Lusatian Fault

Structure ID: LUF
Fault Section IDs:
Related terms: Lusatian fault (cze: lužický zlom)

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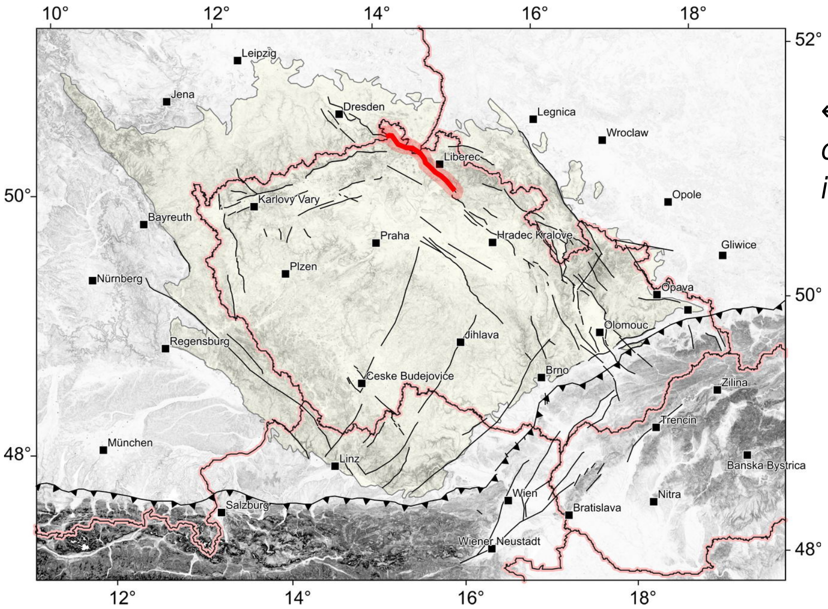
Last update: 22. 5. 2020



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General description

The Lusatian fault is one of the large faults of the NW - SE direction, which forms the structure of the northern part of the Bohemian Massif. Most of them are part of the Elbe fault system (Scheck et al., 2002) - a zone of crustal softening, dominating the construction of part of the Central European platform between the Baltic Sea and the Sudetenland (Fig. 1).

Definition

The Lusatian fault is forming southern limit of the elevated East Sudeten and Lusatian blocks, belonging to the SE part of the Elbe fault system. The fault was defined primarily as the boundary separating the crystalline units of the Lusatian pluton and the Krkonoše-Jizera crystalline (upper Proterozoic to lower Paleozoic), emerging in the pushed NNE block from nonmetamorphic formations of the Bohemian Cretaceous Basin and Permian basins in its bedrock, forming the underlying south-west block (Malkovský, 1977; 1987).

The course of the fault

The fault is approximately 110 km long (Malkovský, 1977, 1979) from the vicinity of Dresden in Saxony to the vicinity of Kozákov near Turnov (Fig. 1). It enters the territory of the Czech Republic in the Šluknov Hook near the settlement of Kopec on the western edge of the village of Mikulášovice. From here it runs as a narrow zone on the border of Upper Cretaceous and crystalline rocks, generally to the SE around the villages of Brtníky, Krásná Lípa, Rybniště, Jiřetín pod Jedlovou and Dolní Podluží, where it rises on the territory of the Republic of Germany. There, it runs near the state border via Kurort Oybin and enters the territory of the Czech Republic again at the Popova skála rocklocality and comes to the Jitravský sedlo saddle via the village of Horní Sedlo. The further course of the fault to the SEE often changes direction and the fault takes the form of a wider zone, deforming rocks of different ages. In this section, it takes place along the south-western and southern slopes of the Ještěd Mountains through the villages of Zdislava, Křižany, Světlá pod Ještědem, Proseč pod Ještědem and the locality of Rašovka to the northern vicinity of Hodkovice nad Mohelkou. From there, in the form of a very wide zone, highlighted by steeply erect layers of the underlying block (especially Upper Cretaceous sediments and Permian rocks), it continues through the villages of Pelíkovice and Frýdštejn to Malá Skála.

Here, the Lusatian fault gradually turns in the direction NW - SE and continues through the northeast of Suché skály to SE to Prosíčko, to north vicinity of Koberovy, then north of Hamštejn Hill to north-western surroundings of Prackovský vrch (250 m from the top) and to the western surroundings of Záhoří (Coubal 1989).

Continuation of the fault to the SE

From here, the Lusatian fault in its characteristic form does not continue. The fundamental question is whether the fault in these places actually ends, or whether it continues in a changed form to the SE or E. On the southwestern slopes of Kozákov, the Lusatian fault is cut off by a transverse Kozák fault (Coubal 1989), running west of Záhoří. Based on the parameters of the applied stress, it can be assumed that this fracture was activated as a left-hand horizontal displacement in the period after the main thrust at the Lusatian fault. The continuation of the Lusatian fault must therefore probably be sought east or northeast of Kozákov within the Upper Paleozoic foothills of the Krkonoše Basin. Significant tectonic lines of the E - W direction are really significantly applied here. One of them is the Kundratice-Javornice disorder (formerly Čikvásecká disorder) - up to 1 km wide range of subparallel faults, flexures and narrow fold structures with steep erect layers. The same direction is also given by the Šodějov thrust fault, forming the northern edge of the Permocarbon Krkonoše foothills between Dolní Bouzov and Hrabačov u Jilemnice. On the contrary, the Koberovy flexure (Coubal 1989), which runs from Kozákov further in the original direction to the SE by the continuation of the Lusatian fault, is most likely not due to a completely different structural style and incomparably smaller amplitude of movement (Prouza, Coubal and Adamovič 2013).

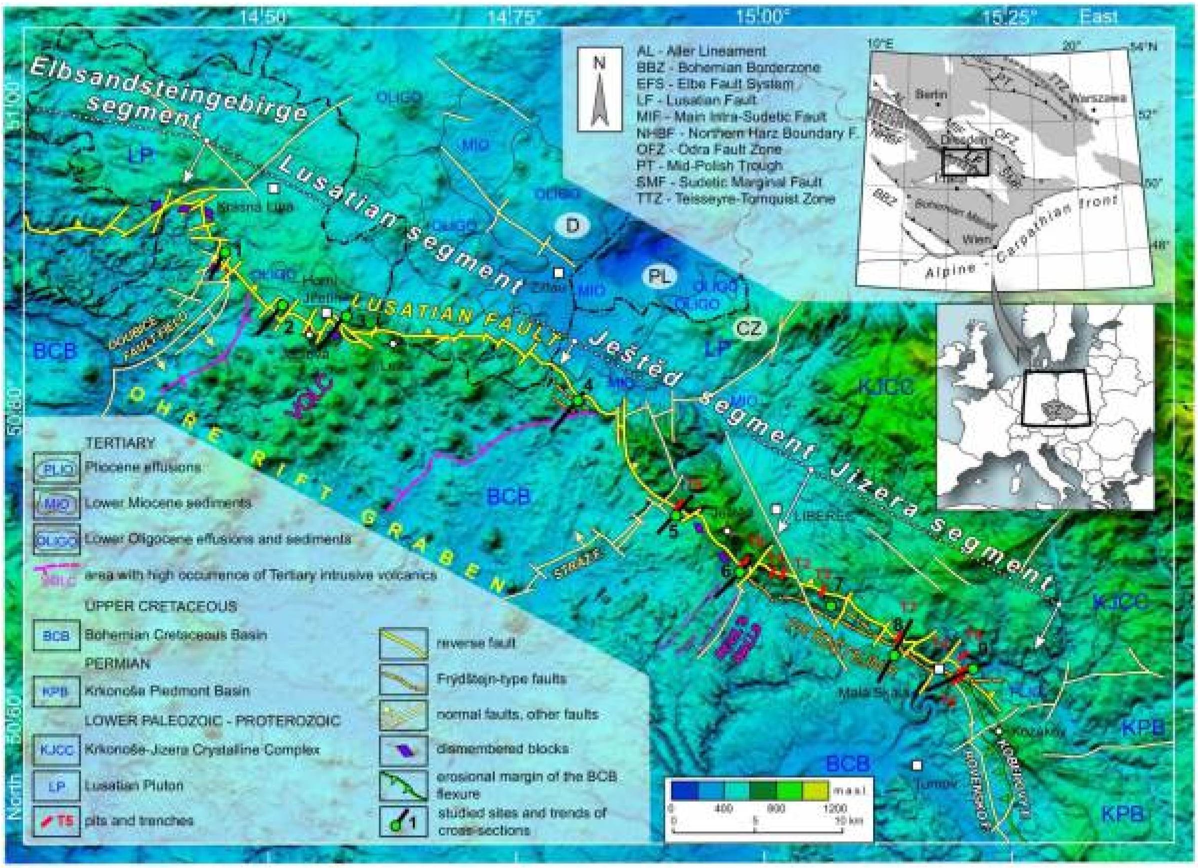

Fig. 1. The course of the Lusatian fault, including its segments on a relief map and with a clear geological sketch of the Bohemian massif.

The Lusatian fault has a rich, polyphase-shaped architecture, i.e. an internal structure (Coubal et al., 2014) which fills a laterally variable, variously wide zone of this regional fault. Therefore, we distinguish between the main fault, referred to as the Lusatian fault, and a conformal accompanying structure of a higher order referred to as the Lusatian fault zone.

The Lusatian fault

is the main fault at the contact of the hanging (i.e. pushed) wall block and the footwall block, on which the largest displacement took place. It includes the fragile structures created in the process of its formation during the main thrust. Between these structures, the core of the fracture can be separated, then the brection zone in the overlying and underlying blocks and the damage zone.

The Lusatian fault zone

includes other elements that arose in the spatial connection to the Lusatian fault, mainly at the time of its origin. It is mainly a zone of silicification (secondary silicification), created in the early stages of the main overthrust, a zone of the lift in the overlying and underlying crust and associated accompanying fractures, and finally a zone with shifts in the strata in the sediments of the underlying crust. These categories are supplemented by other elements that arose during the later stages of polyphase fault development: accompanying fractures of several types and generations, as well as products of later hydrothermal mineralization, such as the commonly present iron-bearing zone. The zone of the Lusatian fault can also include structures whose formation obviously preceded the main thrust at the fault - for example, some continuous deformations (fold deformations) in the underlying block.

Fault structure and dip

Architectural elements of the Lusatian fault

The architectural elements of the Lusatian fault and the Lusatian fault zone are schematically shown in Fig. 2. Because the English nomenclature of architectural elements is used in practice, the English-language version of the scheme is used to facilitate parallelization with other works (Coubal et al. 2014), while the Czech-language version is given in Coubal et al. (2018).

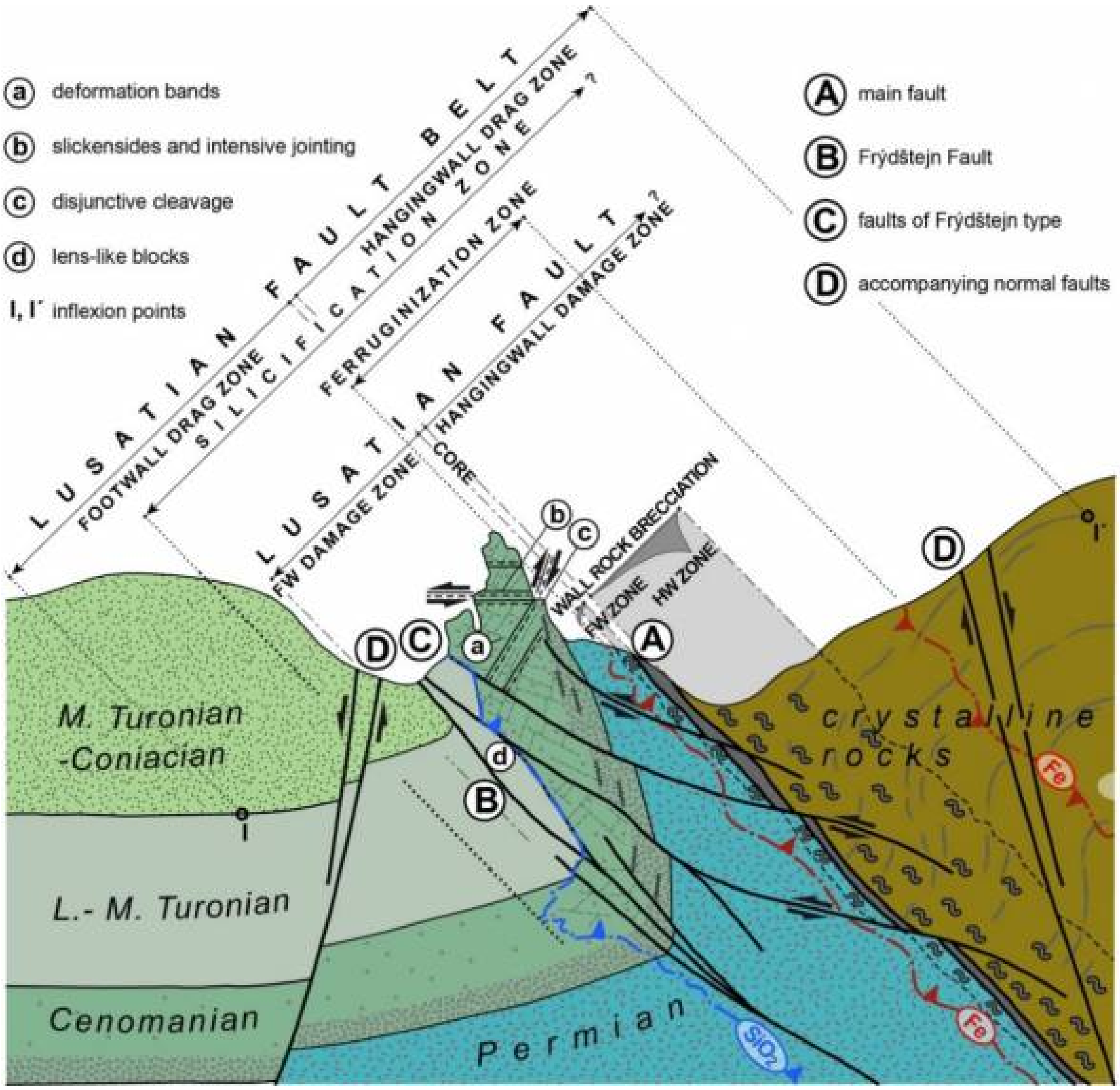

Fig. 2. Architectural elements of the Lusatian fault (Coubal et al. 2018).

Fault core can be observed only exceptionally on natural outcrops. Therefore, it was verified by a series of dug trenches (Prouza et al. 1999), in one case it was penetrated by mining (Reichmann 1979). In most of these localities, the core of the Lusatian fault is formed by its simplest form - a few meters thick position of tectonic clay and fault rocks, discordant with the original rock structure of the hangingwall block and footwall block. From the granular point of view, the core is formed mainly by chaotic breccia, i.e. the type of breccia created by the spread of originally adjacent rock fragments. In addition to finely crushed rocks, the matrix of chaotic breccias also forms clay minerals (Horáček et al. 1975).

In a number of localities, **wide brecciated zones** were documented along the main fault, both in the hangingwall block and footwall block. These zones differ from the actual core in that the rocks were crushed unambiguously in situ. Thus, the rock fragments of these breccias did not undergo further distraction, as can be observed, for example, from the continuity of the crushed lenses of secretory quartz in the phyllites of the hangingwall block. The brecciation cracking subzone was found furthest from the fault, characterized by a small proportion of matrix between rock fragments. The rocks here are only weakly altered, but still densely cracked and permeated with small zones of tectonic clay.

The damage zone is developed in both the hangingwall and the footwall blocks. The character of this zone in the hangingwall block of the Lusatian fault can be difficult to describe due to the ambiguous distinction of Variscan deformations from younger structures. The damage zone adjacent to the fault in the footwall block of the Lusatian fault affects the rocks of the Bohemian Cretaceous basin as well as the rocks of Lower Paleozoic formations. Except for stylolites, we find all types of brittle structures at the Lusatian fault, characteristic of adjacent damage zones of large faults. More or less massively silicified sandstones belonging to various stratigraphic units of the Bohemian Cretaceous basin are most often represented at the contact with the fault. **Deformation bands** are a specific type of failure bound only to them. However, **slickensides with striae** are most often represented in the adjacent damage zone. These surfaces were created mainly in the younger stages of the deformation process by the action of several stress fields. The same areas were often revived, as evidenced by the two generations of preserved striations. A less frequently represented element of this zone is the **disjunctive cleavage**, which has the character of a dense cracking without significant traces of shear movement.

Architectural elements of the Lusatian fault zone

Silicification zone An eye-catching phenomenon near the main fault, especially in the footwall, is the silicification (i.e. silicification) of rocks. The intensity of impregnation of rocks with siliceous cement varies from point cement at the contact of grains to massive filler cement.

Drag zone The drag zone, which affects the parts of the footwall block that are adjacent to the fault, is richly developed at the Lusatian fault both in terms of the number of forms and the area. Between the various forms, we can distinguish two basic groups, namely **torn blocks** and a **continuous bend**. The continuous bend is the most conspicuous building component of its deformation band in the south-eastern part of the fracture. Some authors considered the bend, accompanied by the erection of the layers, to be the Lusatian fault itself, or based on its occurrence, they believed that the fault was replaced by flexure.

The torn blocks are isolated, fault-limited fragments of plate-shaped rocks between the hangingwall and footwall blocks of the Lusatian fault. They have no connection to any continuous fault-adjacent draw-forth unit of a larger scale. They are formed both by rocks of lower members of the Upper Cretaceous sequence and by underlying rocks of Jurassic or Permian age.

Continuous bending structures can be found in all sections of the Lusatian fault. They have different forms, but are always characterized by an asymmetric increase in the intensity of angular deformation towards the main fault surface. This shows that this is a consequence of the trailing effect of the hangingwall block sliding, not the remnant of an older fold structure or flexural character of the fault. Four basic types of trailing half-fold shape, which are characteristic for individual sections of the fault, have been singled out (Coubal et al. 2014, 2018):

Type A. In the section of the Elbe sandstones and in the Lusatian section, the stratification of Upper Cretaceous sediments in the foreland of the fault shows almost no signs of being affected by the drag. Only in the immediate vicinity of the main fault does a reverse drag of the layers appear, manifested by a slight fitting of the layers below the main fault surface.

Type B. Another type of continuous bending appears in the western part of the Ještěd section. As with type A, the basis of the general construction of the zone is a reverse drag. The Cretaceous sediments here fall below the area of the main fault and from the surface outcrop of the main fault they extend at least a few hundred meters to the north below the pushed crystalline complex. In type B - in contrast to type A - a mild form of a normal drag newly appears in the more distant foreland of the fault, which creates a low anticline (compare Fig. 3a).

Type C, best observed on Suché skály, represents a clean normal drag of the layers. This type of drag is typically found in the eastern part of the Ještěd section (compare Fig. 4c).

Type D. Together with the previous type, a specific form of continuous bending is represented in the Jizera section, the morphologically striking manifestation of which in the landscape is an almost continuous strip of erected Upper Cretaceous sandstones. A characteristic feature of this type is the doubling of the Lusatian fault by the accompanying fault, which takes place in parallel with the main fault a few hundred meters further southwest inside the footwall block (compare Fig. 4b).

It can be summarized that in the fracture zones of types A and B the manifestations of simple shear along the fracture predominate, in types C and D the manifestations of pure shear.

Ferriffication zone The vast majority of ruptures in the Lusatian fracture fault zone are filled with iron oxyhydroxides. In most localities, the ferrification is very intense up to the distance of the first tens of meters from the core of the fault and gradually decreases.

Zone with shifts along layered surfaces On the stratified surfaces of subhorizontally placed sandstones of the footwall block already outside the damage zone, slickensides with striae are documented in many places (Seifert 1932, Doležel 1976, Adamovič and Coubal 1999). They are developed on selectively silicified surfaces, following mainly sandstone inserts with a higher clay content or significantly different grain size. These shifts are known mainly along the section of the Elbe sandstones and from the Lusatian section of the fault. In contrast to the western part of the fault, we find layer shifts in the forefield of the Jizera section only exceptionally: they are assumed, for example, in Klokočské skály in the wider vicinity of Suché skály (Mertlík and Adamovič 2005).

Accompanying faults In connection with the polyphase kinematic activity of the Lusatian fault, other faults, spatially close to it or their systems, were also revived. Some of them are directly related to the process of pushing on the main fault, others represent its reactivation or failure during the younger tectonic phases.

In the Ještěd section of the fault, the **doubling of the main thrust** fault was described from several places by a steep accompanying fault.

Another type of accompanying faults, represented by the **Frýdštejn fault**, is related to the thrust on the main fault and the associated drag of the layers. It is a directional thrust in the base of the main fault with a maximum documented displacement of about 550 m near Frýdštejn. By course of this fault, steeply erected blocks were formed in the Jizera section, formed by the basal members of the Upper Cretaceous layered sequence on subhorizontally deposited parts of the more distant southern foreland of the fault. Faults of a similar function, damaging more advanced types of continuous bending at the main fault, are referred to as **Frýdštejn-type faults**.

The sections of the main fault with a deviated direction NW – SE to NNW – SSE are probably related to numerous **associated faults** that transversely disrupt the zonal structure of the Ještěd crystalline hangingwall block. The relationship to the Lusatian fault is illustrated by the two largest of them: the Šimonovice-Machnín fault and the fault, breaking the Ještěd crystalline in the area NW of Malý Ještěd. Both faults converge to the main fault without significantly disrupting it.

Another group of accompanying faults are **transverse faults** in the NNE-SSW direction. They are based on a dense system of transverse ruptures in the damage zone, some of which continue to more distant parts of both blocks. These faults, established during the main thrust as a tensile ruptures, usually do not play a significant role in the more distant foreland.

Size of overthrust on the Lusatian Fault The size of the total overthrust on the Lusatian Fault, i.e. the sum of the amplitudes of all partial movements of the hangingwall block, was and is the subject of only rough estimates. The reason is the complete erosion of non-metamorphic (i.e. upper Paleozoic and younger) sediments from the hangingwall block. The stratigraphy and facial development of the Upper Cretaceous sediments and their comparison with the north Sudetic Cretaceous show that at least during the Lower Turonian and the late Upper Turonian, the two sedimentation areas were connected. Thus, it can be assumed that the crystalline formations of the hangingwall block were originally covered by at least some parts of the Upper Cretaceous layer sequence that are now eroded. Besides, none of its stratigraphic members shows sedimentary features of the immediate vicinity of the coast at the Lusatian fault (Voigt et al. 2006).

Estimates of the size of the total thrust at the Lusatian fault are based on the difference between the altitude of the base of non-metamorphosed sediments of the footwall block near the fault and the highest peaks of the adjacent parts of the crystalline complex of the hangingwall block. However, the sizes determined in this way are probably significantly lower than the fact, because they are not able to affect the thickness of the crystalline in the hangingwall block, eroded together with the platform sediments. In this way, various authors estimated the size of the **vertical component of the total thrust**, generally at more than 800–1000 m.

The full magnitude of the displacement vector along the fracture is given not only by the above-mentioned vertical difference of the two blocks but also by the slope of the fault plane and the orientation of the displacement along it. The geometric parameters of the situation in the northwestern part of the fault (slope of 16 ° to the north, the thickness of submerged Upper Cretaceous sediments about 950 m and their slope of 4 ° to the north, representing the site Vápenný vrch near Doubice) correspond to the total displacement of at least 4700 m. Participation of drag structures on total movement of both blocks in the southeastern part of the fault shows that here we can count on the magnitude of the total thrust of at least 2000 m.

Cross structures and Segmentation

A characteristic feature of the Lusatian fault is the variability of the structure of its zone. In the individual sections of the fault, the form of both the main fault and other architectural elements of the zone, such as the damage zone, drag zone, the nature of silicification, and several other phenomena, gradually changes from NW to SE. Although these changes are usually not completely sudden, it is possible to define partial sections of the fault with a similar structure. Analysis and comparison of the changing character of individual architectural components in different parts of the fault showed that especially changes in the slope of the main fault were the main cause of lateral changes in the structure of the entire zone, resulting in significantly different forms of its NW and SE parts. Based on a similar development of architectural elements, four basic sections of the Lusatian fault were defined (Coubal et al 2014); from northwest to southeast it is the section of the Elbe sandstones, the Lusatian section, the Ještěd section and the Jizera section (Fig. 1). The section of the Elbe sandstones and the Lusatian section are characterized mainly by a slight slope of the main fault, the drag structures are represented here mainly by torn blocks. In the Jizera section, on the other hand, the medium to the steeper slope of the main fault dominates, and the fault-adjacent drag has the character of a continuous bend, associated with the pulling of layers into high slopes. The Ještěd section represents a transition between the two types.

The slightly inclined main fault in the **Lusatian section** was favorably oriented towards the applied stress **α1** in terms of the possibility of shear recovery. The result was a **slightly inclined thrust** with a displacement length exceeding 4 km. In the vicinity of the main fault, only a very narrow zone of accompanying disruptions is developed. The rocks of the footwall block are minimally deformed in the close fault-adjacent parts and only locally silicified. In the sections with a lower slope of the fault, we find from the range of drag structures mainly isolated torn blocks of rocks of lower members of the upper Cretaceous layered sequence or rocks of its Permian or Jurassic bedrock; the sediments of the footwall block usually fit at a very slight angle below the fault plane (reverse drag). One of the more significant types of rock disruption of the footwall block is layered shifts, breaking subhorizontally deposited upper Cretaceous sediments in the forefield of the fault. Because their occurrences so far are related to sections with a milder fault slope (section of the Elbe Sandstones, or Ještěd), it is considered to be the consequences of the subhorizontal movement of the hanging wall block on its immediate bedrock.

A part of the fault between the settlement Kopec on the western edge of the village Mikulášovice and the locality Popova skála near Horní Sedlo in the length of approx. 32 km was defined as the Lusatian section. (Fig. 1). Data on its geological conditions and tectonic structure are contained mainly in the works of Chrt 1956, Fediuk et al. 1958 and Brzák et al. 2007.

Towards the NW, the fault continues with a section of the Elbe Sandstones, which is located in the territory of the Republic of Germany, except for a small part. The first works of German authors mostly concerned the Lusatian fault in the section of the Elbe sandstones with an overlap into the Lusatian section (e.g. Weiss 1827, Cotta 1838), an overview of knowledge about this part of the Lusatian fault was provided by Wagenbreth (1966, 1967).

A gradual increase in the slope of the fault plane in SE part of the fault led to the fact that here, in the so-called **Jizera section**, the same stress **α1** sometimes acted almost perpendicularly (up to 80 °) to the area of the main fault. The movement of the hangingwall block could be only partially realized by a thrust at the main fault; most of the stress was transmitted across the fault plane to the rocks of both blocks with a substantial increase in their compression. The result is the disruption identified by Coubal et al. 2014 as a **“bulldozer” style**. As a result, in the Jizera section, a continuous zone of structures of the normal drag was created in the fault areas of the footwall block (Fig. 4 c). The intensity of their angular deformation generally increases towards the SE, as the fracture slope increases at the same time. In addition to the main fault, the internal structures of the hangingwall block also contributed to the steep uplift of the hangingwall block, especially the numerous thrust faults documented in the Ještěd crystalline complex, or at the main fault also the folds of the drag. In SE part of the Jizera section, the inclination of the main fault to the applied pressure was so unfavorable that it was doubled by the newly created plane of the Frýdštejn fault with a significantly lower slope, allowing full stress relief by shear movement (Fig. 3 b).

A part of the fault from the intersection with the main vein of the Devil's Walls zone near Proseč pod

Ještědem to Kozákov in the length of approx. 18 km was defined as the Jizera section (Fig. 1). Data on its geological conditions and tectonic structure are given by Krejčí 1869, Zahálka 1902, Coubal 1989, Coubal et al. 2014.

The Ještěd section is a space where the characteristic features of the two extreme forms of the Lusatian fault zone merge into each other. Although the crossing takes place gradually within a section several kilometers long, the most significant changes occur at the fault, which forms part of the Devil's Wall zone, which crosses the Lusatian fault roughly in the middle of the Ještěd massif (Fig. 1). In the immediate NW vicinity of the Devil's Walls area, at the Jiříčkov site, the main fault, which is slightly inclined (22° to the NNE), is accompanied by a narrow zone with the blocks being pulled out only to slight slopes (max. 25° to the S). Southeast of the Devil's Walls zone, the main fault suddenly gains a slope of more than 40°. At the same time, we find here a very wide drag zone with slopes of layers here and there exceeding 60° to S. The change in the slope of the main fault in the Devil's Walls is the result of gradual development when the older steep fault (Jizera section) was NW from the zone of the Devil's Walls (Ještěd section) replaced by a more advantageous slightly inclined plane. The original fracture has been preserved as an accompanying one, and the abnormally high thickness of the tectonic clays of its core is probably evidence of anomalous stress before reactivation of the new fracture. With the increasing slope of the main fault towards the SE, a normal drag also appears in the Ještěd section, mainly in the form of a slight anticline in the forefield of the main fault (Fig. 3 a).

A part of the fault from the Popova skála locality near Horní Sedlo after the crossing with the main vein of the Devil's Walls zone near Proseč pod Ještědem in the length of approx. 20 km was defined as the Ještěd section (Fig. 2). In addition to the first findings (Krejčí 1869, Zahálka 1902), a lot of knowledge about the structure of the surroundings of the Lusatian fault in this section was obtained in the search, exploration, and mining of minerals and are presented in mostly unpublished reports, e.g. Rousek and Týlová 1956, Sedlář and Krutský 1963, Krutský 1971, Bělohradský and Petrin 1977, Reichmann 1979.

Scarp morphology

In term of relief, the Lusatian fault zone is a zone where very contrasting geomorphological units meet, which is a reflection and at the same time a proof that they underwent different morphotectonic development related to faults, especially during the Tertiary and Quaternary. The Lusatian fault stretches from Meissen to the Czech Republic along the northern edge of the Saxon and Bohemian Switzerland national parks. In these places, it is not yet easy to clearly trace the direct course of the fault in the relief, even though it already separates the Děčín Highlands in the south from the Šluknov Uplands in the north. The clear course of the Lusatian fault is further to the southeast, where it borders their northern marginal slope of the Lusatian Mountains. The fault slope is divided by several watercourses, which divide it into triangular or trapezoidal facets of various sizes (see Štěpančíková et al. in Coubal et al. 2018). The Lusatian Mountains also contrast significantly with the adjacent Zittau Basin, the northernmost part of which, the Hradec Basin, is formed by Tertiary sediments up to 400 m thick. It was formed by tectonic subsidence along faults in the NE-SW and NW-SE directions.

At the southern end of the Lusatian Mountains, the Lusatian fault significantly turns its course from the NW to the south, which is also accompanied by a steep slope, from a slope of 16 ° to the NE (Elbe sandstones), in the southern continuation - the Jizera section reaches a slope of up to 61 °. After crossing the Jitravské sedlo, it now limits the higher relief to its southern block - the Ještěd-Kozák ridge, which is its most significant expression. This almost 60-kilometer-long ridge was raised in the Tertiary as an elongated block of Paleozoic metasediments and metavulcanites of the Ještěd crystalline complex along the Lusatian fault above the level of the Paleogene leveled surface at the SW and along the parallel Šimonovice-Machnín fault above the bottom of the Liberec basin to the NE. The ridge is asymmetric, which is also reflected in the asymmetric river network, where larger, longer and deeper valleys always run from the ridge to the northeast and shorter streams run down a steeper fault slope to the southwest, which is so younger and where the uplift was more intense (Štěpančíková et al. in Coubal et al., 2018).

Furthermore, the Ještěd ridge continues as the Hlubocký ridge, which is dominated by a quartzite knob with the highest peak, Ještěd. The relief stands out significantly more than 600 m above the contrasting relief of the Ralsko uplands and the Liberec basin. Not far from Světlá pod Ještědem, the Lusatian fault is running towards the ESE into the marginal fault slope of the Ještěd ridge, while the parallel faults follow its foot and control the current morphology of the mountain range. These parallel faults thus limit another part of the ridge, the Kopaninský ridge, separated by the Rašovka saddle and sloping towards the deeply incised valley of Jizera river. The morphological contrast between the ridge and the adjacent Českodubská uplands in the southwest is particularly sharp in the elongated structural-tectonic Hodkovice basin extending along the foot of the Kopaninský ridge. This foot is characterized by illustrative triangular and trapezoidal facets, formed by erosive division of the fault slope, especially on the Permocarbon volcanics. The erect Cretaceous sandstones (Cenoman) at the foot then form expressive rock formations, the most prominent of which are the Maloskalský or Vranovský ridge, limited by the Frydštejn and Lužice faults and highlighted by erosion along these faults. After the Jizera breakthrough, this rock ridge continues to the southeast as the Suché skály ridge, where, however, the left-hand side bounces along the Jizera fault in the NNE – SSW direction, which runs at that point by the Jizera flow axis. The asymmetric Kozákov ridge begins here, the northern part of which is the horst at the Lusatian fault (Štěpančíková et al. in Coubal et al. 2018).

Seismicity

To be revisited after completion of earthquake catalogue. Fix Me!

Catalog of historical earthquakes compiled by Dr. Ivan Prachař does not mention any earthquakes near the Lusatian fault. According to him, the situation is somewhat complicated by the fact that the Lusatian fault represents a kind of channel through which seismic waves caused by earthquakes in eastern Bohemia spread well. Therefore, it is relatively difficult to distinguish observations of more distant earthquakes from those that could be related to the Lusatian fault, and the reliability of historical observations is thus insufficient. Another source of information is a catalog of instrumentally recorded microearthquakes from the Czech Regional Seismic Network (Dr. Jan Zedník, IG CAS). This catalog contains nine microearthquakes, which can perhaps be attributed to the Lusatian fault. The strongest one was the micro-earthquake near Jablonec nad Nisou on October 25, 2010 at night at 2:35:23 GMT (4:35:23 local time). The microearthquake had a magnitude of only 1.6. The mentioned seismic records therefore unambiguously confirm that micro-earthquakes also occur in the area of the Lusatian fault. However, their number is too small to generalize and make unambiguous conclusions about seismic activity. It is not clear whether the micro-earthquakes occur directly at the Lusatian fault or whether it is diffuse seismicity that occurs virtually anywhere. In addition, these shocks may represent so-called induced seismicity, which is related to human activity, such as the extraction of raw materials or the construction of water dams.

Pre-Miocene evolution

Latest Cretaceous and Paleogene tectonic evolution

Tectonic structures were created or reactivated in this period by a group of stress fields α, significant compressions of the general vergency to the north, which were spread from the alpine orogen in this period (Ziegler 1987). Their action was a time-long tectonic process, beginning shortly after the lithification of the youngest Cretaceous sediments preserved near the fault (Coniac, about 88 million years). The compressive stress fields of this group did not act longer than until the beginning of sedimentation of volcanic-sedimentary and sedimentary rocks of the Louč formation in the Hrádek / Zittau Basin in the hangingwall block of the fault (Lower Oligocene, about 33 million years), which already was affected by the influence of later expansion.

The oldest detected member of the relative sequence of post-Cretaceous revived types of structures is deformation strips. They can be considered as an expression of the initial, pre-fracture stage, which affected the horizontally placed (i.e. not dragged out) layers of sediments in the footwall block of the main fault. The stress field responsible for the formation of deformation strips did not differ much from the following stress field α1, the parameters of which were more accurately determined by methods of paleostress analysis. Because it preceded it in time, we marked it by the symbol **α0**.

Their origin was followed by the main thrust at the Lusatian fault, caused by a stress field called **α1**. The direction of maximum compression was roughly perpendicular to the fault strike, resulting in a practically clean thrust motion. The main thrust created a substantial part of the internal structure of the Lusatian fault and is the controlling element of the entire fault zone. It was accompanied mainly by the creation of structures of fault-adjacent drag. Shear structures were also formed, such as slickensides with striae. Also, the stress acted on the most steeply inclined south-eastern part of the fault almost perpendicularly, creating a deformation of the “bulldozer style”, associated with the rotation of the layers near the fault to the vertical or overturned positions.

Another deformation stage is the formation of tensile ruptures, which arose in the environment of continued compression of the NNE-SSW direction, combined with a transverse expansion in the WNW-ESE direction (so-called dilation, compare Fossen 2010). The related stress fields are denoted by the symbol **αβ1–2**. In the footwall block of the Lusatian fault, it enabled the opening of ruptures in the NE – SW to NNE-SSW direction and the penetration of volcanic rocks of polzenite composition (Ulrych et al. 2008, 2014). The veins of the rocks of the polzenite formation are between 80 and 61 million years old and form two populations. One group of veins is cut off by the main fault and their penetration, therefore, occurred before the main thrust on the Lusatian fault, in the stress field **αβ1**. The second group of veins is terminated at the main fault by splitting into several small veins parallel to the fault plane, which indicates the placement of magma only after the formation of the main fault, in the stress field **αβ2**.

The stress field **α2** represents the next, peak stage of the formation of the Lusatian fault, with the direction of maximum compression in the N–S direction (axis σ1 almost horizontal, axis σ3 vertical). On the main fault area, there was a right-hand oblique thrust. Further rotation of the narrow blocks in the close forefield of the fault was prevented by their compression on undeformed blocks in the more distant forefield of the fault, which led to a rapid increase in tectonic stress in the blocks compressed this way. The internal deformation of these blocks was thus fully focused on the formation of ubiquitous shear structures - slickensides with expressive striae. In the sediments of the footwall block, we rarely find slickensides parallel to the main fault. These are mostly thrusts of the same direction, but antithetic, probably representing the second member of the conjugated pair. A characteristic accompanying structure of this phase is disjunctive cleavage, which has not been observed in connection with any other stress field. Under the conditions of the stress field α2, a large part of ruptures perpendicular to the direction of the Lusatian fault was also formed. The remnants of the original plumose structures preserved on their surfaces reveal the formation due to transverse expansion inside the body of the compressed rock. The stress field α2 is also probably associated with the formation of displacements along the layered surfaces in the farthest forefield (Seifert 1932, Doležel 1976, Adamovič and Coubal 1999). The group of stress fields α identified at the Lusatian fault is closed by the compression stage in the NNW-SSE direction, labelled α3. Its manifestations were found mainly on medium-scale ruptures, often oblique or transverse to the main fault.

Oligocene to Early Miocene tectonic evolution

Changing the stress field parameters (swapping the σ2 / σ3 axes and twisting the σ1 axis to the NNE) led to the loading of faults that combine expansion and horizontal displacement (transtension, compare Fossen 2010). In the stress field labelled as **αβ3**, at the same time arose numerous tensile cracks in the direction N-S to NNE-SSW or at the same time the opening of already existing transverse ruptures occurred. The addition of iron, started in the previous stage of α2, culminated, and some transverse ruptures were completely filled with iron oxyhydroxides. This period is considered to be a stage of increased hydrothermal output, including ore-bearing solutions during the Tertiary (Chrt 1956). The dating that the revived faults break the bodies of the sodalite phonolite in Tolštejn and Jedlová, the latter of which was dated to 37.2 million years, contributes to the dating of this kinematic stage (Vokurka et al. 1992).

This was followed by a period of several million years (Lower Oligocene), during which erosion reduced the relief of the raised blocks and prepared the terrain on both sides of the Lusatian fault for the settling of continental sediments within the newly emerging graben of the Ohře rift. The graben-entrenched block is extended in the NE-SW direction between Cheb and Žitava, it is 190 km long and 20–30 km wide. At the time of its creation, especially in the Oligocene, it concentrated on itself the largest volumes of volcanic products, the erosion relics of which today form the Central Bohemian Highlands and the Doupov Mountains. In the zone of the Lusatian fault, which the graben crosses almost vertically, a floor of normal faults was loaded on the thrust structure created during the previous stress fields of the α group. The stress field **β**, calculated from the motion records on them, has an extension character. In fact, it is a group of at least two stress fields, of which the older (middle? Oligocene to lower Miocene) represents the expansion in the NE-SW direction and the younger (lower Miocene) corresponds to the expansion in the NW-SE direction. The immediate vicinity of the main fault, which was strengthened and silicified in the α compression stage, functioned mostly as a rigid horst during expansion. The horst is followed on both sides by directional normal faults and zones of smaller ruptures with slickensides. The most significant event of this stage was the subsidence of the originally thrusted hangingwall, i.e. the north-eastern block of the Lusatian fault. In the hangingwall block, relics of the cover of volcanic-sedimentary and sedimentary rocks of the Loučeň Formation (lower Oligocene, about 33 million years) are preserved, whose base lies at an altitude of 500 m. On the contrary, in the footwall (SW) block - in the Lusatian Mountains - products of volcanism of the same age are deposited at altitudes of 700–800 m. This results in a subsidence of the hangingwall block of the Lusatian fault after the lower Oligocene by about 300 m. Another significant event of this stage was a transverse disruption of the Lusatian fault zone by marginal faults of Eger rift, respectively entrenching of Lusatian and part of the Ještěd section within its inner block. The marginal faults of the graben are generally of a subsiding character and transversely disrupt the older thrust structures of the Lusatian fault. In the north-eastern continuation of the graben, already in the hangingwall block of the Lusatian fault, a Hrádek basin was formed. This basin was then entrenched even more due to intense expansion in the NW-SE direction. The base of the Loučeň formation in the basin lies at an altitude of -100 m, which indicates an additional decrease of 600 m. Most of this decrease was probably simultaneous with the filling of the basin with sediments of the Hrádek formation in the youngest Oligocene and Lower Miocene (Václ and Čadek 1962).

Fault activity in late Cenozoic

Tertiary

Middle to Upper Miocene tectonic evolution

After the creation of the Eger rift graben and the activation of the normal faults in the Lusatian fault zone, the fault on the main fault area was revived once again due to the subsequent compression of the NE – SW direction, labelled as **γ**. In the circle of large-scale structures, this is best seen in the area of the intersection of the marginal faults of the Eger rift graben with the Lusatian fault, when the graben faults were evidently left-hand shifted at the Lusatian fault (cf. Malkovský 1977). In the terrain, the structures created in this stage express themselves as small shear faults with slickensides, clearly younger than the normal faults associated with the previous β expansion. The temporal classification of the manifestations of the stress field γ in the vicinity of the Lusatian fault can be determined only approximately. Their low age results, for example, from imbrication and shear damage of basalt veins, probably of Oligocene to Miocene age, or by shear rotations of blocks of Miocene sediments in the Hrádek basin.

Quaternary

Pliocene to Quaternary tectonic evolution

In the youngest stage of the formation of the Lusatian fault zone, mainly steep faults were reactivated, transversely disrupting the Lusatian fault zone. There was a left-lateral horizontal shift on them due to the stress field δ, with the nature of compression in the NW-SE direction. Such reactivated faults appear as the youngest members of the sequence of brittle failure at several sites along the entire length of the fault. One of the typical examples is the left-lateral horizontal shift at the Jizera fault in Malá Skála. The key site for dating these tectonic events is the area of the Kozákov hill in the Jizera section, where steep faults reactivated by the stress field δ break the body of basaltic lava flow, radiometrically and paleomagnetically dated to 5 million years, i.e. the lower Pliocene, by oblique horizontal shifts (Cajz et al. 2009). This indicates a very young, probably upper Pliocene to old Quaternary age of the stress field δ.

The youngest Quaternary history of the fault has not been studied thoroughly yet. The survey of Bělohradský and Petrin (1977) mentions the trenching survey near Křižany, where the siltstone/marlstone bedrock overlain by Quaternary deposits of unknown detailed age is thrusted over those Quaternary deposits along two sub-parallel faults at the distance of 200-400 m from the main Lusatian fault.

Related local evidence

(See layer **Local evidence** *on a map. The sites are listed in south-to-north order.)*

Deposit conditions and rock damage at the Lusatian fault were documented by detailed descriptions of extremely well exposed natural outcrops, quarries and trenches, situated across the fault (Coubal et al. 2014). These are locations:

- 1. Vápenný vrch near Doubice (natural outcrops and quarries)
- 2. Žulový vrch near Horní Podluží (natural outcrops and deep borehole)
- 3. Jedlová near Horní Jiřetín (natural outcrops and quarries)
- 4. Horní Sedlo near Hrádek nad Nisou (natural outcrops and quarries)
- 5. Křižany (natural outcrops and trench)
- 6. Jiříčkov (trench)
- 7. Hodkovice nad Mohelkou (natural outcrops and trenches)
- 8. Frýdštejn (natural outcrops, quarries and trenches)
- 9. Suché skály near Malá Skála (natural outcrops and trenches)

Study of Bělohradský and Petrin (1977) shows the trenching survey near Křižany, where the siltstone/marlstone bedrock overlain by Quaternary deposits of unknown detailed age is thrusted over those Quaternary deposits along two sub-parallel faults at the distance of 200-400 m from the main Lusatian fault.

Main data sources for fault map

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Other notes

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