



ORIGINAL PAPER

APPLICATION OF MORPHOMETRIC INDICES ON ŽELEZNÉ HORY MTS. FAULT (CENTRAL BOHEMIAN MASSIF; CZECHIA) TO ASSESS ITS NEOTECTONIC ACTIVITY

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ARTICLE INFO

Article history:

Received 27 November 2025

Accepted 23 January 2026

Available online 2 March 2026

Keywords:

Geomorphology

Morphometric indexes

Železné Hory Mts.

Bohemian Massif

Tectonics

Thrust

Strahler hypsometric integral

Mountain front sinuosity

Asymmetry

Longitudinal profiles

ABSTRACT

The Železné hory Mountains, a highland region within the central Bohemian Massif in Czechia, are bordered to the southwest by a prominent 70 km-long fault formed through Cenozoic thrust tectonics. Along this fault—known as the Železné hory Fault—the crystalline bedrock has been thrust over Cretaceous sediments, forming a sharp and distinct geological boundary. Despite its pronounced geomorphological expression, the fault has traditionally been considered inactive, largely due to a lack of detailed observations and focused research.

To evaluate its potential neotectonic activity during the Late Cenozoic, we applied a range of geomorphometric indices, including the Strahler hypsometric integral, asymmetry factor (AI), mountain-front sinuosity (Smf), and stream-gradient index (SL). High-resolution digital elevation models and topographic maps were used to analyze fault scarp morphology and to assess the drainage network, a commonly sensitive indicator of tectonic deformation. The results suggest spatial variability in tectonic influence, with different indices highlighting distinct areas of potential activity. Through cross-comparison, we identified several locations as promising candidates for further field investigation. Notably, the Počátek Valley exhibits consistently high values across multiple indices, while the Bumbálka Valley features a pronounced knickpoint along its longitudinal profile within the fault zone.

INTRODUCTION

The Bohemian Massif, a geological unit situated in the Alpine foreland, represents the principal geological province of Czechia. Located within the intraplate region of Central Europe, it has been the focus of numerous geological studies. The Bohemian Massif is generally considered tectonically stable, with notable exceptions along its margins. These peripheral zones, shaped by ongoing tectonic processes since the Alpine orogeny, include several seismically active regions. Prominent examples are the Mariánské Lázně Fault in the west (Štěpančíková et al., 2019), the Sudetic Marginal Fault in the northeast (Špaček et al., 2006), and the Nysa–Morava Zone in the east (Špaček et al., 2015), all of which have been instrumentally monitored and documented (Košťák et al., 2011). In contrast, the central part of the Bohemian Massif shows no evidence of significant seismicity (Prachař and Pazdírková, 2022) and is generally regarded as tectonically inactive. One such region is the Železné hory Mountains (ZH).

To initiate an assessment of tectonic activity in the study area, it is first necessary to evaluate its geomorphic characteristics. Geomorphological analysis often begins with a quantitative description of

landforms, typically starting with elevation data. However, landforms shaped by ancient tectonic events are frequently modified by long-lasting erosional processes, which may obscure their original features.

Among geomorphic indicators, the river network is particularly sensitive to tectonic deformation and thus serves as a valuable diagnostic tool in neotectonic research. The combined analysis of terrain and drainage characteristics—using topographic maps and digital elevation models (DEMs)—can yield a variety of descriptive parameters. These are collectively referred to as geomorphometric indices, a group of methods enabling rapid quantification of terrain attributes across broad areas. While individual index values may hold limited interpretive power in isolation, their spatial comparison may enable identifying landscapes with differing tectonic or geomorphic histories and rates of development (Keller and Pinter, 1996; Štěpančíková, 2007).

The geomorphological context of the Czechia, surrounded by a ring of mountains, renders its border regions particularly suitable for morphostructural analysis. This is reflected in several regional studies from peripheral zones, including the Novohradské hory Mountains (Flašar et al., 2023), Vsetínské hory

Mountains (Bíl, 2002), Budějovice Basin (Popotník et al., 2013), Orlické Mountains (Różycka and Migoń, 2021), and the eastern Sudetes (Badura et al., 2007; Štěpančíková et al., 2008; Sobczyk et al., 2014).

In contrast, the central highlands of the Bohemian Massif have been studied to a much lesser extent. The research in the Železné hory Fault (hereafter referred to as ZHF) started with early observations by Culek (1953) and was followed by state-funded uranium exploration involving deep boreholes with the records archived by the Czech Geological Survey. The first study focusing explicitly on the marginal fault zone was conducted by Prachař and Urban (1967). Subsequent works by Pošmourný (1984), Vodička (1997), Borská (2008), and Coubal (2019) addressed various aspects such as regional geology, fluvial system, and structural characteristics along the fault.

In this study, we employ geomorphometric indices as a preliminary tool to identify areas suitable for subsequent non-invasive and invasive methods aimed at evaluating the recent tectonic activity and geological evolution of the ZHF. The primary objective is to delineate geomorphological features within the fault zone that may indicate neotectonic control. Identifying such features will guide future field investigations and contribute to a broader understanding of local neotectonic processes, thereby enhancing knowledge of tectonic activity in central Bohemia.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The study area forms part of the geomorphological unit of the ZH (Montes Ferrei; Iron Mountains), located in the central Bohemian Massif. The region has a triangular shape elongated in a northwest–southeast direction, with its longest axis of approximately 70 km (Fig. 1). Positioned at the boundary between the orogenic Bohemian-Moravian Highlands and the sedimentary Labe (Elbe) Lowland, the ZH exhibits the character of an elevated, flat highland gently tilted toward the northeast. The maximum elevation reaches 738 m a.s.l. and is generally increasing from west to east and from north to south (Vodička, 1997; Vodička and Pošmourný, 1984). The height difference of ZH and the adjacent geomorphological units reaches up to ~400 metres due to the Central Elbe Lowland's altitude ranging from 200 to 300 m a.s.l. and Svitavy Uplands reaching 380 m a.s.l.

The ZH comprise of crystalline bedrock and are surrounded on three sides by the lower terrain made of sediments of the Cretaceous Basin (Fig. 2). In the southeast, they connect to the higher terrain of Upper-Sázava Upland and Žďárské vrchy Mts. The crystalline bedrock of the ZH is uplifted along its southwestern boundary above the Cretaceous Basin (Figs. 2, 3). The uplift is controlled by NW-SE striking the ZHF, with an approximate length of 70 km, being a reverse fault dipping 50–60° to the northeast (Prachař

and Urban, 1967). This structure marks a distinct tectonic and lithological boundary, where Cretaceous sediments terminate abruptly, and the ZH rises steeply along fault scarps with slopes reaching up to 25°. In contrast, the northern part of the ZH gently descends beneath Cretaceous sandstones overlain by loess deposits. Although the northern termination of the ZHF is generally mapped near the Elbe River crossing, geological maps—and interpretations by other authors (Badura and Rauch, 2014) — suggest a possible continuation of the fault deeper into the Cretaceous Basin.

The geology of the ZH is very complex, with the oldest rocks dated to the Precambrian. Within its 900 km² extent, over 100 distinct rock types have been identified, allowing a variety of of rock-related landforms (Vodička and Pošmourný, 1984; Vodička, 1997; Dudíková Schulmannová, 2008). The structural framework of the region was established during the Precambrian to Paleozoic evolution, including Cadomian and Variscan tectonic events, which formed the crystalline basement of the Bohemian Massif and major fault systems such as the ZHF (Dudíková Schulmannová, 2008; Chlupáč et al., 2002). Following the Variscan consolidation of the massif into a single crustal block (~370–300 Ma), tectonic activity was largely limited to localized vertical movements, particularly during the Alpine orogeny (~65–2.5 Ma). These movements were expressed by reactivation of pre-existing fault zones during Late Cretaceous and Cenozoic Saxonian tectonics, leading to uplift of major basement blocks and the inversion of Late Paleozoic and Mesozoic grabens. Ziegler (1985) also places main inversion phase of Bohemian Massif into the mid-Paleocene age. Uplift of ZH relative to the surrounding areas enhanced erosion of the overlying Cretaceous sediments (Ziegler, 1985; Chlupáč et al., 2002). The ZH drainage network is oriented predominantly northward, consistent with the regional slope aspect. The main river, the Chrudimka, incises crystalline bedrock in the southern part of the area and flows through Cretaceous sediments further north. Near Třemošnice, the river abruptly shifts direction in a sharp V-turn from a west-northwest orientation to the northeast—only a few kilometers from the ZHF. This suggests a paleodrainage system originally oriented westward before tectonic uplift reoriented fluvial flow to the northeast (Vodička, 1997). The fault scarp controlled by the ZHF is dissected by numerous short southwest-flowing tributaries of the Doubrava River, which have carved steep valleys and canyons. ZH represents a structurally significant boundary between crystalline basement and Cretaceous sediments and forms a genetically related structure to the Elbe Fault within the southeastern segment of the Elbe Fault Zone within the broader framework of the Elbe Shear Zone. This regional fault system, active since at least the Late Palaeozoic, played a crucial role during the Cenomanian transgression by controlling the orientation and localization of palaeodrainage systems and associated depocentres within the

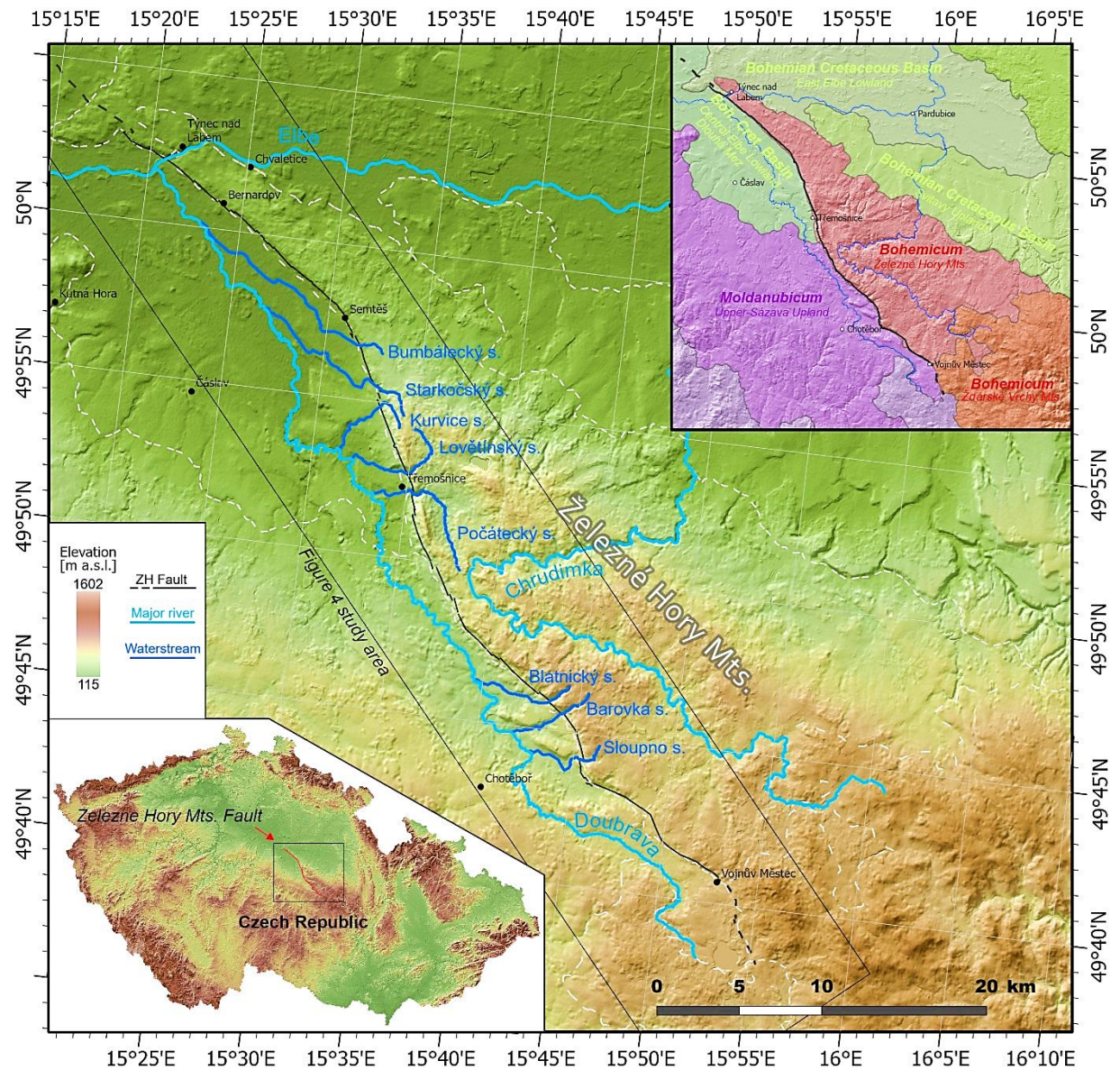


Fig. 1 Location of the ZH, elevation map of the study area, and map of the main geomorphological units. Confirmed fault and its suspected continuation (dashed lines) is marked, and major waterstreams (s.) chosen for longitudinal profile analysis (Fig. 6) are highlighted. Based on elevation, the ZH can be distinguished from the surrounding geomorphological units: Central Elbe Lowland (also referred to as Dlouhá Mez basin) and East Elbe Lowland, both being parts of the Bohemian Cretaceous basin; Upper Sázava Upland is a flat highland across the valley of Doubrava river, sharing a short border in the east with the Žďárské vrchy Mts., elevated higher than the ZH.

Bohemian Cretaceous Basin. The ZHF, together with the Elbe and Lužice fault zones, forms a distributed shear belt that structurally guides the southeastern margin of the basin, influencing both sediment pathways and subsidence patterns. Inherited from Variscan tectonics and later reactivated during Cretaceous and Alpine phases, these fault structures delineated palaeohighs and lows that governed basin infill architecture and drainage network evolution. (Uličný et al., 2009) Such tectonic inheritance highlights the critical role of the ZHF not only in the local neotectonic context but also in the regional geodynamic framework of the Bohemian Massif.

The major tectonic phase affecting the area is associated with Saxonian tectonics during the Alpine orogeny (Prachař and Urban, 1967; Coubal, 2019). In terms of present-day activity, only minimal seismicity has been recorded in the vicinity of the ZHF. Prachař and Pazdírková (2022) identified a single historical earthquake near Koudelov (1 km east of Čáslav) in 1821 with an intensity of $I = 4$. However, the epicentre lies within the footwall of the ZHF, in the Cretaceous Basin, and may not be directly related to ZHF activity. According to the earthquake catalogues dating back to 1267, no documented epicentres or macroseismic activity were registered along ZHF and the southern

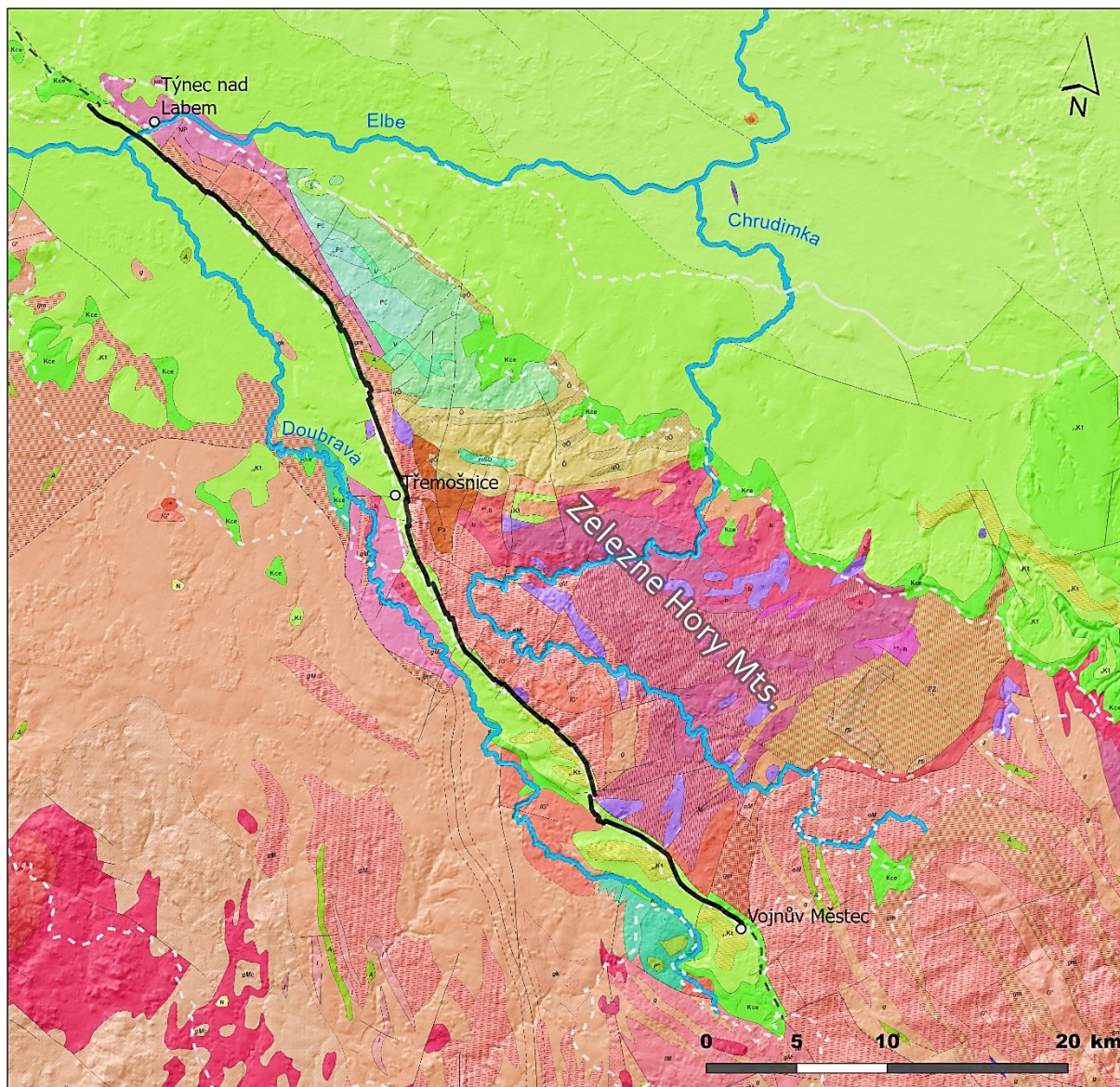


Fig. 2 Geological map of ZH without Quaternary cover, 1: 500 000 (Czech Geological Survey, 2023). For the corresponding legend see the next Figure 3.

part of ZH. (Lenhardt et al., 2007) Thus, the most promising indicators of potential tectonic activity are geomorphic in nature—particularly those associated with fluvial systems. Borská (2008) identified numerous streams near the fault with convex longitudinal profiles, a characteristic often associated with tectonically disturbed river courses.

The Fault zone is cut by numerous perpendicular fractures, outlining its frequently changing strike, mainly in the central and southern parts. Except for short subparallel faults noted in the close forefield north of Třemošnice and south of Sloupno, the only parallel boundaries accompanying the fault strike are lithological (Czech Geological Survey, 2023). Near Bernardov in the north, this parallel diverse lithology forms a set of terrain steps with granite outcrops. Deep valleys of Lovětínský and Počáteký streams near Třemošnice in the central part are exposing granodiorite bedrock. At Sloupno in the south,

metagranodiorites and metadiorites are being quarried near the fault zone, and although the fault itself is not excavated, a fracture zone can be observed (Coubal et al., 2019). Such crystalline outcrops pose an opportunity for structural geology to study the local tectonics.

METHODS

This preliminary study aimed to identify areas with the highest likelihood of tectonic activity along the ZHF for subsequent field investigations. A belt approximately 60 km in length and 4 km in width along the fault zone was selected for analysis. We applied several geomorphometric indices, including the Strahler hypsometric integral (SHI), mountain-front sinuosity (Smf), asymmetry factor (AI), and stream-length gradient index (SM), which were further complemented by the interpretation of longitudinal river profiles.

TERTIARY BOHEMIAN MASSIF		UNDIFFERENTIATED	
Cenozoic		Neoproterozoic	
Tertiary		NP shales, greywackes (rhythmic alternation, flysch), black shales, volcanites, metamorphosed	
tb leukocratic trachybasalts, trachyandesites, trachytes, trachytic volcanites, trachyte breccias		Variscan intrusives	
b _o olivine alkaline basalts and basanites, olivine foidites, limburgites, melilitic olivine rocks		p veined granitoid and tonalitic rocks	
b _{1o} + older effusions and intrusions in the middle of the Eger Rift, predominantly shallow subaquates		g ⁺ granites rich in trace elements and tourmaline varieties	
Neogene		g two-mica granites (muscovite > biotite, muscovite < biotite), finely (to medium) granular	
N Sands, gravels, clays		g two-mica granites (muscovite > biotite, muscovite < biotite), coarse (to medium) granular	
MESOSOIC BOHEMIAN MASSIF		Mg nebulitic-ophthalmic migmatites to inhomogeneous biotite or two-mica granites	
Mesozoic, Cretaceous		gb biotite granites finely (to medium) granular	
Upper Cretaceous		gb biotite granites coarse (to medium) granular	
mKts calcareous claystones and marlstones; Upper Turonian - Santorian		p ^o gb porphyritic biotite granites finely (to medium) granular	
Kt calcareous and clayey fine-grained sandstone; Middle - Upper Turonian		g ⁺ biotite and two-mica granites to granodiorites of the inner Carpathians	
Kt calcareous claystones, marlstones, less clayey limestones; Lower - Upper Turonian		gd ⁺ biotite and amphibole-biotite monzogranites to granodiorites and trondhjemites	
Kt glauconitic, calcareous and clayey sandstones, marlstones, silicified in places; Turonian		p ^o gdh porphyritic amphibole-biotite and biotite-amphibonic granodiorites	
Kce claystone, siltstone, sandstone, conglomerate; Cenomanian		dg biotite-amphibolic, Amphibole-Biotite and Amphibolic (±Biotite) tonalities, quartz diorites	
PALEOZOIC OF THE BOHEMIAN MASSIF		d diorite	
Paleozoic		n gabbro	
Pa red and grey sludge silty claystones, sandstones, arkoses; Lower Permian-Upper Carboniferous		Pre-Variscan intrusives of unknown age (often deformed and metamorphic)	
PZ weakly metamorphosed siliciclastic sediments; Cambrian-Lower Carboniferous		IG ⁺ leucoshorts, alkaline-feldspar muscovitic metagranites and orthogneisses	
mSD limestone (marbles), graptolite shales underneath, metamorphosed; Silurian - Lower Devon		g ⁺ biotite and two-mica granites and granodiorites, deformed and metamorphosed in places	
Fs phyllites, metasiltites; Silurian		G ⁺ muscovite-chloritic, -biotitic, biotite metagranites to metagranodiorites and orthogneisses	
O shale, siltstone, sandstone, very weakly to strongly metamorphosed; Ordovician		d ⁺ diorite, metadiorite	
qO quartzite, very weakly to weakly metamorphosed; Ordovician		n ⁺ gabbro	
E shale, sandstone; Cambrian		Inserts in the Precambrian and Paleozoic	
NEOPROTEROZOIC / CAMBRIAN		Precambrian undifferentiated	
Paleozoic		q quarcites	
PE shales, greywackes, conglomerates, very weakly metamorphosed		m marble	
crPE conglomerates		Precambrian and Paleozoic volcanics and metavolcanites	
UNDIFFERENTIATED		Precambrian undifferentiated	
Precambrian / Paleozoic, undifferentiated		V undifferentiated metavolcanites, very weakly metamorphosed	
Precambrian / Paleozoic		I metarhyolites, metadacites (porphyroids, quartz keratophyres), their metatuffs	
gm schists and gneisses, garnet and staurolite zone		A green slate	
gk gneisses: higher pressure		Lower crustal and mantle rocks	
g gneisses: lower and low pressure biotite and sillimanite-biotite gneisses, partly migmatized)		Precambrian undifferentiated	
gMc gneisses: low pressure (cordierite gneisses, cordierite migmatites)		Gr felsic granulites, slightly to very strongly retrograde metamorphosed	
gM migmatized gneisses, migmatites, predominantly stromatolitic and phlebitic			
om biotite ophthalmic migmatites, locally with garnet, sillimanite and (or) cordierite			

Fig. 3 Legend of Geological map of ZH without Quaternary cover (Czech Geological Survey, 2023).

Digital elevation model (DEM) is one of the key products to use for the identification of terrain characteristics (Mayer, 2000). In this study, the indices were derived primarily from the 5th-generation national DEM of Czechia, based on LiDAR data with a spatial resolution of 1 m and a vertical mean error of 0.18 m in open terrain and 0.3 m in forested areas. The indices were calculated and visualized in ArcGIS Pro software. Supplementary information was extracted from topographic maps. Longitudinal river profiles were also constructed using the LiDAR-based DEM and analysed with Microsoft Excel.

Calculation of the Strahler hypsometric integral and the asymmetry factor required the delineation of drainage basins along the fault zone. These basins were identified and extracted using a combination of DEM-based hydrological analysis and manual refinement with reference to topographic maps, similarly, in ArcGIS Pro.

STRAHLER HYPSONETRIC INTEGRAL

This method, developed by Strahler (1952) from the hypsographic curve, aims to describe the current state of a drainage basin in relation to the Davisian geomorphic cycle. Strahler defined a formula to estimate the degree of tectonic activity within a catchment. The x-axis represents the proportion of the total basin area, while the y-axis shows the proportion of total elevation. The Strahler hypsometric integral (SHI) is calculated for the entire basin:

$$SHI = (E_{mean} - E_{min}) / (E_{max} - E_{min})$$

E_{min} , E_{max} and E_{mean} stand for the lowest, highest and average elevation of the individual drainage basins. Lower values (approaching 0) typically indicate lower tectonic influence. Strahler associated values above 0.6 with a youthful stage of landscape development, values between 0.6 and 0.35 with a mature or equilibrium stage, and values below 0.35 with an old stage. A limitation of this method is that basin elevation and shape result not only from tectonic uplift but also from erosion, whose intensity varies across the study area due to differences in lithology and land cover. As such, reliable comparisons can only be made between similar basins. Nevertheless, the SHI offers valuable insight into terrain evolution.

MOUNTAIN FRONT SINUOSITY (SMF)

The mountain front sinuosity index (Smf), introduced by Bull and McFadden (1980), identifies tectonically active landscapes by comparing the contour line length (Lmf) to the straight-line distance (Ls) along segments of a mountain front:

$$Smf = Lmf / Ls$$

According to their concept, tectonically active mountain fronts tend to be relatively straight compared to more eroded, mature landscapes. Thus, lower Smf values (1.0-1.4) may indicate active tectonics in a given area, >3.0 values are describing inactive and heavily eroded mountain front (Keller and Pinter, 2002). Alanazi and Bashir (2025) disclose 1.0-1.5 values as proofs of tectonic activity. For this analysis, the mountain front is divided into several

segments where these distances are measured. Following Topal et al. (2016), who divided the 60 km-long Akşehir fault into seven segments based on fault bends, we applied a similar approach and divided the fault into five segments according to changes in the general azimuth of the fault strike.

SM INDEX

The stream length-gradient index (SL), developed by Hack (1957, 1973), is calculated for equal-length stream segments using the ratio of elevation difference to the distance from the midpoint of the segment to the stream source. This index is useful for identifying lithological and tectonic influences on river profiles. However, since the SL index was empirically derived for large drainage basins with main streams extending hundreds of kilometers, it is not well-suited for smaller areas like ours. To address this, Bíl and Máčka (1999) developed the SM index, which is better adapted to smaller streams and rivers in the mountainous regions:

$$SM = (\Delta H / \Delta L) * M$$

In the SM index, M replaces L as the total upstream length and represents the Shreve magnitude, where headwater streams have a magnitude of 1, and each downstream segment receives a value equal to the sum of the magnitudes of its two tributaries. The Shreve magnitude correlates strongly with the drainage area of the stream segment, as verified by the authors across 40 drainage basins. The term $\Delta H / \Delta L$ represents the gradient (descent) of the studied segment. Higher SM values indicate frequent changes in bedrock resistance or active tectonics. Since both SM and SL indices reflect the energy distribution required for fluvial processes, and because this study uses the SM index to infer river responses to tectonic movements, calculations should exclude artificially regulated streams near the fault zone.

ASYMMETRY FACTOR

Assymetry factor, also further referred to as an Asymmetry index (AI) in this study, is based on the premise that tectonic movements equally influence erosion rates on both sides of a stream. Keller and Pinter (2002) proposed the following formula:

$$Af = 100 \left(\frac{Ar}{At} \right)$$

A_r represents the area on the hydrographic right side of the drainage basin, while A_t denotes the total basin area. Ideally, fluvial erosion affects both sides of the drainage basin simultaneously and with equal intensity. A significant imbalance in the proportion of basin area between the left and right banks suggests tilting on one side, potentially indicating tectonic activity through differential movement of a mountain block counteracting erosion. Similar to the SHI method, however, these variations may also be influenced by lithological differences.

LONGITUDINAL PROFILES

Rivers serve as valuable indicators of tectonic activity. The longitudinal profile of a stream can reveal sections of increased incision, reflecting higher stream energy (Sklar and Dietrich, 1998). For selected larger, perennial streams crossing the fault zone—originating in ZH and flowing southwest into the Doubrava river—longitudinal profiles were generated using a DEM from the Land Survey Office (2025). These profiles extend from the stream sources to their confluence with the Doubrava, which acts as the local base level of erosion. The analysis focused on identifying significant anomalies in the river profiles near the fault zone that could suggest recent tectonic movements.

VF INDEX

Bull and McFadden (1980) introduced an index to detect recent tectonic activity based on variations in river valley width. This index is frequently applied to identify active tectonic regions. However, it has been noted that very few streams have developed a flat valley bottom. Specifically, only the Lovětínský and Počáteký streams (Fig. 4), located less than 1 km apart, exhibit this feature. Both streams lie within the segment showing the greatest elevation difference between the mountain ridge and the fault scarp, and their deeply incised valleys have formed bottoms up to 30 meters wide. Given that only two streams display this characteristic, any numerical comparison would lack significance, so this index was not applied.

AI were calculated for 61 drainage basins. The SM index was computed for 501 stream segments within a 2 km zone around the ZHF, and these values were subsequently interpolated further in our study.

RESULTS

The spatial distribution of all indices is compared on the map shown in Figure 4 and plotted in Figure 5. The SHI and

STRAHLER HYPSONETRIC INTEGRAL

SHI has been computed for 61 drainage basins. According to the SHI, drainage basins can be divided into three groups. Higher SHI values occur in the northern and southern parts of the fault, with the highest values found in the north. In contrast, large basins in the middle section show lower SHI values. This pattern may be explained by the higher incision in single-stream drainage basins compared to multi-stream basins, where erosion is more evenly distributed among multiple watercourses.

Short streams that cut into the steep fault slope typically lack tributaries, so their single channels naturally create greater elevation differences in elevated terrain. Rana et al. (2016) similarly linked lower hypsometric values to the presence of fissile bedrock, such as phyllite. Lithology is clearly an important factor, but given the diverse rock types in ZH, its influence is difficult to quantify precisely.

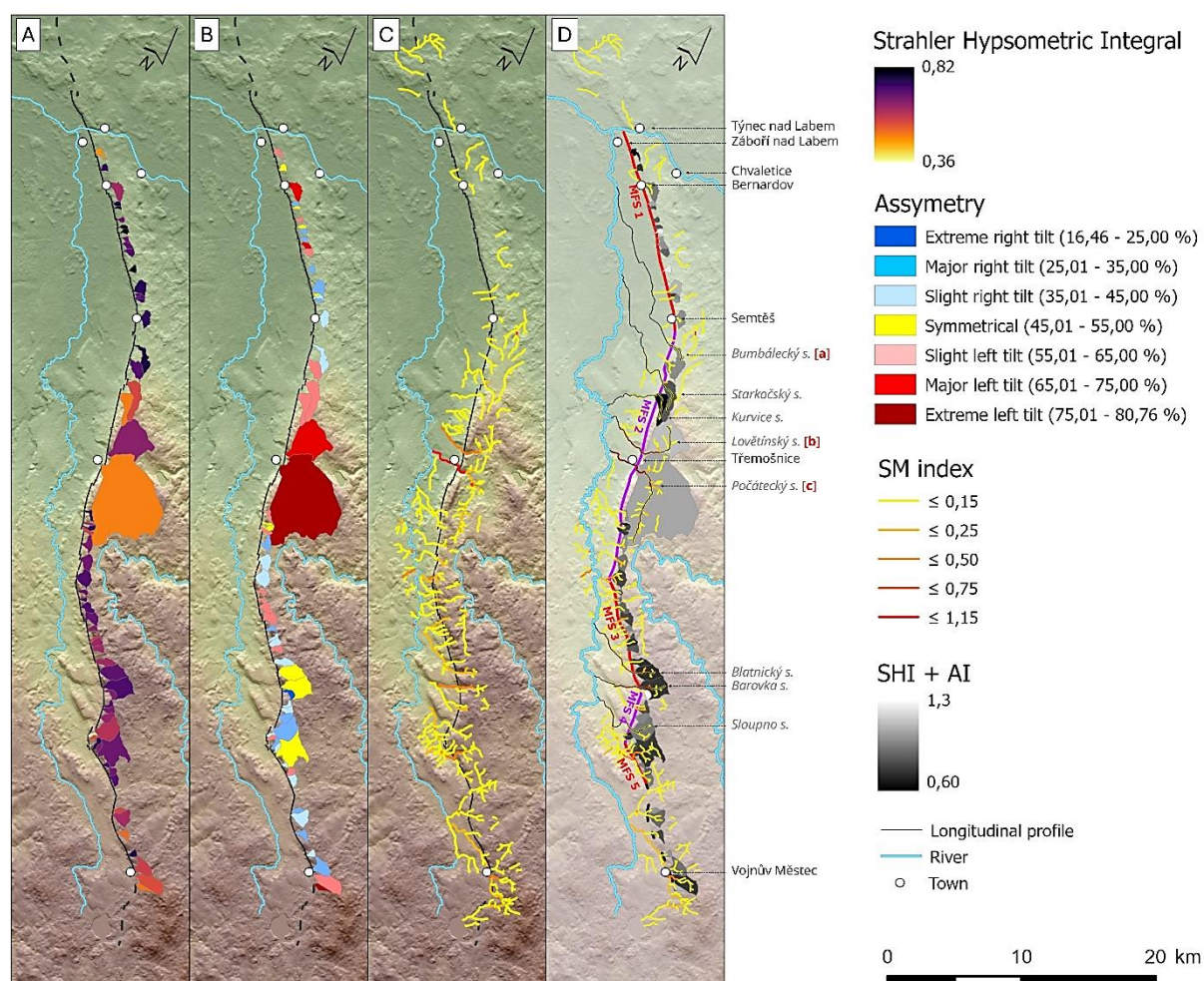


Fig. 4 Results of (A) hypsometric integral and (B) asymmetry index for individual drainage basins, along with (C) SM index analysis for stream segments within a 2 km zone around the fault. (D) Combined overlay of all indices also highlights the longitudinal profiles (shown in Fig. 6) and the Smf segments. Marking of drainage basins with high/low overall values of both SHI and AI is included. Locations of Bumbálecký [a], Lovětínský [b] and Počátecký streams [c] are highlighted as points of interest.

Based solely on Strahler's (1952) framework, nearly the entire fault zone has drainage basins with SHI values above 0.6, especially in the northern and southern parts, indicating the possibility of recent landscape development.

ASYMMETRY INDEX

Analysis of 61 drainage basins have yielded 61 values of Asymmetry index. The AI generally ranges between 10–15% of the total tilt, regardless of whether it occurs on the left or right side. The highest values are observed in the largest catchments of the Lovětín and Počátecký streams, as well as in a small catchment in the southern part of the ZHF (Fig. 4). Since lithology changes abruptly along the fault, these differences may result from tectonic influences or varying rock resistance to erosion on either side of the drainage basins. Overall, the greatest total tilt is found in the northern and central parts of the study area, while the southern section of the fault zone—characterized by smaller altitude differences between the crest of fault scarp and the foreland valley

bottom—exhibits more symmetrical basins.

Streams running parallel with the fault zone before crossing it towards the Doubrava valley should be of the greatest interest (at Bernardov, Bumbálka, Lovětínský s., Počátecký s.). Tectonic movements along the fault zone, lifting one bank, would then naturally affect the asymmetry of their drainage basin. On the other hand, asymmetry of the streams running perpendicular to the fault cannot be that easily interpreted as a result of active tectonics, but more probably the lithology.

Based on the difference in calculation and observation of different characteristics, the drainage basins usually show a mismatch in the height of SHI and AI values, one pointing on higher tectonic influence while the other does not. Both SHI and AI theoretically range from 0 to 1 (or 0 to 100 %), with higher values pointing to a higher probability of recent tectonic movements. Their values were therefore summed to identify drainage basins exhibiting the height of the overall values of both indices, as shown in Figure 4 (D)

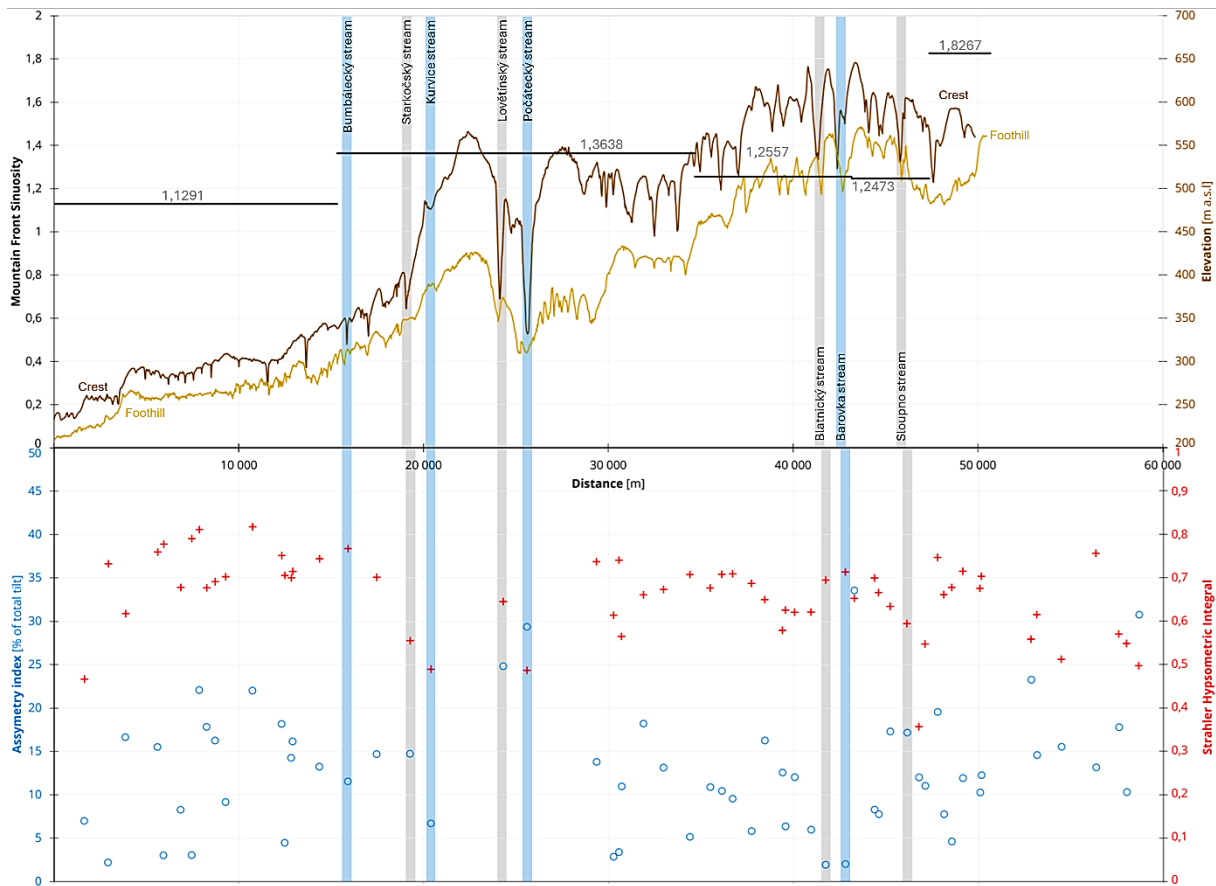


Fig. 5 Geomorphometric indices of the ZHF. Fault distance was measured along the scarp from the Elbe River at the NW to Vojnův Městec town in the SE. At the top: a combination of Smf for each segment (black line), comparison of the elevation of the line along the foothill of the fault scarp and the upper crest of the scarp (for the fault scarp see Fig. 1) is shown. At the bottom: SHI values (crosses) and AI values (total tilt regardless of the side; circles) are visualized for all catchment basins along the fault. Highlighted are locations and parameters of 8 streams whose longitudinal profiles were characterized.

SM INDEX

The index has been computed for 501 stream segments. The index was calculated for stream segments within 2 kilometres of the fault. All streams crossing the ZHF lie within the Doubrava River drainage basin, which flows northwest along the fault. Consequently, the Shreve magnitude increases from 1 at the northeast slope of the fault scarp crest toward the Doubrava river. The Doubrava, Labe (Elbe), and Chrudimka Rivers were excluded from the SM index analysis because they flow too far outside the study area. Additionally, the Labe River is better evaluated using the SL index, so combining these methods on the same map would not be comparable.

Since the SM index can take any positive value, the raw numbers alone do not directly indicate tectonic activity; instead, values must be compared relative to each other. Almost 90 % of streams showed low SM values below 0.2, suggesting little or no significant tectonic influence.

The highest value (1.133) was found in the lowest segment of the Počátecký stream (Fig. 4), which features one of the deepest canyons in the central part of the fault zone. Lovětínský stream, near the northern part of Počátecký stream, and with

a deeply incised canyon, showed a higher SM value but much lower than Počátecký's, likely due to having fewer tributaries. In the southern fault area, the Barovka and Sloupno streams also exhibited somewhat elevated SM values compared to other streams.

MOUNTAIN FRONT SINUOSITY (SMF)

Five values for five segments have been obtained. Figure 5 shows four segments (1 to 4) with Smf index values lower than 1.5. The lowest Smf index (1.13) occurs at the northernmost segment of the fault, near the Doubrava-Elbe influx. Segment 2 reached a higher value of 1.36, which corresponds to the greatest height difference between the fault crest and its foothill, where deep valleys cut through the ridge. A high Smf index in this area may result from the incising nature of the Doubrava River downstream, which forms the lowlands from which the fault emerges. Conversely, the highest value (1.83) was recorded at segment 5, located at the southern part of the Doubrava valley, due to the segment's short length and multiple small streams cutting into the rising scarp.

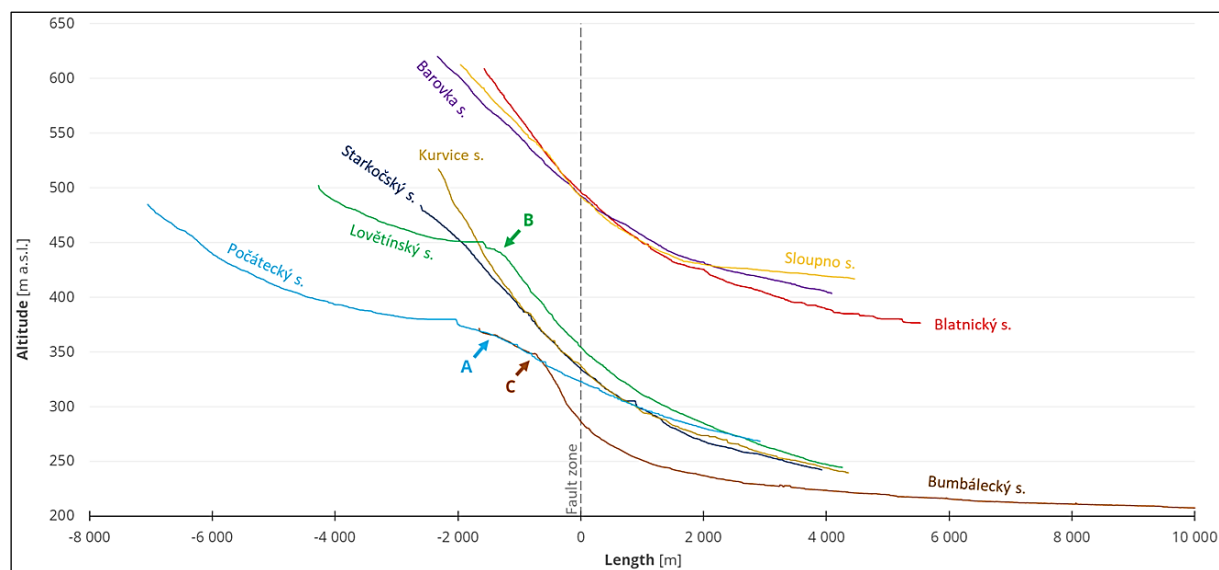


Fig. 6 Longitudinal profiles of selected streams from their sources to their confluence with the Doubrava river. Stream length is shown relative to the fault strike, marked at 0 metres. Minor local ‘teeth’ reflect irregularities in the base DEM, while flat steps indicate dams and ponds built along most of the streams. Arrows A (Počáteký s.), B (Lovětínský s.), and C (Bumbálecký s.) mark the notable convex bends on the respective profiles.

Therefore, the main factors controlling the S_{mf} are both possibly recent tectonic movements and the erosional activity of the Doubrava River in the foreland. Streams closer to the Doubrava’s confluence with the Labe River must cross greater elevation differences within the fault scarp, which increases their energy and incision rates, leading to the erosion of larger valleys.

LONGITUDINAL PROFILES

Longitudinal river profiles were constructed for 7 streams. As shown in Figures 1 and 4, all streams in the ZH area flowing southwest originate near the top of the ZHF scarp crest. These streams, which cross the fault zone, are generally short and flow into the nearby Doubrava River. Some streams flow northwest along the mountain range for a short distance before turning southwest and incising deeply into the fault scarp, such as the Kurvice and Počáteký streams. Others start directly on the ridge crest, forming deeply incised valleys from their sources, like Blatnický, Barovka, and Sloupno streams. Most streams have been artificially straightened or otherwise altered, especially in the lower, flatter areas. The majority exhibit a concave longitudinal profile without marked slope changes.

The middle segments of Lovětínský and Počáteký streams are notable for a convex bend interrupting their otherwise concave profiles (Figs. 6 – A, B). A similar, though less pronounced, convex bend occurs near the source of Bumbálecký stream about 1000 metres above the fault zone (Fig. 6 – C). Given the homogeneous lithology, these convexities could have been controlled by tectonic uplift.

DISCUSSION

With drainage basins being the basic spatial units of the study, observation of their characteristics and potential for further research has been summed up in Figure 7. High SHI values in drainage basins do not necessarily indicate tectonic influence. Still, values above 0.6 may suggest recent topographic changes (Topal et al., 2016). Such values were found in most of the studied catchments (Fig. 2), which might imply recent activity, though it is uncertain whether this is tectonically driven. Bíl (2002), through cross-comparison of various geomorphometric indices, demonstrated that landscape development in flysch areas is predominantly controlled by lithology. Although this conclusion cannot be directly applied to the crystalline bedrock of the ZH due to different geomorphic behavior, it suggests that lithology may paradoxically be a dominant factor in methods meant to observe tectonics, since most of these methods quantify erosion.

The southern section of the fault zone, characterized by gentler relief, contains more symmetrical drainage basins. The lowest S_{mf} index in the southernmost segment also supports the idea of limited or no recent tectonic activity in this area. Average values of the asymmetry index in the southern section, combined with frequent lithological changes, suggest that young tectonic activity likely did not shape the region’s recent development. Barovka and Sloupno streams in the south yielded high SMI, SHI, and SM values, but their longitudinal profiles do not show any anomalies. While Barovka and Sloupno streams may be of interest individually, the southern area is probably not tectonically active.

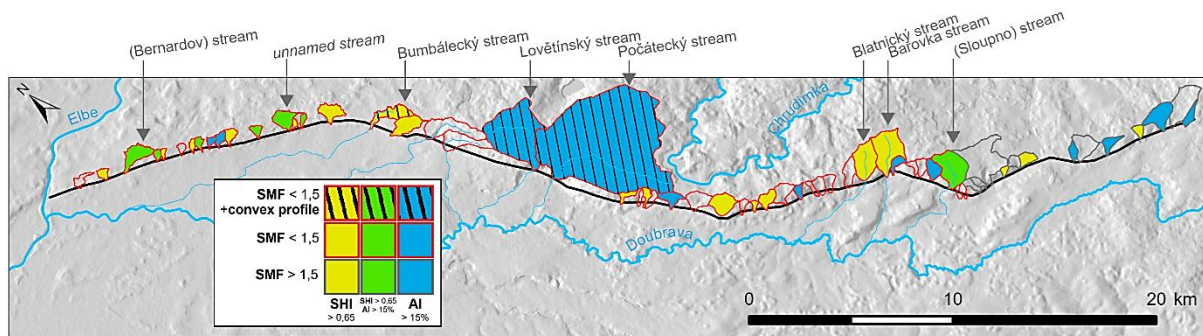


Fig. 7 Drainage basins of interest – based on the acquired values, speaking of possible tectonic influence. Basins are evaluated based on their position within fault segments (Smf value), and are characterised with high SHI (>0.65) and/or AI ($>15\%$ tilt) values; some with observed convex longitudinal profile. Larger basins with the biggest perspective for further research are marked and named.

The highest asymmetry values were found in the Lovětínský and Počátecký stream basins, located in the central part of the study area. These findings may indicate possible tectonic uplift. The alignment of the convex section of the Lovětínský stream above the mapped tectonic lines has been noted by Borská (2008). The presence of major faults may correspond with drainage basin asymmetry, as observed by Hare and Gardner (1985) in the tectonically active Nicoya Peninsula in Central America. However, the asymmetry index distribution within the ZH fault zone appears random and does not clearly correspond with fault traces in the area. Drainage basins with asymmetry higher than the standard deviation of 14.3 of our datasets, described as ‘major tilt’ in Figure 4, are also highlighted in Figure 7.

One of the most promising sites for further investigation is the Počátecký stream near Třemošnice, in the central section of the fault zone. It shows high AI, SM, and Smf values, although its SHI value is average. Its longitudinal profile displays a convex bend, potentially signaling recent tectonic activity. The nearby Lovětínský stream also warrants closer examination—it shares similar deviations in index values and has a convex longitudinal profile. Additionally, its lack of a developed flat valley floor supports the idea of a young valley age (Borská, 2008). Both long and deeply incised, these streams exhibit several indicators that may reflect tectonic influence.

Another basin of interest is that of the Bumbálecký stream, which has a convex profile near the fault zone—again suggesting possible tectonic impact. This has been supported by Borská (2008), who identified a tectonic line at the base of the convex segment. A higher SHI value reinforces this interpretation. These three streams are evidently affected by the fault’s presence; however, it remains uncertain whether this is due to active tectonics or the boundary between contrasting lithologies, as suggested by Borská (2008), who highlighted the role of tectonic fractures.

In general, the northern and central portions of the study area show greater basin asymmetry, which

could point to recent tectonic activity. The central segment, however, lies within more homogeneous and stable bedrock (Czech Geological Survey, 2023), composed mainly of paragneiss and migmatite/orthogneiss. This makes lithologically-induced asymmetry less likely there. In contrast, the northern and southern parts of the fault experience more frequent lithological changes, which may affect their asymmetry and SHI values.

The northernmost part of the fault zone is notable for its relatively low ridge elevation. Nevertheless, the streams crossing it form multiple deeply incised valleys, reflected in high SHI, AI, and Smf values. These elevated values cannot be conclusively linked to tectonic activity, as lithological changes are common in this part of the study area (Czech Geological Survey, 2023). However, many of the basins in the north are too small for bedrock variation alone to fully explain the results, suggesting that the northern part of the fault could be a suitable area for identifying signs of neotectonic activity.

CONCLUSION

The used morphometric indices (summarized in Fig. 7) suggest most promising areas from tectonic activity point of view in the northern and central parts of the ZH fault zone. These areas generally show higher basin asymmetry index values, while higher SHI values occur in both the northern and southern sections. Streams in the central and southern parts reach higher SM index values. The most promising combination of indices appears in the central section, where the highest Smf index value was also recorded—suggesting the potential presence of young tectonic activity. The Lovětínský and Počátecký streams, both deeply incised in this central location, show the strongest indications of young tectonic uplift. These include convex longitudinal profiles near the fault, similarly observed at the nearby Bumbálecký stream.

Although the northern section lacks major streams, it contains several dry valleys. Observed index values, such as a low Smf value of the entire

segment or high SHI found in small drainage basins in this area are unlikely to be caused by lithology alone, suggesting that the entire northern section may be tectonically influenced. The north segment near Bernardov and Bumbálka stream and the central valleys of Lovětínský and Počátecký stream are expressing major signs of potential tectonic activity and therefore showing the greatest potential for further field research.

As the results of the individual geomorphometric indices are not always fully consistent with each other, interpretation requires caution and a critical, detached perspective. Each method highlights different areas, with minimal overlap, and the complex lithological setting further complicates the analysis. The research revealed significant discrepancies across the various approaches. While each method can contribute to identifying tectonically active landscapes, they assess different geomorphic characteristics. Therefore, no single index should be considered reliable on its own.

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