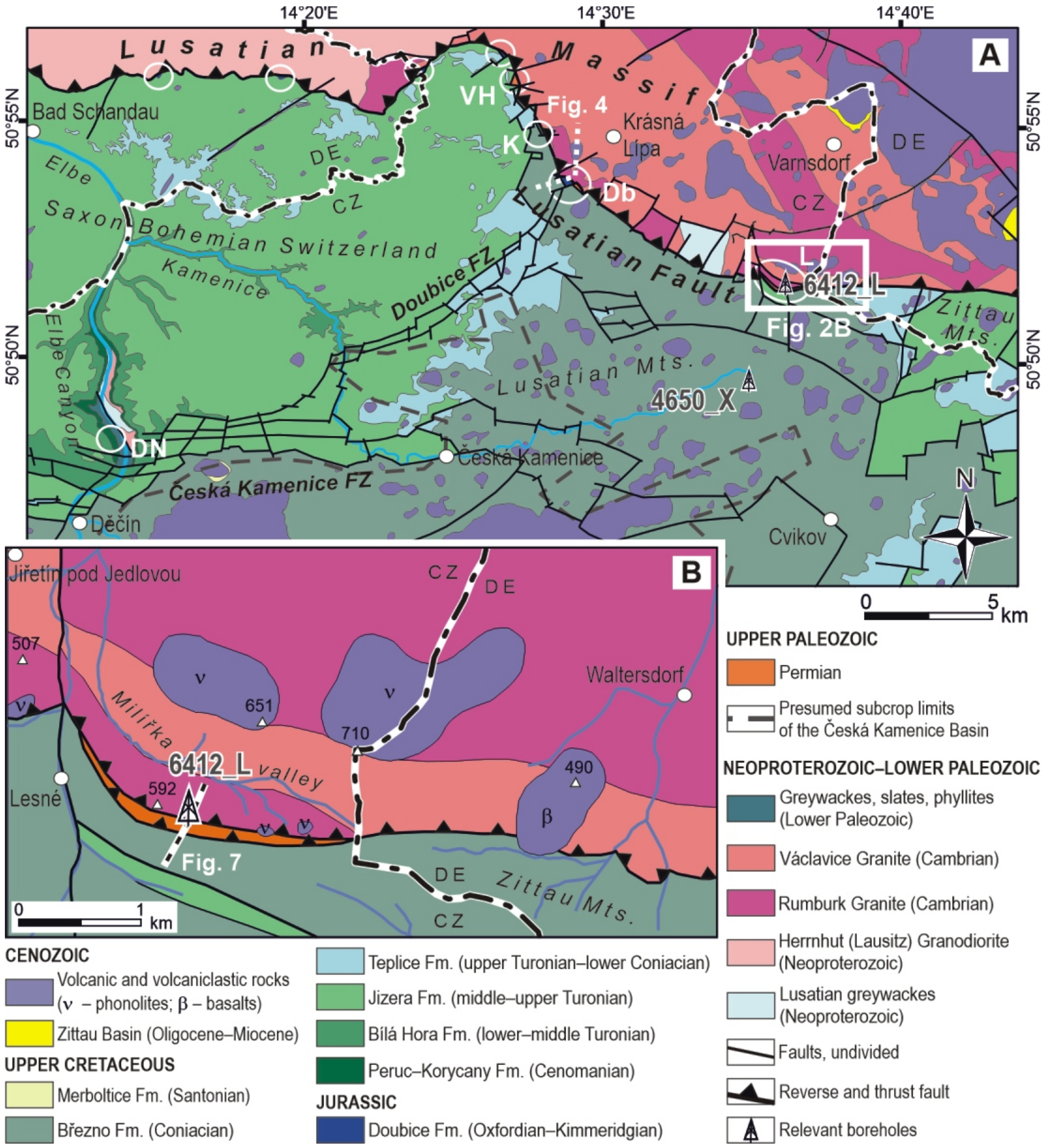


Fig. 2A – detailed geological map of the study area derived from a geological map of the Resibil project area by Mrázová et al. (2020). Tectonic outliers are highlighted by white ellipses. Permian outliers: Db – Doubice; DN – north of Děčín; K – Kyjov; L – Lesné (with borehole 6412_L); VH – Vlčí Hora). B – detailed geological setting of the vicinity of borehole 6412_L (Lesné). Geophysical section (Fig. 7) indicated

and Tásler, 1974; Wojewoda and Mastalerz, 1989; Solecki, 1994; Wojewoda, 2007). Although these basins were likely established as transtensional/pull-apart basins (e.g., Lützner, 1988; Benek, 1989; Mastalerz and Wojewoda, 1991; Mattern, 1995a, b; Schröder et al., 1997; Uličný et al., 2002; Zeh and Brätz, 2004; Hofmann et al., 2009; Zieger et al., 2019), their formation was likely not synchronous and was related to at least two phases of strike-slip movement (cf. Mattern, 2001).

Unlike the Pennsylvanian–Permian basins with well-established stratigraphy, the Permian outliers along the Lusatian Fault and in the Elbe Valley have been a geological enigma for decades. Because of their poor preservation as relatively narrow, tectonically tilted, and heavily deformed units (*sensu* Coubal et al., 2014), it has been virtually impossible to determine their stratigraphic position. However, in 2018 an exploratory borehole located directly at the Lusatian Fault near Lesné (northern Bohemia; Figs. 1 and 2), drilled a ~55 m-thick Permian succession, unknown until that time. The borehole data (core, well-logs) were integrated with field geological and geophysical data to explore the depositional record and stratigraphy of the Permian as well as the nature of its deformation.

This paper explores the depositional and tectonic events that affected the northern Bohemian Massif, particularly during Late Pennsylvanian–Permian times. We address this issue by comparison with surrounding basins with well-established stratigraphy: the Döhlen Basin in Saxony, the Česká Kamenice Basin (ČKB) in northern Bohemia, and the Krkonoše Piedmont Basin (KPB) in eastern Bohemia. Finally, we discuss the sequence of events related to the formation and deformation of the Permian outliers in northern Bohemia within the framework of the NE part of the European Variscan belt.

GEOLOGICAL SETTING

The study area is located in the NW part of the Bohemian Massif, at the junction of the Lugian, Saxothuringian and Teplá–Barrandian tectonic domains (Fig. 1A), all of which are overlain to some extent by Late Paleozoic to Cenozoic successions (e.g., Kozdrój et al., 2001; Cháb et al., 2007; Mlčoch and Konopásek, 2010). The Lugian unit is formed of Upper Neoproterozoic greywackes intruded by Late Neoproterozoic–Cambrian granitoids (~540–504 Ma; Kozdrój et al., 2001; Kemnitz, 2007; Białek et al., 2014; Zieger et al., 2018). The Variscan intrusions (Fig. 1B; the most recent ages as well as a summary of older dating in Käßner et al., 2021) are represented by the Meißen Massif and Königshain and Stolpen plutons intruding the Lusatian Massif, and the Markersbach Massif (~327 Ma; Hofmann et al., 2009) emplaced at the boundary of the Lusatian Massif and Elbtalschiefergebirge ('Elbe schist belt', ETSG; Fig. 1B). The ETSG is a NW–SE-oriented synclinorium formed of weakly metamorphosed sedimentary rocks (Late Proterozoic–Early Paleozoic) exposed in the Elbe Valley in Saxony and northern Bohemia (e.g., Pietzsch, 1917; Ebert, 1934; Hoth et al., 1995). In the west, it is separated from the neighbouring Erzgebirge Crystalline Complex by the Mid-Saxon Fault (Fig. 1B) and, towards the east, it continues along the West Lusatian Fault beneath the Upper Paleozoic and the Upper Cretaceous and eventually joins intensely deformed low-grade metamorphic complexes in the outer rim of the Krkonoše–Jizera Massif (e.g., Ebert, 1934; Chaloupský, 1970, 1973; Kozdrój et al., 2001). The sedimentary cover within the study area (Figs. 1B and 2) is represented by the Upper Paleozoic, Jurassic, and Upper Cretaceous (Fig. 3). Elements of the Upper Paleozoic are as follows:

(1) The Česká Kamenice Basin (ČKB), completely concealed beneath younger deposits. A handful of deep boreholes that reached the pre-Pennsylvanian basement suggest that the basin comprises three sub-basins separated by basement highs (Pešek, 2001). The most complete succession was drilled by borehole Vf-1 (Holub et al., 1984; for location see Fig. 1B) that recorded an up to ~620-m-thick succession of alternating mudstones, sandstones and conglomerates with intercalations of basic to intermediate volcanic and volcaniclastic rocks, Gzhelian–Asselian in age (Kučera and Pešek, 1982; Vejlupek et al., 1986). The basin fill comprises three grey and/or varicoloured horizons of shales and mudstones, the uppermost of which is correlated to the Rudník Member as defined (e.g., Pešek, 2001) in the Mnichovo Hradiště (MHB) and Krkonoše Piedmont (KPB) basins. The latter two basins form parts of the Pilsen–Trutnov Basin Complex (PTBC; *sensu* Cháb et al., 2010; Fig. 1C), an extensive complex of non-marine, so-called intermontane basins.

(2) The Permian outliers along the Lusatian Fault (Fig. 2A) comprise alternations of sandstones and conglomerates with intercalations of volcanic and volcaniclastic rocks (Fig. 3; e.g., Fediuk et al., 1958). Compared to the infill of the ČKB, they are only several tens of metres thick with a reduced stratigraphic range due to intense deformation. It was assumed that they once formed a single depositional space with the ČKB underlying the Upper Cretaceous (Fig. 4; cf. Malkovský, 1987, after unpublished sketch of J. Dvořák, 1962; Klein, 1971).

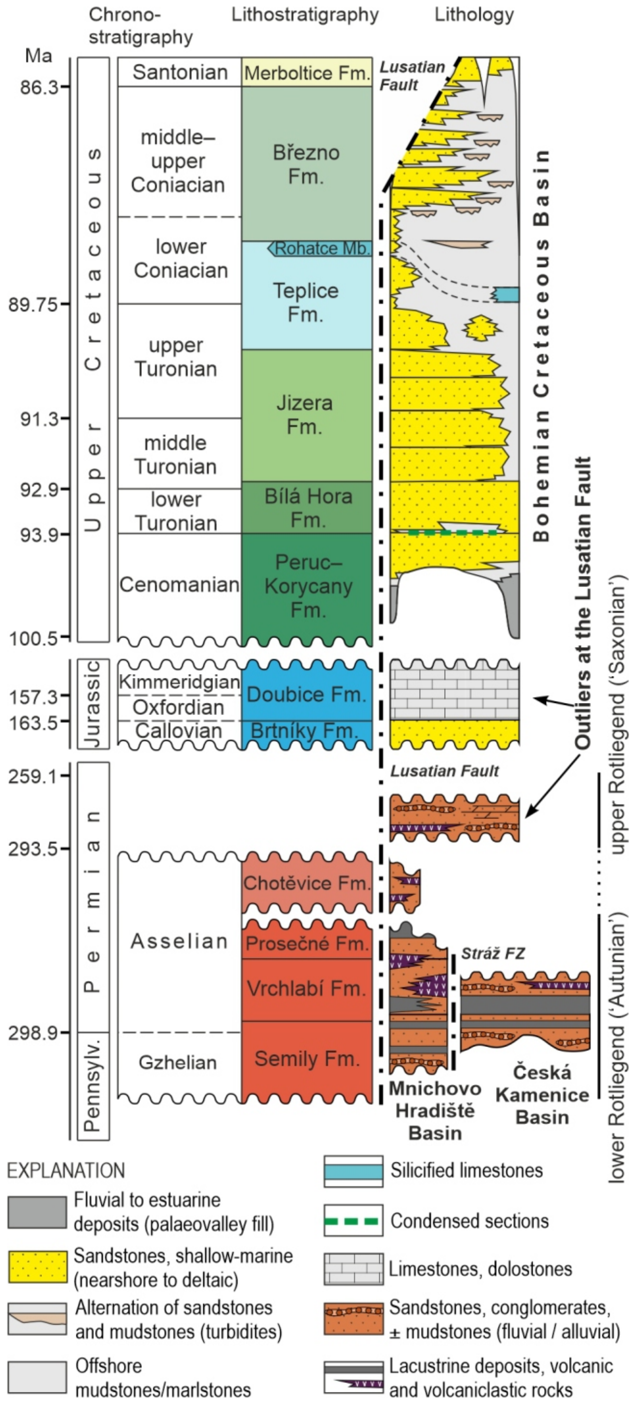


Fig. 3. Schematic juxtaposition of basin fills within the study area with respect to their stratigraphic age and tectonic relationships

The Middle–Upper Jurassic (e.g., Eliáš, 1981) rocks are exposed in several deformed and tilted 'tectonic slices' (up to a few tens of metres long) along the Lusatian Fault. Sandstones (quartzose and dolomitic) at the base of Jurassic are overlain by limestones and dolostones (Fig. 3). The original depositional and tectonic setting of the Jurassic deposits has been considered to be related to activity along the NW–SE faults (e.g., Eliáš, 1981; Malkovský, 1987; Voigt, 2009; Valečka, 2019).

The Upper Cretaceous in the vicinity of the Lusatian Fault is represented by middle Turonian–Coniacian formations (Fig. 3). The latter dominate in terms of both extent and thickness – over

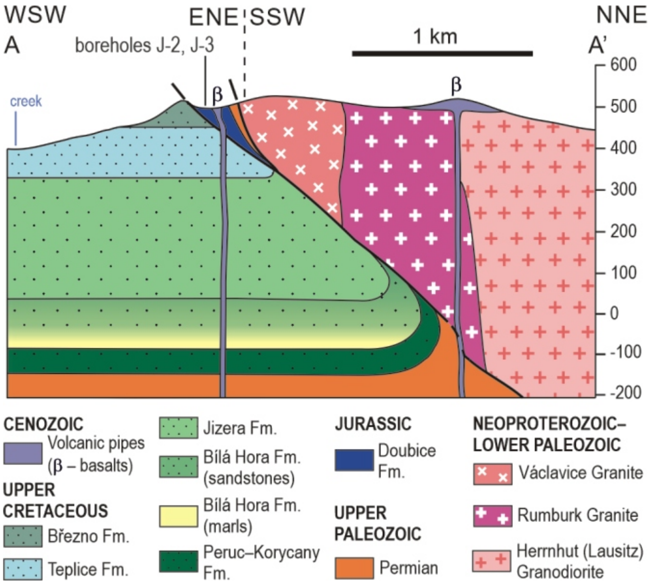


Fig. 4. Simplified geological section at the boundary between the Bohemian Cretaceous basin and the Lusatian Massif (amended after Klein and Opletal, 1971)

The section is located between the Doubice and Krásná Lípa municipalities in northern Bohemia (for approximate location see Fig. 5) Distance between A and A' is ~3.5 km. Details of boreholes J-2 and J-3 in Eliáš (1981)

230 m (Valečka, 2001, 2006), and comprises mainly quartzose sandstones with subordinate argillaceous or calcareous sandstones and dm–m thick intercalations of mudstones and siltstones.

TECTONIC SETTING

The study area represents a tectonically complex region situated at the intersection of major, crustal-scale tectonic zones: (1) The Elbe Zone System (*sensu* Scheck et al., 2002), comprising NW–SE trending faults within a wide zone of intense ductile and brittle deformation (Fig. 1A); (2) The WSW–ENE, and E–W trending faults of the Eger Graben formed during the Oligocene–Miocene opening of the Eger Rift (e.g., Rajchl et al., 2009; Cajz and Valečka, 2010) and, thus post-dating the tectonic processes discussed herein. In addition to them there is a subordinate group represented by NNE–SSW faults purportedly (Brandmayr et al., 1995) representing oblique faults to the controlling Late Paleozoic NW–SE fault zones. The Elbe Zone (EZ; Fig. 1B) is represented by a series of NW–SE trending faults surrounding the Elbe Valley. It forms a part of the crustal-scale Elbe Zone System *sensu* Scheck et al. (2002), extending from the North Sea to the SE margin of the Bohemian Massif and active since Carboniferous times (e.g., Edel and Weber, 1995). The EZ comprises a number of parallel faults defined within the the ETSG and adjacent units in Saxony, such as the Mid-Saxon Fault and the West Lusatian Fault (Fig. 1B; as defined by Kossmat, 1927). The Mid-Saxon Fault is interpreted as a SE-vergent thrust fault (e.g., Pietzsch, 1963), possibly reactivated as strike-slip shear zone (Mattern, 1996). The EZ is bounded to the NE by the Lusatian Fault, the most prominent fault within the NE Bohemian massif (e.g., Malkovský, 1987; Sedlák et al., 2007; Coubal et al., 2014). This fault was defined primarily as a boundary separating crystalline units of the Lusatian Massif and the Krkonoše–Jizera Crystalline Complex from post-Variscan sedimentary formations on the underlying Saxothuringian basement (Fig. 1B; Malkovský, 1977, 1987; Cháb et al., 2007). It also represents a distinct boundary between the crystalline basement and sedimentary formations of the Bohemian Cretaceous Basin (BCB) with most likely a syndepositional role (e.g., Uličný et al., 2009a, b). The Lusatian Fault formed during the Variscan Orogeny (cf. Brandmayr et al., 1995; Tomek et al., 2019). The neighbouring 'Sudetic' faults, e.g., Machnín, Intra-Sudetic and Vratislavice faults (Fig. 1B), have their evolution recorded by syntectonic Pennsylvanian to Permian magmatic bodies (Klomínský et al., 2005; Žák et al., 2013; Awdankiewicz, 2022). In contrast to that, the pre-Cenozoic (cf. Coubal et al., 2015) evolution of the Lusatian Fault is only inferred from the depositional record (Voigt, 1994, 2009) and the provenance of clastic material deposited within the surrounding basins (e.g., Hofmann et al., 2018; Niebuhr, 2018; Nádaskay et al., 2019b). Since the latest Cretaceous, a complex evolution of the NW–SE faults was documented from normal to reverse/thrust faulting with intermittent phases of strike-slip movements and related emplacement of volcanic bodies (Müller and Wächter, 1970; Adamovič and Coubal, 1999; Coubal et al., 2014, 2015; Tietz and Büchner, 2015). In the case of the Lusatian Fault, this resulted in the present-day stepped anatomy of individual fault segments, involving releasing, restraining bands and splays (Coubal et al., 2014, 2015; Krentz and Stanek, 2015). In the study area, the fault segments are characterized by a gentle (~16°) dip of the main fault surface towards the NE, a narrow (<150 m) damage zone, and tectonic-drag effects restricted to dismembered blocks of Permian and Jurassic rocks adjoining the main fault (Coubal et al., 2014). These segments are interpreted to have been exposed to alternating phases of thrusting, transtension, and extension from the latest Cretaceous onwards (Coubal et al., 2015).

THE PERMIAN IN NORTHERN BOHEMIA – OUTLINE OF PREVIOUS RESEARCH

The Permian deposits in northern Bohemia were first reported by Herrmann and Beck (1897) from Vlčí Hora (Wolfsberg; labeled 'VH' in Fig. 2A). At this locality, they described dark-red fine- to coarse-grained sandstones with abundant kaolinized feldspars, quartz pebbles in places, and rare pebbles of 'quartz porphyry' allegedly "rich in feldspars and dark mica". Apart from sandstones, Herrmann and Beck (1897) noted tectonically fractured dark-red breccia with fragments of "felsitic quartz porphyry, partly with fluidal bands". The Permian deposits at Vlčí Hora were mentioned by Pietzsch (1963) together with the Döhlen and Weißig basins (Fig. 1B), to be in direct association with the NW–SE faults. In Saxony, less extensive Permian outliers are present associated with the Lusatian Fault near Radebeul, Rossendorf and Rosinendörfchen (e.g., Huhle and Lange, 2010; Fig. 1B).

In 1957, the ore exploration borehole VH-1 (located within the Vlčí Hora outlier; Fig. 2A) drilled a subcrop section of the Lusatian Fault for the first time. Beneath granitoids, it recorded a ~5-m-thick fault damage zone dipping towards the NE, represented by tectonic gouge with clay and quartz fragments. The damage zone was underlain by ~25-m-thick red-to-brown 'quartz porphyry' (Chrt, 1957). The remaining Permian outliers cropping out along the Lusatian Fault – Doubice and Kyjov ('D' and 'K' in Fig. 2A) – were mapped by Fediuk et al. (1958) whose depiction of all the outliers was largely followed by later mapping geologists (Klein et al., 1971; Opletal et al., 2001; Valečka, 2006). In addition, the outlier near Kyjov was explored in more

Table 1

The overview of lithofacies recorded by borehole 6412_L (Lesné) and found in outcrop (lithofacies 'Gl'; Nádaskay et al., 2019b) and interpretation of their depositional setting

Lithofacies	Lithology	Description	Interpretation of the depositional environment
Ccs	Conglomerate	Clast-supported, polymictic, red-to-brown (secondary whitish) coloured (Fig. 6A). Clasts are mostly semi-angular with substantial portion of rounded pebbles (Fig. 6B) represented by carbonates – dolomitic limestones (Table 2).	Deposited by a high-energy fluvial stream, possibly on a braided fan; transport of coarse-grained material over a relatively short distance.
Gl	Greywackes	Lithic. Coarse-grained, matrix-supported, poorly sorted. Greyish-coloured. Framework dominated by floating, coarse-sand (up to 2 mm) lithic clasts (fine-grained metasedimentary rocks or shales). Subordinate quartz grains (~5 %) are represented by coarse silt to coarse sand. Clay in matrix up to 20%. No macroscopic clasts of contemporary volcanic rocks. Contain chiefly Cadomian zircons and no younger.	Short distance-transport (from local source) by density flow (debris flow) either in fluvial channels or in marginal lacustrine to deltaic setting.
Sm, Scb	Sandstones	Fine- to medium-grained (Fig. 6F), subordinately coarse-grained or with an admixture of coarse sand and granules, all with a substantial admixture of silt and clay. They form single or less frequently amalgamated ~15 cm to several dm thick beds, sometimes fining upwards. Bases of individual beds may be sharp or erosive. Massive (Sm) or locally with primary cross-bedding (Scb; Fig. 6E).	Deposited as fluvial channel fills. Cross-bedding, present in places, indicates the transport of sand as a fluvial bedload.
M	Mudrocks (claystones to siltstones)	Predominantly mudstones to siltstones, locally with fine-sand admixture. Bedding commonly deformed (with slickensides); deformation sometimes with mineral (?pyrite) impregnations. Red-to-brown or brown-coloured (Fig. 6G). Basal pale grey mudstone (Fig. 6E) but did not yield any microfossils. Sieved material contained angular to subangular quartz and subordinate opaque grains, sometimes idiomorphic (Fig. 6F). Lower Si/Al ratio, low $CaCO_3$ values and higher values of Mn, Ni and V (Table 3).	Deposited on the alluvial plain from mud-dominated suspension transported by overbank flow common during riverine floods. Grey mudstone is Permian in age and probably contains juvenile, volcaniclastic material.
L	Carbonates	Represented by (Fig. 5): (1) limestone bed, ~30 cm thick, overlying the sandstone; (2) strongly calcified sandstone to locally sandy limestone, ~1.5 m thick; (3) pebbles (rounded and subrounded, up to 3 cm across) of dolomitic limestone (Table 3) within lithofacies Ccs (Fig. 6A, B). Both originally micrite-dominated, although micrite was progressively replaced by microsparite (Fig. 6C, K, L). Both may contain accessory (>1%) coarse-silt, rarely to fine-sand (up to 0.01 mm in diameter) as well as feldspar grains. No macro- or microscopic fossil remains or trace fossils preserved, compared to limestones in the Döhlen Basin. In addition, several sandstone beds (such as that at ~20 m; Fig. 6) are capped by heavily calcified sandstones (up to 5 cm) with rather gradual lower boundaries.	Interpreted as deposits of fluvial channels; may have been formed as non-pedogenic calcrete that developed in association with a fluctuating water table (valley calcrete or channel calcrete).

detail by two boreholes (KV-H-1, KV-H-2) that drilled Permian sandstones and mudstones up to 7 m below the surface, thrusted over the Upper Cretaceous. The Permian outlier at Lesné ('L' in Fig. 2) was neither displayed on these maps nor corroborated by boreholes. However, its existence was inferred by Kolaříková (2002) who discovered fragments of reddish rocks of allegedly Permian age scattered on slopes near Lesné.

Permian rocks at subcrop were revealed by shallow boreholes in the Elbe Valley north of Děčín (Absolon, 1979; labelled 'DN' in Fig. 2A). Reddish deposits underlying the Upper Cretaceous in Bohemian Switzerland north of the ČKB were discovered by drilling (displayed in e.g., Nádaskay et al., 2024), although they are considered to represent pre-Late Cretaceous weathering profiles rather than Permian deposits.

Based on comparison with the tectonic setting of the Permian near Hodkovice nad Mohelkou (~35 km SE outside the study area; e.g., Prouza et al., 1997), Coubal et al. (2014), inspired by previous authors (Fig. 4; e.g., Klein et al., 1971; Malkovský, 1987, after J. Dvořák, 1962, pers. comm.), suggested that the Permian outliers may have formed a part of the ČKB prior to their Meso-Cenozoic deformation.

METHODS

LITHOFACIES

Lithofacies were studied primarily in core from borehole 6412_L while exposures of Permian deposits at the Lusatian fault (e.g., Vlčí hora) brought some additional information. Both lithofacies found in outcrop and in core are summarized in Table 1. Lithofacies description follows the widely applied scheme of Miall (1977) and considers lithology, grain size, texture, style of bedding, sedimentary structures, sorting and clast roundness. Geometries and spatial relationships were not studied due to the scarcity of exposures and their limited dimensions.

TECTONIC AND GEOPHYSICAL INVESTIGATIONS

Juxtaposition of the Permian and the Upper Cretaceous (Fig. 3) and their tectonic deformation was studied in the core from borehole 6412_L (location in Fig. 2B). Physical observations were further supplemented by a range of well-logs including acoustic and caliper logs in order to: (1) verify the possible shift between core description and the actual depth of individual beds as recorded by well-logs; (2) explore the original dip direction of individual tectonic features as observed in core.

Field investigation allowed for interpretation of the geological setting of the drilling site and its vicinity in close detail, i.e., at scale 1:10,000 (Fig. 2B), compared to previous mapping at 1:50,000 (Valečka et al., 2001) and 1:25,000 (Valečka, 2006) scales. In addition, a geophysical survey was conducted as a series of case studies on this segment of the Lusatian Fault. Electrical profiling (dipole configuration $A_{20}B_{40}M_{20}N$) and vertical electrical sounding (VES; 50 m increment), electrical tomography (MEM/ERT), and gravimetry were employed to determine the extent of the Permian rocks in order to select the most suitable location for borehole 6412_L. The geophysical survey was performed on four, ~N–S-oriented sections, each of them ~700 m long. In this paper, we illustrate one VES section that intersects the location of borehole 6412_L (location in Fig. 2).

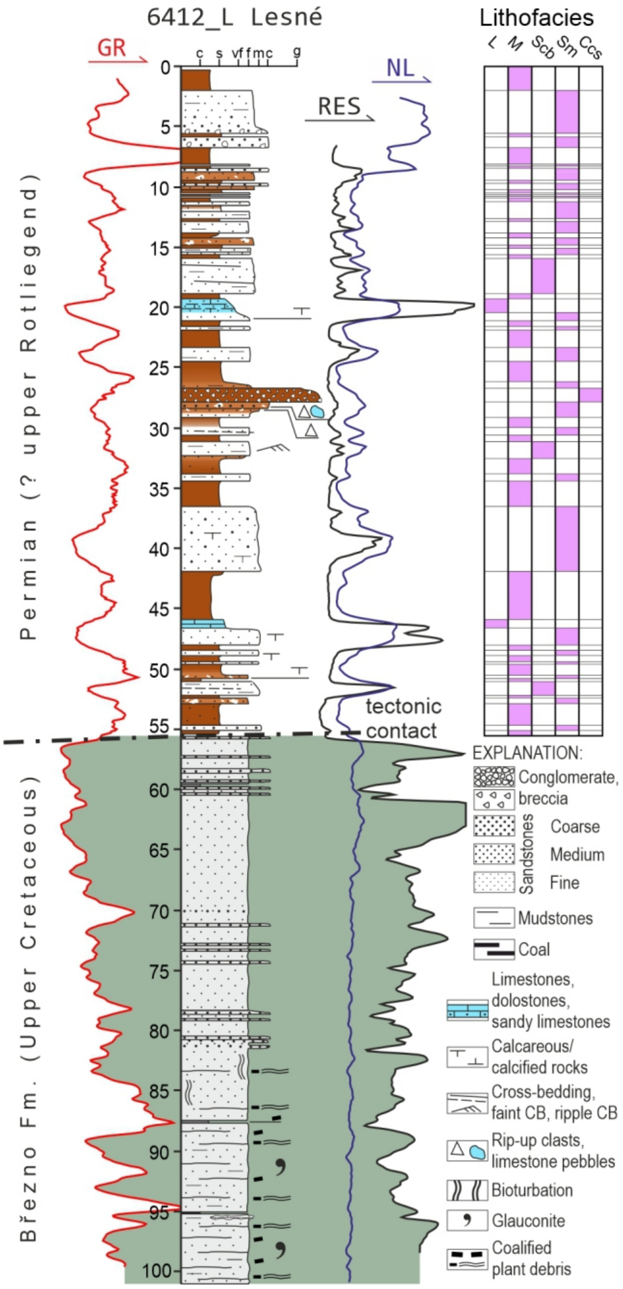


Fig. 5. A sedimentological section of the borehole 6412_L Lesné

Lithofacies (as summarized in Table 1) indicated in the right column

RESULTS

LITHOLOGY AND FACIES OF THE PERMIAN OUTLIERS ASSOCIATED WITH THE LUSATIAN FAULT

The section studied, borehole 6412_L (Fig. 5) is dominated by cyclic alternations of sandstones and mudstones with intercalations of carbonates and conglomerate. Lithofacies are listed by decreasing energy of the depositional environment, and are summarized in Table 1.

Lithofacies **Ccs** refers to a single conglomerate bed, ~1.2 m thick, found in the core. The bed is formed by clast-supported, polymictic pebble conglomerate (Fig. 6A, B). Originally red-to-brown, the conglomerate is whitish in places due to bleaching that may be attributed to a spectrum of processes at different phases of diagenesis (cf. Aehnelt et al., 2021). Clasts are mostly semi-angular, although a substantial portion of well-rounded pebbles is also present. Rounded clasts are represented by fine-grained carbonates (Fig. 6B) – dolomitic limestones by chemical composition (Table 2). This lithofacies is interpreted to be deposited by high-energy streams, possibly on a braided fan, that facilitated transport of coarse-grained material over a relatively short distance.

Lithofacies **Gl** represents lithic greywackes that were not present in the core, but were found in an outcrop near Vlčí Hora (Fig. 2A) and described by Nádaskay et al. (2019b). Its thickness is uncertain because of the limited exposure. The greywackes have been exposed to intense recent/sub-recent surface weathering. They are greyish, coarse-grained, matrix-supported and poorly sorted. The framework is matrix-supported, dominated by “floating”, coarse sand-sized (up to 2 mm) lithic clasts, exclusively of fine-grained metasedimentary rocks (phyllites, slates). Subordinate quartz (~5%) is represented by coarse silt to coarse sand grains. The muddy matrix constitutes up to 20%. The greywackes do not contain macroscopic clasts of contemporaneous volcanic rocks. Lithofacies Gl represents relatively poorly sorted, immature material transported over a short distance (a local source in the Lusatian Massif as shown by Nádaskay et al., 2019b) and probably deposited from debris flows, stream flows, or sheet floods associated with hyperconcentrated flows (Miall 1977, 1996; Collinson et al. 1996).

Lithofacies **Sm** and **Scb** refer to predominantly fine- to medium-grained sandstones, subordinately coarse-grained or with admixture of coarse sand and granules (Fig. 6F). The sandstones are argillaceous or contain substantial admixtures of silt and clay. These sandstones form single or less frequently amalgamated beds ~15 cm to several dm thick, some fining upwards. Bases of individual beds may be sharp or erosive, but are frequently not preserved due to tectonic deformation. Most commonly, the sandstones appear massive (Sm; Fig. 6A, E); primary cross-bedding is preserved only in a few cases (Scb; Fig. 6E). Lithofacies Sm and Scb are interpreted to be deposited as fluvial channel-fills. Cross-bedding, present in places, indicates transport of sand as fluvial bedload.

Lithofacies **M** comprises a variety of fine-grained rocks referred to as ‘mudstones’. This lithofacies is represented predominantly by variously silt-rich mudstones to siltstones, in beds from several cm up metre-scale thick. A fine sand admixture may also be present. These rocks are usually red-to-brown or brown (Fig. 6G) with greyish reduction spots or bleached greyish areas; in one case (at the boundary with the Upper Cretaceous sandstones), the entire mudstone bed is pale grey (Fig. 6H). Locally, primary horizontal bedding is preserved, though it is commonly deformed. The deformation is frequently accompanied by slickensides (Fig. 6G), in places also with mineral (possibly pyrite) impregnations. The pale grey mudstone at the top of the Permian (Fig. 6H) was originally confused with the Upper Cretaceous – similar grey mudstones are frequently found within the Coniacian of the Lusatian/Zittau Mts. and their vicinity (e.g., Valečka, 2006; Nádaskay et al., 2019b). However, washed and sieved (using 0–15 mm sieve) samples taken from that mudstone did not yield any microfossils (e.g., foraminifers) diagnostic for the Late Cretaceous. The sieved material only contained quartz and subordinate opaque mineral grains

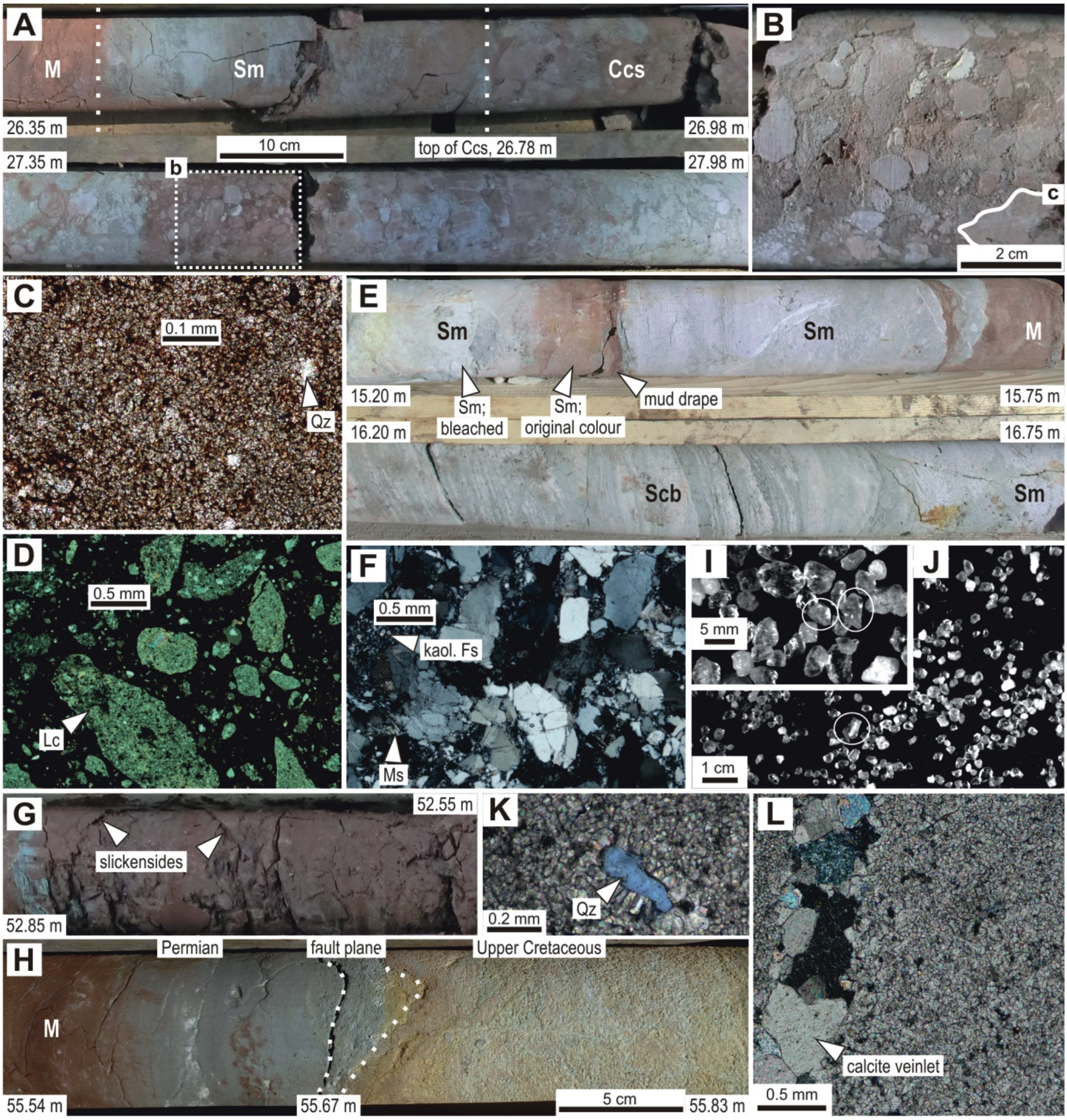


Fig. 6. Photographic plate of the main lithofacies of the Permian outliers. All figures are from borehole 6412_L (Lesné outlier) if not stated otherwise

A – section of core illustrating the transition from lithofacies Ccs (clast-supported conglomerate, detail in Fig. 10B) through Sm (massive sandstone) to M (mudstone); **B** – detail of lithofacies Ccs (clast-supported conglomerate) deposited by debris flow (debrite), depth 27.5–27.6 m; note abundant rounded to subangular clasts of carbonate rocks; one of the highlighted clasts is shown in Figure 10C; **C –** photomicrograph of one of the carbonate clasts from Figure 10B; the rock is texturally dominated by microsparite with rare "floating" silt-sized quartz grains; **D –** coarse-grained lithic greywacke with argillaceous matrix from the Vlčí Hora outlier (for location see Figs. 1 and 3); Lc – lithic clast, cross-polarized light; **E –** section of core illustrating the macroscopic appearance of sandstone lithofacies Sm (massive) and Scb (cross-bedded), note bleaching of sandstone in the upper left side of the figure; parts of the sandstone bed displayed as white in stratigraphic section were most likely also bleached (except those with a kaolinite matrix); **F** – poorly sorted sandstone with abundant brittle fracturing of quartz grains, depth 47.00 m, cross-polarized light; **G** – section of core illustrating the macroscopic appearance of lithofacies M (mudstones and siltstones), the slickensides are most likely tectonic in origin; **H** – close-up of tectonic contact between Permian mudstone and Upper Cretaceous sandstone; **I, J –** sieved material from a sample of grey mudstone in Figure 10H, quartz grains are notably angular, some even idiomorphic (e.g., indicated by circles); **K, L** – photomicrographs of sparitic limestone (lithofacies L) from depth 46.00 m, note the quartz grain with a rim of coarser oriented sparry calcite grains in Figure 10I, cross-polarized light

Table 2

Bulk-rock major-element composition of carbonate rocks in borehole 6412_L

Sample/depth (m)	Lithology	Fe_2O_3	FeO	MgO	MnO	CaO	CO_2	$CaCO_3$	$MgCO_3$
		wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
27.60	dolomitic limestone	2.10	0.19	16.61	0.239	21.48	33.71	38.43	34.75
46.00	limestone	0.59	0.20	1.74	0.186	39.26	33.71	70.08	3.64

(Fig. 6I, J), mostly angular to subangular. Some grains show idiomorphic crystals (Fig. 6I, J) that may indicate an input of juvenile, volcaniclastic material. An Upper Cretaceous age of this mudstone is excluded by major element concentrations and ratios (Table 3). The Upper Cretaceous mudstones from neighbouring borehole 4650_X (Svor; Fig. 2A) show a higher Si/Al ratio, elevated $CaCO_3$ values (at least ~14%) and very low (below detection threshold) values of Mn, Ni and V. Lithofacies M was likely deposited on an alluvial plain from a mud-dominated suspension transported by overbank flow common during riverine floods.

Lithofacies **L** is represented by carbonate rocks. A strongly calcified sandstone to locally sandy limestone between ~19.00–21.50 m (Fig. 5) and a compact limestone bed, ~30 cm thick at depth of 45.70–46.00 m, overlie the massive sandstone (facies Sm). These two carbonate beds are also well-defined by maxima in well-logs (Fig. 5): resistivity (RES) and neutron log (NL). The carbonate rocks are also represented by abundant pebbles (rounded and subrounded, up to 3 cm in diameter) within lithofacies Ccs (Fig. 6A, B). It is evident from their microstructure and chemical composition (Table 2) that the carbonates are partly dolomitic, particularly the pebbles. As indicated by microstructure (Fig. 6C, K, L), the carbonates were originally micrite-dominated, although most of the micrite has been progressively replaced by microsparite; in places, sparite crystals up to 1 mm are visible. Within the carbonate matrix, accessory (<1%) coarse-silt, rarely to fine sand (up to 0.01 mm in diameter) quartz as well as feldspar grains are present. No macro- or microscopic fossil remains or trace fossils were found, compared to limestones reported from the Döhlen Basin (Gebhardt and Schneider, 1993; Schneider, 1994). In addition, several sandstone beds (such as that at ~20 m; Fig. 5) are capped with heavily calcified sandstones, up to 5 cm thick, with generally gradual lower boundaries. No structures were found that would indicate dessication or dissolution.

The depositional environment of the carbonates (limestones, dolomitic limestones) is impossible to interpret due to the high degree of recrystallization. No fossils or structures were found that would indicate deposition in a lacustrine environment (cf. Gebhardt and Schneider, 1993). Similarly, no pedogenic features (such as rhizoconcretions) were found, suggesting that these carbonates did not form in soils (cf. Gebhardt, 2024). The vertical association of the carbonates with sandstones, interpreted as deposits of fluvial channels, suggests that they may have been formed as non-pedogenic calcrete that developed in association with a fluctuating water table (valley calcrete or channel calcrete; e.g., Carlisle, 1983; Machette, 1985; Khadkikar et al., 1998).

Table 3

Selected element proxies for fine-grained rocks at different levels of the Permian and Upper Cretaceous

Sample	Lithology	Si/Al	Ti/Al	Zr/Al	Mg	Fe	Ti	Mn	Ni	V	Sr	$CaCO_3$
					%	%	ppm	ppm	ppm	ppm	ppm	%
Permian (borehole 6412_L)												
14.80	siltstone (sandy)	2.88	0.037	0.004	0.80	1.20	2450	92	11	51	47	0.83
33.40	mudstone	2.59	0.050	0.004	1.27	3.80	3987	231	21	71	59	2.19
49.95	claystone	2.38	0.071	0.004	1.33	4.30	4491	216	16	77	44	1.08
50.98	claystone	2.17	0.056	0.003	1.80	2.48	5459	188	33	73	162	1.69
55.50	mudstone (?tufitic)	2.06	0.034	0.002	1.93	2.22	4748	69	50	79	63	0.24
Upper Cretaceous (borehole 4650_X)												
78.12	siltstone (sandy)	8.89	0.173	0.005	0.91	1.12	5900	nd	nd	nd	105	22.50
90.14	siltstone (calcareous)	4.55	0.070	0.003	0.65	1.75	3200	nd	nd	nd	203	21.82
116.71	mudstone (calcareous)	4.60	0.064	0.004	0.84	1.65	3500	nd	nd	nd	145	16.26
175.84	mudstone	3.52	0.060	0.003	1.01	2.03	4800	nd	nd	nd	65	14.51

Element concentrations below the detection limit are labelled as ‘nd’

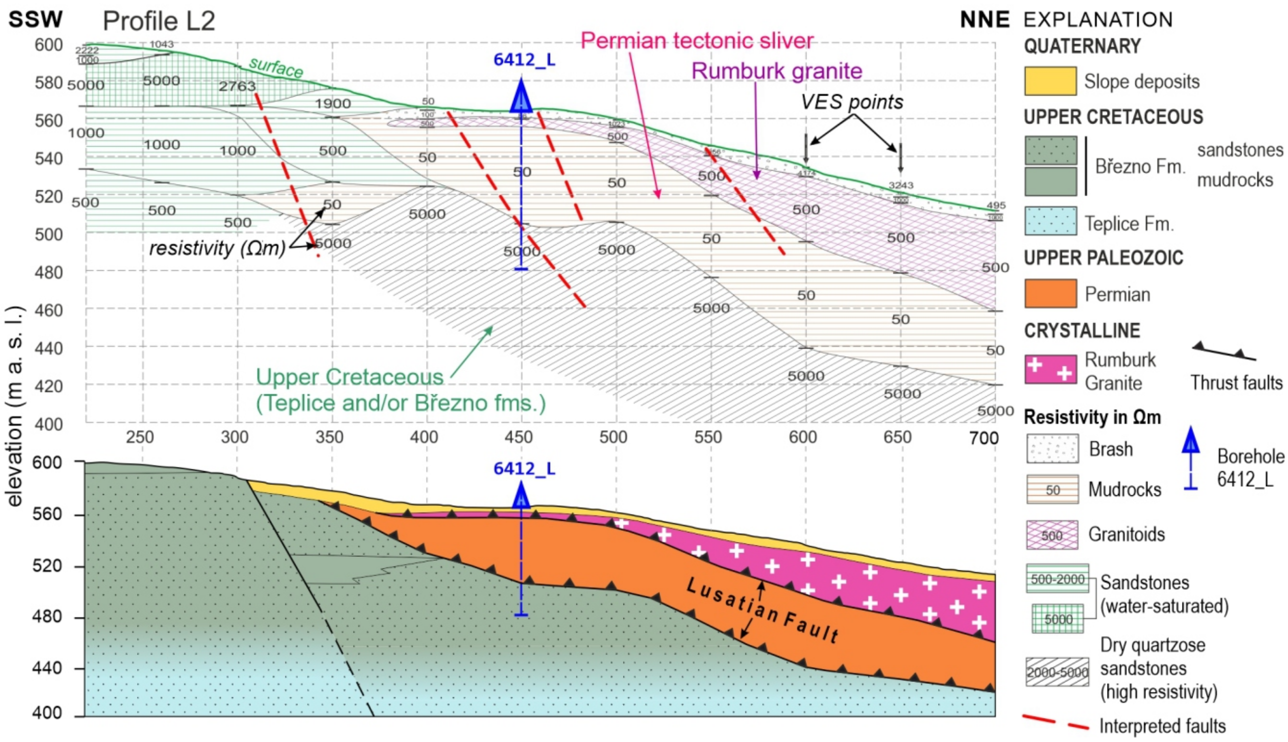


Fig. 7. Geophysical (VES) section showing electric resistivity of subsurface rocks in the vicinity of borehole 6412_L (Lesné outlier)

TECTONIC DEFORMATION OF THE SECTION STUDIED

Geophysical measurements indicated that the planned borehole 6412_L could reach the presumed base of the Permian ~70 m below the surface. At this depth, high-resistivity rocks of unknown composition were revealed, presumably volcanic rocks of Paleozoic age or granitoids (Fig. 7). The base of the Permian tectonic sliver was drilled 55.5 m below the surface. It overlies Upper Cretaceous sandstones of a high resistivity explained by the absence of pore water, even though these well-sorted, porous sandstones act as groundwater aquifers in the vicinity of the borehole. The boundary between the Permian and the Upper Cretaceous is tectonic and is represented by a fault plane at the base of a grey siltstone (Fig. 6H); there is no accompanying deformation penetrating the immediate vicinity of the fault plane.

According to relevant well-logs (Figs. 8 and 9), the most obvious deformation of the core is found in the topmost part of the section (0–10 m) as a result of intense near-surface weathering and gravity effects, since the borehole was located at the brink of a steep topographic slope. Tectonic deformation of the section (mosty fracture zones, with slickensides in places) was further observed at depths of ca. 20, 23, 27, 31–35, 45 and 58 m (Figs. 8 and 9). Within the entire section (incl. the Upper Cretaceous), only a few intervals with moderate tectonic deformation are present. In the core, macroscopically conspicuous fracture zones with diagnostic features such as slickensides with striae are mostly found within the Permian deposits, notably fine-grained rocks (mudstones, siltstones). However, the fine-grained rocks were heavily disintegrated, so measuring these tectonic features was not possible. Measurable, steep slickensides (ranging from 45 to 85°) were visible in the sandstones. Steep dislocations with subhorizontal grooves (striations) were also found in one case, and another case with less pronounced grooves around 20° was recorded in the interval of ~20 m depth. Crack dislocations in sandstones show a wide dispersion of plunge from ~30 to ~90°. Some of the cracks are covered by a thin veneer, up to a few mm thick, probably of clay minerals, in places accompanied by secondary pyrite and calcite mineralization. However, the veneers of secondary minerals do not exhibit any striae. As for the primary structures, i.e., depositional, unrelated to the tectonic deformation, it was difficult to clearly distinguish sharp erosional bases from the stratification. Undoubted primary stratification was found in a handful of cases: horizontal (0°) at 15.5 m, subhorizontal (up to 5°) at 19.25 m, 39.5 m and 51.7 m, 20° at 50.8 m, 40° at 52.2 m. Primary bedding was found at 16–16.5 m (20–30°) and at 18.5 m (~ 30°). Corrugated (undulose) or deformed (convolute) stratification was found in the interval 16.5–16.7 m, and wavy lamination between 31.3 and 31.7 m. In the Cretaceous part of the section studied, mostly insignificant inhomogenities are interpreted from the caliper log, while the Permian part of the section locally shows moderate to strong inhomogeneities (Fig. 8; close-up of deformed interval in Fig. 9). However, the effects of tectonic deformation in the core are not as pronounced as expected. As evident from well-logs, particularly the acoustic televiewer log (Fig. 9), the drillcore was shortened by tectonic deformation and related core loss by ~1 m within the Permian interval.

DISCUSSION

DEPOSITIONAL ENVIRONMENT

The depositional environment of the section studied is interpreted as an alluvial system, from the alternation of fluvial sandbodies (lithofacies Sm and Scs) and alluvial-plain mudstones (lithofacies M). The presence of lithofacies Ccs, interpreted as deposited from hyperconcentrated- or debris-flows, as well as from poor sorting and the presence of im-

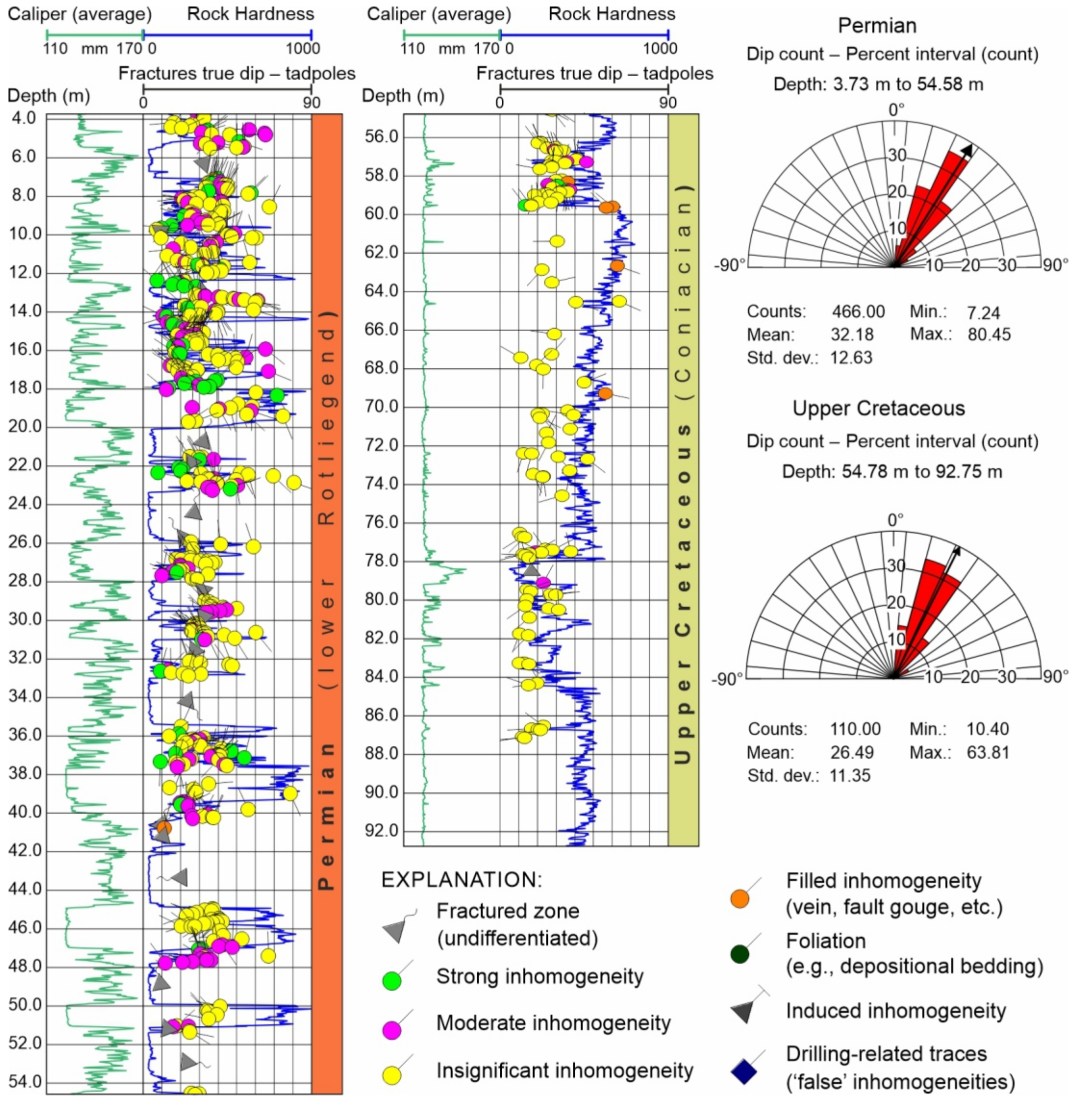


Fig. 8. Caliper log measured in borehole 6412_L with interpreted dip direction of Permian and Upper Cretaceous deposits

mature material within both lithofacies Ccs and Gl, imply transport over a short distance and local sources of clastic material, presumably the Lusatian Massif and its cover. Thus, the alluvial system may have been located near to the basin margin, likely bordered by a high-topography, uplifted area.

Interpretation of the depositional environment of the carbonates (lithofacies L) in the section studied is impossible due to high degree of recrystallization obscuring the diagnostic features of the carbonate microfacies. Due to their vertical association with channel-fill sandstones, these carbonates may represent valley or channel calcretes similar to those documented from the Trutnov Fm. (Martínek, 2008). As a result of gradual aridification since the latest Pennsylvanian (e.g., Roscher and Schneider, 2006), carbonate deposits (limestones to dolostones), or even evaporite beds, can be frequently found within Permian successions in the post-Variscan basins of central Europe.

In the Bohemian basins, sedimentary features associated with aridification (calcretes, aridisols with Ca-rhizoconcretions, evaporites and aeolian deposits) are most commonly found within the Trutnov Fm. ('Saxonian', upper Rotliegend; Fig. 10) and younger, upper Permian–Triassic formations (cf. Holub and Tásler, 1978; Uličný, 2002). Although early diagenetic carbonate cementation of channel-fill fluvial sandstones is already present in the basal Permian Vrchlabí Fm. (e.g., Štolfová, 2004; Schöpfer et al., 2022), contemporaneous carbonates are more frequent within lacustrine successions (e.g., Blecha et al., 1999; Martínek et al., 2006; Stárková and Čáp, 2017). Early Permian lacustrine successions with carbonates are present within the Vrchlabí, Prosečné, and Chotěvice formations of the Krkonoše Piedmont Basin (KPB; Fig. 5) and are interpreted as deposits of more or less perennial lakes with variations in their hydrological regime, oxygenation and prevailing nature of deposits (shales vs. carbonates; e.g., Martínek et al., 2006). In the Döhlen Basin, limestones are present within the Niederhäslich Fm. (Fig. 6) and are interpreted as playa lake deposits (Gebhardt und Schneider, 1993; Schneider, 1994). Such lakes may have expanded across the basin as a result of wetter intervals within a long-term aridification trend (cf. Roscher and Schneider, 2006).

Comparison of lithofacies development of the section studied with successions in Bohemia and Saxony (Fig. 10) suggests that the Lesné outlier is related neither to the Česká Kamenice and Krkonoše Piedmont basins nor to the Döhlen Basin, namely the lower part of its fill. Based on this comparison, the Lesné outlier is likely younger Permian, comparable to younger Permian ('Saxonian', upper Rotliegend) basins in the eastern

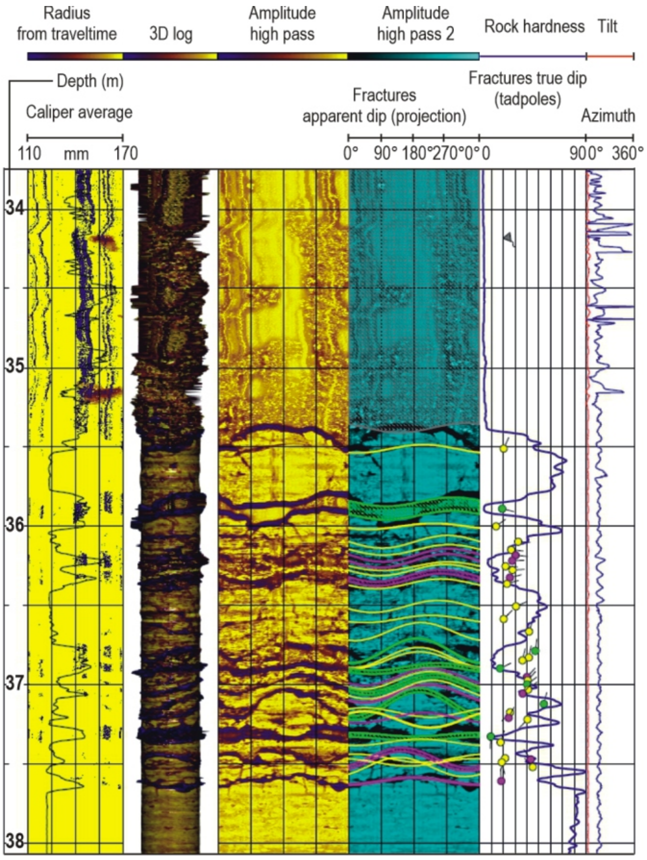


Fig. 9. Acoustic log of a selected section of borehole 6412_L (~34–38 m) to illustrate the style of tectonic deformation of the Permian sedimentary rocks

Explanation of tectonic symbols in Figure 8

Bohemia – Trutnov–Náchod sub-basin (of the KPB) and Orlice Basin. By contrast, the Permian deposits at Vlčí hora bear more lithological similarity to the basal part of the Döhlen Basin and the Weißig Basin, particularly due to their association with volcanic rocks.

AGE OF THE SUCCESSION STUDIED AND ITS CORRELATION TO NEIGHBOURING BASINS

The absence of stratigraphic markers including fossils within borehole 6412_L (Fig. 5) did not allow for precise dating of the section; a relative stratigraphic dating was only possible by correlation of lithological markers in the core with the sedimentary record of neighbouring basins of Permian age (Fig. 10). The most relevant for this discussion are the Döhlen and the Weißig basins in Saxony, and the adjacent Česká Kamenice (ČKB), Mnichovo Hradiště (MHB) and Krkonoše Piedmont (KPB) basins in the Czech part of the Bohemian Massif. The KPB is some distance away, but its fill is exposed over a large area and has a well-explored stratigraphy.

The Permian section recorded by borehole 6412_L is relatively coarse-grained compared to the lower Permian deposits of the ČKB recorded by borehole Vf-1 Volfartice (cf. Vejlupek et al., 1986) where the Pennsylvanian–Permian section is dominated by mudrocks. The depositional record of the ČKB is correlated with that of the MHB and the KPB (Pešek, 2001) and the presence of lacustrine horizons within both basins indicates a relatively more humid environment despite the overall aridification trend expected for this part of Pangaea from the Late Pennsylvanian onwards (e.g., Roscher and Schneider, 2006).

This is consistent with the depositional record of the Döhlen Basin that comprises a series of relatively thick, economic coal seams (from ~1 to 9 m thick; Reichel and Schneider, 2012) within the Döhlen Fm. in the lower part of the basin fill. The presence of these coal seams and the fossil record led to considering the lower part of basin fill, comprising the basal Unkersdorf Fm. as well as the Döhlen Fm., as being Late Pennsylvanian in age (e.g., Schneider, 1994; Schneider and Hoffmann, 2001, Reichel and Schneider, 2012; Schneider et al., 2020). Both the palaeoflora and the fauna from the Döhlen Basin clearly indicate Late Pennyslvanian to early Permian age of the basin fill. The palaeoflora of the Döhlen Fm. was summarized by (Barthel, 1976, 2016) who compared it with that of the Manebach Fm. of the Thuringian Forest Basin and Netzkater Fm. of the Ilfeld Basin, to which he assigned early Asselian (earliest Permian) age. Although Barthel (2016) suggested an early Permian age of the Döhlen Fm. based on its comparison with the Manebach Fm., he also admitted that the Döhlen Fm. contains stratigraphically an older Carboniferous flora. Evaluation of the species listed by Barthel (2016) clearly shows that nearly all have their first occurrence in the Late Pennsylvanian, some even in its lower part. Only *Scolecopteris oreopteridia* and *Lobatopteris geinitzii* have their first occurrence in the middle Autunian, which Wagner and Álvarez Vázquez (2010) assigned to the latest Gzhelian. A late Gzhelian age is further supported by common presence of *Pecopteris integra*, the last occurrence of which is in the Stephanian C, while the rarity of conifer remains typical of Asselian age is surprising (Wagner, 1984; Wagner and Álvarez Vázquez, 2010). Late Pennsylvanian age is further supported also by a fossil fauna most notably represented by blattids, of the blattid zone *Sysciophlebia ilfeldensis-Spiloblattina weissigensis*. Identification of this zone also indicates the age of the formation around the Pennyslvanian-Permian boundary (e.g., Reichel and Schneider, 2012; Gebhardt et al., 2018; Schneider et al., 2020). This is in agreement with the most recent high-precision U–Pb CA–ID–TIMS dating of the Manebach Fm. (Käßner et al., 2024) which at 299.1 ±0.2–0.4 Ma clearly indicates its late Gzhelian (latest Pennsylvanian) age. High-precision dating by Käßner et al. (2024) also constrained the age of the Döhlen Fm. to between 299.5 ±0.2–0.4 Ma (age of the Wilsdruff-Potschappel Porfyr in the underlying Unkersdorf Fm.) and 299.0 ±0.1–0.4 Ma (age of the Zauckerode Tuff in the lower part of the overlying Niederhäslich Fm.). Both the similar palaeoflora as well as the numerical ages allow correlation of the Döhlen Fm. to the Ploužnice Horizon in the KPB (Fig. 10), to the Klobuky Horizon in central Bohemia, and the coal-bearing Rosice–Oslavany Fm. in the Boskovice Basin (Fig. 1C; Opluštil et al., 2013, 2016a, b, 2017). The age of volcanic rocks in the basal part of the Weißig Basin (299.1 ±0.4; Käßner et al., 2021) suggests that the grey deposits within the Hutberg Fm. may be a counterpart of the Döhlen Fm. coals, and of the Bohemian Ploužnice and Klobuky horizons.

The age of the Zauckerode Tuff (299.0 ±0.1–0.4 Ma; Käßner et al., 2024) indicates that the Pennsylvanian-Permian boundary lies within the Niederhäslich Fm., the upper part of which contains lacustrine limestones and thin coal interbeds (cf. Gebhardt and Schneider, 1993). As indicated by lithology, these lacustrine deposits may be coeval with the lacustrine Rudník Member, or possibly the younger Kalná Horizon of the KPB (Opluštil et al. 2013, 2016b). Even Käßner et al. (2024) admits that the age of the Niederhäslich Fm. is in conflict with the age that has been derived from biostratigraphic correlations

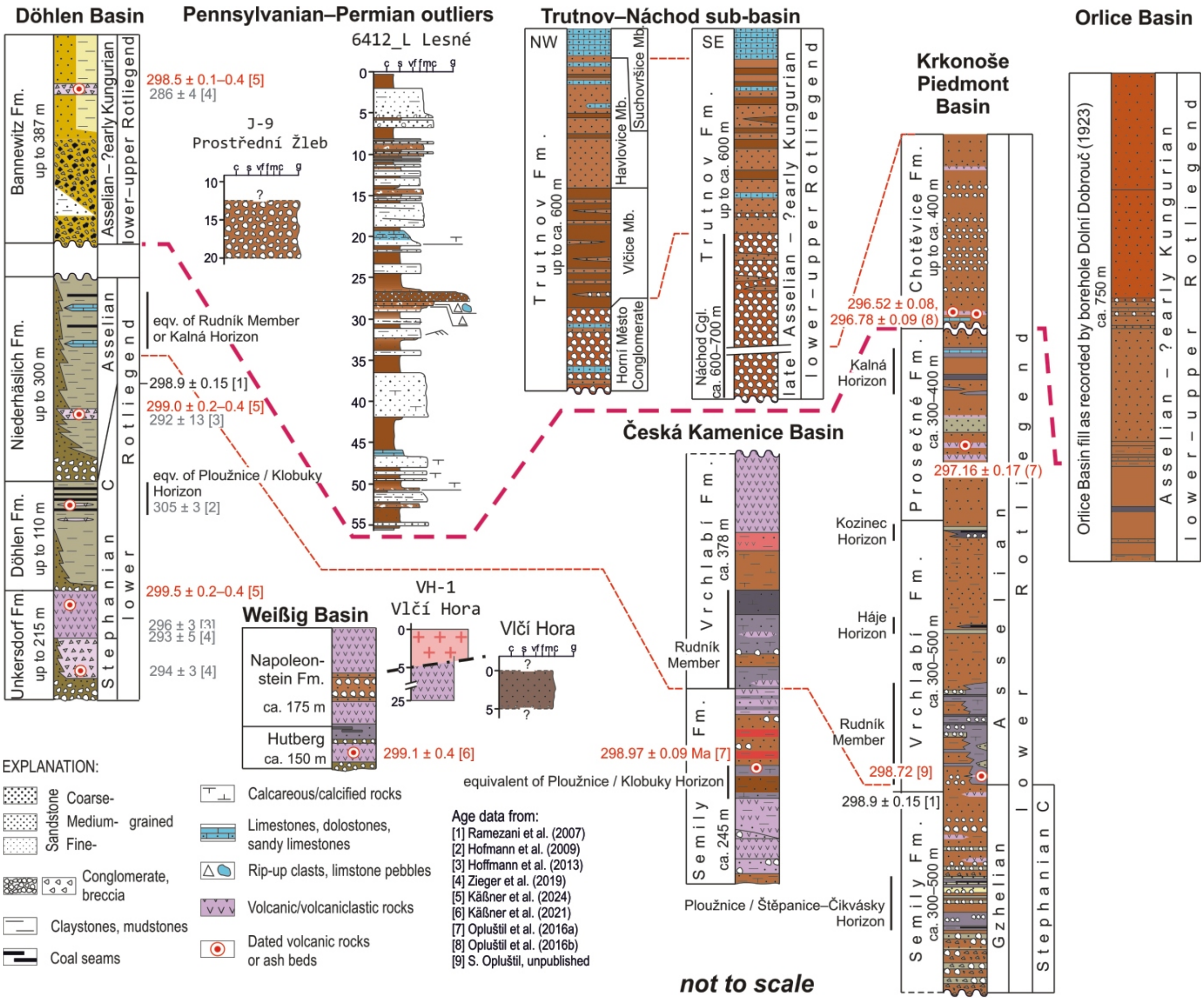
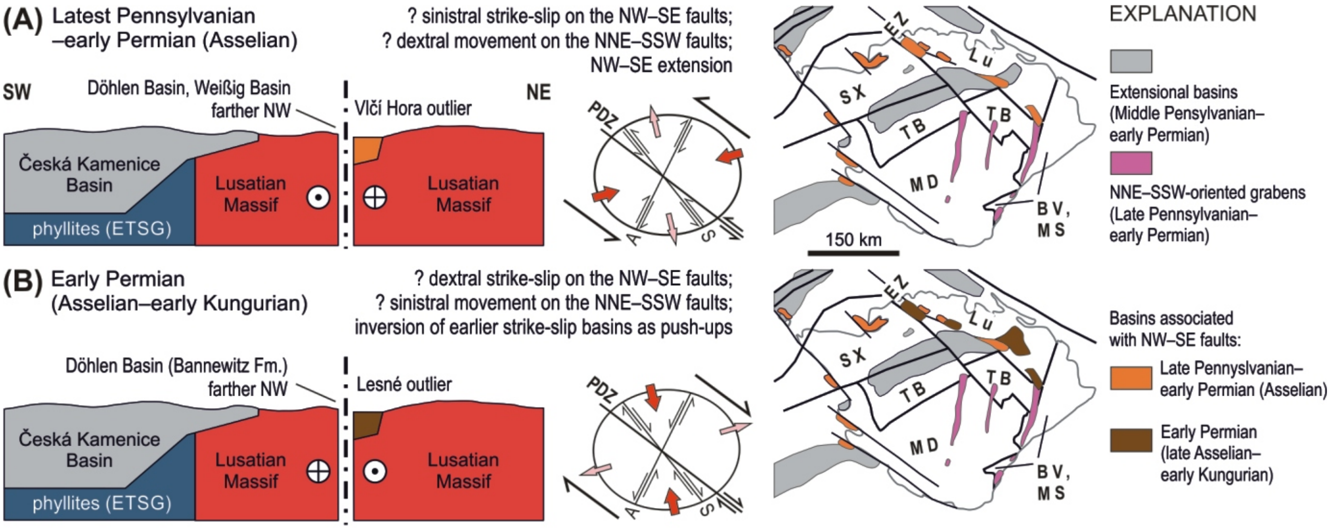


Fig. 10. Correlation of the Permian along the Lusatian Fault as recorded by borehole 6412_L (near Varnsdorf, N Bohemia) with the Elbe Valley (north of Děčín) and other relevant Pennsylvanian–Permian basins on the NE Bohemian Massif

Idealized lithological section and thickness of individual formations of the Döhlen Basin in Saxony after Reichel and Schneider (2012, and references therein) and Zieger et al. (2019); for the Weißig Basin after Schneider and Reichel (1989) and Reichel (2012); for the Česká Kamenice Basin after Pešek (2001); for the Krkonoše Piedmont Basin after Opluštil et al. (2016b); for the Trutnov–Náchod sub-basin and Orlice Basin after Pešek (2001). The Pennyslvanian-Permian boundary according to [1] Ramezani et al. (2007). Datums for the Döhlen Basin after [2] Hofmann et al. (2009), [3] Hoffmann et al. (2013), [4] Zieger et al. (2019), [5] Käßner et al. (2024); for the Weißig Basin after [6] Käßner et al. (2021). Correlation between the ČKB, KPB and Kladno–Rakovník basins based on data of [7] Opluštil et al. (2016a), [8] Opluštil et al. (2016b) and [9] S. Opluštil (unpublished). Red datums represent the most recent numerical ages, in grey are numerical ages by previous authors and ages in black denote the stage boundary ages. Well-logs: GR – gamma-ray log, RES – resistivity log, NL – neutron log

based on amphibian assemblage zones that suggest a younger age by from 1.6 to 2.1 MY, corresponging to the Broumov Fm. in the Intra-Sudetic Basin (Fig. 1C), i.e., the upper part of the Vrchlabí to Prosečné Fm. in the KPB (Opluštil et al., 2016b). Thus, the unconformity between the Niederhäslich Fm. and the overlying Bannewitz Fm. may be the equivalent of the unconformity between the Prosečné and Chotěvice formations. However, the age of the Wachtelberg Tuff in the Bannewitz Fm., at 298.5 ±0.1–0.4 Ma (Käßner et al., 2024), is notably older than than the volcaniclastic/volcanic rocks dated from the Prosečné (297.16 ±0.17; Opluštil et al. 2016a) and Chotěvice (296.49 ±0.08 Ma and 296.81 ±0.05; Opluštil et al., 2016b) formations. The age of the Bannewitz Fm. as described by Käßner et al. (2024) falls within the Rudník Member in the basal Permian (298.72 Ma; S. Opluštil, unpublished).

The apparently older ages of both Niederhäslich and Bannewitz formations were explained by Käßner et al. (2024) to be caused by protracted zircon crystallization – i.e., the actual eruption ages would be younger, and more in accord with the lithofacies development (Fig. 10) and biotic (plant and arthropod fossils) record (e.g., Barthel et al., 2001; Schneider and Romer, 2010; Schneider et al., 2020). With respect to the lithofacies development and overall context, we interpret the Lesné outlier studied as corresponding to relatively younger Rotliegend deposits of the Chotěvice or even Trutnov forma-



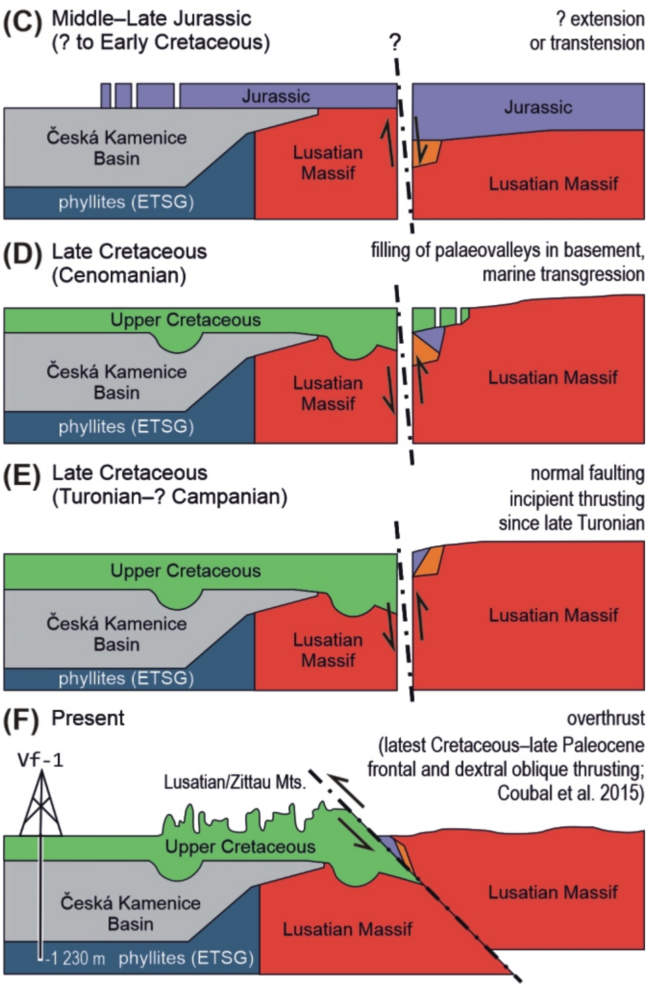


Fig. 11. Idealized 2D model of Late Paleozoic and subsequent Meso-Cenozoic tectonic evolution of the Lusatian Fault and adjacent geological units

Not to scale. The overview maps for the Late Paleozoic show the juxtaposition of basins formed during different tectonosedimentary phases. The strain ellipses indicate the dominant stress regime during the strike-slip phases. Explanation to geological units: BV, MS – Brunovistulian, Moravosilesian; ETSG – Elbtalschiefergebirge (‘Elbe schist belt’); EZ – Elbe Zone; Lu – Lusatian Block; MD – Moldanubian; SX – Saxothuringian; TB – Teplá–Barrandian; PDZ = Principal displacement zone

tions, and the Bannewitz Fm. The Vlčí Hora outlier is probably older, corresponding to the fill of the Weißig Basin and of the lower part of the Döhlen Basin.

TECTONIC SETTING OF THE PERMIAN

Although borehole 6412_L provided new and unique data on the tectonic deformation of the rock formations exposed adjacent to the Lusatian Fault, these data alone are insufficient for unambiguous interpretation of the tectonic history of the area, particularly during the pre-latest Cretaceous interval (cf. Coubal et al., 2015). Well-logs as well as borehole cores show that the Permian rocks are markedly more deformed than the Upper Cretaceous. Striae and steep slickensides found sparsely in the core imply a horizontal σ_1 stress during thrusting of the Permian over the Upper Cretaceous.

Coubal et al. (2014, 2015) focused on interpreting field tectonic data collected from the Upper Cretaceous sandstones along the Lusatian Fault. These data are, however, related to the latest phases of development of the Lusatian Fault, such as the thrusting of the crystalline basement over the Upper Cretaceous. Furthermore, some authors (e.g., Klein et al., 1971; Malkovský, 1987) interpreted the original position of the Permian and the Jurassic as underlying the infill of the BCB, from where these rocks were dragged by thrust faulting (Fig. 4). The Permian is, however, not present beneath the Upper Cretaceous within ~6 km of the vicinity of the Lusatian Fault. This may be a result of formation of the Pennsylvanian–Permian outliers as part of a larger basin or basins, together with the Weißig and Döhlen basins whose formation has been associated directly with strike-slip faults (Hofmann et al., 2009; Zieger et al., 2019; Käßner et al., 2021, 2024). Likewise, the Jurassic has not been recorded in the subcrop of the entire NW part of the BCB so far, despite relatively dense borehole coverage in this territory. As conceived by Voigt (2009), the absence of *in-situ* Permian and Jurassic formations from which the outliers along the Lusatian Fault could have been derived, resulted from inversion of tectonic blocks separated by the fault and subsequent erosion of these formations prior to the Late Cretaceous (Fig. 10). This notion is supported by sedimentary provenance studies (Hofmann et al., 2018; Nádaskay et al., 2019b) as well as thermochronology data (Käßner et al., 2020).

FORMATION AND DEMISE OF THE PERMIAN BASINS IN A WIDER GEODYNAMIC CONTEXT

Comparison of the depositional setting as well as the stratigraphic correlation of the Pennsylvanian–Permian outliers in northern Bohemia with coeval basins in the NE Bohemian Massif revealed a relation to the Weißig and Döhlen basins located within the Elbe Zone, several tens of km to the NW (Fig. 1B).

The Late Paleozoic tectonic activity within the Bohemian Massif, accompanied by localized basin formation, was related to deeply rooted basement faults. The timing of this tectonic activity indicates the possibility of polyphase Late Paleozoic strike-slip tectonic events (cf. Arthaud and Matte 1977; Edel et al. 2018; Elter et al. 2020).

The present-day northern Bohemian Massif, including the study area, was significantly affected by late-Variscan to early post-orogenic tectonic processes between ~330–310/305 Ma, i.e., during the Late Mississippian to Middle Pennsylvanian (cf. Žák et al., 2013, 2018; Opluštil et al., 2016b; Edel et al. 2018; Tomek et al., 2021). At that time, WNW–ESE extension related to orogenic collapse within the Variscan belt (e.g., Zulauf, 1994; Henk, 1997; Žák et al., 2012, 2018) led to dextral movement along crustal-scale NW–SE shear zones (e.g., Arthaud and Matte, 1977; Edel et al. 2018). During this phase, NW–SE faults accommodated the relative westward oblique convergence of Gondwana and Laurussia (e.g., Arthaud and Matte, 1977; Martínez Catalán, 2012) and caused the marked right-lateral offset of the Lusatian Massif and the Erzgebirge (Fig. 1A, B; Mattern, 1996). Additionally, this process may have driven formation of the NNE–SSW-oriented shear zones within the Bohemian Massif representing Riedel joints to the NW–SE dextral faults (cf. Arthaud and Matte, 1977; Matte, 1986; Matte et al., 1990) at ~329–327 Ma (Zachariáš and Trubač, 2014).

The transition from post-orogenic to intraplate tectonic processes occurred around 306/305 Ma (cf. Opluštil et al., 2016b; Žák et al., 2018). It was marked by accumulation of Late Pennsylvanian (through early Permian) strata that were deposited after a significant change in palaeogeography (cf. Opluštil and Pešek, 1998), particularly the Líně–Semily–Vrchlabí formations. These formations were deposited within the Pilsen–Trutnov Basin Complex (PTBC; Fig. 1C), formed by NNE–SSW extension, of which ČKB was part. In addition, recent high-precision dating (Käßner et al., 2021) indicates that fill of the Weißig Basin, as well as that of the lower part of the Döhlen Basin, is coeval to the deposits of the ČKB and the KPB.

The extensional tectonics that affected the Bohemian Massif may have interfered in its northern part with a phase of strike-slip reactivation of the NW–SE faults (cf. Mattern, 2001). This phase purportedly occurred between ~310 Ma and approximately the Pennsylvanian-Permian boundary (~300/298 Ma; Mattern, 2001; Edel et al., 2018; Bárta et al., 2021) and involved sinistral strike-slip movements on the NW–SE-oriented faults driven by NE–SW compression (Aleksandrowski et al., 1997; Mattern, 2001; Edel et al., 2018; Fig. 11A). Within the Elbe Zone, this deformation was identified by Mattern (1996) as ductile sinistral strike-slip deformation of the SE margin of the Meißen Massif. The potential heat source facilitating this ductile deformation may be found in the Stolpen Massif, emplaced around 298.4–298.3 Ma (Käßner et al., 2021): its age roughly sets the upper boundary for this tectonic phase. These sinistral strike-slipe movements are also indicated by the formation of transtensional basins at the western margin of the Bohemian Massif (Mattern, 1995a, b). Additionally, during this phase, approximately around or after ~305 Ma (cf. Zachariáš and Trubač, 2014) the NNE–SSW-oriented shear zones noted above (Riedel joints to the NW–SE faults; Brandmayr et al., 1995) may have been reactivated as sinistral strike-slip faults to form NNE–SSW-oriented grabens (Fig. 11A). The geometry of these grabens, i.e., the Blanice, Jihlava and Boskovice basins (Fig. 1C), is strikingly oblique to the axis of the extensional Pilsen–Trutnov Basin Complex. The explanation for the sinistral strike-slip reactivation of the NW–SE fault zones (and related NNE–SSW-oriented shear zones) can be found in the far-field stress transfer from the Uralian Orogeny between ~310–270 (e.g., Mattern, 2001). This likely initiated the Late Pennsylvanian–early Permian sinistral wrench movements along the Trans-European Shear Zone (TESZ; Fig. 1A) that caused disruption and erosional truncation of the Variscan Foreland Basin (Fig. 1A) and the external Variscan fold-and-thrust belt (Kiersnowski and Buniak, 2006).

With respect to these interpretations, we assume that some of the Permian outliers at the Lusatian Fault in northern Bohemia may represent remnants of a basin or basins formed during this tectonic phase. The most likely candidate is the Vlčí Hora outlier (Fig. 11A) whose lithological development with greyish sedimentary rocks (greywackes) and felsic volcanic rocks resembles the fill of the Weißig Basin (Fig. 5). The provenance of the Vlčí Hora outlier points to a local source in the adjacent Lusatian Massif and suggest no recycling of inverted fill of the ČKB (Nádaskay et al., 2019b) whose provenance is expected to be more varied, similarly to that of the Krkonoše Piedmont Basin (Martínek and Štolfová, 2009). The involvement of NW–SE faults reactivated during the late Pennsylvanian to early Permian in the formation of the Weißig and Döhlen basins was also suggested by Käßner et al. (2024).

The most pronounced strike-slip reactivation of the NW–SE faults occurred during the late early Permian, i.e., the late 'Autunian' (late Asselian–early Sakmarian, ~296.8–291 Ma) through 'Saxonian' (whose base is informally placed between the late Sakmarian and the early Kungurian; ~291–283 Ma). The reactivation of the NW–SE faults may have been controlled during this phase by reactivation of major fault zones of central Europe of generally NW–SE trend, e.g., the Elbe Zone and the TESZ, that generated widespread subsidence in the Southern Permian (Rotliegend) Basin (e.g., McCann, 1998). This phase substantially overlaps with the Asturian and Saalian (~300–290 Ma) tectonic phases of the Variscan Orogeny that have been interpreted to be associated with final consolidation of the Variscan terranes with Baltica, décollement folding of the Variscan foredeep and formation of the Southern Permian (Rotliegend) Basin in its place (Ziegler, 1975; Praeg, 2004). This basin was shaped predominantly by transtensional strike-slip movements during the early Permian (Gast and Gundlach, 2006). Their timing is interpreted at ~300–290 Ma (Gzhelian–Sakmarian), although Hoffmann (1990) interpreted a continuation of (waning) strike-slip tectonic activity until ~283 Ma (Artinskian/Kungurian). This is in accord with the duration of the mantle-plume magmatism that affected northern Europe between ~300–240 Ma (Neumann et al., 2004; Heeremans et al., 2004). The post-Variscan tectonic reorganization of central Europe led to thermal relaxation of the lithosphere as the dominant subsidence mechanism in the Southern Permian (Rotliegend) Basin (van Wees et al., 2000; Kiersnowski and Buniak, 2006) neighbouring the N/NE Bohemian Massif.

During this phase, the Döhlen Basin was formed as a 'strike-slip basin' according to Zieger et al. (2019), based on provenance, i.e., interpreted shift of source areas as well as U–Pb LA–ICP–MS dating of the Wachtelberg Tuff of the Bannewitz Fm. (286 ±4 Ma). Although recently dated by Käßner et al. (2024) as older (298.5 ±0.1–0.4) than expected by Zieger et al. (2019), the Bannewitz Fm. is likely younger due to possible protracted zircon crystallization which Käßner et al. (2024) admits as likely due to other factors (lithology, biotic record, overall climatic and tectonostratigraphic framework) that point to a younger age of the formation in reality.

The onset of deposition in the Döhlen Basin may have been roughly coeval with deposition of the Chotěvice Fm. in the KPB (Fig. 10). This formation unconformably overlies the older early Permian formations, and comprises fluvial strata markedly coarser than those of the underlying Prosečné Fm. (cf. Pešek, 2001) while its lacustrine deposits occupy a different part of the KPB, suggesting depocentre shift. Arguably, the deposition of the Chotěvice Fm. may have occurred as a result of incipient tectonic rearrangement of the KPB when the NW–SE faults gradually took over the E–W faults that dominated the earlier, extensional basin geometry (Schöpfer et al., 2022). It is even more significant that, during this phase, the infill of the KPB was inverted and this was accompanied by pervasive brittle deformation and coeval formation of the Trutnov–Náchod sub-basin (TNSB; Fig. 1C). The latter represents a structurally distinct tectonic element that is superimposed on the older strata in the KPB and is interpreted (Uličný et al., 2002; Wojewoda, 2007; Martínek, 2008) to have formed by dextral motion on NW–SE trending strike-slip faults. The Trutnov Fm. (Fig. 10), which represents the oldest and the thickest part of the infill of the TNSB, is correlated with the Radków Fm. of the Intra-Sudetic Basin (Fig. 1C), dated as younger than 293 ±4 Ma (Awdankiewicz, 2022). In both cases, the basin-floor subsidence was accompanied by generation of a high-gradient topography within surrounding crystalline complexes. Danišík et al. (2010) proposed that successive unroofing and erosion of the Krkonoše–Jizera Plutonic Complex took place during the late early Permian (‘Saxonian’), based on the presence of large volumes of coarse clastic material within basins south, east, and north of the Krkonoše Mts. Within the TNSB, this is indicated by the presence of alluvial-fan conglomeratic facies in the NE flank of the basin (Horní Město Conglomerate; Fig. 10). Tectonic uplift of the Lusatian Block is suggested by a predominant input of Cadomian zircons into the Niederhäslich Fm. of the Döhlen Basin (Zieger et al., 2019). It is also possible that the NW–SE geometry of the Orlice Basin (Fig. 1C), located ~130 km farther SE from the study area, is a result of transtensionally-generated subsidence during this phase, overprinting the basin’s earlier extensional geometry – as suggested by the basal part of the basin fill, correlative to the KPB (cf. Pešek 2001; Fig. 10).

Data from the Lesné outlier together with a report of Permian deposits in the Elbe Valley near Děčín that resemble those of the Döhlen Basin (Absolon, 1979) indicate that either the latter spanned farther SW (to present-day Děcín; Fig. 1B) or was neighboured to the SW by a basin of similar origin (Fig. 11B). This basin was deformed and almost completely eroded following the Late Paleozoic (Fig. 11C–F; cf. Coubal et al., 2015). In the early Permian, the neighbouring ČKB was likely located more to the south, in the proximity of the MHB and KPB, as suggested by their similar lithofacies development (e.g., Pešek, 2001). The Döhlen Basin may have existed for up to 17 Myr some time between ~300–282 Ma (Fig. 10), with the final development phase between the middle Artinskian and early Kungurian (cf. Zieger et al., 2019; Käßner et al., 2024). This is in accord with the approximate dating of activity of transcurrent faults affecting the Sudetes at ~288–281 Ma (Edel et al., 2018).

IMPLICATIONS FOR EVOLUTION OF THE LUSATIAN FAULT IN RELATION TO ADJACENT GEOLOGICAL UNITS

The interpreted geological structure of the pre-Cretaceous basement (Mrázová et al., 2020) demonstrates that granitoids of the Lusatian Massif north of the Lusatian Fault were laterally shifted ~6 km to the SE compared to the same granitoids south of the fault. In the western part of the Lusatian Massif in Saxony, the Upper Pennsylvanian–lower Permian rocks have been preserved directly alongside the Lusatian Fault as the Weißig Basin (Fig. 1B) as well as several outliers (Fig. 1B; Huhle and Lange, 2010). Following the Late Paleozoic strike-slip tectonic movements and related basin formation, the uplifted basement of the Lusatian and Krkonoše–Jizera blocks was gradually eroded and the entire area peneplained (e.g., Danišík et al., 2010) and surrounded by a continental to marginal marine depositional environment during the late Permian and Triassic (cf. Doornenbal and Stevenson, 2010). During the Jurassic, the area north of the Lusatian Fault probably subsided and was flooded by an epicontinental sea. The Jurassic was deposited within a basin likely covering the entire Lusatian Block (Fig. 11C; Hofmann et al., 2018; Nádaskay et al., 2019b) and probably a vast area of pre-Mesozoic basement between the Lusatian Fault and Prague (Valečka, 2019). This contradicts the entrenched concept that the Jurassic underlies the Upper Cretaceous (e.g., Malkovský, 1987) and that remnants of the Jurassic as well as the Permian were dragged from beneath the base of the Upper Cretaceous (Fig. 4). Erosion of the Jurassic deposits must have taken place prior to the Late Cretaceous transgression (Fig. 11D), and only subtle remnants of these Jurassic rocks have been preserved in the vicinity of the Lusatian Fault. There is no unambiguous direct evidence on whether the blocks north of the Lusatian Fault had been uplifted and its sedimentary cover eroded, or whether they subsided during the Early Cretaceous. The Late Cretaceous transgression is interpreted to be governed by interplay of eustatic sea-level rise and tectonic inversion of the blocks adjacent to the Lusatian Fault with subsidence of the block south of the fault (e.g., Uličný et al., 2009b; Voigt et al., 2021). As a result of the wide-scale tectonic processes (convergence of Africa, Iberia, and Europe and Alpine Orogeny; Kley and Voigt, 2008; Voigt et al., 2021), the stress field within the Bohemian Massif was reoriented (Coubal et al., 2014, 2015). Unlike the case of the Jurassic, the subcrop of Permian rocks beneath the Upper Cretaceous has been documented by boreholes farther south of the Lusatian Fault (e.g., in the ČKB; Fig. 1B). This led several previous authors (e.g. Malkovský, 1987) to infer that the Permian outliers along the Lusatian Fault are related to the Permian subcrop of the ČKB. According to Coubal et al. (2014), the Permian rocks along the Lusatian Fault in the vicinity of Varnsdorf were deformed in the same fashion as the Permian rocks at the NW tip of the KPB, i.e., pulled from the subcrop and dislocated during the thrust phase of the Lusatian Fault. This is contradicted by our current interpretation. The present-day structural position of the Late Paleozoic, as well as the Jurassic deposits associated with NW–SE faults, indicates that remnants of the Upper Paleozoic and Jurassic on the Lusatian Block that survived until the final inversion of the BCB, were thrusted over the Upper Cretaceous of the BCB as a result of the latest Cretaceous–Cenozoic tectonic activity on the Lusatian Fault, and subsequently eroded.

CONCLUSIONS

1. Based on their lithofacies development, the Permian outliers along the Lusatian Fault are interpreted to have been deposited in an alluvial system located close to the basin margin with a steeper topography. The succession of the Lesné outlier studied contains carbonate rocks (some redeposited) whose presence is in accord with the general trend of gradual aridification with its onset in the late Pennsylvanian and continuing throughout the Permian.

2. The Pennyslvanian–Permian outliers along the Lusatian Fault are unrelated to the subcrop Česká Kamenice Basin (formed as part of the extensional Pilsen–Trutnov Basin Complex) and represent remnants of basins associated with NW–SE faults of the Elbe Zone System. Comparison of their depositional recod with basins in Saxony and within the "Bohemian" Pilsen–Trutnov Basin Complex as well as published absolute ages from both Saxony and Bohemia allow for lithostratigraphic correlation of the dated basin fills associated with the NW–SE faults. Consequently, the Vlčí Hora outlier is correlated with the Weißig Basin (Hutberg Fm.; ~299 Ma) while the Lesné outlier is correlated with the upper part of the Döhlen Basin (Bannewitz Fm.; <296 Ma). Thus, the Lesné outlier could be late Assellian to ?early Kungurian in age and possibly correlates with the 'Saxonian' (lower–upper Rotliegend) deposits of basins of the Trutnov–Náchod sub-basin and the Intra-Sudetic Basin.

3. During the Late Paleozoic, the Bohemian Massif experienced polyphase evolution involving late orogenic to post-Variscan extensional as well as transtensional/strike-slip tectonic processes. The Late Mississippian–Middle Pennsylvanian (~330–310/305 Ma) phase (1) of late orogenic strike-slip tectonic movements was followed by formation of the extensional basins related to orogenic collapse. This process was overtaken by intraplate extension by ~306/305 Ma at the latest. It has been considered that the NW–SE faults (Elbe Zone System) were reactivated in a strike-slipe regime (phase 2) during the Middle Pennsylvanian–early Permian (Moscovian–early Asselian; ~310–300/298 Ma), i.e., concurrently with the intra-plate extension. Another phase (3) of strike-slipe reactivation of the NW–SE faults occurred during the early Permian (late Asselian–early Kungurian; ~297–283 Ma). The timing of large-scale tectonic processes (including activity of strike-slip and wrench faults) within the Variscan Orogeny (cf. Edel et al., 2018; Elter et al., 2020) supports this inferred history.

4. The origin of the Late Paleozoic tectonic movements that affected the NE Bohemian Massif can be found in large-scale, or even global, geodynamic processes (cf. Mattern, 2001; Edel et al., 2018; Elter et al., 2020). Phase (1) was driven by dextral movement along the NW–SE shear zones that accommodated convergence of Gondwana and Laurussia. Phase (2) involving sinistral strike-slip reactivation of NW–SE faults as well as related NNE–SSW shear zones, is thought to have been caused by far-field stress transfer from the Uralian Orogeny. Phase (3) is defined by dextral strike-slip tectonic movements of the faults of the TESZ and Elbe Zone System that were likely reactivated as a result of emplacement of magmatic bodies related to mantle-plume magmatism in the area of the nascent Southern Permian Basin.

Acknowledgements. Finalization of this paper was supported by the Czech Science Foundation (GAČR) project No. 22-11661K. Data acquisition in 2017–2020 was facilitated by the Czech-Saxon applied project ResiBil – transboundary water resource management in the context of climate change sponsored by the European Union (No. 100267011). We thank Štěpánka Mrázová, Václav Tenenko, Sr., and Ottomar Krentz for collaboration on the borehole 6412_L, Olaf Elicki is thanked for microfossil separation, and Miloš Karous (Geonika, s. r. o.) and Svatopluk Kořalka (SG-Geotechnika, a. s.) for high-quality geophysical sections and well-logs, respectively. For valued comments on earlier versions of the manuscript, RN is indebted to Filip Tomek and to Karel Schulmann for his advice under the auspices of the Mentoring program supported by the Strategic Research Plan of the Czech Geological Survey (DKRVO/ČGS 2023–2027). We are grateful to Aleksander Kowalski, Ute Gebhardt and an anonymous reviewer for constructive comments and suggestions that greatly improved the manuscript, to Tadeusz Peryt for careful editorial handling, and to Jan A. Zalasiewicz for language corrections.

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