Charles University

Faculty of Science

Institute of geology and palaeontology

Study programme: Geology

Study branch: Geology

Mgr. Jan Flašar

Late Cenozoic response of the selected fluvial systems of the Bohemian Massif to tectonics

Doctoral thesis

Supervisor: Mgr. Karel Martínek, Ph.D.

Prague, 2022

Univerzita Karlova

Přírodovědecká fakulta

Ústav geologie a paleontologie

Studijní program: Geologie

Studijní obor: Geologie

Mgr. Jan Flašar

Reakce vybraných říčních systémů Českého masivu na tektonické vlivy během pozdního kenozoika

Disertační práce

Školitel: Mgr. Karel Martínek, Ph.D.

Praha, 2022

Prohlašuji, že jsem tuto dizertační práci zpracoval samostatně a že jsem použil pouze zde citované informační zdroje uvedené v seznamu literatury. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

V .... dne .... podpis autora

I declare that I prepared this dissertation thesis independently under the guidance of my supervisor, and that I used only the sources I quote and include in the list of references. This thesis, or a substantial part of it, has not been submitted to obtain another or the same academic title.

In .... date .... signature of the author

Abstract

Despite its intraplate tectonic setting, the Bohemian Massif underwent relatively intense tectonic activity during the Cenozoic. This activity has significantly formed the terrain morphology and river geometry, which can easily be observed from the present status of the streams and relief. Although the effect of tectonics and climate on the terrain morphology has been already researched in previous studies, the effect on the geometry of the river systems has not been surveyed complexly. The author´s previous master thesis found two remarkable areas within the Bohemian Massif, where the effect of climate and tectonics on the river system geometry and its changes is very probable – the area of western Bohemia along the Mariánské Lázně Fault and the area of the Novohradské hory Mountains and their foothills.

The focus of this thesis is to study the mutual interactions between the tectonic activity and the geometry of selected river systems in the Bohemian Massif. The goal is not only to prove the connection but also to test and evaluate the set of methods that can be useful for localizing those places with recent tectonic activity and which can be applied in similar areas in the future.

Both areas – along the Mariánské Lázně Fault and in the Novohradské hory Mts. and their foothills - were surveyed by identical or similar methods in order to compare the results of particular areas to each other and to evaluate the methods used and improve them for further use. The geomorphological methods of remote sensing were used in this thesis (and in the individual papers, which are the essential parts of it) – morphotectonic analysis, analyses of longitudinal stream profiles, stream gradient, Stream-Length index, Hypsometric index, Basin asymmetry, Mountain-front sinuosity, Valley-floor ratio and valley cross-sections. The results obtained were verified by aerial geophysics, field applied geophysics and a field structural survey. Moreover, the localities of Miocene, Pliocene, and Pleistocene fluvial deposits and river terraces, which could be used for to reconstruct the geometry of the previous stream network, were mapped during the research. Therefore, the results obtained help to evaluate the tectonic activity and also explain the evolution of the stream network in the late Cenozoic in both study areas.

The results of this thesis have proved that the methods used make a useful working set which can be applied in similar areas elsewhere. Their usefulness and reliability were proved by independent studies focused on a geophysics survey applied in the field (ERT, DEMP) and palaeoseismology in the area of the Mariánské Lázně Fault. The use of the geomorphological methods could also be reliable in the area of the Novohradské hory Mts. Based on the results, it is suggested that both study areas have undergone a significant tectonic uplift during the Late Pliocene, Pleistocene and probably - in the case of the Mariánské Lázně Fault – even Holocene. The tectonic activity did not take place in a single event,

instead it has been segmented activity along the Mariánské Lázně Fault, or the uneven uplift of blocks in the area of the Novohradské hory Mts. This segmented activity has made a significant impact on the changes in water stream geometry and the evolution of the drainage network in general (river capturing, etc.) The diversely located fluvial deposits of Pliocene and Pleistocene age act as evidence of the drainage's evolution. On the basis of the morphostratigraphical analysis and on the survey of the relationship between fluvial deposits and tectonic structures, it is possible to reconstruct the evolution of the river network. It appears that two main tectonically induced changes to the drainage pattern have occurred in both study areas: first between the Late Miocene/Early Pliocene and the Late Pliocene, and second between the Late Pliocene/Early Pleistocene and the Late Pleistocene or the present. The exact timing of the processes is the subject of future research. This thesis helps to find those localities that are suitable for future dating and palaeoseismological analysis.

Abstrakt

Přesto, že je Český masiv vnitrodeskovým územím, v průběhu pozdního kenozoika se na jeho území vyskytovala relativně intenzivní tektonická aktivita. Tyto procesy významně utvářely jak morfologii terénu, tak geometrii vodních toků, což můžeme v dnešní krajině snadno pozorovat. Zatímco vliv tektoniky a klimatu na utváření morfologie terénu byl studován a popisován už mnohokrát, vliv na geometrii říčních systémů nebyl dosud komplexně zkoumán. Předchozí autorovy výzkumy v rámci diplomové práce lokalizovaly dvě perspektivní oblasti v Českém masivu – okolí mariánskolázeňského zlomu v západních Čechách a Novohradské hory a jejich podhůří v jižních Čechách. V těchto oblastech je vliv tektonických pohybů a klimatu na změny geometrie vodních toků velmi pravděpodobný, a proto jsou tyto oblasti vhodným prostředím pro výzkum takových interakcí.

Tato práce je zaměřena na studium vzájemných interakcí mezi tektonickou aktivitou a geometrií (změnami geometrie) vybraných říčních systémů v Českém masivu. Cílem není pouze prokázat souvislost a vliv tektoniky na říční systémy, ale také testovat a vyhodnotit použitý soubor metod, které mohou být vhodné pro nalezení lokalit s recentní tektonickou aktivitou a které jsou použitelné v budoucnu i v jiných podobných územích.

Obě oblasti – podél mariánskolázeňského zlomu a v Novohradských horách a podhůří - byly zkoumány pomocí stejných metod, aby bylo možné výsledky z obou oblastí navzájem porovnávat a také, aby bylo možno použité metody vyhodnotit pro případné další vylepšení a použití v jiných podobných oblastech. Geomorfologické metody založené zejména na dálkovém průzkumu Země a vyhodnocování digitálních modelů reliéfu byly použity jak v této práci, tak v jednotlivých článcích, které jsou přiloženy. Jednalo se zejména o: morfotektonickou analýzu, analýzu podélných profilů vodních toků, měření gradientů vodních toků, SL indexu, hypsometrického indexu, asymetrie povodí, sinuosity zlomového svahu, šířky údolního dna, analýzu příčných profilů údolí atd. Výsledky - a tedy použitelnost - těchto metod byly zejména v oblasti mariánskolázeňského zlomu ověřovány pomocí výsledků letecké geofyziky, užité geofyziky (zejména geoelektrických odporových metod), terénním výzkumem zaměřeným na strukturní geologii, částečně též paleoseismologickými metodami. Na základě poměrně dobré shody mezi výsledky získanými DPZ a výsledky nezávislých metod bylo konstatováno, že geomorfologické metody DPZ jsou použitelné a spolehlivé i v oblasti Novohradských hor.

Výsledky naznačují, že obě oblasti prošly výrazným, tektonicky podmíněným výzdvihem v průběhu svrchního Pliocénu, Pleistocénu a pravděpodobně - v případě mariánskolázeňského zlomu – zřejmě i Holocénu. Tektonická aktivita se nicméně zřejmě neodehrávala v rámci jedné události, ale spíše šlo o časově oddělenou aktivitu jednotlivých částí mariánskolázeňského zlomu nebo případně nerovnoměrný tektonický výzdvih jednotlivých bloků v oblasti Novohradských hor a podhůří. Tato

časově a prostorově oddělená tektonická aktivita měla významný dopad na změny geometrie vodních toků a obecně na vývoj říční sítě ve sledovaných oblastech (docházelo k říčnímu pirátství atd.) Bylo zjištěno, že ve sledovaných oblastech nejsou Pliocenní a Pleistocenní říční sedimenty rozmístěny podle stejného plánu, což svědčí o změnách a vývoji geometrie říční sítě. Na základě morfostratigrafického posouzení výskytu fluviálních sedimentů bylo možné tento vývoj alespoň zhruba rekonstruovat. V obou oblastech došlo ke dvěma hlavním, tektonicky podmíněným změnám v geometrii říční sítě jako celku. První změnou bylo přerušení miocenního směru odvodňování (tj. Chebsko-domažlický příkop k severu, jihočeské pánve k jihovýchodu do alpsko-karpatské předhlubně apod.), druhou změnou byl přechod ze svrchně pliocenního/spodně pleistocenního stavu do takového, který odpovídá střednímu a svrchnímu Pleistocénu nebo dnešku. Přesné datování těchto procesů je předmětem dalšího výzkumu, zaměřeného na datování kosmogenními nuklidy a paleoseismologickou analýzu. Vhodné lokality pro tento výzkum pomohla vybrat právě tato práce. Absolutní datování získané těmito metodami pomůže dále zpřesnit časoprostorové určení vztahů mezi tektonickými pohyby a geometrií říčních sítí.

Acknowledgements

First of all, I would like to express many thanks to Karel Martínek, the principal advisor, for supervision of the thesis, for reviewing the texts not only of this thesis but also of numerous study reports, grant applications, conference abstracts and papers. Also, I would like to acknowledge Daniel Nývlt, the thesis consultant, who has helped a lot during the design of the thesis and during its finalization.

A special acknowledgement goes to Petra Štěpančíková, who has been the consultant and also the co-author of two papers included in the thesis. She has significantly helped with their publication, not only through her advice as a co-author, but also by providing the time and space for their creation as a head of the Department of Neotectonics and Thermochronology of the IRSM CAS.

An acknowledgement also goes to Jiří Žák, Jaroslava Pertoldová and Barbora Dudíková-Schullmanová and Radka Kalinová for providing a significant part of the field structural data.

Kryštof Verner provided field photographs, part of the field structural data and their analysis as well as valuable consultations. Many thanks to Petr Tábořík for providing the figures of geophysical research and for many valuable thoughts. Also, I would like to thank the Institute of Physics of Earth for providing the database of seismic events and the Czech Geological Survey, which provided the airborne geophysics dataset and the geological maps of the study area.

I would also like to thank also my colleagues and superiors from my several workplaces (The Institute of Geology and Palaeontology, Faculty of Science, Charles University; The Czech Geological Survey; The Department of Biology of the Faculty of Education, University of South Bohemia, and the Department of Neotectonics and Thermochronology of the Institute of Rock Structure and Mechanics, CAS) for their support, tolerance, and many important advice during the research. I gratefully acknowledge Richard R. H. Withers for English proof reading. The research was supported by the Grant Agency of the Czech Republic no. 21-29826S and also by an internal grant from the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences, no. 2019/ 350.

Last but not least, I would like to express many thanks to my family for their support. I am especially grateful to my daughter Žofie (for her patience) and to my partner Tereza (for her even greater patience), who promised to read the whole thesis, if I express my many thanks to her here.

Table of contents

Introduction

Despite its intraplate tectonic setting, the Bohemian Massif underwent relatively intense tectonic activity during the Cenozoic. This activity has significantly formed the terrain morphology and river geometry, which can easily be observed from the present status of the streams and relief. Although the effect of tectonics and climate on the terrain morphology has been researched many times in previous studies, the effect on the geometry of the river systems has yet to be surveyed in detail. The effect of tectonics on the river geometry have been mentioned in numerous studies (Malkovský, 1975; Cloetingh et al., 2006; Ziegler and Dèzes, 2007; Bridgland and Westaway, 2008; Tyráček and Havlíček 2009; Balatka et al., 2015), however, often it has only been discussed as a result of the general uplift of the area of the Bohemian Massif without any connection to the particular tectonic structures and movements along them and their direct influence on the particular river systems and their geometry.

The author´s previous study (Flašar, 2012) has found some remarkable areas within the Bohemian Massif, where the effect of climate and tectonics on the river system geometry and its changes is very probable. The areas of southern Bohemia (the rivers Vltava, Malše and Lužnice), western Bohemia (the rivers Mže, Radbuza, Úhlava and Úslava) and eastern Bohemia (the rivers Cidlina, Mrlina, Javorka and Bystřice) were studied. The first hypotheses, supposing the lithology and tectonics had a significant effect on the water streams under study, have been set based on analyses of the stream gradient, SL index and stream sinuosity. In particular, the areas of southern and western Bohemia have shown remarkable results. Based on the aforementioned results, the relatively poor knowledge of the tectonics-rivers interactions, but strong indications of recent tectonic activity (Popotnig et al., 2013; IPE, 2014; Špaček et al., 2017; Štěpančíková et al., 2019), the areas of southern and western Bohemia were selected for further, in-depth research within this study. Also, the study areas were delineated more precisely.

In Western Bohemia, the research has focused on the area of the Mariánské Lázně Fault and the possible effect of its tectonic activity on the evolution and geometry of the adjacent river systems. In Southern Bohemia, the study area was delineated as the catchment of the Malše River. This river (together with its tributaries) showed the most interesting results in the author´s previous study. Furthermore, this area contains many interesting tectonic structures that can be responsible for the evolution of the local stream network, as previous results indicate. Finally, there are abundant localities of Miocene, Pliocene, and Pleistocene fluvial deposits and river terraces, which could be used to reconstruct the geometry of the previous stream network. Therefore, it can help to explain the evolution of the stream network in the late Cenozoic.

Both areas were surveyed using identical or similar methods (respecting the limitations due to the character of the study area – e. g., the Mariánské Lázně Fault is a single, but extremely long tectonic structure) to be able to compare the results from particular areas with each other and evaluate the methods used and improve them for future use. The area of the Mariánské Lázně Fault has been surveyed thoroughly in the past, however, methods regarding the geometry of the water stream were only used in a limited part near the NW end of the fault. However, this part of the fault was also surveyed by various methods of applied geophysics and palaeoseismology. This provides a great opportunity to use the methods for studying river geometry along the rest of the fault, or in the other study areas (e.g., Southern Bohemia), with the possibility of comparing and verifying the results.

Individual results from the study areas are presented and discussed in three chapters, as integral parts of this thesis. **Chapter 1 "Geomorphological evidence of tectonic activity of the Mariánské Lázně Fault (Czech Republic) and its influence on stream network evolution"** is focused on the area of the Mariánské Lázně Fault. This study evaluates the geomorphological methods used and proposes the evolution of the river network in the area with regard to the tectonic activity along the Mariánské Lázně Fault. The other two chapters are focused on the area of the Novohradské hory Mts. **Chapter 2 „Neogene-Quaternary response of the Novohradské hory Mts. (Czech Republic) fluvial systems to tectonics – morphotectonic, stream-length index and field structural analyses"** is aims to study the tectonic activity and its interactions with the fluvial systems in the area - which has not been detailly studied yet – by various methods. **Chapter 3 "Plio-Pleistocene paleodrainage reconstruction using moldavite-bearing and morphostratigraphically related deposits (Southern Bohemia, Czech Republic)"** is focused on the reconstruction of the river network in the area with the respect to the tectonic activity and it extends the results of the Chapter 2.

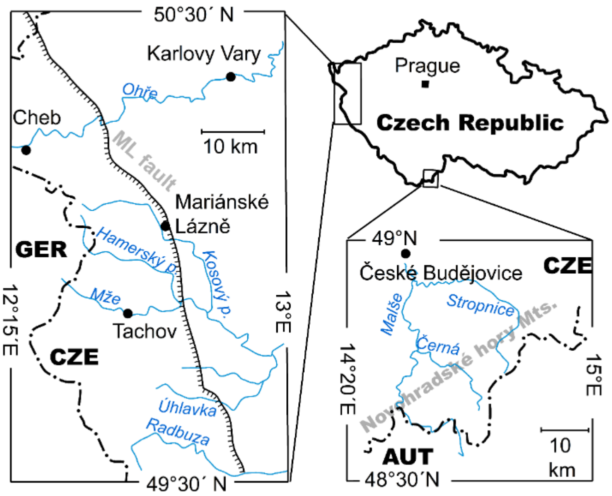


Fig. 1: Localization of the study areas – the Mariánské Lázně Fault area and the Novohradské hory Mts. Area. For detailed terrain and geological maps see Fig. 2ab and Fig. 3ab

Geological and tectonic setting of the area of the Mariánské Lázně Fault

The Mariánské Lázně Fault limits several geological units which have often undergone different geological processes. Therefore, its geological history and lithological structure are very variable. There is the Saxothuringian unit in the NW, the Moldanubian unit in the W and S, the Teplá-Barrandian unit in the eastern part of the study area and the Mariánské Lázně complex between those units. Some of these crystalline rocks can be overlaid by the Cenozoic sedimentary units of the Cheb basin (Mlčoch and Skácelová, 2009).

The Saxothuringian crystalline rocks - paragneisses, schists, and orthogneisses - of Proterozoic and Cambrian age, which were intensely metamorphosed during the Variscan orogeny, are the most frequent rock types in this unit. In addition, less metamorphosed phyllites of Ordovician age can be found (Chlupáč et al., 2002). The Mariánské Lázně complex is composed of mafic and ultramafic rocks: serpentinized peridotite in the basement and sets of amphibolites, eclogites and metagabbros (Cháb et al., 2008) as it has filled the suture between the two former microcontinents amalgamated during the Variscan orogeny (Mlčoch and Konopásek, 2010). The Teplá-Barrandian unit is less affected by metamorphosis than the other units, phyllites, schists and paragneisses can be found along the fault (Chlupáč et al., 2002). The Moldanubian unit is composed mostly of Variscan metamorphosed rocks like paragneisses, orthogneisses and migmatites. Granitic intrusions are also presented in the study area of pre-Variscan or Variscan age (Cháb et al., 2008). The Cheb Basin is infilled by sands, gravels and clays of upper Eocene age overlaid by sets of coal seams, clays, sands and volcaniclastics of Oligocene and Miocene age (Špičáková et al., 2000). The uppermost part of the basin infill is represented by the Miocene Cypris Formation and the Pliocene Vildštejn Formation. The latter formation is composed of fluviolacustrine sands, gravels and clays and it is not present just in the Cheb basin, but also in several relicts in the Cheb-Domažlice Graben along the Mariánské Lázně Fault (Pešek, 1972; Teodoridis et al., 2017).

The tectonic structures of the study area are mainly represented by the extremely prominent Mariánské Lázně Fault, which is 150 km long and has a general orientation NNW-SSE. Another important structure is the Eger Graben of NE-SW orientation, which is bounded by faults on both sides, however it is not a target structure of this study, just as the number of smaller faults that cross the Mariánské Lázně Fault in generally perpendicular direction (see Fig. 2a)

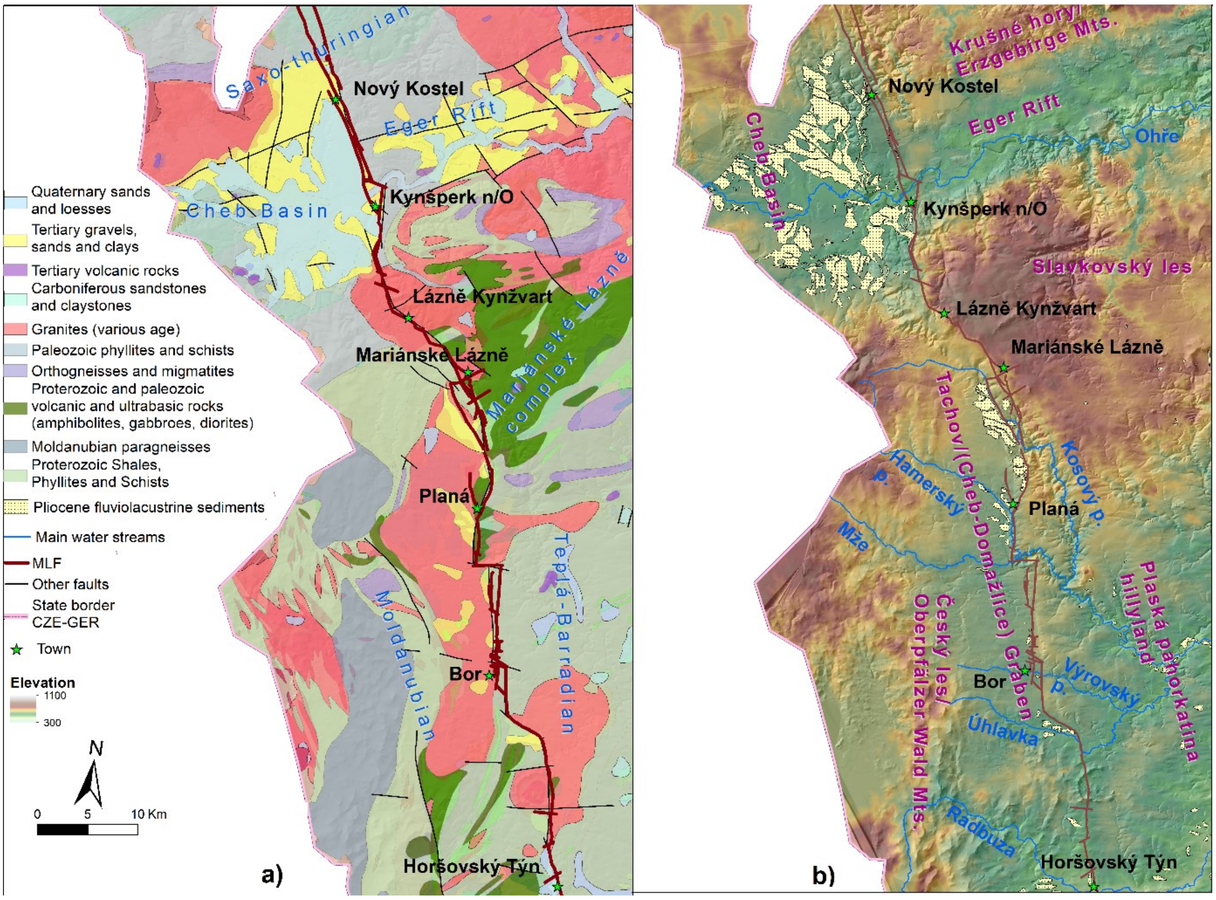


Fig. 2: a) Geological map of the area of the Mariánské Lázně Fault, b) Terrain map of the area. Note the occurrence of Pliocene fluviolacustrine sediments and the configuration of the water streams (according to Flašar and Štěpančíková, 2022).

Geological and tectonic setting of the area of the Novohradské hory Mts.

The Novohradské hory Mountains and their foothills are composed mainly of metamorphic rocks from the Moldanubian Unit and granites of the Moldanubian Batholith. The Moldanubian Unit is represented here by its Monotonous Group, which is formed by biotitic, biotite-muscovitic and biotite-cordieritic paragneisses and migmatites. In addition, biotite-muscovitic orthogneisses can be found locally. Granites of Moldanubian Batholite are particularly represented by several granite types: porphyritic biotite granite (Weinsberg type), muscovite-biotite granite (Mrákotín type), porphyritic muscovite-biotite granite (Eisgarn type) and biotite granodiorite (Freistadt type) according to Mísař et al. (1983) and Bankwitz et al. (2004).There are significant differences between granites of Moldanubian Batholite, especially in the age of their origin. The Weinsberg and Eisgarn types were formed during the main phase of batholite intrusion (328 Ma, respectively 324 Ma), whereas the Freistadt type was formed in its late phase (303 Ma) (Bankwitz et al., 2004). This could play an important role in forming the tectonic setting of the whole area. In addition, other types of granitic rocks can occur locally, but mostly in the form of small bodies or dykes.

The Třeboň and Budějovice Basins are filled with Cretaceous and Cenozoic clastic sediments of lacustrine and fluvial origin. The Cretaceous rocks are represented mostly by sandstones and claystones from the Klikov Formation; clays and sands of Mydlovary, Domanín and Ledenice Formations are typical for Cenozoic period (Chlupáč et al., 2002; Pešek, 2010). There are also small deposits of Neogene, probably Pliocene, lacustrine or fluviolacustrine sediments in the area of the Kaplice Furrow (Fig. 3ab; Březinová et al., 1963; Bezvoda et al., 1983). The abundant fluvial sediments and river terraces of Pliocene and Pleistocene age, which are scattered across the area, are described in **Chapter 3** (section 2.3).

There are several fault systems in the area of the Novohradské hory Mts. Their orientations are SSW-NNE, ESE – WNW, SW-NE, SSE-NNW and E-W (Slabý and Holásek, 1992a; Slabý and Holásek, 1992b; Vrána and Holásek, 1992; Vrána and Novák, 1993) The faults with ESE-WNW orientation (parallel with Danube fault system) are very significant are because they border the Třeboň and Budějovice Basins and they are often visible in the present relief, probably due to their recent activity. The Kaplice Graben is founded along the other distinctive fault system with SSW-NNE orientation (the Blanice-Rodl fault system). There are also several smaller faults with E-W and S-N orientations in the study area. They do not form distinctive fault systems, but they can be significant in the morphology, and recent activity on these faults is also possible (see Fig. 3b).

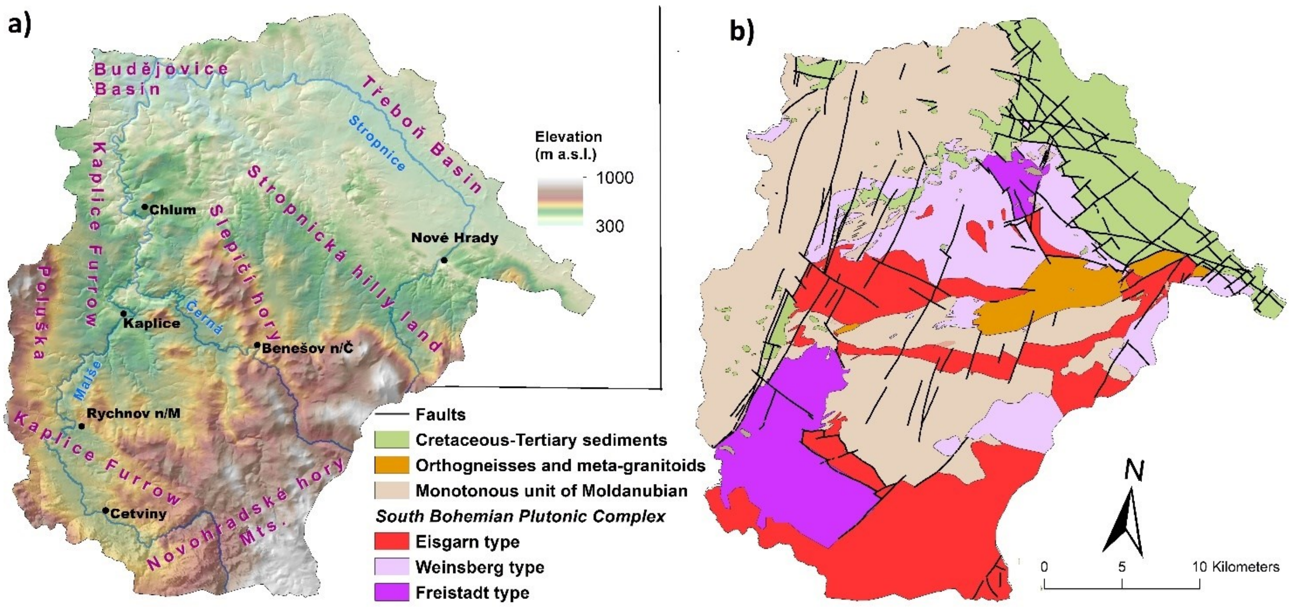


Fig. 3: a) Terrain map of the area of Novohradské hory Mts. and foothills. b) Geological map of the area. Note the configuration of the water streams and faults systems.

Aims and goals

The focus of this thesis is to study the mutual interactions between the tectonic activity and the geometry of selected river systems in the Bohemian Massif. The goal is not only to prove a connection but also to test and evaluate the set of methods that can be useful for localizing those places with recent tectonic activity and which can be applied in similar areas in the future. The main questions of this study are:

- Is the shape of the drainage network, river section orientation, longitudinal profiles, etc. of the streams within the areas of Southern and Western Bohemia influenced by tectonic activity?
- When did the tectonic activity take place? Could the Pleistocene uplift significantly affect the geometry of water streams?
- Is it possible to reconstruct the evolution of the water stream network during the Pliocene-present period?
- Is the set of methods used robust enough to find the places with probable recent tectonic activity? Is it possible to use these methods for e.g. seismic hazard assessment?
- Where are the best places for subsequent palaeoseismological research and dating analyses?

Reaction of fluvial systems to tectonics: examples from active tectonics areas

The tectonic activity along the fault can significantly affect the general orientation of the water stream, river network shape, or the course of the stream longitudinal profile. If the water stream crosses (ideally in the perpendicular direction) the uplifting fault, a steepening on the longitudinal profile – a knickpoint – is formed (Maroukian et al., 2008). The erosion effect of the water stream tends to smooth its longitudinal profile, so the preserved knickpoint could be an important sign of recent active tectonics (Carretier et al., 2006). Due to incision and backward erosion of the water streams, the knickpoints can migrate up the stream – as much as 10 mm/year in active tectonic areas (Burbank and Anderson, 2001). The knickpoints can migrate relatively easily up a stream in a short period of time and they can recede from the tectonic fault (or lithological boundary) where they have originated (Bishop et al., 2005). This effect can pose a difficulty for interpretating the feature's origin and evolution, and the rate of knickpoint migration in various lithological and tectonic conditions have not been satisfactorily solved yet (Burbank and Anderson, 2001).

Local tectonic activity can be preserved in the knickpoints, but stream profiles can also say something about the tectonics on larger scales. The typical longitudinal profile of mature, stable water streams (so-called graded rivers) has a hyperbolic shape as a result of the long-term balance between erosion and deposition. Any divergence of this shape is an indication of unstable conditions; however, there are many factors which could influence the shape: erosion base level, geological setting, hydrological setting, climate, tectonics (Burbank and Anderson, 2001). If the longitudinal profile of a particular stream is close to the 'graded river shape', there is a lower probability of disturbances by lithological, tectonic, hydrological, and other influences during stream evolution. Theoretically, the profiles of older streams should have been smoother and closer to ideal, because the possible knickpoints should have been smoothed by erosion (Burbank and Anderson, 2001; Radoane et al., 2002). The profile itself results from the influence of a combination of factors; however, studies Radoane et al. (2002) or Carretier et al. (2006) suggest that the lithotectonic effect on the longitudinal profiles is stronger than the other factors, even in the conditions of Central Europe.

The general shape of the longitudinal profile curve can be an indicator of regional uplift. If the curve shape differs from the hyperbolic one and tends to a straight line, it could be a sign of a regional uplift (Burbank and Anderson, 2001).

The pattern of the river network or its general shape can also be sensitive to regional uplift. Water streams can tend to deflect their course from the areas of uplift or when the terrain is tilting. Classical examples of water streams' reaction to growing anticlines or tilting areas are described for the areas of active orogeny (e.g., California) by Burbank and Anderson (2001). However, some authors have also tried to find a similar process in the Bohemian Massif. Moschelesová (1930) and partially Kopecký (1983) have offered the idea of the mega-anticlinal structure of the Šumava Mts. and the formation of a relief and river network with respect to that tectonic structure. Chábera et al. (1985) has suggested that the remarkable bend of the Vltava River on its middle part towards the west could be caused by the gradual uplift of the Central Bohemian Hilly Land Some patterns that could suggest an uneven rate of regional uplift were recorded in all study areas. In **Chapter 3** (section 7.4), the eastward migration of the Malše River is discussed as a result of the uplift of the Novohradské hory Foothills.

Regional uplift can also influence the sinuosity (the ratio between the distance along the stream and the straight distance) of the water streams. The changes in sinuosity along the water stream are interlinked with changes in sedimentation, which can be affected by a change in the tectonically induced stream gradient (Ouchi, 1985). The sinuosity increases if the stream crosses an uplifting area and the stream gradient is lowered. On the other hand, if the uplift stops, or the longitudinal profile is smoothed by erosion, sinuosity drops (and the meanders are shortened). The character and amount of sediment influx is important; however, the resulting reactions of the water stream are similar (Ouchi, 1985). Many rivers in the Bohemian Massif have, in fact, incised meanders, instead of free ones, at least on a part of its course. However, the incised meanders themselves are the sign of regional uplift and their shapes can be inherited from the previous free ones. Therefore, the existence, distribution, and shapes of the incised meanders can also be an important sign of tectonic uplift (Harden, 1990).

Horizontal tectonic movements along faults can have a significant effect on the evolution of a stream's drainage pattern. A typical feature, it is called a 'beheaded stream' (Burbank and Anderson, 2001) or an 'off-set valley' (Štěpančíková et al., 2010). The best examples can be found in the areas with active tectonics – South California (Huggett, 2003) or New Zealand (Little et al., 2009); however, signs of similar features can be even found in intraplate areas like the Bohemian Massif (Štěpančíková et al., 2010; Štěpančíková et al.,2019). Similarly, uneven uplift along the Mariánské Lázně Fault probably significantly influenced the evolution of the local river network, which is further discussed in **Chapter 1** (section 5.2).

In addition to active tectonics, the tectonic structure itself can play a role in the shape of the river network and the orientation of the stream. Faults, shear zones, and joint systems act like discontinuities in the rock massif, their surrounding is usually more erodible and therefore streams are preferably oriented along such discontinuities, especially in hard crystalline rocks (Chorley et al., 1985). The existence of a similar orientation of joints and fault systems and stream sections in a particular area does not automatically mean that the stream is necessarily oriented along those tectonic structures, however, usually it does so (Beavis, 2000). The streams of lower orders (Strahler) are usually oriented more frequently along the tectonic structures than the streams of higher orders because smaller streams are more easily influenced by lithologic and tectonic conditions, as their discharge is lower (Ribolini and Spagnolo, 2007).

Distribution and origin of late Cenozoic fluvial deposits in the Bohemian Massif

There are many localities of late Cenozoic fluvial deposits in the Bohemian Massif. Various authors (Balatka and Sládek, 1962; Tyráček, 2001; Tyráček et al., 2004; Tyráček and Havlíček, 2009; Balatka et al., 2015; Balatka et al., 2019) assign them to the time period from the (Late) Pliocene to the Holocene. Traditionally, these fluvial deposits are dated morphostratigraphically. Studies using methods of chronometric dating (OSL, ^{10}Be) are very rare. Some studies (Homolová et al., 2012) agree with the previous results for the morphostratigraphical dating of terraces; the results of others (Schaller et al., 2016a; Schaller et al., 2016b; Štor et al., 2019) differ from the traditional setting. Generally, the issues regarding the absolute dating of deposits are still a matter of discussion. The fluvial deposits naturally provide an excellent archive for reconstructing river network evolution during the late Cenozoic. The spatial distribution of Late Pliocene and Pleistocene fluvial deposits is in general agreement with the present status and style of drainage - regarding the fact that the main change of the drainage direction probably happened in the Early Pliocene (Malkovský, 1975). Some changes in the orientation of the stream sections could have occurred during the Pliocene-Pleistocene (e.g., the lateral migration of the

Labe River, by several kilometres, near Říp or Vštetaty (Tyráček, 2001; Burda et al., 2021)); a change in the stream orientation of the lower Ohře River caused by tectonics (Tyráček a Havlíček, 2009; Balatka et al., 2015) or glacially driven changes of the Ploučnice River (Štor et al., 2019). However, Tyráček (2001) mentioned that no significant changes in gravel petrology (= no significant changes in the source areas) have happened in general in the Bohemian Massif during the late Pliocene-Holocene. Generally, the Pliocene-Pleistocene climate changes and tectonics have had an affect (with different intensity), particularly on the longitudinal profiles of the streams.

Therefore, many past studies have highlighted the altitudinal distribution of particular river terraces with respect to the current stream altitudinal level. The position is important for the morphostratigraphical setting and also for interpreting the rate of and reasons for river incision. Most rivers in the Bohemian Massif have a character similar to their terrace staircases – the oldest documented terraces are located high above the present floodplain (100-150 m; Tyráček a Havlíček, 2009) and are often located on the Cenozoic peneplain. These high terraces are traditionally assigned to the Pliocene (Balatka and Sládek, 1962; Novák, 1983). There is typically a terrace staircase on the slopes of the incised valley of the river, one or two levels of terraces, and the present floodplain on the valley floor. Together 11–15 levels of terraces (depending on the deposit's preservation) can be found along the rivers in the Bohemian Massif (Tyráček and Havlíček, 2009) as a result of repeated alternation of down-cutting and aggradation phases. This configuration is not unique, and it can be found along many other streams across Europe (Gibbard and Lewin, 2002; Bridgland and Westaway, 2008; Font el al., 2010). According to Tyráček (1983), Bridgland (2000) and Westaway (2002) the alternation of erosion and aggradation phases is driven by climate changes and the beginning of terrace formation corresponds with the start of significant alternation of glacials and interglacials, which are typical for the Quaternary era. Therefore, the formation of modern drainage patterns and the highest terraces has always been correlated with the onset of the Quaternary or, at the oldest, with the Late Pliocene (Tyráček and Havlíček, 2009).

However, various studies have still been resolving the main questions: what drives the river incision (climate or tectonics) and when these processes happened (= the age of particular river terraces). Many authors have traditionally assigned (e.g. Balatka and Sládek, 1962) the uppermost terraces to the Pliocene (see above); whilst some newer studies (Tyráček and Havlíček, 2009; Balatka and Kalvoda, 2010) have preferred the early Pleistocene (which is, however, also caused by moving the Pliocene-Pleistocene boundary to 2.58 Ma in 2009). Terraces located on the slopes of incised river valleys were deposited in the periods that were suitable for sedimentation, but generally this part of the terrace staircase is typical for the most intensive incision during the entire Pleistocene. Most current authors (Tyráček 2001, Tyráček et al., 2004; Bridgland and Westaway, 2008; Schaler et al., 2016a; Schaller et al., 2016b) have connected the beginning of an intensive incision with the Mid-Pleistocene transition. The change from the 41 ka cyclicity (Laplace period) to the 100 ka cyclicity (Milankovic period) during the Mid-Pleistocene transition, associated with drastic climate changes typified by the latter and relatively mild glacials during the former period; Tyráček and Havlíček, 2009) has also led to the intensification of the incision.

Is the climate the main factor influencing the rate – or the variability of the rate – of incision? It may seem that climate is the single driving agent, based on the remarkable change in the Middle Pleistocene. Balatka and Kalvoda (2015) suggest that the incision of Bohemian rivers is mainly caused by the regional uplift of the Bohemian Massif.Tyráček et al. (2004) also agreed and specified that the main incision phase, caused by the uplift, began after MIS 22 and became even more intensive after MIS 18 (= Lysolaje terrace). The trend of uplift is also known from other parts of Europe and, indeed, worldwide, as an important factor in terrace formation (e.g.; Maddy, 1997; Bridgland, 2000; Westaway, 2002; Bridgland and Westaway, 2008). Similarly, the increase in uplift rates, in particular after ~0.9 Ma (Van den Berg and van Hoof, 2001; Westaway, 2001), is detectable in other parts of Europe and shifts the start of the main terracing phase close to the Lower–Middle Pleistocene boundary.

Many authors mention that both tectonics and climate have played their roles, or, respectively, that both of these factors are intensively interlinked to each other during the Pleistocene. It is highly probable that the climate change of (or after) the Mid-Pleistocene transition has led to changes not only in glaciation, but also in hydrological regimes and erosion rates (Tyráček and Havlíček, 2009). Bridgland and Westaway (2008) suggested that there is a reason to suggest that climate and uplift are coupled through an isostatic response to changes in erosion rates. That could lead to the more significant uplift and rise of the Bohemian Massif after the Mid-Pleistocene transition. The incision itself is the result of the combined effect of progressive surface uplift and the cyclic climatic triggering of fluvial activity (Bridgland and Westaway, 2008; Tyráček and Havlíček, 2009).

It is very probable that it is not possible to distinguish the effect of climate and tectonics on river incision at a general scale. However, on the local scale, it is possible to evaluate the influence of tectonic activity on the water streams in the case where there is an interaction between a particular tectonic structure and a particular stream. The methods used in this study can significantly help this evaluation.

There are many fluvial deposits and river terraces of various ages in the area of the Novohradské Hory Mts. Moldavite-bearing sediments – Vrábče beds and Koroseky sand and gravel belong among them, as well as other, probably Pliocene, fluvial deposits. Furthermore, all the main rivers (Vltava, Malše and Stropnice rivers) in the study area have developed a system of terrace staircases with a sequence finished by the present infill of a floodplain. All these deposits, their relationship to tectonics, their mutual relationships, possible dating, etc. are described in detail in Chapter 3 (sections 2.3, 7.1, 7.2 and 7.3).

Furthermore, the area of the surroundings of the Mariánské Lázně Fault provides many localities of fluvial deposits because of a well-developed river network. The uppermost part of the sedimentary infill of the Cheb Basin is represented by the Pliocene Vildštejn Formation of fluvio-lacustrine origin. The probable equivalents of these layers can also be found in the Cheb-Domažlice Graben along the Mariánské Lázně Fault (Pešek, 2010; Teodoridis et al., 2017). In addition, the biggest streams (Ohře, Mže, Kosový, Hamerský, Radbuza rivers) in the area have built terrace staircases throughout the Quaternary (Balatka and Sládek, 1962). It is not clear, whether the Pliocene sediments have had any evolutionary relationship to the Pleistocene river terraces of the Ohře, Mže and other rivers. However, it seems, from their spatial relationship, that the interlink between the Pliocene, Pleistocene and present river network has existed. The distribution of fluvial deposits, as well as the proposed evolution of local river network, is further discussed in Chapter 1 (section 5.2).

Overview of late Cenozoic tectonic activity in the Bohemian Massif

The Bohemian Massif itself was amalgamated during the Variscan orogeny, when most of the present tectonic faults (Fig. 4) were formed, often as a boundaries or sutures between particular units forming the Bohemian Massif (Chlupáč et al., 2002). The faults within the Bohemian Massif have typical directions of NW-SE, SW-NE or NNE-SSW (Mísař et al., 1983). Many of these faults have been reactivated several times since the Variscan orogeny and this process has played its role during the evolution of the post-orogeny Bohemian Massif. In particular, the final Plio-Plestiocene reactivation of faults, with mainly NW-SE and NNW-SSW orientation, has changed the appearance of the present relief (Coubal et al., 2015). The gently undulated denudation (or planation) surface developed during a prolonged period (most of the Mesozic; Malkovský, 1975; Ziegler and Dèzes, 2007) of tectonic quiescence after the Variscan orogeny. The Cenozoic reactivation of Variscan origin faults due to the incoming Alpine orogenetic phase is widely accepted by various authors (Malkovský, 1975; Ziegler and Dèzes, 2007; Coubal et al., 2015). Several phases of reactivation in different stress regimes have occurred since the late Cretaceous to recent (Coubal et al., 2015). Many of the abovementioned reactivations have left traces in the geological record; however, the youngest tectonic events (Miocene – recent) are the most significant regarding terrain morphology and river geometry.

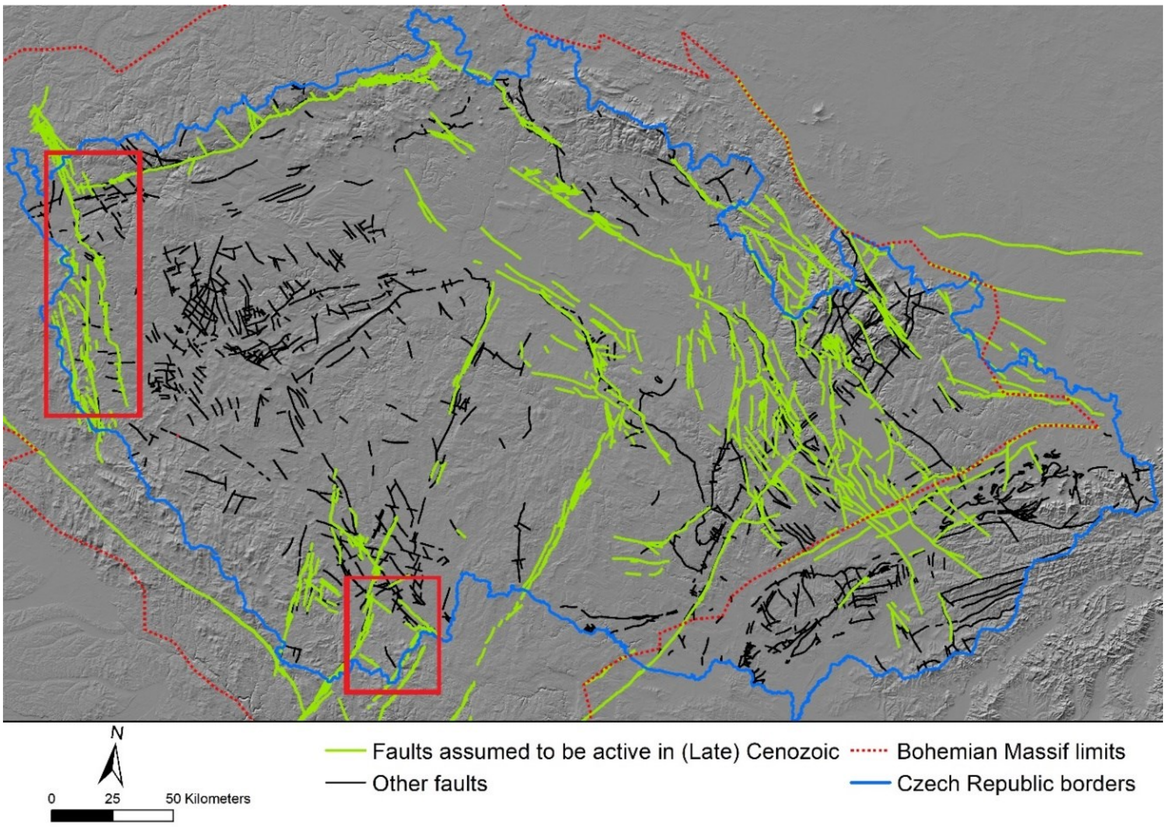


Fig. 4: Main tectonic faults of the Bohemian Massif (according to Špaček, 2021) with the study areas highlighted (see Fig. 1)

Despite the compressive events in its neighbourhood, the Bohemian Massif was subjected to extension in the Early Miocene. This tectonic regime has been linked to the subsidence and sedimentation in the Eger Graben and in the Třeboň and Budějovice Basins. In addition, intensive volcanic activity has been presented in the České středhoří Uplands, which preceded the main phase of subsidence in the Eger Graben (Coubal et al., 2015).

During the early Langhian (early Badenian, c. 16 – 15 Ma) temporary marine incursions advanced northward from the Alpine–Carpathian foreland basin along river valleys into the Třeboň and Budějovice basins. This is a sign of the existence of a flat terrain at a low altitude above sea level (Ziegler and Dèzes, 2007).

The western part of the Alpine foreland was governed by a NE–SW compression starting from the earliest Miocene (Bergerat, 1987). However, this compression regime was restored as late as the Middle Miocene in the Bohemian Massif. In the Western Carpathians, near the Bohemian Massif margin, the stress state changed considerably with the onset of the NE–SW compression during the Late Langhian (≈14 Ma). Probably the only sedimentary record of the onset of this regional compression in the Bohemian Massif is the change in the character of deposition in the South Bohemian basins in the Late Badenian (≈14 Ma), when the lacustrine deposition characteristic for the

subsidence period (Mydlovary Fm.) was replaced by fluvially coarser clastics (Domanín Fm. or Vrábče beds; Pešek, 2010; Coubal et al., 2015). The change from a tensional to a compressional paleostress regime also resulted in the end of sedimentation in the basins of the Eger Graben (Coubal et al., 2015). During the Pliocene and Pleistocene, the NE-SW-oriented compression was succeeded by a period governed by a NW-SE compressional paleostress pattern, lasting until the present in the Alpine foreland around the Bohemian Massif. The change in stress orientation has been dated mainly to the latest Miocene (Coubal et al., 2015).
Despite the generally rising tendency of the Bohemian Massif in this period, the effects of uplift stagnation or even subsidence are documented by the presence of late Pliocene lacustrine sediments in the Cheb Basin (Vildštejn Fm.) and in the South Bohemian basins (Ledenice Fm.; Pešek, 2010; Coubal et al., 2015). By the end of the Pliocene (Piacenzian, ≈3.6–2.6 Ma), lacustrine sedimentation in the three abovementioned basins stopped due to the influx of coarse clastics (Koroseky sand and gravel in the South Bohemian basins), which can be interpreted as a possible effect of accelerated uplift of the Bohemian Massif (Bouška, 1992; Pešek, 2010). The uplift of the Bohemian Massif (Malkovský, 1979; Ziegler and Dèzes, 2007), which has been related to the latest stress patterns (NW-SW and NW-SE) and is reflected in various geomorphic features, such as disruption of the pre-existing peneplain, block-like mountain building and the gradual development of its present physiographic relief (Ziegler and Dèzes, 2007), enhanced river incision, the divergence of flights of fluvial terraces, river pattern changes etc. (Coubal et al., 2015). The uplift was probably even accelerated during the Pleistocene - this change in the uplift rates is interlinked by various authors (e.g. Tyráček and Havlíček, 2009) with the Mid-Pleistocene transition (see section 'Distribution and origin of late Cenozoic fluvial deposits in the Bohemian Massif'). The very recent, Holocene, tectonics in the Bohemian Massif is also governed by a similar NNW–SSE/NW–SE stress pattern, as evidenced by focal mechanisms breakout analyses or as inferred from monitoring micro-displacements on faults (Coubal et al., 2015 and references therein). This agrees with the present-day plate-driven compression in Western Europe, where maximum stress is subparallel to the direction of the relative plate motion between Africa and Europe (Müller et al., 1992; Ziegler and Dèzes, 2007; Coubal et al., 2015).

Despite the general consensus regarding the Pliocene and Pleistocene uplift of the Bohemian Massif, the detailed spatial and time localization of the tectonic movements is still a matter of discussion. Based on the general terrain morphology, most authors assume a more intensive Pleistocene uplift in the bounding mountainous areas of the Bohemian Massif (Krkonoše Mts., Krušné hory Mts., Šumava Mts., Novohradské hory Mts.). This hypothesis was mentioned by Kopecký, 1983, Kopecký, 1970, Kopecký and Vyskočil, 1969, Malkovský, 1979, Chábera et al., 1985, Bouška, 1992, however, often only in a general view without any relation to the particular tectonic structures.

Only individual studies have investigated the possibility of Pleistocene or Holocene activity along particular tectonic faults. Probably the most studied structure (Peterek et al., 2011; Fischer et al., 2012; Blecha et al. 2018; Štěpančíková et al., 2019) is the Mariánské Lázně Fault, due to the intensive recent tectonic activity and the mantle-derived CO2 emanations. The Sudetic Marginal Fault (Badura el al., 2007; Štěpančíková et al., 2008; Štěpančíková et al., 2010; Štěpančíková et al., 2012) or Hluboká fault (Popoting et al., 2013; Špaček et al., 2017) have also been studied. On the basis of the independent methods, both direct and indirect, the Pleistocene or Holocene tectonic activity along those faults has been proven by the aforementioned studies. The uplift of the Bohemian Massif has been proven not only by the measurements of river incision rates (Tyráček and Havlíček, 2009; Schaller et al., 2016b) but also by direct geodetic measurements (Vyskočil, 1973). The latter study not only proved the general uplift of the whole area, but also the relatively stronger uplift of the bounding mountains, e.g. the Šumava Mts. and Novohradské hory Mts., compared with the interior of the Bohemian Massif. Furthermore, the uplift (0.2 mm/year) of the N and NE edges of the Budějovice Basin was mentioned by Vyskočil (1973) and Popoting et al. (2013).

The present tectonic activity is also proved by seismic measurements. Although the Bohemian Massif is intraplate and therefore a relatively calm area regarding seismic activity, relatively strong earthquakes can be found through the history of measurement. The areas of the Cheb Basin and NE Bohemia (Hronov-Poříčí fault) are the most active ones, with measured or estimated events of ML 5.0, which corresponds approximately to Mw 4.3 (Jakoubková et al., 2017). However, smaller earthquakes were also recorded in the other areas of the Bohemian Massif (e.g. Mw 2.1-2.5 in the Šumava Mts. (IPE, 2014)). The history of measured seismic events is rather short but the studies of Štěpančíková et al. (2010; 2019) suggest there were Holocene earthquakes with an intensity of Mw ~ 6.5 in the area of the Cheb Basin and the Sudetic Marginal Fault. Therefore, rather strong earthquakes within the area of the Bohemian massif cannot be ruled out even in the time period of the Holocene.

On the basis of the numerous studies , it can be expected that there was rather intensive reactivation (in the stress regime of NW-SE compression) of the older faults during the Pleistocene and (locally) Holocene and that the tectonic activity had a strong influence on the terrain morphology and river network geometry.

Methods

The topic of interactions between fluvial systems and tectonic activity is widely studied throughout the world. A number of methods have been developed for studying such relationships and processes. However, many of those methods can only be used in areas with strong recent active tectonics (California, Alpine-Himalayan orogenic belt). Furthermore, some areas provide an opportunity to observe the morphology of the terrain without anthropogenic or vegetational influence, due to climate or remoteness. Unfortunately, the Bohemian Massif – due to its location in Central Europe - does not provide either of these advantages. The set of methods, which can be used under the conditions of the Bohemian Massif, has to be carefully selected (also based on the methods used in similar intraplate study areas throughout Europe – Jordan et al., 2005; Štěpančíková et al., 2008; Troiani et al., 2008; Font et al., 2010; Štěpančíková et al., 2019. In addition, there was a focus on those methods that are not only used for evaluating the effects of tectonics on the river systems but also on those methods, which can locate the proposed places of tectonic activity based on the changes in the rivers' geometry. This 'inverse' relationship is very useful in areas where recent tectonic activity is not frequent and is easily visible.

Throughout this study, several types of primary data are used. The basic topographic information, necessary for morphotectonic analysis as well as other geomorphologic analyses (SL index, hypsometric index, basin asymmetry, valley-floor ratio, mountain front sinuosity) and the longitudinal and perpendicular profiles of water streams or fluvial deposits were obtained from the digital elevation model (DEM), which was based on the basic topographic maps 1: 10 000 (ČUZK, 2015) or Lidar surveying (ČUZK, 2017). Information on lithology and tectonic structure was obtained from the basic geological maps (mostly scales of 1:50 000 or 1:25 000) of the study areas (Zoubek et al., 1963; Vejnar et al., 1978a; Vejnar et al., 1978b; Vejnar et al., 1980; Mahel et al., 1984; Slabý and Holásek, 1992a; Slabý and Holásek, 1992b; Vrána and Holásek, 1992; Vrána and Novák, 1993; Müller et al., 1998; Seifert and Straka, 1998; Adamová et al., 2001; ČGS, 2003; Geologische Bundesanstalt, 2012), and were locally specified by field survey. For the morphotectonic analysis the airborne geophysical data - gravimetry, radiometry, magnetometry - were also used (ČGS, 2015). Historical sources were used to repair some faults in topographic maps or to avoid the anthropogenic influence on water streams. The historical maps (JEPU and ME, 2014) and historical aerial photographs (MGHO, 2014) were used for these adjustments.

To gain the SL index values from the selected streams, it is important to select the right source of elevation data. For the area of Novohradské hory Mts., the digital elevation model (DEM), based on a basic topographical map (Základní mapa ČR 1:10 000 (ČÚZK 2006)) was used. The resolution of 10 x 10 m per pixel is optimal for such an area, because it is detailed enough, especially regarding the stream geometry. However, in the case of the area of the Mariánské Lázně Fault, a more detailed DEM was needed in order to carry out a more localized study of shorter water streams: a DEM based on aerial laser surveying and measurement: LiDAR – pixel resolution <1 m (ČUZK, 2017) was used.

Most of the streams in the study areas were distributed in 100 m long reaches, where the SL index was calculated. In some cases (shorter streams in the area of the MLF), they were distributed to 10 m reaches to detect even small changes in the stream gradient/SL index values.

Morphotectonic analysis

In the Novohradské hory Mts. area, morphotectonic analyses were performed to localize the faults and other tectonic structures, such as the main fracture zones or shear zones. The goal of the analysis was to interpret a number of linear indications that could represent tectonic structures. Compared to the area of the Mariánské Lázně Fault, this analysis was necessary, because of the rather poor previous knowledge of the tectonic structures in the area mentioned. The results of the analysis were validated by a field survey that aimed to study structural geology and brittle tectonic deformations. Data for tectonic analysis were obtained from several independent sources: a) geological and tectonic maps of the study area (Mahel et al., 1984; Slabý and Holásek, 1992; Vrána and Holásek, 1992; Vrána and Novák, 1993) b) airborne geophysical data (gravimetric, radiometric, magnetic survey) (CGS, 2015) and c) morphotectonic analysis made from the digital elevation model.

Stream-length (SL) index

The stream-length (SL) index is a simple, but very strong tool for evaluating the influence of tectonics on the geometry and fluvial style of river systems. It was first used by Hack (1973), but the main progress in this method has been come in recent years due to the wider usage of modern methods such as remote sensing and geographical information systems.

The SL index can be calculated by the equation

$$SL=(\Delta H/\Delta L)Ldm$$

where *(ΔH/ΔL)* is the stream gradient and *Ldm* is the length of the stream reach between the stream source and the middle of the measured part (see Fig. 3).

The SL index values react very sensitively to gradient changes in the stream, including lithological, tectonic, hydrological, and even anthropogenic influences. Therefore, using the SL index for geomorphological analyses is more precise than using the simple stream gradient values or stream gradient profile. The anomalous (usually higher) values of the SL indexes and, in particular, sudden changes in the index values indicate changes in the stream gradient. The origin of these changes can be evaluated with the help of other sources or analyses (e.g., geological maps or morphotectonic analysis). Therefore, it is often possible to determine whether the gradient changes have been caused by tectonic effects or by some other factors. The presence of morphologically prominent tectonic linear indications or even documented tectonic faults in a place with SL index anomalies can indicate the influence of tectonic movements on stream gradient with a high probability. However, the sensitivity of the SL index can also be a disadvantage - the peaks of the SL index curve are very sharp and local maxima can follow local minima very suddenly. It can be useful to use some statistical methods to obtain more robust results – such as a moving average when evaluating SL longitudinal curves. If just one stream is of interest, the SL index values can be represented by a single curve alone. If a larger area and its possible tectonic activity is of interest, it is very useful to obtain SL values from several neighbouring streams and make a grid – as in this study. A grid made from raw values can be unsuitable for gaining results from places lying further from the streams. The use of some statistical methods, such as IDW or Kriging, is necessary for interpolating values.

In many cases the raw data was rather unsuitable for subsequent analyses. It was necessary to repair some values in those places that had been heavily influenced by anthropogenic activities (millraces, dams, weirs etc.). The historical maps and historical aerial photographs (see above) were used for these adjustments.

In the area of the MLF, the SL index values were processed in the form of curves along the longitudinal stream profiles. In the area of Novohradské hory Mts. the SL index values were represented by individual points along the streams and the Kriging method was used for interpolating the values between those calculated points to also obtain the planar image of the possible tectonic effects studied by SL index analysis.

Hypsometric index

The hypsometric index (Hypsometric Integral or Elevation/Relief Ratio - Wood and Snell, 1960; Pike and Wilson, 1971; Scheidegger, 1987) is a value, which describes the relationship between the mean and maximum/minimum elevation of the catchment area. This index can evaluate the particular area's rate of denudation, tectonic uplift and relief maturity. According to (Cheng et al., 2012), hypsometric index values below 0.3 represent a mature and tectonically stable relief, while values over 0.6 usually represent young, unstable and uplifting catchments. Carefully use of this index is necessary, because of the influence the geological, tectonic and climatic effects have on its value.

The hypsometric index is calculated thus:

$$HI = (E_{mean} – E_{min}) / (E_{max} – E_{min})$$

Where E_{mean} represents *mean elevation* of a basin, E_{min} represents *minimum elevation* of a basin (outlet) and E_{max} represents *maximum elevation* of a basin (Pike and Wilson, 1971).

In this study, the HI index was used in the area of the Novohradské hory Mts. as a supplementary analysis to the measurement of the SL index. The HI index is calculated for the area (basin), so it is not able to give a more precise location of possible tectonic movements. However, it could be used as a proof of SL index analysis (with spatially interpolated values) because it describes the characteristics of an entire, larger area of river catchment and not only the character of the water stream. Through a combination of these methods it is possible to locate the areas where tectonics affect the water stream geometry and terrain morphology.

Basin Asymmetry

Basin Asymmetry is used for detecting tilting in the particular basin due to tectonic movements (Keller and Pinter, 2002; Badura et al., 2007; Gutierrez, 2013). It is defined as:

$$Af = 100\ (Ar/At)$$

where *Ar* is the area of the basin on the right side of the main stream, *At* is the total area of the basin. A value of 50 indicates stability, whereas deviations from 50 suggest tilting (Gutierrez, 2013). Moreover, the asymmetry suggests the direction of tilting.

The basin asymmetry analyses were used differently in both study areas. The basins of shorter streams flowing westward down the fault slope were studied in the area of the MLF in order to investigate the segments with recent tectonic movements and possibly to localize the trends of tilting along the MLF. Then the drainage basins of the rather larger, main streams (Malše, Černá, Stropnice, Svinenský, Klenský, Keblanský, Pašinovický) were surveyed in the study area of Novohradské hory Mts. - to get a regional insight of possible tilting and uplift, to compare the streams to each other and to get a better understanding of the evolution of the drainage system.

Cross sections and Valley floor ratio

In the area of Novohradské hory Mts., 27 cross sections across the valleys of water streams were made during the survey to clarify the evolution of their drainage and, with the help of the valley floor ratio, to evaluate the possible effect of the tectonic uplift on the river geometry.

The valley floor ratio (Burbank and Anderson, 2001; Keller and Pinter, 2002), was calculated along these profiles as:

$$V_f = 2V_{fw}/[(E_{ld}-E_{sc})+(E_{rd}-E_{sc})],$$

where V_f is valley floor width-to-height ratio; V_{fw} is width of the valley floor, E_{ld} and E_{rd} are elevations of the left and right valley divides, respectively, and E_{sc} is the elevation of the valley floor.

This index differentiates between broad-floored canyons, with relatively high V_f values, and V-shaped valleys, with relatively low values. High V_f values are associated with a low uplift rates, so that the streams cut broad valleys. Low values reflect deep valleys with actively incising streams, commonly associated with uplift. This index is often measured on a number of parallel valleys cross cutting a mountain front and therefore is used for evaluating possible uplift (Keller and Pinter, 2002).

Mountain-front sinuosity

The mountain front sinuosity index (*Smf*) was used in the area of the MLF as it is a tool for evaluating the age of the tectonic activity and the uplift on the fault (Bull and McFadden, 1977; Burbank and Anderson, 2001; Bull, 2007). The main idea is to compare the length of the mountain front *(Lmf*) with a straight line *(Ls*):

$$Smf = Lmf/Ls$$

If the uplift has happened recently, the mountain front is straighter (= the index is lower). When the tectonic movements are inactive for a longer time, fluvial erosion produces a sinuous mountain front (= the index is higher) (Gutierrez, 2013). This tool is ideal for evaluating the tectonic activity along a single long fault, as the MLF is.

Longitudinal profiles and stream gradient

Longitudinal profile analysis is a classical method for detecting the tectonic effect on a water stream (Wheeler, 1979; Burbank and Anderson, 2001). The typical longitudinal profile of a mature, stable water stream (a so called graded river) has a hyperbolic shape. Any divergence from this shape is an indication of unstable conditions, however there are many factors which could influence the shape: erosion base level, geological setting, hydrological setting, climate, tectonics (Burbank and Anderson, 2001; Keller and Pinter, 2002; Willet, 2006; Sougnez and Vanacker, 2011). Therefore, it is very difficult to uncover the ruling factor affecting the particular water stream. However, the longitudinal profiles can be compared between each other and it could be a strong lead for evaluating the evolution of water steams or a particular catchment. Measurement of the stream gradient could be an additional tool. Values of stream gradient were calculated on 100 m long reaches of a stream according to Keller and Pinter (2002) as:

$$(Sg = \Delta H/\Delta L)$$

where *Sg* is the stream gradient, *ΔH* is the height difference along the reach*; ΔL* is the length of the reach (100 m).

The courses of longitudinal profiles as well as the stream gradient values were compared with the lithological composition (ČGS, 2003) to find the possible knickpoints and other places of changing water stream geometry and therefore the tectonic influence.

In this study, it was mainly the longer water streams that were analysed regarding their longitudinal profiles for an evaluation of the catchment and terrain evolution at the regional scale. However, in the area of the MLF, the analyses of the shorter streams flowing down the fault slope also helped to delineate different segments of the MLF, in combination with other methods, such as mountain-front sinuosity and basin asymmetry.

Fluvial deposits occurrences and longitudinal profiles

To get the first ideas about the evolution of the stream network and the possible effect of tectonics, the occurrences of fluvial deposits were mapped in both study areas.

The outcrops of the various Neogene and Quaternary deposits were mapped using sources from previous studies and maps (Mayer, 1959; Krátká, 1966; Březinová et al., 1963; Puchta and Volšan, 1965; Žebera, 1967; Chábera and Novák, 1975; Švára, 1981; Novák, 1983; Bezvoda et al., 1983; Kroupa, 1984; Mahel et al., 1984; Bittman et al., 1985; Bouška and Konta, 1990; Slabý and Holásek, 1992a; Slabý and Holásek, 1992b; Vrána and Holásek, 1992; Vrána and Novák, 1993; Nesrovnal et al., 1995; ČGS, 2003; Homolová et al., 2012) and locally extended and corrected by field survey.

The longitudinal profiles of fluvial deposits (especially in the area of the Novohradské hory Mts.) of various ages were reconstructed on the base of DEM and were compared to each other morphostratigraphically, based on their elevation above the current flood plain – using a similar principle as in many other studies from the Bohemian Massif (Balatka and Sládek, 1962; Novák, 1983; Tyráček, 2001; Tyráček et al., 2004; Balatka and Kalvoda, 2010).

Based on the morphostratigraphical position of the fluvial deposits, it is possible to reconstruct the evolution of the river geometry through the Pliocene-Pleistocene. Dating these deposits is rather difficult (range of methods, inappropriate condition of deposits, etc.). However, there are several studies (Březinová et al., 1963; Ševčík et al., 2007; Homolová et al., 2012, Teodorodis et al., 2017; Štěpančíková et al., 2019) where proper dating was done by different methods and those dated deposits can be fixed and assigned to others that are morphostratigraphically defined.

Discussion and results

Evaluation of methods used

As was mentioned in the 'Methods' section, a set of independent techniques and methods was used in both areas to study the interactions between water stream and tectonic activity. The applicability of particular methods is discussed in detail in the individual chapters; however, it is necessary to evaluate the methodical set as a whole and across both study areas. The particular methods were selected to make an evaluation between each other and also for an evaluation by a field survey where possible and necessary.

The first step was to delineate promising tectonic structures that can affect fluvial systems. The situation was different in both study areas, because, in the Western Bohemia area, there was only one, especially remarkable, distinct and previously mapped tectonic structure, the Mariánské Lázně Fault. The area of the Novohradské hory Mts. had to be surveyed by morphotectonic analysis before subsequent research, because this area was not mapped in detail. The results of morphotectonic analysis were validated by a field structural survey and show a generally satisfactory fit. On the basis of the field structural analysis, mapped faults, and remote sensing analysis, a significant concordance in the orientation and frequency of faults and lineaments has been found. The combination of analyses of remotely sensed data (DEM, airborne geophysics) is therefore a very robust and reliable way to identify the brittle tectonic structures in areas with no previous survey. However, a thorough field survey is necessary in order to eliminate linear structures in the rocks such as lithological boundaries, fold axes, cleavage or foliation.

The SL index analysis was used in both study areas as an important indicator of tectonic activity (see 'Methods') as it can be more focused than other methods and is easily connected to a particular tectonic indication or fault. As the characteristics of the water stream are different throughout both study areas, the focus was on sudden and remarkable changes in SL index values, rather than its absolute values. These sharp peaks in the SL index values can be found e. g. along the west flowing short streams in the central part of the Mariánské Lázně Fault (for details see **Chapter 1**, section 4.4.2) and also along some bigger streams in the same area (**Chapter 1**, section 4.4.1) and in the area of the Novohradské hory Mts. (**Chapter 2**, section 4.1). The results from the area of western Bohemia are a good fit with the results of other methods used in the same area: the results of mountain-front sinuosity, basin asymmetry and longitudinal profiles suggest the youngest tectonic activity is along the same segments and in the same areas along the Mariánské Lázně Fault. the results of the study by Štěpančíková et al. (2019) are also very important as they have directly interlinked the SL index measurement with methods of applied geophysics, paleaoseismology and dating in the NW part of the Mariánské Lázně Fault. The study proved the presence of recent active tectonics (as did e.g. Halpaap et al., 2017; Švancara et al., 2008) and also proved the reliability of using the SL index analysis. Therefore, the results of SL index analysis and also the analysis of mountain-front sinuosity, basin asymmetry and longitudinal profiles performed along the Mariánské Lázně Fault as a part of this thesis seem fairly reliable. The area of the Mariánské Lázně Fault is very valuable, because of the mentioned possibility of testing various remote sensing geomorphological methods with relatively easy verification based on the many previous studies focused on various topics of field survey. Furthermore, similar methods – SL index or mountain-front asymmetry were also used by Badura et al., (2007), Štěpančíková et al., (2008), Tschegg and Decker (2013) or Popotnig et al. (2013) in the various areas of the Bohemian Massif with very similar results. Therefore, a significant reliability of the results obtained could also be expected in the area of the Novohradské hory Mts. Nevertheless, at least a partial verification of the results from remote sensing geomorphological methods using a field survey (e. g. applied geophysics, structural geology measurements) is crucial for a full understanding of tectonic activity in the particular area.

The interconnection of results between the relatively well-known and well-surveyed area, Western Bohemia, and the relatively unknown one, Southern Bohemia, shows that the set of methods used can also be successfully applied in other similar areas in the Bohemian Massif and other intraplate areas. It is possible to use the aforementioned methods for studies similar to this thesis, but also – at least partially and at a rough scale – for seismic hazard assessment in those areas, where the other data sources are limited, but where Pleistocene tectonic activity could be expected (actually large parts of the Bohemian Massif area).

In the ideal case, the methods used could be complemented by some dating methods. The precise dating can pinpoint the tectonic activity ,not only spatially, but also temporally. Unfortunately, many dating methods cannot be used in intraplate areas like the Bohemian Massif (e.g. direct dating of the active fault planes). Therefore, some of the indirect dating methods must be used. In the case of Holocene tectonic activity, it is possible to use palaeoseismological methods (Štěpančíková et al., 2019). However, as concerns this study, the palaeoseismological methods are probably limited to the area of the Mariánské Lázně Fault, as no significant Holocene tectonic activity is expected in the area of the Novohradské hory Mts. Generally, any significant tectonic activity within the area of the Bohemian Massif typically took place during the (late) Pliocene and Pleistocene (Štěpančíková et al., 2008; Tyráček and Havlíček, 2009; Balatka and Kalovoda, 2015; Špaček et al., 2017; Štěpančíková et al., 2019). Thus, it is necessary to select another method than those aforementioned for this time period. The dating of fluvial terraces appears to be a suitable method because it can clarify the details regarding the stream networks' evolution and the effect of tectonics. Although there are many suitable deposits for dating within the two study areas - as well as within the entire Bohemian Massif – the biggest issue is the age of these deposits' origin. Many of them, as well as the proposed tectonic movements which could have influenced them, originated in the late Pliocene or early Pleistocene. This time period is beyond the range of many dating methods (e.g. OSL or ^{14}C). One possible solution is to use cosmogenic nuclides dating methods (e. g. ^{10}Be), which can be used for similar localities and deposits (although mostly significantly younger – Popotnig et al., 2013; Schaller et al., 2016a; Schaller et al., 2016b; Štor et al., 2019). One of the goals of this study is the preselection of those localities suitable for such dating and also for the subsequent palaeoseismological survey.

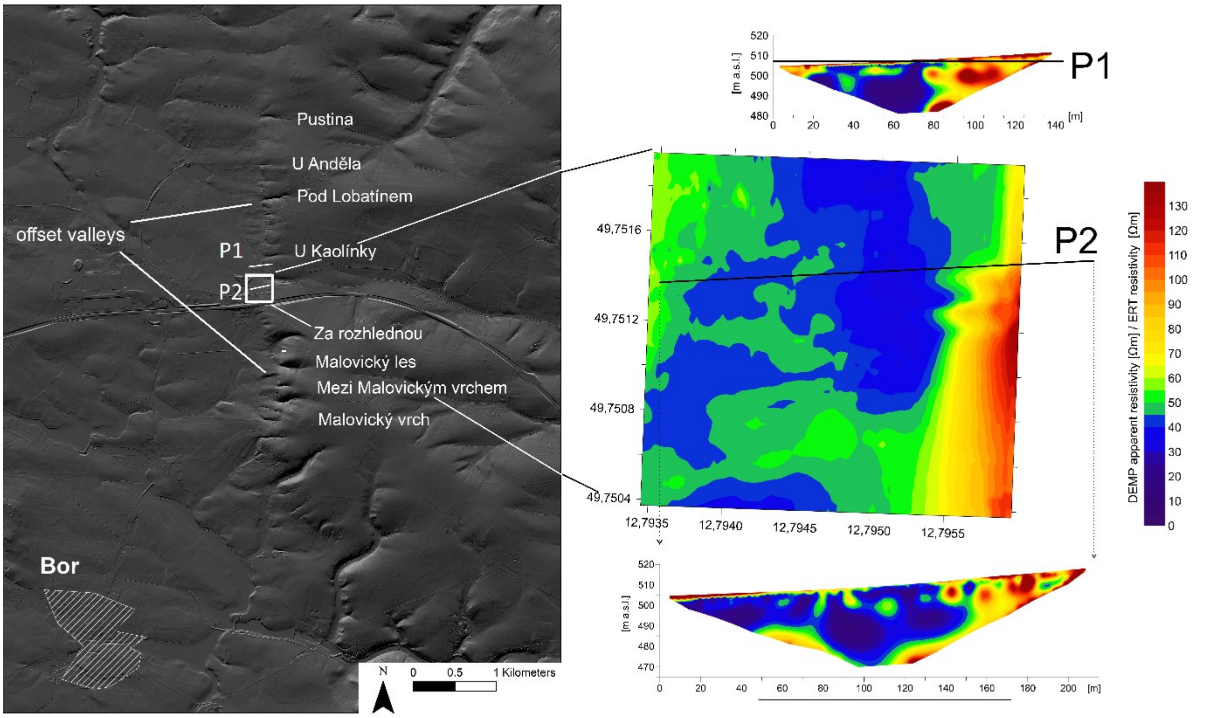


Fig. 5: The locality of Nová Hospoda (the Mariánské Lázně Fault): Comparison of the terrain morphology and the results of the geoelectric methods (profiles P1 and P2 by ERT (Electrical resistivity tomography, square field by the DEMP (Dipole ElectroMagnetical Profilation)) clearly shows the course of the fault.

The use of the aforementioned methods in this study can pinpoint a location for subsequent dating in terms of the most suitable place regarding its position relative to tectonic structures. The planned outputs of dating methods can make the results of this study more precise with respect to the evolution of the stream network over time and their interactions with the tectonic processes. In the area of the Mariánské Lázně Fault, the very promising – but still poorly surveyed – locality of Nová Hospoda (Fig. 5 and also see **Chapter 1**, section 4.4.2 and Figs. 11, 12 and 13) was selected. Based on the results obtained, recent – probably Holocene – tectonic activity is fairly probable. Currently, the new geophysical research is taking place and the palaeoseismological trenching is being prepared.

Likewise, several localities for the future dating of fluvial deposits were selected in the area of the Novohradské hory Mts. (Vrábče, Byňov, Trhové Sviny, Rychnov n/M and Římov, for map see **Chapter 3**, Fig. 3).

Reaction of the fluvial systems to tectonics

The results of the individual chapters of this thesis suggest that the recent tectonics - Plio-Pleistocene and probably Holocene - have had a significant impact on the fluvial systems and water stream geometry (**Chapter 1**, sections 4.3, 4.4 and 5.2; **Chapter 2**, sections 4.1, 4.3, 5.1, 5.4; **Chapter 3** sections 6 and 7.4). The methods used in this thesis for localizing possible localities or areas with tectonic activity are partially based on the measurement of the river geometry changes; therefore, it must be expected that a significant interlink between tectonic activity and fluvial systems exists in the study areas. The effects of lithology, hydrology, and anthropogenic influence on the water streams cannot be ruled out completely, but a combination of these factors with the influence of tectonic activity leads to similar results in both study areas. Similar processes can also be expected in the other areas of the Bohemian Massif because of the similar lithological composition, tectonic evolution and activity in the late Cenozoic.

Naturally, the tectonic processes could not be identical across both study areas (and some other places within the Bohemian Massif). Although having very similar lithotectonic conditions, there are certainly some differences – at the very least caused by the presence of a single, large, prominent tectonic structure in the area of Western Bohemia compared to the rather complex situation of several fault systems in the area of Southern Bohemia. According to the results of **Chapter 1** (section 4) and the results of various previous studies (Peterek et al., 2011; Fischer et al., 2012; Halpaap et al., 2017; Jakoubková et al., 2017 Blecha et al., 2018; Štěpančíková et al., 2019), the tectonic activity along the Mariánské Lázně Fault has taken place more recently, and perhaps more intensively compared to the situation in Southern Bohemia. Analyses of the SL index or longitudinal profiles of the water streams and fluvial deposits (and partially the basin asymmetry analysis) suggest that a significant role was played by tectonically induced uplift in both study areas. It could be hard to distinguish the effect of local uplift connected to a particular tectonic structure (e.g. the Mariánské Lázně Fault) and the regional uplift of the Bohemian Massif as a whole (as suggested by Vyskočil, 1973; Chábera, 1985; Tyráček and Havlíček, 2009). Anomalies in the longitudinal profiles of particular streams (Mže, Kosový, Radbuza etc. (see **Chapter 1**, section 4.3.1) or in the SL index (see **Chapter 1**, section 4.4) in the area of

Western Bohemia; Malše, Svinenský, Stropnice etc. in the area of Southern Bohemia (see **Chapter 3**, section 6.4 for profiles and **Chapter 2** section 4.3 and 5.2 for SL index), however, suggest that both areas have gone through an uneven uplift of the individual tectonic blocks during the Plio-Pleistocene. In the area of Western Bohemia, the hilly areas of the Slavkovský les Mts. And the Plaská pahorkatina Hilly Land have been relatively uplifted along the Mariánské Lázně Fault, compared to the relatively flat subsiding Cheb Basin and Cheb-Domažlice Graben (**Chapter 1**, Fig. 2). Similarly, in the area of Southern Bohemia, the ridges of the Novohradské hory Mts., Slepičí hory Mts., Poluška and Lišov Horst have been relatively uplifted compared to the Třeboň and Budějovice Basins and Kaplice Graben (**Chapter 3**, Fig. 2).

Accepting the idea of a tectonic influence on the river systems and their geometries, it is also important to realize that the tectonic activity has varied in its intensity, timing, and space during the Plio-Pleistocene period. The signs of this variability can be seen from the results of **Chapter 1** (sections 4 and 5.1), when an uneven uplift along the Mariánské Lázně Fault is suggested. Furthermore, the longitudinal profiles of fluvial deposits suggest uneven rates of tectonically induced river incision (**Chapter 1**, section 4.3 or **Chapter 3** section 6.4). It is very likely that the varying tectonic activity has significantly influenced the shape and evolution of the river networks in both study areas.

Is it possible to reconstruct the Plio-Pleistocene evolution of particular river networks in the Bohemian Massif? Naturally, it is very difficult without precise, absolute dating of the fluvial deposits (which are often only poorly preserved) and the tectonic faults (which are often impossible to date in the lithological, climatic, etc. conditions of the Bohemian Massif). However, it is possible to get at least a general idea based on careful use of the morphostratigraphy of fluvial deposits and an analysis of the river geometry-tectonic structures' relationships.

Promising knickpoints, changes in stream gradient, SL index, and general stream orientation were located in this study – such localities could be signs of important changes during the evolution of the river network. In the area of the Novohradské hory Mts., the gradient and orientation changes of the Malše River near Rychnov n/M and the Stropnice and Svinenský streams near Trhové Sviny, Jílovice and Borovany were in focus (**Chapter 2**, section 4.2 and 5.3). In the area of Western Bohemia, the whole river network of the Mže River was in focus, especially the Kosový, Hamerský and Mže stream near their crossing with the Mariánské Lázně Fault (**Chapter 2**, sections 4.3 and 4.4). The changes of geometry could be influenced by a number of individual factors (see above). However, those particular localities lay on the crossing, or very near the crossing of a water stream and a prominent tectonic fault – the Rychnov Fault, the Kaplice Fault, the Stropnice Fault (**Chapter 2**, Fig. 1 and Fig. 5) or the Mariánské Lázně Fault (**Chapter 1**, Fig. 1 and Fig.2), see also Špaček (2021). Therefore, it is highly likely that the geometry changes were induced by tectonic activity. Geomorphological analyses (see above 'Evaluation of methods used') have provided a strong indication of the existence of recent tectonic activity, so its effect on the evolution of the river network during the Plio-Pleistocene is very probable. It is not possible to date the particular tectonic movements that influenced the rivers' geometries. However, the results from the area of Western Bohemia, suggest that the movement (mainly uplift) has not been a single tectonic event or gradual slow regional uplift, but rather a temporally segmented tectonic activity along the Mariánské Lázně Fault. This could have significantly affected the evolution of the Mže River network (**Chapter 1**, section 5.2) as the particular streams have breached the fault slope at different times. These events have led to a change in the geometry of the river network, which is further supported by the occurrence of fluvial deposits of various age throughout the area (Balatka and SLádek, 1962; Pešek, 1972; Teodoridis et al., 2017). According to many similarities in the lithotectonic conditions and results, it can be expected there will be similar principles in the evolution of the river network in the area of the Novohradské hory Mts., although the tectonic structure is much more complex there (**Chapter 3**, section 7.4).

Generally, the results of this thesis suggest the Plio-Pleistocene tectonic activity had a strong influence on the geometry and evolution of water streams in the study areas. Naturally, lithology and other factors have certainly played their role, but it seems that the main factor, which affects the river networks in their complexity, has been tectonic activity (mainly uplift).

However, to get an evolution of the overview of the river network's evolution, it is necessary to also add a time scale. The ideal way to solve the evolution of the river network is to date the fluvial deposits (see section 'Methods'). However there is a general lack of absolute dating for fluvial deposits in the area of the Bohemian Massif (see section "Distribution and origin of late Cenozoic fluvial deposits in the Bohemian Massif"). The morphostratigraphical relationship between particular fluvial deposits was used in this thesis (as well as in many previous studies – Balatka and Sládek, 1962; Chábera and Novák, 1975; Novák, 1983; Tyráček and Havlíček, 2009; Balatka and Kalvoda, 2010; Balatka and Kalvoda 2019, Balatka et al., 2019). Although this method has its limits (see sections 'Distribution and origin of late Cenozoic fluvial deposits in the Bohemian Massif' and 'Methods'), it is often the only way to date, at least generally, the steps in the evolution of a river network. The results obtained in individual chapters (**Chapter 1**, section 5.2; **Chapter 3**, sections 6.3, 6.5) show a fair concordance with the previous studies focused on morphostratigraphical dating (Balatka and SLádek, 1962; Chábera and Novák, 1975; Novák, 1983; Havlíček and Tyráček, 2009; Popoting et al., 2013), but also with the studies that dated the fluvial deposits absolutely (Březinová et al., 1963; Ševčík et al., 2007; Popotnig et al., 2013; Špaček et al., 2017; Teodoridis et al., 2017). Therefore it is possible to come to a hypothesis regarding the river networks' evolution over time, however, the final proof can only be done with absolute dating.

The distribution pattern is different for the fluvial deposits from the mid- to late Pleistocene in both study areas. Their localities differ in areal localization and also in the elevation above the present flood plain. The occurrences in different places are signs of the changes in stream section orientation or changes in the incision rate that have happened during the Pliocene-Pleistocene – also some previous studies have suggested this (Novák 1983; Chábera et al., 1985; Bridgland and Westaway, 2008; Tyráček and Havlíček, 2009 and others see above). The differences are clearly visible when comparing the position of the Pliocene (e.g., Koroseky sand and gravel) and the fluvial deposits of the Middle and Late Pleistocene along the Malše River (**Chapter 3**, sections 6.3, 6.5, 7.1, 7.2, 7.3), or the position of the Pliocene Vildštejn Fm. and the terraces of the Middle and Late Pleistocene along the Mže River (**Chapter 3**, section 5.2). Still, there is an unanswered question: aren´t those deposits - traditionally assigned to the Pliocene - actually younger, early Pleistocene? Many studies (Bouška, 1992; Tyráček and Havlíček, 2009; Balatka and Kalvoda, 2010), have suggested that, however a final answer cannot be given without detailed, spatial absolute dating.

Nevertheless, this thesis suggests that, in the period of the Middle Pleistocene or shortly before it, the drainage pattern, water streams geometry, and incision rate changed significantly in both study areas; also, it suggests that the main influencing factor was tectonic activity (mostly uplift). On the other hand, the main change of the drainage direction in the area of the Bohemian Massif suggested by Malkovský (1975) and assigned to the Late Pliocene, had probably happened earlier (Early Pliocene?). Malkovský (1975) suggested Pliocene drainage through the Cheb-Domažlice Graben to the north, and from the Budějovice and Třeboň Basins to the south. Based on the occurrences of Vildštejn Fm. (**Chapter 1**, section 5.2) and Koroseky sand and gravel (**Chapter 3**, section 7.4), their longitudinal profiles and their relationship to present water streams etc. It appears that the general drainage direction in the late Pliocene was similar to the direction in the middle/late Pliocene or present. The drainage suggested by Malkovský (1975) could certainly exist, but since that time (Early Pliocene?) the drainage pattern, water streams and their geometries have undergone significant changes to the Late Pliocene/Early Pleistocene status and then to the Late Pleistocene/present status. Both changes have probably been caused mainly by tectonic activity, as often mentioned by previous studies (Chábera et al., 1985; Bridgland and Westaway, 2008; Tyráček and Havlíček, 2009). It is not definitively a final proof of this hypothesis. The thesis has aimed at making the dating of the tectonic processes and fluvial changes more precise, and the results can be used for pinpointing the right localities for absolute dating and finishing the puzzle. Also, it can be a hint for solving similar issues in other areas of the Bohemian Massif.

References

Adamová, M., Čurda, J., Lochmann, Z., Majer, V., Müller, V., Opletal, M., Pošmourný, K., Tomášek, M., Veselý, J. and Volšan, V.: 2001, Set of the geological and ecological special maps of natural resources 1:50 000, Geological map. Sheet 11-41 Mariánské Lázně. Český geologický ústav, (in Czech).

Badura, J. Zuchiewicz, W., Štěpančiková, P., Przybylski, B., Kontny, B. & Cacoń, S., 2007. The Sudetic marginal fault: A young morphotectonic feature at the NE margin of the Bohemian Massif, Central Europe. *Acta Geodyn. Geomater*., vol. 4, No. 4 (148), p. 7-29

Balatka, B., Kalvoda, J., 2010. Vývoj údolí Sázavy v mladším kenozoiku. Česká geografická společnost, Praha. 200 p.

Balatka, B. & Sládek, J., 1962. *Říční terasy v českých zemích*. Nakladatelství československé akademie věd, Praha. 250 pp.

Balatka, B., Kalvoda, J., Gibbard, P., 2015. Morphostratigraphical correlation of river terraces in the central part of the Bohemian Massif with the European stratigraphical classification of the quaternary, AUC Geographica, 50, 1, pp. 63–73. https://doi.org/10.14712/23361980.2015.87

Balatka, B., Kalvoda, J., Steklá, T. and Štěpančíková, P.: 2019, Morphostratigraphy of river terraces in the Eger valley (Czechia) focused on the Smrčiny Mountains, the Chebská pánev Basin and the Sokolovská pánev Basin. Acta Univ. Carol. Geogr., 54, 2, 240–259. DOI: 10.14712/23361980.2019.21

Bankwitz, P., Bankwitz, E., Thomas, R., Wemmer, K. & Kämpf, H. 2004. Age and depth evidence for pre-exhumation joints in granite plutons: fracturing during the early cooling stage of felsic rock. In: Cosgrove, J.W. & Engelder, T. (eds) 2004. *The initiation, Propagation and Arres of Joints and Other Fractures*. Geological Society, London, Special Publications, vol. 231, p. 25-47

Beavis, S.G., 2000. Structural controls on the orientation of erosion gullies in mid-western New South Wales, Australia. *Geomorphology* 33 (1), p. 59-72

Bergerat, F., 1987. Stress field in the European platform at the time of Africa–Eurasiacollision. Tectonics 6, 99–132.

Bezvoda, V., Novák, V. & Vrána,M. 1983. Příspěvek k poznání vysoko položených klastických sedimentů u Horního a Dolního Dvořiště. *Sborník Jihočeského Muzea, přírodní vědy*, vol. 23, p. 61-65

Bishop, P., Hoey, T.B., Jansen, J.D. and Artza, I.L.: 2005, Knickpoint recession rate and catchment area: the case of uplifted rivers in Eastern Scotland. Earth Surf. Process Landf., 30, 6, 767–778. DOI: 10.1002/esp.1191

Bittman, J., Homolka, M., Vašta, V., 1985. Třeboňská pánev – jižní část – JIVAK. Hydrogeologický průzkum. Stavební geologie Praha, závod České Budějovice

Blecha, V., Fischer, T., Tábořík, P., Vilhelm, J., Klanica, R., Valenta, J. and Štěpančíková, P.: 2018, Geophysical evidence of the Eastern Marginal Fault of the Cheb Basin (Czech Republic). Stud. Geophys. Geod., 62, 660-680. DOI: 10.1007/s11200-017-0452-9

Bouška, V., 1992. Tajemné vltavíny. Nakladatelství Gabriel. Praha, 84 p.

Bouška, V., Konta, J., 1990. Moldavites-Vltavíny. Univerzita Karlova. Praha, 126 p.

Březinová, D., Pacltová, B.& Špinar, Z. 1963. Stáří sedimentů kaplické pánvičky v jižních Čechách (M-33-113-D-d). *Časopis pro mineralogii a geologii*, vol. 1, p. 65-73

Bridgland, D.R., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quaternary Science Reviews 19, 1293–1303.

Bridgland, D., Westaway, R., 2008. Climatically controlled river terrace staircases: A worldwide Quaternary phenomenon. Geomorphology. 98. 285-315. 10.1016/j.geomorph.2006.12.032.

Bull, W.: 2007, Tectonic geomorphology of mountains: A new approach to paleoseismology. Blackwell Publishing, 306 pp. DOI: 10.1002/9780470692318

Bull, W.B. and McFadden, L.D.: 1977, Tectonic geomorphology north and south of the Garlock Fault, California. In: Doehring, D.O., Ed., Geomorphology in Arid Regions: A Proceedings Volume of the 8th Annual Geomorphology Symposium, State University of New York, Binghamton, 23-24 September 1977, 115-138.

Burbank, D. and Anderson, R.: 2001, Tectonic geomorphology. Blackwell Science, 273 pp. DOI: 10.1002/9781444345063

Burda, J., Herrmann, Z., Hroch, T., Kůrková, I, Bruthans, J, Holásek, O, Flašar, J., Bůzek, F., Kadlecová, R., Kondrová, L., 2021. Kvartér Labe: Hydrogeologické rajony 1151, 1152, 1171 a 1172. GEOLOGIE A HYDROGEOLOGIE, stanovení zásob podzemních vod. Svazek 15. 230 s. – Česká geologická služba. Praha

Carretier, S., Niviere, B., Giamboni, M., Winter, T., 2006. Do river profiles record alongstream variations of low uplift rate? *Journal of geophysical research*, 111, p. 1-16

Český úřad zeměměřický a katastrální (ČUZK): 2017, Digital elevation model of the Czech Republic, 5th generation (DEM 5G). Český úřad zeměměřický a katastrální, Praha, (in Czech).

Český úřad zeměměřičský a katastrální. 2006. Základní mapa ČR, 1:10 000, ČÚZK, Praha

ČGS - Česká geologická služba/ Czech Geological Survey, 2003. Geologická mapa ČR, 1: 50 000, ČGS, Praha

Cháb, J., Breiter, K., Fatka, O., Hladil, J., Kalvoda, J., Šimůnek, Z., Štorch, P., Vašíček, Z., Zajíc, J. and Zapletal, J.: 2008, Outline of the Geology of the Bohemian Massif: the Basement Rocks and their Carboniferous and Permian Cover. Vydavatelství ČGS, Praha, 283 pp., (in Czech).

Chábera, S., Demek, J., Hlavác, V., Kríž, H., Malecha, A., Novák, V., Odehnal, L., Suk, M.,Tomášek, M. & Zuska, V. 1985. *Neživá příroda (Jihočeská vlastivěda, řada A*). Jihočeské nakladatelství, České Budějovice. 150 pp.

Chábera, S., Novák, V., 1975. Terasy Vltavy mezi Českým Krumlovem a pánví Českobudějovickou. Sborník Jihočeského muzea v Českých Budějovicích – Přírodní vědy, 15, p. 1-9.

Cheng, K.-Y; Hung, J.-H., Chang, H.-C., Tsai, H. & Cheng-Sung, Q. 2012. Scale independence of basin hypsometry and steady state topography. *Geomorphology*, vol. 171-172, p. 1-11

Chlupáč, I., Brzobohatý, R., Kovanda, J. & Stráník, Z. 2002. *Geologická minulost České republiky*. Academia, Praha. 300 pp.

Chorley, R.J., Schumm, S.A, Sugden, D.E., 1985. *Geomorphology*. Routledge, London, 605 pp.

Cloetingh, S., Cornu, T., Ziegler, P.A., Beekman, F., & ENTEC. 2006. Neotectonics and intraplate continental topography of the northern Alpine Foreland. *Earth Science Reviews*, vol. 74, p. 127-196

Coubal M., Málek J., Adamovič J., Štěpančíková, P., 2015. Late Cretaceous and Cenozoic dynamics of the Bohemian Massif inferred form the paleostress history of the Lusatian Fault Belt. *Journal of Geodynamics*, vol. 87, p. 26-49

ČÚZK - Český úřad zeměměřický a katastrální/Czech Office for Surveying, Mapping and Cadastre, 2017. Digitální model reliéfu České republiky 4. generace (DMR 4G)/Digital Elevation Model of Czech Republic 4th generation (DEM 4G). Český úřad zeměměřický a katastrální, Praha

Czech Geological Survey (Česká geologická služba). 2015. Database of airborne geophysics, 1: 25 000. CGS, Praha

Fischer, T., Štěpančíková, P., Karousová, M., Tábořík, P., Flechsig, Ch. and Gaballah, M.: 2012, Imaging the Mariánské Lázně Fault (Czech Republic) by 3-D ground-penetrating radar and electric resistivity tomography. Stud. Geophys. Geod., 56, 1019-1036. DOI: 10.1007/s11200-012-0825-z

Flašar, J., 2012. Odezva vybraných řek Českého masivu na litologické a tektonické podmínky

(Response of selected rivers of the Bohemian Massif to lithological and structural conditions). Master Thesis. Univerzita Karlova. Přírodovědecká fakulta. Praha

Font, M., Amorese, D. & Lagarde, J.L., 2010. DEM and GIS analysis of the stream gradient index to evaluate effects of tectonics: The Normandy intraplate area (NW France). *Geomorphology*, vol. 119, p. 172-180

Geologische Bundesanstalt (Geological Survey of Austria); 2012. Geologische Karte der Republik Österreich (Geological map of Austria), 1:50000, [online], accessible at: http://www.geologie.ac.at/ [15/05 2014], Geologische Bundesanstalt, Wien

Gibbard, P. L., Lewin, J. , 2009. River incision and terasse formation in the Late Cenozoic of Europe. Tectonophysics, 474, p. 41–55. https://doi.org/10.1016/j.tecto.2008.11.017

Gutierrez, M., 2013. Geomorphology. London: CRC Press; 1014 p. https://doi.org/10.1201/b12685

Hack, J.T.: 1973, Stream-profile analysis and stream-gradient index. J. Res. U.S. Geol. Surv., 1, 4, 421-429.

Halpaap, F., Paschke, M. and Bleibinhaus, F.: 2017, Shallow reflection seismic evidence of tectonic activity in the Cheb Basin, NW Bohemia. Stud. Geophys. Geod., 62, 80-101. DOI: 10.1007/s11200-016-0386-7

Harden, D. 1990. Controlling factors in the distribution and development of incised meanders in the central Colorado Plateau. *Geological Society of America Bulletin,* vol. 102, p. 233-242

Hartvich, F. & Valenta, J. 2013. Tracing an Intra-montane Fault: An Interdisciplinary Approach. *Surveys in Geophysics*, vol., 34, p. 317-347

Homolová, D., Lomax, J., Špaček, P. & Decker, K. 2012. Pleistocene terraces of the Vltava River in the Budějovice basin (Southern Bohemian Massif): new insights into sedimentary history constrained by luminescence data. *Geomorphology*, vol. 161-162, p. 58-72

Huggett R., J., 2003. *Fundamentals of geomorphology*. Routledge, London, 386 pp.

IPE (Institute of Physics of the Earth – Ústav fyziky Země). 2014. Database of seismic events 1880-2014.

J.E. Purkyně University in Ústí and Labem, Ministry of the Environment of the Czech Republic (JEPU and ME): 2014, Second Military Mapping Survey of Austrian Empire, 1: 28800, [online] accessible at: http//oldmaps.geolab.cz, [15/05/2021], Laboratoř geoinformatiky Fakulta životního prostředí Univerzity J.E.Purkyně, Ustí nad Labem, (in Czech).

Jakoubková, H., Horálek, J. and Fischer, T.: 2017, 2014 mainshock-aftershock activity versus earthquake swarms in West Bohemia, Czech Republic. Pure Appl. Geophys., 175, 109–131. DOI: 10.1007/s00024-017-1679-7

Jordan, G., Meijninger, B.M.L., van Hinsbegen, D.J.J., Meulenkamp, J.E. & van Dijk, P.M. 2005. Extraction of morphotectonic features from DEMs: development and applications for study areas in Hungary and NW Greece. *International Journal of Applied Earth Observation and Geoinformation*, vol. 7. p. 162-183

Keller, E., Pinter, N., 2002. Active tectonics – Earthquakes, Uplift and Landscape. Prentice Hall, New Jersey, 362 p.

Kopecký, A. 1983. Neotektonický vývoj a stavba šumavské horské soustavy. *Antropozoikum*, vol. 15, p. 71-159

Krátká, J., 1966. Zpráva o Inženýrskogeologickém mapování zátopného území vodního díla Doudleby na Malši. IGHP, závod Praha, 59 p.

Kroupa, J., 1984. Bukvice, Hydrogeologický průzkum. Stavební geologie Praha, závod České Budějovice

Legrain, N., Stüwe, K. & Wölfler, A. 2014. Incised relict landscapes in the eastern Alps. *Geomorphology.* vol., 221. p. 124–138

Little, T.A., Van Dissen, R., Schermer, E., Carne, R., 2009. Late Holocene surface ruptures on the southern Wairarapa fault, New Zealand: Link between earthquakes and the uplifting of beach ridges on a rocky coast. *Lithosphere* 1, p. 4-28.

Maddy, D., 1997. Uplift-driven valley incision and river terrace formation in southern England. Journal of Quaternary Science 12, 539–545.

Mahel, M., Kodym, O., Malkovský, M., 1984. Tektonická mapa CSSR, 1: 500 000, Geologický ústav Dionýza Štúra, Bratislava.

Malkovský, M., 1975. Paleogeography of the Miocene of the Bohemian Massif. Věstník Ústředního ústavu geologického, 50, p. 27-31

Malkovský M., 1979. Tektogeneze platformního pokryvu Českého masivu. Ústřední ústav geologický. Academia. Praha, 176 p.

Maroukian, H., Gaki-Papanastassiou, K., Karymbalis, E., Vouvalidis, K., Pavlopoulos, K., Papanastassiou, D., Albanakis, K., 2008. Morphotectonic control on drainage network evolution in the Perachora Peninsula, Greece. *Geomorphology* 102 (1), p. 81-92.

Mayer, V., 1959. Zpráva o průzkumu staveniště určeného pro rozšíření závodu MOTOR – Kaplice. Státní projektový ústav pro výstavbu měst a vesnic Č.Budějovice, 9. p.

Military Geographic and Hydrometeorologic Office (MGHO) - Ministry of Defence of the Czech Republic + GEODIS Brno s.r.o., 2014., Historical aerial map of Czechoslovakia, 1:20000, [online] available at http//: kontaminace.cenia.cz, [15/05/2021] CENIA – Česká informační agentura životního prostředí, Praha, (in Czech).

Mísař, Z., Dudek, A., Havlena, V., Weiss, J., 1983. Geologie ČSSR I. – Český masiv. Státní pedagogické nakladatelství, Praha, 333p.

Mlčoch B. and Skácelová Z.: 2009, Digital elevation model of the crystalline basement of the Cheb and Sokolov Basin areas (Western Bohemia, Central Europe). Z. Geol. Wiss., 37, 3, 145-152.

Mlčoch, B. and Konopásek, J.: 2010, Pre-Late Carboniferous geology along the contact of the Saxothuringian and Teplá–Barrandian zones in the area covered by younger sediments and volcanics (western Bohemian Massif, Czech Republic). J. Geosci., 55, 81–94. DOI: 10.3190/jgeosci.068

Moschelesová, J., 1930. Vlnité prohyby o velké amplitudě v jižních Čechách. (Megasynklinals and megaanticlinals in Southern Bohemia). In Czech. Sborník Československé společnosti zeměpisné 36: 155 - 158, Praha.

Müller, B., Zoback, M.L., Fuchs, K., Mastin, L., Gregersen, S., Pavoni, N., Stephansson,O., Ljunggren, C., 1992. Regional patterns of tectonic stress in Europe. J. Geophys.Res. – Solid Earth 97 (B8), 11783–11803.

Müller, V., Burda, J., Dubec, O., Hrazdíra, P., Hrkal, Z., Jinochová, J., Lochmann, Z., Majer, V., Manová, M., Mlčoch, B., Rejchrt, M., Sáňka, V., Schovánek, P., Skácelová, D., Šalanský, K. and Šantrůček, P.: 1998, Legend to the set of geological and ecological special maps of natural resources, 1 : 50 000. Sheets 11 - 13 Hazlov, 11 - 14 Cheb. Český geologický ústav, (in Czech).

Nesrovnal, I., Šimek, J., 1995. Českobudějovicko – vyhledávací průzkum cihlářské suroviny**,** G E T s.r.o., 10 p.

Novák V., 1983. Terasy řeky Malše. Dissertation thesis. UK Praha. 100 pp.

Ouchi, S.,1985. Response of alluvial rivers to slow active tectonic movement. *Geological Society of America Bulletin,* 96, p. 504-515. https://doi.org/10.1130/0016-7606(1985)

Pešek, J.: 1972, Tertiary sediments in the central and western Bohemia. Sborník Západočeského muzea Příroda, 6, 56 pp., (in Czech).

Pešek, J. (ed.), 2010. Terciérní pánve a ložiska hnědého uhlí České republiky. Vydavatelství České geologické služby, Praha.

Peterek A., Reuther C.D. and Schunk R., 2011. Neotectonic evolution of the Cheb Basin (Northwestern Bohemia, Czech Republic) and its implications for the late Pliocene to Recent crustal deformation in the western part of the Eger Rift. *Z. Geol. Wiss.*, 39, 335–365.

Pike, R. & Wilson, S. 1971. Elevation-Relief Ratio, Hypsometric Integral, and Geomorphic Area- Altitude

Analysis. *Geological Society of America Bulletin*, vol. 82, p. 1079-1084

Popotnig, A., Homolová, D. & Decker, K. 2013. Morphometric analysis of a reactivated Variscan fault in

the southern Bohemian Massif (Budějovice basin, Czech Republic). *Geomorphology*, vol. 197, p. 108-

122.

Puchta, J., Volšan V., 1965. Závěrečná zpráva. Jihočeské pánve – Stropnice, surovina: písky a štěrky. Geologický průzkum, Praha.

Radoane, M., Radoane, N., Dumitriu, D., 2003. Geomorphological evolution of longitudinal river profiles in the Carpathians. *Geomorphology*, 50, p. 293-306

Ribolini, A., Spagnolo M., 2008. Drainage network geometry versus tectonics in the Argentera Massif (French-Italian Alps). *Geomorphology* 93 (3-4), p. 253-266

Schaller, M., Ehlers, T.A., Stor, T., Torrent, J., Lobato, L., Christl, M., Vockenhuber, C., 2016a. Spatial and temporal variations in denudation rates derived from cosmogenic nuclides in four European fluvial terrace sequences Geomorphology, 274, p. 180-192

Schaller, M., Ehlers, T.A., Stor, T., Torrent, J., Lobato, L., Christl, M., Vockenhuber, C., 2016b. Timing of European fluvial terrace formation and incision rates constrained by cosmogenic nuclide dating. Earth and Planetary Science Letters, 451, p. 221-231

Scheidegger, A.E. 1987. *Systematic Geomorphology*. Springer – Verlag. Wien

Seifert, A. and Straka, J.: 1998, Geological map, 1: 50 000, sheet 11-43 Bor. ČGS, Praha, (in Czech).

Ševčík, J., Kvaček, Z., Mai, D.H., 2007. A new mastixioid florula from tektite-bearing deposits in South Bohemia, Czech Republic (Middle Miocene, Vrábče Member). Bulletin of Geosciences 82 (4), p. 429–426. https://doi.org/10.3140/bull.geosci.2007.04.429

Slabý, J. & Holásek, O., 1992a. Geologická mapa ČR 33-31 Pohoří na Šumavě 1:50 000, Český geologický ústav, Praha.

Slabý, J., Holásek, O., 1992b. Geologická mapa ČR 33-13 České Velenice 1:50 000, Český geologický ústav, Praha.

Sougnez, N. and Vanacker V.: 2011, The topographic signature of Quaternary tectonic uplift in the Ardennes massif (Western Europe). Hydrol. Earth Syst. Sci., 15, 1095–1107. DOI: 10.5194/hess-15-1095-2011

Špaček, P., Valenta, J., Tábořík, P., Ambrož, V., Urban, M., Štěpančíková, P., 2017. Fault slip versus slope deformations: Experience from paleoseismic trenches in the region with low slip-rate faults and strong Pleistocene periglacial mass wasting (Bohemian Massif), Quaternary International, 451, p. 56-73, https://doi.org/10.1016/j.quaint.2017.05.006.

Špaček, P. (ed.), 2021. Faults of the Bohemian Massif: Source of Analytical Data on Main Faults and Faulted Areas with Seismic Potential. Available at: https://faults.ipe.muni.cz/ (Accessed 15. 11. 2021)

Špičáková, L., Uličný, D. and Koudelková, G.: 2000, Tectonosedimentary evolution of the Cheb Basin (NW Bohemia, Czech Republic) between the Late Oligocene and Pliocene: A preliminary note. Stud. Geophys. Geod., 44, 556–580. DOI: 10.1023/A:1021819802569

Štěpančíková, P., Stemberk, J., Vilímek, V. and Košťák, B.: 2008, Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic). Geomorphology, 102, 68-80. DOI: 10.1016/j.geomorph.2007.06.016

Štěpančíková, P., Hók, J., Nývlt, D., Dohnal, J., Sýkorová, I., Stemberk, J., 2010. Active tectonics research using trenching technique on the south-eastern section of the Sudetic Marginal Fault (NE Bohemian Massif, central Europe). Tectonophysics. 485. 269-282. 10.1016/j.tecto.2010.01.004.

Štěpančíková, P., Danisik, M., Evans, N., 2012. Thermochronological record of long term faulting, burial and exhumation history in the Sudetes (Bohemian Massif, Central Europe): a multi-system thermochronological approach. 13553.

Štěpančíková, P., Fischer, T., Stemberk, J. (Jr.), Nováková, L., Hartvich, F. and Figueiredo, P.M.: 2019, Active tectonics in the Cheb Basin: youngest documented Holocene surface faulting in central Europe? Geomorphology, 327, 472-488. DOI: 10.1016/j.geomorph.2018.11.007

Štor T., Schaller, M., Merchel, S., Martínek, K., Rittenour, T., Rugel, G., Scharf, A., 2019. Quaternary evolution of the Ploučnice River system (Bohemian Massif) based on fluvial deposits dated with optically stimulated luminescence and in situ produced cosmogenic nuclides, Geomorphology, 329, p. 152-169, https://doi.org/10.1016/j.geomorph.2018.12.019.

Švancara, J., Havíř, J. and Conrad, W.: 2008, Derived gravity field of the seismogenic upper crust of SE Germany and West Bohemia and its comparison with seismicity. Stud. Geophys. Geod., 52, 567-588. DOI: 10.1007/s11200-008-0038-7

Švára, O., 1981. Zpráva o průzkuimu základových poměrů pro přístavbu pavilonu v areálu ZDS – Kaplice. Stavoprojekt, České Budějovice, 13 p.

Teodoridis, V., Bruch, A.A., Martinetto, E., Vassio, E., Kvaček, Z. and Stuchlik, L.: 2017, Plio-Pleistocene floras of the Vildštejn Formation in the Cheb Basin, Czech Republic – a review and a new paleoenvironmental evaluation. Palaeogeogr. Palaeoclimatol. Palaeoecol., 467, 166-190. DOI: 10.1016/j.palaeo.2015.09.038

Troiani, F., Della Seta, M. & 2008. The use of the Stream Length–Gradient index in morphotectonic analysis of small catchments: A case study from Central Italy. *Geomorphology*, vol.102, p. 159-168

Tschegg, D., Decker, K., 2013. Distinguishing Quaternary and Pre-Quaternary clastic sediments in the vicinity of České Budejovice (Southern Bohemian Massif, Czech Republic). Austrian Journal of Earth Sciences, 106, p. 72-89.

Tyráček, J., 1983.: River terraces – important paleoclimatic indicator. – In: Billiards, O., Conchon, O. & Shotton, F., W. (eds.): Quaternary glaciations in the Northern Hemisphere. IGCP Project 73-1-24. Report No. 9. UNESCO International Geological Correlation Programme, Paris, 34–41

Tyráček, J., 2001. Upper Cenozoic Fluvial history in the Bohemian Massif. Quaternary International, 79, p.37-53. https://doi.org/10.1016/S1040-6182(00)00121-X

Tyráček, J., Westaway, R., Bridgland, D., 2004. River terraces of the Vltava and Labe (Elbe) system, Czech Republic, and their implications for the uplift history of the Bohemian Massif. Proceedings of the Geologists' Association, 115, p. 101-124. https://doi.org/10.1016/S0016-7878(04)80022-1

Tyráček, J., Havlíček, P., 2009. The fluvial record in the Czech Republic: A review in the context of IGCP 518. Global and Planetary Change 68, p. 311–325. https://doi.org/10.1016/j.gloplacha.2009.03.007

Van den Berg, M.W., van Hoof, T., 2001. The Maas terrace sequence at Maastricht, SE Netherlands: evidence for 200 m of late Neogene and Quaternary surface uplift. In: Maddy, D., Macklin, M.G., Woodward, J.C. (Eds.), River Basin Sediment System: Archives of Environmental Change. Balkema, Abingdon, pp. 45–86.

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1978a, Legend to the base geological map of Czechoslovakia 1:25 000, sheet 21-214 Mířkov. Ústřední ústav geologický, Praha, (in Czech).

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1978b. Legend to the base geological map of Czechoslovakia ČSSR 1:25 000, sheet 21-232 Horšovský Týn. Ústřední ústav geologický, Praha, (in Czech)

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1980. Legend to the base geological map of Czechoslovakia ČSSR 1:25 000, sheet 21-212 Staré Sedlo. Ústřední ústav geologický, Praha, (in Czech).

Vrána, S., Holásek, O., 1992. Geologická mapa ČR 32-24 Trhové Sviny 1:50 000. Český geologický ústav, Praha

Vrána, S., Novák, V., 1993. Geologická mapa ČR 32-42 Rožmberk nad Vltavou 1:50 000, Český geologický ústav, Praha.

Vyskočil, P., 1973. The investigation of vertical crustal movements in the geodynamical polygon Lišov. Edice výzkumného ústavu geodetického, topografického a kartografického v Praze, řada 4, p. 1-96,

Westaway, R., 2001. Flow in the lower continental crust as a mechanism for the Quaternary uplift of the Rheinish Massif, north-west Europe. In: Maddy, D., Macklin, M.G., 324 J. Tyráček, P. Havlíček / Global and Planetary Change 68 (2009) 311–325 Woodward, J.C. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Abingdon, pp. 87–167

Westaway, R., 2002. Long-term river terrace sequences: evidence for global increases in surface uplift rates in the Late Pliocene and early Middle Pleistocene caused by flow in the lower continental crust induced by surface processes. Netherlands Journal of Geosciences 81, 305–328.

Wheeler, D. A.: 1979, The overall shape of longitudinal profiles of streams. In A.F. Pitty (ed.), Geographical Approaches to Fluvial Processes, Norwich GeoAbstracts, 241-260.

Willet., S. D.(ed.), 2006. Tectonics, Climate and Landscape Evolution. The Geological Society of America, Special paper 398. https://doi.org/10.1130/SPE398

Wood, W. F., & Snell, J. B. 1960. A quantitative system for classifying landforms. Natick, Mass, Headquarters, Quartermaster Research and Engineering Command, US Army, Quartermaster Research & Engineering Centre. 20 pp.

Žebera, K., 1967. Moldavite-bearing sediments between Koroseky and Holkov in South Bohemia. Věstník ústředního ústavu geologického, 42, p. 327-337

Ziegler, P.A., Dèzes, P., 2007. Cenozoic uplift of Variscan Massifs in the Alpine foreland: Timing and controlling mechanisms. Global and Planetary Change, 58, p. 237–269. https://doi.org/10.1016/j.gloplacha.2006.12.004

Zoubek, V.: 1963, Legend to the base geological map of Czechoslovakia 1: 200 000, sheet M-33-XIII Karlovy Vary, ÚÚG ČSAV, Praha, 290 pp., (in Czech).

Chapter 1: Geomorphological evidence of tectonic activity of the Mariánské Lázně Fault (Czech Republic) and its influence on stream network evolution

by Jan Flašar and Petra Štěpančíková

a study published in the Acta Geodynamica et Geomaterialia, v. 19, No. 1 (205), 2022

(DOI: 10.13168/AGG.2021.0039)

Abstract

The Mariánské Lázně Fault (western Bohemia, CZE) is a morphologically, geologically and tectonically prominent structure that is 150 km long with an NNW-SSE orientation. Its tectonic activity, especially in the NW part and in the neighbouring Cheb basin, is well known and has been proven by present-day earthquake swarms, mantle-derived CO_2 emanations, geophysical and paleoseismological research. It seems that other parts of the MLF (especially segments of NNW-SSE and N-S orientation) might also have been active during the Pleistocene, possible even in the Holocene. This study provides a robust set of morphometric analyses – mountain-front sinuosity, basin asymmetry, longitudinal stream profiles, SL-index, which assesses the possibility of recent tectonic activity. The results suggest that the activity of the central and southern part of the MLF could have been very young. A reconstruction of the evolution of the stream network of the Mže River, as a result of different timing of the activity of particular segments of the MLF, is also put forward. The first ideas about the evolution of terrain morphology and the stream network are proposed by this study, however subsequent field research (geophysics, paleoseismology) could prove and date the tectonic activity. The delineation of segments with young activity may also have a great implication for seismic hazard assessment.

Keywords: neotectonics, mountain front sinuosity, basin asymmetry, stream network, Bohemian Massif

1. Introduction

The Mariánské Lázně Fault (MLF) is a structure in western Bohemia (Czech Republic), which is about 150 km long and has a prevailing orientation of NNW-SSE (see Fig. 1). Its prominence can be seen both in the geology and terrain morphology (Fig. 1 and Fig. 2). The fault itself was formed during the Variscan orogeny 380 - 300 Ma (Pitra et al., 1999) and it separates the main geological units building the Bohemian Massif – Moldanubian, Saxothuringian and Teplá-Barrandian (Fig. 1). The fault was reactivated several times during the Cenozoic, the last reactivation is of Neogene age and persists to this day (Švancara et al., 2008; Fischer et al., 2012). It controls significant effects in the terrain morphology such as a mountain front fault scarp that is up to 300 m high. The study area is also famous for its Pleistocene volcanic activity (Ulrych et al., 2011, 2013), mineral springs, mantle-derived CO_2 emanations (Fischer et al., 2017) and the present-day earthquake swarm activity which are still observed (Fischer et al., 2014; Jakoubková et al., 2017; Štěpančíková et al., 2019). Due to these manifestations, the NW part of the MLF is considered to be the youngest as concerns tectonic activity (Štěpančíková et al., 2019). The age of tectonic activity along the rest of the MLF has not been studied in detail yet, but it is considered to be of Miocene-Pliocene age (Špičáková et al., 2000).

In this study morphometric methods were used (mountain front sinuosity, basin asymmetry, water stream longitudinal profiles, stream-length index) to evaluate the intensity and possible relative age of the tectonic activity along the MLF. The results suggest that the activity could have been younger than Miocene-Pliocene - possibly Pleistocene - and most intensive in the central part of the MLF. This uneven tectonic activity, mainly uplift, in particular segments of the MLF could have influenced the evolution of the local stream network. Here a possible reconstruction of the stream network evolution is put forward.

2. Geological and geomorphological setting

2.1. Geological setting

The Mariánské Lázně Fault is a tectonic structure, which is located in the western part of the Bohemian massif in the Czech Republic (for location see Fig. 2). The MLF limits several geological units which have often undergone different geological processes. Therefore, their geological history and lithological structure is very variable (see Fig. 1). There is the Saxothuringian unit in the NW, the Moldanubian unit in the W and S, the Teplá-Barrandian unit in the eastern part of the study area and the Mariánské Lázně complex between those units. Some of these crystalline rocks can be overlaid by the tertiary sedimentary units of the Cheb basin (Mlčoch and Skácelová, 2009).

The Saxothuringian crystalline rocks are present along the NW part of the MLF and they also underlay the sedimentary infill of the Cheb basin. These rocks are originally of Proterozoic and Cambrian age; however, they were intensively metamorphosed during the Variscan orogeny, 360 - 330 Ma (Mlčoch and Konopásek, 2010). Paragneisses, schists and orthogneisses are the most frequent rock types in this unit. However less metamorphosed phyllites of Ordovician age can also be found, especially along the fault in the segments *a* and *b* of the MLF (Fig. 2; Chlupáč et al., 2002). The Mariánské Lázně complex is a specific lithological unit of highly metamorphosed rocks, which have probably infilled the suture between the Saxothuringian unit and the Teplá-Barradian unit – the two former microcontinents amalgamated during the Variscan orogeny (Mlčoch and Konopásek, 2010). It is composed of mafic and ultramafic rocks: serpentinized peridotite on the basement and sets of amphibolites, eclogites and metagabbros in the upper part (Cháb et al., 2008).

The Teplá-Barrandian unit is less affected by Variscan metamorphosis than the others, however, the parts along the MLF are more intensively metamorphosed than the rest of this unit as the intensity of metamorphosis rises towards the NW. Phyllites, schists and paragneisses can be found along the fault (Chlupáč et al., 2002).

The Moldanubian unit is composed mostly of Variscan metamorphosed rocks like paragneisses, orthogneisses and migmatites. The granitic intrusions are also presented in the study area of pre-Variscan or Variscan age (Cháb et al., 2008).

The MLF bounds the Cheb Basin in the NW, which is a half-graben and originated on the crossing of distinct tectonic features: the ENE trending Eger Rift and Cheb-Domažlice Graben (NNW-SSE). The thickest sedimentary infill (up to 400 m) of the basin is located in its eastern part controlled by the MLF. The oldest deposits in the basin involve sands, gravels and clays of upper Eocene age (the Starosedelské and Novosedelské Formations) overlaid by sets of coal seams, clays, sands and volcanoclastic (Oligocene and Miocene Sokolov formation; Špičáková et al., (2000)). The uppermost part of the Miocene deposits is represented by the Cypris Formation, which contains typical greenish clays and claystones (Chlupáč et al., 2002). The Vildštejn formation of Pliocene/Pleistocene age is the youngest member of the basin's sedimentary infill. This formation is composed of fluviolacustrine sands, gravels and clays and it is not present only in the Cheb basin, but also in several relicts in the Cheb-Domažlice Graben along the MLF (Pešek, 1972; Teodoridis et al., 2017).

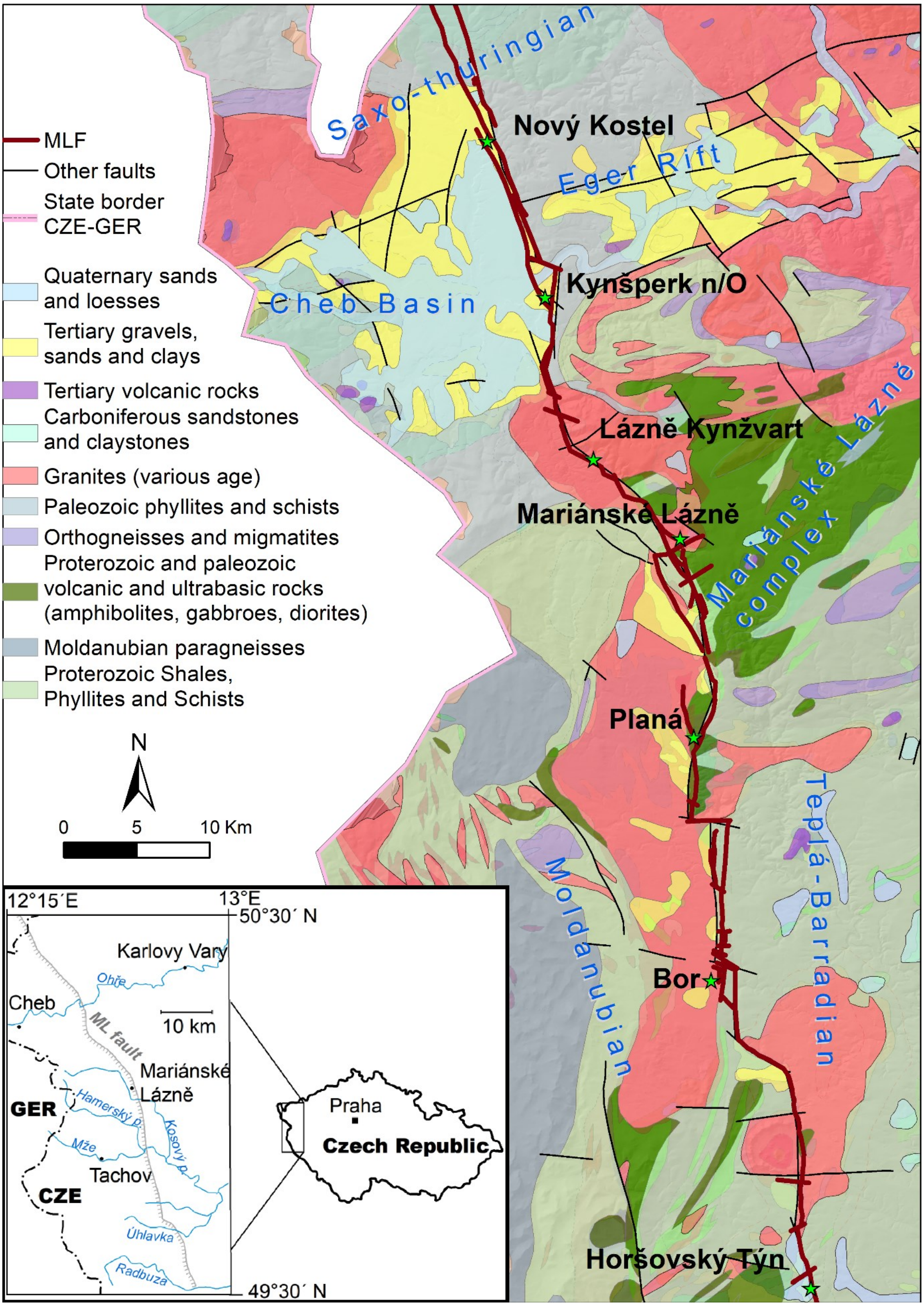


Fig. 1: Simplified geological map of the surroundings of the MLF (based on Zoubek, 1963; Vejnar et al., 1978; Vejnar et al., 1978b; Vejnar et al., 1980; Mahel et al., 1984; Müller et al., 1998; Seifert et al., 1998 Adamová et al., 2001).

2.2. Geomorphological setting

The Mariánské Lázně Fault (MLF) is a NNW-SSE trending, morphologically prominent structure, more than 150 km in length (see Fig. 2). According to Pitra et al. (1999) the fault zone originated in the late-Variscan (380–300 Ma) as a normal fault with a dextral component. The normal character of the fault zone controlled the formation of the Cheb basin from the late Eocene until the Pliocene (Špičáková et al., 2000). However, the MLF is remarkable mainly due to its Quaternary activity. During the Pleistocene, the wider area of the MLF also witnessed the latest volcanic processes in the Bohemian Massif – the activity of the Komorní Hůrka and Železná Hůrka volcanoes and Mýtina maar (e.g. Ulrych et al., 2011, 2013). Balatka et al. (2019) inferred the tectonic uplift along the MLF (10-15 m) also from the truncated Pleistocene fluvial terraces of the Ohře River in the Cheb Basin. The Holocene activity of the MLF, even with surface rupturing, was documented by displaced sediments along the NW part of the MLF (Štěpančíková et al., 2019). The activity of this part of the MLF has continued until today and it overlaps with the West Bohemia/Vogtland earthquake swarm region (Fischer et al., 2014; Štěpančíková et al., 2019). Earthquakes have been registered since the Middle Ages, the strongest one in the instrumental era gives an upper magnitude estimate of the West Bohemia/Vogtland swarms of M_L 5.0, which corresponds approximately to Mw 4.3 (Jakoubková et al., 2017). In addition, numerous mineral springs and mantle-derived carbon-dioxide emanation were documented from the surrounding of this part of the MLF (Weinlich et al., 1999; Bräuer et al., 2005; Fischer et al., 2017). The NW part of the MLF is probably the most and best studied area of recent tectonic activity in the Bohemian Massif.

The morphological evidence of the MLF in the terrain can be traced for as long as 120 km. A well-expressed escarpment, which is from 50 to 400 m high, is visible along almost the entire fault (Fischer et al., 2012). The highest fault scarp can be found in the central part of the fault, near Lázně Kynžvart. The fault became less morphologically distinct towards both ends, the north-western near Plauen (in Germany) and the south-eastern near Horšovský Týn. However, the character of the fault escarpment varies in different parts of the MLF, it is possible to observe different grades of tectonic facets evolution, water stream erosion etc. This can indicate a complicated tectonic history and possibly the difference in age and rate of the tectonic movements in the particular segments of the MLF (Badura et al., 2007; Švancara et al., 2008). The MLF separates two distinct types of relief (Fischer et al., 2012): higher terrain on the eastern side and lower on the western. The crossing of the MLF with the Eger Rift is the only part of the fault where the relatively flat terrain is present on both sides of the MLF. The lower relief is represented by the flat terrain of the Cheb basin, or by the gently hilly relief of the Cheb - Domažlice Graben. The uplifted eastern part is represented by the Krušné hory Mountains in the NW part of the fault, the very rugged terrain of the Slavkovský les highland in the central part and the rather gentle terrain of the Plaská hilly land (Balatka and Kalvoda, 2006; Bína and Demek, 2012).

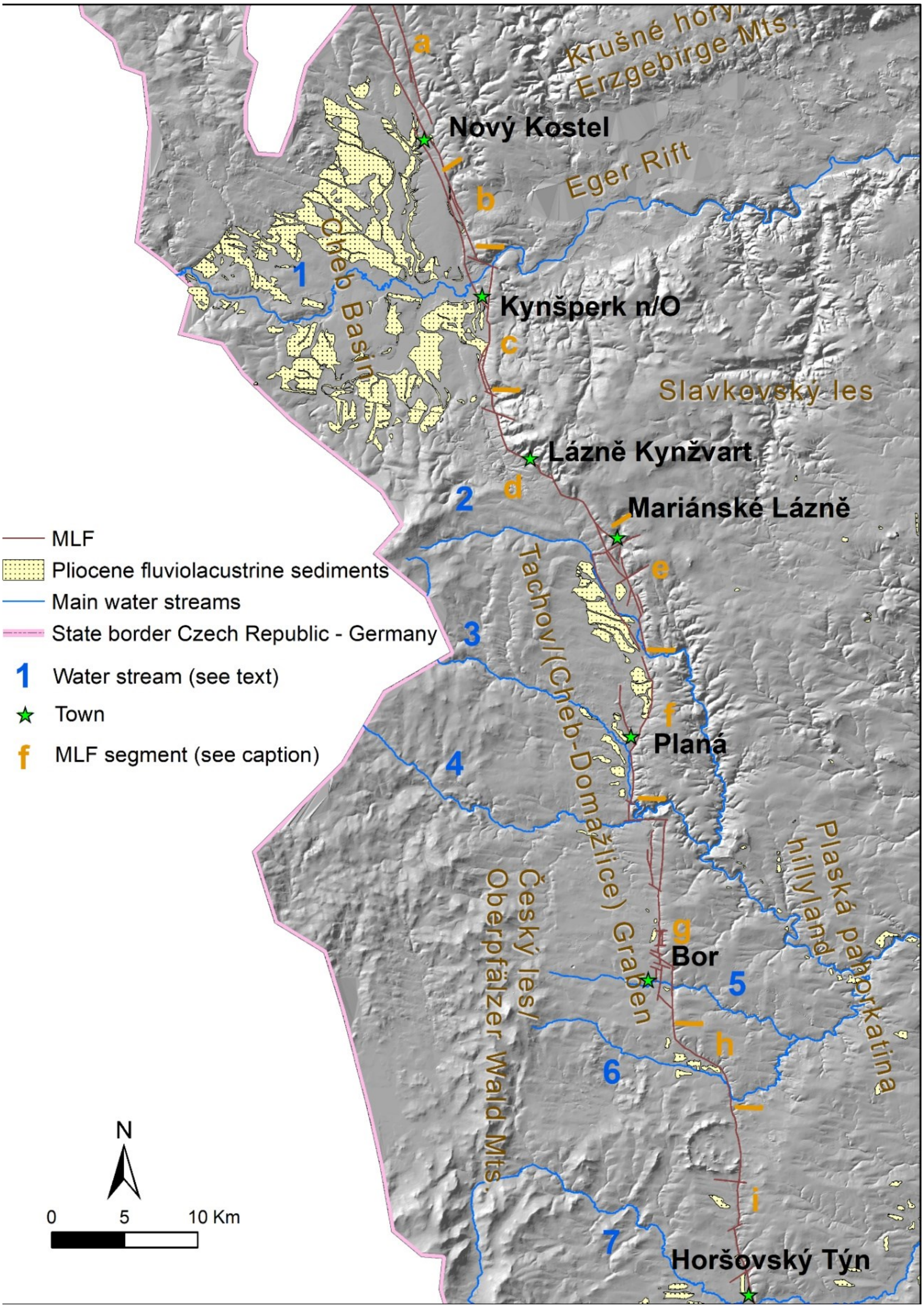


Fig. 2: Terrain overview map of the MLF. Names of the streams: 1 – Ohře, 2 – Kosový, 3 – Hamerský, 4 – Mže, 5 – Výrovský, 6 – Úhlavka, 7 – Radbuza. Please note the coding of the MLF segments by letters (further used through the text).

3. Data and methods

3.1. Data

Several types of primary data were used during this study. The basic topographic information for calculating morphometric indices was obtained from the digital elevation model (DEM), which was based on aerial laser surveying and measurement: LiDAR – resolution <1 m (ČUZK, 2017). The information about the lithology and tectonic structure was obtained from basic geological maps of the area (Zoubek, 1963; Vejnar et al., 1978; Vejnar et al., 1978b; Vejnar et al., 1980; Mahel et al., 1984; Müller et al., 1998; Seifert et al., 1998 Adamová et al., 2001), and were locally specified by field survey. Historical sources were used for correcting some faults in topographic maps or for avoiding the anthropogenic influence on water streams. The historical maps (JEPU and ME, 2014) and historical aerial photographs (MGHO, 2014) were used for those adjustments.

3.2. Mountain-front sinuosity (Smf)

The mountain front sinuosity index (Smf) (Bull and McFadden, 1977; Burbank and Anderson, 2001; Bull, 2006) is a tool for evaluating the maturity of the tectonic activity and uplift along the fault. The main idea is to compare the length of the mountain foot *(Lmf*) with the straight line *(Ls*).

$$Smf = Lmf/Ls$$

When the uplift is a recent occurrence, the mountain front is straighter (= the index is lower). When the tectonic movements are inactive for a longer time, the fluvial erosion produces the sinuous mountain front (= the index is higher). However, other factors like rock resistance should be evaluated as they can influenced the values of the *Smf* (Gutierrez, 2013). The MLF was divided to 17 segments, based on the orientation of the fault and natural breaks in the fault slope (valleys of longer, east-flowing streams). The measurement of the *Smf* also helped divide the MLF into the particular segments based on the *Smf* values. These segments can be further compared to each other regarding *Smf*, but also regarding the results of the other methods used.

3.3. Stream-length (SL) index

The SL index (Hack, 1973) can be calculated by the equation

$$SL=(\Delta H/\Delta L)Ldm,$$

where *(ΔH/ΔL)* is the stream gradient and *Ldm* is the length of the stream reach between the stream source and the middle of the measured part (see Fig. 3).

The values of the SL index react very sensitively to gradient changes of the stream, including lithological, tectonic, hydrological and even anthropogenic influences. However, the sensitivity of the

SL index can also be a disadvantage – peaks of the SL index curve are very sharp and local maxima can follow local minima very suddenly. It is useful to use some statistical methods to obtain robust results – such as moving the average when evaluating the SL longitudinal curves, as was done here.

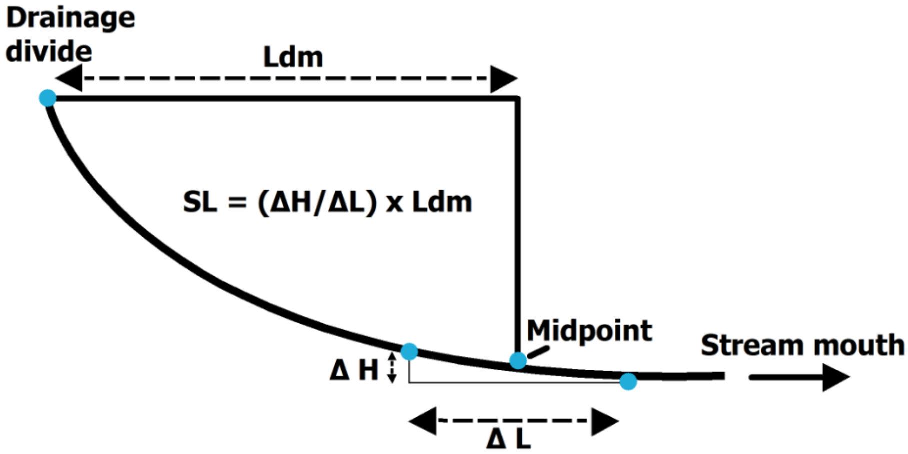


Fig. 3: Calculation of SL index (according to Hack, 1973)

To successfully obtain the SL index values from the selected streams, it is important to select the right source of elevation data. The digital elevation model (DEM) based on LiDAR data was used in this study. The resolution of the DEM was 1 m, which is optimal for such a study, because it provides enough detail, especially regarding the stream geometry.

The longer, east-flowing streams (Kosový, Hamerský, Mže, Výrovský, Úhlavka, Radbuza, see Fig. 2) were distributed to 100 m long reaches, where the SL index was calculated. The shorter, streams were distributed to 10 m reaches in order to detect any of the small particular changes in the SL index at a smaller scale. However, the raw data was rather unsuitable for the subsequent analyses. It was necessary to modify some values in those places, which were influenced by anthropogenic activities (millraces, dams, weirs etc.). The historical maps and historical aerial photographs (see section 3.1.) were used for those adjustments.
The SL index values were represented by longitudinal curves along the stream profiles and were smoothed by the moving average method (10 values).

The streams situated to the N from the Ohře River were surveyed by previous studies of Štěpančíková et al. (2019), where the SL index values were obtained and the results were considered in this study.

3.4. Basin Asymmetry (Af)

Basin Asymmetry is used to detect tilting in a particular basin due to tectonic movements (Badura et al., 2007; Gutierrez, 2013):

$$Af = 100\ (Ar/At)$$

Ar is the area of the basin of the right side of the main stream, *At* is the total area of the basin. A value of 50 indicates stability, whereas deviations from 50 suggest tilting. Moreover, the asymmetry suggests the direction of tilting, however the effect of lithology (strata dip) should be evaluated (Gutierrez, 2013). The asymmetry in the study area was surveyed in the drainage basins of the smaller, west-flowing streams running down the fault slope. In all, 243 basins were tested in order to find a possible regional trend of titling along the MLF.

3.5. Longitudinal profiles

Longitudinal profile analysis is a traditional method for detecting a tectonic effect on a water stream (Wheeler, 1979; Burbank and Anderson, 2001). The typical longitudinal profile of a mature, stable water stream (a so called graded river) has a smooth concave shape. Any divergence of this shape is an indication of unstable conditions, however there are many factors which could influence the shape: erosion base level, geological setting, hydrological setting, climate, tectonics (Burbank and Anderson, 2001; Keller and Pinter, 2002; Willet, 2006; Sougnez and Vanacker, 2011). Therefore, it is very difficult to find out the ruling factor affecting a particular water stream. However, the longitudinal profiles can be compared between each other and it could be a strong lead for evaluating the evolution of water steams or a particular catchment.

In this study, two groups of water streams were investigated separately: longer, east-flowing streams, which head towards the fault scarp where they cut it by antecedent valleys (Kosový, Hamerský, Mže, Výrovský, Úhlavka, Radbuza); and shorter streams (243 streams) up to 10 km long, flowing down the fault slope, generally from E to W. The analyses of the longer streams were used to evaluate catchment and terrain evolution at the regional scale, the analyses of the shorter streams helped to delineate different segments of the MLF, in combination with other methods such as mountain-front sinuosity and basin asymmetry. The Ohře River is one of the main streams crossing the fault from W to E, flowing through the Cheb basin. Its evolution and tectonic control have been studied by e.g. Čtyroký, (1996) and Balatka et al., (2019). As it is also influenced by tectonic processes in the Cheb basin and Eger Graben, it is not comparable with the other streams mentioned and has not been used in this study.

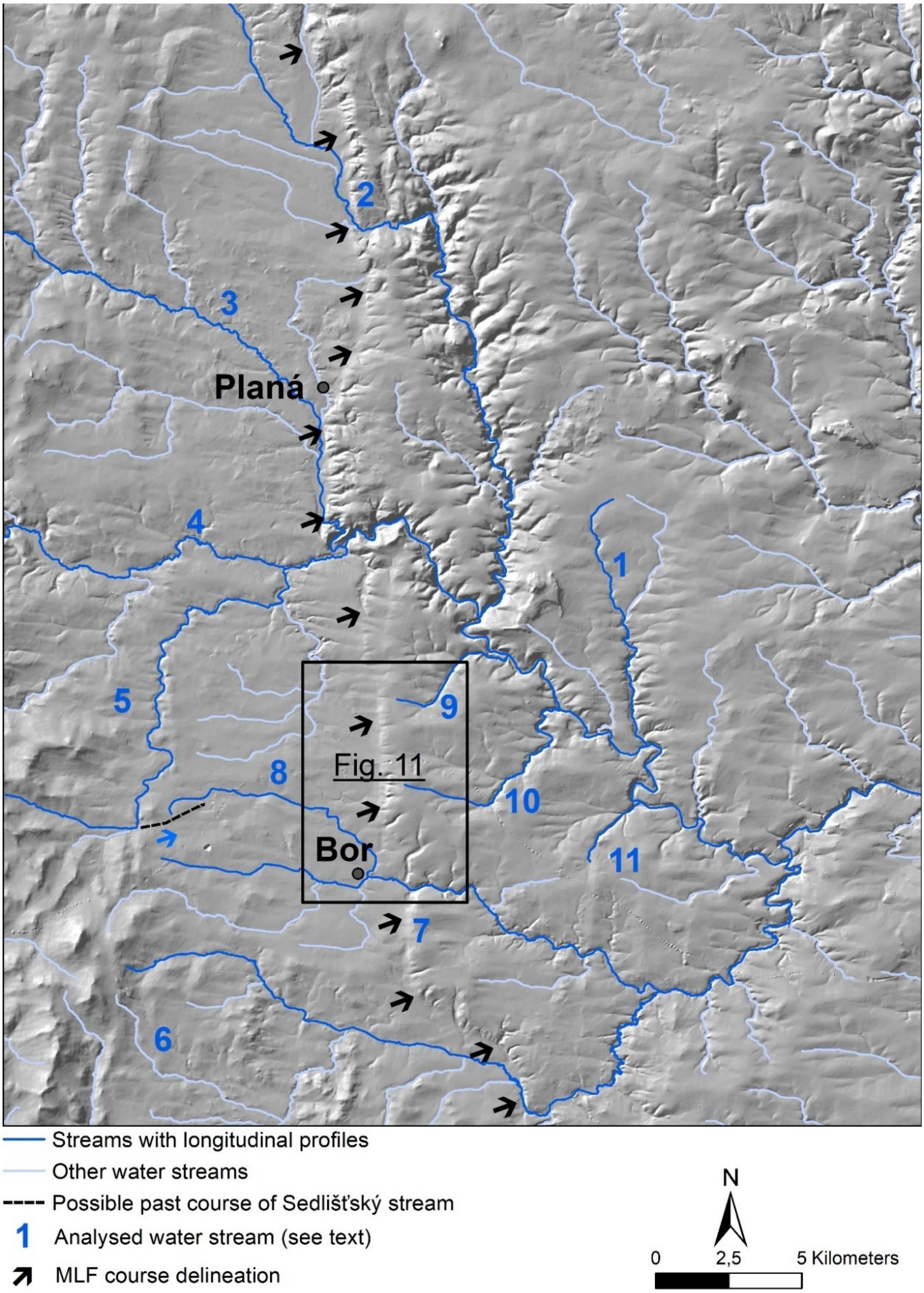


Fig. 4: Detailed map of the central part of the MLF. Area around Bor is enlarged on Fig. 11. Names of the streams: 1 – Černošínský, 2 – Kosový, 3 – Hamerský, 4 – Mže, 5 – Sedlišťský, 6 – Úhlavka, 7 – Výrovský, 8 – Lukavický, 9 – Veský, 10 – Šárka, 11 – Lomský. Note the proposed past course of the Sedlišťský stream (see section 5.2, Fig. 8 and Fig. 14).

4. Results

4.1. Mountain-front sinuosity

Mountain-front sinuosity varies significantly along the MLF (see Fig. 5). The range of values is between 1.06 to 1.63 (see Tab. 1). The highest values were recorded in the small, relatively isolated segments, however, an interesting series of neighbouring segments with relatively high values can be found in the area of Slavkovský les (segments no. 4-8). The lowest values (1.06) were found in the NW part of the MLF (segment no. 1). The low values are located (1.2 – 1.23) in the central part of the MLF (segments no. 11-14). Those results might not be so surprising, as the most recent tectonic activity is expected to be primarily in those parts of the MLF.

Segment no.	**Lmf (m)**	**Ls (m)**	**Smf**
1	2664	2515	**1.06**
2	3375	2574	**1.31**
3	4537	4080	**1.11**
4	3543	2754	**1.28**
5	8146	5951	**1.36**
6	8182	6059	**1.35**
7	4387	3450	**1.27**
8	5462	4140	**1.31**
9	4089	2585	**1.58**
10	4860	3891	**1.25**
11	4118	2525	**1.63**
12	4546	3675	**1.23**
13	10747	8956	**1.20**
14	2064	1381	**1.49**
15	5578	4723	**1.18**
16	6363	4863	**1.30**
17	11885	9760	**1.21**
18	8191	5200	**1.57**

Tab. 1. Values of the mountain-front sinuosity (Smf). Lmf = length of mountain front*, Ls* = length of straight line.

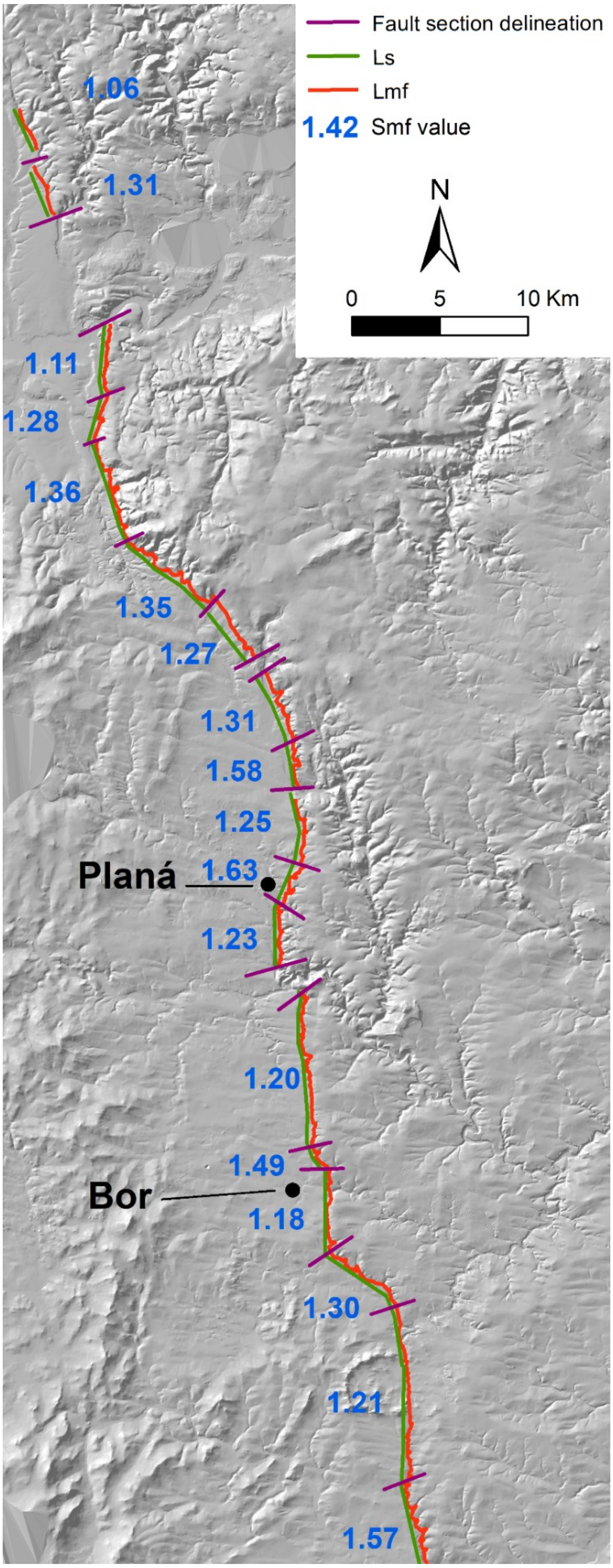


Fig. 5. Mountain front sinuosity and delineation of the segments of the MLF in the study area. *Lmf* = length of the mountain front, *Ls* = length of straight line. For evaluation of the influence of lithology see Fig.1

4.2. Basin Asymmetry

The values of basin asymmetry are variable along the MLF (see Fig. 6a). Out of 243, there are 121 basins with higher symmetry (*Af* = 50-60), 69 basins with a value *Af* between 60 and 70, and 53 basins with an *Af* between 70 and 100 (see Tab. 2 – supplementary file, attached as “asym.xls”). No obvious spatial trend of basin asymmetry values along the MLF was found. However, some segments containing basins with higher asymmetry could be located. Segments *a* and *b* contain 8 basins with an *Af* higher than 70. In addition, the segments *e, f* and *g* show a higher number of asymmetric basins (out of 90 basins there are 9 x *Af*>80, 15x *Af*>70, 30x *Af*>60). On the other hand, the parts of the MLF which bend towards the W (segments *d* or *h*) seem to have more symmetric basins compared to those mentioned above (see Fig. 2 and Fig. 6a for the position of particular segments).

Another expression of tectonic control in the basins could also be the direction of the basin asymmetry (see Fig. 6b and 6c). The movement of the trunk stream to the north part of the basin could be a result of the basin tilting to the north and the uplift of its southern part. This could be a trace of regional tilting, which can be found along some segments of the MLF, however the results are not very strong and the fact that there is no particular spatial trend indicate that the effect of strata dip may well play its role (see section 5.1.). The segment *a* has signs of tilting to the north. Tilting to the north also could be present in the very southern end of the studied part of the MLF (segment *i*) and also in segments *f* and *g* in the central part of the MLF (see Fig. 6b). Less distinctive tilting to the south was found in the central and southern part, segment *h* (see Fig. 2 and Fig. 6c).

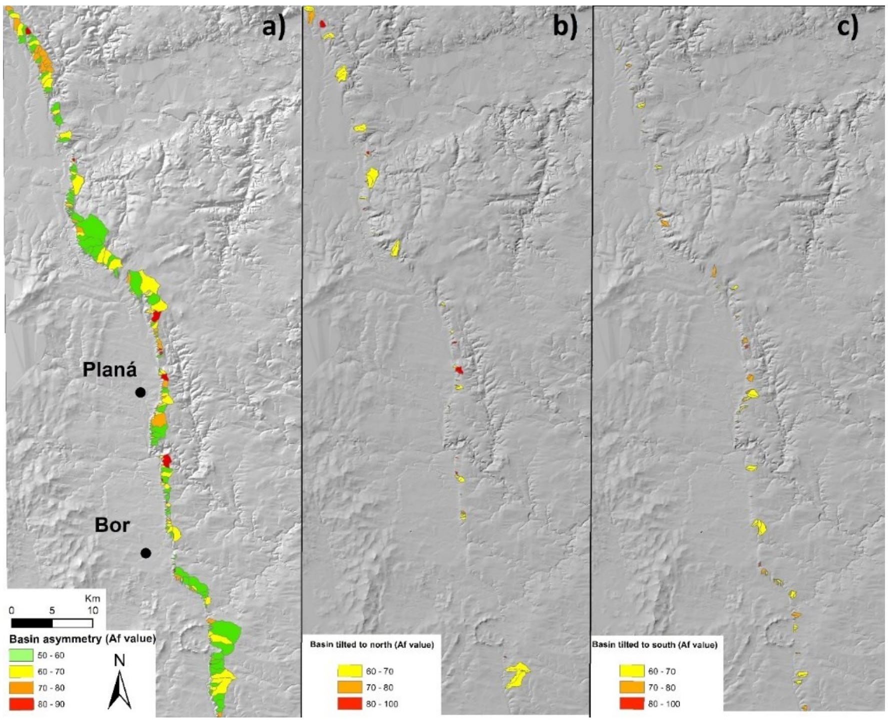


Fig 6.a) Basin asymmetry values along the MLF, b) Basins tilted to the north, c) Basins tilted to the south

4.3. Longitudinal profiles and stream gradient

4.3.1. East-flowing streams

The longer, older streams flowing towards the MLF-related fault scarp, where they cut it by antecedent valleys, show signs of maturity. However, there are parts on the streams which diverge significantly from the ideal profile, which might be a possible result of tectonic activity.

The steepest section (or knickpoint) on the Mže River is located roughly between 35 and 40 km from the source: Fig. 8 and Fig. 10. It lays down the stream from the crossing of the MLF, so a direct effect of the fault could be excluded. The steepening of the gradient (7-10 ‰) could be a combination of bedrock resistance, headward erosion and regional uplift.

The Kosový stream has a very interesting course with two rectangular bends, which might indicate a stream capture (Fig. 4). These changes in course orientation can also be partially detected in the changes of the stream gradient. The section between 25 and 30 km (see Fig. 7) shows a gentle rise in the stream gradient (from 2‰ to 10 ‰). This section lays directly down the stream from the rectangular bend where the Kosový stream changes its direction from WSW-ENE to NNW-SSE (see Fig. 4). These gradient changes could be correlated with the processes of stream capturing (Demek and Czudek, 1957). The most interesting knickpoint on the Kosový stream lies between 35 and 39 km. This section has an untypically high stream gradient (locally over 20 ‰), incomparable with similar streams in the area. It could partially be controlled by bedrock resistance, however, a tectonic effect cannot be ruled out. The neighbouring Mže River also has a similarly steep section (see Fig. 7), however it seems that its origin differs in time and/or cause, because of differences in the steepness, exact localization etc.

The Hamerský stream has quite a mature longitudinal profile, however, with an untypical, steep section near the confluence with the Mže River (Fig. 4. Fig. 7, Fig. 10; over 10‰ gradient) which is related to the valley section being deeply incised through the fault slope. The origin of these features is probably caused by headward erosion from the incising main stream of the Mže River.

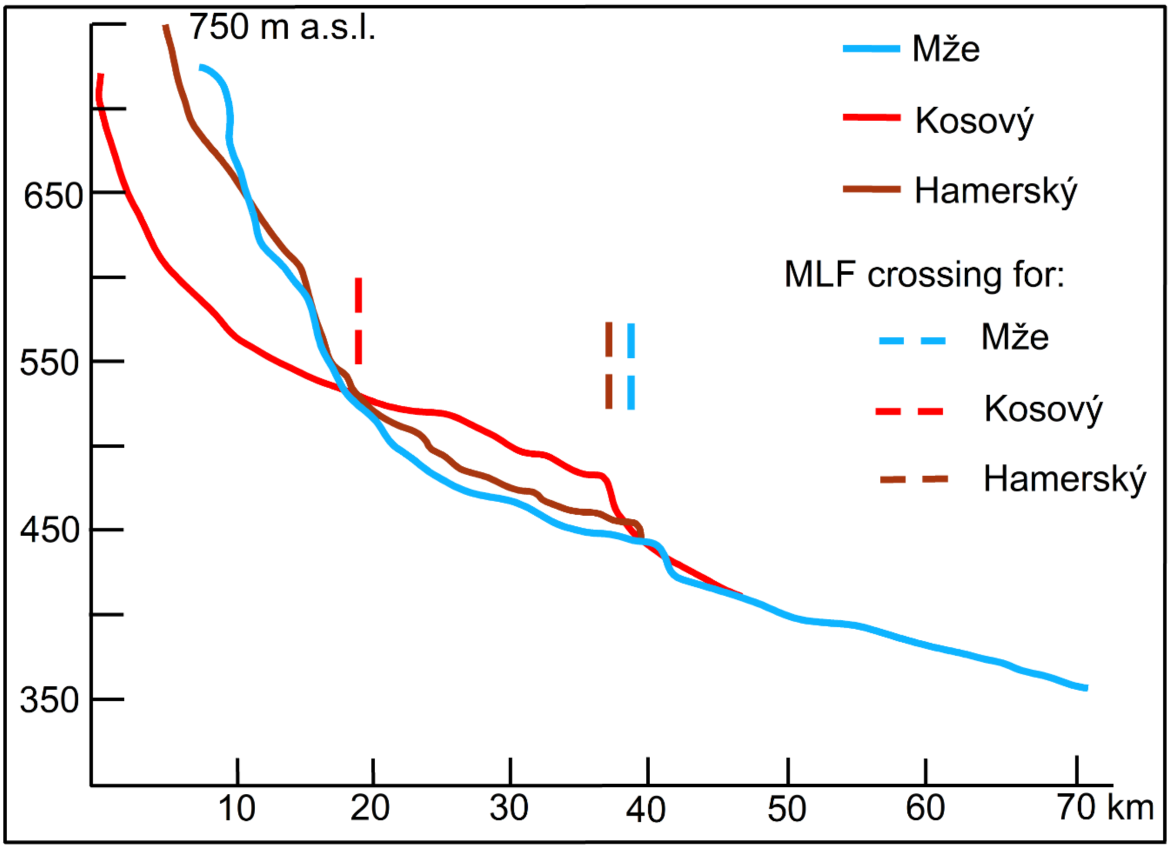


Fig 7. Comparison of the longitudinal profiles of the Mže River and its tributaries. Horizontal distance is measured form the source of the Kosový stream. Note the crossings with the MLF. For the topographical position of the crossing see Fig. 4

The Úhlavka River is a right-sided tributary of the Mže River. Its longitudinal profile is more mature, compared to other streams in the area (see Fig. 8 and 9). However, its tributary, the Výrovský stream, has a stepped profile with several knickpoints (locally a 25-30 ‰ gradient).

The lower part of the Výrovský stream (respectively its tributary the Lukavecký stream) is almost an ideal continuation of the upper parts of the Úhlavka River and the Sedlišťský stream considering the shape of the longitudinal profile. This relation between longitudinal profiles as well as geographical relations, suggests that stream capturing here was very probable (see section 5.2., Fig. 4, Fig. 8 and Fig. 14).

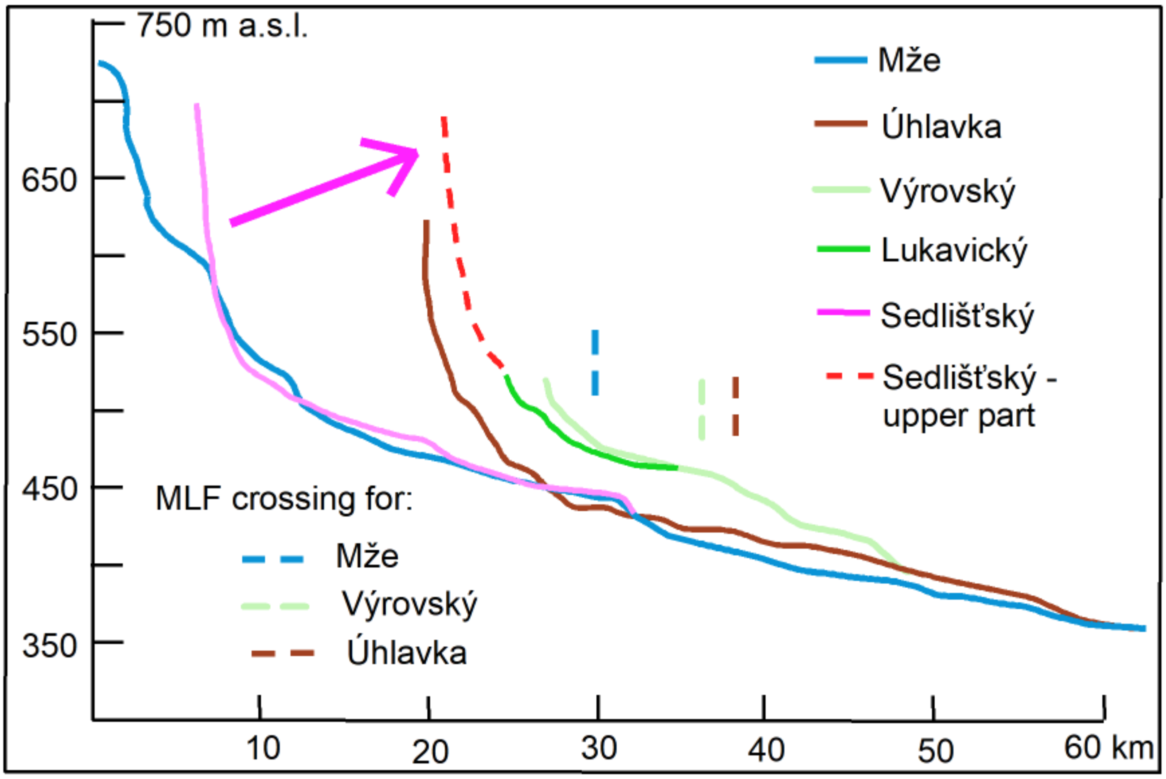


Fig 8. Comparison of the longitudinal profiles of the Mže River and its tributaries. Note the almost ideal possible former connection between the upper part of the Sedlišťský stream and the lower part of the Lukavický stream (see section 5.2., Fig. 4 and Fig. 14). Horizontal distance is measured from the source of the Mže River. Note the crossings with the MLF. For the topographical position of the crossing see Fig. 4

The tributaries of the Mže River, which are located between the Kosový stream and the Úhlavka River (Šárka, Veský, Lomský and Černošínský streams – see Fig. 4 and 9), have very steep longitudinal profiles (3-10 ‰ along the majority of their length). They are very similar to each other, however they are quite different from the other streams mentioned above, which have more mature, hyperbolic profiles. None of them cross the MLF, their profiles seem to be undisturbed by distinctive knickpoints and their steep profile should be a results of intensive incision of the trunk stream, the Mže.

The longitudinal profile of the Radbuza River has a similar shape as that of the Mže River (see Fig. 10). There are several smaller knickpoints (21 km and 45 km – 10 and 8 ‰) along the course, but they can be more likely interpreted as a result of changes in the lithological composition. The most interesting part is the low gradient (max 3 ‰) section between 3 and 8 km. The sharp change to a higher gradient part down the stream (over 10 ‰) is linked with the stream's sudden change of direction in from S-N to W-E. Past stream capturing is very probable here.

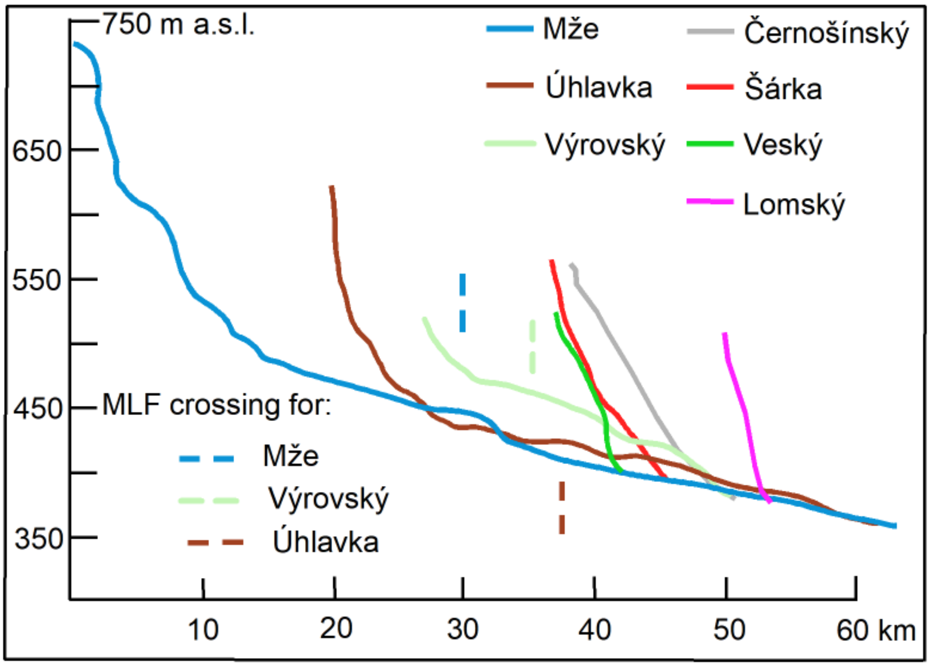


Fig 9. Comparison of the longitudinal profiles of the Mže River and its tributaries. Horizontal distance is measured from the source of the Mže River. Note the crossings with the MLF. For the topographical position of the crossing see Fig. 4

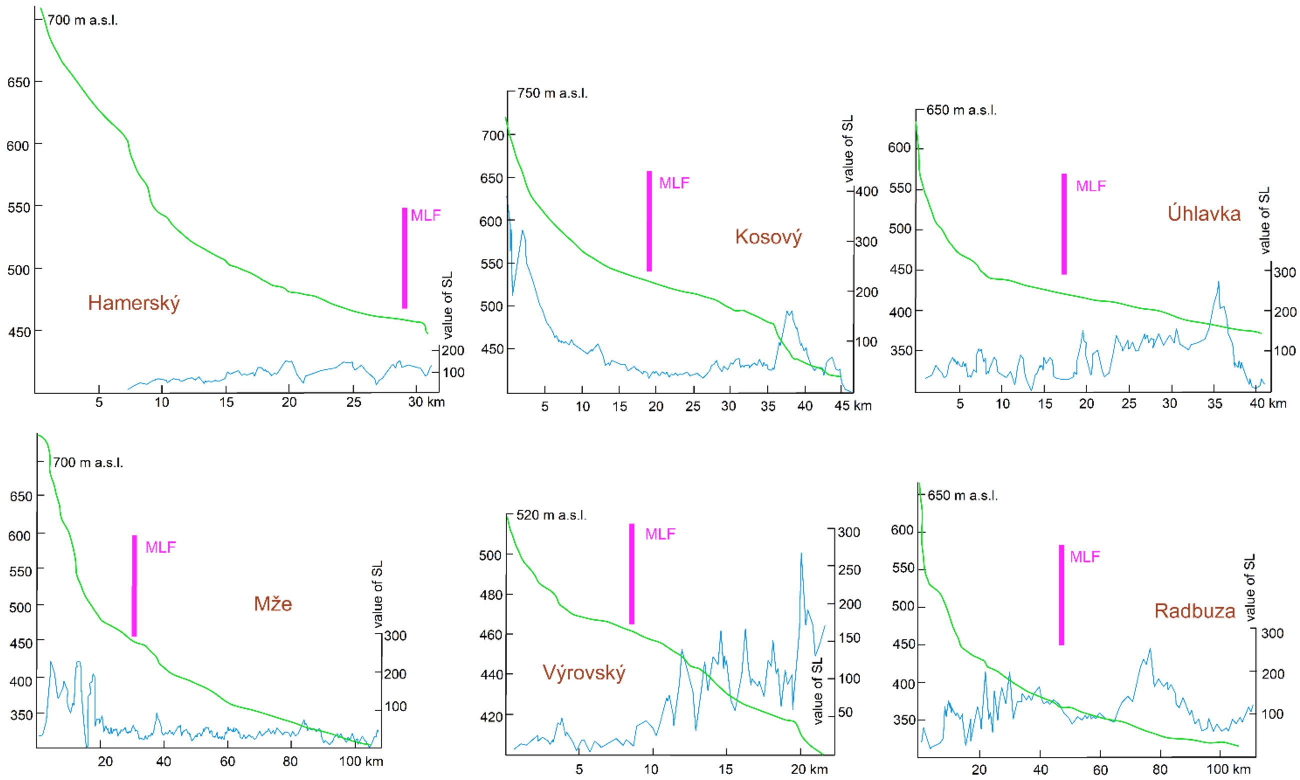


Fig. 10. Longitudinal profiles of the east flowing streams + SL index curves

4.3.2. West-flowing streams

The longitudinal profiles of the W-flowing streams show great variability. However, there are streams with similar profiles near to each other, so the study area can be classified into several clusters or segments. Concave longitudinal profiles (graded profiles) can be found in the area of Slavkovský les and also between the Výrovský and Úhlavka streams (Fig. 4). This probably means a longer period of erosion activity (compared with the relatively low basin asymmetry within those parts of the MLF– Fig. 6). On the other hand, a higher number of convex profiles can be found in particular areas: in the SE near Horšovský Týn, in the NW between Kynšperk n/O and the Czech-German border, and, especially, in the central part between Planá and Bor (where the values of basin asymmetry are relatively higher – Fig. 6). The central part of the MLF was investigated in detail, as the most promising area for subsequent field research of recent tectonic activity. There are 20 west-flowing streams in segments *f* and *g* of the MLF (Fig. 2, Fig. 12). In particular, the area 5 km N from Bor (see Fig. 11) shows 8 streams (Pustina, U Anděla, Pod Lobatínem, U Kaolínky, Za Rozhlednou, Malovický les, Malovický vrch, Mezi Malovickým vrchem) with particularly convex profiles (see underlined stream names in Fig. 12). It is also possible to find the morphologically very prominent course of the MLF fault slope foot and the stream valleys, which are significantly offset, in this part of the MLF (see Fig. 11). This situation is very similar to the NW part of the MLF (Štěpančíková et al., 2019). Therefore, young tectonic activity with both vertical and horizonal component of movements can also be expected and it should be a subject for further research.

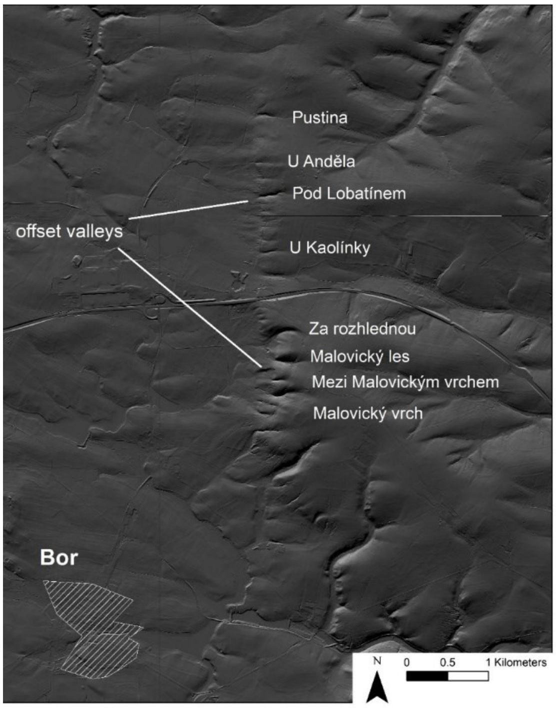


Fig. 11: Segment of the MLF to the north from the town of Bor with west-flowing streams with highly convex longitudinal profiles (see Fig. 13). Note also the significant course of the fault slope foot and the offset valleys (particularly “Mezi Malovickým vrchem”, “Pod Lobatínem” and “Pustina”).

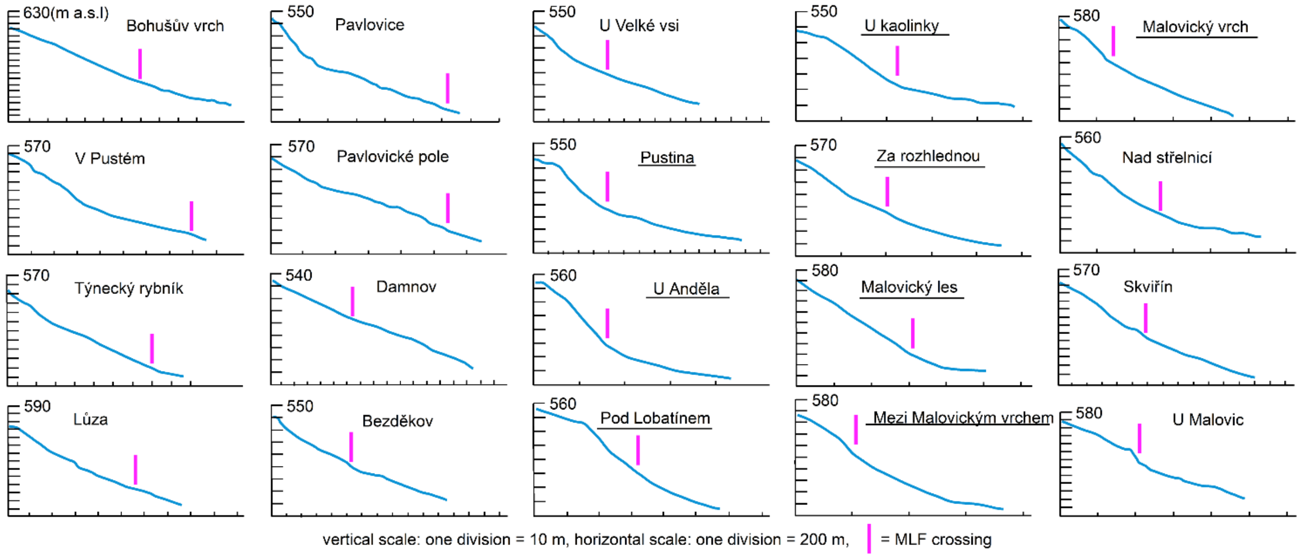


Fig. 12. Longitudinal profiles of the streams between Planá and Bor. Note the significant convex profiles - with underlined stream names (for detailed profiles see Fig. 13, for the morphological situation see Fig. 11).

4.4. SL index

4.4.1. East-flowing streams

The values of the SL indices were smoothed by the moving average tool to obtain a better view of the regional trends of values. No strong anomalies of SL index values were measured near the crossings of the streams and the MLF. Instead, a rise of SL index values (up to 300) was measured in the whole area that lays down the stream from the MLF crossing. Still, differences between particular streams can be observed, which could be caused by different lithology, an uneven rate or age of the uplift or other effects (see section 3). The Mže River (see Fig. 10) has two main increases (220 and 100) in the SL index value: around 15 km and 40 km. The first one is linked to the knickpoint following the flat section on the upper part of the stream. A more important peak in high SL index values lies at 40 km (5 km down the stream from the MLF crossing). The Kosový stream has the most interesting changes in its SL values on its lower course: a gentle rise in SL index values between 26 km and 35 km (SL = 50) and, in particular, a very prominent peak of values between 36 km and 39 km (SL= 180). Compared to the Mže River and Kosový stream, the Hamerský stream does not have any prominent peaks in its SL index values. There is only a gentle rise of values (SL= 100) by the crossing of the fault. The Výrovský stream is remarkable due to its two knickpoints (12-15 km and 20-22 km, SL= 160 and 260) down the stream from the MLF. The SL index values on the Úhlavka River show a gradual rise downstream from the MLF crossing (SL = 40-130), but the main peak is located near its mouth to the Mže River (SL= 280; see Fig. 10). The Radbuza River has different SL index values along its course, compared to other streams in the area. A rise in the values is located several kilometres down the stream from the crossing; the values are untypically low here (SL= 100). A remarkable rise in the SL index values is located around 80 km (SL= 250).

4.4.2. West-flowing streams

The SL indices measured on the consequent W-flowing streams span from 0 to 1000. Due to the difficulty of comparing the SL indices between the streams, sudden changes in values on particular streams were investigated rather than comparing the absolute values. The high values and sudden changes in SL index are located on the slopes of Slavkovský les, in segment *d* of the MLF. The high SL index values are linked with the high stream gradient in the area, where the upper parts of the streams are flat and then very steep in the middle part. Segment *i* is the other area that has sudden changes in SL index values. Remarkable results were obtained by Štěpančíková et al., (2019) in segment *a*, where several fault segments were marked as active based on the SL-index values. Despite the distinctive fault scarp morphology and suspected valley offsets in segment *g* of the MLF (Fig. 2 and enlarged on Fig. 11), no high SL index values were obtained from this central part of the MLF. This might be caused by the lower relief and lower water discharge in the area, so the valleys are young and undeveloped. The streams Pod Lobatínem, U Kaolínky, Za Rozhlednou a Malovický les showed very similar longitudinal curves (Fig. 13). The peaks of SL index values correlated with the foot of the fault slope, and therefore young MLF activity is probable.

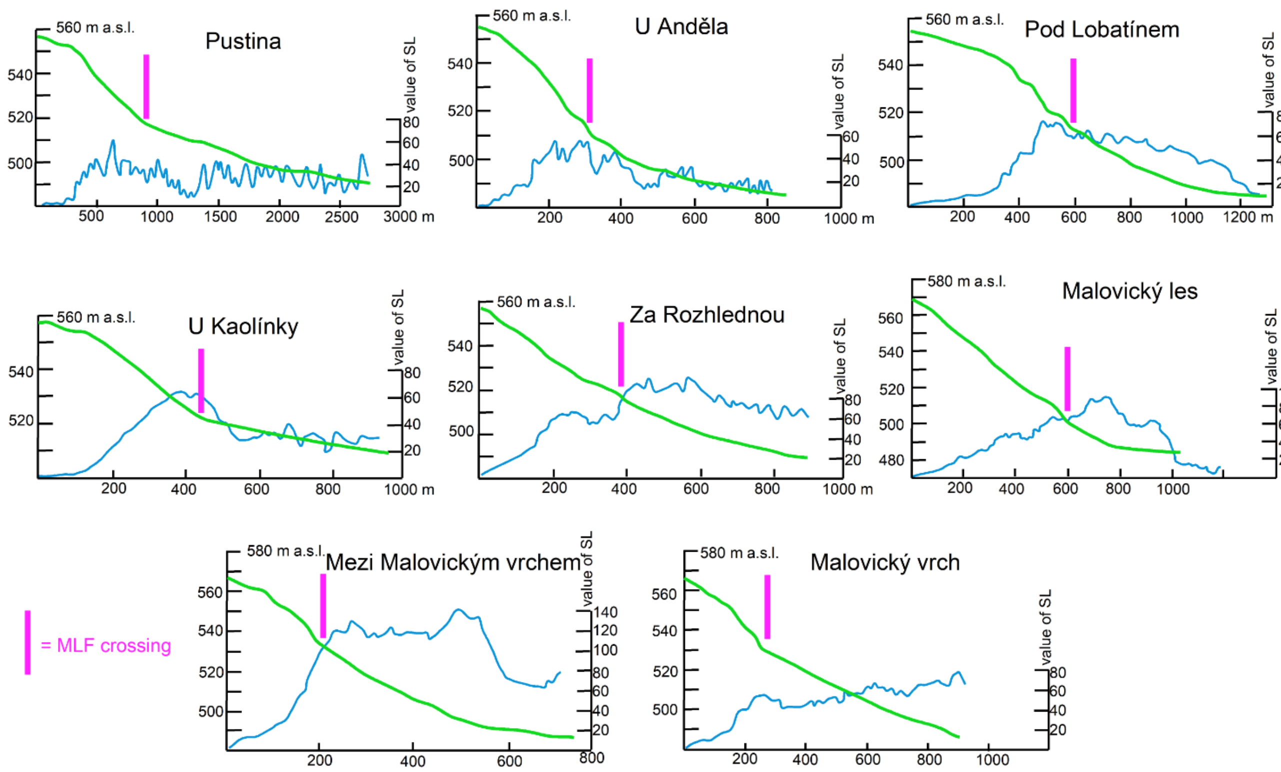


Fig. 13. Longitudinal profiles and SL value curves of the selected west-flowing streams in the central part of the MLF (see Fig. 11, Fig. 12)

5. Discussion

5.1. Segmentation of the MLF and evaluation of the methods used

The delineation of the MLF to the particular segments was based on the values of mountain front sinuosity and its strike. Nevertheless, the results of the other methods used– mainly the basin asymmetry and partially the longitudinal profiles analyses – led to a very similar delineation. The results of these different methods suggest that the tectonic activity occurred at different times and/or with variable intensity along the MLF. The NW part – segments *a* and *b* - (orientation NNW-SSE), the central part – segments *f* and *g* - (orientation N-S), and the southern part – segment *i* - (orientation NNW-SSE) are the segments, where the activity probably occurred most recently. On the other hand, the bended segments – *d* or *h* - (orientation NW-SE to NNW-SSE), are probably the ones which experienced uplift for a longer time.

The methods used in this study were also applied in several studies from different parts of the Bohemian Massif (Badura et al., 2007; Štěpančíková et al., 2008). The lithological and tectonic setting there is similar to the study area along the MLF. Particularly, the study by Badura et al. (2007) of the Sudetic Marginal Fault showed very similar results. The methods of mountain front sinuosity and basin asymmetry could provide quite valuable results for assessing tectonic activity at the regional scale, especially where possible lithological control can be ruled out. For example, the mountain front sinuosity values can be strongly affected by the bedrock's resistance to erosion (softer rocks, e.g. sediments, can show higher values of sinuosity), nevertheless, the lowest values of mountain front sinuosity can be found in the softer rocks (phyllites, shales) along the MLF. So, it is assumed that the effect of tectonics overrules the effects of lithology in this case. The other issue is the orientation of the rock structures (e.g. strata dip) which could influence the geomorphological indices as well. In particular, the values of basin asymmetry and the direction of basin tilt could be strongly affected. The dip of the phyllites and schists (ČGS, 2003) in segments *a* and *b* is N or NNW, which is in concordance with the proposed tilt of basins in this area. Therefore, it can be expected there is a strong lithological influence here, but it is possible to find basins with a similar tilt in segment *c,* where a granite basement without any specified dip is located. However, the basin tilt direction cannot be used as a strong proof of tectonic evolution along the MLF because of the aforementioned reasons.

The results of the longitudinal profile analyses of the shorter west-flowing streams are concordant to the results of mountain front sinuosity and basin asymmetry and they suggest more recent tectonic activity on the same segments (segments *a* and *b*, segment *g;* see section 4.1., 4.2., 4.3. and figures therein). However, the hydrological and lithological conditions might also have controlled the results in some parts, since these conditions vary regionally.

Moreover, the results of SL indices on the west-flowing streams show a similar pattern as the results of mountain front sinuosity, basin asymmetry and longitudinal profiles. The highest SL index values can be found in segment *d* of the MLF (Fig. 2), where the stream gradient and elevation differences are high. However, interesting SL index values – the sudden changes indicating young tectonic activity – can be found on the streams in segments *a* and *b* (for details see Štěpančíková et al., 2019) or segment *i* and particularly in the central part of the fault (segments *f* and *g*): "Pod Lobatínem", "U Kaolínky", "Za Rozhlednou" and "Malovický les streams". Those streams also have significantly offset valleys, which suggest horizontal movement along the MLF, which is in concordance with the kinematics proposed by Špičáková et al. (2000). In addition, the morphology of the very recent fault scarp, similar to segments *a* and *b* (where the neotectonic activity was proved by paleoseismic survey by Štěpančíková et al., 2019) in this area supports the hypothesis of quite young tectonic activity in this segment of the MLF.

In contrast, the of SL index values measured on the longer, east-flowing streams are not significant for any MLF segmentation. The peaks in the SL index, which would suggest the effect of vertical tectonic movements, can be found on some of them. The higher values of gradient and, therefore, also the SL index on the Mže River (around 15 km from the source) could be caused by the general uplift of the Český les mountains. The most significant peaks in the SL index values are, however, located downstream from the MLF crossing - Mže (40 km), Hamerský (30 km), Výrovský, Kosový, Úhlavka, Radbuza. Those can be interpreted as a result of uplifting of the whole block to the west from the MLF and therefore induced backwards incision, or – in the case of the Výrovský stream (peak at 12-15 km) – as a result of lithological change (granites vs. metapelites). The peak of values on the Radbuza River (80 km), which differs from the other streams, may be caused by lithological change or by the different uplift rate of a separated tectonic block. The remarkable peaks in SL index values on the lowest parts of the Kosový (36-39 km), Úhlavka (36 km) and Výrovský (20-22 km) streams can be explained as the result of an incision of the trunk stream (the Mže River), which led to the formation of knickpoints on tributaries, and was probably caused by the final (Plio-Pleistocene?) phase of the regional uplift (Fig. 10), suggested by relief character and sedimentation in the Cheb-Domažlice Graben. This situation further supports the hypothesis about the evolution of the local stream network (see section 5.2.).

The division into particular segments based on varying fault strike and geology is distinct and in strong correlation with the results of the morphometric methods applied, so it supports the hypothesis of variable tectonic activity along the MLF. It is proposed that segments *a, b, c, f, g* and *i* were the more active ones in recent history (Pleistocene – Holocene?). Unfortunately, only segments *a* and *b* have been previously studied by palaeoseismology or detailed geophysics so far (Procházková et al., 1998; Švancara et al., 2008; Fischer et al., 2012, Halpaap et al., 2017, Blecha et al., 2018; Štěpančíková et al., 2019). These studies agree on that the youngest tectonic activity occurred in this NW part of the MLF. Švancara et al. (2008) calculated the relative reactivation potential for faults in the area of western Bohemia. He suggested that the particular segments of the MLF with orientation from NNW-SSE to N-S are oriented favourably to reactivation, which are exactly the segments mentioned above. So recent tectonic activity along these segments is very probable.

5.2. Effect of the uneven uplift on the evolution of the stream network

The evaluation of longitudinal profiles as well the analysis of the SL indices of the streams flowing to the east toward the fault scarp is much more complex due to the varying hydrological situation and the evolution of the streams. The shapes of the profiles could be a hint to the regional terrain and river network evolution, but it is not the definitive final prove of the following proposal for stream network evolution.

Traditionally, anomalies in the longitudinal profiles of the main rivers in the Bohemian Massif were linked to climatically controlled changes of the erosion base-level. However, the profile anomalies in the area of the MLF could also have different causes (i.e., tectonic uplift, lithological changes). If the wave of the headward erosion has moved up the streams simultaneously from the trunk stream to its tributaries, the present location of knickpoints could be comparable (Bishop et al., 2005). However, the location of knickpoints on the trunk stream of the Mže River differ from their location on its tributaries. Therefore, their origin could be linked to tectonic activity. Moreover, the shorter tributaries of the Mže (Černošínský, Šárka, Veský, Lomský) that are not crossing the MLF, do not express any distinctive knickpoints. This suggests that they have been affected by the general uplift of the area of the Plaská pahorkatina hillyland and their steep profiles originated in the incision of the trunk stream - the Mže River (Fig. 9). Therefore, it is assumed that the different locations of the knickpoints along the streams (Kosový, Hamerský, Úhlavka, Výrovský, Mže) are caused by uneven uplift along the MLF, which might possibly have occurred in a few chronologically separated events. The tectonic activity of particular segments of the MLF - and thus the incision of streams - could have varied in time. In that case, incision through the fault slope by the particular streams and capturing the catchment to the west from the MLF could also have happened at different times. The traces of such a process can be seen in the present shape of the stream network (direction changes, stream capturing). A hypothesis of the subsequent evolution of the present-day morphology is presented here (see Fig. 14):

Stage **a)** might have taken place in the Pliocene: The Cheb-Domažlice Graben was an area of fluvial and fluviolacustrine sedimentation (dated by Teodoridis et al., 2017). The MLF scarp formed a barrier, so shallow lakes could have originated, however, drainage to the west was probably still possible by the wide, flat valleys of the predecessors of the present Mže River and Kosový stream.

Stage **b)** early Pliocene or late Pleistocene: The uplift along the MLF increases, gently around the current Úhlavka River and more intensively in the central part of the MLF. Due to incision caused by uplift, the Kosový stream and the Mže formed an antecedent valley. The area could also have been drained through the Úhlavka River (or its predecessor). Due to uplift, the upper parts of the Kosový, Hamerský and Úhlavka streams were diverted to the south and continued eastwards through the incised valleys.

Stage **c)** lower Pleistocene: The uplift along the MLF was continuing in segments *f* and *g* around Planá, the Mže River was further incising and developing its catchment within the Cheb-Domažlice Graben. The evolution of the Hamerský stream is not clear - it was either still going along the fault slope and not breaching it (Balatka and Sládek, 1962) or it may have begun to form its antecedent valley (preserved to the present). The Výrovský stream also breached the slope due to incision (though less intensive).

Stage **d)** middle Pleistocene until the Holocene: a strong final phase of uplift along the MLF in the area between Planá and Bor (segments *f* and *g*). The Mže River was incising intensively and creating its deep canyon through the Plaská pahorkatina hilly land. Due to this incision, knickpoints on the Mže and Kosový streams were created near their confluence. Also, the knickpoints on the Úhlavka and Výrovský streams originated as a reaction to the incision of the trunk stream. Finally, Sedlišťský stream was captured by the Mže River (previously it was connected to the upper part of the Výrovský stream; see Fig. 4, Fig. 8 and Fig. 14) and the Hamerský stream breached the fault slope due to strong incision or it may has further deepened its canyon. Also, the tributaries of the Výrovský stream underwent minor changes (sharp 90° bends to the west from the fault) due to the incision of the Výrovský stream (Fig. 14).

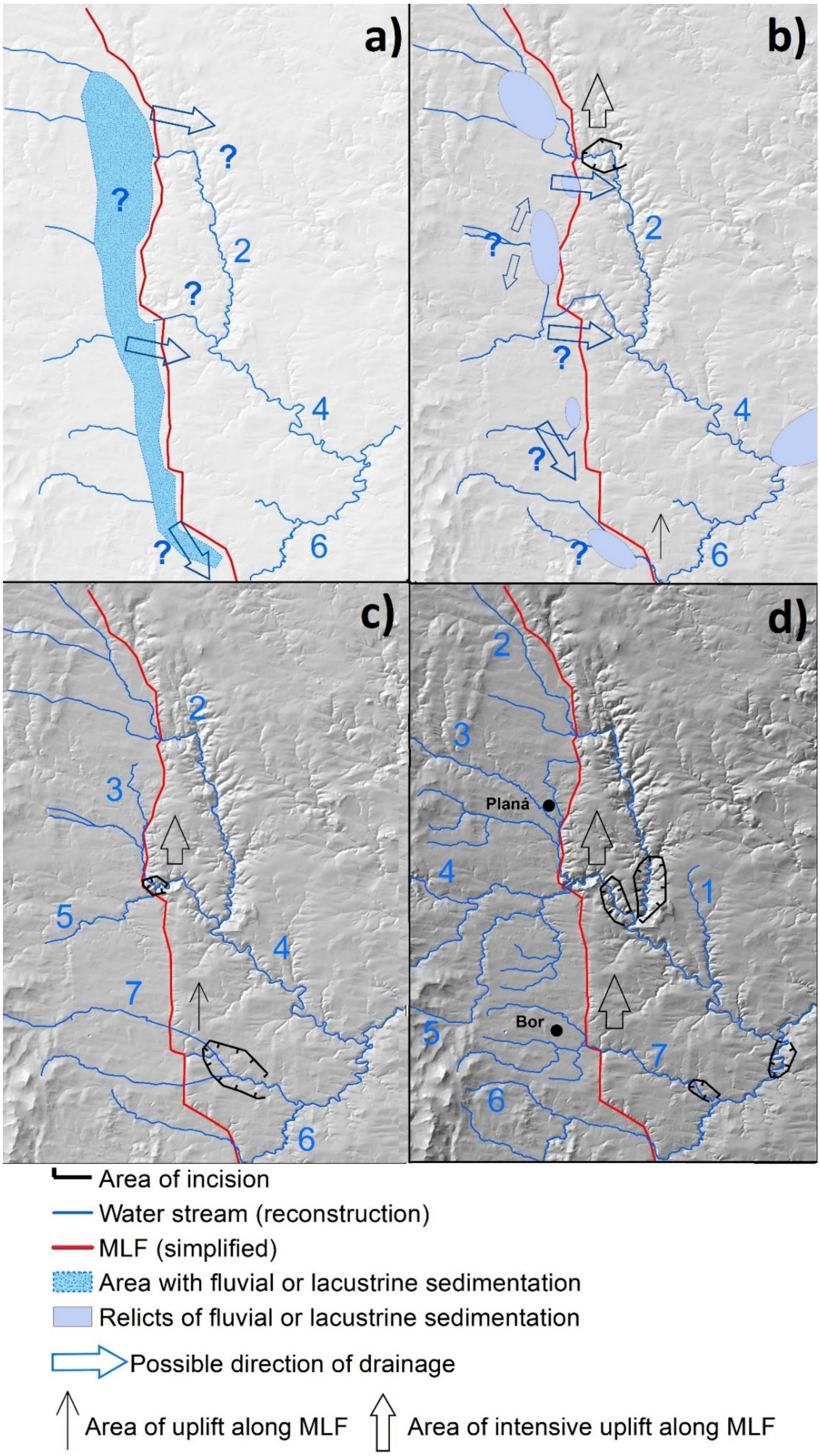


Fig. 14. Proposed evolution of the stream network. For a description of a particular stage (a, b, c, d) see text. Names of the present streams: 1 – Černošínský, 2 – Kosový, 3 – Hamerský, 4 – Mže, 5 – Sedlišťský, 6 – Úhlavka, 7 – Výrovský.

The possible timing of the above proposed events is only approximate due to a lack of dating. The fluviolacustrine sediments in the Cheb-Domažlice Graben have been palynologically dated to the Pliocene (Teodoridis et al., 2017). It is also possible to find two levels of river terraces along the Mže River (upstream from the MLF). The upper level, which follows almost the entire river, was morphostratigraphically set to "Günz" or "Pregünz". The lower level has been dated to "Riss" (Balatka and Sládek, 1962). This setting should be evaluated carefully, unfortunately more precise data are not available in the area. Based on the data, the present course of the Mže River through the fault slope of the MLF has existed at least since the lower Pleistocene, however it might have been older, draining the lakes in the Graben to the east. Based on these data, the stages are *a)* to the upper Pliocene, *b)* and *c)* to the lower Pleistocene and *d)* to the middle Pliocene (see Fig. 14). An important factor for the proposed order of the events is also the position and elevation of the depositional relicts of the Pliocene fluviolacustrine sediments (Teodoridis et al., 2017). The highest elevation known from the Cheb-Domažlice Graben is 560 m a.s.l. (near Mariánské Lázně). The elevation decreases towards the south: 480 m (Planá), 430 m (Úhlavka), 400 m (Horšovský Týn), see Fig. 2. This situation can be a sign of the proposed drainage towards S along the graben or towards SW by the predecessor of the Úhlavka River. Some of the deposit remnants were recorded to the east from the MLF. Some of them, closer to the fault (along the Mže River), are at a higher elevation than those in the Cheb-Domažlice graben (about 30 m height difference), which would suggest their uplift. Occurrences of deposits in the Plzeň basin (further to the east, near the mouth of the Mže River) are on the same level or lower, compared to the deposits in the Cheb-Domažlice Graben. They can be remnants of the Pliocene Mže River (or its predecessor), whose existence has been proven by Pliocene terraces in the Plzeň basin (Balatka and Sládek, 1962). This is in accordance with the proposed uplift (or tilt) of the Plaská pahorkatina hilly land and the gradual incision of the Mže River (and tributaries) during the Pleistocene. Future work focused to sediments dating would be desirable for a final clarification of the evolution of the local stream network and the tectonic movements along the MLF.

6. Conclusions

The combination of morphometric methods used in this study (mountain-front sinuosity, basin asymmetry, stream longitudinal profiles, SL index) appeared to be an useful way to evaluate tectonic activity along the 150 km long Mariánské Lázně fault (MLF) and to compare its variable intensity. The results show that the tectonic activity has not occurred along the whole structure at the same periods, rather, particular MLF segments were active in different periods with different intensity, which is supported by the concordance of the results from the several methods used. This segmented activity of the MLF leads to significant changes in the drainage pattern in the study area, including several stream captures. Based on the scarce dated fluvial deposits, a reconstruction of the river network was suggested as was the estimated timing of its evolution from the late Pliocene until the middle Pleistocene (possibly until the Holocene). The finding from Štěpančíková et al. (2019) that the youngest tectonic activity can be located in segments *a* and *b* around Nový Kostel in the northwest is in concordance with morphometric results of this study and similar signs of recent (Pleistocene – Holocene) tectonic activity have been recognised in the central part of the MLF: segments *f* and *g* (Planá-Bor) and in the southeast, segment *i* (Horšovský Týn). However, the final answer about the timing of tectonic activity should be proved by e.g. paleoseismological research and proper fluvial deposits dating.

Acknowledgements

The research was supported by the Grant Agency of the Czech Republic no. 21-29826S. The ideas were also evolved within project no. LTV20022 of the Ministry of Education, Youth and Sports. We gratefully acknowledge Richard R. H. Withers for English proof reading. We also wish to thank Jacek Szczygieł and an anonymous reviewer for their invaluable comments and suggestions, which significantly helped to improve the manuscript.

References

Adamová, M., Čurda, J., Lochmann, Z., Majer, V., Müller, V., Opletal, M., Pošmourný, K., Tomášek, M., Veselý, J. and Volšan, V.: 2001, Set of the geological and ecological special maps of natural resources 1:50 000, Geological map. Sheet 11-41 Mariánské Lázně. Český geologický ústav, (in Czech).

Badura, J., Zuchiewicz, W., Štěpančíková, P., Przybylski, B., Kontny, B. and Cacoń., S.: 2007, The Sudetic Marginal Fault: A young morphotectonic feature at the NE margin of the Bohemian Massif, Central Europe. Acta Geodyn. Geomater., 4, 4 (148), 7-29.

Balatka, B. and Kalvoda, J.: 2006, Geomorphological regionalization of the relief of Bohemia. Kartografia a.s., Praha, 79 pp., (in Czech).

Balatka, B., Kalvoda, J., Steklá, T. and Štěpančíková, P.: 2019, Morphostratigraphy of river terraces in the Eger valley (Czechia) focused on the Smrčiny Mountains, the Chebská pánev Basin and the Sokolovská pánev Basin. Acta Univ. Carol. Geogr., 54, 2, 240–259. DOI: 10.14712/23361980.2019.21

Balatka, B. and Sládek, J.: 1962, *River terraces in the Czech lands*. Nakladatelství československé akademie věd, Praha, 250 pp., (in Czech).

Bína, J. and Demek.: 2012, From lowlands to mountains: Geomorphological units of the Czech Republic. Academia, Praha, 343 pp., (in Czech).

Bishop, P., Hoey, T.B., Jansen, J.D. and Artza, I.L.: 2005, Knickpoint recession rate and catchment area: the case of uplifted rivers in Eastern Scotland. Earth Surf. Process Landf., 30, 6, 767–778. DOI: 10.1002/esp.1191

Blecha, V., Fischer, T., Tábořík, P., Vilhelm, J., Klanica, R., Valenta, J. and Štěpančíková, P.: 2018, Geophysical evidence of the Eastern Marginal Fault of the Cheb Basin (Czech Republic). Stud. Geophys. Geod., 62, 660-680. DOI: 10.1007/s11200-017-0452-9

Bräuer, K., Kämpf, H., Niedermann, S. and Strauch, G.: 2005, Evidence for ascending upper mantle-derived melt beneath the Cheb basin, central Europe. Geophys. Res. Lett., 32, 8, L08303. DOI: 10.1029/2004GL022205

Bull, W.B. and McFadden, L.D.: 1977, Tectonic geomorphology north and south of the Garlock Fault, California. In: Doehring, D.O., Ed., Geomorphology in Arid Regions: A Proceedings Volume of the 8th Annual Geomorphology Symposium, State University of New York, Binghamton, 23-24 September 1977, 115-138.

Bull, W.: 2007, Tectonic geomorphology of mountains: A new approach to paleoseismology. Blackwell Publishing, 306 pp. DOI: 10.1002/9780470692318

Burbank, D. and Anderson, R.: 2001, Tectonic geomorphology. Blackwell Science, 273 pp. DOI: 10.1002/9781444345063

Cháb, J., Breiter, K., Fatka, O., Hladil, J., Kalvoda, J., Šimůnek, Z., Štorch, P., Vašíček, Z., Zajíc, J. and Zapletal, J.: 2008, Outline of the Geology of the Bohemian Massif: the Basement Rocks and their Carboniferous and Permian Cover. Vydavatelství ČGS, Praha, 283 pp., (in Czech).

Chlupáč, I., Brzobohatý, R., Kovanda, J. and Stráník, Z.: 2002, Geological history of the Czech Republic. Academia Praha, Praha, 436 pp., (in Czech).

Česká geologická služba - Czech Geological Survey (ČGS): 2003, Geological map of the Czech Republic, 1: 500 000, CGS, Praha, (in Czech).

Český úřad zeměměřický a katastrální (ČUZK): 2017, Digital elevation model of the Czech Republic, 5th generation (DEM 5G). Český úřad zeměměřický a katastrální, Praha, (in Czech).

Čtyroký, J.: 1996, Evolution of the valley of the Ohře River in the Slavkovský Forest. Master thesis. Charles University, Faculty of Science, Prague, 150 pp., (in Czech).

Demek, J. and Czudek T.: 1957, Geomorphological conditions of the Jilmový Stream in the Teplá Highlands, Sborník ČSSZ, 62, 3, 193–205, (in Czech).

Fischer, T., Štěpančíková, P., Karousová, M., Tábořík, P., Flechsig, Ch. and Gaballah, M.: 2012, Imaging the Mariánské Lázně Fault (Czech Republic) by 3-D ground-penetrating radar and electric resistivity tomography. Stud. Geophys. Geod., 56, 1019-1036. DOI: 10.1007/s11200-012-0825-z

Fischer, T., Horálek, J., Hrubcová, P., Vavryčuk, V., Bräuer, K. and Kämpf, H.: 2014, Intra-continental earthquake swarms in West-Bohemia and Vogtland: a review. Tectonophysics, 611, 1-27. DOI: 10.1016/j.tecto.2013.11.001

Fischer, T., Matyska, C. and Heinicke, J.: 2017, Earthquake-enhanced permeability - evidence from carbon dioxide release following the ML 3.5 earthquake in West Bohemia. Earth Planet. Sci. Lett., 460, 60–67. DOI: 10.1016/j.epsl.2016.12.001

Gutierrez, M.: 2013, Geomorphology. London, CRC Press, 1014 pp.

Hack, J.T.: 1973, Stream-profile analysis and stream-gradient index. J. Res. U.S. Geol. Surv., 1, 4, 421-429.

Halpaap, F., Paschke, M. and Bleibinhaus, F.: 2017, Shallow reflection seismic evidence of tectonic activity in the Cheb Basin, NW Bohemia. Stud. Geophys. Geod., 62, 80-101. DOI: 10.1007/s11200-016-0386-7

Jakoubková, H., Horálek, J. and Fischer, T.: 2017, 2014 mainshock-aftershock activity versus earthquake swarms in West Bohemia, Czech Republic. Pure Appl. Geophys., 175,109–131. DOI: 10.1007/s00024-017-1679-7

J.E. Purkyně University in Ústí and Labem, Ministry of the Environment of the Czech Republic (JEPU and ME): 2014, Second Military Mapping Survey of Austrian Empire, 1: 28800, [online] accessible at: http//oldmaps.geolab.cz, [15/05/2021], Laboratoř geoinformatiky Fakulta životního prostředí Univerzity J.E. Purkyně, Ustí nad Labem, (in Czech).

Keller, E. and Pinter, N.: 2002, Active tectonics – Earthquakes, Uplift and Landscape. Prentice Hall, New Jersey, 250 pp.

Mahel, M., Kodym, O. and Malkovský, M.: 1984, Tectonic map of the Czechoslovakia, 1: 500 000. Geologický ústav Dionýza Štúra, Bratislava, (in Czech).

Military Geographic and Hydrometeorologic Office (MGHO) - Ministry of Defence of the Czech Republic + GEODIS Brno s.r.o., 2014., Historical aerial map of Czechoslovakia, 1:20000, [online] available at http//: kontaminace.cenia.cz, [15/05/2021] CENIA – Česká informační agentura životního prostředí, Praha, (in Czech).

Mlčoch, B. and Konopásek, J.: 2010, Pre-Late Carboniferous geology along the contact of the Saxothuringian and Teplá–Barrandian zones in the area covered by younger sediments and volcanics (western Bohemian Massif, Czech Republic). J. Geosci., 55, 81–94. DOI: 10.3190/jgeosci.068

Mlčoch B. and Skácelová Z.: 2009, Digital elevation model of the crystalline basement of the Cheb and Sokolov Basin areas (Western Bohemia, Central Europe). Z. Geol. Wiss., 37, 3, 145-152.

Müller, V., Burda, J., Dubec, O., Hrazdíra, P., Hrkal, Z., Jinochová, J., Lochmann, Z., Majer, V., Manová, M., Mlčoch, B., Rejchrt, M., Sáňka, V., Schovánek, P., Skácelová, D., Šalanský, K. and Šantrůček, P.: 1998, Legend to the set of geological and ecological special maps of natural resources, 1: 50 000. Sheets 11 - 13 Hazlov, 11 - 14 Cheb. Český geologický ústav, (in Czech).

Pešek, J.: 1972, Tertiary sediments in the central and western Bohemia. Sborník Západočeského muzea Příroda, 6, 56 pp., (in Czech).

Pitra P., Burg J.P. and Guiraud M.: 1999, Late Variscan strike-slip tectonics between the Tepla-Barrandian and Moldanubian terranes (Czech Bohemian Massif): petrostructural evidence. J. Geol. Soc. London, 156, 1003–1020. DOI: 10.1144/gsjgs.156.5.1003

Procházková, D. and Šimůnek, P.: 1999, Regional earthquake catalogue and focal regions in central Europe. Acta Montana IRSM AS ČR, Ser. A, 13 (111), Praha, 83 pp.

Seifert, A. and Straka, J.: 1998, Geological map, 1: 50 000, sheet 11-43 Bor. ČGS, Praha, (in Czech).

Sougnez, N. and Vanacker V.: 2011, The topographic signature of Quaternary tectonic uplift in the Ardennes massif (Western Europe). Hydrol. Earth Syst. Sci., 15, 1095–1107. DOI: 10.5194/hess-15-1095-2011

Špičáková, L., Uličný, D. and Koudelková, G.: 2000, Tectonosedimentary evolution of the Cheb Basin (NW Bohemia, Czech Republic) between the Late Oligocene and Pliocene: A preliminary note. Stud. Geophys. Geod., 44, 556–580. DOI: 10.1023/A:1021819802569

Štěpančíková, P., Stemberk, J., Vilímek, V. and Košťák, B.: 2008, Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic). Geomorphology, 102, 68-80. DOI: 10.1016/j.geomorph.2007.06.016

Štěpančíková, P., Fischer, T., Stemberk, J. (Jr.), Nováková, L., Hartvich, F. and Figueiredo, P.M.: 2019, Active tectonics in the Cheb Basin: youngest documented Holocene surface faulting in central Europe? Geomorphology, 327, 472-488. DOI: 10.1016/j.geomorph.2018.11.007

Švancara, J., Havíř, J. and Conrad, W.: 2008, Derived gravity field of the seismogenic upper crust of SE Germany and West Bohemia and its comparison with seismicity. Stud. Geophys. Geod., 52, 567-588. DOI: 10.1007/s11200-008-0038-7

Teodoridis, V., Bruch, A.A., Martinetto, E., Vassio, E., Kvaček, Z. and Stuchlik, L.: 2017, Plio-Pleistocene floras of the Vildštejn Formation in the Cheb Basin, Czech Republic – a review and a new paleoenvironmental evaluation. Palaeogeogr. Palaeoclimatol. Palaeoecol., 467, 166-190. DOI: 10.1016/j.palaeo.2015.09.038

Ulrych, J., Dostal, J., Adamovič, J., Jelínek, E., Špaček, P., Hegner, E. and Balogh, K.: 2011, Recurrent Cenozoic volcanic activity in the Bohemian Massif (Czech Republic). Lithos, 123,133–144. DOI:10.1016/j.lithos.2010.12.008

Ulrych, J., Ackerman, L., Balogh, K., Hegner, E., Jelínek, E., Pécskay, Z. and Foltýnová, R.: 2013,Plio-Pleistocene basanitic and melilititic series of the Bohemian Massif: K-Ar ages, major/trace element and Sr–Nd isotopic data. Chem. Erde-Geochem., 73, 429–450. DOI: 10.1016/j.chemer.2013.02.001

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1978a, Legend to the base geological map of Czechoslovakia 1:25 000, sheet 21-214 Mířkov. Ústřední ústav geologický, Praha, (in Czech).

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1978b. Legend to the base geological map of Czechoslovakia ČSSR 1:25 000, sheet 21-232 Horšovský Týn. Ústřední ústav geologický, Praha, (in Czech)

Vejnar, Z., Šalanský, K. and Skrbek, J.: 1980. Legend to the base geological map of Czechoslovakia ČSSR 1:25 000, sheet 21-212 Staré Sedlo. Ústřední ústav geologický, Praha, (in Czech).

Weinlich, F.H., Bräuer, K., Kämpf, H., Strauch, G., Tesar, J. and Weise, S.M.: 1999, An active subcontinental mantle volatile system in the western Eger rift, central Europe: gas flux,isotopic (He, C, and N) and compositional fingerprints. Geochim. Cosmochim. Acta,63, 21, 3653–3671. DOI: 10.1016/S0016-7037(99)00187-8

Willet., S.D. (ed.): 2006, Tectonics, climate and landscape evolution. The Geological Society of America, Special paper 398, 150 pp.

Wheeler, D. A.: 1979, The overall shape of longitudinal profiles of streams. In A.F. Pitty (ed.), Geographical Approaches to Fluvial Processes, Norwich GeoAbstracts, 241-260.

Zoubek, V.: 1963, Legend to the base geological map of Czechoslovakia 1: 200 000, sheet M-33-XIII Karlovy Vary, ÚÚG ČSAV, Praha, 290 pp., (in Czech).

Chapter 2: Neogene-Quaternary response of the Novohradské hory Mts. (Czech Republic) fluvial systems to tectonics – morphotectonic, stream-length index and field structural analyses.

by Jan Flašar, Karel Martínek, Kryštof Verner and Radka Kalinová

a manuscript submitted in the *International Journal of Earth Sciences*

Abstract

In intraplate setting, using conventional methods is limited when studying active tectonics due to indistinct expressions of tectonics in terrain morphology. To study the effects of Alpine collision in the terrain evolution of the Bohemian Massif, the Novohradské hory Mts. were selected for notable changes in river geometry, well-known bedrock lithology and structural geology. Previous authors accept that some of the local faults were reactivated in the Cenozoic. However, the localization, scale and dating of tectonic processes is still poorly understood. This study focuses on bringing new morphotectonic and fluvial geomorphology data combined with field structural mapping to better understand the evolution of this relatively stable intraplate area. Prominent linear indications revealed by morphotectonic analysis were validated by geological maps, airborne geophysics (magnetometry, gravimetry, radiometry) and a field structural survey to indicate possible Neogene-Quaternary reactivation of these structures. Stream gradient and stream-gradient length (SL) index were analysed along dozens of streams. Sudden changes of SL index values located the places with young tectonic movements. The influence of lithology, hydrology and anthropogenic activities were carefully evaluated. Assuming a reactivation of faults under the recent stress-field (S_{Hmax}=146°) a kinematic model is proposed. When S_{Hmax} is horizontal in the ~NNW-SSE direction, the ~NE(NNE)-SW(SSW) faults would reveal a sinistral strike-slip to reverse oblique-slip movement. Subvertical ~NW(WNW)-SE(ESE) faults could be reactivated in a dextral strike-slip regime or as reverse oblique-slip faults.

Keywords: neotectonics, fluvial systems, SL index, morphotectonic, Bohemian Massif

1. Introduction

The Bohemian Massif is part of the stable European platform in the northern foreland of the Alpine–Carpathian fold–thrust belt, which has traditionally (Kopecký 1970) been regarded as a tectonically stable intracontinental region. This view was based on the low level of historical seismicity (ACORN 2004; Lenhardt et al. 2007) in most parts of the region and GPS studies considering the massif as part of Stable Europe (Bus et al. 2009). However, it is generally believed, that some areas – particularly the bordering mountains – went through massive tectonic uplift in the Cenozoic and older fault systems were rejuvenated (Kopecký and Vyskočil 1969; Kopecký 1970; Chábera 1982; Coubal et al. 2015; Štěpančíková et al. 2019).

Post-Variscan tectonics in this crystalline basement complex were thought to have been restricted to the reactivation of Paleozoic fault systems (e.g. Donau (NW-SE), Elbe (NW-SE), Blanice-Rodl (NNE-SSW) or Ohře fault system (WSW-ENE)) (Brandmayr et al. 1995, 1997) in Cretaceous and Neogene times due to compression in the foreland of the Carpathian–East-Alpine orogeny (Ziegler and Dèzes 2007). There are many studies identifying significant differential tectonic movements within the Bohemian Massif (Vyskočil 1969; Přibyl 1995; Schenk et al. 2001), by recent geomorphological and paleoseismological analyses of reactivated Paleozoic faults (Badura et al. 2007; Štěpančíková et al. 2008, Štěpančíková et al. 2019) and by regional geomorphological and geodetic studies indicating the ongoing large-scale uplift of the Bohemian Massif as a whole (Kopecký and Vyskočil 1969; Legrain et al. 2014).

The working hypothesis suggests – in accordance with the above studies and further with Tyráček et al. (2004), Cloething et al. (2006), and Štěpančíková et al. (2019) - that the tectonic activity was present even until the late Quaternary in the Bohemian Massif. The area of interest of this study is situated in the southern part of the Bohemian Massif, in Novohradské hory Mountains and their foothills (Fig. 1a,b). Older studies (Chábera 1982) mentioned that the tectonic activity along local faults was very significant during the formation of the present relief. In addition, it is believed, that the tectonic movements were very rapid and happened in the youngest part of the Tertiary and probably in the Quaternary (Chábera 1982; Kopecký 1983). Kopecký and Vyskočil (1969) and Vyskočil (1973) suggested the ongoing vertical movement on the bounding faults of the Budějovice Basin, not far from the Novohradské hory Mts. Study of Popotnig et al. (2013) led to similar conclusions, using morphometric analyses. However, similar studies, as well as the exact localization, evaluation and timing of the tectonic movements, are still missing in the Novohradské hory Mts.

The goal of this study is *a)* to test the influence of local tectonic movements on changes in terrain morphology and river geometry and *b)* find the indications of recent/Quaternary/Neogene movement on local faults and c) to test the suitability of the various numerical geoinformation methods, such as calculations of SL index and hypsometric index, for solving such issues.

Morphotectonic analysis based on a digital elevation model, as well as data from geological maps and from field structural mapping, were used in this study to obtain possible locations of active faults. The probability of these faults being active in Quaternary was tested by various geoinformation methods, including measuring the stream gradient profile, stream-length index (SL index) or hypsometric index

(Hack 1973; Willgoose and Hancock 1998). The outcomes of these analyses were combined together in order to indicate the localities, where the Quaternary and perhaps recent tectonic movements were highly probable. This approach, integrating remote sensing, geomorphology, Quaternary geology, tectonic geomorphology and geoinformation techniques, has rarely been used in the Bohemian Massif and is very promising with regard to solving questions about the Quaternary tectonic development of the Novohradské hory Mountains and other areas with weak tectonic activity where conventional geomorphic parameters may not indicate tectonic uplifts. An indication of active faults combined with the knowledge of present-day stress orientation in the study area enabled a kinematic model to be put forward to explain the observed geomorphology and stream gradient changes.

2. Geology, geomorphology and hydrology of the study area

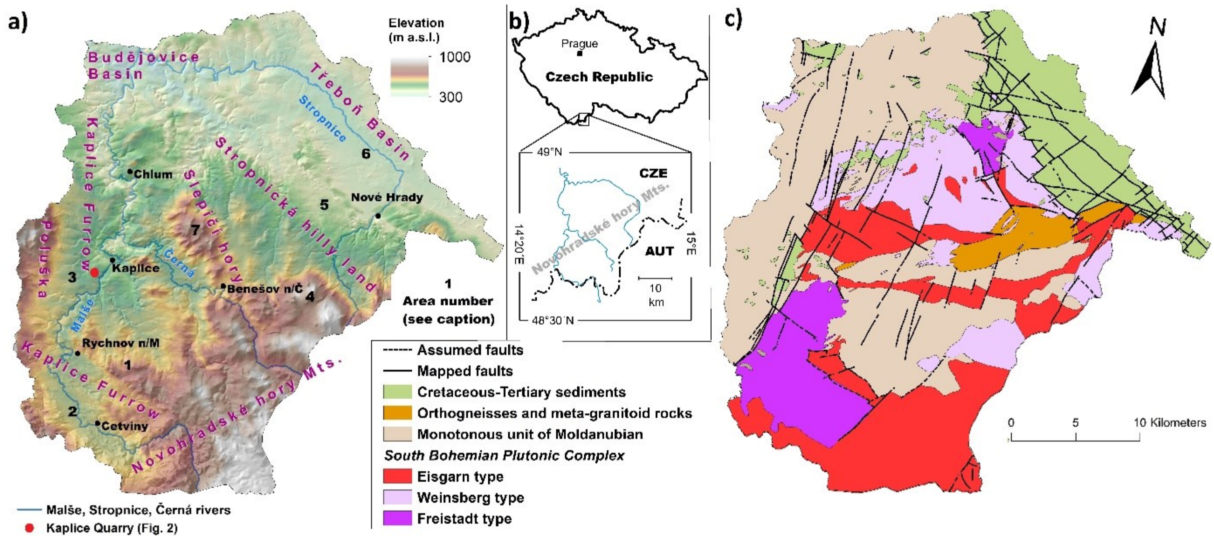


Fig.1: (a) Geomorphological map of the study area with linear indications and the areas discussed in detail in text, 1 – Bukovský hřbet Ridge, 2,3 – Kaplice Furrow, 4 – Novohradské hory Mts., 5 – Stropnická vrchovina Highlands, 6 – Třeboň Basin, 7 – Slepičí hory Mts.; (b) Location of the study area within the Czech Republic; (c) Simplified geological map of the study area - catchment of the Malše River. Mapped faults (solid line) and assumed faults (dashed line) adopted from geological maps (Mahel et al. 1984; Slabý and Holásek 1992a, Slabý and Holásek, 1992b; Vrána and Holásek 1992; Vrána and Novák 1993).

2.1. Geomorphological setting

The study area, defined by a catchment of the Malše River, is quite variable in its geological and geomorphological structure. The ridges of the Novohradské hory Mountains occupy the largest part of the study area. This area is quite rugged, and it was primarily shaped by fluvial and periglacial processes. However, the traces of recent tectonic activity are still visible in some places of the local relief (Fig. 1a). The altitude of the terrain varies between 500 m (valley of the Malše River) to 1100 m a. s. l. An elongated depression – Kaplice Furrow -, lies in the western part of the study area. This area is bounded by tectonic faults and it generally has a gentler relief than the surrounding highlands. The north-eastern part of the area is occupied by the flat terrain of the Třeboň Basin. It is also tectonically bordered, particularly on its western and southwestern edge, where it is adjacent to the Novohradské hory Mountains (Balatka and Kalvoda 2006).

2.2. Hydrological setting

The Malše River and its tributaries drain the majority of the selected area. However, a small part lies in the catchment of the Lužnice River (mainly on the Austrian side of the Novohradské hory Mts.) and some areas have small streams draining southwards, to the basin of the Danube River. The Malše River is the longest watercourse in the study area; it is 101 km long from source to its mouth into the Vltava River and it has a catchment area of 971 km^2 (Balatka and Sládek 1962; Vlček 1984). This river is atypical for its unusual style - a broad, flat valley is present in the upper part of the stream and a narrow, V-shaped valley is more frequent in the lower part of the stream. The Malše River is particularly important for the study due to the sudden changes of gradient and river style close to the tectonic faults in its upper part. The general orientation of some parts of the Malše River (Rychnov-Kaplice) is parallel with the fault system of the Kaplice Furrow (Fig. 1). It could be connected with the vertical movements in the Kaplice Furrow, or with the orientation of the original free-meandering river at the bottom of the furrow.

The Stropnice River is the longest tributary of the Malše River and it drains the eastern part of the study area. The middle part of this stream crosses or sometimes follows the tectonic border between the Moldanubian rocks of the Novohradské hory Mountains and the Cretaceous sediments of the Třeboň Basin. Also, the gradient conditions, fluvial styles and relief types vary quite often along this stream and it is possible to make a valuable comparison to the Malše River. The Černá River, drains the central part of the study area and is a typical mountain stream with a high gradient and a narrow, deep valley (Balatka and Sládek 1962; Vlček 1984). This stream crosses several tectonic and lithological borders, therefore it is essential for this study (Fig. 1).

2.3. Geological and tectonic setting

The Novohradské Hory area (Fig. 1c) comprises of (a) migmatites and migmatized paragneisses of the Monotonous Group belonging to the Moldanubian Zone, referred as the Variscan orogenic root domain and post-collisional granitoids of the Moldanubian Batholith (e.g. Franke 2000; Schulmann et al. 2009; Žák et al. 2014). These metamorphic rocks underwent several geodynamic events during the Variscan Orogeny (Stampfli and Borel 2002; Schulmann et al. 2009 and references therein). The oldest episode was characterized by ca. 360 to 346 Ma continental collision and synchronous HP-MP/MT-LT metamorphism, followed by rapid exhumation and the partial melting of deep-seated rocks (ca. 345 to 335 Ma) and post-collisional HT metamorphic overprint (ca. 334 to 320 Ma) overlapping with emplacement of numerous post-collisional granitoids of the Moldanubian Batholith (e.g. Weinsberg, Eisgarn and Freistadt types) at ca. 330 to 305 Ma (for details see Holub et al. 1997; Janousek et al. 2010; Žák et al. 2005; Schulmann et al. 2009; Žák et al. 2014). The later stages of Variscan orogeny were associated with wrench tectonics along ductile to brittle-ductile WNW(NW)-ESE(SE) and NNE(NE)-SSV(SV) shear or fault zones (e.g. Pfahl, Danube and Kaplice-Rodl shear zones; Brandmayr 1995; Pitra et al. 1999; Edel et al. 2003). Post-Variscan tectonic phases during the Permian to Oligocene related to polyphase reactivation of regional shear / fault zones in various kinematic pattern, uplift, erosion and origin of the land surface topography (Fig. 1c).

The orientation lithological boundaries of the rock lithologies and units are defined by a regional metamorphic foliation or by intrusive contacts of granitoid bodies, partly modified by younger ~NNE(NE)-SSW(SW) or NW(WNW)-SE(ESE) trending faults. In the metamorphic rocks, the relatively older compositional banding dipping steeply to moderately to N(NNE) were heterogeneously reworked to flat-lying foliation. Granites predominantly form several steep, predominantly ca. E–W trending sheets cropping out in the central part of the studied area and several larger intrusions (plutons) in southeastern part (Fig. 1c). A relatively older margin-parallel magmatic foliation (defined by the shape-preferred orientation of K-feldspar phenocrysts and mafic minerals) was identified. This foliation dips steeply and strikes ~E–W to ~WNW–ESE and is associated with a magmatic lineation plunging to the ~ENE to ~NE. Higher up within the sheets, this magmatic fabric becomes pervasively overprinted by a high-temperature solid-state fabric, characterized by subhorizontal foliation and WSW–ENE trending lineation. Furthermore, studied rocks was affected by polyphase, late-Variscan to post-Variscan brittle-ductile to brittle ~NW(NNW)–SE(ESE) and NE(NNE)–SW(SSW) trending shear / faults zones (e.g. Brandmayr et al. 1995; Büttner 2007; Siebel et al. 2008; Verner et al. 2009; Pitra et al. 1999). These structures have been heterogeneously reactivated in the post-Variscan era.

In the studied area, faults and shear joints reveal two principal orientational maxima evenly distributed in granites and metamorphic rocks. Predominant faults dip steeply to the WNW or ESE bearing fault lineations (slickensides) which plunge gently to NNE or SSW (Fig. 2a). These structures also contain a mineral infill composed of quartz, chlorite and Fe-oxides (up to 1 cm). Kinematic indicators here show a prevailing left-lateral and subordinate right-lateral sense of movement parallel to the fault lineation. Subordinate NW-SE trending faults (Fig. 2b) dip steeply to moderately to the NE bearing two generations of fault lineations. A relatively older generation reveals mostly subhorizontal lineations with evidence of right-lateral shearing. Younger reactivation was mainly associated with normal movement. Extensional joints are mostly subvertical and largely lack mineral infill. Two significant sets of orthogonal extensional joints were identified evenly in all lithologies. The predominant trend in the orientation of subvertical extensional joints is WNW–ESE with an average frequency ~70 centimeters. A subordinate set of extensional joints trending NNE–SSW reveal an average frequency of ~110 centimeters. However, these extension joints reveal gentle variability in their orientation and intensity across the studied area. In the northern part ~N–S trending joints form the predominant brittle anisotropy of the rocks. In contrast, ~NNE–SSW trending joints form the most distinctive brittle anisotropy of rocks in the central and western part of the area. In the southern part approximately equal ~E–W and ~N–S trending joints were identified.

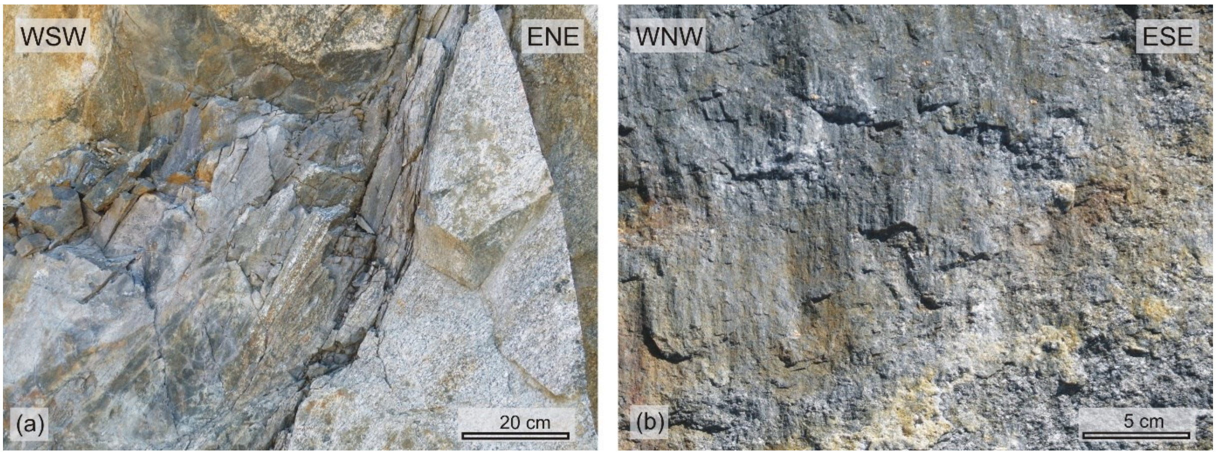


Fig. 2. Field photographs of regional brittle structures (Kaplice Quarry): (a) Fault plane dipping steeply to the WNW associated with fault lineations (slickensides) plunging gently to SSW (Kaplice Quarry); (b) Fault plane dipping steeply to the NE bearing evidence of younger reactivation in a normal kinematic pattern.

The Třeboň Basin is filled with Cretaceous and Tertiary clastic sediments of lacustrine and fluvial origin. The Cretaceous rocks are represented mostly by the sandstones and claystones of the Klikov Formation; clays and sands of Mydlovary Formation are typical for the Tertiary period (Chlupáč et al. 2002, Pešek 2010). There are also local deposits of Neogene and Pleistocene lacustrine and fluvial sediments in the area of the Kaplice Furrow outside of the Třeboň Basin (Bezvoda et al. 1983). These deposits are located in the flat terrain of the Kaplice Furrow floor and they are probably remnants of shallow lakes and meandering water streams, dated to the younger Pliocene (Březinová et al. 1965). These sediments occur roughly 50 m above the present flood plain of the Malše River. It is very probable, that tectonic movements, which led to the partial uplift of the terrain, the incision of the Malše River and the formation of the deep river valley, is younger than those late Pliocene deposits.

It is generally believed that the gentle relief of most of the Bohemian Massif was formed during the erosive phase following the Variscan orogeny. However, this type of relief was uplifted as a result of increased radial tectonic pressure induced by the development of the nearby Alpine system and also consequently formed, in particular, by fluvial erosion (Chábera et al. 1985; Ziegler and Dèzes 2007; Hartvich and Valenta 2013). Older studies (Chábera 1982; Kopecký 1983) suggest that these tectonic movements and deformations were mostly ductile and complicated systems of anticlines and synclines were created. Modern studies from the Bohemian Massif (Štěpančiková et al. 2008; Coubal et al. 2015; Štěpančíková et al. 2019) prefer the brittle tectonic models with movements along tectonic faults. However, the character of the tectonic deformation as well as the proper dating of these processes hasn't been satisfactorily cleared yet. Studies focused on the neotectonic in the area of the Novohradské hory Mts. have yet to be made, but some work was done in the neighboring areas of the Šumava Mts. (Hartvich and Valenta 2013) or the Budějovice Basin (Popotnig et al. 2013). These works suggest the reactivation of Variscan faults in the late Cenozoic or Quaternary.

3. Data and methods

3.1. Data

The basic topographic information for the morphotectonic analysis and analyses of the SL index and hypsometric index was obtained from the digital elevation model (DEM), which was based on LiDAR remote sensing (Digitální model reliéfu České republiky 4. generace/Digital Terrain Model of the Czech Republic of the 4th generation (DEM 4G)), vertical resolution 1 m (ČÚZK, 2017). The information about lithology and tectonic structure was obtained from basic geological maps of the area (Mahel et al. 1984; Slabý and Holásek 1992a; Slabý and Holásek 1992b; Vrána and Holásek 1992; Vrána and Novák 1993). The coverage of adopted tectonic data is rather inhomogeneous, due to variable geology (basin infill vs. crystalline rocks), the uneven distribution of previous geological studies and the area's remoteness. Therefore, remote sensing based morphotectonic analyses were done in the study area to complement the tectonic data where needed. Airborne geophysical data - gravimetry, radiometry, magnetometry (CGS 2015), were used for further complement and validate the morphotectonic analysis. Historical sources were used for repairing some faults in the topographic maps or for avoiding the anthropogenic influence on water streams. The historical maps (UJEP and MŽP 2014) and historical aerial photographs (VGHMÚř 2014) were used for these adjustments. Finally, a number of field survey measurements, as well as brittle tectonics data were used for validating the results of the morphotectonic analysis.

3.2. Morphotectonic analysis

An important step in the study was to localize the faults and other tectonic structures, such as the main fracture zones or shear zones. The goal of the analysis was to interpret a number of linear indications, which could represent tectonic structures. The results of the analysis were validated by a field survey aimed at the structural geology and brittle tectonic deformations. Data for the tectonic analysis were obtained from several independent sources: a) geological and tectonic maps of the study area (Mahel et al. 1984; Slabý and Holásek, 1992a; Slabý & Holásek 1992b; Vrána and Holásek 1992; Vrána and Novák 1993) b) airborne geophysical data (gravimetric, radiometric, magnetic survey) (CGS 2015) and c) two methods of morphotectonic analysis made from the digital elevation model. In order to obtain the best results, two separated methods for extracting the tectonic structures from hillshaded reliefs were used. 1) the simple visual interpretation method and 2) the semi-automatic method based on Jordan et al. (2005) and Kopačková et al. (2011), who also used her method in the Bohemian Massif. Method of Kopačková et al. (2011) was originally developed for extracting the lineaments from radar and Landsat data. However, the initial part of extracting can be also used for DEM processing. So, an attempt was made to apply Kopačková´s method to this study in order to obtain more precise results from DEM and to have an opportunity to compare it with the results from the visual extraction to obtain the best outcome. Both visual and semi-automatic methods were applied to four illumination directions of the hillshaded relief (0°, 45°, 90° and 315°) – Fig. 4a.

All of these results were integrated in the workspace of ArcGIS software focusing on areas, where two or more linear indications interpreted from different datasets were conforming (see Fig. 5). Different weights were assigned to the results of particular methods (Tab. 1). The methods with deep reach (gravimetry) or geographical prominence (long linear indications) or proved by field survey (faults from geological maps) were assigned a higher weight.

Table 1. Overview of methods used for linear indications evaluation with assigned weights used in this study.

Data and methods	weight
Morphotectonic analysis (semi-automatic method)	1
Morphotectonic analysis (manual method) – short linear indications	1
Morphotectonic analysis (manual method) – long (more than 5 km) linear	2
Airborne Geophysics – magnetic survey	1
Airborne Geophysics - gravimetry	2

Only those linear indications, where the sum of the weights was equal or higher than 2, were interpreted as important features of possible tectonic origin and used for the subsequent study (e.g. comparing with the results of the field survey), and the term 'tectonic linear indication' is used in the succeeding text (Fig. 5). The results of radiometry were removed from the evaluation as its results show no concordance with any other method, therefore this method was not used and nor is it mentioned in Tab. 1

It is very important to compare the results of several independent methods to avoid misinterpretation of possible tectonic features. Some of the extracted structures were eliminated due to their nontectonic origin (e. g. morphologically distinctive lithological boundaries) after comparison with a geological and tectonic map (Mahel et al. 1984; Slabý and Holásek 1992a; Slabý and Holásek, 1992b; Vrána and Holásek 1992; Vrána and Novák 1993).

3.3. Stream-length (SL) index

Stream-length (SL) index is a simple, but very strong tool to evaluate the influence of tectonics on the geometry and fluvial style of river systems. It was first used by Hack (1973) but the main progress in this method has been done recently, due to the wider usage of modern remote sensing methods and geographical information systems. The SL index can be calculated by the equation

$$SL=(\Delta H/\Delta L)Ldm$$

where $(\Delta H/\Delta L)$ means the stream gradient and Ldm means the length of stream reach between stream source and the middle of the measured part (Fig. 3). The values of SL index react very sensitively to gradient changes in the stream, including lithological, tectonic, hydrological and even anthropogenic influences. The anomalous (usually higher) values of SL indexes and particularly sudden changes of the index values indicate changes in the stream gradient. The origin of these changes can be evaluated with the help of other sources or analyses (e.g. geological maps or morphotectonic analysis). The presence of the morphologically prominent tectonic linear indications or even documented tectonic faults in those places with SL index anomalies can indicate the influence of tectonic movements on stream gradient with a high probability. However, the sensitivity of SL index can be also a disadvantage – the peaks of the SL index curve are very sharp and local maxima can follow local minima very suddenly. It can be useful to use some statistical methods to obtain robust results. Being interested in larger area and its possible tectonic activity, it its very useful to obtain SL values from several neighboring streams and make a grid (Font et al. 2010). Some statistical methods, like IDW or Kriging, are necessary for interpolating values.

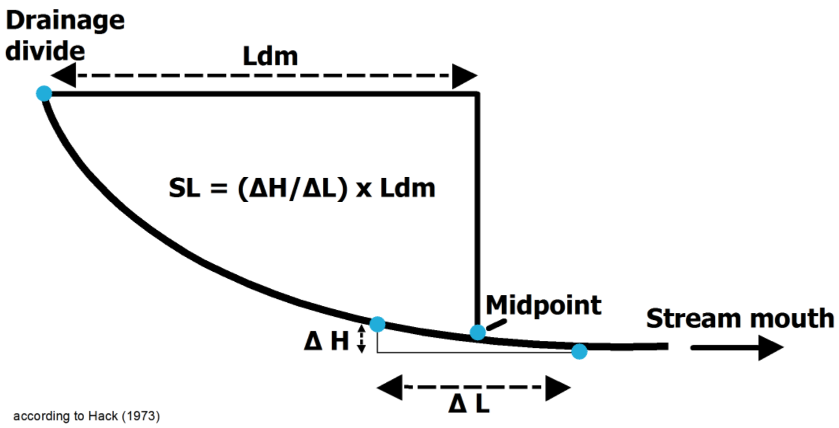


Fig. 3: Calculation of SL index (according to Hack 1973)

The digital elevation model (DEM), based on based on LiDAR remote sensing), was used in this study as an elevation data source (see section 3.1. for details).

The selected streams were divided into 100 m long reaches, where the SL index was calculated. The result was about 1800 values of SL indexes in the study area. It was necessary to repair some values in those places, which were seriously influenced by anthropogenic activities (millraces, dams, weirs etc.). The historical maps and historical aerial photographs (see section 3.a.) were used for these adjustments.

Values of SL index were represented by individual points along the streams and the Kriging method was used for interpolating values between those calculated points. The Kriging was used via the Statistic Analyst extension of the ArcGIS software, and its parameters were optimized to obtain the best representation of the studied values. The spherical Kriging was used, with values of *9.14* for partial sill, *5.03* for range, and *100* for lag.

3.4. Hypsometric index

The hypsometric index (Scheidegger 1987), or Hypsometric Integral or Elevation/Relief Ratio (Wood and Snell 1960; Pike and Wilson 1971) is a value, which describes the relationship between the mean and maximum/minimum elevation of the catchment area. It is very useful for comparing several basins (Willgoose and Hancock 1998). This index can help to evaluate the effects of denudation, tectonic uplift and relief maturity in the selected basin. It can be a suitable complement to the SL index, because the hypsometric index describes the characteristics of the whole larger area of a river catchment and not only the character of the water stream. According to (Cheng et al. 2012), values of hypsometric index below 0.3 represent a mature and tectonically stable relief, while values over 0.6 usually represent young, unstable and uplifting catchments. Willgoose and Hancock (1998) put this border at 0.5. However, one must be very careful, when using this hypsometric index, because various basins formed by various processes (geological, tectonic, climatic etc.) can have very similar or identical HI index values.

The hypsometric index for a basin or simply for the study area is calculated using:

$$HI = (E_{mean} – E_{min}) / (E_{max} – E_{min})$$

Where E_{mean} represents the *mean elevation* of a basin, E_{min} represents the *minimum elevation* of a basin (outlet) and E_{max} represents the *maximum elevation* of a basin (Pike and Wilson 1971). In this study, a HI index combined with the SL index was used. It could be used as proof of an SL index analysis and to select the areas, where the SL index is possibly influenced by tectonics. For gaining the elevation data, the same DEM was used as that for calculating the SL index (see section 3.c.). The distribution of river catchments created by the VÚV TGM (2016) was used, which often divides the catchments of larger streams into several smaller areas.

3.5. Field structural geology

Brittle structures (faults, shear and extensional joints) were measured at 119 rock outcrops through the majority of the study area and in total 400 structures were identified. The strike (trend) of brittle structure was the most important value for the subsequent comparison with the results from the remote sensing methods. The results from the field survey as well as the results of the remote sensing methods were represented by rose diagrams (Fig. 7).

The archive of seismic events (IPE 2014) in the area was studied in order to get some proof of active tectonic movements. It was planned to get a map of the hypocenters of seismic events and to compare it with the results of the morphotectonic analyses. However, it was found out that the area of the Novohradské hory is a tectonically stable region, at least in the most recent part of the Holocene, when instrumental seismic measurement was available (1900-2015). Only one hypocenter from a weak seismic event (2.7 Mag.) from the year 2001 was found near Rychnov nad Malší, and it could probably be connected with tectonic activity on the prominent fault north of the village.

4. Results

4.1. Morphotectonic analysis and evaluation of airborne geophysical data

During morphotectonic analysis, several very promising lineaments of probable tectonic origin were localized. However, in the study area, there are many tectonic faults (located by conventional geological mapping), which are not morphologically distinct and - on the other hand - there are morphologically noticeable linear geomorphological features, which have no documented tectonic origin so far. Often, the mapped tectonic faults continue as linear indications in the study area. For the subsequent survey, the focus was on those areas, where linear indications were located by analyses of the DEM and their presence was proved by at least one other method (see section 3.b., Fig. 4a, b).

Among the independent methods, the airborne gravimetry survey was the most reliable one, as in it can detect significant and deeply founded tectonic structures (Sedlák et al., 2011). The whole area of interest belongs to the negative field of the Bouguer anomalies ranging from –60 to –30 mGal (Fig. 4b). The most significant relatively negative anomalies can be found to the N of Nové Hrady, to the Třeboň Basin; and in the S of the study area around Cetviny (Fig. 1b). The relatively positive anomalies can be found in the E of the study area and in the centre, around Benešov n/Č. Both of these anomalies are connected with the occurrence of metamorphic rocks and relatively high altitudes (Fig. 5). The remarkable gradient between relatively high and low values of the Bouguer anomalies can be found especially between Rychnov n/M, Kaplice and Chlum, where a significant tectonic structure is probably located. The parallel situation can be found to the east from Rychnov n/M or in the surroundings of Nové Hrady. All of these steep gradients were interpreted as tectonic structures with remarkable geomorphological manifestation, however, some of them also represent the lithological boundaries (most of them of tectonic origin, Fig. 5).

One of the most distinct linear indications lies to the north from Rychnov nad Malší (Fig. 5) and it is partially documented as a fault (Fig. 1c). This structure can be followed for 15 km, where it is visible in the terrain, but the fault itself is probably much longer. It has a WNW-ESE orientation, which is typical for this part of the study area. The fault is very prominent, because it separates two very different terrain styles: To the south of the fault, there is the very gentle landscape of the Kaplice Furrow (Fig. 5, Fig. 1a) while a more rugged and elevated terrain occurs to the north. In addition, the faults bounding the Třeboň Basin (WNW-ESE and WSW-ENE orientation) near Nové Hrady are very distinct. The major bounding fault of the Budějovice Basin (NNE-SSW orientation) near the confluence of Malše and Stropnice rivers is partially visible, but most of its length lies out of the study area. There is a major fault system associated with the Kaplice Furrow in the western part of the study area. This tectonic structure is very deep and prominent and clearly visible by a gravimetry survey (Fig. 4b). However, the terrain morphology of this fault system is not very distinctive. Several parts of the Malše River valley are situated along this fault system (e.g. between Rychnov nad Malší and Chlum), but the typical straight parts of river valleys following the faults are usually missing here.

Very promising results were also obtained from the central part of the study area, where a fault of WNW-ESE orientation is located between Kaplice and Benešov nad Černou and there are also several faults of a NE-SW orientation east of Benešov (Fig. 5, Fig. 1c).

The field survey and brittle tectonic measurement (Fig 2a, 2b) were used for proving the results of morphotectonic analysis. To give a better comparison, rose diagrams were used as a representation of the direction values obtained by different methods (Fig. 7). It is assumed that the longer linear indices more probably represent a tectonic fault than the shorter ones. So, the rose diagrams are weighted by the tectonic indication length (each tectonic indication was multiplied by its own length, giving 8114 entries of direction) with the help of OATools, an extension of the ArcGIS software. The prevailing NNE-SSW and WNW-ESE orientations of the tectonic indications can be seen in the summarizing rose diagram, representing the whole study area.

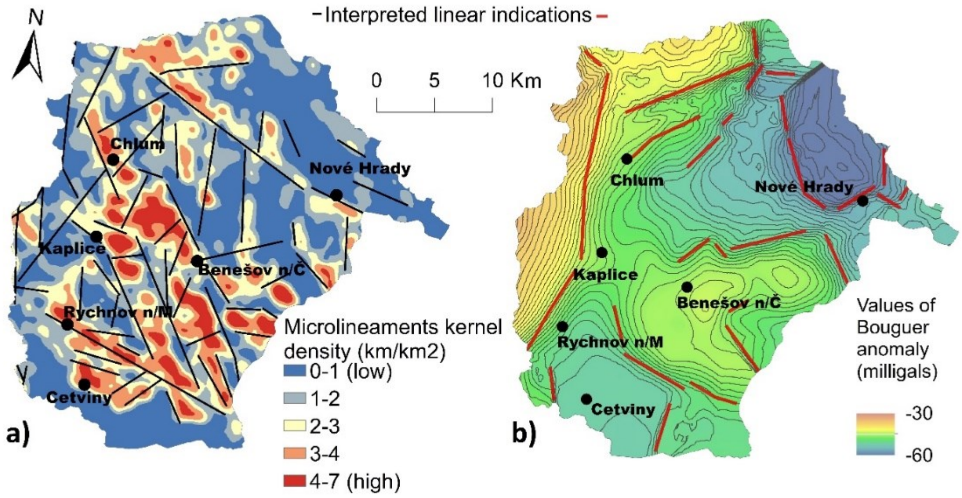


Fig.4: (a) Map of the density of microlineaments extracted from DEM with interpreted linear indications; (b) Map of the Bouguer gravity anomalies

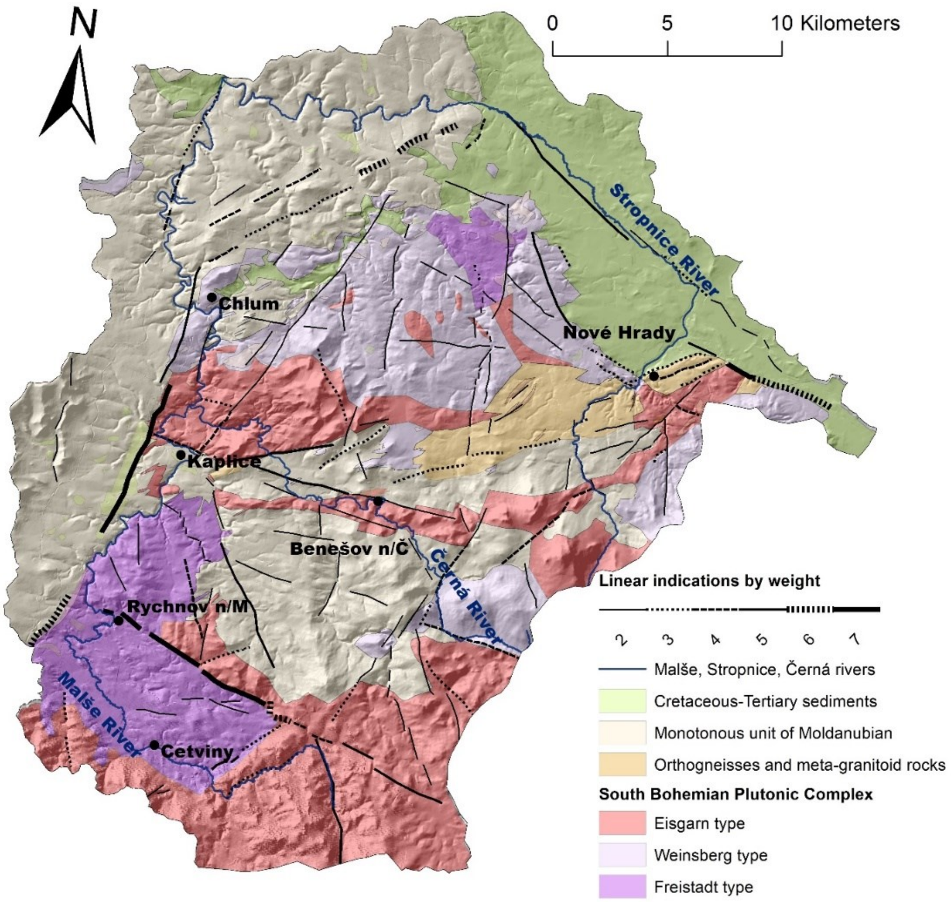


Fig. 5: Simplified geological map (Mahel et al. 1984; Slabý and Holásek, 1992a; Slabý and Holásek, 1992b; Vrána and Holásek 1992; Vrána and Novák 1993) with the results of morphotectonic analysis – weighted linear indications (see Tab 1.)

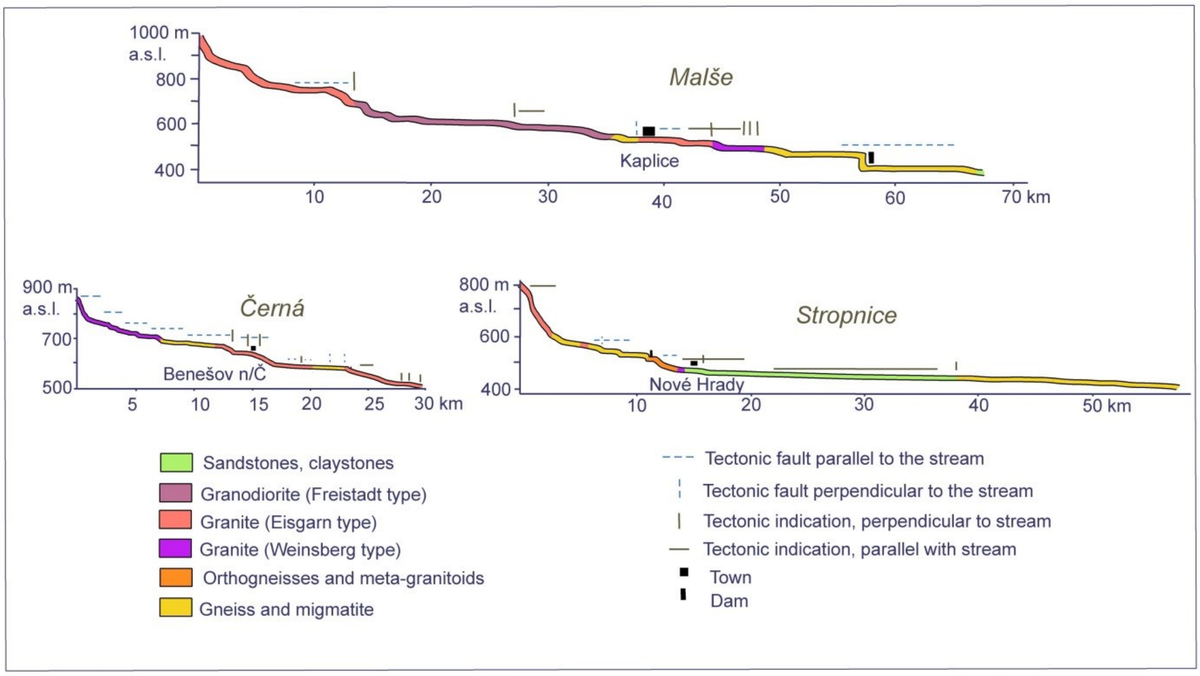


Fig**.** 6 Stream gradient profile of Černá, Malše and Stropnice rivers with simplified lithology and localization of tectonic faults and tectonic linear indications (for definition see section 3.b.). Note that the orientation and character of lithological boundaries is not considered due to the simplified and schematic illustration.

4.2. Field structural geology

In the western part of the studied area (see Fig. 1c), a strong population of extensional joints of NW-SE orientation was obtained, as were two smaller populations of NNE-SSW and NE-SW orientation. The direction of NNW-SSE dominates in the central part of the study area (gneisses and migmatites, various types of granites) a perpendicular WNW-ESE direction is also present. In the north (equigranular Eisgarn type granites), the N-S direction is strongly dominating, together with the much less present direction of NW-SE. Finally, the south (Weinsberg + Freistadt type granites) contains various directions of extensional joints, however, N-S and WSW-ENE are the strongest populations.

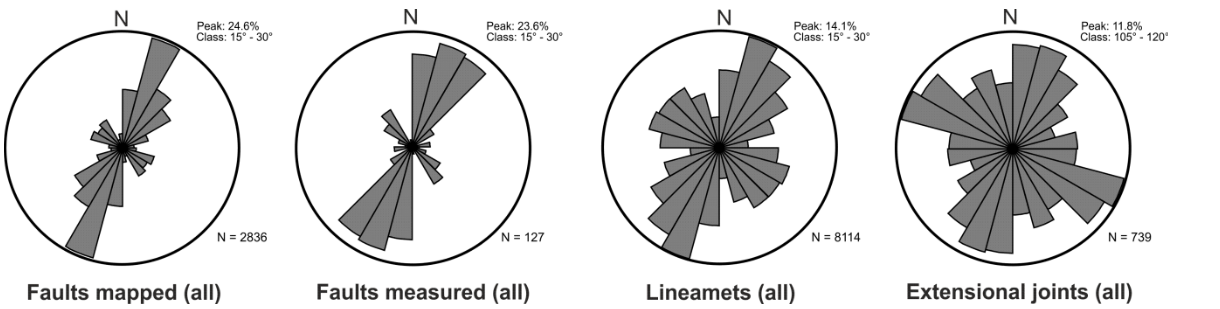


Fig 7. Field structural measurements and morphotectonic analysis (rose diagrams of strike directions): (a) mapped faults; (b) measured faults; (c) linear indications; (d) extensional joints.

4.3. SL index

The main focus was on those places, where the values change rapidly and, on those areas, where the stream crosses a tectonic indication or faults obtained from previous analysis (see sections 2.c., 4.a. and Fig. 1c, 5).

Very interesting results were gained from the Malše River, where the SL index changes take place near a crossing with a tectonic indication, particularly near Cetviny, Rychnov nad Malší, Kaplice and Chlum (Fig. 8a). The Stropnice River has a gentler stream gradient profile then the Malše River and also its SL index values are often lower, especially in the middle part (flat terrain of the Třeboň Basin) of the stream (Fig. 6, Fig. 8a). However, the SL index can reach very high values near the boundaries of the Třeboň Basin (near Nové Hrady), where the Stropnice River crosses tectonic indications and faults or in lower part of the stream (Fig. 6, Fig. 8a). There is also remarkable locality on the Černá River NE from Kaplice and in the surroundings of Benešov nad Černou. The tectonic situation in the Benešov area is not completely clear, but in the area NE from Kaplice there are several very prominent tectonic indications, which are possibly connected with changes in index values.

There are also many other interesting localities in the study area: the upper part of the Černá River and the area to the south from Benešov n/Č seemed to be very promising. Also, the morphotectonic analyses showed tectonic indications in this part of the study area (Fig. 5). In the northern part of the study area, there are several minor areas of sudden changes in the SL index values, particularly on Žárský potok Creek near Hrádek (area 1 on Fig. 8a), Svinenský potok Creek near Žumberk (area 2 on Fig. 8a) and on Klenský potok Creek in the area of Trhové Sviny (area 3 on Fig. 8a). However, these localities are probably connected with N-S tectonic indications parallel to streams, so the direct tectonic influence is not very clear. However, in the area of Hrádek, a N-S tectonic indication crosses the prominent fault system (bounding the Třeboň Basin) of a NW-SE orientation (Fig. 5).

4.4. Hypsometric index (HI)

No areas with high values (over 0,7) of HI were found in the study area. Such values can be found in the active mountain belts or similarly tectonic active areas. The Novohradské hory Mountains are a tectonically and morphologically less active area, but still some marks of Quaternary tectonic activity can be found here. Several catchments of the smaller water streams (Pohořský potok Creek (1), Mladoňovský potok Creek (2), Klenský potok Creek (3), see Fig. 8b) showed relatively high values of HI (0,4 – 0,6) in comparison to neighboring basins. In addition, some parts of the Malše River show similarly high HI values. There are several nice examples of differences in HI between neighboring areas on the Malše River, e.g. between Kaplice and Chlum. The particular areas are separated by tectonic indications and the values of HI change quite remarkably. Interesting results were obtained from the

Stropnice River. The upper part of the stream shows higher values of HI, there are low values in the middle part, in the flat relief of the Třeboň Basin, and again higher values are present in the lower part of the Stropnice River. There are quite high values of HI in the surroundings of Nové Hrady. This part of the Stropnice River is separated by a tectonic indication from another, lower part of the stream, where the values of HI are remarkably low.

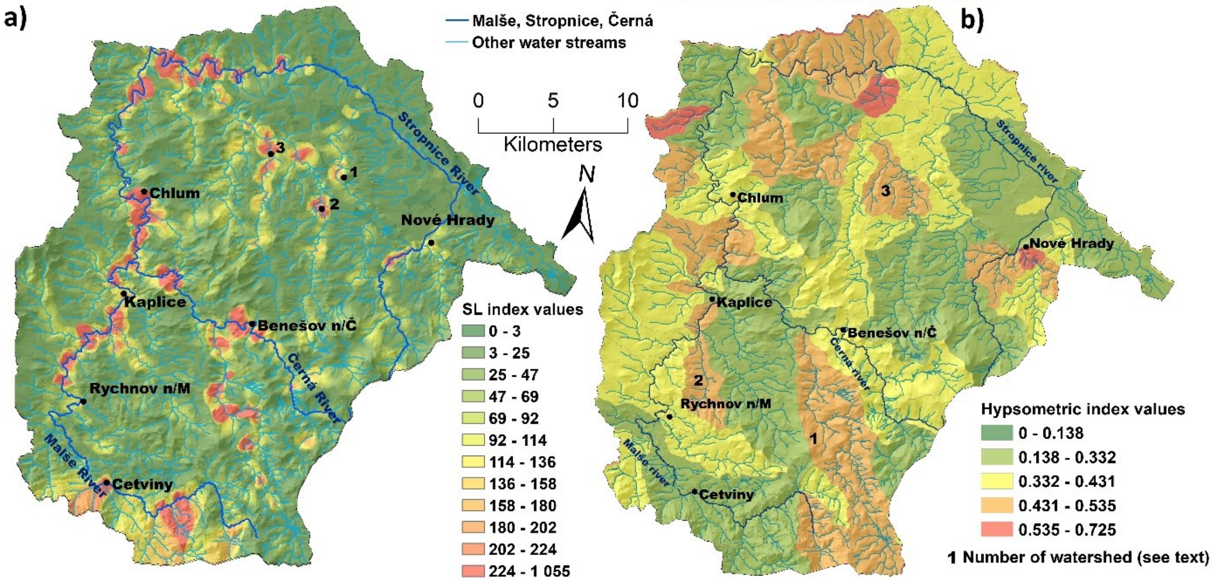


Fig.8: (a) Interpolated values of SL index. (b) Values of hypsometric index in particular watersheds (see section 4.d. for areas of interest)

5. Discussion

The methods used in this study are widely used in the tectonically active areas throughout the world to understand active tectonics (Ferranti et al. 2009; Allanic et al. 2013; Rothis et al. 2019). However, several studies exist which also take place in intraplate regions with weak tectonics (Štěpančíková et al. 2008; Font et al. 2010, Štěpančíková et al. 2019). The surveys in the tectonically active areas can often be validated by an analysis of seismic activity, or by the field observations of the extensive uncovered fault planes. Neither of these can be used in this study area due to weak recent seismic activity and due to a poorly exposed area – only small, scattered localities exposing fault planes are available.

5.1. Morphotectonic analysis

The results of morphotectonic analysis and the field structural survey show a generally satisfactory fit (Fig. 7). Based on the field structural analysis, mapped faults and remote sensing analysis, a significant concordance in orientation and frequency of faults and lineaments has been found (Fig. 1b, 5, 7). The morphological features have been predominantly affected by the occurrence and polyphase reactivation of orthogonal sets of subvertical faults and joints originally trending ~NNE–SSW and ~WNW(NW)–WSE(SE). The rock anisotropy defined by the preferred orientation of rock-forming minerals has no significant influence on the recent morphology. In many cases, the strongest population of extensional joints was found, which have a different orientation than the main tectonic indications lines. This could be caused by the high number of S- joints in granite, which are not often parallel to the faults (Twidale 1982; Bankwitz et al. 2004). It is almost impossible to identify the long, regional structures, visible from morphotectonic analysis, on the particular rock outcrop, especially in the area of metamorphous rocks with only small, scattered outcrops. It was found that the combination of analyses of remotely sensed data (DEM, airborne geophysics) used is a very robust and reliable way to identify the brittle tectonic structures. However, a thorough field survey is necessary in order to eliminate linear structures in the rocks like lithological boundaries, fold axes, cleavage or foliation.

5.2. SL and hypsometric indices

The SL index was used as the second main indicator of tectonic activity in this study. The SL index can be more focused than other methods and easily connected with a particular tectonic indication or fault. On the other hand, the hypsometric index represents the entire catchment of a particular stream, so it could be evaluated only on a bigger, regional scale or as a simple analysis of terrain morphology. The results of hypsometry analysis do not respect lithology and also the differences in the area of a particular catchments could have played a significant role, so the results were only used as supporting characteristics. Still, it was found that a combination of both methods can be a very robust and easy way to analyze possible tectonic activity on a complex scale.

The areas with sudden changes in the SL index were compared with the tectonic, morphotectonic and geological data. In some places lithological boundaries can significantly affect the values of the SL index, more than tectonic or morphotectonic structures. Many promising localities with a sudden change in the SL index were found in the study area. In fact, many of them are lying on or near the lithological boundary of paragneisses/granites. There is high probability of a lithological influence on the SL index values in those areas. Plus, if no tectonic indication is found in the vicinity of such an area, there is an even higher probability that local values of SL indexes are heavily influenced by variable rock resistance against stream erosion. Those places were omitted from the final evaluation. However, it is not possible to simply rule out the possibility of tectonic influence, because there still might exist tectonic faults on lithological boundaries, which have not been detected yet.

Many localities were identified that are lying in lithologically uniform area (so the effect of lithological variability is negligible) and where the SL index values show sudden changes. Nevertheless, there are also numerous areas, where there is no documented fault or tectonic indication in neighborhoods and where sudden changes in the SL index are documented (e.g. Klenský potok Creek near Trhové Sviny, Fig. 8a). It is not easy to explain changes in SL index values in such cases. It may be caused, for example, by a different level of weathering of bedrock or small local changes in lithology. This could be verified only by very detailed field mapping. Therefore, it is necessary to interpret such areas very carefully and to rather eliminate them from final conclusions in order to avoid unreliable results.

Even if we locate some faults or linear tectonic indication in the neighborhoods of an area with promising SL index values, it is not clear that it is caused by tectonic activity. Linear indications can also show inactive faults, joints, or shear zones (e.g. gravity anomalies). The bedrock properties (rock strength) can considerably change at such places and the SL index can be heavily influenced. On those places, the results can only be used as an indication and a subsequent field survey for verifying the existence or activity of faults is necessary (e.g. the area of Cetviny).

Localities, where there was the presence of tectonic fault indicated by the analyses, are the most auspicious and we can expect Neogene-Quaternary tectonic activity here. Those places have helped pinpoint active faults with a high probability and use them for final kinematic analysis (see section 5.c.). The rapid change of SL index values on the Malše River near Rychnov (Fig. 8a.) is very remarkable. The Malše River crosses a very prominent fault. Also, the values of the Hypsometric Index are relatively high in the current basin (Fig. 8b.), which can really indicate the presence of Quaternary tectonic movement on the 'Rychnov Fault'. A similar situation of SL and Hypsometric index values was observed on the Malše River near Chlum, where there are high values again, and local faults have been proven by a field survey. On the Stropnice River, such a locality can be found near Nové Hrady, where the stream crosses the bounding faults of the Třeboň Basin. It can be said, that there is high probability of recent tectonic movements at those localities. There is also very promising place on the Černá River near Benešov nad Černou. The values of the SL index change at almost exactly the same place as where the stream crosses the tectonic fault. However, the hypsometric index is quite low in the basin of the Černá River, so the tectonic activity in this area could be lower, or the fault could be inactive. Unfortunately, there are very few proven tectonic faults in the area to the south of Benešov n/Č. The values of the SL and Hypsometric indexes are very high, but only tectonic indications obtained by morphotectonic analysis and an analysis of airborne geophysics are known. The field mapping and dating of fluvial sediments of selected streams should follow this study to set the timing of tectonic movements.

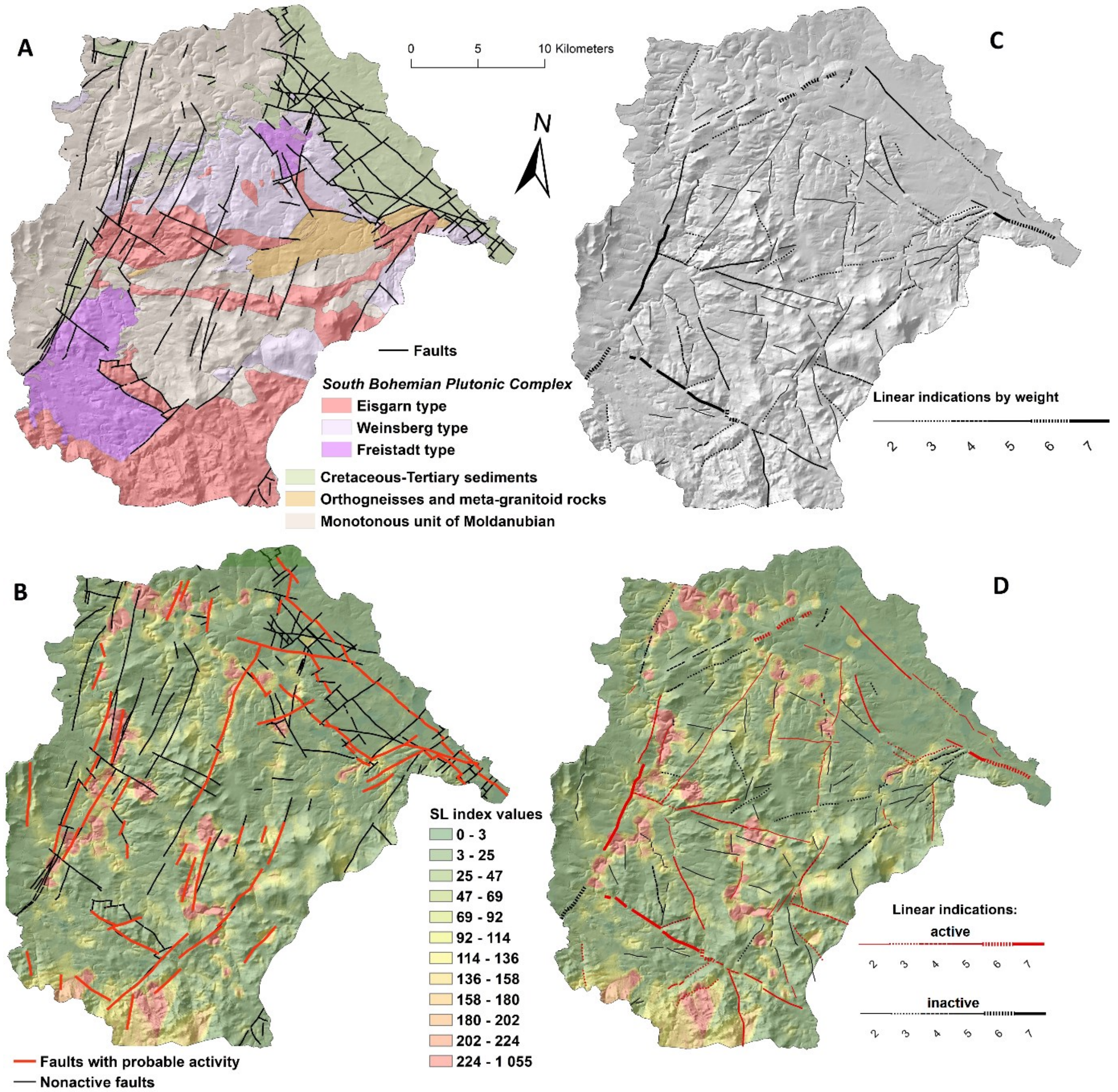


Fig. 9: (a) Simplified geological map; (b) Faults obtained from geological maps with interpreted active faults based on values of the SL index and geomorphology, (c) DEM with results of morphotectonic analysis, (d) Linear indications with interpreted active indications considered as faults, based on the values of the SL index and terrain morphology.

5.3. Tectonics and fault activity

Based on the field structural analysis (Fig. 2, Fig. 7), in combination with a re-interpretation of the mapped faults (Fig. 1c, Fig. 9a - CGS 2003), morphotectonic analysis (Fig. 6, Fig. 9c) and SL index calculation (Fig. 8a), a set of fault structures (Fig. 9b, Fig. 9d) with possible Neogene-Quaternary reactivation were identified in the studied area and their kinematics were interpreted under the current stress-field (Grünthal and Stromeyer 1994; Heidbach et al. 2018) (Fig. 10). The prominent faults are mostly steep, trending (a) ~NNE(NE) to ~SSW(SW) and belong to the 'Kaplice-Rodl fault zone' and

(b) ~NW(WNW) to ~SE(ESE) as part of the 'Pfahl fault zone' (e.g. Brandmayr et al. 1995). A scenario showing the overall visualization of the brittle fabric pattern of the Novohradské Hory Mts. (southern Moldanubian Zone) is given below.

The fault anisotropy, in combination with the heterogeneous lithological composition and the thickness of the individual rock types, affect the temperature distribution and also the overall stability of the rock environment according to the orientation, character and intensity of a recent stress-field. The recent stress field is controlled by several factors such as the North Atlantic seafloor spreading, the northward motion of the African and the Arabian plate, and the increased stiffness of the Bohemian Massif (Grünthal and Stromeyer 1992, 1994; Stampfli and Borel 2004). The recent maximum horizontal stress (S_{Hmax}) is considered to be in a ~NNW(NW)-SSE(SE) direction (azimuth 146 °) for the Bohemian Massif (Grünthal and Stromeyer 1994). In addition, the World Stress Map (Heidbach et al. 2018) provides two stress measurements of maximum compression axis at a distance of about 50 km based on borehole breakouts (in azimuth 121° and 131°) revealing an average maximum compression axis in the ~WNW–ESE direction (azimuth 126 °).

The possible reactivation of individual faults (Fig. 10) is assumed under the recent stress-field (S_{Hmax} = 146 °). If S_{Hmax} is horizontal in the ~NNW–SSE direction (azimuth 146 °) and $S_{Hmax} > S_v > S_{Hmin}$ ('strike-slip faulting regime'; Heidbach et al. 2018) the prevailing ~NE(NNE)–SW(SSW) trending faults would mostly reveal a sinistral strike-slip to weak reverse oblique-slip movement. A second set of subvertical ~NW(WNW)–SE(ESE) faults could be predominantly reactivated in a dextral strike-slip regime or as gentle reverse oblique-slip faults. In both cases, the oblique slip angle increases with the changing orientation of the fault plane to the direction perpendicular to S_{Hmax}.

5.4. Tectonic activity and terrain evolution

If the results of morphotectonic and SL index analyses (Fig. 9) are compared with the proposed reactivation of faults (Fig. 10) and overall topography (Fig. 1a), it is possible to find areas, which were probably affected by young tectonics, particularly by uplift. It would be possible to find several indications of tectonic uplift of the whole region of the Bukovský hřbet Ridge (area 1 on Fig. 1a), compared to the flat terrain of the Kaplice Furrow (areas 2 and 3 of Fig. 1a). The change from the wide valley of the Malše River south of Rychnov (area 2 on Fig. 1a) to a deep valley with incised meanders north of Rychnov (area 3 on Fig. 1a) is also visible. Another morphologically remarkable situation can be found in the eastern part of the study area, in the surroundings of Nové Hrady. Here the high mountainous terrain of the Novohradské hory Mts. can be seen rising above the lower level of the Stropnická vrchovina Highlands (area 5 on Fig. 1a) and the lowest level of the Třeboň Basin (area 6 on Fig. 1a) with a very low and flat terrain. Faults separate these morphologically distinctive units from each other (see Fig. 8a, 9c and 9d). A major uplift of area 4 (on Fig. 1a) and a moderate uplift of area 5 (on Fig. 1a) is fairly possible here. The rather hilly terrain of the Slepičí hory Mts. (area 7 on Fig. 1a) differs significantly from the flat valley of the Černá River between Kaplice and Benešov nad Černou. The uplift of the Slepičí hory and Novohradské hory, separated from each other by the lower terrain of the Černá River valley, is very probable. Besides the facts mentioned above, the gravimetric data (Fig. 4b) also show significant differences in areas 1, 4, 7 and 2, 3, 5 and 6. It can be interpreted that the whole area of the Novohradské hory Mts. was uplifted along the bounding faults. This is in agreement with other studies, which suspected an uplift of the Novohradské hory Mountains area (Chábera 1982; Kopecký 1983; Popotnig at al. 2013).

The flat, wide valley of the Malše River near Rychnov nad Malší, so untypical on an upper part of water streams and so noticeable in the surrounding hilly terrain, could also be a sign of tectonic movements. The existence of such a valley could be explained as a Tertiary remnant of the valley of an old stream ('Paleo-Malše River valley') existing before the tectonic activity in the area. Many authors also noticed this striking terrain feature, changes of fluvial style, river geometry and river orientation (Balatka and Sládek 1962; Malkovský 1975) and they suggested Miocene drainage of the upper part of Malše and Vltava rivers to the south, towards Alpine-Carpathian foredeep, and the subsequent change of drainage northwards. The fluvial and fluvial-lacustrine sediments found in the Kaplice Furrow are very probably of Pliocene age (Březinová et al. 1965; Novák 1983; Bezvoda et al. 1983). This is not in contradiction with the theory of drainage direction change, but it suggests that the change happened later, probably during the (upper) Pliocene. The distribution of the Pliocene fluvial deposits in the Kaplice Furrow suggest the migration of the Malše River towards the east during the Pliocene-Pleistocene, probably due to the uplift of the mountainous area of Poluška (Chábera 1982). Also, the same changes of the river network geometry may have happened due to tectonic uplift in the foothills of Novohradské hory Mts., which is discussed in detail by Flašar and Štěpančíková (2022). Regardless, the effect of tectonic activity on rivers is apparent in this study area. However, the exact dating of drainage direction changes is a matter for future debate and research, and also the exact dating of fluvial sediments is necessary to prove some of the proposed hypotheses as well for a more complete tectonic and palaeogeographic reconstruction of the study area.

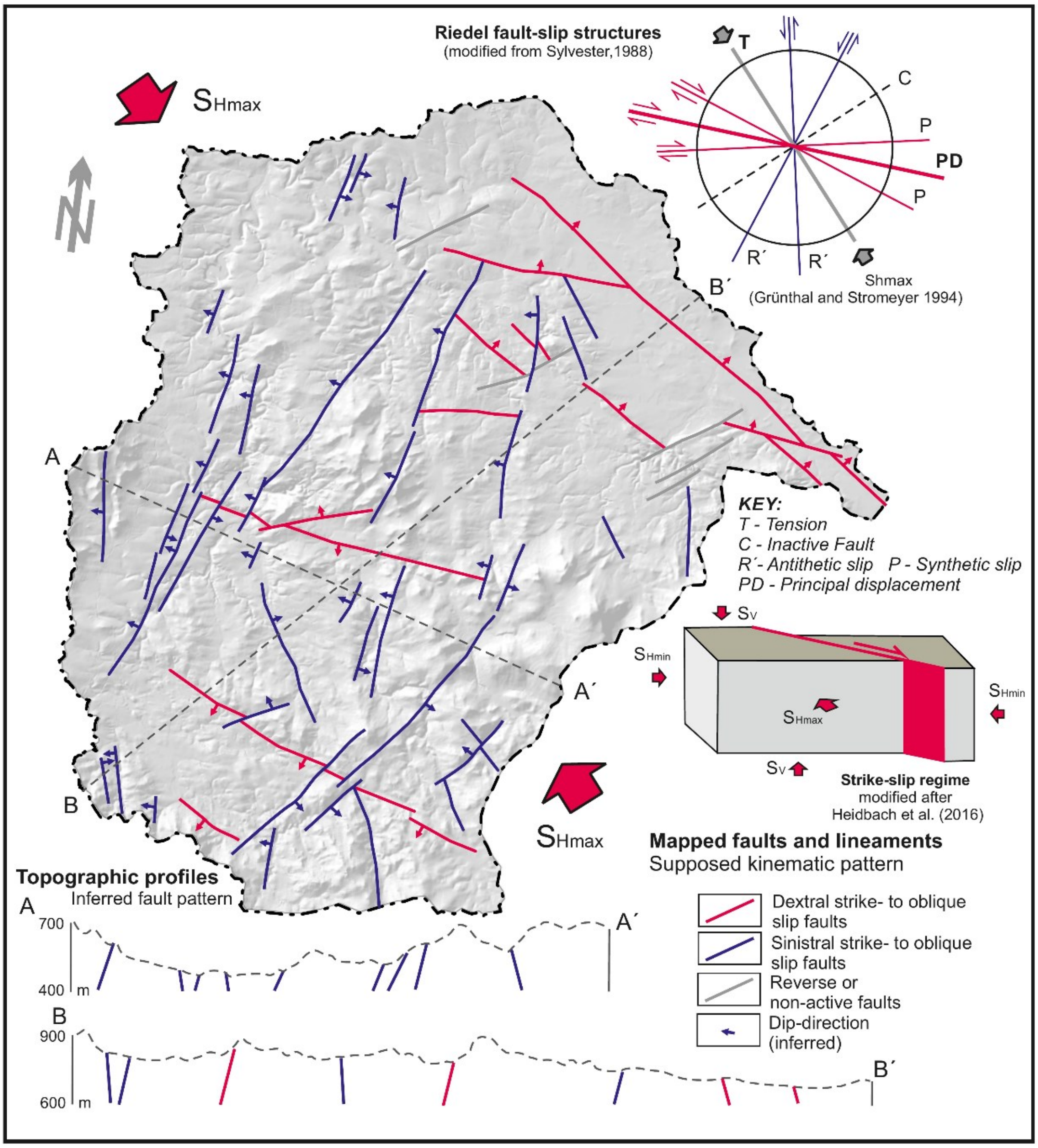


Fig. 10. Schematic map showing a possible reactivation of individual faults under the recent stress-field (SHmax = 146°) including topographic profiles with the supposed dip of faults. Active faults/linear indications were adopted from Fig. 9b and 9d.

6. Conclusions

The integration of morphotectonic analysis with an SL index calculation and airborne geophysical measurements, and validation with field geological and structural data, is a powerful tool for understanding Quaternary-Neogene active tectonics in intraplate areas with low deformation rates. This study reveals these particular conclusions:

- The combination of morphotectonic analysis and airborne geophysics is a very fast and relatively easy way to find indications of tectonic faults possibly active in the Neogene - Quaternary.

- Analysis of the SL index can be used for pinpointing the possible localities of active tectonics; however it has to be used carefully with respect to lithology, hydrology and anthropogenic influence.

- The hypsometric index can only be used as a complementary analysis at the regional scale, because its results are too rough to get detailed conclusions on particular faults.

- The analyses of remotely sensed data (DEM and airborne geophysics) combined with numerical geomorphology (SL and hypsometric indices calculations) were validated with field geological and structural mapping showing a good fit for both datasets.

- It is assumed there is a possible reactivation of individual faults under the recent stress-field (S_{Hmax} = 146°). If S_{Hmax} is horizontal in the ~NNW–SSE direction, the prevailing ~NE(NNE)–SW(SSW) trending faults would mostly reveal a sinistral strike-slip to weak reverse oblique-slip movement. A second set of subvertical ~NW(WNW)–SE(ESE) faults could be predominantly reactivated in a dextral strike-slip regime or as gentle reverse oblique-slip faults. The minor steeply dipping faults perpendicular to the S_{Hmax} = 146° are not active.

- Based on these results it is assumed that the whole region of the Novohradské hory Mountains experienced a significant uplift, compared to the neighboring areas of the Kaplice Furrow and the Třeboň Basin. The most significant features of this uplift can be found near Rychnov nad Malší, and on the tectonic border between the Kaplice Furrow and the Bukovský hřbet Ridge, respectively. This uplift took place probably in the late Pliocene and Pleistocene, after the sedimentation of lacustrine sediments in the Kaplice Furrow.

- Although the combination of GIS, morphotectonic and geophysical analyses with a validation by field structural data do not provide the final proof of young tectonic activity, it was found that there was a strong indication of Neogene-Quaternary reactivation of several faults in the study area, which was not indicated by previous studies.

- It can be supposed that many areas in the Alpine Foreland and Bohemian Massif underwent similar tectonic evolution, but further research is necessary to prove it.

Acknowledgements

Special acknowledgement goes to Jiří Žák, Jaroslava Pertoldová and Barbora Dudiková-Schullmanová for providing a significant part of the field structural data as well as valuable consultations. Radka Kalinová provided photographs and part of the field structural data. Also, we would like to thank the Institute of Physics of Earth for providing the database of seismic events, and the Czech Geological

Survey, which provided the airborne geophysics dataset and geological maps of the study area. We also gratefully acknowledge Richard R. H. Withers for English proof reading.

Statements and Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Contributions

All authors contributed to the study conception and design. Data collection and geomorphological analyses were performed by Jan Flašar, with supervision of Karel Martínek. The field survey and the structural geological interpretations were made by Kryštof Verner. The first draft of the manuscript was written by Jan Flašar and all authors commented on previous versions of the manuscript. Radka Kalinová contributed during the field survey and finalizing of the manuscript. All authors read and approved the final manuscript.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

References

ACORN (2004) Catalogue of Earthquakes in the Region of the Alps – Western Carpathians – Bohemian Massif for the period from 1267 to 2004. Computer File, Vienna (Central Institute for Meteorology and Geodynamics), Brno (Institute of Physics of the Earth)

Allanic C, Gumiaux C (2013) Are there any active faults within the Lepontine dome (central Alps)? Bull. Soc. géol. France, 184, 4-5: 427-440 https://doi.org/10.2113/gssgfbull.184.4-5.427

Badura J, Zuchiewicz W, Štěpančiková P, Przybylski B, Kontny B, Cacoń S (2007) The Sudetic marginal fault: A young morphotectonic feature at the NE margin of the Bohemian Massif, Central Europe. Acta Geodynamica et Geomaterialia 4:7-29

Balatka B, Kalvoda J (2006) Geomorfologické členění reliéfu Čech. Kartografia a.s., Praha

Balatka B., Sládek J (1962) Říční terasy v českých zemích. Nakladatelství československé akademie věd, Praha

Bankwitz P, Bankwitz E, Thomas R, Wemmer K, Kämpf H (2004) Age and depth evidence for pre-exhumation joints in granite plutons: fracturing during the early cooling stage of felsic rock. In: Cosgrove JW, Engelder T (eds) The initiation, Propagation and Arres of Joints and Other Fractures. Geological Society, London, pp 25-47

Bezvoda V, Novák V, Vrána M (1983) Příspěvek k poznání vysoko položených klastických sedimentů u Horního a Dolního Dvořiště. Sborník Jihočeského Muzea 23:61-65

Brandmayr M, Dallmeyer RD, Handler R, Wallbrecher E (1995) Conjugate shear zones in the Southern Bohemian Massif (Austria): implications for Variscan and Alpine tectonothermal activity. Tectonophysics 248:97-116. https://doi.org/10.1016/0040-1951(95)00003-6

Brandmayr M, Loizenbauer J, Wallbrecher E (1997) Contrasting P-T conditions during conjugate shear zone development in the Southern Bohemian Massif, Austria. Mitteilungen der Österreichischen Geologischen Gesellschaft 90:11-29

Březinová D, Pacltová B, Špinar, Z, Cimbálníková A (1965) Stáří sedimentů kaplické pánvičky v jižních Čechách (M-33-113-D-d). Časopis pro mineralogii a geologii 10:65-74

Bus Z, Grenerczy G, Toth L, Monus P (2009) Active crustal deformation in two seismogenic zones of the Pannonian region – GPS versus seismological observations. Tectonophysics 474:343–352. https://doi.org/10.1016/j.tecto.2009.02.045

Büttner SH (2007) Late Variscan stress-field rotation initiating escape tectonics in the south-western Bohemian Massif: a far field response to late-orogenic extension. Journal of Geoscience 52:29–43. http://doi.org/10.3190/jgeosci.004

CGS (Czech Geological Survey, 2003) Geologická mapa ČR, 1: 500 000. Praha

CGS (Czech Geological Survey, 2015) Database of airborne geophysics, 1: 25 000. Praha

Chábera S (1982) Geologické zajímavosti jižních Čech (Jihočeská vlastivěda, řada B).Jihočeské nakladatelství, České Budějovice. 130 p.

Chábera S, Demek J, Hlavác V, Kríž H, Malecha A, Novák V, Odehnal L, Suk M,Tomášek M, Zuska V (1985) Neživá příroda (Jihočeská vlastivěda, řada A). Jihočeské nakladatelství, České Budějovice

Cheng KY, Hung JH, Chang HC, Tsai H, Cheng-Sung Q (2012) Scale independence of basin hypsometry and steady state topography. Geomorphology 171-172: 1-11. https://doi.org/10.1016/j.geomorph.2012.04.022

Chlupáč I, Brzobohatý R, Kovanda J, Stráník Z (2002) Geologická minulost Českérepubliky. Academia, Praha

Cloetingh S, Cornu T, Ziegler PA, Beekman F, Environmental Tectonics (ENTEC) Working Group (2006) Neotectonics and intraplate continental topography of the northern Alpine Foreland. Earth Science Reviews 74:127-196. https://doi.org/10.1016/j.earscirev.2005.06.001

Coubal M, Málek J, Adamovič J, Štěpančíková P (2015) Late Cretaceous and Cenozoic dynamics of the Bohemian Massif inferred from the paleostress history of the Lusatian Fault Belt. *Journal of Geodynamics* 87:26-49. https://doi.org/10.1016/j.jog.2015.02.006

ČÚZK (Czech Office for Surveying, Mapping and Cadastre, 2017). Digitální model reliéfu České republiky 4. generace (DMR 4G)/Digital Elevation Model of Czech Republic 4th generation (DEM 4G). Český úřad zeměměřický a katastrální, Praha

Edel JB, Schulmann K, Holub F (2003) Clockwise rotation of the Eastern European Variscides accommodated by dextral lithospheric wrenching: paleomagnetic and structural evidence. Journal of the Geological Society London 160:209-218

Ferranti L, Santoro E, Mazzella ME, Monaco C, Morelli D (2009) Active transpression in the northern Calabria Apennines, southern Italy, Tectonophysics, 476, 1–2: 226-251. https://doi.org/10.1016/j.tecto.2008.11.010.

Flašar J, Štěpančíková P (2022) Plio-Pleistocene paleodrainage reconstruction using moldavite-bearing deposits (South Bohemia, Czech Republic). Palaeogeography, Palaeoclimatology, Palaeoecology 586:110783. https://doi.org/10.1016/j.palaeo.2021.110783

Font M, Amorese D, Lagarde JL (2010) DEM and GIS analysis of the stream gradient index to evaluate effects of tectonics: The Normandy intraplate area (NW France). Geomorphology 119: 172-180. https://doi.org/10.1016/j.geomorph.2010.03.017

Franke W (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. Geological Society, London, Special Publications 179:35-61. https://doi.org/10.1144/GSL.SP.2000.179.01.05

Gerdes A, Wörner G, Henk A (2000) Post-collisional granite generation and HT-HP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. Journal of the Geological Society 157:577—587. https://doi.org/10.1144/jgs.157.3.577

Gerdes A (2001) Magma homogenization during anatexis, ascent and/or emplacement? Constraints from the Variscan Weinsberg Granites. Terra Nova 13:20-45. https://doi.org/10.1046/j.1365-3121.2001.00365.x

Grünthal G, Stromeyer D (1992) The recent crustal stress field in central Europe: trajectories and finite element modeling. Journal of Geophysical Research: Solid Earth 97:11805-11820. https://doi.org/10.1029/91JB01963

Grünthal G, Stromeyer D (1994) The recent crustal stress field in Central Europe sensu lato and its quantitative modelling. Geologie en Mijnbouw 73:173-80

Hack JT (1973) Stream-profile analysis and stream-gradient index. Journal of Research of the U.S. Geological Survey 1:421-429

Hartvich F, Valenta J (2013) Tracing an Intra-montane Fault: An Interdisciplinary Approach. Surveys in Geophysics 34:317-347. https://doi.org/10.1007/s10712-012-9216-9

Heidbach O, Rajabi M, Cui X, Fuchs K, Müller B, Reinecker J, Reiter K, Tingay M, Wenzel F, Xie F, Ziegler MO (2018) The World Stress Map database release 2016: Crustal stress pattern across scales. Tectonophysics 744:484-498. https://doi.org/10.1016/j.tecto.2018.07.007

Holub FV, Klečka M, Matějka D (1995) Igneous activity of the Moldanubian Zone.In: Dallmeyer RD, Franke W, Weber K (Eds) Tectonostratigraphic evolution of the Central and East European Orogen*s*. Springer Verlag, Berlin, pp 444–452

Holub FV, Cocherie A, Rossi P (1997) Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of the thermal and tectonic events along the Moldanubian–Barrandian boundary. Earth Planetary Science Letters 325:19–26. https://doi.org/10.1016/S1251-8050(97)83268-5

IPE (Institute of Physics of the Earth, 2014) Database of seismic events. 1880-2014

Janoušek V, Holub, FV, Magna, T, Erban, V (2010). Isotopic constraints on the petrogenesis of the Variscan ultrapotassic magmas from the Moldanubian Zone of the Bohemian Massif. In: Awdankiewicz, M., Awdankiewicz, H. (eds): Lamprophyres and related mafic hypabyssal rocks: Current petrological issues. *Mineralogia – Special Papers*, **37:** 32–36.

Jordan G, Meijninger BML, van Hinsbegen DJJ, Meulenkamp JE, van Dijk PM (2005) Extraction of morphotectonic features from DEMs: development and applications for study areas in Hungary and NW Greece. International Journal of Applied Earth Observation and Geoinformation 7:162-183. https://doi.org/10.1016/j.jag.2005.03.003

Klomínský J, Jarchovský T, Rajpoot G (2010) Atlas of plutonic rocks and orthogneisses in the Bohemian Massif. Česká geologická služba, Praha

Kopačková V, Franěk J, Verner K, Martínek K, Tesař M (2011) Structural approach combining ALOS PALSAR linear feature extraction with field structural and geophysical investigations. Geological Remote Sensing Group Workshop Advances in Geological Remote Sensing (Including the Oil and Gas Earth Observation Group Workshop), ESA/ESRIN, Frascati, Italy

Kopecký A, Vyskočil P (1969) Současné vertikální pohyby zemského povrchu v západní polovině Českého masivu. Věstník Ústředního ústavu geologického 5:273-281

Kopecký A (1970) Úloha kvartérní tektoniky při dotváření současné struktury a geomorfologie Českého masivu. Časopis pro mineralogii a geologii 15:347-355

Kopecký A (1983) Neotektonický vývoj a stavba šumavské horské soustavy. Antropozoikum 15:71-159

Legrain N, Stüwe K, Wölfler A (2014) Incised relict landscapes in the eastern Alps. Geomorphology 221:124–138. https://doi.org/10.1016/j.geomorph.2014.06.010

Lenhardt WA, Švancara J, Melichar P, Pazdírková J, Havíř J, Sýkorová Z (2007) Seismic activity of the Alpine–Carpathian–Bohemian Massif region with regard to geological and potential field data. Geol. Carpathica 58:397–412

Mahel M, Kodym O, Malkovský M (1984) Tektonická mapa CSSR, 1: 500 000. Geologický ústav Dionýza Štúra, Bratislava

Malkovský M (1975) Paleogeography of the Miocene of the Bohemian Massif. Věstník Ústředního ústavu geologického 50:27-31

Pešek J (2010) Terciérní pánve a ložiska hnědého uhlí České republiky. Vydavatelství České geologické služby, Praha

Pike R, Wilson S (1971) Elevation-Relief Ratio, Hypsometric Integral, and Geomorphic Area-Altitude Analysis. Geological Society of America Bulletin 82:1079-1084.https://doi.org/10.1130/0016-606(1971)82[1079:ERHIAG]2.0.CO;2

Pitra P, Burg JP, Gueraud M (1999) Late Variscan strike-slip tectonics between the Teplá-Barrandian and Moldanubian terranes (Czech Bohemian Massif). Journal of the Geological Society 156:1003–1020. https://doi.org/10.1144/gsjgs.156.5.1003

Popotnig A, Homolová D, Decker K (2013) Morphometric analysis of a reactivated Variscan fault in the southern Bohemian Massif (Budějovice basin, Czech Republic).Geomorphology 197:108-122. https://doi.org/10.1016/j.geomorph.2013.04.042

Přibyl V (1995) Testing selected methods of geomorphological analysis when studying dynamics of relief-building processes. Acta Universitatis Carolinae. Geographica 30:57-78

Rothis LM, Perucca LP, Malnis PS, Alcacer JM, Haro FM, Vargas HN (2019) Neotectonic, morphotectonic and paleoseismologic analysis of the Las Chacras Fault System, Sierras Pampeanas Occidentales, San Juan, Argentina, Journal of South American Earth Sciences,

91: 144-153, https://doi.org/10.1016/j.jsames.2019.02.001.

Scheidegger AE (1987) *Systematic Geomorphology*. Springer – Verlag, Wien

Schenk V, Schenková Z, Kottnauer P (2001) Geodynamic terrains of the Moravo-Silesian area, the Bohemian Massif. Topical Conference of the European Geophysical Society Quantitative Neotectonics and Seismic Hazard Assessment: New Integrated Approaches for Environmental Management, Balatonfüred

Schulmann K, Konopásek J, Janoušek V, Lexa O, Lardeaux J-M, Edel J-B, Štípská P, Ulrich S (2009) An Andean type of Palaeozoic convergence in the Bohemian Massif. Comptes Rendus Geoscience 341:266–286. https://doi.org/10.1016/j.crte.2008.12.006

Sedlák J, Gnojek I, Verner K, Franěk J, Zabadal S, Motschka K, Slovák J (2011) Geophysical and structural pattern of the Knížecí Stolec pluton and its host rocks in the south-western part of the Moldanubian Zone, Bohemian Massif. Journal of Geosciences, 56, 2: 143 – 162. http://doi.org/10.3190/jgeosci.096

Siebel W, Shang CK, Reitter E, Rohrmüller J, Breiter K (2008) Two Distinctive Granite Suites in the SW Bohemian Massif and their Record of Emplacement: Constraints from Geochemistry and Zircon ^{207}Pb/^{206}Pb Chronology. *Journal of Petrology* 49:1853–1872. https://doi.org/10.1093/petrology/egn049

Slabý J, Holásek O (1992a) Geologická mapa ČR 33-31 Pohoří na Šumavě 1:50 000. Český geologický ústav, Praha

Slabý J, Holásek O (1992b) Geologická mapa ČR 33-13 České Velenice 1:50 000. Český geologický ústav, Praha

Stampfli GM, Borel GD (2002) A plate tectonic model for the Palaeozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and Planetary Science Letters 196:17-33. https://doi.org/10.1016/S0012-821X(01)00588-X

Stampfli GM, Borel GD (2004) The TRANSMED transects in space and time: constraints on the paleotectonic evolution of the Mediterranean domain. In: Cavazza W, Roure F, Spakman W, Stampfli GM, Ziegler PA (eds) The TRANSMED Atlas. The Mediterranean region from crust to mantle. Springer, Berlin, Heidelberg, pp 53-80

Štěpančíková P, Stemberk J, Vilímek V, Košťák B (2008) Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic). Geomorphology 102:68-80. https://doi.org/10.1016/j.geomorph.2007.06.016

Štěpančíková P, Fischer T, Stemberk J, Nováková L, Hartvich F, Marques FP (2019) Active tectonics in the Cheb basin: Youngest documented Holocene surface faulting in Central Europe? Geomorphology 327:472-488. https://doi.org/10.1016/j.geomorph.2018.11.007

Tyráček J, Westaway R, Bridgland D (2004) River terraces of the Vltava and Labe (Elbe) system, Czech Republic, and their implications for the uplift history of the Bohemian Massif. Proceedings of the Geologists' Association 115:101-124. https://doi.org/10.1016/S0016-7878(04)80022-1

Twidale CR (1982) Granite Landforms. Elsevier Scientific Publishing Company, Amsterdam-New York – Oxford

UJEP and MŽP (University of Jan Evangelista Purkyně in Ústí nad Labem and Ministry of the Environment of the Czech Republic, 2014) II.vojenské mapování – Františkovo, 1: 28800. Laboratoř geoinformatiky Fakulta životního prostředí. http//oldmaps.geolab.cz. Accessed 15 May 2016

Vellmer C, Wedepohl KH (1994) Geochemical characterization and origin of granitoids from the South Bohemian Batholith in Koser Austria. *Contributions to Mineralalogy and Petrology* 118:13-32. https://doi.org/10.1007/BF00310608

Verner K, Žák J, Pertoldová J, Šrámek J, Sedlák J, Trubač J, Týcová P (2009) Magmatic history and geophysical signature of a post-collisional intrusive centre emplaced nearby a crustal-scale shear zone: the Plechý granite pluton (Moldanubian batholith, Bohemian Massif). International Journal of Earth Sciences 98:517-532. https://doi.org/10.1007/s00531-007-0285-9

VGHMÚř (Vojenský geografický a hydrometeorologický úřad, Ministerstvo obrany ČR, GEODIS Brno s.r.o, 2014) Historická ortofotomapa Č(S)R, 1:20000. CENIA - Česká informační agentura životního prostředí, Praha. http//: kontaminace.cenia.cz. Accessed 15 May 2014

Vlček V (1984) Zeměpisný lexikon ČSR-Vodní toky a nádrže. Academia, Praha

Vrána S, Holásek O (1992) Geologická mapa ČR 32-24 Trhové Sviny 1:50 000. Český geologický ústav, Praha

Vrána S, Novák V (1993) Geologická mapa ČR 32-42 Rožmberk nad Vltavou 1:50 000, Český geologický ústav, Praha

VÚV TGM (T. G. Masaryk Water Research Institute, 2016) Database of water management data, 1: 10 000. DIBAVOD – digitální báze vodohospodářských dat. http://www.dibavod.cz. Accessed 15 May 2016

Vyskočil P (1973) The investigation of vertical crustal movements in the geodynamical polygon Lišov. *Edice výzkumného ústavu geodetického, topografického a kartografického v Praze* 4:1-96

Willgoose G, Hancock G (1998) Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment. Earth Surface Processes and Landforms 23:611-623. https://doi.org/10.1002/(SICI)1096-9837(199807)23:7%3C611::AID-ESP872%3E3.0.CO;2-Y

Wood WF, Snell JB (1960) A quantitative system for classifying landforms. Headquarters, Quartermaster Research and Engineering Command, US Army, Natick

Ziegler PA, Dèzes P (2007) Cenozoic uplift of Variscan Massifs in the Alpine foreland: timing and controlling mechanisms. Global Planet Change58:237–269. https://doi.org/10.1016/j.gloplacha.2006.12.004

Žák J, Holub FV, Verner K (2005) Tectonic evolution of a continental magmatic arc from transpression in the upper crust to exhumation of mid-crustal orogenic root recorded by episodically emplaced plutons: the Central Bohemian Plutonic Complex (Bohemian Massif). *Int J Earth Sci (Geol Rundsch)* **94,** 385–400. https://doi.org/10.1007/s00531-005-0482-3

Žák J, Verner K, Janoušek V, Holub FV, Kachlík V, Finger F, Hajná J, Tomek F, Vondrovic L, Trubač J (2014) A plate-kinematic model for the assembly of the Bohemian Massif constrained by structural relationships around

granitoid plutons. Geological Society, London, Special Publications 405:169-196.
https://doi.org/10.1144/SP405.9

Chapter 3: Plio-Pleistocene paleodrainage reconstruction using moldavite-bearing and morphostratigraphically related deposits (Southern Bohemia, Czech Republic)

by Jan Flašar and Petra Štěpančíková

a study published in the Palaeogeography, Palaeclimatology, Palaeoecology, v. 586, 2022

(DOI: 10.1016/j.palaeo.2021.110783)

Abstract

The area of Southern Bohemia between Novohradské hory Mountains and the Třeboň and Budějovice Basins – the Novohradské Foothills (in the south of the Czech Republic) is known for the occurrence of moldavites. These tektites are abundant in fluvial Koroseky sands and gravels. This study focuses on reconstructing the paleostreams, which deposited the moldavite-bearing sediments, and their relationship to present streams. Based on a review of the deposits' occurrences, a connection between moldavite-bearing sediments and deposits of the present watercourses, Vltava, Malše, Stropnice and Svinenský, is proposed. The link between moldavite-bearing deposits and the current streams were further supported by analyses of river geometry (longitudinal profiles, stream gradient) and terrain morphology (valley floor ratio, basin asymmetry). It is suggested that the moldavite-bearing deposits were sedimented during the Pliocene or Pleistocene by predecessors of the present streams. The occurrences of particular fluvial deposits and changes in terrain morphology and river geometry can be traces of changes in the river network and the dynamic evolution of local relief induced by tectonic activity during the Pliocene and Pleistocene.

Keywords: tektite, moldavite, fluvial deposits, river network changes, Late Pliocene, Pleistocene, Novohradské hory Mts., Malše River

1. Introduction

The fall of moldavites (Central European tektites) 14.8 Ma ago induced by the Ries impact (Di Vincenzo and Skála 2009; Buchner et al. 2010; Schwarz and Lippolt 2014) was a significant event for the area of what is now Central Europe. The deposits containing moldavites can be found mainly in the Czech Republic, but also in Germany, Poland and Austria. Their age is generally unknown and have been given a wide range - from 14.8 Ma to Pleistocene – by various authors (Žebera, 1967; Bouška and Konta, 1990; Ševčík et al., 2007; Welser et al., 2020). In the studied area – the area of Novohradské Foothills between Třeboň and Budějovice in the north and the ridges of the Novohradské hory Mountains in the south (Southern Bohemia in the south of the Czech Republic) – there are the largest occurrences of moldavite-bearing deposits. They, known as Koroseky sands and gravels or Vrábče beds have been traditionally dated to the Miocene, which was suggested due to deposits from unspecified streams, which differed from the Pleistocene or current stream network (Žebera, 1967; Trnka and Houzar, 2002). There are also many Pliocene and Pleistocene fluvial sediments along the current Vltava, Malše and Stropnice Rivers (Puchta and Volšan, 1965; Chábera and Novák, 1975; Novák, 1983; Přibyl, 1999) and significant changes in river geometry were suggested as a result of the mainly Plio-Pleistocene tectonic uplift of the surrounding mountains (Malkovský 1979; Chábera, 1982). Therefore, this area is ideal for the proposed paleodrainage reconstruction.

Since it appears that the moldavite-bearing deposits and younger Pleistocene fluvial deposits are morphostratigraphically very close to each other, the traditional consideration of a Miocene age for the Koroseky sands and gravels could be put in doubt. Based on their morphostratigraphical position, many studies (Bouška and Konta, 1990; Bouška, 1992; Ševčík et al., 2007; Pešek, 2010) suggest that they can be significantly younger, Pliocene or early Pleistocene. However, a detailed study of the spatial and morphostratigraphical relationship between moldavite-bearing deposits and other, younger fluvial sediments has not been made yet.

This study reviews the age and morphostratigraphical position of all those sediments. This new view on the issue is not based solely on combining older data, but also on selecting the reliable ones regarding the morphostratigraphical position of the fluvial deposits. Using moldavite-bearing deposits as a stratigraphic marker is a new approach in the area of Southern Bohemia and such a complex view (e.g., a detailed evaluation of the moldavite-bearing sediments in longitudinal profiles) has not been used so far. The information obtained from previous studies was complemented by new analyses of morphometric indicators based on DEM from LiDAR data. The study puts forward a reconstruction of the Pliocene paleo-drainage and its possible evolution through the Pleistocene to the present and endeavours to map the most significant palaeogeographical changes. The results cannot answer all questions about the complex palaeogeographical evolution of the area of SouthernBohemia, but they can specify the localities needed for further research, such as dating the sediments or paleoseismological survey to reconstruct the tectonic movements resulting in the drainage changes etc. Similar approach can be used not only in central Europe, where the moldavite-bearing sediments are located, but also in other areas, where the fluvial and tectonic history is complex and not completely solved yet.

2. Geological setting

2.1. Crystalline basement and Cretaceous-Pliocene deposits

The Novohradské hory Mts. and their foothills are composed mainly of metamorphic rocks of the Moldanubian Unit and granites of the Moldanubian Batholith (see Fig. 1 for detailed composition). The post-Variscan tectonics in this crystalline basement complex were thought to have been restricted to the Mesozoic and Cenozoic reactivation of Palaeozoic fault systems (e.g., Donau (NW-SE) and Blanice-Rodl (NNE-SSW; Brandmayr et al., 1995, 1997). The late reactivation of these faults has been described by various authors (Kopecký a Vyskočil, 1969; Kopecký 1970; Vyskočil, 1973; Malkovský 1979; Kopecký, 1983; Popotnig et al., 2013). They supposed the most intensive reactivation to have been at the end of Pliocene, however with the continuation of the uplift (geodetically measured) until the present (Kopecký and Vyskočil, 1969).

There are two main sedimentary basins in Southern Bohemia: the Budějovice Basin and the Třeboň Basin. Both have a common geological history from the upper Cretaceous until the Pliocene. The origin of the basins is Cretaceous when the Bohemian Massif reacted to the ongoing Alpine Orogeny (Malkovský, 1979). The main faults of NW-SE orientation and subsidiary ones of NNW-SSE and N-S orientation were formed or reactivated during these processes and sedimentary basins were formed along them (see Fig. 1). The basin infill is mainly formed by the lacustrine sediments of the Upper Cretaceous (sandstones and claystones from the Klikov formation) and Tertiary, however several marine ingressions were documented during the Tertiary (Chlupáč et al., 2002). The Tertiary infill begins with sandstones and sands from the Lipnice formation, probably from the Eocene. After a long hiatus, it is followed by lower Miocene Zliv formation made of clays, sandstones and conglomerates. The largest area of the basins is covered by the Mydlovary formation, which is composed of clayish sands and conglomerates on the base, green clays with a coal seam in the middle and greenish clays and diatomites in its upper part. The Mydlovary formation is dated to the lower or middle Miocene and it is followed by the Domanín Formation, which has a rather similar character of sediments – greenish diatomite clays (Malkovský, 1975). The most important thing is that the Domanín Formation is the first recorded layer with the occurrence of moldavites as the Vrábče beds are put to the Domanín Fm. by some authors (e.g., Bouška (1992), see Fig. 4). The upper Miocene rocks are not preserved in the basins. The Ledenice formation follows after a long hiatus and it is of a Pliocene age. It is formed by grey and green sands and clays, and it is similar to the Vildštejn formation in the Cheb Basin (Teodoridis et al., 2017), however it contains no moldavites. The Ledenice formation is the last member of a sedimentary infill, and it can be found in both basins (Pešek, 2010). After its sedimentation, the tectonic activity was strongly reactivated in the whole Bohemian Massif. The Budějovice Basin was separated from the Třeboň Basin by the uplifting of Lišov Horst, the Novohradské hory Mts. were significantly elevated (several hundreds of metres) and the erosion and sediment transportation processes became stronger. The deposition of moldavite-bearing gravels is set to this period (Chábera and Novák, 1975; Chábera, 1982; Bouška, 1992; Chlupáč et al., 2002).

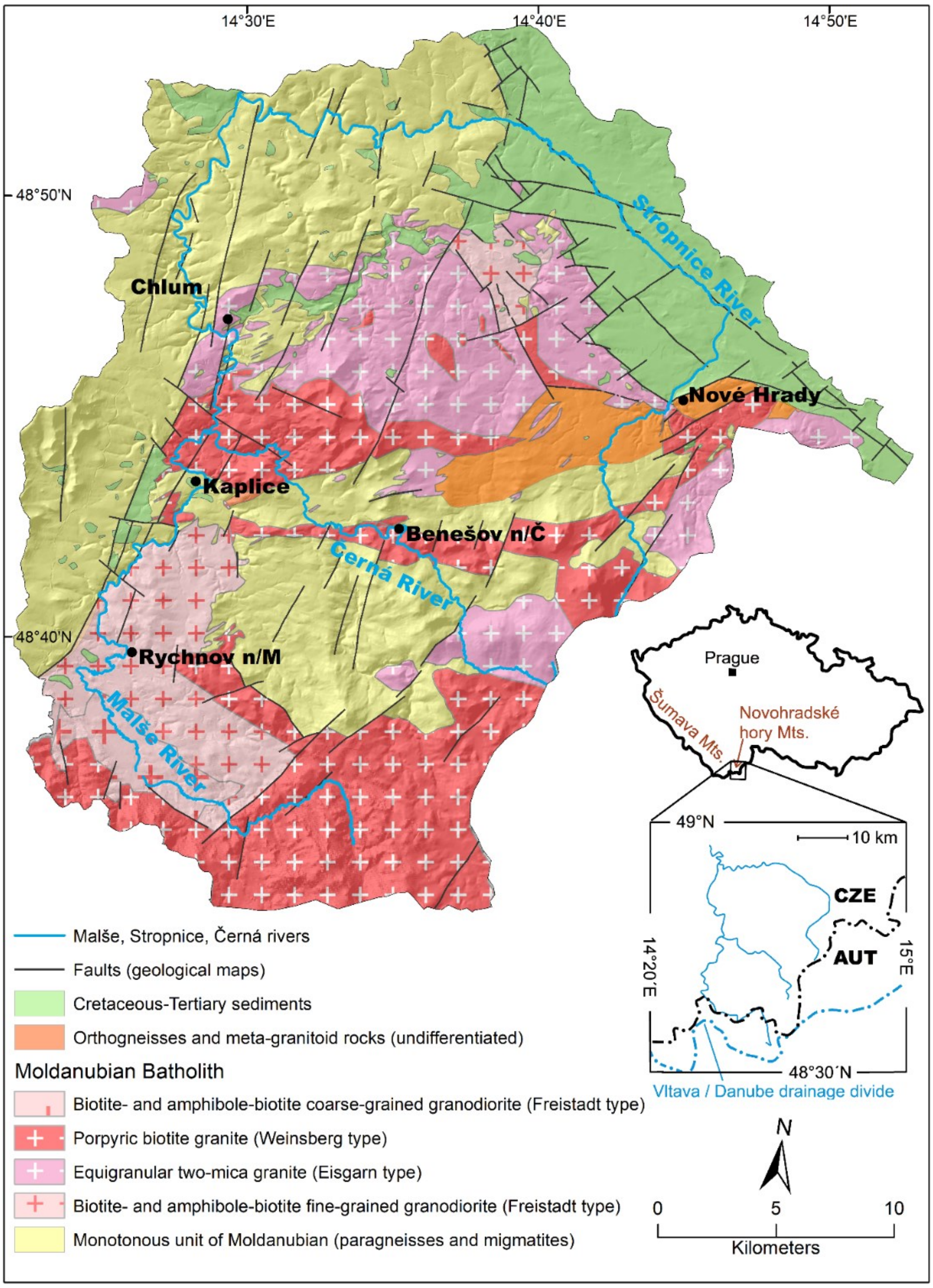


Fig. 1: Location of the study area and the basic geological situation (according to Malkovský, 1979; Mísař et al., 1983; Chlupáč et al., 2002; ČGS, 2003; Pavlíček, 2004 and Bankwitz et al., 2004). Note the Blanice-Rodl fault system (between Rychnov n/M and Chlum) and bounding faults of the Třeboň Basin. Elevation data source - DEM 4G (ČÚZK, 2017). Note that the coordinate system S-JTSK is used, also for other figures.

2.2. Moldavites

Moldavites (named after the Moldau/Vltava River), or Central European tektites, known for their attractive deep-green colour were formed from the uppermost sedimentary rocks layer during the Ries impact event in Miocene (Skála et al., 2016; Buchner et al., 2020). The best estimates of the moldavite age as well as that of the Ries crater (Bavaria, Germany), corrected for most recently suggested ^{40}K decay constants, (Jourdan et al. 2012 in Skála et al., 2016) currently vary between 14.74 ± 0.20 Ma and 14.83 ± 0.15 Ma (Di Vincenzo and Skála 2009; Buchner et al. 2010; Schwarz and Lippolt 2014; Schmieder et al., 2018). The moldavite tektites were formed by an early ejection of surficial impact melt or from condensates of vaporized surficial sediments, Oligocene and Miocene fluviatile-lacustrine sediments (mainly sands and limestones of up to 50 m total thickness; see Stöfler et al., 2013 and references therein). For a further overview regarding the impact itself and the preimpact geology see Artemieva et al., 2002; Sturm et al., 2015; Buchner et al., 2020). Moldavites are known from their strewn fields (see Fig. 2a) in Southern Bohemia, Western Moravia, the Cheb Basin in the Czech Republic; Lusatia in Germany, Waldviertel in Austria (Trnka and Houzar, 2002) and Lower Silesia in Poland (Skála and al., 2016; Brachaniec, 2019).

Despite the long-lasting scientific interest in moldavites and their known age of origin, the age of younger deposits containing them as reworked pebbles is still a matter of discussion (see Fig. 4).

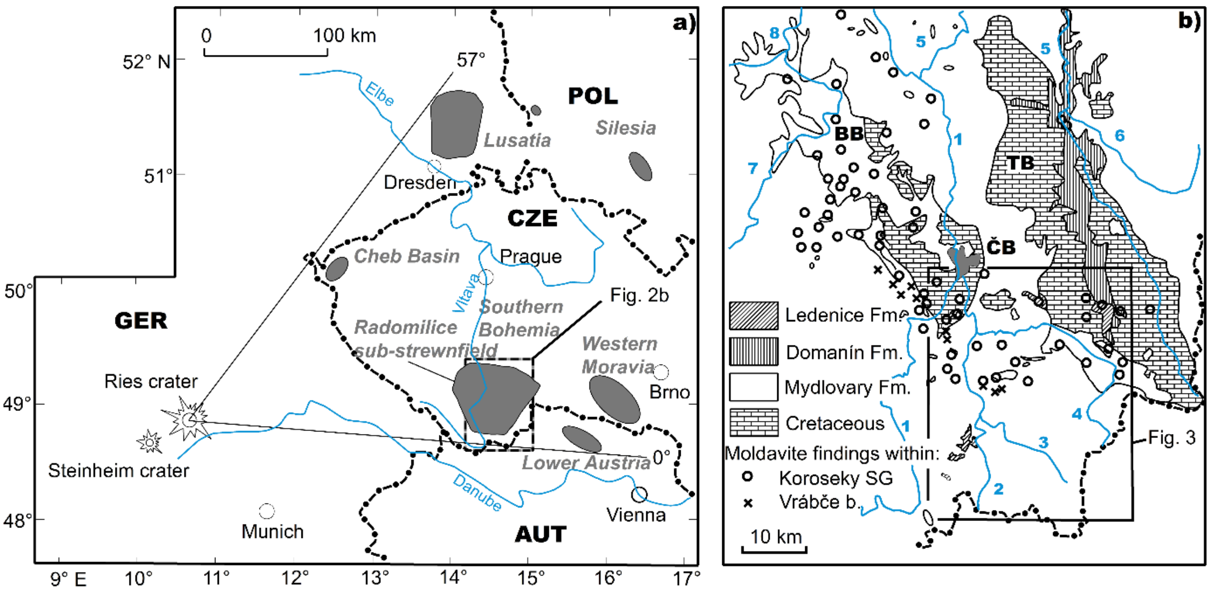


Fig. 2a: Map showing the Ries crater and the Moldavite strewn field (Artemieva et al., 2002); Fig. 2b: Mesozoic and Late Cenozoic deposits with the localities of moldavites in the area of Southern Bohemia, modified after Bouška, 1992 (BB – Budějovice Basin, TB – Třeboň Basin, ČB – České Budějovice; rivers: 1 – Vltava, 2 – Malše, 3 – Černá, 4 – Stropnice, 5 – Lužnice, 6 – Nežárka, 7 – Blanice, 8 – Otava).

2.3. Fluvial deposits and moldavite-bearing sediments in the area

There are many localities of lacustrine, fluviolacustrine or fluvial deposits of Neogene age in Southern Bohemia. Their proper age is a subject of discussion and various authors set their age into the period from the upper Miocene to the lower Pleistocene. The largest extent of these Neogene deposits can be found as an uppermost layer in these two sedimentary basins (Pešek, 2010). However, their occurrence outside the basins on the crystalline basement is more interesting for reconstructing the paleodrainage. Many scattered occurrences of these deposits can be found along the southern edges of the Budějovice and Třeboň Basins in a 40 km long belt of NW-SW orientation. Other abundant occurrences can be found further to the south in the Kaplice Furrow and along the Malše River (Bouška, 1992; ČGS, 2003). Also, scattered deposits can be found along the Vltava River, Stropnice River (and its tributaries) and in an isolated locality near Horní Dvořiště (see Fig. 2b and Fig. 3).

However, among the deposits outside the sedimentary basins, the equivalents of the Mydlovary formation can be found (probably the locality of Horní Dvořiště; Bezvoda at al., 1983), the Ledenice formation (deposits in the Kaplice Furrow; Březinová et al., 1963) and almost certainly also the younger Pliocene or Pleistocene deposits, which can often contain moldavites (Bouška and Konta, 1990; Bouška, 1992). Moldavite-bearing deposits are called Vrábče beds (**VB hereinafter**) and Koroseky sands and gravels (**KSG hereinafter**) in the area of Southern Bohemia. They have been traditionally classified to the Middle Miocene (Žebera, 1967; Trnka and Houzar, 2002), however the exact dating of these sediments has not been solved properly yet and many authors (see section 4) put at least part of them to the Pliocene/Pleistocene period. According to Žebera (1967, 1977), they were formed in different depositional environments in the neighbourhood of the shores of receding lakes.

The VB are deposited on crystalline rocks or on the Middle Miocene sediments of the Mydlovary Formation. They are considered as lateral part of Domanín Fm. by some authors (Žebera, 1967, Bouška 1992). Most of the sediments are colluvial-fluvial sandy clays and/or clayey sands with an admixture of angular psephitic material. They fill stream depressions, ravines or form dejection cones. The thickness of these sediments is usually several metres (Trnka and Houzar, 2002). The psephitic material is composed mainly of quartz, angular clasts of crystalline rocks (mostly Moldanubian metamorphites or granites) from the near surroundings (Bouška and Konta, 1990; Nesrovnal, 1992) and deeply corroded angular moldavites. According to Bouška (1992), the heavy mineral association of the VB from the locality of Besednice indicates local source of material: mainly composed from andalusite 16.84 %, tourmaline 8.66%, and disthen 8.57%. All of the parameters suggest that the material of the VB had not been transported for a long distance (Žebera, 1967; Bouška and Konta, 1990, Bouška; 1992; Nesrovnal, 1992). Moldavites within the VB are traditionally described by various authors (Žebera, 1967; Bouška, 1992) as “moldavites of a strewn-field”. They are typical due to their surface, shaped by corrosive furrows and pits formed by the long-term chemical action of underground water (Bouška, 1992).

The KSG represent fluvial, fluviolacustrine or sometimes deltaic facies. In contrast to the VB, the KSG are coarser. The usual size of pebbles is 1–2 cm, up to 10 cm at the most. The thickness of the sediments can reach up to 25 m. The main component of these gravels and sands are quartz and feldspars (Trnka and Houzar, 2002). Very often they contain moldavites, however there are bodies within the KSG without any moldavites (Bouška, 1992). The KSG can also often contain bodies of clays, which originated in the Ledenice Fm., Domanín Fm. or the VB and were redeposited to the KSG (Bouška, 1992). According to Bouška (1992), the heavy mineral association of the KSG (locality of Chlum) represents a slightly wider source area of sedimentary material (zircon 11.86%, rutile 1.32%, leukoxen 0.54%, disthen 0.51%). A similar situation can also be found at the other localities of KSG/VB in the area, there are no significant spatial differences in the heavy mineral associations (Bouška, 1992). The moldavites themselves in the KSG also differ from the moldavites in the VB. They are more rounded, as the other pebbles in the sediment (Žebera, 1967; Bouška and Konta, 1990; Bouška, 1992, Nesrovnal 1992). The moldavites from the KSG localities in the southern part of Southern Bohemia (e.g., Chlum) seem to be less rounded than those from the northern part (e.g., Koroseky). Also, the ratio of rounded pebbles to angular ones rises roughly in direction from S to N or NW (Bouška and Konta, 1990). Moreover, the weight of moldavite pebbles differs in the VB/KSG and at particular localities. The typical weight of moldavites in the VB is around 2 g (Bouška, 1992), the weight of moldavites in the KSG are typically higher, because of better resistance and sediment sorting during transport (Bouška and Konta, 1990; Bouška, 1992). Those characteristics are explained by the aforementioned authors as a sign of longer transport than in the case of the VB. The total length of moldavites' transport in the VB from the place of their fall is estimated at about 1 km at the most. Therefore, the VB are marked as strewn-field sediments. Moldavites underwent a longer transport, usually of a few kilometres, in KSG (Bouška, 1992). The VB and the KSG can sometimes be found in one locality. The KSG can be found in a superposition over the VB (Bouška, 1992; Nesrovnal, 1992) and also differences in the roundness of moldavites can help to distinguish those layers.

According to Žebera (1967, 1977), the KSG are the lateral equivalent of the VB. However, according to other authors (Bouška and Konta, 1990; Bouška, 1992; Ševčík et al., 2007; Pešek, 2010) they are much younger than the VB, Pliocene or Pleistocene. In any case, the KSG are very probably a polygenetic formation, which includes deposits of various origin and perhaps even various ages. The main problem is the varying angularity of the quartz pebbles in particular places, from angular to oval, caused by the sediment's different transport distance at a particular locality (Welser, 2020).

This study assumes the age of the KSG to be Pliocene and they are compared with the other fluvial deposits based on the many similarities of their morphostratigraphic position in the terrain and along the streams, and on the similarity of their sedimentological and petrological characteristics (Novák, 1983; Bouška and Konta, 1990; Nesrovnal, 1992). We cannot rule out that these deposits were actually formed during the same events. However, no authors have discussed that possibility yet. There are many localities of such deposits to the south of the Budějovice and Třeboň Basins and they are dated by various authors to the Pliocene (Novák, 1983; Bezvoda et al., 1983; Přibyl, 1999; ČGS, 2003). As they occur along the present flows of the Malše River, Vltava River or Stropnice River, they are often described as the oldest, Pliocene, fluvial terraces of these rivers (Novák, 1983; Přibyl, 1999) according to the classical setting known from other parts of Czech rivers (Balatka and Sládek, 1962; Tyráček and Havlíček, 2009, Balatka et al., 2015). Novák (1983) morphostratigraphically delineates five levels of Pliocene terraces (named Terrace 1-5) along the Malše River. This nomenclature is further used in this study because of its general overview of the study area and the fair concordance with other studies (Chábera, 1965, Popotnig et al., 2013). The terraces along other streams in the study area have not been surveyed so thoroughly, therefore the general term "Pliocene terrace/deposits" or "Pleistocene terrace/deposits" was used in this study. The delineation between Pliocene and Pleistocene terraces/deposits is based mostly on their morphostratigraphical position, due to the lack of other usable methods. The main difference between them is their position above or below the incised valley edge, following the preceding delineation used by Gibbard and Lewin (2009) and Tyráček and Havíček (2009).

The topographical, morphological and chronological connections between fluvial sediments with and without moldavites are not clear yet and are a subject of this study.

All the main rivers (Vltava, Malše and Stropnice) in the study area have developed a system of Quaternary river terraces. However, the proper description, dating and mapping (Puchta and Volšan, 1965; Novák, 1983; Přibyl, 1999; Homolová et al., 2012) of those terraces have only been carried out on the lower part of the streams in the surroundings of the Budějovice and Třebon Basins due to the very sparse occurrences of fluvial deposits on the upper parts of the streams. However, these terrace systems are complex enough to compare them with the course of the present water stream and also with the possible Pliocene deposits (see Fig. 3 for occurrences in the area and Fig. 10 for the Pliocene/Pleistocene terraces of the Malše). Note, that the Pleistocene terraces in the Bohemian Massif are traditionally dated by Alpine glaciation chronology. According to van Husen and Reitner (2001), the terrace levels can be assigned as: Würm - MIS 2-4, Riss – MIS 6, Mindel – MIS 12, Günz - MIS 16, Donau – MIS 22. Tschegg and Decker (2013) studied the Pleistocene terraces of the Vltava River in the Budějovice Basin. They found that the heavy mineral association differs in the (middle)

Pleistocene and pre-Pleistocene deposits, mostly due to a higher presence of amphibolites in the Pleistocene deposits. Unfortunately, they did not study the KSG and other Pliocene fluvial deposits, however, according to them and Bouška (1992), the delineation between the Pleistocene and older deposits can be clearly done since the source rocks and area remain similar through time.

Itis not possible to obtain the same spatial resolution for the position of the Pliocene deposits - because of their limited preservation - as in the case of reconstructing the Pleistocene terraces and their levels. It is possible to delineate some of the deposit levels, roughly at the scale described by Novák (1983), thus giving at least a division of the younger- and middle Pleistocene terraces from the older ones. This resolution is, however, sufficient to make a robust morphostratigraphical link to other Tertiary deposits in the study area and it can enlighten the major changes in stream network geometry from the Miocene until the present (supposed by Žebera, 1967; Malkovský, 1979). Žebera (1967), Malkovský (1979) and later also Tyráček (2001); Tyráček et al. (2004) and Ziegler and Dèzes (2007) proposed Southern Bohemia drained to the Alpine Foredeep in the Miocene-Late Pliocene time period. Přibyl (1999) investigated the possibility of southward Pliocene drainage of PaleoVltava by survey of the fluvial deposits (probably Pliocene – Bezvoda et al. (1983) and ČGS (2003)) near Horní Dvořiště (see Fig. 3), however he rather disagreed with the hypothesis. Chlupáč et al., (2002) and Bouška (1992) supposed the rejuvenation of the relief after sedimentation of Ledenice Fm. (see Fig. 4), the uplift of the Novohradské hory Mts. and Lišovský Horst and a change in drainage direction. All the studies are in concordance in principle about the succession of events leading to the change in drainage direction, however they differ from each other in the proper dating of the process.

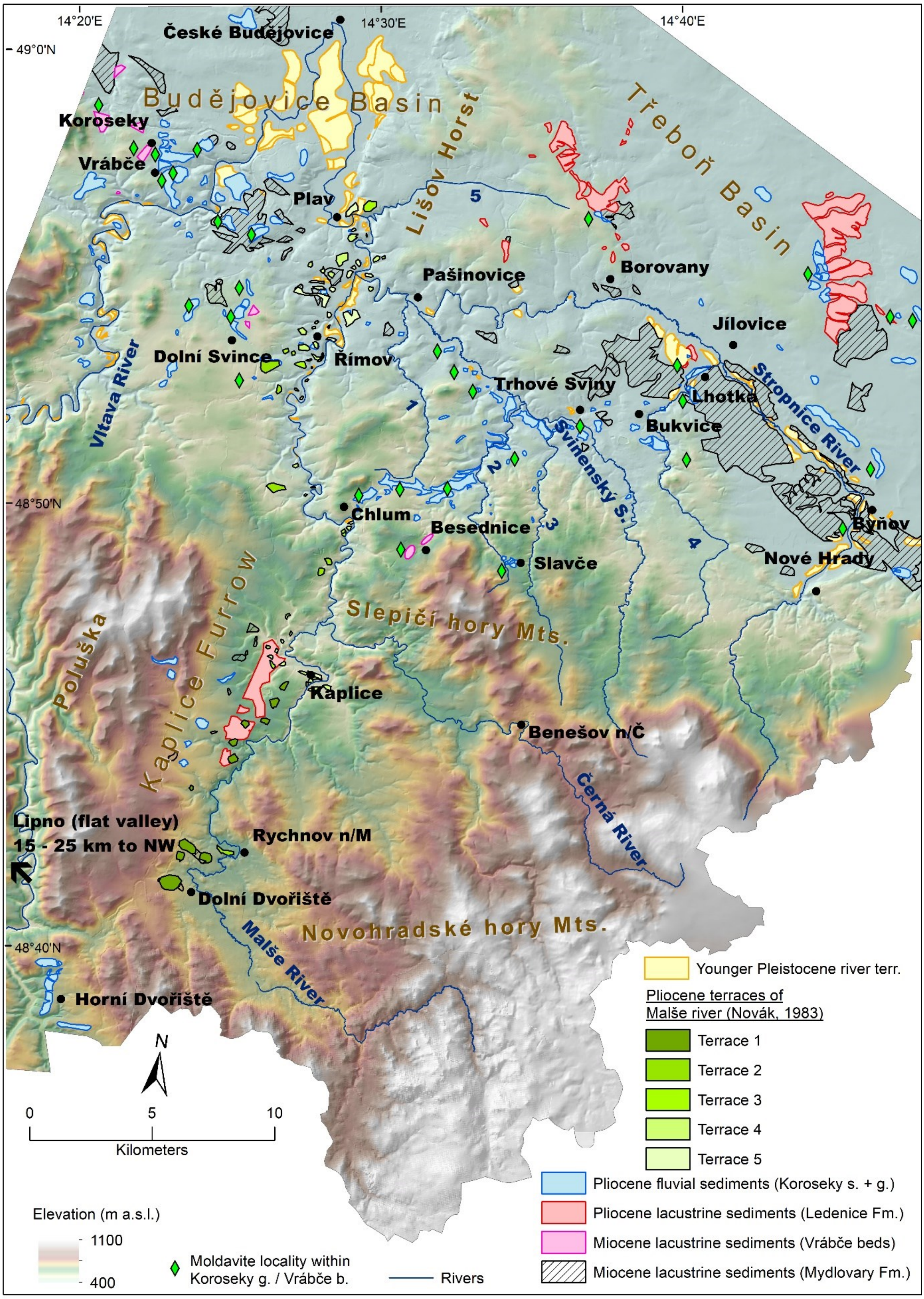


Fig. 3: Tertiary (Miocene and younger) sediments in the study area (1 – Pašinovický Stream, 2 – Keblanský Stream, 3 - Klenský Stream, 4 – Žárský Stream, 5 – Zborovský Stream). Elevation data source - DEM 4G (ČÚZK, 2017).

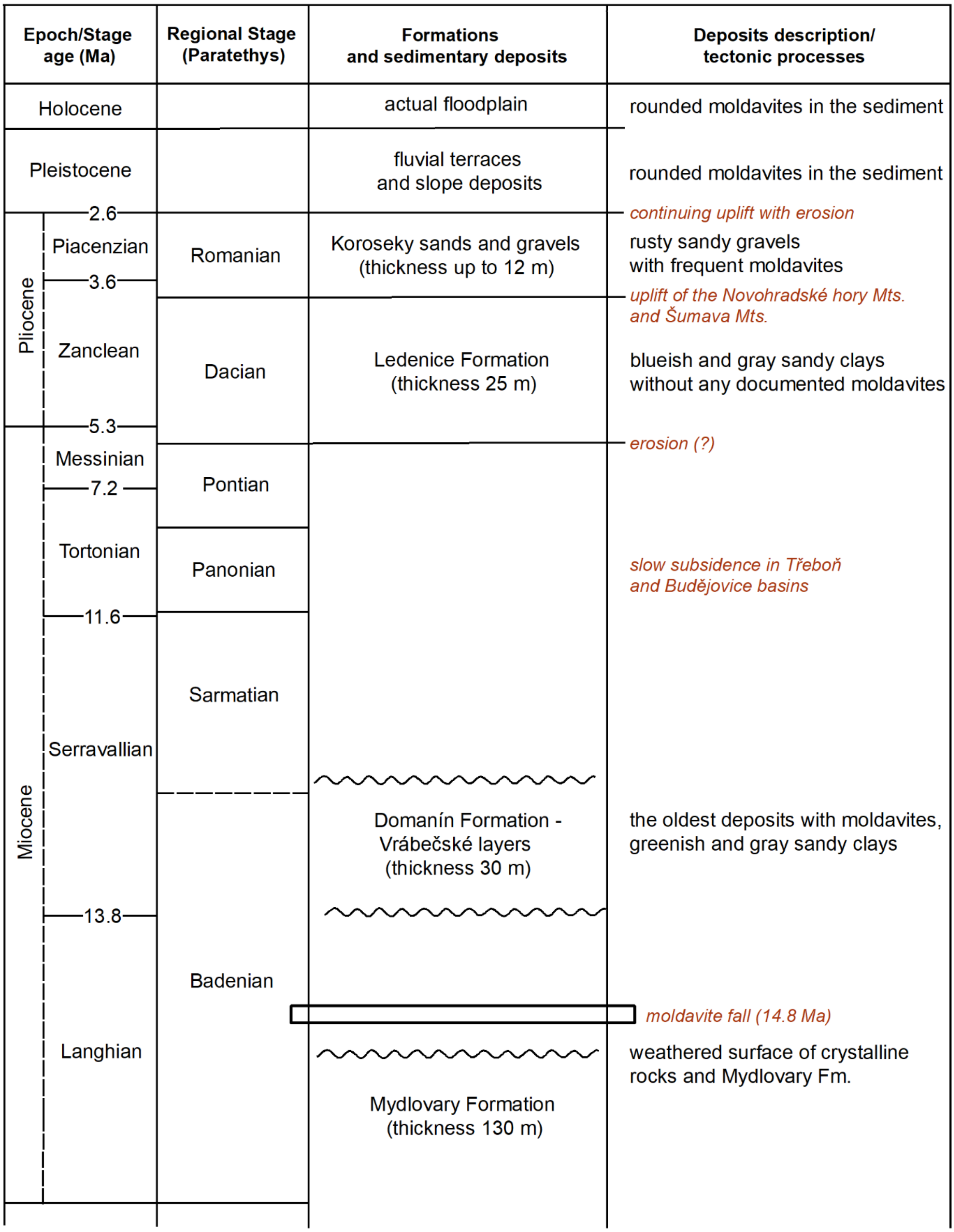


Fig. 4: Stratigraphical chart of the Tertiary deposits in the study area (Bouška, 1992).

3. Geomorphological and hydrological setting

A large part of the study area (see Fig. 3) is occupied by the ridges of the Novohradské hory Mts. (Gratzener Bergland/Weinsberger Wald). They were shaped by tectonic, fluvial and particularly periglacial processes (Rypl et al., 2017; Rypl et al., 2020). The Novohradské hory Mts. transform into the foothills (Rypl, 2004), with morphologically prominent Soběnovská Highlands (its highest part is locally known as Slepičí hory Mountains). Tectonically bounded, an elongated depression with a gentle relief - the Kaplice Furrow - separates the Novohradské hory Mts. and Slepičí hory Mts. from Poluška (part of the Šumava Foothills; Rypl, 2004). The north and north-eastern part of the area is occupied by the flat terrain of the Budějovice and Třeboň Basins. They are bounded by faults of NW-SE and NNE-SSW orientation, and they are tectonically separated from each other by Lišov Horst (Balatka and Kalvoda, 2006). Many water streams in the study area have formed deeply incised valleys, typical for areas with a young uplift regime. Most of the selected area is drained by the Malše River and its tributaries to the catchment of the Vltava River (Moldau in German), the main river for this part of the Bohemian Massif. However, a significant part lays in the catchment of the Lužnice River (Třeboň Basin) and some small areas are drained by small streams southwards, to the catchment of the Danube River (see Fig. 2b and Fig. 3 for the location of streams).

The Malše River is typical for its broad, flat valley in the upper part of the stream and a narrow, V-shaped valley in the lower part of the stream (Lett, 2004). This river style can also be found in the other mountainous regions throughout Bohemian Massif and it is a sign of the recent tectonic rejuvenation of these areas (Balatka a Kalvoda, 2006). Gradient conditions and fluvial styles vary quite often along the Stropnice River: from a mountainous stream in the upper part, through the meandering, low gradient part in the middle, to the deeply incised valley in the lower part (Lett, 2004). The Svinenský Stream is interesting for its significant course changes, as well as for the asymmetric catchment. Another important feature is the flat wide valley of the lower part, untypical for a low order (Strahler) stream in such a hilly terrain (Lett, 2004). The Černá River is a typical mountain stream with a high gradient and a narrow, deep valley (Balatka and Sládek, 1962; T. G. Masaryk Water Research Institute, 2021).

The Vltava River is not a key part of this study. Its course, longitudinal profiles and fluvial deposits are mainly used for comparing with those of the Malše and other streams and for an overall reconstruction of the palaeogeographical situation. For a more detailed understanding of the Vltava River see Chábera and Novák (1975); Přibyl (1999); Tyráček (2001); Tyráček et al. (2004); Balatka et al. (2015).

4. Critical review

The outcrops of various Tertiary and Quaternary deposits in the study area were mapped by many previous studies and maps (Mayer, 1959; Krátká, 1966; Březinová et al., 1963; Puchta and Volšan, 1965; Žebera, 1967; Chábera and Novák, 1975; Švára, 1981; Novák, 1983; Bezvoda et al., 1983; Kroupa, 1984; Mahel et al., 1984; Bittman et al., 1985; Bouška and Konta, 1990; Slabý and Holásek, 1992; Vrána and Holásek, 1992; Vrána and Novák, 1993; Nesrovnal et al., 1995; ČGS, 2003; Homolová et al., 2012). The localization and extent of the sedimentary bodies can be considered as reliable, as many of these studies are in concordance. Studies by Chábera (1965), Žebera (1967), Konta (1972), Novák (1982), Bouška and Konta (1990), Bouška (1992), Nesrovnal (1992), Trnka and Houzar (2002), Tschegg and Decker (2013), Welser et al. (2020) give a very detailed description of the petrological, sedimentological and other parameters of fluvial deposits, particularly the KSG and Pleistocene river terraces. Many of the aforementioned studies also try to find the correct time the various fluvial deposits originated. Only a few of them (Březinová et al., 1963; Ševčík et al., 2007; Homolová et al., 2012) use absolute dating methods (because of a lack of suitable methods and datable materials in the fluvial deposits). Studies by Chábera (1965), Chábera and Novák (1975), Novák (1983), Bouška and Konta (1990) try to date the fluvial deposits morphostratigraphically. These methods cannot be precise, however, many publications from the Bohemian Massif (Tyráček, 2001; Tyráček et al., 2004; Tyráček and Havlíček, 2009; Balatka and Kalvoda; 2010; Balatka et al., 2015) show, that they can work, especially combined with modern methods (e.g., LiDAR DEM). Chábera (1965) and Novák (1983) did very precise work and their results can be directly compared with radiometrically dated Pleistocene deposits by Homolová et al. (2012). Therefore, these studies and their approach are essential for further research. Unfortunately, some studies, Žebera (1967), partially Malkovský (1979) or Welser et al. (2020) – despite their other contributions – underestimate the importance of the morphostratigraphical position of fluvial deposits and therefore these studies cannot be fully used in a study like this. The evaluation of the morphostratigraphical position of the deposits can be easily improved by using morphometric analysis (e.g., basin asymmetry, valley floor ratio, stream gradient). Many studies around the world show that the morphostratigraphic relations is important sources of information regarding terrain and stream network evolution (e.g., Burbank and Anderson, 2001; Keller and Pinter, 2002; Guttierrez, 2013).

One of the biggest issues is the correct dating of the moldavite-bearing deposits, especially KSG. According to Žebera (1967), who assigns the KSG to the middle or upper Miocene (as well as the VB), they contain iron oxides, as evidence of the warm and humid climate of the Miocene. Similarly, Novák (1983) dated the "oldest" fluvial terraces of the Malše River to "Tertiary", probably Pliocene, or upper Miocene. However, Bouška (1992) suggests the redeposition of the "red soil" into much younger sediments (of Pliocene or Pleistocene age) and he further proves the younger age of them by the presence of non-weathered feldspars (so they must have originated in a colder climate). Also, other studies by Chábera (1965); Konta (1972); Chábera and Novák (1975); Bouška (1992); Shrbený et al. (1994); Ševčík et al. (2007); Skála et al. (2016) put the KSG in the Pliocene or even Pleistocene (see Fig. 4). They agree that the KSG are separated at least by the Ledenice formation from the VB and therefore are much younger. It could be proved by the palynological dating made by Ševčík et al. (2007) and the superposition of the KSG over the Ledenice formation described by Bouška (1992). The Ledenice formation is traditionally dated to the Pliocene (Březinová et al., 1963; Pešek, 2010). It is then much younger than the moldavite fall (ca 14.8 Ma), the Domanín formation and possibly the VB. However, it contains no moldavites (Bouška, 1992). The deposits of the Kaplice Furrow, which were dated to the late Pliocene (Březinová et al., 1963) and possibly are a lateral equivalent of the Ledenice formation, also do not contain any moldavites. Nevertheless, deposits of the Ledenice formation or those in the Kaplice Furrow are quite often accompanied or overlaid by the KSG which do contain moldavites and they are probably younger. This was proven by Bouška (1992), when he described the superposition of moldavite-bearing gravels over the Ledenice formation in the clay-pit in Borovany. This situation can be explained by the higher erosive activity during the Pliocene, which followed the deposition of the Ledenice formation and was caused by a significant tectonic uplift. This resulted in exposure of older deposits with moldavites (probably the Domanín formation and similar), their erosion, transport and formation of fluvial moldavite-bearing KSG above the Ledenice formation.

Welser et al. (2020) describe an outcrop in the KSG with a possible, lateral transition to the VB near Chlum, which is in contrast with Bouška (1992). However, this situation can be also interpreted by later (Pliocene) erosive activity and exposure of the older formations (see above). Moreover, this discrepancy can be explained by the polygenetic character of the KSG when deposits from particular places can actually originate in different ages.

Nevertheless, moldavite-bearing gravels can be found of both Miocene and Pliocene-Pleistocene age, but, according to their morphostratigraphic position, it seems that most of them are the younger ones. In this study, it is assumed the KSG is Pliocene. This could be rather problematic and in contrast with the traditional view of Žebera (1967), Trnka and Houzar (2002), Welser et al. (2020) and others (see above). However, this question has been discussed for many years and the precise analysis of previous studies has discovered that many authors put the KSG to the Pliocene as well (e.g., Bouška and Konta, 1990; Bouška, 1992; Nesrovnal, 1992) and others (see above).

Most of the authors (e.g., Kopecký and Vyskočil, 1969; Malkovský, 1979; Chábera, 1982; Bouška, 1992; Tyráček et al., 2004; Popotnig et al., 2013) are in concordance that the area of the Novohradské hory Mts. and its foothills underwent a significant uplift, which have affected the terrain morphology and stream geometry. They proposed that these events happened during the Pliocene or Pleistocene

(Chábera, 1982). Despite the lack of a more precise dating, these are the only available studies it is possible to rely on.

5. Data and methods

5.1. Basin Asymmetry, Valley floor ratio, Stream gradient and longitudinal profiles

Simple geomorphological methods were used to assess the evolution of the relief and stream network (see Tab. 1, particularly for references).

Tab. 1: Geomorphological methods used during the study

Method	Equation	Details	References
Basin asymmetry	Af = 100 (Ar/At)	*Ar* = the area of the basin of the right side of the main stream *At* = the total area of the basin.	Keller and Pinter, 2002; Badura et al., 2007; Gutierrez, 2013
Valley floor ratio	$V_f = 2V_{fw}/[(E_{ld}-E_{sc})+(E_{rd}-E_{sc})]$	V_f = valley floor width-to-height ratio V_{fw} = width of the valley floor E_{ld}, E_{rd} = elevations of the left and right valley divides E_{sc} = the elevation of the valley floor	Keller and Pinter 2002; Burbank and Anderson 2001; Hamdouni et al., 2008; Bull, 2007; Štěpančíková et al., 2008
Stream gradient	Sg = ΔH/ΔL	*Sg* = stream gradient *ΔH* = height difference along the reach *ΔL* length of the reach (100 m)	Wheeler, 1979; Burbank and Anderson, 2001; Keller and Pinter, 2002; Willet, 2006

Basin Asymmetry is used for detecting the tilting of a particular basin due to tectonic movements. A value of 50 indicates stability, whereas deviations from 50 suggest recent tectonic influence on the catchment Also, the asymmetry suggests the direction of tilting. Typically, smaller catchments are used for this analysis, however some studies (Dhanya, 2014; Baioni, 2016) show that basin asymmetry can be used even at a larger scale or along particular streams in order to study the evolution of the basin itself. The asymmetry in the study area was surveyed on the main streams - (Malše, Černá, Stropnice, Svinenský, Klenský, Keblanský, Pašinovický). The left/right - directed asymmetry is not the main aim of this analysis, as we studied the catchments in larger scale to get a regional insight into possible uplift, and for a better understanding of the drainage system's evolution.

The *Valley floor ratio* differentiates between broad-floored canyons, with relatively high values of V_f , and V-shaped valleys, with relatively low values. Studies from active tectonic regions suggest that Vf values lower than 1 indicate active uplift whereas higher values indicate a steady state (e.g., Hamdouni et al., 2008). However, in regions like the Bohemian Massif rather higher values are obtained and the tool itself is better for a relative comparison within the study area. High values of V_f (typically >3 in the study area) are associated with low uplift rates, so that streams cut broad valleys. Low values (typically <2 in the study area)reflect deep valleys with actively incising streams, commonly associated with uplift. 27 cross sections across the valleys of water streams were made during the survey.

Stream gradient is usually expressed in *‰*, because the values are typically in the scale of *m/km*. Related longitudinal profiles of the water streams (Vltava, Malše, Černá, Stropnice, Svinenský, Klenský, Keblanský, Pašinovický) were made based on the DEM. Rivers that are not tectonically perturbed typically develop a smoothly changing, concave longitudinal profile. Departures of the river gradient from this ideal smooth shape may reflect variations in the lithology of the riverbed, or variations in the rock uplift rate of the riverbed. The courses of longitudinal profiles as well as values of stream gradient were compared with the lithological composition (ČGS, 2003) to find the possible knickpoints and other places of changing water stream geometry and therefore of tectonic influence.

5.2. Occurrences of fluvial deposits and their longitudinal profiles

The basic topographic information, necessary for the morphostratigraphical correlation and placing of fluvial deposits, was obtained from the digital elevation model (DEM), which was based on LiDAR remote sensing (Digitální model reliéfu České republiky 4. generace/Digital Terrain Model of the Czech Republic of the 4^{th} generation (DEM 4G)), vertical resolution 1 m (ČÚZK, 2017). The information about lithology, fluvial deposits and moldavite-bearing sediments was obtained from basic geological maps of the area (Mahel et al., 1984; Vrána and Novák, 1993; Slabý and Holásek, 1992a; Slabý and Holásek, 1992b; Vrána and Holásek, 1992), borehole documentation (Mayer, 1959; Krátká, 1966; Švára, 1981;

Kroupa, 1984; Bittman et al., 1985; Nesrovnal et al., 1995) as well as from many previous studies (Březinová et al., 1963; Puchta and Volšan, 1965; Žebera, 1967; Chábera and Novák, 1975;Novák, 1983; Bezvoda et al., 1983; Bouška and Konta, 1990; Homolová et al., 2012). The occurrence and extent of the fluvial deposits and moldavite-bearing sediments described in the studies above was extended and locally specified by a simple field survey focused on the basic character and composition of the sediment (e.g., the location of pits for illegal moldavite mining were used to extend previously mapped deposits). On the other hand, it was found that many previously described localities of KSG or VB are Pleistocene alluvium or even anthropogenic layers created during gold mining (Ernée et al., 2014). Historical sources were used for correcting some faults in the topographic maps or for avoiding the anthropogenic influence on water streams. The historical maps (2^{nd} military Survey, Austrian State Archive/Military Archive Vienna and UJEP and MŽP, 2014) and historical aerial photographs (VGHMÚ, 2014) were used for these adjustments.

The longitudinal profiles of the fluvial deposits were constructed along the watercourses Vltava, Malše, Stropnice, Svinenský Stream and several tributaries. Unfortunately, other streams in the area (e.g., Černá River) do not have fluvial deposits complex enough to reconstruct the profile.

It cannot be ruled out that there are significant effects from solifluction and other soil and rock movements linked to the climate changes during the Pleistocene. When re-evaluating, the altitude relationship between particular fluvial deposits, only those occurrences of deposits where the slope inclination was up to 2° were used and where the possible effect of solifluction is insignificant.

6. New results

6.1. Basin Asymmetry

The basin asymmetry was studied in the basins of the watercourses Malše, Černá, Stropnice, Svinenský, Klenský, Keblanský, Pašinovický (Fig. 5). It is thought there is possible stream capturing through the evolution of basins and the overall shapes of the basins are often remarkable. For that reason and for a better comparison between parts of the basins, the Malše, Stropnice and Svinenský basins were also divided into several sub-basins (lower/upper part of the stream). The basins of the Stropnice and Svinenský streams show an indication of basin tilting towards NE, possibly due to uplift of the main mountain massif of the Novohradské hory Mts. (Fig. 5). If the streams are assessed separately, the asymmetry is even more conspicuous.

Rather asymmetric basins can be found in the study area, with the Af values between 23 - 37. However, the remarkable feature is that the upper parts (of approx. S-N orientation) of the Malše, Stropnice and Svinenský Stream basins (Af = 34 - 46) are more symmetrical than the lower parts or the basin as a whole (Af = 23 - 33). Therefore, it could be a sign of a different evolution of those particular parts. The upper part of the Stropnice River is still rather asymmetrical, a possible capture of part of its basin by the Žárský stream can´t be ruled out.

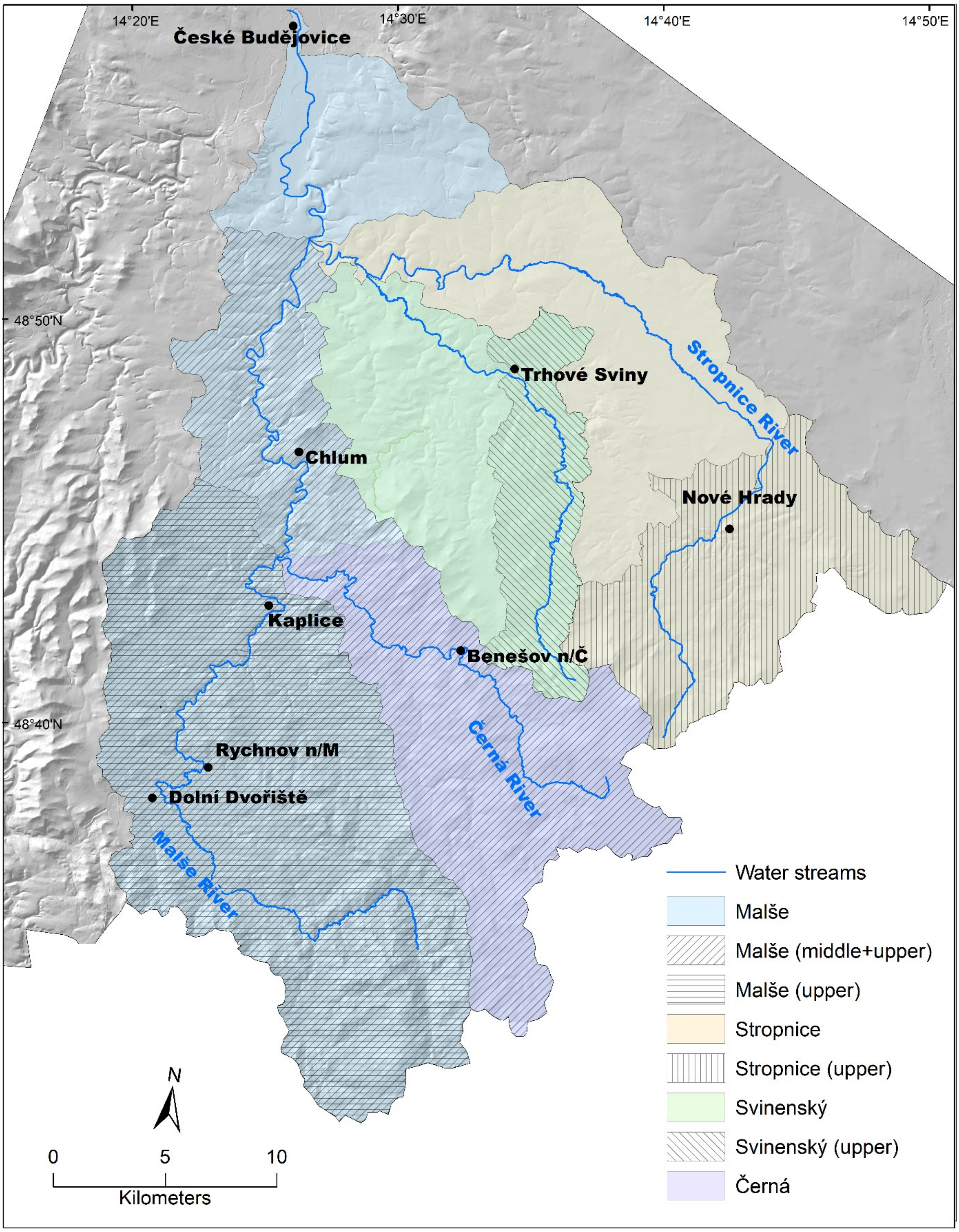


Fig. 5: Basins of the particular streams, where Basin Asymmetry (Af) was calculated (see Tab. 2). Elevation data source - DEM 4G (ČÚZK, 2017).

Table 2: The streams' basin asymmetry values (stream length and basin area obtained from T. G. Masaryk Water Research Institute, 2021)

Water stream	*Af*	*Stream length (km)*	*Basin area (km^2)*
Černá	31	29.3	148
Klenský	37	14.2	23.7
Keblanský	28	9.6	29.7
Pašinovický	33	10.2	18
Stropnice	34	54	402.4
Stropnice (upper part)	34	20	105.5
Svinenský	23	30	129.4
Svinenský (upper part)	42	18	50
Malše	33	96	979.1
Malše (middle+upper part)	46	80.3	650.1
Malše (upper part)	43	60	244

6.2. Valley floor ratio

Various Vf values can be found throughout the study area (see Tab. 3). The most interesting are the changes in values within the particular streams. The upper part of Svinenský stream has lower values (profiles no. 4-6, values 1.3-2.2), which differ significantly from values from the lower part and its wide valley (profiles no. 1-3, values 3.2 – 4.8), which is rather untypical for such a small stream in hilly terrain (see profiles 2 and 3 on the Fig. 6). In contrast, the lower part of the Stropnice River has low values (profiles no. 7-10; values 0.85-1.4) due to its deeply incised valley (see profile 9 and 3 on the Fig. 6). The wide, shallow valley of the river flowing through the Třeboň Basin (profiles no. 11-13) has values of 4.17 – 15.8 and the upper part (profile no. 14) has values under 1, which is typical for streams in mountainous terrain. Most of the course of the Malše River is in an incised valley (profiles no. 16-19, values 1-2.7). However, its lower part, in the Budějovice Basin (profile no. 15), has high values (13.81) due to flat terrain, as well as the upper part above Rychnov nad Malší (profile no. 20, value 6.22), where the terrain is untypically flat and is a possible remnant of a Neogene peneplain (Balatka and Kalvoda, 2006). A similar pattern can be observed on the Vltava River, with a wide flat valley (now flooded by the Lipno dam lake) on the upper part and a deeply incised valley (profiles no. 26-27, values 0.55-0.62) towards the Budějovice Basin.

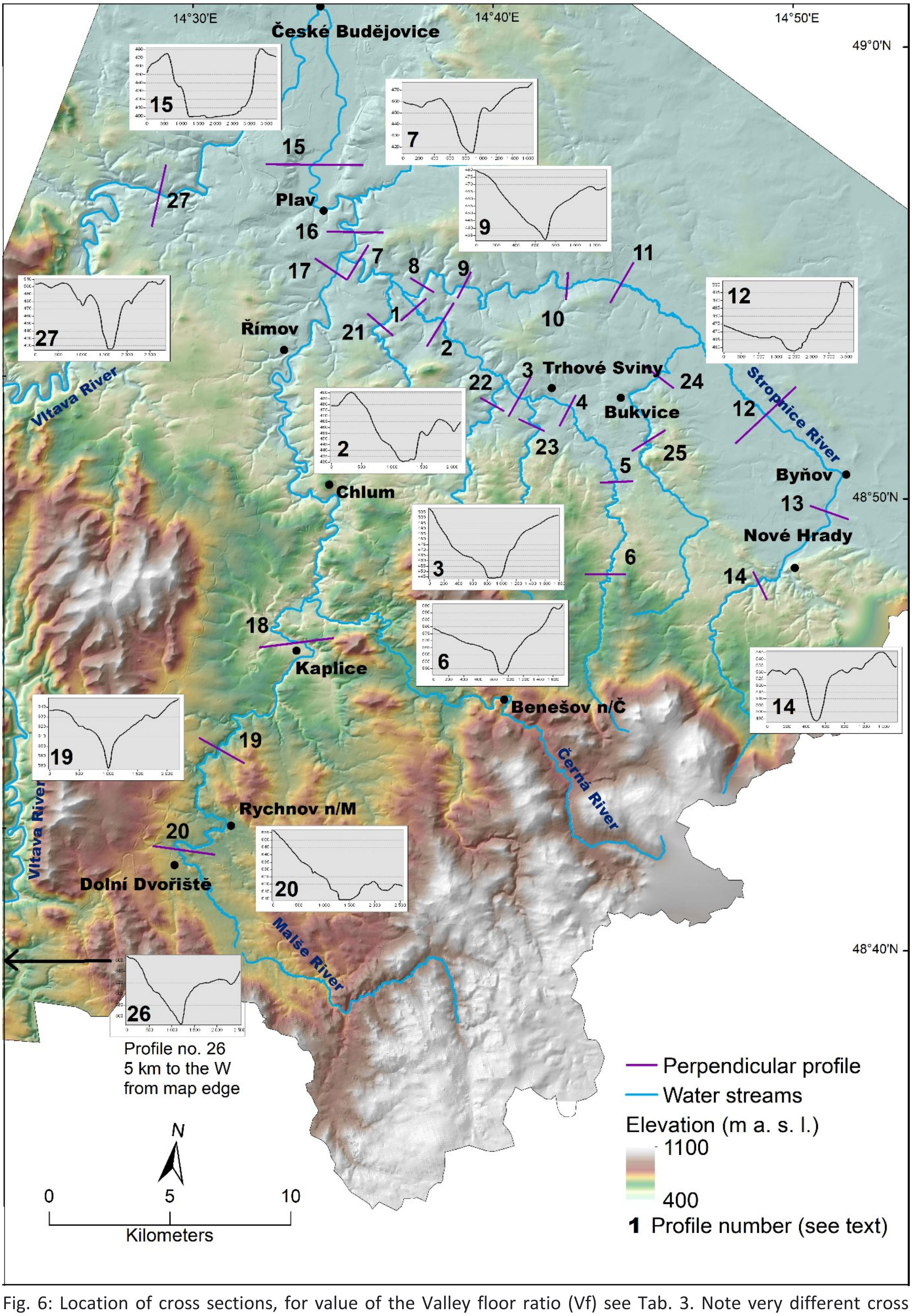


Fig. 6: Location of cross sections, for value of the Valley floor ratio (Vf) see Tab. 3. Note very different cross sections on the particular parts of the streams (see section 6.2). Elevation data source - DEM 4G (ČÚZK, 2017).

Table 3: Values of the valley floor ratio (Vf) on profiles. The cross sections of the selected (underlined) profiles can be seen on Fig. 6

no. of profile	*Stream – profile location*	*Vf*
1	Svinenský – Komařice	4.72
2	Svinenský – Stradov	4.41
3	Svinenský – mouth of Klenský	3.36
4	Svinenský – Trhove Sviny	2.16
5	Svinenský – Pěnčín	1.33
6	Svinenský – Kamenná	1.37
7	Stropnice - confluence with Malše	0.85
8	Stropnice - Komařice	1.10
9	Stropnice - Jedovary	1.90
10	Stropnice - Borovany	1.40
11	Stropnice - Dvorec	9.90
12	Stropnice - Petříkov	15.79
13	Stropnice - Štipoň	4.17
14	Stropnice - Terčino údolí	0.88
15	Malše - Včelná	13.81
16	Malše - Doudleby	1.02
17	Malše - mouth of Stropnice	2.35
18	Malše - Kaplice	5.41
19	Malše - Nažidla	2.71
20	Malše - Dolní Dvořiště	6.22
21	Pašínovický - Sedlo	1.38
22	Keblanský - Lniště	0.82
23	Klenský - Lniště	1.08
24	Žárský - Olešnice	3.02
25	Žárský - Hrádek	0.80
26	Vltava - Hrudkov	0.55
27	Vltava - Jamné	0.62

6.3. Spatial distribution of fluvial deposits along streams

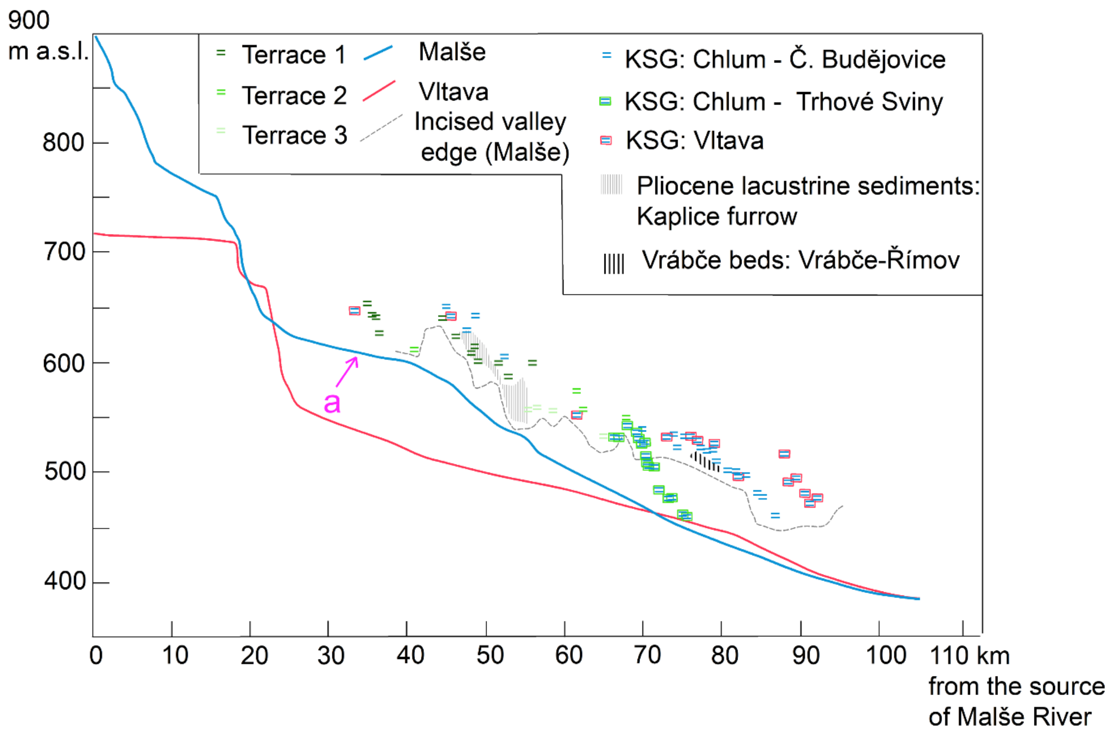
The number of Pliocene fluvial deposits occurring along the Malše River were recorded. Most of them are located on the left bank (see Fig. 3). Their occurrences generally follow the direction of the present course of the Malše and Vltava.

There is a significant asymmetry in the location of the Pliocene and Pleistocene terraces along the Malše River. In the section between Dolní Dvořiště and Chlum, the deposits are only on the left (west) bank of the river. However, in the lower part of the stream, the terraces (Mindel and younger) were located rather symmetrically on both banks. This could be a sign of stream migration from W to E in that particular section of the stream, possibly caused by the gently inclining left bank. It could also be explained by the strong uplift of the eastern bank along the faults of the Blanice-Rodl system (Novohradské hory Mts. and Slepičí hory Mts.) and the subsequent intensive erosion, which destroyed the fluvial deposits. The left bank (Kaplice Furrow) could have been relatively stable (however inclining), or even subsiding, and fluvial deposits were preserved there. This phenomenon is also accordingly described by Novák (1983). In contrast, the Vltava River terraces of various ages can be found on both its banks, where the processes of uplift and erosion were probably different.

The Pliocene and Pleistocene fluvial deposits can also be found along the Stropnice River and the Svinenský Stream. Due to the mountainous terrain, these deposits remained mainly in the gentle relief of the Třeboň Basin (middle part of the stream), where the Pleistocene and Pliocene terraces are located. Also, the middle part of the Svinenský stream is typical for its abundance of KSG outcrops. An interesting distribution of deposits can be found along those streams. There are very few documented localities of Pliocene deposits along Stropnice River in the section between its confluence with the Svinenský Stream and Jílovice; in this section only younger, Pleistocene terraces were recorded. However, many of the Pliocene deposits (KSG) are well preserved in the section between Jílovice and Byňov and the deposits can be found even on the flat watershed between the Stropnice River and the Svinenský Stream in the surroundings of Bukvice. Remarkably, numerous outcrops of KSG can be found along the central lower part of Svinenský Stream (see Fig 2.). Younger Pliocene terraces are documented scarcely in this section of the stream, in contrast to the situation on the lower section of the Stropnice River. This could be one sign of stream capturing (see section 7.).

6.4. River longitudinal profiles

Generally, the longitudinal river profiles have a higher stream gradient in the upper parts and are gentler in the lower parts, however, a significant steepening of the gradient can be observed in particular sections of each stream. This can be an effect of lithology or, more probably, a tectonic uplift. The remarkable sections (see Fig. 8) can be found on the Stropnice River. Significant steepening (up to 15 ‰) can be found near Nové Hrady (15 km from the stream source) on the edge of the Třeboň Basin (see point a) in Fig. 8 and Fig. 11). It is caused by backward erosion, which could have been induced by the uplift of the foothills or subsidence of the basin, respectively. The untypical steepening of the gradient (4 ‰) can also be found on the lower part of the stream (see point c) in Fig. 8), compared to the central part (1 ‰, see point b) in Fig. 8 and Fig. 11) or to its tributary – the lower part of the Svinenský Stream (1-2‰). The Svinenský Stream itself has a complex profile, with several steepening sections and a low gradient on the lower part, which are not present on other streams in the area. This can suggest a complex evolution for the stream, affected by multiple phases of uplift and possible stream capture in the area between Jílovice and Trhové Sviny (see Fig. 11 and Fig. 8 for the profile). The section with an exceptionally low gradient on the upper stream is also on the Malše River (1.8 ‰) near Rychnov (see point a) in Fig. 7 and Fig. 11), possibly as an intact remnant of a pre-uplift valley from the Miocene/older Pliocene (see Fig. 7).



ig. 7: Longitudinal profiles of the Malše and Vltava Rivers, including Pliocene deposits and valley edge (left bank) of the Malše River. Note that the surfaces of deposits are expressed in profiles. For section a) with remarkable gradient see text.

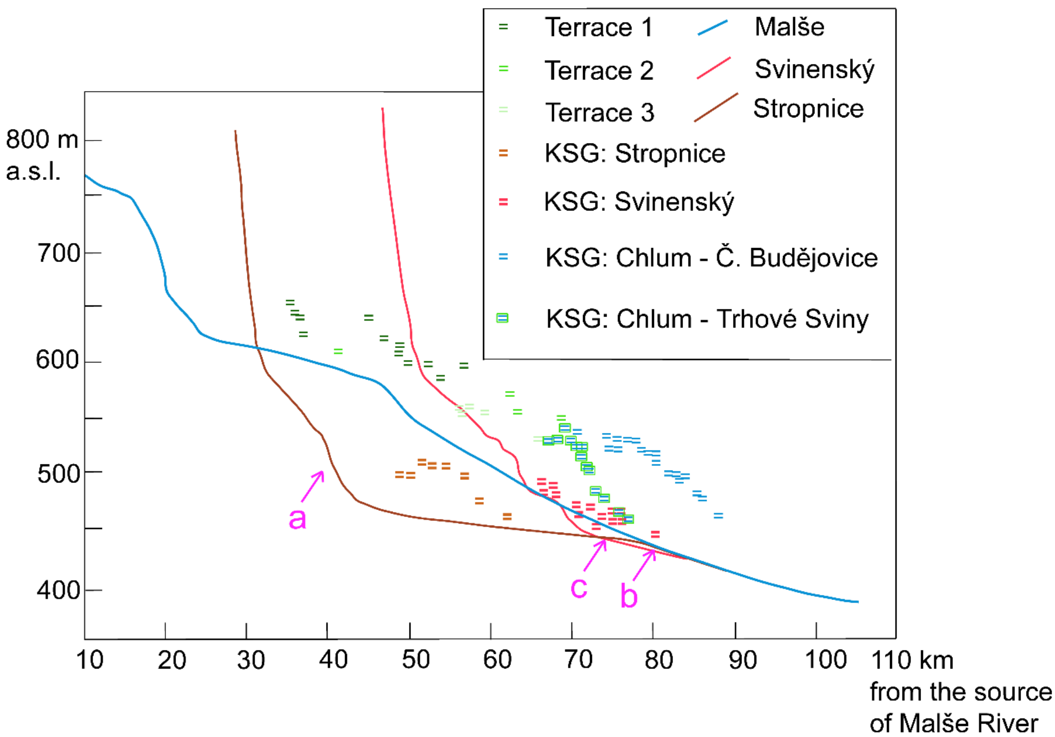


Fig. 8: Longitudinal profiles of the Malše River and its tributaries. Note two main levels of fluvial deposits. Surfaces of deposits are expressed in profiles. For sections a), b), c) with remarkable gradient see text. Note that different symbol for KSG: Chlum – Trhové Sviny is used only for better delineation from other symbols.

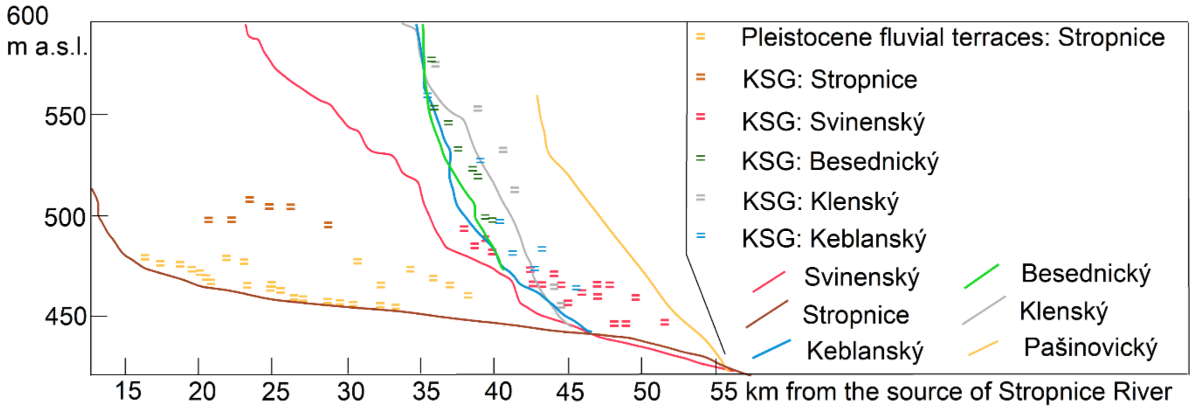


Fig. 9: Longitudinal profiles of lower part of Stropnice River and its tributaries. Note a difference in elevation and gradient between deposits along Stropnice/Svinenský and the rest of the streams. Surfaces of deposits are expressed in profiles.

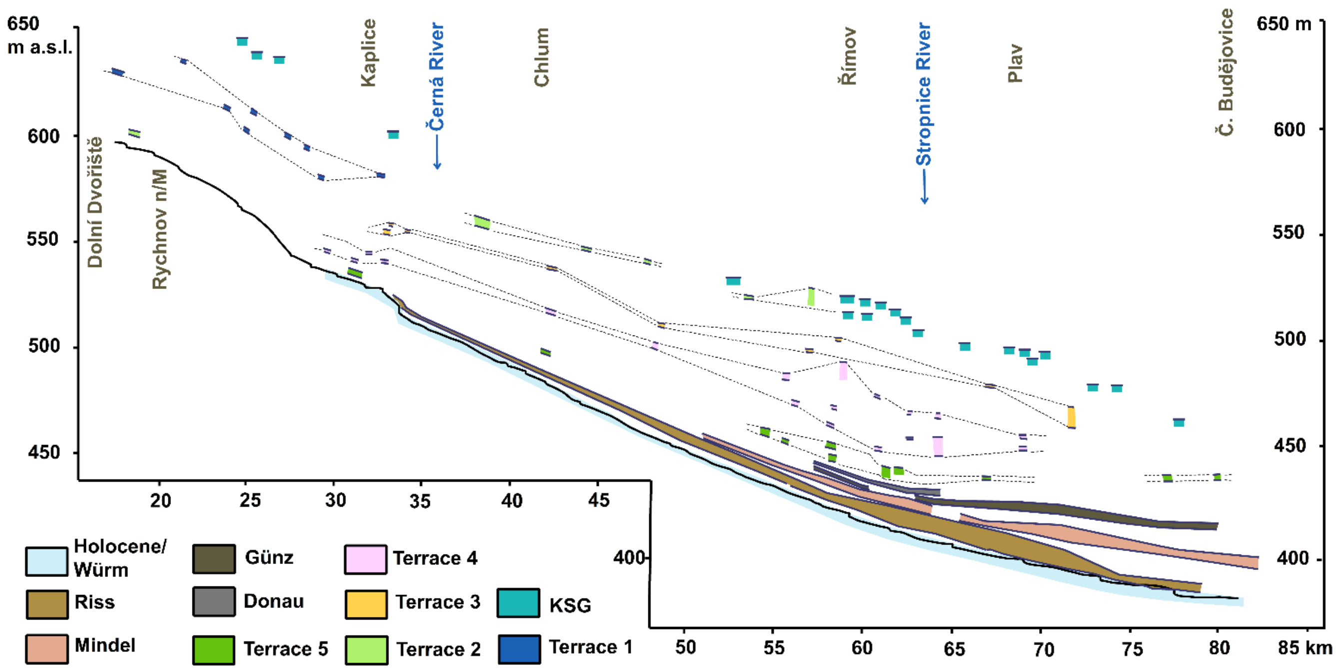


Fig. 10 Comparing the KSG, Pliocene terraces (1-5) and Pleistocene terraces (Donau-Holocene) of the Malše River, according to Novák (1983). Note the traditional terrace setting, MIS stages according to van Husen and Reitner (2011): Würm - MIS 2-4, Riss – MIS 6, Mindel – MIS 12, Günz - MIS 16, Donau – MIS 22. Surfaces and bases (where possible) of deposits are expressed.

6.5. Longitudinal profiles of Pliocene fluvial deposits

6.5.1. Malše

The KSG and Pliocene terraces 1-5 described by Novák (1983) are very abundant along the Malše River and significantly separated from the younger Pleistocene terraces below the edge of the incised valley. This study shows that the occurrences of KSG (as traditionally delineated) fit best to terrace levels 2 or 3 as they were defined by Novak (1983; see Fig. 7). The occurrences of KSG between Chlum and Trhové Sviny (57-66 km) (see Fig. 3) can also be seen, where they have a significantly steeper profile, which is probably caused by Pleistocene redeposition along shorter tributaries of the Svinenský Stream – the Klenský, Keblanský and Pašinovický streams (see Fig. 7). The altitude of deposits is decreasing from 650 to 460 m a.s.l. along the Malše River. The deposits lay between 15 m and 90 m, but mostly around 50 m above the flood plain (for the altitude of particular terraces, see Fig. 7). Comparably, the Pliocene terraces along the neighbouring Vltava River lie in a similar altitude range, however significantly higher above the present flood plain (110 -55 m) due to more intense incision during the Pleistocene. The morphostratigraphical position of the palynologically dated Pliocene lacustrine sediments in the Kaplice Furrow (Březinová et al., 1963) underlying some of the terrace levels also suggest a younger age for the KSG.

6.5.2. Stropnice

Pliocene deposits along the Stropnice River are much less complex. Most of the terraces of Pliocene or Pleistocene age are in the central part of the stream. The valley is very shallow and wide without distinct valley edges. The deposits along the Stropnice River can be found at an altitude of 510 – 445 m a. s. l. and 50-20 m above the present flood plain (see Fig. 8 and 7). The altitude difference between deposits and the present flood plain as well as absolute altitude is much lower than along the Malše and Vltava Rivers. In contrast, the altitudinal position is very similar to the deposits' position along the Svinenský Stream. Because of this smaller relative height of the deposits, it is difficult to delineate more than two Pliocene levels. However, they can be clearly morphostratigraphically distinguished from the younger Pleistocene deposits, which show at least two levels as well (probably one from Riss and the older one).

6.5.3. Svinenský Stream and its tributaries

The occurrence of fluvial deposits along the Svinenský stream have a very similar character as along the Stropnice River: 490 – 445 m a. s. l. and 30-15 m above the present flood plain (see Fig. 9). Also, the longitudinal profile of deposits is similar to the current stream profile within its upper and central part.

A significant steepening in the longitudinal profile of the KSG can be seen in the area between Chlum (Besednice) and Trhové Sviny along the tributaries of the Svinenský (Klenský, Keblanský, Pašinovický streams) (Fig. 3 and 7). The deposits are in a wide range of altitudes: 580 - 455 m a. s. l., however very often only 20-15 m above the present flood plain. The longitudinal profiles of gravels are in fair concordance with the longitudinal profiles of present streams. The whole situation differs significantly from the profiles along the Svinenský Stream and along the Stropnice and Malše Rivers. This is probably caused by the intensive uplift of the mountainous area of Slepičí hory Mts. and the associated strong denudation and redeposition of the sediments during the Pleistocene.

7. Discussion

As the many issues - regarding the age of the deposits, their spatial relationship, effect of tectonics etc. - rise from the previous parts of this study, it is necessary to divide the Discussion to several sections for better clarity.

7.1. General issues of dating and relationships between the fluvial deposits.

Generally, the connections between fluvial deposits in the study area is problematic due to a lack of absolute dating. Therefore, this study must proceed very carefully when using morphostratigraphical relationships and scarce dated deposits (Březinová et al., 1963; Homolová et al., 2012); and carefully reassess the results from older studies (see section 4. Critical review).

The classification of the older fluvial deposits at a higher relative position (above the upper edge of the incised valley slopes) is much disunited and it differs in published studies (see section 4. Critical review). Many of the deposits can actually be younger or older than is currently suggested in the studies. Some authors put the deposits laying close to each other, on the same level, i.e., to "Günz", some to "Pliocene" (e.g., difference between Novák (1983) and the Geological map 1:50 000 (ČGS, 2003). In this study, it is assumed, in concordance with Novák (1983) and Tyráček and Havlíček (2009) that deposits laying above the incised valley are minimally of older Pleistocene age or Pliocene age.

There are many occurrences of fluvial deposits that are mentioned and dated in the older studies in the study area that raise issues (too high, or don't fit in the longitudinal profiles). It is caused by a lack of instrumental dating and by the strong visual, sedimentological and partially petrological similarity of the deposits. It is for these reasons that it is difficult to delineate which deposits in some parts of study area are of Pleistocene, Pliocene, or even Cretaceous age (e.g., the weathered rocks of Klikov Fm.).

Many terraces are actually Pliocene rather than Pleistocene, according to their elevation level (e.g., the surroundings of Lhotka, Bukvice (Virt, 2009)). The occurrence of the moldavite-bearing gravels at an elevation higher than 600 m a. s. l. is very rare and it can be explained by the significant Pleistocene uplift also described by Chábera (1982). Many of the moldavite-bearing gravels were eroded during the Pleistocene uplift, but they can be preserved in rare cases. However, the majority of the occurrences have been located on parts of the terrain that are relatively subsiding or along the water streams, where they could have been redeposited during the Pleistocene.

7.2. Relationship between moldavite-bearing sediments and other fluvial deposits and directions of paleostreams

The other issue is the relationship between deposits that bear moldavites and with those which do not contain any of them. Traditionally, these two types of deposits have not been compared to each other. However, the relation can be easily explained by the position on the longitudinal profiles, the character of the moldavite strewn field and by the character (roundness etc.) of the sediments.

This study is focused on the morphostratigraphic relationship of deposits. Many occurrences of the fluvial deposits were re-evaluated during this study and a spatial-temporal relation between the KSG and other fluvial deposits is proposed.

In most cases, the KSG fit strongly to the morphostratigraphical positions or profiles of other Pliocene fluvial deposits, described by Novák (1983) or Chábera and Novák (1975). The best way to relate the deposits with no moldavites to KSG, can be explained by Bouška (1992). He described cases, where the roundness and shapes of moldavites don´t corelate with the other (quartz or feldspar) clasts in the sediment; moldavites are often less rounded. This could be caused by later incorporation of the moldavites into the transported sediment – the water stream could erode a moldavite-free basement on its upper part and deposits with moldavites on its middle or lower part. This situation can be found in the Novohradské hory Mts. – the "Tertiary" river terraces of the Malše River on the upper stream (Novák, 1983) are moldavite-free, but they contain moldavites downstream (around Kaplice). There are only a few localities of moldavite-bearing gravels in the northern parts of the Budějovice and Třeboň basins and further (Bouška, 1992; Skála et al., 2016). It can be explained by the limited transport resistance of moldavites (several tens of kilometres), which is well proved from the Czech Republic or Poland (Žebera, 1967; Brachaniec, 2018; Brachaniec, 2019). Similarly, there is no known occurrence of moldavite south of the Besednice (Bouška, 1992), e.g., in the terraces of the upper part of the Malše River. This may have been caused by the character of the strewn field (Artemieva et al., 2002). It is probable, that the strewn field of moldavites is not a continuous area, but several separated regions (see Fig. 2a) This can be caused by the mechanism of the moldavites origins (the character, speed, angle and orientation of the extra-terrestrial impactor, the lithological conditions in the place of impact etc.) and it is in accordance with models from Artemieva et al. (2002).

The mechanism mentioned above could also be an explanation of a longstanding problem, why there are no known findings of moldavites south of the Novohradské hory Mts. and in the gaps between particular regions. Naturally, if the upper Miocene-Pliocene water streams would have drained this way, the moldavites must have been localized to the south of the Novohradské hory Mts. They could have been destructed during the transport, however there are no documented occurrences of moldavites in the Mühlviertel and other nearby regions of Austria in the Malše source area (Bouška, 1992). Due to this, the traditionally proposed drainage direction towards the south until the Pliocene (Žebera, 1967; Malkovský; 1979) seems rather improbable.

This is further supported by the spatial distribution of moldavite-bearing deposits and the moldavites themselves.
It can be hard to find a trend in the distribution of both types of sediments (VB, KSG) and therefore both types of moldavites ("strewn-field", "rounded", see section 2.3.). However, in this rather rough view, the "strewn-field", angular moldavites are present more in the southern part of the study area at higher altitudes and the rounded moldavites are present in the lower parts of the terrain in the north, towards the Budějovice and Třeboň basins. Also, the roundness and weight of moldavites within the KSG are rising towards the north (see section 2.3.). Similar results were obtained by Trnka and Houzar (1991) Houzar (1992) from the Western Moravian moldavite-rich area (for location see Fig. 2a). The "strewn-field" moldavites are mostly missing in the Moravian area, however, there are more rounded moldavites, often with higher weight than in the Southern Bohemia area (also mentioned by Bouška, 1992). The roundness of Moravian moldavites, as well as their weight and the petrographic maturity of the hosting fluvial deposits, increases from NW to SE, therefore the authors suppose the transport of moldavites was in this direction. This is further supported by the altitudinal distribution of moldavite-bearing deposits, which are also decreasing to the SE. The age of the fluvial deposits is set by the authors to the Pliocene or Pleistocene, however it does have a significant rate of uncertainty. Finally, the largely missing strewn-field moldavites and their deposits is explained by the effect of the tectonic uplift on the area to the W and NW from the moldavite-rich area. If the results of Trnka and Houzar (1991) and Houzar (1992) are applied in the area of Southern Bohemia, based on many similarities, it can be expected that the prevailing transport direction of moldavite-bearing sediments is towards the north from their original place of fall (see Fig. 2a, 2b and Fig. 3). Also, missing moldavite-bearing deposits in the hilly land in the southern part of the study area can be explained by tectonic uplift of this relief.
It is also necessary to address the issue of why no moldavites have been found in the layers of Ledenice Fm., which certainly sedimented after the fall of moldavites and very probably between the sedimentation of the VB and KSG (see Fig. 4). This could be explained by the sedimentation of Ledenice

Fm. in a tectonically calm period during the Pliocene, which is proposed by Bouška (1992), Chlupáč et al. (2002) and Pešek (2010). In that time, moldavites were still deposited within the VB or similar sediments of the strewn-field and were not redeposited to other layers. Following the significant uplift of the Novohradské hory Mts. and Lišov Horst, also expected by the aforementioned authors, the erosion of the VB, Ledenice Fm. and the redeposition of those layers and moldavites to e.g., KSG can be induced. This process of redepositing the VB to the KSG is clearly described by Nesrovnal (1992) and Bouška (1992). It can be also an explanation for the existence of Pliocene fluvial deposits or KSG without any moldavites, which can originate from the moldavite-free layers of Ledenice Fm.

7.3. Longitudinal profiles of the fluvial deposits and their possible relationship to tectonics

Accepting the linkage between KSG and other fluvial deposits and accepting their Pliocene age, it is also necessary to face other issues.

Two different distributions of Pliocene fluvial deposits can be observed: 650 – 460 m a. s. l. along the Malše and Vltava Rivers (110-55 m or 90-15 m respectively, above the present flood plain of the Vltava River and the Malše River) and mostly above the valley edge – see Fig. 3 and Fig. 9), and at 510 – 445 m a. s. l. along the Stropnice and Svinenský watercourses (50-20 m above the present flood plain) – see Fig. 3 and Fig. 8.

Two theories can explain this situation: the different age of the particular series of deposits or the effect of tectonics and river incision. If it is assumed, that the deposits along the Malše (+ Vltava) and Stropnice (+ Svinenský) differ in age based on their relative height above the streams, those along the Stropnice would be much younger than the first group, and certainly the Pleistocene. However, all of the deposits have a similar character and composition (Konta, 1972; Bouška, 1992 and others in section 2.3), therefore this theory of different age is rather improbable. The uplift of the Šumava Mountains and the Novohradské hory Mts. could have resulted in placing the Pliocene deposits at a higher altitude and in the subsequent significant incision of the Vltava and Malše rivers. On the contrary, the area of the Třeboň Basin and the foothills of the Novohradské hory Mts. along the Stropnice and Svinenský watercourses underwent much weaker uplift, if any. However, some traces of uplift for the Lišov Horst and Slepičí hory Mts. can be found along the tributaries of the Stropnice and Svinenský streams (Zborovský, Pašinovický, Klenský, Keblanský streams). Those tributaries are significantly incised, as is the lower part of the Stropnice River in comparison with the Svinenský Stream (see section 6.4 and Figs. 8 and 9).

The position of all levels of the fluvial deposits diverges from the source towards the mouth. There are Pleistocene fluvial deposits in the Budějovice basin, which are 0-50 m (in the case of Pliocene deposits up to 100 m) above the present flood plain (Chábera, 1965; Novák, 1983). However, deposits only 10 m above the present stream of the Malše River can be found on its upper part (near Rychnov nad

Malší) (Novák, 1983). Similarly, 3 levels of river terraces of the Vltava River are only within 5 m high above the floodplain in its upper part, now flooded by the Lipno dam lake (near Černá v Pošumaví) (Záruba et al., 1967; Ložek, 1973). This can be a proof of the preservation of an ancient ("Tertiary") section of the river on its upper parts and it is possible to observe the huge effect of backward erosion and the Quaternary deepening of the middle parts of the valleys (upwards from the Budějovice Basin). It is worth mentioning that the deepening is more significant on the Vltava River, which can be caused by hydrological effects (the Vltava is the river with the highest discharge in the study area) in combination with the stronger uplift in the western part of the study area.

Some interesting features can be found on the Malše River between Plav and Římov. There is an incised cut-off meander on the confluence of the Malše River with the Zborovský stream and a similar structure, probably also a cut-off meander, 1 km to the north from Římov. According to Novák (1983) and ČGS (2003), the abandoned parts of meanders are infilled with fluvial deposits of Riss age.

This would mean that the incision and the cut off meander is younger than approx. 130 Ka. According to Ouchi (1985) and Harvey (2007), the incision (and formation of the meanders) may be linked to uplift (high to moderate). Also, the stream gradient of the Malše River steepens (up to 1%) higher upstream from the northern meander (and the confluence with the Zborovský stream. The incision and backward erosion of the Zborovský stream certainly helped with forming the meander and, according to Popotnig et al., 2013, it is significantly incised due to the uplift of the Lišov Horst. Generally, this situation can be proof that the uplift of the Lišov Horst could still be significant relatively recently.

7.4. Reconstruction of the Pliocene-older Pleistocene paleostream spatial pattern

Based on the results obtained and an awareness of the above issues (such as the discussion regarding the age of the KSG, possible tectonic influence, etc.), it is possible to discuss the probable geometry of the Pliocene river network and its differences from the present status.

Generally, the paleostream direction of particular sections cannot be obtained from most fluvial deposits of older ages. They are composed mainly of rough gravels with isolated pebbles and the occurrence of crossbedding in sandy deposits are very rare. Therefore, the reconstruction must be based on the morphostratigraphic relationship and other signs (changes in stream gradient, valley floor ratio, basin asymmetry etc.).

The paleostream of the Malše River can be traced by the deposits roughly following the current stream. Terrace 2 and Terrace 3 (Novák, 1983) fit strongly to the upper part of the longitudinal profile of the Malše River. This unusually flat valley at km 15-30 (Fig. 7) is traditionally described as a remnant of a Tertiary river valley. (Malkovský, 1979; Chábera, 1982). Terraces 2 and 3 have a similarly gentle longitudinal profile (along the entire course of the Malše River), as the flat valley at km 15-30. Those terraces can therefore represent a stream with a gentler profile (Fig. 7 and 8) which existed before the main uplift of the Novohradské hory Mts. or in the early phases of the uplift when the incision of the stream had not been so intensive yet – the evolution of relief also suggested by Bouška (1992). Žebera (1967) and Malkovský (1979) suggest of the Malše River had a S-N course (and the subsequent continuation of the paleostream through the Budějovice Basin and then turning to the east to the Třeboň Basin and southwards to the Alpine-Carpathian foredeep) already in the Miocene, certainly before the uplift of the Novohradské hory Mts. However, the superposition of some terraces over the Pliocene lacustrine sediments near Kaplice (Březinová et al., 1963), suggest an upper Pliocene or lower Pleistocene age for the terraces, which is also proposed by Novák (1983). The watercourse of the Malše was migrating eastwards during the continuing uplift of the Poluška massif and the Novohradské hory Mts. (see Fig. 11). In the area close to the Budějovice Basin edge, the situation is not clear. There are many occurrences of KSG in this flat terrain of the water divide and it is not clear if the deposits used to belong to the Vltava River, the Malše River or their tributaries.

A strikingly flat area can be found near the confluence of the Malše and Stropnice Rivers (between Pašinovice and Plav), which lies 30-60 m above the current stream level and which host Pliocene and lower Pleistocene fluvial deposits. Their current location is a result of the complex uplift of the Novohradské hory Mts. and its foothills, combined with subsidence of the basin respectively, during the Pleistocene. This effect can also be seen on the diverging Pleistocene terraces towards the basin (see Fig. 10), which is most visible on the levels of Günz, Mindel and Riss.

An interesting phenomenon can be observed on the lower parts of the Stropnice and Svinenský Stream. The Stropnice River, as a trunk stream, has a much deeper and narrower valley than its tributary, Svinenský Stream (see section 6.2, and Fig. 3 for a map). The narrow floor of the Stropnice River valley, with a very narrow flood plain, is even at a higher elevation than the wide flood plain of Svinenský Stream in some places (see section 6.4). The Stropnice River has a deeply incised valley, typical for resistant crystalline rocks. Its lower part is a wide and shallow valley in the softer rocks of the Třeboň Basin on its middle part. However, a very untypical wide and shallow valley can be found on the lower part of Svinenský Stream, where it goes through a Moldanubian gneisses or even granites. Both the Stropnice River and Svinenský Stream have increased levels of stream gradient (see Fig. 8 and Fig. 11) in their lower parts, which is not very typical for a stream with a balanced longitudinal profile (Burbank and Anderson, 2001). It could be caused by the higher erosive activity of the Malše River as a trunk stream. Or it can be a sign of an uplift in the whole region, which can be proven by the incised valley of the Stropnice as well as the increased sinuosity on the lower part of the Svinenský Stream. However, it is not easy to find the real cause, as the whole Bohemian Massif has been significantly uplifted.

Generally, the lower part of the Svinenský Stream gives the impression of an old trunk stream, instead of a tributary. Therefore, it is put forward that the Svinenský Stream may have played the role of a trunk stream in the past. Its tributary, the Stropnice, has been massively deepened and it has caught an upper part of a catchment in the Třeboň Basin.

This theory can be supported by the occurrence of Pliocene fluvial deposits along the lower part of the Svinenský Stream (see Fig. 3). In contrast, older (Pliocene) deposits cannot be found, but only river terraces of Riss age and younger along the lower part of the Stropnice River (see Fig. 3 and 7). The intense erosion of those deposits cannot be supposed, because of the flat and subsiding terrain of the Třeboň Basin, moreover many of these deposits are well preserved in the section between Byňov and Jílovice. Also, many of the Pliocene deposits can be found on the flat watershed between the Stropnice River and Svinenský stream in the surroundings of Bukvice (Fig. 3).

The levels of Pliocene deposits along the Stropnice River fit to the longitudinal profile of the current upper and central part of the stream, but they differ from the higher gradient profile in the lower part (see Fig. 8 and Fig. 11). This situation is caused by stronger incision in the lower part of the stream during the Pleistocene. This and the complicated altitudinal relationship in the central part of the stream (32-37 km from the source - unclear delineation between Pleistocene and Pliocene deposits) can be a sign of stream capturing between the Stropnice River and the Svinenský stream and that the Pliocene stream of the Stropnice followed the path towards today's Svinenský stream.

The values of basin asymmetry and the general shape of the river basins further support this theory. If the Svinenský stream would have been the trunk stream (instead of being a tributary to the Stropnice River) the lower part of the stream (with its remarkably developed valley) lies almost in the perfect axis of the combined present basins of the Stropnice and Svinenský (see Fig. 3).

Several interesting changes of orientation in the current streams can be observed, however most of them can be located on their upper parts. The tectonic predisposition regarding the orientation of fissure systems in granites (Rypl et al., 2016; Rypl and Kirchner, 2017) is likely there. The remarkable feature is the change of direction in the Svinenský Stream and the Stropnice River from a general S-N orientation to SE-NW, towards the Budějovice Basin. It seems, that the strong incision of the Malše and Stropnice respectively (caused locally by the uplift of the Lišov Horst) could have led to the change in stream direction and the possible capturing of the upper parts of those streams. However, the heading of the streams towards the north, to the Třeboň Basin, at some point in history of their evolution cannot be ruled out. According to Bouška (1992), the Třeboň Basin drained northwards in the Pliocene. This can be further supported by the S-N direction of the Pliocene fluvial and the lacustrine sediments in the basin, which is different from the Miocene and older deposits. Bouška (1992) also speculated about the longer existence of a lake in the Třeboň Basin compared to the Budějovice Basin. He supports it with the lack of moldavite-bearing sediments in the Třeboň Basin on the surface while they are buried by lake sediments (Ledenice Fm.), however it could also be explained by the character of the moldavite strewn field (see above) and therefore the question about where both basins emptied remains unsolved.

Generally, this theory about the Pliocene fluvial network is not in contradiction with Bouška (1992). He also suggests the area of the Novohradské hory Mts. drained northwards to the Budějovice Basin, without any connection to the Alpine-Carpathian foredeep when the KSG originated. He links the uplift of the Novohradské hory Mts. with the beginning of the northwards draining and with the intensive incision of the water streams into older moldavite-bearing sediments and their redeposition in the form of Pliocene river terraces.

8. Conclusions

The real age of the Koroseky sands and gravels and other moldavite bearing sediments as well as the proposed Pliocene fluvial deposits along the rivers in the study area is not clear yet. Many of the previous studies and the results of this study, however, assume at least the Pliocene age, or even younger. This study suggests a new idea for the reconstruction of the paleostream network based on the occurrence Koroseky sands and gravels and their linkage to other Pliocene or Pleistocene fluvial deposits.

The reconstruction of the paleostream network on the basis of the occurrences of fluvial deposits, shape and weight of moldavite pebbles, stream geometry and terrain morphology provides the first ideas for the rather dynamic evolution of the river network from the Miocene to the present. The uneven uplift of the Novohradské hory Mts., Šumava Mts., and Lišov Horst has led to multiple stream capturing and changes in stream direction. It is probable, that the stream of the Malše River has migrated to the E. The trunk stream of the NE part of the study area could have used the valley of the present lower Svinenský stream and had an upper part similar to the present-day Stropnice River. Generally, it appears that the distinct changes of the river geometry induced by tectonics may be younger (Pliocene or Pleistocene) than previously proposed.

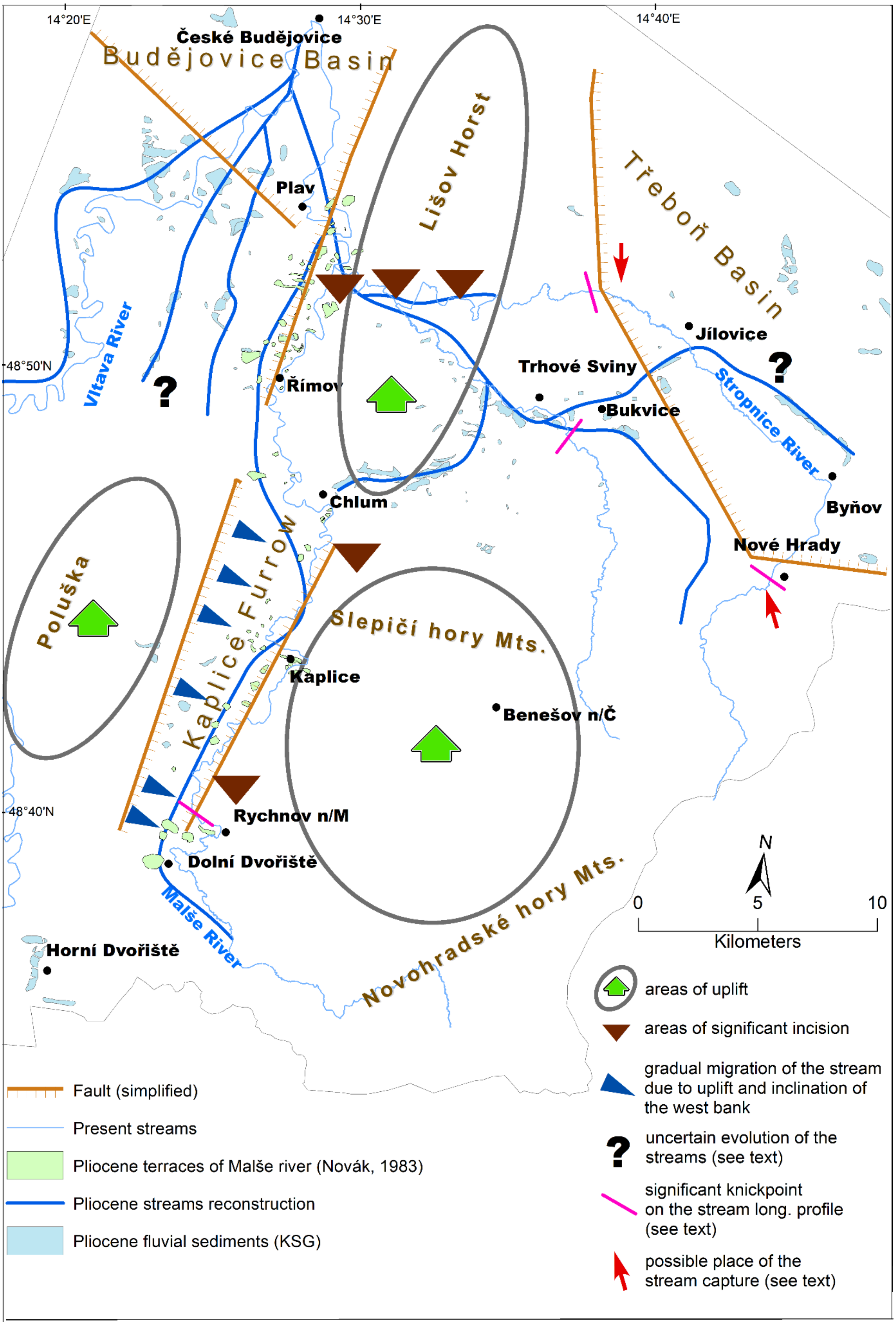


Fig. 11: Proposed Pliocene stream network and its relationship to the current topographic situation

The study itself provides a solid base for subsequent research: it is possible to pinpoint important localities, where ^{10}Be dating (or other using of cosmogenic nuclides, alternatively OSL dating) of the deposits can be done (with respect to the deposits' character) and are highly desirable – Byňov and Bukvice (Pliocene or Pleistocene deposits of Stropnice River); Chlum (Pliocene deposits); surroundings of Trhové Sviny (Pliocene deposits); Kaplice – Rychnov n/M (Pliocene deposits); Koroseky (Pliocene deposits). After obtaining those data, at least from some of the localities, the tectonic evolution as well as the development of the river network in the area will be even clearer. The geomorphological and morphostratigraphical methods used in this study can also be applied to the other areas in the Bohemian Massif. Tectonic activity during the Pliocene and Pleistocene was widely present, however its proper dating, scale and effect on the river geometry and terrain morphology has not been entirely clear yet. Many deposits of Late Cenozoic, without proper dating, can be found also in the other areas through the world. This study can show the approach, how to reconstruct the palaeodrainage and the effects of tectonics on it.

Acknowledgements

This study was supported by internal grant from the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences, no. 2019/350 "Reconstruction of the Pliocene river network in the area of Novohradské Foothills". We gratefully acknowledge Richard R. H. Withers for English proof reading. We also wish to thank the two anonymous reviewers for their invaluable comments and suggestions, which significantly helped to improve the manuscript.

References

Artemieva, N., Pierazzo, E., Stöffler, D., 2002. Numerical modelling of tektite origin in oblique impacts: Implication to Ries-Moldavites strewn field. Bulletin of the Czech Geological Survey, 77 (4), p. 303–311

Baioni, D., 2016. Analysis of Drainage Basin Asymmetry in the Ventena River, Northern Apennines (Central Italy). *Int J Earth Environ Sci* 1: 121., p. 2-5. https://doi.org/10.15344/2456351X/2016/121

Balatka, B., Sládek, J., 1962. Říční terasy v českých zemích. Nakladatelství československé akademie věd, Praha., 578 p.

Balatka, B., Kalvoda, J., 2006: Geomorfologické členění reliéfu Čech. Kartografia a. s., Praha,

79 p.

Balatka, B., Kalvoda, J., 2010. Vývoj údolí Sázavy v mladším kenozoiku. Česká geografická společnost, Praha. 200 p.

Balatka, B., Kalvoda, J., Gibbard, P., 2015. Morphostratigraphical correlation of river terraces in the central part of the Bohemian Massif with the European stratigraphical classification of the quaternary, AUC Geographica, 50, 1, pp. 63–73. https://doi.org/10.14712/23361980.2015.87

Bankwitz, P., Bankwitz, E., Thomas, R., Wemmer, K., Kämpf, H., 2004. Age and depth evidence for pre-exhumation joints in granite plutons: fracturing during the early cooling stage of felsic rock. In: Cosgrove, J.W., Engelder, T. (eds). The initiation, Propagation and Arres of Joints and Other Fractures. Geological Society, London, Special Publications, 231, p. 25-47. https://doi.org/10.1144/GSL.SP.2004.231.01.03

Badura, J. Zuchiewicz, W., Štěpančiková, P., Przybylski, B., Kontny, B., Cacoń, S., 2007. The Sudetic marginal fault: A young morphotectonic feature at the NE margin of the Bohemian Massif, Central Europe. Acta Geodyn. Geomater. 4, No. 4 (148), p. 7-29

Bezvoda, V., Novák, V., Vrána, M., 1983. Příspěvek k poznání vysoko položených klastických sedimentů u Horního a Dolního Dvořiště. Sborník Jihočeského Muzea, přírodní vědy, 23, p. 61-65

Bittman, J., Homolka, M., Vašta, V., 1985. Třeboňská pánev – jižní část – JIVAK. Hydrogeologický průzkum. Stavební geologie Praha, závod České Budějovice

Bouška, V., 1992. Tajemné vltavíny. Nakladatelství Gabriel. Praha, 84 p.

Bouška, V., Konta, J., 1990. Moldavites-Vltavíny. Univerzita Karlova. Praha, 126 p.

Brachaniec, T., 2018. Variations in fluvial reworking of Polish moldavites induced by hydrogeological change. - Carnets Geol.,8 (10), p. 225-232. https://doi.org/10.4267/2042%2F68186

Brachaniec, T., 2019. Relationship between the abrasion of tektite clasts and their host sedimentary facies, Pleistocene, SW Poland. Annales Societatis Geologorum Poloniae vol. 89, p. 83–90. https://doi.org/10.14241/asgp.2019.08

Brandmayr, M., Dallmeyer, R.D., Handler, R. &Wallbrecher, E. 1995. Conjugate shear zones in the Southern Bohemian Massif (Austria): implications for Variscan and Alpine tectonothermal activity, *Tectonophysics*, vol. 248, 1–2, p. 97-116. https://doi.org/10.1016/0040-1951(95)00003-6

Brandmayr, M., Loizenbauer, J. & Wallbrecher, E. 1997. Contrasting P-T conditions during conjugate shear zone development in the Southern Bohemian Massif, Austria. *Mitteilungen der Österreichischen Geologischen Gesellschaft*, vol. 90, p. 11-29.

Březinová, D., Pacltová, B., Špinar, Z., 1963. Stáří sedimentů kaplické pánvičky v jižních Čechách (M-33-113-D-d). Časopis pro mineralogii a geologii, 1, pp- 65-73

Buchner E., Schwarz, W.H., Schmieder, M., Trieloff, M., 2010. Establishing a 14.6 ± 0.2 Ma age for the Nördlinger Ries impact (Germany) – a prime example for concordant isotopic ages from various dating materials. Meteorit Planet Sci 45: 662–674. https://doi.org/10.1111/j.1945-5100.2010.01046.x

Buchner, E., Sach, V.J., Schmieder, M., 2020. New discovery of two seismite horizons challenges the Ries–Steinheim double-impact theory. Scientific Reports, 10:22143, 14 p. https://doi.org/10.1038/s41598-020-79032-4.

Bull, W., 2007. Tectonic Geomorphology of Mountains: A New Approach to Paleoseismology. Blackwell Publishing. 306 p. https://doi.org/10.1002/9780470692318

Burbank, D., Anderson, R., 2001. Tectonic Geomorphology. Blackwell Science. 273 p. https://doi.org/10.1002/9781444345063

ČGS - Česká geologická služba/ Czech Geological Survey, 2003. Geologická mapa ČR, 1: 50 000, ČGS, Praha

Chábera, S., 1965. Příspěvěk k poznání teras Vltavy a Malše v Českobudějovické pánvi. Sborník Jihočeského muzea v Českých Budějovicích – Přírodní vědy, 5, p. 3-18.

Chábera, S., 1982. Geologické zajímavosti jižních Čech (Jihočeská vlastivěda, řada B).

Jihočeské nakladatelství, České Budějovice., 157 p.

Chábera, S., Novák, V., 1975. Terasy Vltavy mezi Českým Krumlovem a pánví Českobudějovickou. Sborník Jihočeského muzea v Českých Budějovicích – Přírodní vědy, 15, p. 1-9.

Chlupáč, I., Brzobohatý, R., Kovanda, J., Stráník, Z., 2002. Geologická minulost České

republiky. Academia, Praha, 436 p.

ČÚZK - Český úřad zeměměřický a katastrální/Czech Office for Surveying, Mapping and Cadastre, 2017. Digitální model reliéfu České republiky 4. generace (DMR 4G)/Digital Elevation Model of Czech Republic 4th generation (DEM 4G). Český úřad zeměměřický a katastrální, Praha

Di Vincenzo, G., Skála, R., 2009. 40Ar–39Ar laser dating of tektites from the Cheb Basin (Czech Republic): evidence for coevality with moldavites and influence of the dating standard on the age of the Ries impact. Geochim Cosmochim Acta, 73, p. 493–513. http://dx.doi.org/10.1016/j.gca.2008.10.002

Dhanya, V., 2014. Basin asymmetry and associated tectonics: A case study of Achankovil river basin, Kerala. *Trans. Inst. Indian Geographers*, 36, 2, p. 207 - 215

Ernée, M., Hrubý, P., Malý, M., Tomášek, J., Valkony, K., 2014. Early exploitation of the secondary gold deposits by Český Krumlov, Acta rerum naturalium, 16, p. 185-108.

Gibbard, P. L., Lewin, J. , 2009. River incision and terasse formation in the Late Cenozoic of Europe. Tectonophysics, 474, p. 41–55. https://doi.org/10.1016/j.tecto.2008.11.017

Gutierrez, M., 2013. Geomorphology. London: CRC Press; 1014 p. https://doi.org/10.1201/b12685

Hamdouni, R., Irigaray, C., Castillo, T., Chacón, J., Keller, E., 2008. Assessment of relative active tectonics, southwest border of the Sierra Nevada (southern Spain). Geomorphology, p. 150-173. https://doi.org/10.1016/j.geomorph.2007.08.004.

Harvey, A., 2007. High sinuosity bedrock channels: response to rapid incision - examples in SE Spain. Cuaternario y geomorfología: Revista de la Sociedad Española de Geomorfología y Asociación Española para el Estudio del Cuaternario, 21,3-4, p. 21-47.

Homolová, D., Lomax, J., Špaček, P., Decker, K. 2012. Pleistocene terraces of the Vltava River in the Budějovice basin (Southern Bohemian Massif): new insights into sedimentary history constrained by luminescence data. Geomorphology, 161-162, p. 58-72. https://doi.org/10.1016/j.geomorph.2012.04.001

Houzar, S., 1992. Naleziště moravských vltavínů. *Přírodovědný sborník Západomoravského muzea v Třebíči*, 18, p. 159-166

Keller, E., Pinter, N., 2002. Active tectonics – Earthquakes, Uplift and Landscape. Prentice Hall, New Jersey, 362 p.

Konta, J., 1972. Quantitative petrographical and chemical data on moldavites and their mutual relations. Acta Universitatis Carolinae – Geologica, 1, p. 31-45

Kopecký, A., 1970. Úloha kvartérní tektoniky při dotváření současné struktury a geomorfologie

Českého masivu. Časopis pro mineralogii a geologii, 15, 1-4, p. 347-355

Kopecký, A., 1983. Neotektonický vývoj a stavba šumavské horské soustavy. Antropozoikum,

15, p. 71-159

Kopecký A., Vyskočil, P., 1969. Současné vertikální pohyby zemského povrchu v západní

polovině Českého masivu. Věstník Ústředního ústavu geologického, 5, p. 273-281

Krátká, J., 1966. Zpráva o Inženýrskogeologickém mapování zátopného území vodního díla Doudleby na Malši**.** IGHP, závod Praha, 59 p.

Kroupa, J., 1984. Bukvice, Hydrogeologický průzkum. Stavební geologie Praha, závod České Budějovice

Lett, P., 2004. Povrchové vody Novohradských hor. in: Kubeš, J. (ed.), Krajina Novohradských hor:Fyzicko-geografické složky krajiny. Jihočeská univerzita v Českých Budějovicích, Pedagogická fakulta,Katedra geografie, 160 p.

Ložek, V., 1973. Příroda ve čtvrtohorách. Academia. Praha. 372 p.

Mahel, M., Kodym, O., Malkovský, M., 1984. Tektonická mapa CSSR, 1: 500 000, Geologický ústav Dionýza Štúra, Bratislava.

Malkovský, M., 1975. Paleogeography of the Miocene of the Bohemian Massif. Věstník Ústředního ústavu geologického, 50, p. 27-31

Malkovský M., 1979. Tektogeneze platformního pokryvu Českého masivu. Ústřední ústav geologický.

Academia. Praha, 176 p.

Mayer, V., 1959. Zpráva o průzkumu staveniště určeného pro rozšíření závodu MOTOR – Kaplice. Státní projektový ústav pro výstavbu měst a vesnic Č.Budějovice, 9. p.

Mísař, Z., Dudek, A., Havlena, V., Weiss, J., 1983. Geologie ČSSR I. – Český masiv. Státní pedagogické nakladatelství, Praha, 333p.

Nesrovnal, I., 1992. Nové poznatky o vltavínonosných sedimentech v okolí Vrábče. Přírodovědný sborník Západomoravského muzea v Třebíči, 18, p. 154 – 159

Nesrovnal, I., Šimek, J., 1995. Českobudějovicko – vyhledávací průzkum cihlářské suroviny, G E T s.r.o., 10 p.

Novák V., 1983. Terasy řeky Malše. Dissertation thesis. UK Praha. 100 pp.

Novák, V., 1985. The high terrace of the River Vltava near Boršov nad Vltavou. Sborník Jihočeského muzea v Českých Budějovicích – Přírodní vědy, 25, p. 7.

Ouchi, S.,1985. Response of alluvial rivers to slow active tectonic movement. *Geological Society of America Bulletin,* 96, p. 504-515. https://doi.org/10.1130/0016-7606(1985)96%3C504:ROARTS%3E2.0.CO;2

Pavlíček V., 2004. Geologie Novohradských hor. in: Kubeš, J. (ed.), Krajina Novohradských hor: Fyzicko-geografické složky krajiny. Jihočeská univerzita v Českých Budějovicích, Pedagogická fakulta, Katedrageografie, 160 p.

Pešek, J. (ed.), 2010. Terciérní pánve a ložiska hnědého uhlí České republiky. Vydavatelství České geologické služby, Praha.

Popotnig, A., Homolová, D., Decker, K., 2013. Morphometric analysis of a reactivated Variscan fault insouthern Bohemian Massif (Budějovice basin, Czech Republic). Geomorphology, 197, p. 108-122.https://doi.org/10.1016/j.geomorph.2013.04.042

Přibyl, V., 1999. Vltava River Terrace System between Lipno and Rožmberk na Vltavou. Acta Universitatis Carolinae – Geographica, 2, p. 157-171

Puchta, J., Volšan V., 1965. Závěrečná zpráva. Jihočeské pánve – Stropnice, surovina: písky a štěrky. Geologický průzkum, Praha.

Rypl, J., 2004. Geomorfologie Novohradských hor. In: Kubeš, J. (ed.), Krajina Novohradských hor: Fyzicko-geografické složky krajiny. Jihočeská univerzita v Českých Budějovicích, Pedagogická fakulta, Katedra geografie, 160 p.

Rypl, J., Kirchner, K., 2017. Scientific values of landforms as the basis for the declaration of protected sites (A Case Study of Mt. Kraví hora in the Novohradské hory Mts., Czech Republic). Applied Ecology and Environmental Research, 15 (3): 1537-1550. https://doi.org/10.15666/aeer/1503_15371550

Rypl, J., Kirchner, K., Dvořáčková, S., 2016. Geomorphological Inventory as a Tool for Proclaiming Geomorphosite (a Case Study of Mt. Myslivna in the Novohradské hory Mts. — Czech Republic), Geoheritage, 8 (4), 393-400. https://doi.org/10.1007/s12371-015-0169-5

Rypl, J., Kirchner, K., Blažek, M., 2017. The spatial distribution of rock landforms in the Pohořská Mountains (Pohořská hornatina) Czech Republic. Acta Geographica Slovenica, 57 (2), p. 45–55. https://doi.org/10.3986/AGS.1184

Rypl, J., Kirchner, K., Kubalíková, L., Divíšek, J., 2020. Geological and geomorphological conditions supporting the diversity of rock landforms in the Pohořská Mountains (South Bohemia, Czech Republic). Geoheritage. 12 (1), 2, p. 1-9. https://doi.org/10.1007/s12371-020-00430-1

Schmieder, M., Kennedy, T., Jourdan, F., Buchner, E., Reimold., W.U., 2018. A high-precision $^{40}Ar/^{39}Ar$ age for the Nördlinger Ries impact crater, Germany, and implications for the accurate dating of terrestrial impact events, *Geochimica et Cosmochimica Acta,* 220, p. 146–157. https://doi.org/10.1016/j.gca.2017.09.036

Schwarz, W., H., Lippolt, H., J., 2014. 40Ar–39Ar step-heating of impact glasses from the Nördlinger Ries impact crater – implications on excess argon in impact melts and tektites. Meteorit Planet Sci, 49, p. 1023–1036. https://doi.org/10.1111/maps.12309

Ševčík, J., Kvaček, Z., Mai, D.H., 2007. A new mastixioid florula from tektite-bearing deposits in South Bohemia, Czech Republic (Middle Miocene, Vrábče Member). Bulletin of Geosciences 82 (4), p. 429–426. https://doi.org/10.3140/bull.geosci.2007.04.429

Shrbený, O., 1994. Terciér v Českém masivu, in Klomínský (Ed.), Geologický atlas České republiky – stratigrafie, Český geologický ústav, Praha

Skála, R., Jonášová, Š., Žák, K., Ďurišová, J., Brachaniec, T., Magna, T., 2016. New constraints on the Polish moldavite finds: a separate sub-strewn field of the central European tektite field or re-deposited materials?, Journal of Geosciences, 61, p. 171–191. https://doi.org/10.3190/JGEOSCI.214

Slabý, J., Holásek, O., 1992b. Geologická mapa ČR 33-13 České Velenice 1:50 000, Český geologický ústav, Praha.

Štěpančíková, P., Štemberk, J., Vilímek, V., Košťák, B., 2008. Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic). Geomorphology, 102, p. 68-80. https://doi.org/10.1016/j.geomorph.2007.06.016

Stöffler, D., Artemieva, N., Wünnemann, K., Reimold, U., Jacob, J., Hansen, B.K., Summerson, I.A.T., 2013. Ries crater and suevite revisited—Observations and modelling Part I: Observations. *Meteoritics & Planetary Science,* 48, no. 4, p. 515–589. https://doi.org/10.1111/maps.12086

Sturm, S., Kenkmann, T., WIllmes, M., Pösges, G., Heisinger, H., 2015. The distribution of megablocks in the Ries crater, Germany: Remote sensing, field investigation, and statistical analyses. *Meteoritics & Planetary Science,* 50, no 1, p. 141–171. https://doi.org/10.1111/maps.12408

Švára, O., 1981. Zpráva o průzkuimu základových poměrů pro přístavbu pavilonu v areálu ZDS – Kaplice. Stavoprojekt, České Budějovice, 13 p.

T. G. Masaryk Water Research Institute (Výzkumný ústav vodohospodářský TGM), 2021. Database of water management data (DIBAVOD – digitální báze vodohospodářských dat), 1:10 000 [online], accessible at: http://www.dibavod.cz, [15/05/ 2021], T. G. Masaryk Water Research Institute, Praha

Teodoridis, V., Bruch, A.A., Martinetto, E., Vassio, E., Kvaček, Z., Stuchlik, L., 2017. Plio-Pleistocene floras of the Vildštejn Formation in the Cheb Basin, Czech Republic – a review and a new paleoenvironmental evaluation – Palaeogeography, Palaeoclimatology, Palaeoecology, 467 (2017): 166-190. https://doi.org/10.1016/j.palaeo.2015.09.038

Tschegg, D., Decker, K., 2013. Distinguishing Quaternary and Pre-Quaternary clastic sediments in the vicinity of České Budejovice (Southern Bohemian Massif, Czech Republic). Austrian Journal of Earth Sciences, 106, p. 72-89.

Trnka, M., Houzar, S., 1991. *Moravské vltavíny*. Muzejní a vlastivědná společnost v Brně a Západomoravské muzeum v Třebíči, Brno, 115 p.

Trnka, M., Houzar, S., 2002. Moldavites: a review. Bulletin of the Czech Geological Survey, 77 (4), p. 283–302

Tyráček, J., 2001. Upper Cenozoic Fluvial history in the Bohemian Massif. Quaternary International, 79, p.37-53. https://doi.org/10.1016/S1040-6182(00)00121-X

Tyráček, J., Havlíček, P., 2009. The fluvial record in the Czech Republic: A review in the context of IGCP 518. Global and Planetary Change 68, p. 311–325. https://doi.org/10.1016/j.gloplacha.2009.03.007

Tyráček, J., Westaway, R., Bridgland, D., 2004. River terraces of the Vltava and Labe (Elbe)

system, Czech Republic, and their implications for the uplift history of the Bohemian Massif.

Proceedings of the Geologists' Association, 115, p. 101-124. https://doi.org/10.1016/S0016-7878(04)80022-1

Univerzita J.E. Purkyně, Ministerstvo životního prostředí ČR, 2014. II.vojenské mapování – Františkovo, 1: 28800, [online] accessible at: http//oldmaps.geolab.cz, [15/05/2016], Laboratoř geoinformatiky Fakulta životního prostředí Univerzity J.E.Purkyně, Ustí nad Labem

Van Husen, D., Reitner, J.M., 2011. An Outline of the Quaternary Stratigraphy of Austria. Quaternary Science Journal, 60, no. 2-3, p. 366-387. https://doi.org/10.3285/eg.60.2-3.09

Virt, R., 2009. Revize lokalit vltavínů Lhotka u Nových Hradů a Podeřiště. Sborník Jihočeského muzea v Českých Budějovicích – Přírodní vědy, 49, p. 50.

VGHMÚ - Vojenský geografický a hydrometeorologický Úřad, Ministerstvo Obrany ČR, GEODIS Brno,s.r.o, 2014. Historická ortofotomapa Č(S)R, 1:20000, [online] available at http//: kontaminace.cenia.cz, [15/05/2014]CENIA - Česká informační agentura životního prostředí, Praha

Vrána, S., Holásek, O., 1992. Geologická mapa ČR 32-24 Trhové Sviny 1:50 000. Český geologický ústav, Praha

Vrána, S., Novák, V., 1993. Geologická mapa ČR 32-42 Rožmberk nad Vltavou 1:50 000, Český geologický ústav, Praha.

Vyskočil, P., 1973. The investigation of vertical crustal movements in the geodynamical polygon Lišov. Edice výzkumného ústavu geodetického, topografického a kartografického v Praze, řada 4, p. 1-96,

Welser, P., Zikeš, J., Plecer, V., Málek, O., Maratus, A., 2020. Příspěvek k poznání sedimentace vltavínonosných vrstev na ložisku Chlum u Ločenic. Minerál - svět nerostů a drahých kamenů, 28, vol. 3, p. 217-227

Wheeler, D.A., (1979). The overall shape of longitudinal profiles of streams, in A.F. Pitty (ed.) Geographical Approaches to Fluvial Processes, Norwich GeoAbstracts, p. 241-260

Willet., S. D.(ed.), 2006. Tectonics, Climate and Landscape Evolution. The Geological Society of America, Special paper 398. https://doi.org/10.1130/SPE398

Záruba Q., Zajíc, J., Prokop, F., Röhlich, P., Růžička, K., Štěpánek, M., Záruba, L., 1967. Geologie přehrad na Vltavě – Geology of dams on the Vltava River. Ústřední ústav geologický. Academia. Praha, 222 p.

Žebera, K., 1967. Moldavite-bearing sediments between Koroseky and Holkov in South Bohemia. Věstník ústředního ústavu geologického, 42, p. 327-337

Žebera K., 1977. Moldaviter im Südböhmen, Věstník Ústředního ústavu geologického, 52, 1977, p. 47-53

Ziegler, P.A., Dèzes, P., 2007. Cenozoic uplift of Variscan Massifs in the Alpine foreland: Timing and controlling mechanisms. Global and Planetary Change, 58, p. 237–269. https://doi.org/10.1016/j.gloplacha.2006.12.004

Concluding remarks

- The geomorphological methods used in this thesis - longitudinal profiles of water streams, stream gradient analysis, SL index analysis, hypsometric index analysis, mountain front sinuosity analysis, basin asymmetry analysis, morphotectonic analysis – make a useful working set, which can be applied in similar areas for investigating the relationship between tectonic activity and the geometry and evolution of the fluvial systems.
- The verification of these methods was done by aerial geophysical survey, field applied geophysics survey, field structural survey and palaeoseismological methods. All these methods, as was the case in many previous studies, have shown a satisfactory fit to the results and the usefulness of geomorphological methods for indications of tectonic activity.
- Based on the results of the aforementioned methods, it is suggested that both study areas (the surroundings of the Mariánské Lázně Fault and the Novohradské hory Mts. and their foothills) have undergone a significant tectonic uplift during the Late Pliocene, Pleistocene, and probably - in the case of the area of the Mariánské Lázně Fault – even the Holocene.
- The tectonic activity did not take place in a single event, it has been a rather segmented activity along the Mariánské Lázně Fault, or the uneven uplift of blocks in the area of the Novohradské hory Mts.
- This segmented activity has made a significant impact on the changes of water stream geometry and the evolution of the drainage network (river capturing, etc.) in general.
- The diversely located fluvial deposits of Pliocene and Pleistocene age act as evidence of drainage evolution. Based on the morphostratigraphic analysis and on the survey of the relationship between fluvial deposits and tectonic structures, it is possible to reconstruct the evolution of the river network.
- The Pliocene deposits in both study areas (e.g., Vildštejn Formation and Koroseky Sand and Gravel) probably show a drainage direction similar to the present, although the rivers that have deposited them existed in a rather flat terrain.
- It appears that the two main tectonically induced changes in the drainage pattern happened in both study areas: first between the Late Miocene/Early Pliocene and the Late Pliocene, second between the Late Pliocene/Early Pleistocene and the Late Pleistocene or the present.
- The exact timing of the processes is the subject of future research; this thesis helps to find suitable localities for dating, palaeoseismological analysis, etc.