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Database of fault-related information for SHA in the Czech Republic

Work Package 1 “Faults and Tectonics”

AUTHORS		REVIEW		APPROVAL	
Name	Date	Name	Date	Name	Date
Petr Špaček et al.	2020/05/31	Thierry Camelbeeck Yann Klinger	2020/10/13 09/10/2020	Jiri Fuzer	2020/10/20 YYYY/MM/DD

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Document history

DATE	VERSION	COMMENTS
2018/08/15	*0*	*Early version for getting feedback and opening discussion*
2020/05/31	*1*	*Final version with partly populated databases*

Executive summary

Database of fault-related information has been developed for territory of the Czech Republic and adjacent areas of neighboring countries to become a principal data pool for modeling fault sources in SHA at Czech NPP sites. For the Czech Republic this is the first attempt to give comprehensive database of faults with systematic summary on their evolution and late activity. This report explains the methodical strategy used, describes the database structure, and outlines the technical solution of its interconnection with other data sources into a integrated database system. In addition to its application in SHA the database is made to serve community of geoscientists as a platform for storing and exchange of their knowledge. Therefore, it is connected to interactive map available online at url *faults.ipe.muni.cz* together with rich explanation texts and detailed descriptions of supporting evidence which make the evaluation of fault activity transparent. Some novel approaches are featured in our database, such as recording arguments for local geometry of fault lines in the map or including in the database of observations bringing counterevidence on fault slip in addition to positive evidence. The database's simple structure and standard format should enable connection with other regional databases in future.

Contents

Authors

This report and database structure: **Petr Špaček** (IPE Masaryk University Brno; spacek@ipe.muni.cz)

Database managing editors: **Petra Štěpančíková** (IRSM Prague), **Ivan Prachař** (IP Consult Ltd., Prague), **Petr Špaček**

Calculation of theoretical fault slip tendency: **Josef Havíř** (IPE Brno)

Technical note

This report describes the methodical strategy and structure of the digital database which is connected to interactive map and texts available online at https://faults.ipe.muni.cz. The database components are being populated continuously and their content is subject to changes.

1 Introduction

The Czech Republic is located in the immediate foreland of the Alpine-Carpathian Orogen and partly within its external parts. Most of the Czech territory lies within region of comparatively strong Variscan lithosphere – the Bohemian Massif. The easternmost part is formed by the thin-skinned nappes of the Outer Carpathians formed mostly by flysch-type sediments of inverted foreland basin (comp. Figs 1.1 and 2.1). The Bohemian Massif is largely compatible with the concept of stable continental region (SCR) as defined e.g. in Johnston et al. (1994).

Whole Czech territory is characterised by very low strain rates and seismicity. The strongest earthquakes with epicentre in the Czech Republic in the several-centuries-long historical record reach epicentral intensity of I_{MSK}=7-8° (estimated Mw≈4.7-4.8; e.g. Kárník et al. 1957, Prachař and Pazdírková in prep., SIGMA2, Action 2.5). The instrumental records of the last few decades[1] show a pervasive low-rate and low magnitude background seismicity and several regions of higher seismic rates and magnitudes roughly correlating with location of stronger historical earthquakes. The results of geodetic measurements currently do not seem to show any systematic strain pattern that could be correlated with known faults or seismicity.

Taking into account the low strain rates, long earthquake recurrence intervals must be expected and it is very likely that in the available historical and instrumental records even earthquakes of M≈4 are largely undersampled for most potentially active faults. Earthquakes with magnitudes approaching the maximum potential values with recurrence periods of >>10^3 y (comp. Crone et al. 1997) would most likely remain undetected even after next few centuries of seismological monitoring. To reduce the lack of information on strong local earthquakes we need either to extend the available earthquake catalogues to pre-historic times or rely on theoretical forward seismicity models. This is why we need so urgently to improve our knowledge on local fault behaviour and to survey the geological records for surface breaking paleoearthquakes, strong shaking events and fault slip rates.

Owing to the lack of clear surface evidence of active faulting and in accordance with traditional understanding of the Bohemian Massif as a stable part of Europe, the faults in the Czech Republic were mostly (with few exceptions) considered inactive in late Quaternary by many generations of geologists. Detailed mapping and description of faults were never important issues of field geology and the analytical information on geological and geomorphological aspects relevant for active faulting in the region is rather scarce and superficial. Due to this deficit of relevant information, the assessment of faults as potential seismic sources in the early seismic hazard assessments (SHA) mostly relied on regional scale geological features and seismic catalogues. With few exceptions, the faults in the Czech territory have not been treated as individual seismic sources but were contained in the areal seismogenic zones.

Considering the unclear role of faults in the present-day crustal deformation it is apparent that the characterization of seismic sources in the Czech Republic will continue to be based primarily on a framework of broader areas. Nevertheless, the SHA-relevant parameters are easier to be found at individual faults. It is therefore desirable to (1) systematically mine the information on past behaviour of major faults, (2) estimate their maximum potential magnitude (Mmax) and recurrence, (3) separate the active faults from the adjacent zones of background seismicity where possible, and perhaps (4) try to use the Mmax and recurrence at the faults to model the limits of respective parameters in the background seismicity zones.

[1] The first local instrumental records date back to the early to middle 20. century, however, it is only since 1990s when a relatively good station coverage allows the compilation of reliable national catalogs for M<2 events with well determined earthquake magnitudes. The monitoring infrastructure has been constantly improving and the completeness of current earthquake catalogs is estimated better than M≈1 for the Czech national catalog and around M≈0.1-0.2 for the regions of nuclear power plants.

Since late 2000s we started detailed systematic assessment of some faults near the two Czech nuclear power plants (Fig. 1.1) for SHA while faults in the external parts of the Bohemian Massif were being studied simultaneously as a part of basic research (e.g., Štěpančíková et al., 2010; Špaček et al. 2017). Since then the faulting-related data are being produced slowly but steadily and it is now desirable to prepare a database for systematic recording of this SHA-relevant information to facilitate its usage for modeling the sources of future seismicity. This database should then serve as one of the key inputs for any future SHA or fault displacement hazard analysis in the Czech Republic.

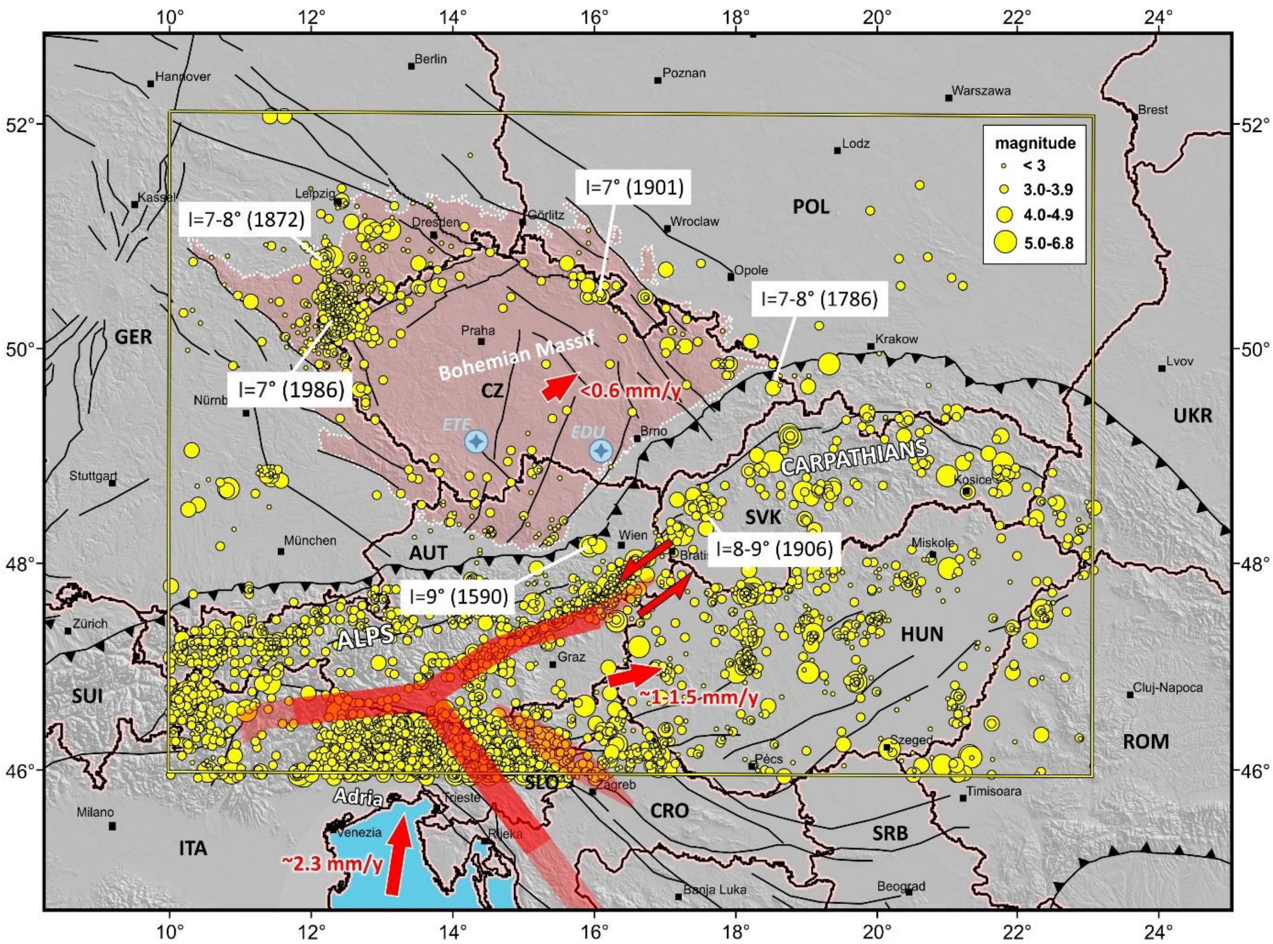

Fig 1.1. General tectonic features and present-day dynamics of the Central-Eastern Europe. The Bohemian Massif is highlighted in red colour and the two Czech NPPs (Temelín, ETE and Dukovany, EDU) are shown by blue symbols. Alpine thrusting front is shown by barbed line. Red belts are approximate microplate boundaries between Adria (south), Alcapa+Tisza block (east) and the "stable" European platform (north) as interpreted by Brückl et al (2010). GPS velocities relative to Eurasia (red arrows) are generalized from Grenerczy et al. (2005) (Note that the value of <0.6mm/y for the "stable" Europe is below the measurement significance level stated by the authors of the study). Epicentres of felt earthquakes (yellow circles) scaled according to calculated magnitude are from an early version of catalog of Prachař and Pazdírková (for years 456 to 2004 A.D.). Epicentral intensities (MSK scale) and years of origin of the strongest recorded earthquakes in the Bohemian Massif and its close neighbourhood are shown.

We have set the following main goals to be aimed for in the frame of Sigma 2 project:

1) Gathering relevant fault-related information and storing it in database in such way that the interpretation can be reproducible and improved in future,
2) Harmonizing the interpretation of key observations in terms of fault activity and finding optimal ways of conversion for SHA inputs,
3) Making the results available to public to serve the community of geoscientists and further promote the active faulting and neotectonics as a topic of broader research interest.

Taking into account the late introduction of systematic field research on active faulting and paleoearthquakes in Central Europe it is clear that filling up the fault database with relevant data will require considerable effort and time. In large parts of the territory concerned the success rate of such research is expected to be low. It may take several decades before we get reliable (correctly interpreted, well dated and well located) paleoseismic events from significant part of the major faults. Before we proceed with these upgrades, it seems inevitable that we are going to keep on working in SHA with persistent deficit of data, large epistemic uncertainties and higher-than-desired importance of “expert judgement”.

In such situation it is especially important to keep all the database resources and processing techniques maximally transparent. The experts’ opinion will likely evolve significantly with increasing number of new data. To allow easy and effective development in future we need to assure that the key primary data are verifiable and all derived parameters are repeatable so that they can be critically assessed. At the same time, the database structure and the processing approach should reflect the lower number and quality of primary input data. Therefore, our purpose is that the database of fault-related information we establish and the algorithms of processing for SHA we define are *simple* and *transparent*. It is expected that the database would be further completed by new field evidence coming from ongoing basic or applied research. In case that the simple structure of the database is no more capable of storing the new data in a user-efficient way, it can be optimized accordingly.

Our present experience suggests that by far not all approaches used in comparatively well explored seismically active regions will be fully applicable in the Czech Republic. We rather need to choose or establish methods optimal for very low strain rate, very low seismicity intraplate regions with weak geological record of paleoseismicity and faulting.

This deliverable is focused at the structure of database of faulting-related observations and concepts used for database population which is still going on. The procedures for conversion of field observations to SHA-inputs are being developed simultaneously and the respective methodical approaches will likely continue evolving in future years.

2 Basic rationale and concept of the databases

The present database of fault-related information is being built primarily for the faults on the Czech territory. The faults of the Bohemian Massif are included first to be followed by the faults in Czech part of the Western Carpathians (compare Fig. 1.1). Adjacent sections of cross-border faults as well as some major faults entirely contained outside the Czech borders are being added at the same time. Linking with databases of neighboring countries thus should be possible in future.

Typically, the research of fault activity in this region is complicated by a combination of some of the following unfavourable factors:

- The expressions of recent faulting and crustal deformation in general are absent (geodetic surface strains are only very slow and tectonically inexpressive; the seismicity has mostly diffuse character and low magnitude; directly observed surface faulting has not been reported).
- The Bohemian Massif has been mostly elevated area during its post-Variscan evolution periods, therefore the extent of its sedimentary cover, especially of Cenozoic age, is limited both geographically and stratigraphically (comp. Fig. 2.1). The exhumed faults and discontinuities in the crystalline complexes, usually poorly exposed, are likely of various reactivation ages which are, however, difficult to date. This situation complicates the first order regional scale assessment of the Cenozoic fault activity and the selection of the faults to be studied in detail.
- Suitable Quaternary in-situ sediment deposits covering the fault are may be rare or missing. Repeated exposure of the Czech territory to periglacial environment has lead to widespread solifluction and various scale slope-related processes which obliterate the records of tectonic deformations. This, in combination with age limits of radiocarbon and OSL dating methods, makes the detailed assessment of the young fault slip challenging.

These factors probably contributed to the relatively low intensity of fault research in the Czech Republic so far. We have to expect that, despite increased effort, these same factors will keep limiting the possibilities of using the geological record to assess the seismic hazard.

In spite of the fact that Bohemian Massif is a part of SCR the possibility of local occurrence of strong earthquake in future is not ruled out. Although having much lower recurrence rate than in active regions, strong earthquakes are not exceptional in SCRs on a global scale (e.g., Johnston et al. 1994 for review of historical seismicity). Therefore, strong earthquake scenarios should be modeled in SHA for the Czech Republic.

Observations in various parts of the world suggest that in SCRs we can not reckon on that the future strong earthquake would be exclusively located on a fault with long term observed seismicity or clear signs of past faulting (Crone et al. 1997, Stein et al. 2015, Calais et al. 2016, Liu and Stein 2016; also accentuated by reviewers of this deliverable). This should also be taken into account in modeling for SHA. However, it is not our goal to present in our database a complete list of all faults posing hazard on a purely theoretical basis. We consider it correct to assume that future strong earthquakes are more likely to occur on faults which have been more active lately in geological history than on any other structures. These lately active faults are most relevant to seismic hazard and it is important in the first place to identify them clearly and learn as much as possible on their past activity and seismicity from geological record.

With this in mind we aim for including (processing) faults in the following categories given in order of decreasing priority:

1) Faults with indicated Quaternary activity. Research on these faults is most likely to bring data on slip rates and paleoseismicity and such faults are best candidates for conversion into parametrized seismic sources.

2) Faults with indications of surface slip postdating the Middle Miocene. At the turn of the Early and Middle Miocene there was the latest peak of tectonic activity on a large-regional scale and in since then the paleogeography and long-term averaged stress-field have been comparable to the present. Therefore, both probability of finding evidence on active slip and probability of their future reactivation are high.

3) Faults which exhibit indications of significant post-Mesozoic slip. As Tertiary deposits are largely missing in the central Bohemian Massif, faulting of the Late Cretaceous strata offers the easiest way to identify faults whose activity may have continued to later periods (comp. Fig. 2.1).

4) Other major faults chosen ad hoc based on their length, proximity to nuclear power plants and high theoretical slip tendency (see further specification in Section 3.1).

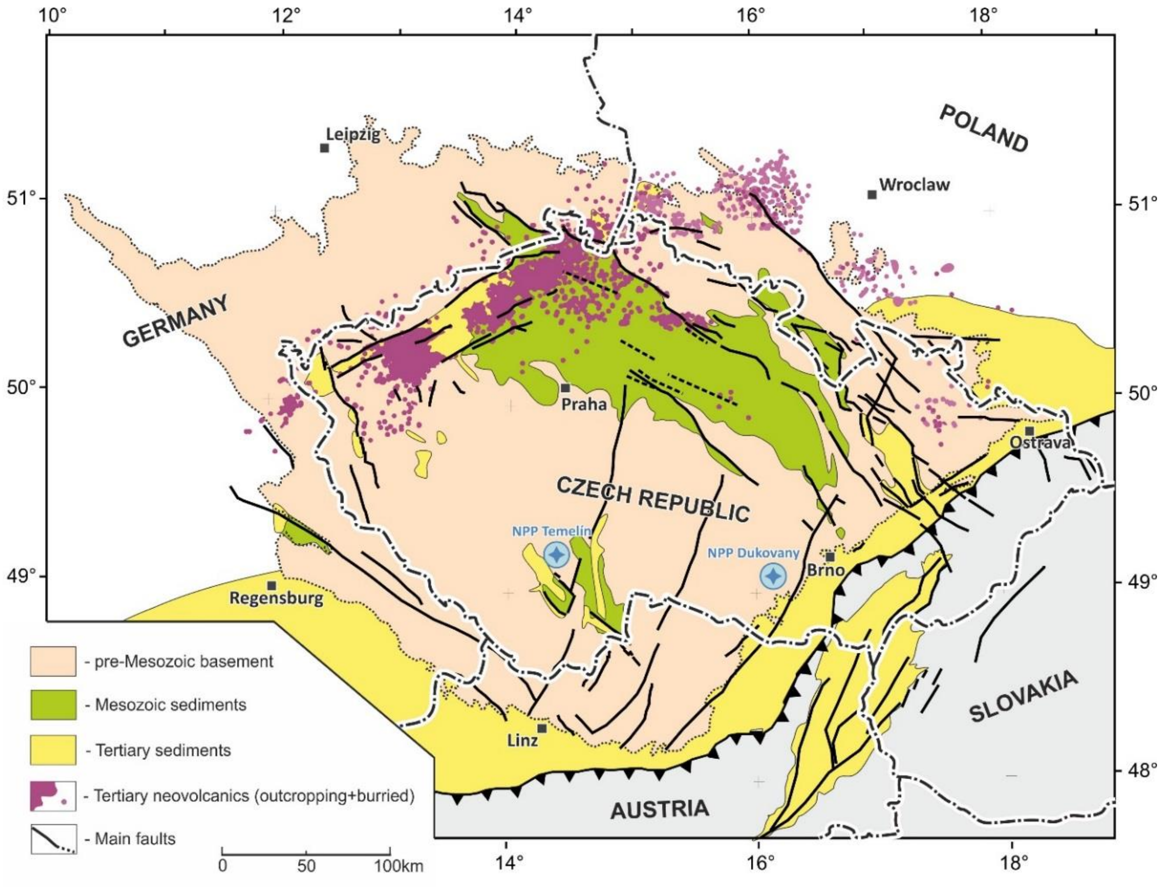

Fig 2.1. Simplified geological map of the Bohemian Massif and adjacent areas. Grey – units of Alpine-Carpathian Orogen; White – thick sediment-covered parts of "stable" European platform. Position of two Czech NPPs are shown by blue symbols. Note the discontinuous sedimentary cover in the Bohemian Massif. Sediments of Late Cretaceous basin are preserved in the central Bohemia. Tertiary sediments are mainly of Early to Middle Miocene age and are mostly restricted to the foreland basin between the Bohemian Massif and the thrusted Alpine-Carpathian units. Occurrences of Paleogene and Upper Miocene (post Langhian) to Pliocene strata are only very local, being associated with Early to Middle Miocene sediments in the southern and western Bohemia.

Database including such a selection will likely contain nearly all faults with ongoing continuous slip. In addition to that, it will sample large set of other potential future seismic sources and make their basic parameters easily available for source modeling. Of course, the amount and detail of information will swiftly decrease from category 1 to 4 and we must expect permanent deficit of direct observations which will be necessary to complement with assumptions. Table 2.1 illustrates this by a simple evaluation of how easy or difficult we expect it would be to find relevant answers to the key questions of SHA for an average fault suspected of active slip in late Quaternary.

Question on active faulting		**Relevance for SHA**	**Probability of successful field research in CZ and main limiting aspects**	
I	Was there an active slip on the fault in late Quaternary? (Or is it actively slipping at present?)	Fault with active slip (including creep) is directly converted into a seismic source for which it is likely possible to find local observation-based parameters. Further research is focused to finding these parameters.	high	Pros: commonly developed colluvia and loess beds; relatively good resolution of seismological monitoring and satisfactory state of historical earthquake record
II	Was there a surface breaking earthquake on the fault?	In case of detected surface breaking the minimum value of Mmax can be roughly estimated and further use of empirical relations between rupture length, displacement and magnitude is well justified.	high to moderate	Cons: permafrost-enhanced slope deformation
III	What was the fault slip rate in late Quaternary?	Knowing the slip rate and assuming the pure stick-slip mechanism, the theoretical moment rate and recurrence rate of future related earthquakes can be modelled.	moderate	Cons: detailed chronostratigraphy of faulted strata missing
IV	What was the age, surface length of and average surface displacement on the youngest paleoearthquake ruptures?	In case of well known parameters the magnitude of related future strong earthquakes can be well estimated.	low	Cons: limits of dating methods and only local presence of older strata sealing the fault, comparatively low ratio of strain rate/erosion rate
V	What were the ages, surface rupture lengths of and average surface displacements on multiple paleoearthquake ruptures?	In case of well known parameters the recurrence rate of related future strong earthquakes can be well estimated.	lowest	Cons: same as IV + long recurrence periods of surface breaking earthquakes

Table 2.1: Fundamental questions on active faulting, their relevance for SHA and the expected level of detectability in the Czech Republic (CZ).

According to our expectations, the data will be significantly deficit even when questioning the youngest activity. However, finding the answers to even the "easiest" questions as to the presence of active fault slip and surface breaking events (I and II in the Table) can provide direct justification of separating the fault from the zone of background seismicity and assessing it as an individual seismic source.

For the sake of transparency it is convenient to keep separately the data on the past and present faulting processes which can be observed locally in the field and the future-oriented fault parameters which are modeled largely basing on indirect data. This is provided by storing the fault-related information in two separate databases: 1) the Fault database and 2) the Database of seismic sources.

These are, of course, closely related, therefore their structure is being considered simultaneously. However, in this deliverable only the Fault database is further addressed in detail while the Database of seismic sources is only briefly introduced, being elaborated elsewhere. Both database groups will be linked to the Earthquake catalogue. The mutual relations of these intended database components are outlined schematically in Fig 2.2 and more details are give in Sections 3 and 4.

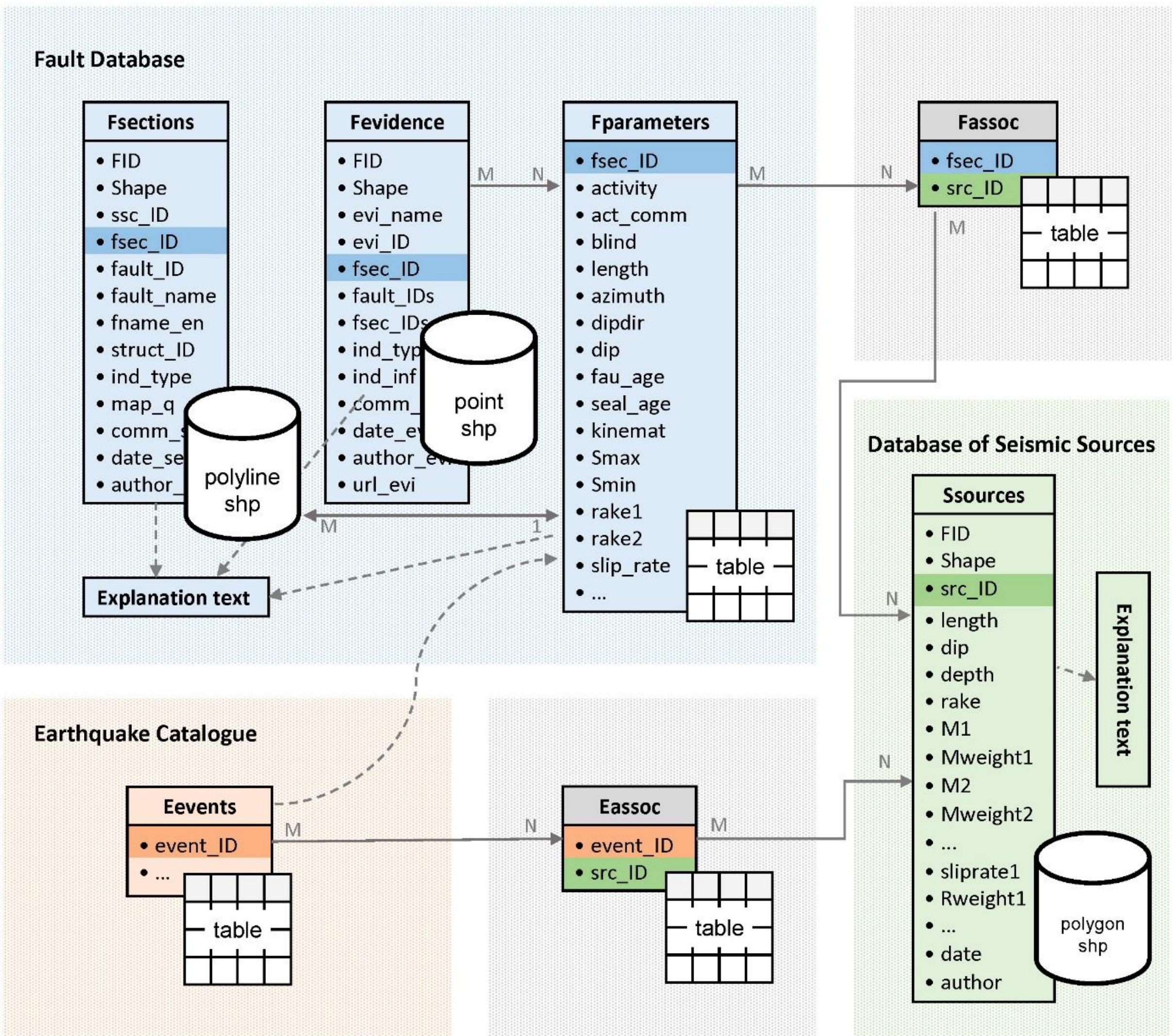

Fig 2.2. Schematic representation of basic intended structure and linking of the databases for Earthquake catalog, Fault database and Database of seismic sources. Connecting fields are highlighted. Shp – ESRI shapefile.

3 Fault database

In the Fault database we define exact map geometry of the faults and record the information on mapping quality, fault dip, past or present faulting processes, paleoearthquakes and other data. When building the structure of the Fault database in 2017/2018, no database with similar intended type, detail and extent has been available to us from neighboring countries (e.g. pers comm. with E. Hintersberger and K. Reicherter 2017). Therefore we took inspiration from other national or regional databases available in literature, e.g. from USA (U.S. Geological Survey 2018), New Zealand (Litchfield et al. 2013), Japan (AIST 2016), Italy (e.g. Basili et al. 2008), Iberia (e.g. Garcia-Mayordomo et al. 2012, 2017), Greece (Caputo and Pavlides 2013), France (e.g. NEOPAL 2009, Palumbo et al. 2013, Jomard et al. 2017) or the database of the SHARE project (Basili et al. 2013). Similarly, the methods of application of these databases in PSHA is being studied thoroughly. Unfortunately, none of these well-elaborated approaches comes from terrains fully comparable in terms of neotectonic activity with the Czech territory and none can be fully adopted for our purpose.

As explained above, the purpose of the Fault database is twofold: It should serve as a basis for building the seismic fault sources and it should organize relevant data for the field research to support its further systematization.

Fault database is arranged into four parts: (1) Analytical fault map, (2) Database of local neotectonic evidence, (3) Fault parameter table, and (4) Explanation texts.

All geometrical features are prepared and stored in ESRI shapefile (.shp) format and all tables are in dBase database file (.dbf) format.

In the Analytical fault map (shapefile *Fsections*) we define the fault map geometry using short segments called fault sections and subsections. Each fault section has a single record in the Fault parameter table (*Fparameters*), which uses the Database of neotectonic evidence (shapefile *Fevidence*) and the Earthquake catalogue as a support. Other non-tabulated information is given in the Explanation text. The structure and interlinking of individual components of the Fault database is outlined in Fig 2.2 and further details are given in Section 3.2.

The amount of assumptions in the Fault database should be minimised, therefore there are only few mandatory fields for which the parameters have to be found or estimated while other may remain empty.

The complete set of Fault database components will be available online after the first campaign of compilation is completed and this deliverable is accepted.

3.1 Selection of faults to be assessed

As explained in Section 2, we aim in the present database for including all faults for which significant Cenozoic activity is anticipated with emphasis on those with strong evidence of surface slip postdating the Middle Miocene. To do this, it is first necessary to consider preliminarily the activity potential of hundreds of faults from geological maps and reduce them to subset for which the above given requirement applies.

The selection must be wide enough to build some safety margins and therefore it should contain faults which may later be evaluated as inactive in Cenozoic. In any case that a fault once included in database is found to be out of these requirements, it will be kept in the databases (with limited detail of description) so that the full list of the evaluated faults and their basic parameters is recorded.

With this in mind we preferentially include those faults which meet at least one of the following criteria:

- faults which cross-cut the Cenozoic sediments or are located at or near the margins of Cenozoic sedimentary basins
- faults which display distinct surface morphology
- faults which are located near a cluster of earthquake epicentres or near important single earthquake epicentres
- faults which were included in previous SHA reports or were regarded as active in any relevant previous study
- major faults in proximity to nuclear power plants, especially those with optimal orientation for slip in the regional stress field

Special attention will be given to suspect structures which are not represented in geological maps but their geomorphological or geophysical expression suggests that they may represent active faults.

Some minor structures are included here, as these may serve as clues to understanding of faulting processes at larger scale. On the contrary, current version of database does not include all small-scale structures in a close proximity of NPPs since these have been studied by special detailed surveys.

Starting selection of faults to be included in the database and morpholineaments to be studied further is shown on a map in Fig. 3.1.1.

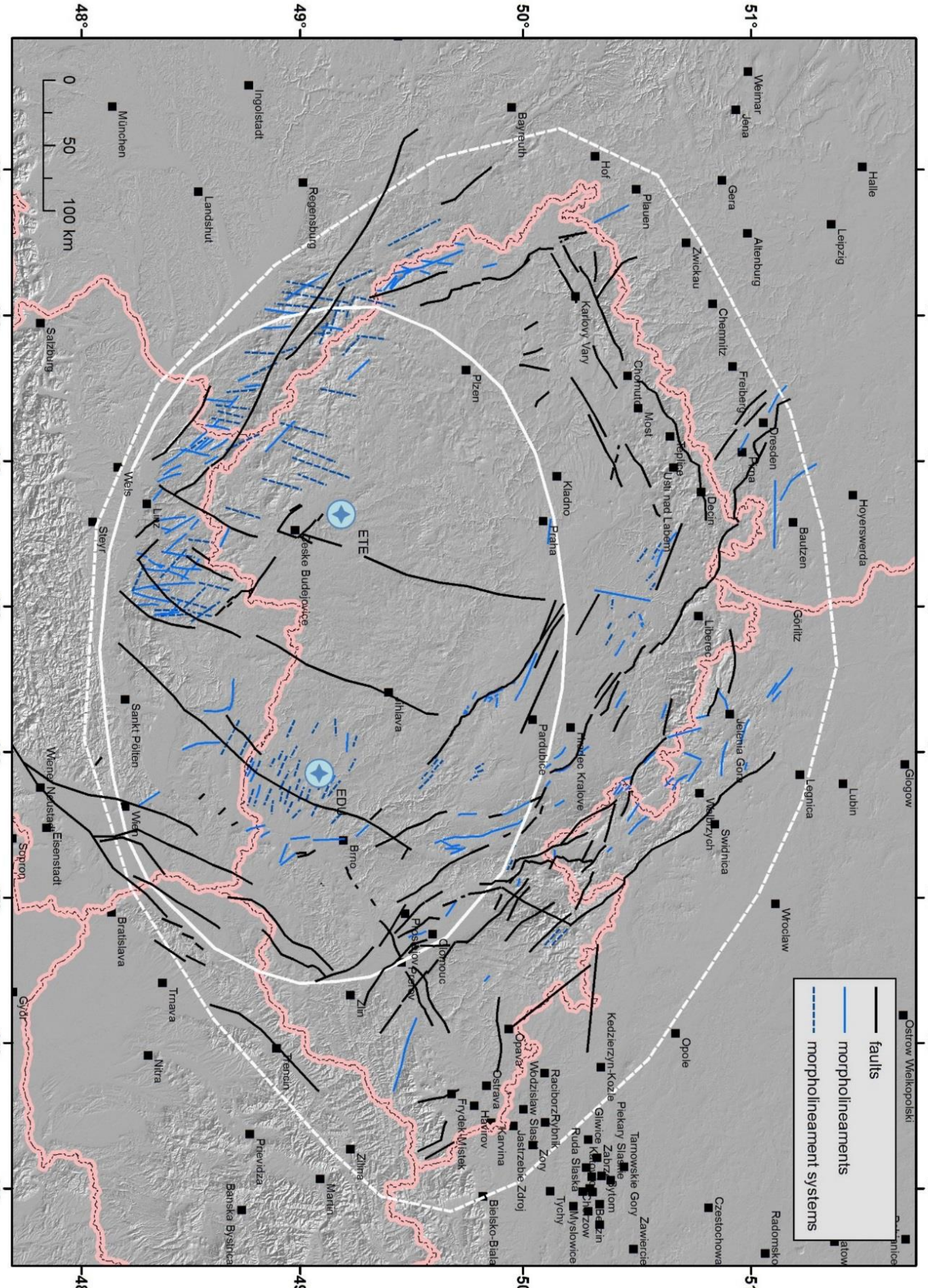

Fig. 3.1.1: Schematic map of faults and morpholineaments (systems of morpholineaments) as yet not identified as faults, included to starting selection. White lines are perimeters of the inner and outer zones of the region of interest. In general, faults within the inner zone (roughly 100 km from NPPs) have higher priority for processing. The map representations of the faults in this selection are schematic, based mostly on regional-scale maps. Improvement of precision takes place during the compilation of the Analytical fault map (section 3.2).

3.2 Analytical fault map

The Czech territory is entirely covered by geological maps at 1:50 000 scale or larger (1:25 000), often in multiple editions. It is often seen that the faults are drawn in different ways in the overlapping or neighbouring maps. In some cases the differences in the very conception of the fault structure used by different geologists are quite fundamental. The classification of the faults in geological maps as the verified and presumed ones is usually not supported by any objective information and it can not be critically assessed, yet it often disagrees with our results of detailed field reconnaissance. The approximate timing of fault activity is not assessed in the maps and for most faults the explanatory texts do not give any detailed information.[2] These imperfections and complexities in the primary data must be taken into account and dealt with when assembling unified database for SHA purposes. Some faults may be missing completely in the geological maps yet they were described in special publications (e.g. blind faults in sedimentary basins) or they can be inferred from well recorded earthquakes for which reliable focal mechanisms are available.

Analytical fault map serves as a unified map of faults assembled from various „primary“ sources[3] and selected out based on criteria defined in Section 3.1. Our intention is not just to make yet another version of the map. We aim to store basic information on local reasons for fault line geometry definition – that is why we call it *analytical*. The main tasks for editors of the fault map are as follows: (1) compiling fault geometries from all earlier map sources, (2) getting over the map inconsistencies and completion by new interpretations based on available data, (3) representing the faults with accurate geometry and unique descriptors for each specific part of the fault for systematic linking with database tables and, (4) adding simplified information on local indications and overall accuracy of a fault line geometry.

Although there is no doubt that the fault geometry will still remain largely influenced by subjective views, recording the main local evidence should facilitate critical reassessment in future. This was not easy to do so far with the available sources and we believe this will later prove to be a significant added value.

[2] The main reason for this information being not given in most sources is surely that the active faulting has never been in focus of interest in Czech Republic and has not been considered of primary importance by mapping geologists. We believe that with the internal motivation of the editors of this database this can partly change.

[3] All available relevant data sources are used for compilation. These include mainly: **Geological maps** (published mostly by the Czech Geological Survey and its predecessors, mainly the 1:50 000 scale maps of various editions covering the whole country, preferrentially the seemless WMS version and the 1:25000 scale maps on >800 sheets); **DEMs** (for Czech territorry mainly the Airborne LiDAR-based DMR 4G of the State Administration of land Surveying and Cadastre, ČÚZK, with whole-country coverage); **Gravity maps** (Whole Czech Rep. is covered by complete Bouguer anomaly map derived from irregular grid with mean desity of 4 points per km^2, for some areas data are available in better resolution; derived horizontal gradients/Linsser indications or residual anomalies are used); **Other geophysical data** (aeromagnetic maps, seismic profiles, local geoelectric and electromagnetic surveys); **Drill profiles** (these are important for interpreting the faults and fault slip in sedimentary basins; we mainly use those available in Geofond archive of the Czech Geological Survey) and **Special reports and publications**.

Database structure and attributes

The database is finalised as a polyline shapefile named *Fsections*. The attribute structure is given in Table 3.2.1. Each fault is organised in two-level hierarchy into the fault sections and fault subsections (Fig 3.2.1):

Fault subsections are the shortest continuous parts of the fault defined by the same set of map attributes describing the type and quality of indication of the fault. Each subsection has a single record (row) in the attribute table and unique ID (*ssc_ID*). The indication type (field *ind_type*) describes which local evidence of the fault existence and position is accepted by map editor for the given subsection. The editor can either choose the better of all variants available in the geological maps or draw a new one. In either case the chosen approach and the type of indications used are recorded by a set of unique letter codes (see the Table 3.2.1).[4] Subjective assessment of the indication quality and the related fault line accuracy is defined together in the field *map_q* following the rules given in the Table 3.2.1.

Fault sections are the shortest portions of the fault defined by common attributes in the Fault parameter table. They are composed of arbitrary number of subsections with similar orientation. The affiliation of individual subsections to the fault section is defined by field *fsec_ID* which is also the unique key linking all components of the Fault database and Database of seismic sources. In this sense, fault sections are the basic elements of Fault database.[5]

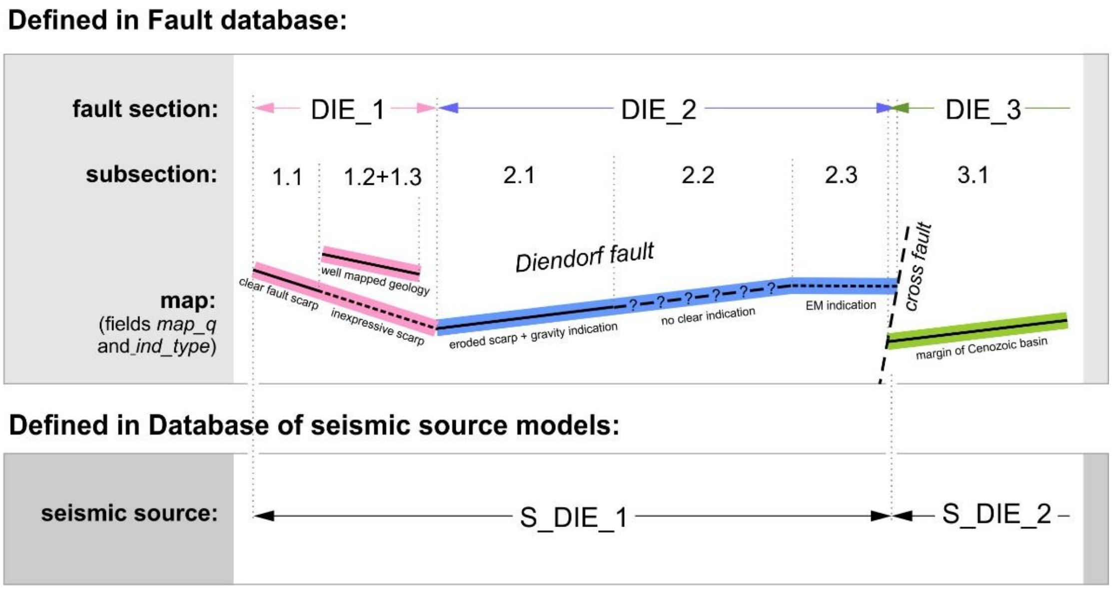

Fig. 3.2.1: Schematic illustration to explain the concept used for description of a fault in the Analytical fault map of Fault database (top). Note that the seismic sources (including proved or hypothetical earthquake segments at capable faults) are defined in Model of seismic fault sources (MSFS; bottom).

[4] Each part of the region concerned is to be compiled by different editor whose opinions on fault interpretation may differ significantly. Furthermore, the number and quality of primary data are different for each area. Therefore it is desirable to unify the editing by filling the *ind_type* and *map_q* fields as carefuly and correctly as possible, using all the data sources available. In case that re-interpretation is not possible, the fault lines are simply taken from the chosen geological map and the field *ind_type* is set to *„m“*.

[5] The importance of the term *fault* is somewhat supressed here since different geologists often link different sections into different structures they call same names. Fault names are used here as a secondary descriptor only to ease linking the fault sections with commonly known terms.

The fault section terminations are based mainly on changes in azimuth, gaps, interactions with cross-cutting faults, significant changes of fault scarp morphology and other discontinuities of indications of the fault. This approach is similar to that used for definition of geometric or structural segments (e.g. dePolo et al. 1991). Where using these criteria can lead to multiple solutions, we prefer short fault sections to ensure that locally observed evidence on fault activity are extrapolated only to those parts of faults where this can be rationalized.

The **fault sections, as defined here, are not understood as segments related to single rupture** related to either past or future earthquakes (earthquake segments), despite similar criteria are commonly used for the latter (e.g. dePolo et al. 1989). In the Fault database we do not deal with definition of seismic sources. All hypothetical earthquakes with surface ruptures are to be modeled by combining adjacent fault sections defined here, into seismic sources stored in the Database of seismic source.[6] Therefore the length of the fault section does not have primary influence on Mmax. To prevent misunderstandings we rather avoid using the term *fault segment* in Fault database because this is sometimes automatically understood as a synonym to *earthquake segment*.

Other parameters stored in *Fsections* table are the fault name (in original and English language; fields *fault_name* and *fname_en*) and ID (*fault_ID*), ID of the larger structure the fault is a part of (istruct_ID) and the see (Table 3.2.1).

[6] Reasons for this approach are mostly technical. We expect that the definition of earthquake segments and seismic sources will not be well constrained by field observations and their interpretation will change significantly as the paleoseismological research will produce new results. Also, the database should enable that the modeled seismic sources overlap each other. For both cases it is more convenient to define the seismic sources separately at different level using simplified geometry and different database structure.

Fsections			
field name	***content***	***description and range of permitted values***	***data type***
FID	ArcGIS ID of graphical feature segment	integer number (compulsory ArcGIS field; not used)	long integer
Shape	ArcGIS descriptor of graphical feature type	fixed string „Polyline" (compulsory ArcGIS field)	text
ssc_ID	fault subsection ID code	integer number 1-999	short integer
fsec_ID	fault section ID code	3-4 character string + "_" + integer number 1-999; letter allowed for special cases (e.g. *_c1 for cross structure). Fsec_ID must be unique to each fault section.	text
fault_ID	fault ID code	3-4 character string (first part of fsec_ID)	text
fault_name	name of the fault in original language	text	text
fname_en	name of the fault in English language	text	text
struct_ID	code of the fault system/zone or regional structure	3-8 character string	text
ind_type	type of fault subsection indication	c - clustering of earthquakes; m – published geological maps; n - newly performed unpublished (to date of record update) geological mapping; r - indications in relief; b - boundary fault of a Cenozoic basin; d - indirect indication by drills; t – trenching/geological outcrop; g - gravimetric indication; e - electric resistivity indication; z - magnetic indication; s - indication in seismic profile; a - aerial photograph; o - other (any combination is allowed; weak indication in parentheses)	text
map_q	quality of the indication and accuracy of the fault line	1 - clear indication and good accuracy; 2 - clear or multiple indication and moderate accuracy; 3 - weak indication or poor accuracy; 4 - only assumed and very approximate; 5 - for working purposes only (topolineaments without clear assoc. to active faults etc.)	short integer
comm_sec	any comment relevant for definition or categorization of the (sub)section	any text (up to 500 characters)	text
date_sec	date of last update	date	date
author_sec	author(s) of the record	any text (up to 100 characters)	text

Table 3.2.1: List of fields in attribute table for shapefile Fsegments.

3.3 Database of local neotectonic evidence

This database stores basic local observations relevant for the assessment of the neotectonic activity of the fault and data on paleoseismic events. Geological evidence is usually limited to sites of detailed research which can be approximated by a point in a map. For purpose of modeling of the fault behaviour the relevant interpretation of the local observations can be extrapolated from these points to the adjacent fault section or multiple sections.

The prevailing type of recorded information should cover the main outputs of the recently performed research, i.e. paleoseismic trenching, studies in river terraces and drill-based or geophysical profiles documenting the faulting or continuity of the sedimentary strata of known or estimated age. Another type of recorded data should be represented by the indications of strong shaking, mainly the liquefaction of soft sandy sediments and the braking of speleothems[7]. Taking into account the very low strain rate of the region concerned, **both findings which support or contradict the neotectonic activity are recorded** – these are considered equally important.

Some other important site-specific information can be stored here, e.g. stronger earthquakes with well constrained focal mechanisms, local data on fault dip or Cenozoic fault kinematics etc.

Database is compiled into multipoint ESRI shapefile *Fevidence* whose structure is given in Table 3.3.1. Each record has a unique ID (field *evi_ID*) and may be associated with single primary and multiple secondary fault sections (*fsec_ID*, *fsec_IDs*). The type of indication and main inference are described by fields *ind_type* and *ind_inf*. The attribute table stores only basic text description with limited length (field *comm_evi*). More detailed information with complete reference list is contained in the Explanation text which is linked via field *url_evi* (see sections 3.5 and 3.6).

Fevidence			
field name	***content***	***description and range of permitted values***	***data type***
FID	ArcGIS ID of graphical feature segment	integer number; not for editing	long integer
Shape	ArcGIS descriptor of graphical feature type	fixed string „Point“; not for editing	text
evi_name	locality name	text string	text
evi_ID	point of evidence ID code	string based on a locality + _suffix	text
fsec_ID	primary fault section ID code to which the evi_ID is related	6-7 character string (see table *Fsections*)	text
fault_IDs	IDs of secondary faults to which the evi_ID is related	Comma delimited, 3-4 character strings (see table *Fsections*)	text
fsec_IDs	IDs of secondary fault sections which relate to evi_ID	Comma delimited, 6-7 character strings (see table *Fsections*)	text

[7] Liquefaction structures can be interpreted in terms of intensity and in case that geographical distribution and/or dating allows to locate the earthquake epicentre, magnitude can be estimated using the upper bound magnitude vs. distance curves (e.g. Galli 2000, Pirrotta 2006, Castilla and Audemard 2006, Maurer et al. 2015). Events of speleothem breaking can be dated and interpreted in terms of minimum intensity reached at the site. However, both phenomena seem to be extremely rare in the Czech Republic, perhaps indicating that strong earthquakes are not common in this region.

ind_type	type of indication	1 - directly observed offset layer/sealing layer or similar; 2 - inferred offset layer/sealing layer or similar; 3 - liquefaction; 4 - broken speleothem; 5 - cross structure; 6 - other	text
ind_inf	inference from indication	n - evidence of inactivity (negative), p - evidence of activity (positive); np - evidence for both activity and inactivity; u - unclear inference related to activity, o - related to other parameter than activity	text
comm_evi	short description of observations and inference	any text	text
date_evi	date of last update	date	date
author_evi	author(s) of the record	any text	text
url_evi	url address of web with text information	any text	text

Table 3.3.1: List of fields in attribute table for shapefile Fevidence.

3.4 Fault parameters

The Fault parameter table (*Fparameters*; Table 3.4.1) records data which evaluate the past and present behaviour of the fault and which is used as input for the Model of seismic sources and SHA. This includes mainly: (1) the overall evaluation of fault activity (fields *activity* and *act_comm*), (2) age bracketing of the last fault slip (fields *fau_age* and *seal_age*), (3) estimate of fault slip rate and kinematics (fields *slip_rate* and *kinemat*), (4) summary of seismic events associated with fault (fields *M_inst*, *M_hist* and *M_paleo*), (5) estimates of fault dip (fields *dip*, *dipdir*, *dip_qual*), and (6) theoretical fault slip tendency and slip geometry (fields *Smax*, *Smin*, *rake1* and *rake2*).

These parameters are either adopted from primary sources, including the Database of neotectonic evidence and Earthquake catalogue, calculated or inferred through complex interpretation.

Each fault section is represented by a single record (row) in the attribute table. Linking with other components of the Fault database is done via field *fsec_ID* as illustrated in Fig. 2.2. More detailed information on the fault is given in the Explanation text which is linked via field *url_evi* (see sections 3.5 and 3.6).

It is clear that many of the parameters will remain unknown - in such case the respective table fields can be left empty. Only some fields are mandatory, including the overall evaluation of activity which is prerequisite for inclusion (or non-inclusion) into models of seismic source, and the fault dip which is needed for estimation of theoretical slip tendency and kinematics (see the fields marked by asterisk in Table 3.4.1).

Evaluation of fault activity

Fault activity is assessed basing on local or regional-scale field evidence. Ideally, the evidence is based on local observations listed in *Fevidence* table. In the absence of clear local evidence it is important to describe the reasons for evaluation of activity in the *act_comm* field of *Fparameters* table and in a more detailed way in the Explanation texts.

The evaluation of relevance of evidence and its interpretation in terms of fault activity is performed by the editor of the record in the database and should later be defended before the editorial board which takes care of harmonization of the approach for the whole database (see section 3.7).

Various kinds of local evidence can be used including direct observations of faulted and sealing strata of known age, relative height levels of correlated strata, interference of a fault with cross structures, scarp morphology or earthquake epicentre distribution and focal solutions. The calculated theoretical slip tendency may also be used as a lead for evaluation of fault activity (see below).

Regional-scale evidence may be used to support the evaluation of fault activity or even taken as primary in the absence of clear local evidence. This may include the extent and architecture of late Cenozoic basins, distinct regional-scale anomalies of seismicity, late Cenozoic volcanic and ongoing post-volcanic activity or features in relief which are interpreted to reflect some trends in late Cenozoic faulting.

Some examples can be found in the Appendix, where explanation texts are given for two major faults which have been subject of recent research.

Fault sections are ranked with respect to their interpreted activity using five classes:

- **1** - Fault sections demonstrably active in the time range ~0-100 ka BP
- **2** - Fault sections with proven last activity in the time range ~100-780 ka
- **3** - Fault sections with proven (excluding 0-780 ka BP) or assumed last activity in Quaternary
- **4** - Fault sections with assumed or proven last activity in Neogene
- **5** - Fault sections presumed or proven inactive in Neogene or Quaternary

The ages of the class boundaries take into account the relevance for SHA and the expected limits of the fault activity dating posed by the average geological situation in the Czech Republic. The 100 ka boundary is defined by the common age range of widespread sediments potentially datable by radiocarbon or OSL methods or by allostratigraphy (morphostratigraphy) using the base of the lowermost river „terrace“.[8] The 780 ka boundary is defined by the approximate age range of commonly occurring sediments potentially datable by allostratigraphy (mostly the higher river terraces) or roughly datable by magnetostratigraphy (Brunhes chron, normal magnetic polarity).

Class 1 or 2 is reserved to those fault sections for which clear evidence of the fault slip (mostly from trenches) with conclusive dating or clearly demonstrated link to present-day or historical seismicity. Class 3 is meant to include those fault sections for which the direct evidence of active slip is missing, yet their slip in Quaternary is considered likely based on indirect or inconclusive evidence. Ranking class 3 should be also considered for fault sections in close proximity to stronger historical or instrumental earthquake. Fault ranking will be updated accordingly to newly found data. All fault sections ranked class 1 through 3 should be directly modeled as seismic sources (either individual or areal) in SHA.[9]

Single fault can contain sections with different activity. This reflects the used concept of recording in the Fault database primarily the observation-based data and setting the fault section as the principal unit to which local observations are extrapolated. In most cases the observations do not provide direct justification to extrapolate the local evidence to the whole fault. The coexistence in a single fault of sections with different activity may be real or only apparent. It is to be decided by the editors of Database of seismic sources whether such case will be modeled as larger fault with undersampled evidence or as multiple faults with different parameters.

[8] This age boundary is formal and approximate. In some cases the OSL/IRSL dating limits can enable getting older ages but such data are expected to be rare and less reliable.

[9] Legal regulation of the Czech law for the placement of nuclear facilities (Decree no. 378/2016, State Office for Nuclear Safety) requires that the evaluation of all faults with proven activity taking place during the last 2.6 My is performed.

Theoretical slip tendency and geometry

Provided that we know the fault orientation, the coefficient of friction and the local reduced stress tensor, we can quantify how close the fault is to an optimal orientation for slip („slip tendency“, e.g. Morris et al. 1996). In reality the uncertainties of all the input parameters hinders calculation of exact values, however, modelling within reasonably chosen ranges can show variations of relative potential fault activity and kinematics.

We carried out such modelling for each fault section in Fault database and regional stress models based on World Stress Map database (Heidbach et al. 2008) and newer data. Six stress models were constructed by smooth interpolation of local data to cover the uncertainties, assuming horizontal compressive stress regime (i.e. with nearly horizontal maximum and minimum stress axes).[10] Minimum and maximum angle between fault normal and local axis of maximum stress was found for each fault section.

Theoretical slip tendency of a fault with known orientation was then described by *fault stability coefficient S* calculated (by J. Havíř, IPE) as a normalized perpendicular distance to Mohr-Coulomb failure envelope using modification of method described in Švancara et al. 2008. Permitted range of Lamé parameter (stress shape factor) was set to [-0.5, 0.5] and that of coefficient of internal friction to [0.2, 0.6].

The minimum and maximum values of *S* calculated for each fault section (within the full range of given uncertainties) is recorded in *Smin* and *Smax* fields of *Fparameters* table (Table 3.4.1; *S* ranges between 0 and 1 and higher value means higher theoretical stability of the fault). At the same time, respective theoretical values of rake are calculated and recorded in *rake1* and *rake2* fields.

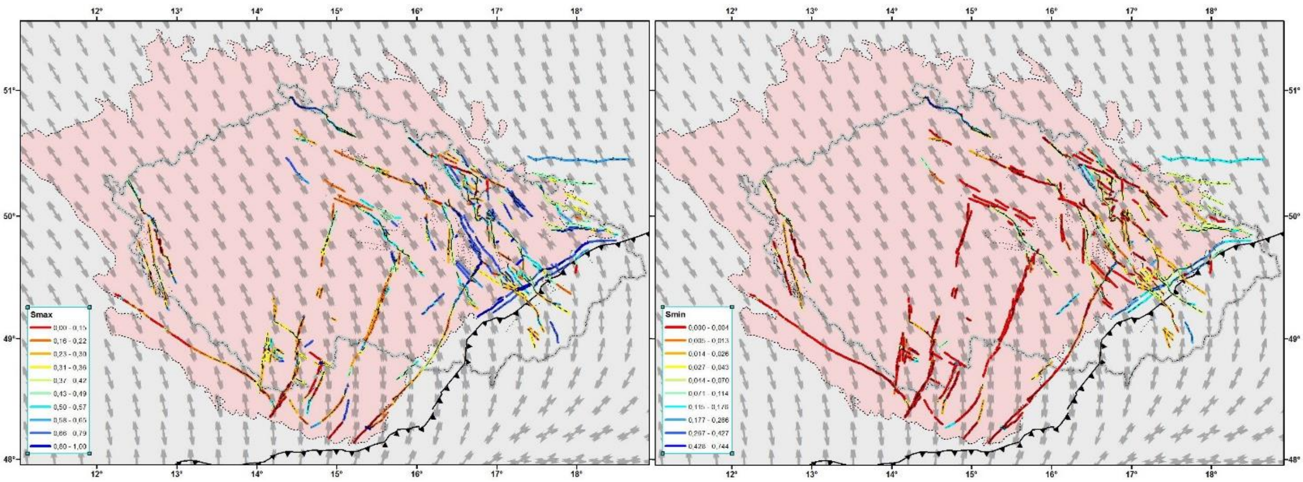

Fig. 3.4.1. Fault maps with color-coded maximum (left) and minimum (right) values of fault stability coefficient S. Variance of maximum stress orientation in the stress models used is shown schematically by grey arrows.

As expected, large variance of *S* values is obtained for most faults processed so far (see Fig. 3.4.1). As the value of *S* is mostly dependent on the angle between the fault normal and stress tensor, the uncertainty of fault dip and stress orientation have largest influence on the variance magnitude. The influence of Lode parameters and

[10] The Czech Republic is situated near or within a transition zone of three regional stress domains: the West-European with NW-SE oreinted S_H, the fore-Carpathian with N-S oriented S_H and the East-Alpine/West-Carpathian with NNE-SSW to N-S oriented S_H (Peška 1992, Reinecker and Lenhardt 1999, Jarosiński 2005, Heidbach et al. 2008, Fojtíková et al. 2010). The modeled stress maps can differ significantly in this region (especially in the SE Bohemian Massif) depending on how the interpolation of sparse local data is performed. Furthermore, there is evidence of thrusting in southernmost parts of the Bohemian Massif submerged beneath the thin-skinned nappes of the Eastern Northern Alps, and indications of possibly transtensional stress domain in the NE. In these starting calculations this is ignored and the stres field is largely simplified.

coefficient of internal friction is secondary.

In spite of large variance, in the general deficit of empirical data on fault activity the slip tendency seems to be useful as a lead for evaluation of fault activity in most problematic cases. For some faults it is suggested by their high *S* values that their activation is very unlikely unless the stress models used are totally wrong. We believe that in some faults with independent evidence on activity, the sensitivity of *S* to fault orientation can be used to re-assess their local dip.

Fparameters			
field name	***content***	***description and range of permitted values***	***data type*****
OID	ArcGIS ID of graphical feature segment	not to be edited	long integer
fsec_ID*	code of the fault section	6-7 character string (see table *Fsections*)	text
activity*	assessment of fault section activity	1 - demonstrably active during the last 100ka, 2 - proven last activity in the time range of ~780-100 ka, 3 - unproven but assumed last activity in Quaternary, 4 - assumed or proven last activity in Neogene, 5 - assumed or proven inactive in Neogene and Quaternary, 0 - not assessed	short integer
act_comm	short comment on assessment of activity	Any short information related to fault activity; (details should be given in the text description outside this table).	text
importance	evaluation of general importance of the fault in terms of size and expected cumulative slip	Primarily for map view purposes. 1 - major fault of regional importance , 2 - moderately large or minor with some regional importance, 3 - minor with only local importance	short integer
blind*	is the fault section blind or buried (supposedly does not reach the surface or the base of Quaternary strata)?	y/n	text
length	maximum continuous surface length in meters	integer number in meters (calculated from dimensions of envelope, not as a cumulative length of all lines within the section)	long integer
azimuth*	mean azimuth of fault section in degrees	integer numbers 0-180	short integer
dipdir*	mean dip direction in degrees	integer numbers 0-360	short integer
dip*	mean dip in degrees	integer number 0-90	short integer
dip_qual*	quality (certainty) of dip_mean value	1 - good (direct observation or inferred from clear results of drilling/geophysics), 2 - moderate (e.g., inferred from neighbouring fault section), 3 - poor (based on some poor evidence/idea), 4 - unknown (filled in only for modeling purposes)	short integer

Fparameters			
field name	***content***	***description and range of permitted values***	***data type*****
fau_age	age of youngest evident faulted strata + quality assessment	[<,>] decimal or integer number, string for time units and quality mark in parentheses (1-good, 2-poor)	text
seal_age	age of oldest evident sealing strata + quality assessment	[<,>] decimal or integer number, string for time units and quality mark in parentheses (1-good, 2-poor)	text
kinemat	Quaternary fault slip kinematics + quality assessment	text (e.g. *dextral strike slip; normal*) and quality mark in parentheses (1-good, 2-poor)	text
Smax*	maximum value of fault stability coefficient	decimal number 0-1 where higher value means higher theoretical stability of the fault	float
Smin*	minimum value of fault stability coefficient	decimal number 0-1 where higher value means higher theoretical stability of the fault	float
rake1*	maximum value of theoretical rake	integer number	short integer
rake2*	minimum value of theoretical rake	integer number	short integer
slip_rate	maximum surface slip rate during the last 100ka [mm/y] + quality assessment	[<,>] decimal number and quality mark in parentheses (1-good, 2-poor)	text
M_hist	maximum magnitude of hist. earthquake attributed to the fault	decimal number (or range of values if necessary)	text
M_inst	maximum magnitude of instr. earthquake attributed to the fault	decimal number (or range of values if necessary)	text
M_paleo	maximum magnitude of interpreted paleoearthquake attributed to the fault	decimal number (or range of values if necessary; rough estimates in parentheses)	text
comm_par	any other comments	any text, e.g. range of dips, …	text
date_par*	date of last update	date	date
author_par*	author(s) of the record	any text	text
contribut	contributors' names	any text	text
url_par	url address of web with text information	any text	text

Table 3.4.1: List of fields in attribute table Fparameters.**) required fields; **) in some fields the data type is set as a text to keep open the possibility of adding non-numeric characters when needed.*

3.5 Explanation texts

Explanation texts are source of data for both the Fault map database and the Database of neotectonic evidence and they are connected with respective tables Fparameters and Fevidence via their *url* fields.

It should give a detailed overview of important information for each major fault or fault system which is not contained in the tables of the Fault database:

- Definition and description of the fault's/fault system's extent
- General characteristics (geological, geomorphological and geophysical expression, fault geometry and structure)
- Description of main cross structures and of the fault segmentation (major gaps, bends or steps) if observed
- Overview on observed seismicity spatially associated with the faults
- Basic summary on current conceptions on evolution and late activity of the fault/fault system
- Overview of evidence or counterevidence on active fault slip including the paleoseismic events where indicated
- Interpretations of SHA-relevant fault parameters which are given in *Fparameters* table (especially the late activity and slip rate)
- References to primary sources of information, including the geological map sources
- Optionally, ongoing research and the needs and possibilities of future research are given

The above outlined scope should cover all the directly observed SHA-relevant information further used in the process of seismic source modeling.

The information should be given in such way that one can understand and critically assess the logical reasoning of the editor for his/her interpretations.

As most of the information stored is of relevance to the broad community of geoscientists, the explanation texts are fully open and accessible online via web interface (see Section 3.6 and the examples for two selected faults in the Appendix).

3.6 Web interface

The web interface has two main sources of online access to data: 1) Interactive map connected to the database and 2) Web encyclopedia with explanation texts and figures. The former is integrated into the latter under single web address. Below we present basic structure and usage of the two components.

3.6.1 Interactive map

Interactive map is the main interface connecting the external user to the database. It allows to visualize the faults and localities with important observations on top of topographic map, to show basic overview of their database records or to filter or query the database using its complete records.

The map is generated and provided using *ArcGis Online* (ESRI). This software was chosen to assure full and easy interoperability with the database prepared in *ArcMap* (ESRI), both serving a broad user community. The map content can be updated any time by uploading a new database files. The system is running under the license of Masaryk University and its maintenance is currently provided by Petr Špaček.

In the current setting the faults are categorized according to their activity and map quality (Fig. 3.5.1). The layer visibility and the type of basemap can be changed by user.

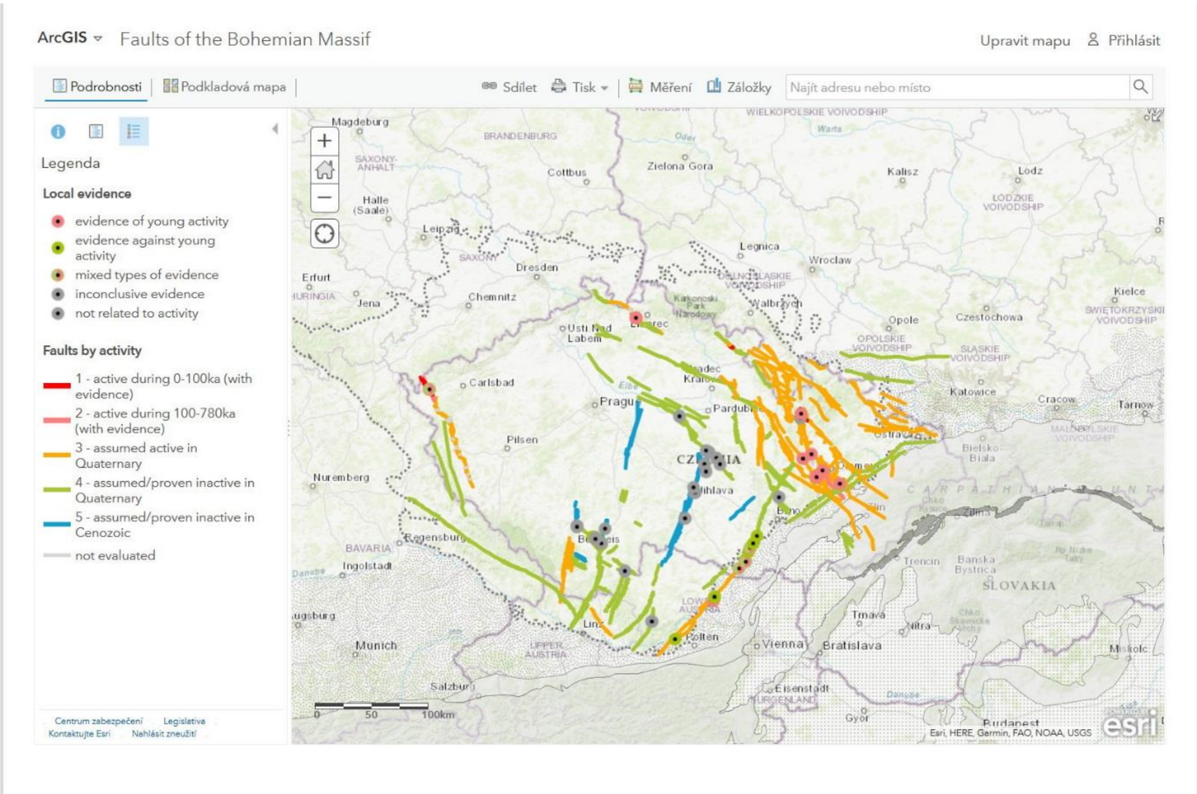

Fig. 3.5.1 Interactive map (default appearance) showing the faults and important local observations.

Clicking the object in a map opens a pop-up window (Fig. 3.5.2 top left) with listing of selected database field records and hypertext link to explanation text[11].

Data filtering and querying can be performed using the *Filter* tool which is activated by clicking the appropriate icon in *Details/Content* view (Fig. 3.5.2 top right). Full list of records may be browsed using Table view (Fig. 3.5.2 bottom).

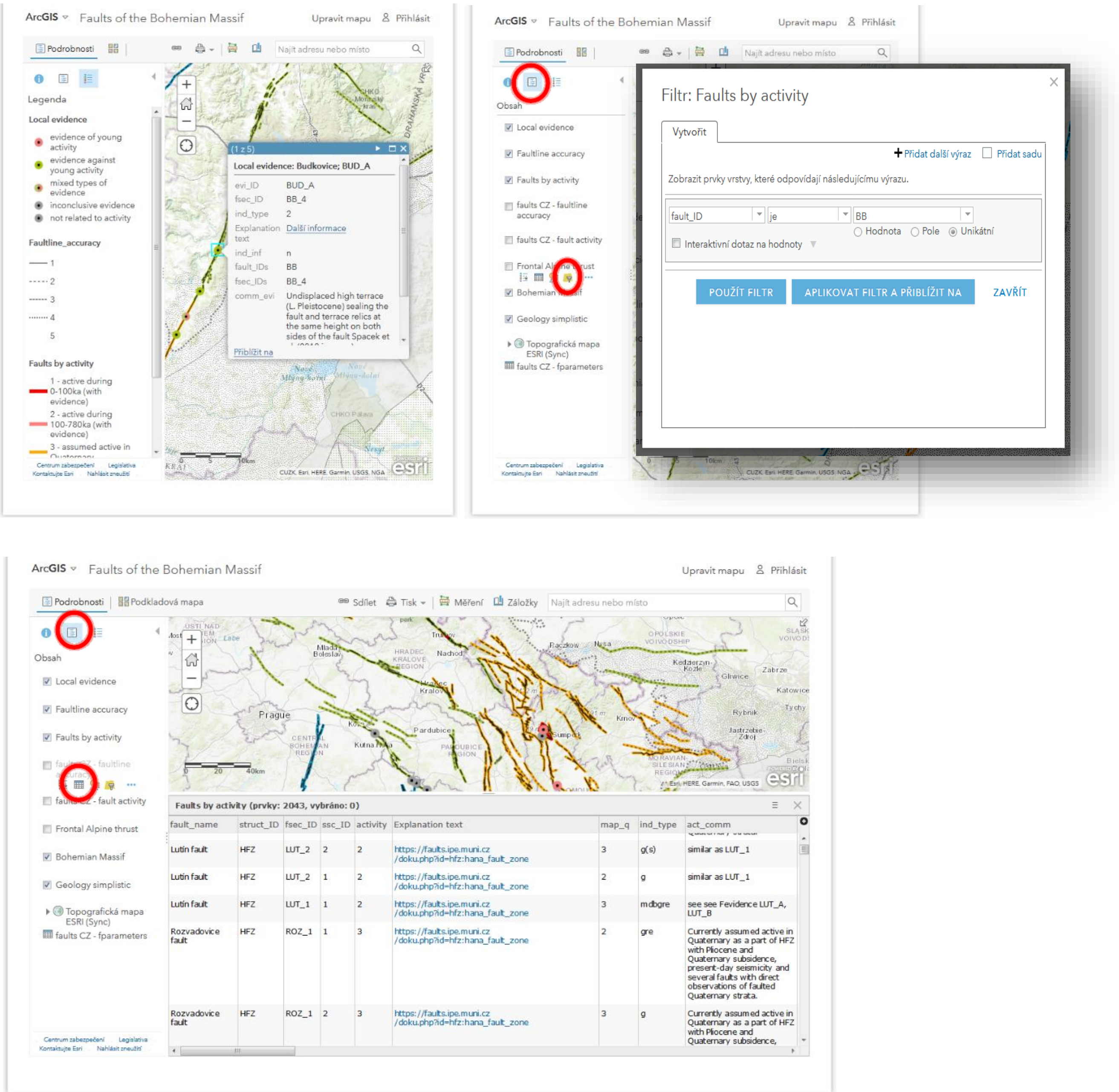

Fig. 3.5.2 Activated pop-up window (top left), Filter tool (top right) and Table tool (bottom).

[11] Note that the link in reverse direction, i.e. from the text to the database and map, is currently not available. The improvements of interoperability is a subject of future work.

3.6.2 Web encyclopedia with explanation texts

The web encyclopedia is a primary source of all explanation texts with figures. Furthermore, it integrates the interactive map and complete information on database structure and use[12]. The web is prepared in *DokuWiki* – an open-source content management system with extensive community of users and developers and easy maintenance and backup. Simple syntax and built in access control allows easy editing by multiple users from different domains. An example of formatting syntax of the DokuWiki code is shown in Fig. 3.5.1. Each editor has separate account and his/her own password set by the administrator at IPE. After logging in they can edit appropriate parts of the web as defined by user permissions.

The internet access is provided by web server of IPE Brno at url https://faults.ipe.muni.cz/. The web written in English language is named „Faults of the Bohemian Massif" and a printscreen of its current startpage is shown in Fig. 3.5.2.

The basic items are accessed from the sidebar menu. There, under the sub-menu *Major faults*, each significant fault or fault system with regional importance will have a link to separate page with explanation text. At the time of this writing, explanation texts for 12 major faults or fault systems are in an advanced stage of realization and other are being in preparation. Lists of faults with local importance will be organized into larger groups by area, together with general information (sub-menu *Faults by Area*). These are currently not being completed.

Explanation texts for local neotectonic observations (given in shapefile *Fevidence*) are integrated together with explaining texts for faults. For more straightforward access, the key localities are also accessed from the list under the sub-menu *Local evidence*.

Each page can be exported to pdf file (see Fig 3.5.2). The interactive map can be accessed either via startpage (Fig. 3.5.2) or via pages of individual faults.

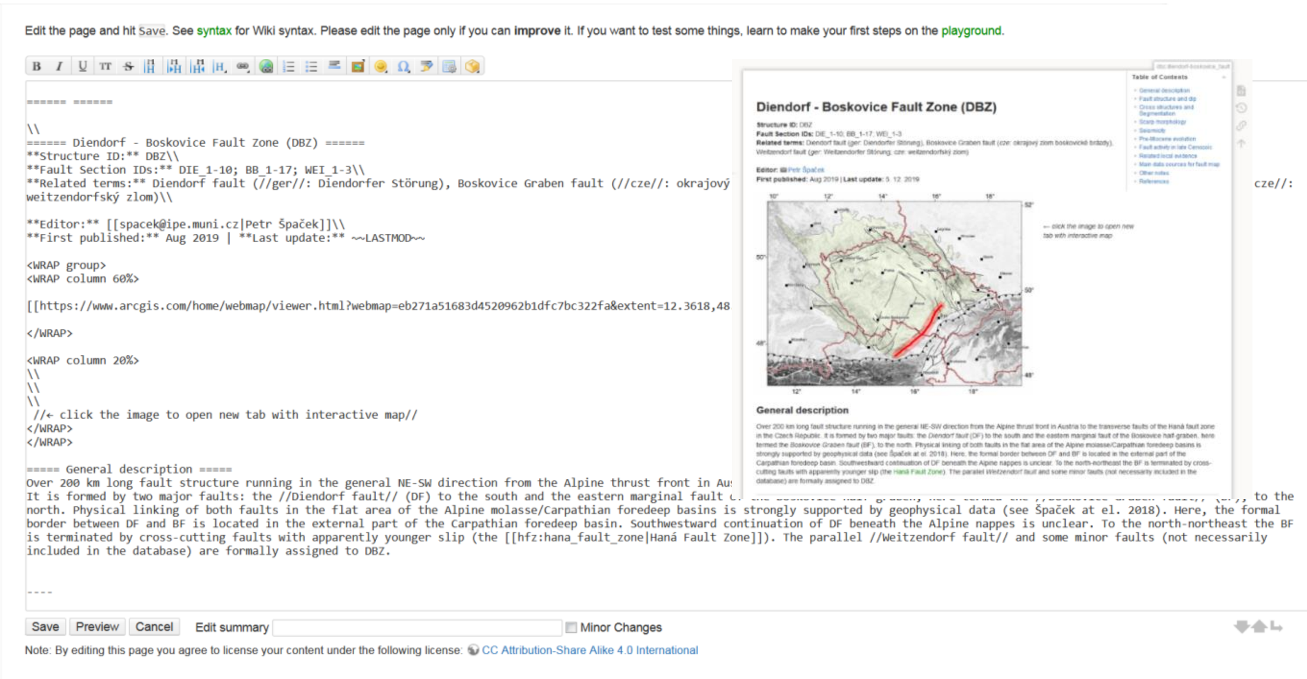

Fig. 3.5.1 Editing window of DokuWiki with sample of code to illustrate its formatting syntax (left) and corresponding part of the page as it appears in web browser (inset on the right).

[12] Completion of this and some other metainformation is planned after the final revision of this deliverable.

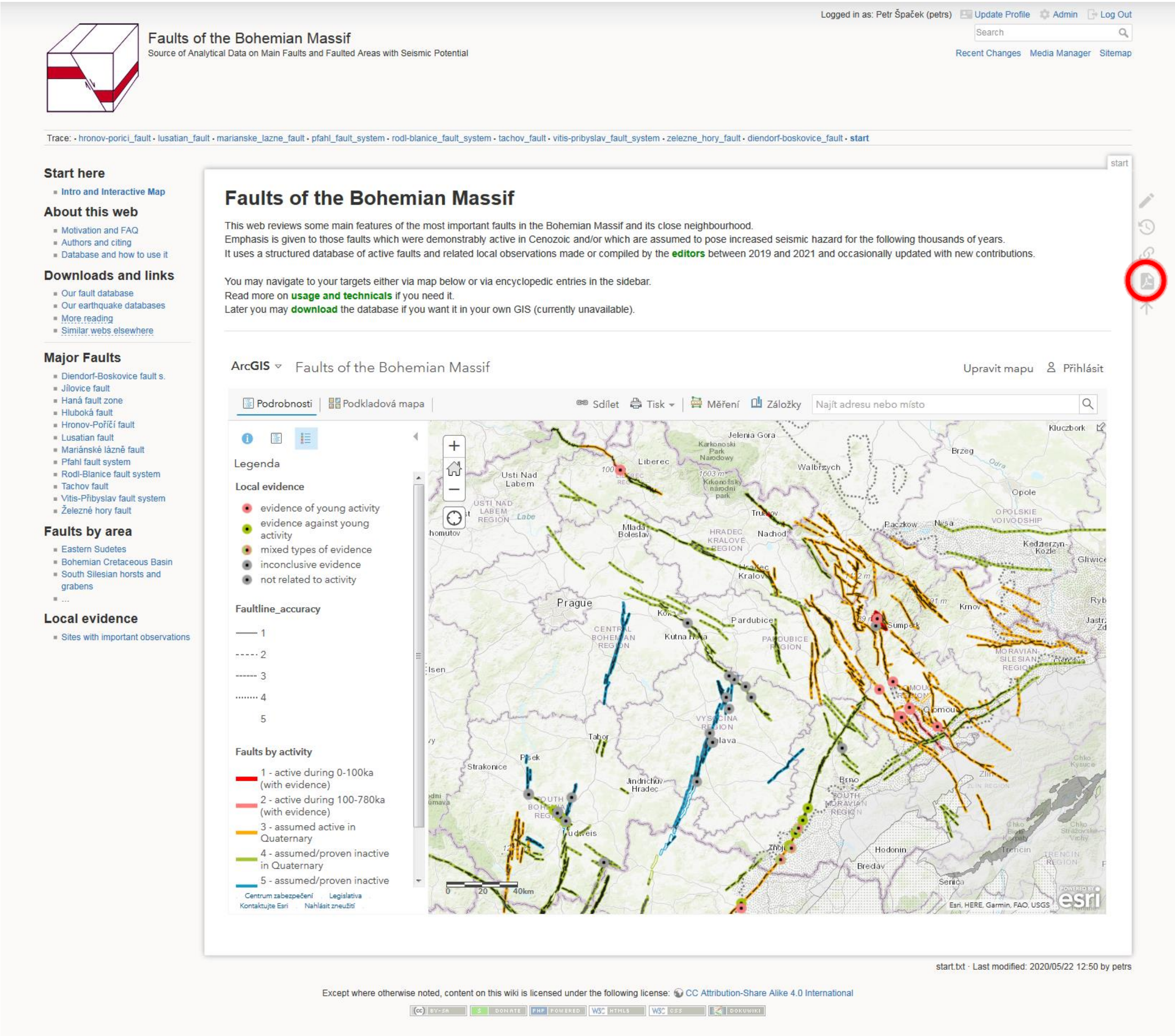

Fig. 3.5.2 Current appearance of "start page" of the web encyclopedia. Button for export to pdf is on the far left, marked by red circle.

3.7 Database population and harmonization: present and future

At the time of this writing we are in the final phase of the first campaign of database population. In this phase we focused to faults of the southern and north-eastern parts of the target region while in other parts only few selected major faults have been processed so far.

The chosen plan to start the development and population of the database within a small team allowed to better harmonize the basic concepts and ways of thinking. The database structure prepared by P. Špaček was first discussed and agreed by the two other main contributors, I. Prachař and P. Štěpančíková. The selected main faults were then distributed among these three editors whose task was to process the faults into the map and database tables. The database structure was optimized on the fly when it appeared necessary.

Unlike the tables, the explanation texts have no strictly prescribed format. Only the general information requirements are defined and basic structure is recommended. The texts have been prepared by the three managing editors named above and their colleagues, each item being edited under single authentication in DokuWiki.

Internal harmonization of the approach to database population was integral part of its development phase. So far only the harmonization of fault activity ranking has appeared to be an issue. With generally scarce data on young slip for most faults, finding a firm consensus on which observations should be taken sufficient to rank such fault class 3 (assumed activity in Quaternary) or class 4 and 5 (assumed last activity before Quaternary), is not easy. In spite of ongoing discusions on this issue, the presented database still needs to be harmonized with respect to fault activity and this seems to remain the most dynamic process for a while. Although we do not aim for complete unification of opinions, it is suggested that for major faults the content of the record in Fault database should be discussed in detail and defended before a board of all other editors contributing to the database.

In future campaigns it will be desirable to invite more editors with best knowledge on the faults to be processed or even to open the possibility to broader community to contribute voluntarily. This will make the harmonization issues even more necessary and more pressing. Managing of the database population in future has not yet been designed and it has to be clarified soon. It is assumed that the chief editor and managing editors will have to direct more strict rules to the contributors. In case of too much contradiction the divergent opinions can be stored in the explaining texts but not in the tables or shapes of the database. Accordingly, the current concept of the web interface should be regarded temporary while the database structure should remain more or less stabilized.[13]

As explained earlier, direct compatibility with databases of neighboring countries or larger regional databases was not among primary conditions for building our database structure. Any inter-database harmonization is another potential task for future. We believe that making our database interoperable should not, in general, pose a major challenge as its structure and file format are both of rather standard type.

13 One of the planned changes is transferring the outputs of fault slip tendency modeling to separate table for technical reasons. The fields Smin, Smax, rake1 a rake2 should then be removed from Fparameters table.

4 Towards the models od seismic fault sources

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Appendix: Examples of Explanation texts

On following pages we give two examples from web encyclopedia of Explanation texts for two faults prepared independently by two different editors: (1) Diendorf-Boskovice fault system and (2) Mariánské lázně fault. These examples should illustrate our approach to description of the fault and evaluation of its activity using different local evidence.

Diendorf - Boskovice fault system

Structure ID: DBF
Fault Section IDs: DF_1-10; BF_1-17; WEI_1-3
Related terms: Diendorf fault (*ger*: Diendorfer Störung), Boskovice Graben fault (*cze*: okrajový zlom boskovické brázdy), Weitzendorf fault (*ger*: Weitzendorfer Störung; *cze*: weitzendorfský zlom)

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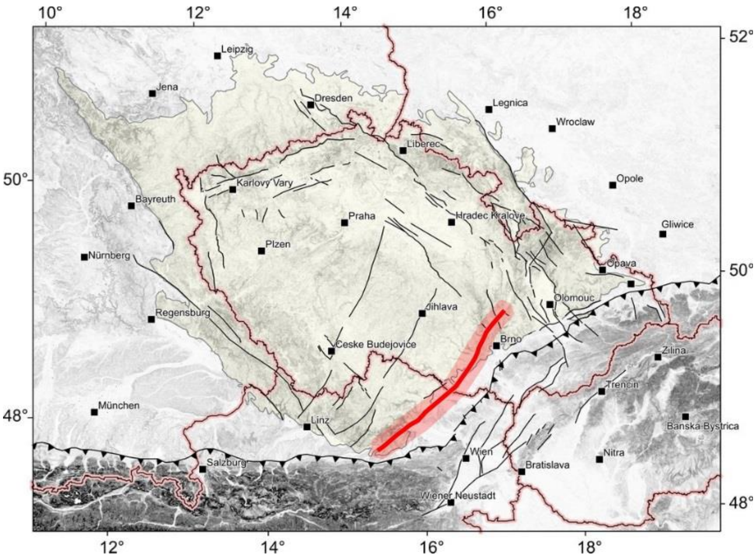


General description

Diendorf-Boskovice fault system (DBF) is more than 200 km long fault structure running in the general NE-SW direction from the Alpine thrust front in Austria to the transverse faults of the Haná fault zone in the Czech Republic. It is formed by two major faults: the *Diendorf fault* (DF) to the south and the eastern marginal fault of the Boskovice half-graben, here termed the *Boskovice Graben fault* (BF), to the north (Fig. 1). Physical linking of both faults in the flat area of the Alpine molasse/Carpathian foredeep basins is strongly supported by geophysical data (see Špaček at el. 2018). Here, the formal border between DF and BF is located in the external part of the Carpathian foredeep basin. Southwestward continuation of DF beneath the Alpine nappes is unclear. To the north-northeast the BF is terminated by cross-cutting faults with apparently younger slip (the Haná Fault Zone). The parallel *Weitzendorf fault* and some minor faults (not necessarily included in the database) are formally assigned to DBF.

Fault structure and dip

At ***shallow levels*** the fault is always steep, dipping either due W or E or vertical in both BF and DF. At ***general scale*** the BF is expected to be steeply inclined to WNW. The azimuth of the fault trace ranges between <20° and >45°.

- At BF, steep dip to the west (Zapletal 1924, 1929, Polák 1959) or east (Suess 1907; Zapletal 1924; Jaroš 1958) was observed. In case of the latter, observations of overturned Permian strata were reported from the fault neighborhood (Jaroš 1958). In the Miroslav horst and further south (BF_1 and 2) a steep western dip is indicated by natural outcrop in an erosional gully, observations in trenches and shallow geophysical profiles (Lesonice, Kadov and Hostěradice; Špaček et al. 2015a, 2017, 2018, Alexa 2017).
- In the commonly adopted models of the Boskovice graben (Jaroš 1961a; Malý 1993; Jaroš & Malý 2001) the BF is shown as a steeply east-dipping fault. However, it must be stressed that clear evidence for deeper geometry is missing and these models should be taken as the authors' concepts. The seismic reflection profile referred to by the authors was made at a short line south of Rosice (Štelcl et al. 1985). Primary data is unavailable but generally low quality is expected considering the technical setting of the survey and the published line-drawing of the profile.
- The importance of thrust component repeated in literature seems to me overrated. Local variations observed near the surface could partly represent flower structures related to the expected prevailing strike-slip kinematics of the post-Stephanian fault displacements.

- At DF, rare observations were reported from excavation near Maissau (DF_4; Posch-Trotzmüller and Peresson 2012) and quarry Limberg (DF_4 to 5; secondary faults; Decker 1999). In both cases the faults are close to vertical.

The ***fault core***, where observed, is often built by several meter wide mélange with fragments or bodies of limestones and greywackes (sections BF_2 through BF_14; Špaček et al. 2002) locally containing dark colored clays. Surface observations near Zöbing (vineyards north of Kammern) suggest that the strongly deformed zone may be >10 m broad there. Similar width is expected elsewhere in Permian and crystalline rocks. In trench near Hostěradice a 5-6 m wide zone of strong shearing and additional >5 m wide damage zone with dense small-scale faults is exposed in Lower Miocene clays and sands. The former contains frequent small fragments of weathered crystalline rocks.

A <20 to 250 m wide ***damage zone*** of the main fault is documented in Early Miocene sediments across a large part of BF_1 section by EM conductivity mapping (Fojt and Špaček, unpublished) and by observations in aerial photographs.

Parallel fault sections (splays of primary fault) are indicated by geological mapping and relief morphology in some parts of DF and BF, in a zone up to 800 m wide. Multiple parallel and oblique faults (observed and assumed) located in a broader zone (within up to 10 km to both sides of the BF and DF) indicate distributed faulting reflecting the complexity of long term evolution in different stress fields.

Cross structures and Segmentation

Cross structures, mostly of general NW-SE strike, traverse the DBF at multiple places, preferentially at its northern, Czech part. These are mainly (from north to south):

- Fault-bounded **Valchov and Blansko „grabens“** (Fig. 1) representing subsided blocks with preserved Upper Cretaceous sediments (e.g. Kettner 1941, Zvejška 1944, Skoršepa and Melichar 2017). These important structures directly disrupt the BF and bring evidence against significant horizontal slip in the northern part of the BF (sections BF_10 through BF_14) after the formation of the depressions in their present-day shape. The sediments of the Blansko depressions are likely disrupted by normal faults collinear with the BF (section BF_11, so called *Klemov fault*). Relict Miocene sediments are present in both depressions.
- Minor cross faults of NW-SE to NNW-SSE direction along the whole eastern margin of the Boskovice graben (BF_3 through BF_15) are often drawn in geological maps and mentioned in texts. They are reported to offset the Permian-Carboniferous fill of the basin both at the surface and in coal mines (např. Čepek 1946, Polák 1954, Jaroš 1960, 1961, 1964a, 1972c). However, their position and geometry differ substantially in different maps and hence I assume they are difficult to trace and probably had very small slip in most cases (comp. Jaroš and Malý 2001).
- Three zones of low relief with relics of Miocene sediments cross the BF in its central and southern parts: the Tišnov-Kuřim zone, the Jihlava river valley near Ivančice and the southern margin of the Boskovice graben. These structures represent either tectonically subsided areas or erosional paleovalleys or combination of both. Post-Early Badenian vertical slip was inferred in the Tišnov-Kuřim fault zone (Fig. 1; currently not included in database) where Early Badenian sediments are juxtaposed to Eggenburgian/Ottnangian ones along a fault of NW-SE strike (Hanžl et al. 2001a). Similarly, at the southern margin of the Boskovice graben (between Rakšice and Lesonice), NW-SE trending faults seem to terminate the relic of Badenian sediment and small-scale slip at one of these cross faults was observed to offset Early Miocene strata in a trench (Prachař et al. 2017a).
- Lower Miocene and relict Middle Miocene sediments of the **Dyje-Svratka Lowland** cover the fault sections DF_6 through DF_8 and BF_1. These sediments represent marginal facies of Alpine-Carpathian Foredeep. It is likely that the sediments are part of subsided area affected by normal

faulting (comp. Dlabač et al. 1969, Dlabač 1976, Prachař 1970a, 1970b, Čtyroký 1982). ERT measurements made at two topolineaments near Hnízdo and Strachotice (Špaček et al. 2016) likely indicate faults with substantial offset of strata. Small scale faults are documented at localities Lechovice and Stošíkovice. However, faults with significant slip have never been observed directly and there is no geophysical indication of clear significant offset in a map. Therefore, only small slip and/or prevailing normal slip component must be assumed.

- One of the more expressive faults in the Dyje-Svratka Lowland with larger normal slip component has been reported as the Slup fault (Fig. 1; Buday et al. 1963; Kalášek et al. 1963, Batík et al. 1970, 1977, Dornič et al. 1984, 1985a,b; currently not included in the database). It has been drawn in geological maps between Šatov, Hnízdo and Slup, with general N-E strike, crossing the DF_6 section. Its geometry, however, seems to be poorly constrained. Based on drills, relative vertical offset of 100-150 m has been inferred between the southern, subsided block with Karpathian sediments and the northern block with only Eggenburgian-Ottnangian sediments preserved.
- South of Melk near Schönbühel a.d. Donau (Fig. 1), a pronounced scarp of WNW-ESE direction, very likely a fault, crosses the DF. As it is not offset by the DF, it provides evidence against significant strike slip at sections DF_1, 1a and 9.

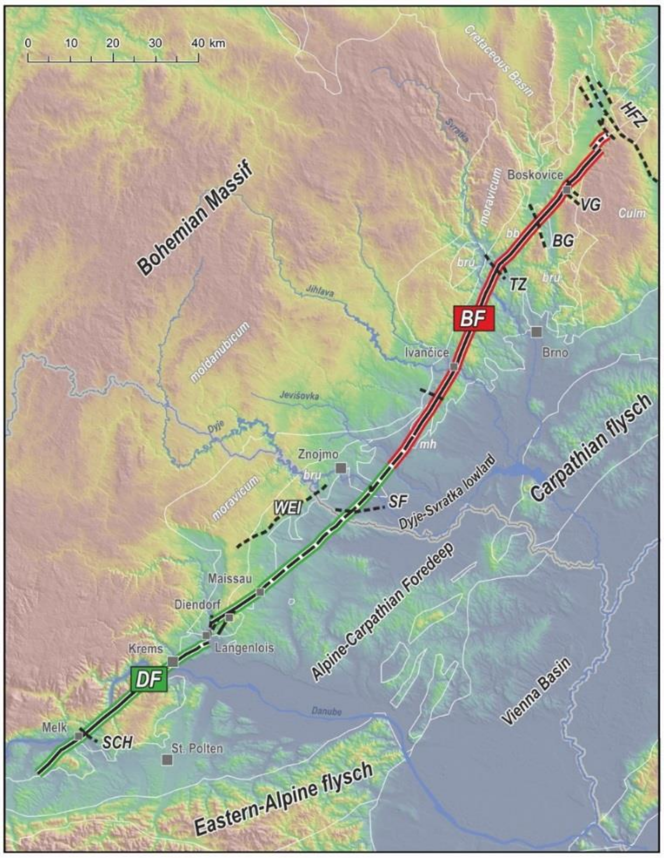


Fig.1. Schematic map of DBF with some basic features mentioned in text: Acronyms alphabetically: bb – Boskovice graben, BF – Boskovice graben marginal fault, BG – Blansko graben, DF – Diendorf fault, HFZ – Haná fault zone, mh – Miroslav horst, SCH – scarp near Schönbühel, SF – Slup fault, TZ – Tišnov—Kuřim zone, VG – Valchov graben, WEI – weitzendorf fault.

Scarp morphology

Surface morphology at the fault trace varies significantly, largely due to different degree of *differential erosion* at contacts of rocks with similar vs. contrasting mechanical properties.

- ***Well developed linear fault scarp*** is observed where Lower Miocene sediments were juxtaposed to crystalline rocks due to the fault slip and were later partly or entirely denudated (fault sections DF_4, BF_2 and very likely DF_1.2 through 1.4). The scarp of fault section BF_2 exhibits number of gullies with disequilibrium profiles breaking at the fault line, suggesting fast fall of erosional base (which I interpret as due to fast erosional exhumation of the old fault scarp; see Fault activity in late Cenozoic.
- ***Eroded scarp*** is common in parts with relics of Middle Miocene sediments on bedrock (sections BF_3, 5, 9, 10.1, 16 through 17) and with increased local river erosion (sections DF_1.5 and BF_7 to 8).
- ***Inexpressive to absent scarp*** is characteristic for large parts of the Boskovice graben where Permian clastic sediments are in contact with crystalline or Carboniferous greywackes and no larger rivers are present (sections BF_4, 6 through 8, 10, 12, 14 to 15).
- In parts where Mesozoic and Tertiary sediments are present at both sides of the fault line the scarp is ***entirely absent*** (sections DF_2, 5, 6, 8, BF_1, 11 and 13).

Observed Seismicity

This section will be revisited after completion of earthquake catalogue (submitted deliverable of Prachař and Pazdírková for WP1)! It is now based on review in Lenhardt et al. (2007) and preliminary compilations of ZAMG Vienna and IPE Brno (Pazdírková, unpublished) – see Fig. 2.

Repeated occurrence of weak earthquakes near the southern part of DF is most noticeable feature along the whole DBF. This cluster of epicentres seems slightly anomalous even on the scale of the southernmost Bohemian Massif.
Maximum macroseismic intensities observed for earthquakes near Krems and Melk are I_0=5-6° EMS-98 (largest intensity reported earthquake near Senftenberg in 1959). The corresponding estimated maximum magnitude is $M_w \approx 3.5$.
Coverage by seismic stations of this part of Austria has been loose until recently and large location errors in order of several kilometres must be expected for older instrumentally recorded earthquakes. The error of location exceeding 10 km should be considered everywhere for historical earthquakes based on infrequent macroseismic observations.
Our knowledge on the earthquake foci spatial distribution is still too poor to allow clear identification of the active structure, however, its association with DF (sections DF-1a, 1 and 2) is not unlikely.

Few other known instrumentally or macroseismically recorded earthquakes are scattered along DBF, with magnitude up to ML=2.5 (near Hostěradice, >3 km away from to BF_1 and BF_2; years 2000 and 2014) and I_0≈4-5° (near Kunštát, <6 km away from BF_11; year 1916).

In general, modern seismicity along BF and northern DF is very weak and similar to background seismicity both in terms of rate and magnitude.

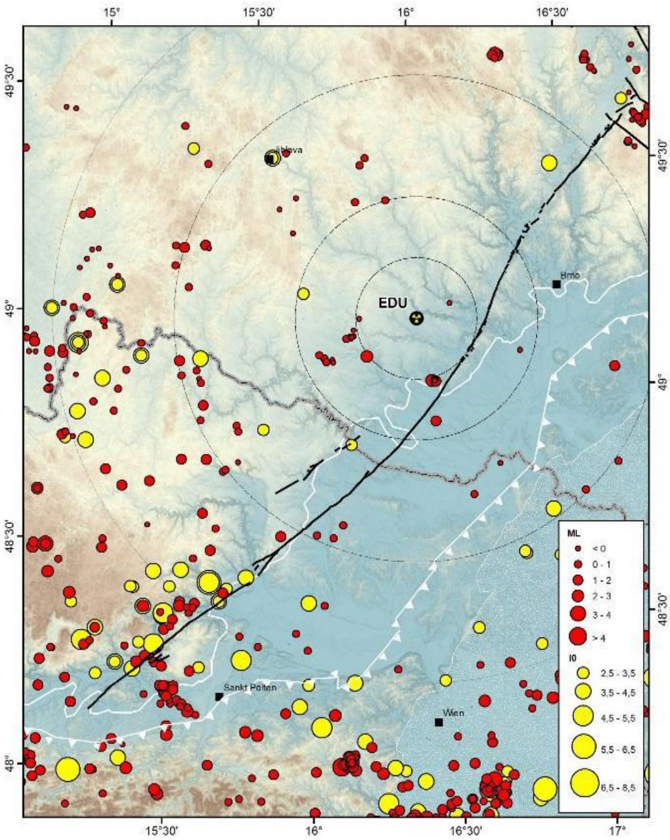


Fig. 2. Epicentre map of historical earthquakes (period 1700-1989; yellow circles) and instrumentally located earthquakes (after 1989; red circles) in the broader vicinity of DBF (from unpublished preliminary catalogue compiled by J. Pazdírková, 2018).

Pre-Miocene evolution

- Both DF and BF have been considered major structures with partly shared evolution since the early geological research (e.g. Suess 1926, Shermann 1966, Jaroš & Mísař 1967, Matura 1976, Figdor and Scheidegger 1977).
- DBF corresponds with the surface trace of Variscan terrane boundary between Brunovistulicum and Moldanubicum. It also correlates with western termination of the Lower Carboniferous flysch (comp. Melichar 1995), i.e. the root zone of Variscan externide nappes.
- Significant synsedimentary slip with vertical component (>1600m) took place at BF during Upper Carboniferous-Permian and produced the Boskovice half graben with StephanianC-Autunian sedimentary fill. Fans of coarse Rokytná conglomerates are associated with BF-bounded eastern margin of the graben. This faulting is assumed to be of normal geometry, related to orogen gravitational collapse (e.g. Jaroš 1961a, Malý 1993, Jaroš and Malý 2001). Locally, dikes and sills of basalt-andesite (sub-)volcanics were observed to penetrate the sediments (e.g. Přichystal 1994). Relic of Permian sediments near Zöbing suggests that analogical subsidence may have been associated with northern/central part of DF.
- Locally observed steep reverse geometry at BF (e.g. Suess 1907, Zapletal 1924, Jaroš 1958, Jaroš 1962) and the intra-basin deformation structures (reverse faults and long wavelength folds, Jaroš a Malý 2001) indicate post-Permian compression or transpression. The age of this phase is unknown and likely pre-Cretaceous as no corresponding structures were observed in Cretaceous strata (Zapletal 1924).
- At DF, strike-slip geometry is accentuated with cumulative post-Variscan (post-collision) left-lateral slip estimated in the range 25-70 km (as inferred from offset of crystalline bodies with mutual affinity; Schermann 1966; Matura 1976; Figdor and Scheidegger 1977).

Fault activity in late Cenozoic

Tertiary

- The post-Eggenburgian/Ottnangian (post-earlier Burdigalian) slip is indisputable for the southern part of Diendorf-Boskovice fault as far as to section BF_3. This is based on direct observations of faulted rocks and geophysical observations of the sharp and steeply dipping contacts of Lower Miocene (Eggenburgian, Ottnangian) sediments with crystalline at segments DF_4,5,7 and BF_1 to 3.
- Strike-slip or oblique slip kinematics is evidenced by fault striations and structure (Kadov and Hostěradice sites at BF_1 and 2; Limberg site near DF_5) but complex kinematics with changing geometry can not be ruled out.
- More precise time constraint of this phase of activity is problematic as a sound evidence from relics of Karpatian and early Badenian (late Burdigalian to early Langhian) is not available and younger Tertiary sediments are missing regionally. I assume, basing on a regional tectonic model and some local observations, that the activity peaked near the early/middle Miocene boundary and ceased towards later Badenian (younger-than-late Badenian faulting on a similarly oriented fault is documented e.g. in Troskotovice pit, situated 11 km to the east of DF).
- Significant large scale post-Badenian strike-slip at DBF is counterevidenced by cross structures described above. The transverse Valchov and Boskovice "grabens" (BF_10,11,13) with well defined, fault-bounded margins and Cretaceous and early Badenian sedimentary fill practically rule out the strike-slip taking place at the northern part of BF after early Badenian (the latter have been locally mapped as continuous bodies on top of BF). Some other depressions (valleys) crossing the central and southern parts of BF and hosting concentrated relics of early and middle Miocene fine clastic sediments (depressions near Čebín, BF_8 to BF_10; Jihlava river valley near Ivančice, BF_5,6; Lesonice depression, BF_3) also do not show any signs for horizontal offset and thus testify against large-scale strike slip.
- Termination of the early Miocene strike-slip phase at BF is further affirmed by development of a system of small-amplitude faults with average NW-SE strike. On the DF such faults are not present in geological maps, however, they are often clearly indicated in relief (e.g. near Schönbühel a.d. Donau).
- In the Dyje basin crossing the DBF in segments DF_6-8, post-Lower Miocene faulting is indicated by apparent strata cut-offs at several ERT profiles crossing some major topolineaments in the basin (Špaček

et al. 2016). Steeply dipping faults of WNW-WSE to NNW-SSE strike were described from near Stošíkovice na Louce.

- Magnitude and timing of dip-slip component is difficult to constrain at most fault sections as the data on well dated stratigraphic bases of Tertiary deposits on the fault are insufficient.
- At fault sections BF_1 (Lesonice) and BF_3 (Hostěradice), however, high resolution refraction seismic survey combined with ERT and seismic reflection (Alexa 2017) shows clearly a fault-related vertical offset of >50m at the base of low-velocity layer (assumed Early Miocene and/or strongly weathered crystalline). Furthermore, at Lesonice profile a pediment (or paleovalley bottom) developed in crystalline and covered by non-offset strata of assumed Eggenburgian/Ottnangian age indicates the termination of vertical-component faulting during or before the Lower Miocene deposition (while the smaller scale strike-slip component is not ruled out).

Quaternary

Following evidence is considered in the assessment of Quaternary activity:

Continuity of overlying strata

- The sealing strata observed in detail in trenches in sections BF_1, BF_2 (Hostěradice and Kadov) bring evidence against surface fault slip after ~23 ka.
- Termination of older strata in Kadov trench on a fault plane allow considering slip with min. vertical component of 2 m in 100 - <23ka time window, however, the non-tectonic model of origin of this structure is preferred (see references for site Kadov) as the tectonic origin would be in conflict with observations at adjacent segments.
- Sealing strata in a trench at DF_7 (Tasovice) bring local evidence against surface fault slip after at least 100 ka and probably much longer.
- Vertically non-displaced base of high terrace and its relics mapped in detail in section BF_4 (site Budkovice) brings evidence against vertical slip component larger than approx. 1 m since the deposition. The assumed age of the terrace is late Early to early Middle Pleistocene based on regional model of a fluvial terrace system evolution.
- Likewise, vertically non-displaced base of high terrace between villages of Dyje, Lechovice, Božice and Hodonice ("Hodonice fluvial level") brings evidence against vertical slip component larger than approx. 2-3 m at section DF_8 since late Early to early Middle Pleistocene.

Geomorphology

- Total absence of systematic horizontal offsets of geomorphological features (or any other piercing lines), including the deeply incised cross-cutting valleys in hard rocks (mainly BF_2, 4, 8, 12), brings evidence against significant active horizontal slip since river incision in Middle Pleistocene.
- The fault scarp morphology reflects the lithologically controlled denudation rather than young or even ongoing dip-slip. Best developed linear scarps are present in those sections where the fault line corresponds with the contact of Early Miocene sediments with crystalline rocks. Conversely, scarp is never developed in soft sediments, regardless of whether young cover is present or absent. Therefore, scarp morphology does not provide clues on Quaternary slip. However, the features of scarps at sections DF_4 and BF_2 require fast exhumation. The disequilibrium profiles in erosional gullies breaking at the fault line at section BF_2 are interpreted as due to fast erosional exhumation of the old fault scarp. Significant contribution of active vertical tectonic slip is considered unlikely as it would make this fault section anomalous in the regional context.

Seismicity and paleoseismicity

- A cluster of epicentres of weak earthquakes between the towns of Langenlois, Gfohl, Ybbs an der Donau and Melk (see Observed seismicity) suggest possible connection with southern Diendorf fault (sections DF_1, 2, 5 and 6). However, the causal links are unclear as the cluster shape (possibly affected by poor accuracy of location) allows for different conclusions. In the area of southern Bohemian Massif the increased seismicity seems to be characteristic. Some observations suggest that unmapped NW-SE striking faults may be responsible for at least part of these earthquakes (see site Schönbühel a.d. Donau as an example). The concerned sections of DF are admitted to take part in this deformation but activation of large segments by a single earthquake seems unlikely.

- To the north of Langenlois the low number and magnitude of historical and instrumental earthquakes and their low spatial correlation with fault line do not allow affiliation of seismicity to any known structures.
- Rare local observations of soft sediment deformation structures are interpreted as due to paleoearthquakes with minimum intensity of 6-7° (sites Lechovice and Tasovice). The source of these hypothetical earthquakes is entirely unknown and they are not necessarily related to Diendorf fault. In case of epicentre located close to observation sites, the minimum magnitude of Mw=5 should be considered.

Geodesy

- Results of some long-term geodetic measurements in the region were interpreted as tectonic deformation in several studies (Pospíšil et al. 2009, 2010, 2012; Roštínský et al. 2013). However, editor of this text is skeptical to interpretation of these observations as due to tectonic strain because:
  1. the reported strain rates are too large (10^{-1} mm/y, i.e. same order as in the eastern Alps) to be in agreement, on a regional scale, with concept of active Alpine orogen vs. stable foreland;
  2. the locally observed geological records rule out that such deformation at BF could have been operative on a long-term scale during Quaternary;
  3. the non-tectonic deformation (climatic/hydrogeological, slope instability, problematic long-term stabilization of measurement points) of the surface is expected to compete with such strain rates or exceed them (see the extensive literature on the effects of water management and climatic change on surface deformation, also see Vyskočil 1996). For example, repeated levelling on a profile crossing the BF near Tetčice (section BF_6; Roštínský et al. 2013) and suggesting vertical strain of 10^{-1} mm/y order, was partly carried out in the area of former pond (see maps of the 1st military mapping from 1764-1768) and therefore likely affected by ongoing sediment compaction.

Basing on this local evidence the fault activity is currently evaluated in a following way:

- In the southern part of DBF, the sections DF_1 to BF_2 are ranked **class 3**, i.e. assumed or admitted to be active in Quaternary but without direct evidence. Quaternary slip rate at the fault sections north of DF_3 is assumed very low (<0.01 mm/y). Southern sections may later be ranked class 1 (demonstrably active) when new earthquake data (better location, focal mechanism) bring clear evidence.
- In the northern part of DBF, the sections BF_3 to BF_ 17 are ranked **class 4**, i.e. assumed or demonstrated to be inactive.

On a theoretical basis, the evaluation of similarly oriented fault sections by different activity ranks may be justified by:

1. expected northward decrease of rate of stress build-up (and hence crustal strain rate), and
2. expected northward decrease of slip potential due to rotation of stress orientation near junction of the Alpine and the West-European stress domains.

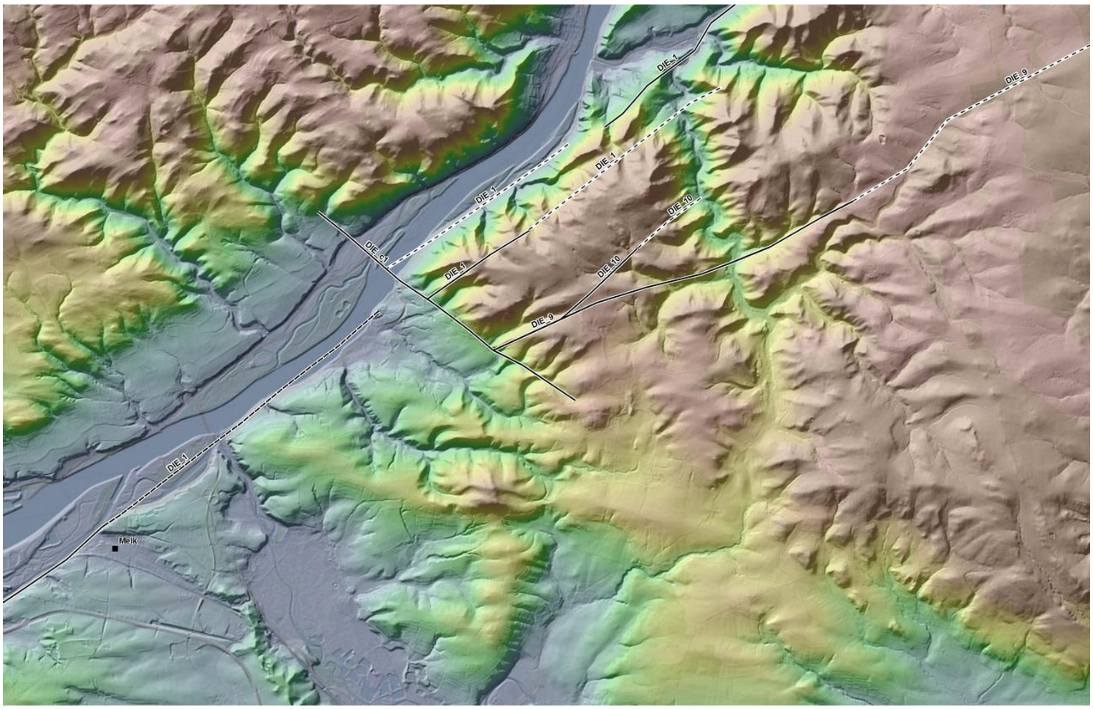
Related local evidence

(See layer **Local evidence** *in the* [map](). *The sites are listed in south-to-north order.)*

Schönbühel a.d. Donau: Cross-structure

evi_ID: SCHO_A
fsec_IDs: DF_1, DF_1a, DF_9
editor: Petr Špaček

- Pronounced scarp of WNW-ESE direction dividing the hilly terrain with narrow valley of Danube to the NE from comparatively flat area with wide Danube valley to the SW. Interrupted and multiple topolineament continues in ESE direction towards Hafnerbach, partly reflecting the structure of the crystalline basement. This scarp, very likely a fault (not identified in geological maps), possibly a minor dip-slip fault once terminating now eroded Tertiary Molasse sediments or thick regolith, seems to lack any horizontal offset by Diendorf fault (sections DF_1, 1a and 9), therefore providing evidence against significant strike slip of the latter after the formation of the former.
- This structure is likely a part of a system of WNW- to NW- striking faults with small slip amplitude documented by multiple observations and indicated by penetrative presence of topolineaments in an extensive area hosting the whole DF and southern BF. The age of these faults is largely unknown but some of them were observed to displace Quaternary strata. In Dunkelsteiner Wald and Wachau this fault system may host sources of weak seismicity.
- Also note the N-S oriented topolineaments near Aggasbach Dorf north of here which seem to coincide with deflected valley of Danube river (out of extent of the map shown here).

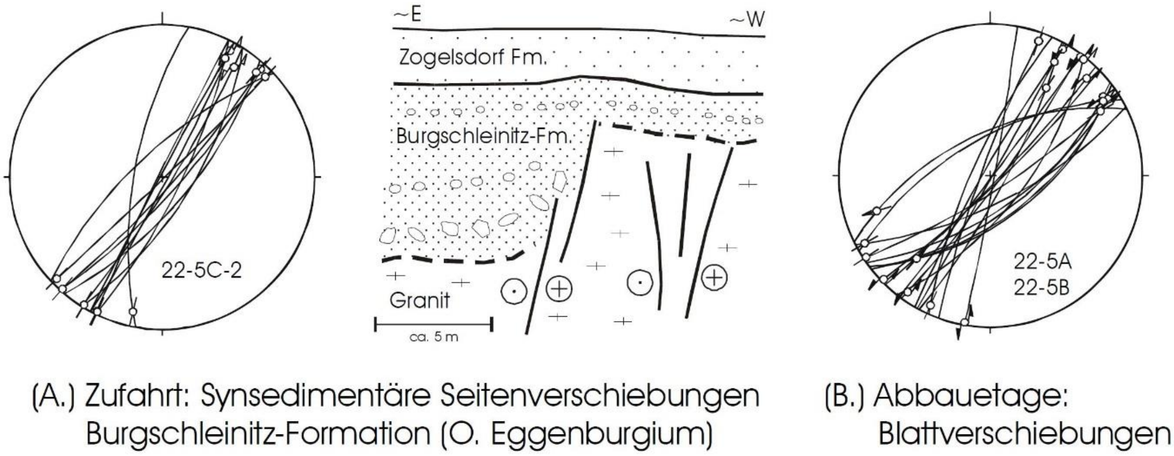


Relief map of the vicinity of Melk.

Limberg: Secondary faults. Timing of dip-slip

evi_ID: LIM_A
fsec_ID: DF_4
editor: Petr Špaček

- Early Miocene synsedimentary faulting near Diendorf fault - parallel secondary faults in Hengel quarry in Limberg (Decker 1999). Faults are steep, on stereodiagrams they seem to be vertical on average with strike-slip kinematics. Both the faulted lower and the non-faulted upper parts of sedimentary sequence were dated as Eggenburgian.



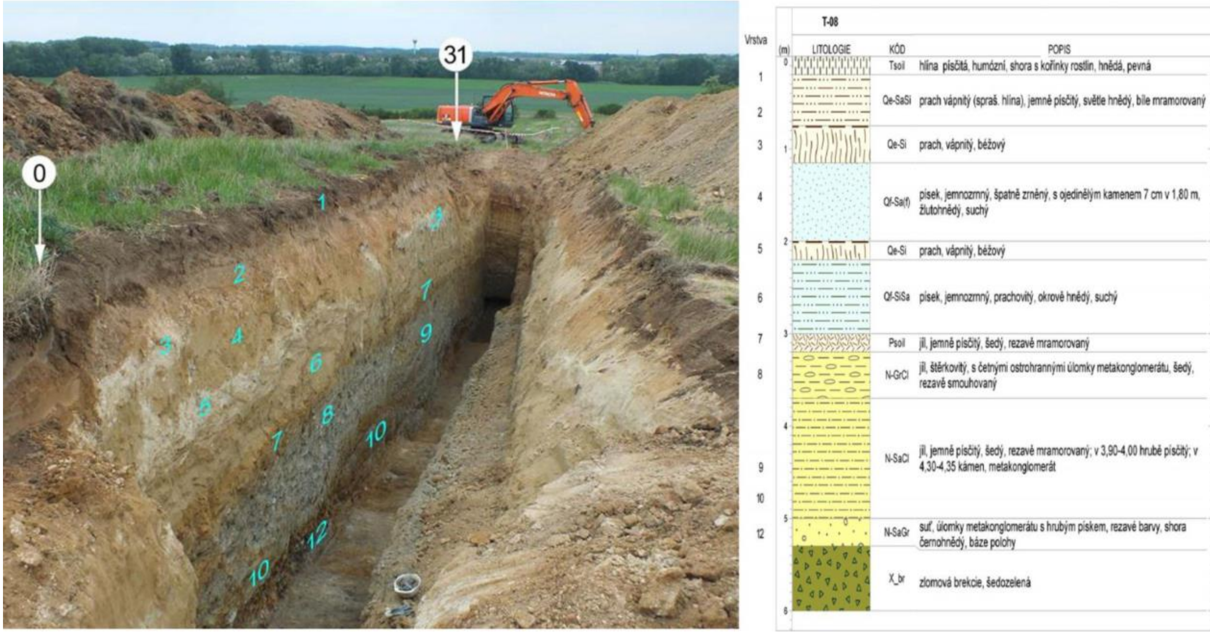
Structures from Hengel quarry near Limberg. A) Schematic profile and stereodiagram of synsedimentary faults developed in Early Miocene strata in quarry entrance. B) Stereodiagram of sinistral strike-slip faults in the upper floor. Adopted from Decker (1999), Fig. 2.2-5.

Tasovice: Observed sealing strata and inferred paleoearthquake

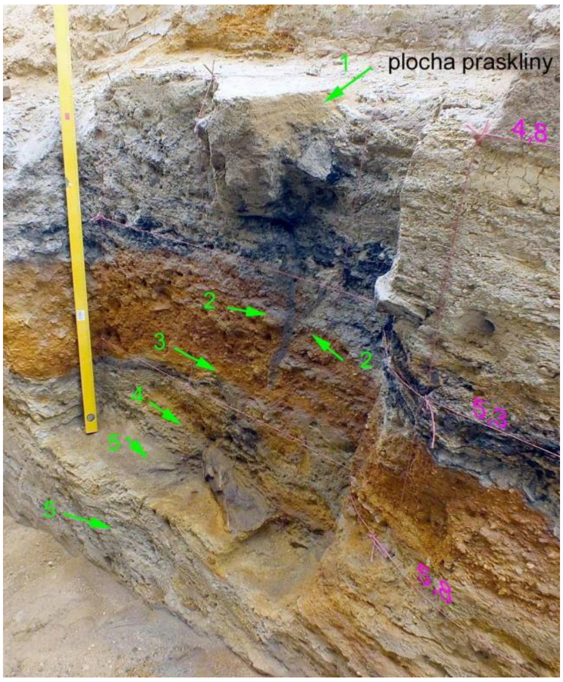
evi_ID: TAS_A
fsec_ID: DF_7
editor: Ivan Prachař, Petr Špaček

- Trench RTAS-3 (length 39 m, max. depth 7.5 m; at profile with several trenches and drills) with sedimentary sequence sealing the bedrock with Diendorf fault, here exposed as broad shear zone juxtaposing metaconglomerate and mylonite.
- The 7 m thick sediment succession includes (from bottom to top; see photo an scheme below left): sandy eluvium, coarse gravels (partly cemented), silty clays with angular detritus, layer of colluvium, fine loams with paleosol, and loess loams to loess with interlayer of laminated or cross bedded fine sands. While the layers no. 6 and 7 (see figure) give OSL ages within the span of 36-63 ka, dating of the deeper strata remains problematic. Ages largely exceeding 100 ka are very likely and Tertiary age is not ruled out (Prachař 2017).
- Clay-filled fault within the shear zone contains slickenside (dipping 66° to NW) with 2 sets of slickenlines, the younger showing normal dip-slip. The fault does not continue to the covering sediment (Prachař 2017).

- Thin blind sand dike cuts through the lower part of the sedimentary sequence above the fault. The dike connects directly to the fault, but no systematic offset of hosting strata was observed, only local disturbation of single bed of coarse sand adjacent to the dike (Prachař 2017).
- This clastic dike is interpreted as an effect of local liquefaction generated by earthquake-induced shaking. Its location above the observed fault is likely an effect of stress concentration within loose and water-saturated deposit above the breakpoint in bedrock topography and lithology (structurally controlled failure of gravitationally unstable sediment) as the coseismic slip at the fault (dynamic control) is ruled out by the absence of strata offset (Špaček et. al. 2018).
- Although the inferred hypothetical earthquake is not necessarily related to Diendorf fault, it is recommended to be assumed related for purpose of SHA (Špaček et. al. 2018).



Trench RTAS-3 and stratigraphic scheme of exposed sequence of sediments covering the faulted bedrock. From Prachař et al. 2017, modified.

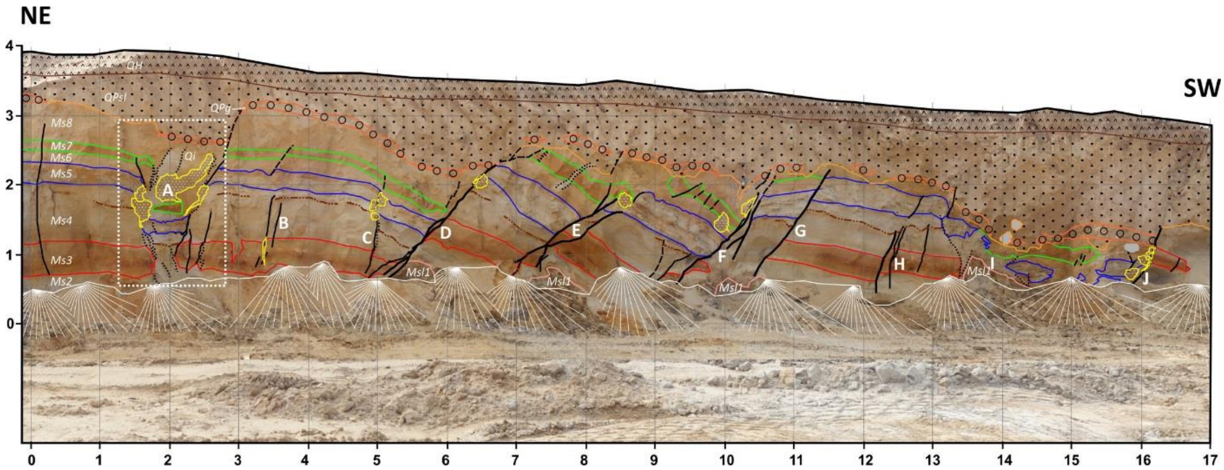


Sand dike cutting through the lower part of sedimentary sequence. From Prachař et al. 2017, modified.

Lechovice: Cross-structure and inferred paleoearthquake

evi_ID: LECH_A
fsec_ID: BF_1
editor: Petr Špaček

- Roadcut (presently rehabilitated) situated ~1.5 km from the Diendorf fault line. System of NNW-striking normal faults displacing Lower Miocene sands (Ms1-8) and Quaternary fluvial sandy gravels (QPg; below left) associated with sand intrusions (Qi; yellow patches in figure below left and detail view on photograph below right). All feeder dikes are blind. Strong block rotation on the observed faults, formation of small-scale graben structures and collocation with sand-intrusions suggest formation by lateral spreading, possibly near-synchronous with deposition of Early to early Middle Pleistocene terrace. The causal link between the hypothetical earthquake and the Diendorf fault or the NW-SE to NNW-SSE oriented cross-faults has not been resolved. The observed faults are similarly oriented as those at Stošíkovice (below) and also sub-parallel to local scarp and to general-scale trend of the Jevišovka river valley. Structural control of the observed faults by either of these features and later reactivation by lateral spreading is possible. (Špaček et al. 2018)



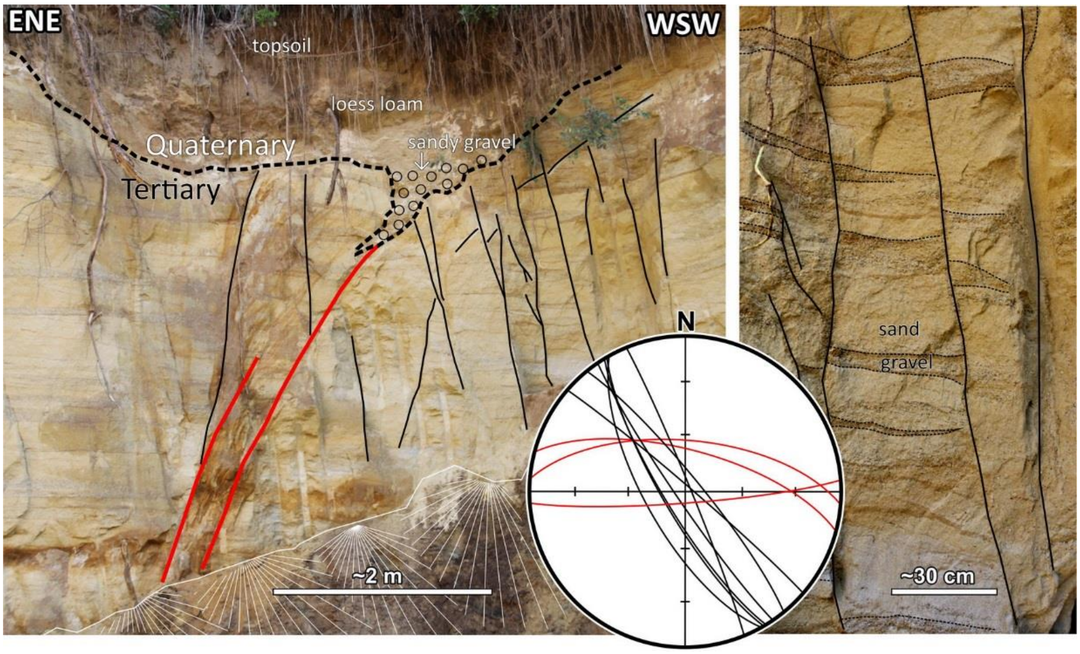
Geological profile in Lechovice roadcut. From Špaček et al. (2018), modified.

Detail of sand blow (structure A in the profile). From Špaček et al. (2018), modified.

Stošíkovice: Cross-structure

evi_ID: STOS_A
fsec_ID: BF_1
editor: Petr Špaček

- Small sand pit in L. Miocene sands situated ~250 m from the Diendorf fault line. WNW-WSE striking fault with incorporated gravel of high terrace relic (explained either by active faulting or structurally controlled cryoturbation) and a system of older, small-displacement, NW-SE to NNW-SSE trending faults (Špaček et al. 2015b). These faults are probably a part of important larger-scale cross-structure of the Dyje basin (link Cross-structures and Segmentation) which may and may not include the faults near Lechovice (see above).



Structures in Stošíkovice sand pit. System of small-amlpitude NW-striking faults is cut by few younger, E-W striking faults with partly incorporated sandy gravels of assumed Quaternary terrace (Špaček, unpublished).

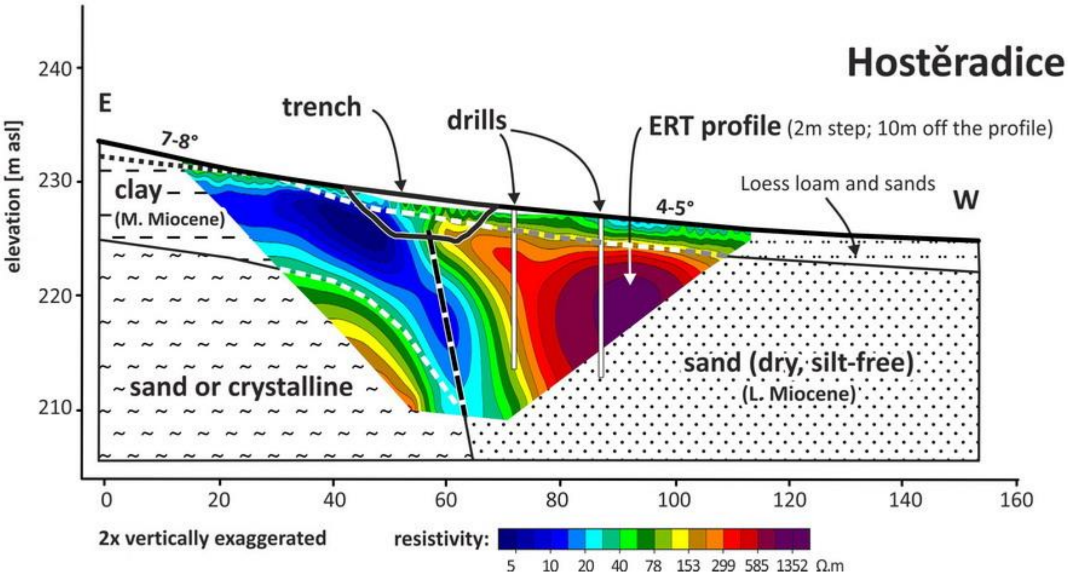
Hostěradice: Observed sealing strata

evi_ID: HOS_A
fsec_ID: BF_1
editor: Petr Špaček

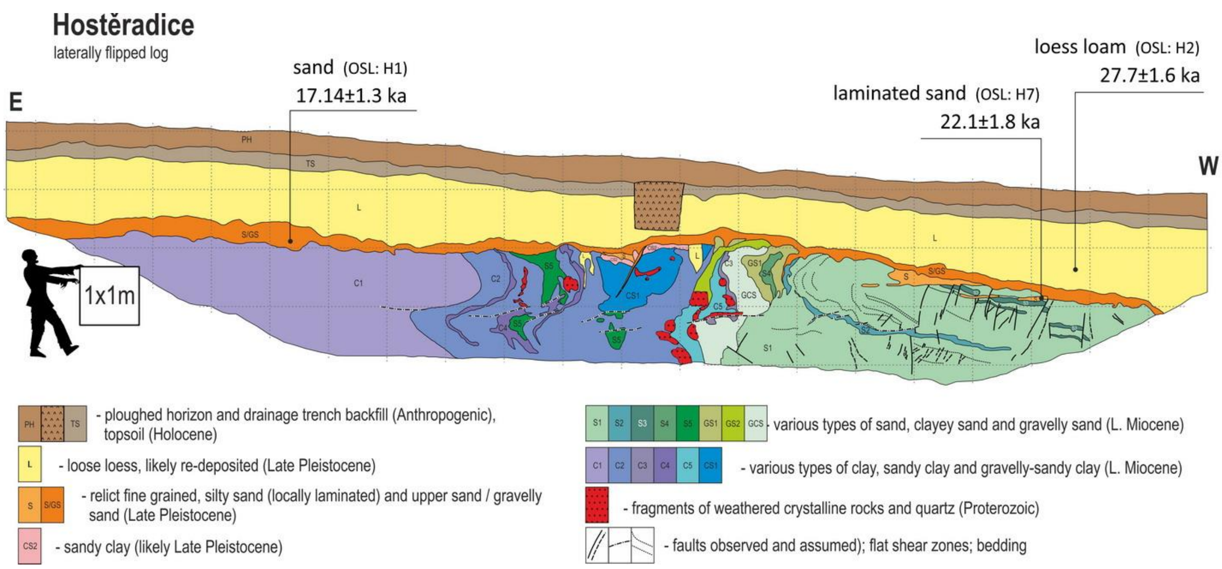
- Trench HOS-1 (25 m long and 4 m deep; WGS84: 48.9476°N, 16.2726°E) with fault in Lower Miocene sediments sealed by Late Pleistocene sands and loess loam. Špaček et al. (2017, 2018)
- Strong imbrication, large density of deformation bands and content of tectonic clasts of kaolinized crystalline rocks at the contact of clays and sands indicate large slip on the fault after deposition of Miocene sediments (assumed age Eggenburgian-Ottnangian based on lithostratigraphic correlation). Horizontal slip component was inferred on small faults which offset the thin clayey beds in sands, but the sense of slip was not resolved.
- Deformed Neogene sediments are unconformably overlain by Pleistocene strata. The irregular, up to 30 cm thick basal layer of sands and gravelly sands with mostly angular clasts of local provenance has a sharp

base and the luminescence dating of a single sample gives the age of 16-18 ka. Locally, at the base of Quaternary a thin sub-horizontal layer of parallel-laminated sand is developed and partly incorporated in coherently bended or apparently undeformed parts of Miocene sand. Luminescence age of a single sample from this layer is 20-24 ka.

- The above described sediments are overlain by 1-1.8 m thick layer of loess loam which is mixed with sands at the base. Its luminescence age is 26-29 ka. This age inversion (if real) suggests the emplacement of the loess loam without resetting of the luminescence signal (e.g. in a form of mudflows derived from older loess). Apparent age inversion due to dating errors can not be ruled out, however.
- These observations together provide evidence against episodic surface fault slip, both vertical and horizontal, at least since 16 ka.
- Younger slope-related deformation reaching the depth of 3 m is indicated by small-scale sub-horizontal shear zones, bending of Miocene strata and wedge-shaped apophyses of Quaternary sand and silt incorporated to small scale NW- to SW-vergent thrusts which fade out within first 85 cm below the surface of Miocene strata.



Hostěradice profile with ERT, interpreted geology and position of the trench. Note vertical exaggeration. From Špaček et al. 2017.

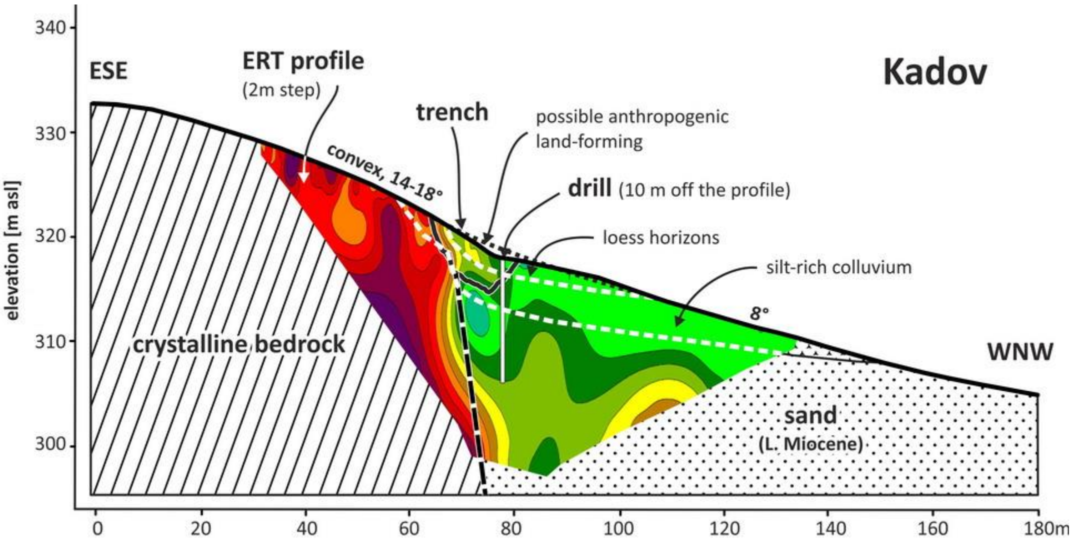


Hostěradice trench log. From Špaček et al. 2017.

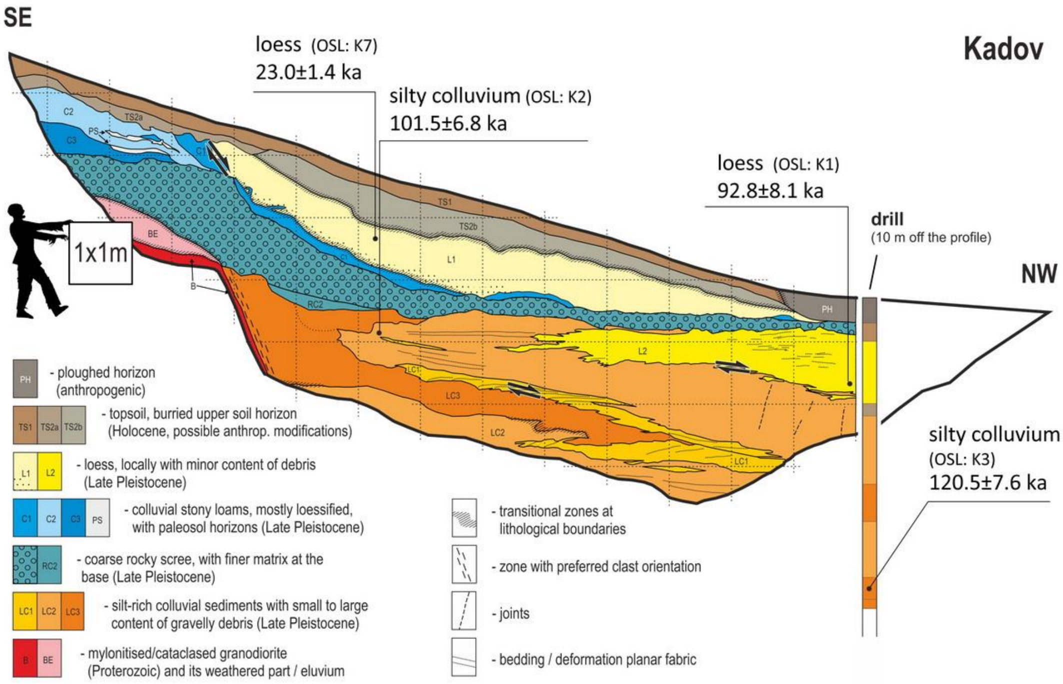
Kadov: Observed sealing strata

evi_ID: KAD_A
fsec_ID: BF_2
editor: Petr Špaček

- Trench KAD-1 (20 m long and 4 m deep; WGS84: 48.9747°N, 16.2937°E) situated at the foot of a relatively low scarp with local slope of 14-18°. The exposure of fault contact crystalline vs. E. Miocene sediment in an erosional gully some 120 m NE from here provided steep fault with slickensides and striations plunging 50° to the NNE.
- The trench exposed a steep fault dipping 75° to the NW with crystalline bedrock in a footwall and Neogene sands in the hanging wall, consistently with two ERT profiles made at the site.
- The fault in the trench is sealed by the 22-24 ky old loess (OSL) and by the non-dated pre-loess scree providing evidence against episodic surface fault slip, both vertical and horizontal, at least since LGM. The origin of coarse scree horizon is assumed to be climatically controlled (via frost shattering in cold and humid climate, likely pre-LGM).
- The silt-rich colluvium beneath the scree, OSL-dated at 85-128 ka (incl. 1 sigma uncertainty) terminates on a sharp and steep contact with cataclased mylonite of granitic protolith. This sediment is strongly deformed (likely by gelifluction but shaking effect is not ruled out) resulting in jagged bedding planes and locally well developed lamination. This penetrative shear deformation seems to have partly affected the overlying strata, likely resulting in the listric termination of top loess in direct continuation of the step in the bedrock.
- Shallow drill located near the lower end of the trench shows that the thickness of this Pleistocene succession is 5 m and it is underlain by 2.5 m-thick loamy sands of uncertain age and the fine sands of assumed Lower Miocene age.
- Total absence of any discrete faults or joints applies to whole exposed part of Quaternary sediment.
- Problematic is the 20 cm broad contact zone of older part of colluvia with the bedrock where increased content was observed of cm- to dm-size slab-shaped clasts oriented parallel with steep bedrock surface. This can be explained either as due to detachment of pieces of jointed bedrock into the colluvium by repeated freezing and thawing or as a result of shear deformation. In the latter case, fault slip in the time range 100 to <23 ka (pre-dating the formation of scree layer) would be likely. However, we did not observe any slickensides or other macroscopic signs of shear deformation within this zone and failed to obtain any data on its microscopic internal structure wherefore its origin can not be resolved.
- From Špaček et al. (2017, 2018)



Profile Kadov with ERT, interpreted geology and position of the trench. Note the vertical exaggeration. From Špaček et al. 2017.

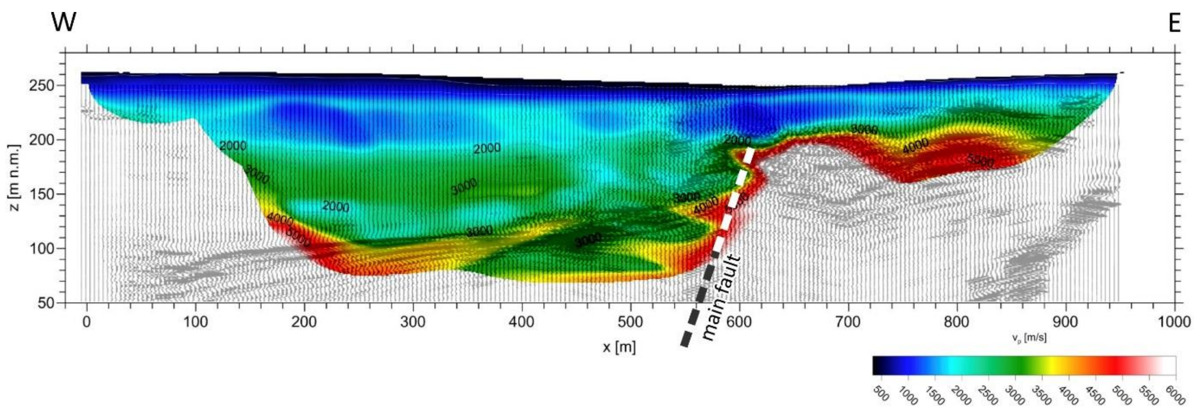


Kadov trench log. From Špaček et al. 2017.

Lesonice: Eroded fault scarp, Timing of last dip-slip

evi_ID: LES_A
fsec_ID: BF_3
editor: Petr Špaček

- Refraction and reflection seismic profile crossing the fault line (Alexa 2017; diploma thesis supervised by J. Valenta) showing a >50 m vertical offset at the base of low-velocity strata (assumed Lower Miocene sediment and/or strongly weathered crystalline) and a >40 m thick, apparently vertically undisplaced, top layer with even lower velocity, covering this offset and a buried pediment in crystalline rocks. The upper sedimentary body is of assumed Eggenburgian/Ottnangian age (~17-21 Ma) and it fills up adjacent paleovalley. The structure documents the erosional destruction of older fault scarp near (or in) the paleovalley and the absence of vertical slip component on the fault after Early Miocene (which is the minimum age of the paleovalley). Note the qualitative similarity of this observation with that at [Limberg site](). Small younger horizontal slip is not ruled out here.

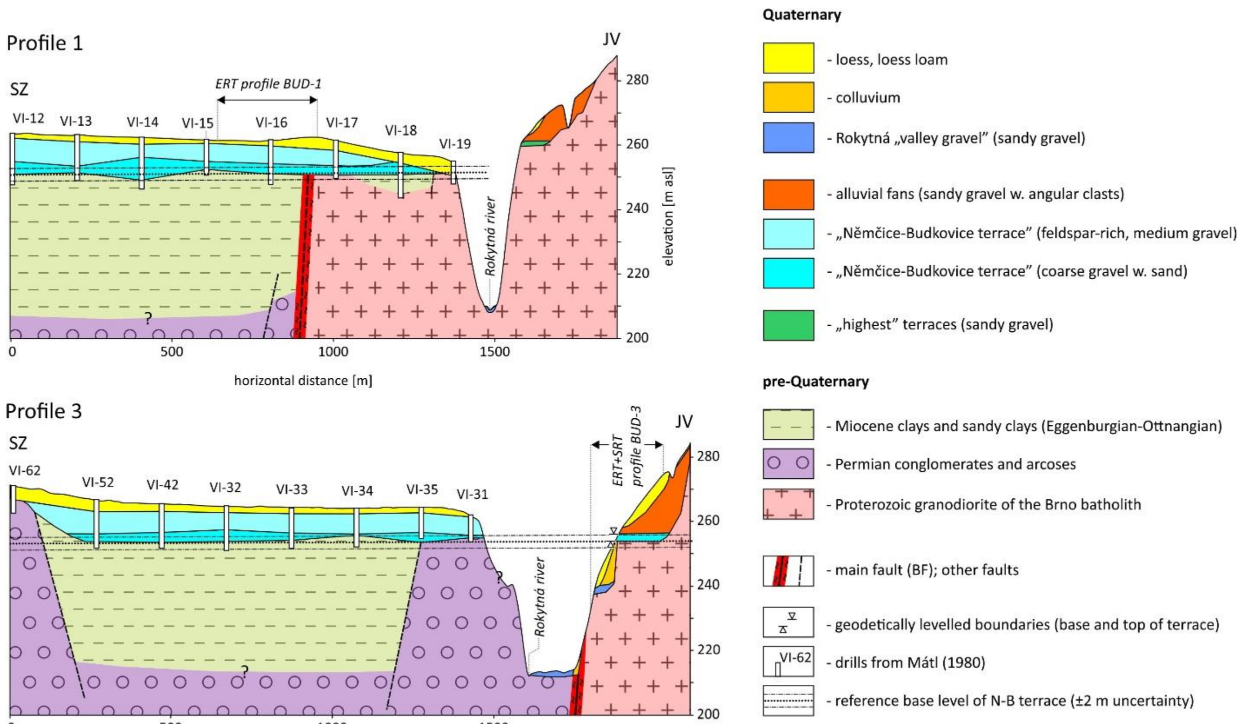


Stack of SRT and seismic reflection profiles near Lesonice. Modified from Alexa 2017.

Budkovice: Sealing strata

evi_ID: BUD_A
fsec_ID: BF_4
editor: Petr Špaček

- Gravels of high level river terrace (40-50 m above present floodplain) with base well defined by drill survey (Mátl 1980), detailed mapping (Špaček et al. 2015a, 2015b) and levelling survey (Špaček and Zacherle 2017) serve as alostratigraphic marker providing evidence against vertical slip on the Boskovice graben fault since the deposition.
- The continuous terrace body is either observed to seal the fault locally (see profile 1 below) or its separated relics are at the same height on both sides of the fault (profile 2). The terrace base is undisplaced within the precision of its definition which is 2 m.
- The age of gravel stratum is estimated from its relative height at Lower to early Middle Pleistocene, based on regional correlation scheme of Zeman (1984). Assuming the uncertainties of age and maximum offset, the maximum average slip rate at this section of BF is calculated at <0.003 mm/year.
- At the same locality (and many other places along the fault), talwegs of numerous valleys deeply incised in bedrock crossing the fault as well as contours of plateaus between, lack any (a fortiori systematic) offset on the fault in the highly accurate DEM, suggesting that horizontal slip must have been small (likely <0.01 mm/year) or zero since the start of incision in Middle Pleistocene.
- More detailed summary in Špaček et al. (2018)



Geological profiles across BF near Budkovice. Modified from Špaček et al. (2018).

Main data sources for fault map

Geological maps and explaining texts:

scale 1:25000:

- sheet 34-133 Hatě (Čtyroký et al. 1978, 1987; Batík et al. 1978)
- sheet 34-132 Božice (Dornič et al. 1983, 1984)
- sheet 34-131 Šatov (Batík et al. 1977, 1982, 1983)
- sheet M-33-117-C-a Šatov (Dlabač et al. 1970)
- sheet M-33-117-C-b Jaroslavice (Batík et al. 1972)
- sheet 34-114 Prosiměřice (Dornič et al. 1985a,b)
- sheet 34-113 Znojmo (Čtyroký et al. 1978, 1983a,b)
- sheet 34-112 Miroslav (Dornič et al. 1987)
- sheet M-33-117-B-a Miroslav (Dornič 1972)
- sheet M-33-105-D-c Moravský Krumlov (Dlabač et al. 1975)
- sheet M-33-105-D-b Ivančice (Jaroš 1964a,b)
- sheet 24-341 Oslavany (Buriánek et al. 2011a,b)
- sheet M-33-105-B-d Rosice (Jaroš et al. 1972c)
- sheet M-33-105-B-b Veverská Bitýška (Mísař and Jaroš 1972; Jaroš et al. 1972a,b)
- sheet 24-321 Tišnov (Hanžl et al. 2001a,b)
- sheet 24-322 Blansko (Hanžl et al. 2000a,b)
- sheet M-33-94-A-d Knínice z Boskovic (Dvořák et al. 1964)

scale 1:50000:

- sheet 37-Mautern (Matura et al. 1983)
- sheet 23-Hadres (Rötzel et al. 2007)
- sheet 22-Hollabrun (Rötzel et al. 1998)
- sheet 21-Horn (Frasl et al. 1991)
- sheet 9-Retz (Rötzel et al. 1999)
- sheet 34-13 Dyjákovice (Čtyroký et al. 1987; Müller et al. 2003)
- sheet 34-11 Znojmo (Matějovská et al. 1988; Müller et al. 2002)
- sheet 24-33 Moravský Krumlov (Matějovská et al. 1991)
- sheet 34-12 Pohořelice (Havlíček et al. 1988; Müller et al. 1995)
- sheet 24-34 Ivančice (Pálenský et al. 1994; Müller et al. 1994; Batík et al. 1994)
- sheets 24-32, 24-14, 24-23, 24-21 (ČGS 2014)

scale 1:200 000: sheet Niederösterreich Nord (Schnabel 2002)

special maps: (Čížek 1976; Mátl 1980; Kolektiv 1994; Špaček et al. 2015, 2016)

Geophysics:

- Regional gravimetry a aeromagnetic survey (compiled maps of Švancara in Špaček et al. 2018; Blaumoser 1992)
- Local airborne magnetic and electromagnetic survey (DF_5, WEI_2; Sieberl et al. 1996, 1997)
- Local gravimetry (DF_1 to DF_5, Figdor and Scheidegger 1977; BF_7-10, Halíř et al. 1987)
- Electrical resistivity tomographic profiles, seismic refraction and reflection profiles (Valenta and Tábořík et al. in Špaček et al. 2016, 2018 and references therein; Alexa 2017)
- Local high-resolution electromagnetic conductivity survey between Hostěradice and Lechovice (BF_1; as yet unpublished data by Fojt and Špaček)
- Vertical electrical sounding in the sediments on sections DF_6-8, BF_1 and BF_9,10 (Kraus 1989, Synek 1980, Hron 1980, Bláha a Synek 1987, *none of these surveys have good enough resolution and none of them shows changes of physical properties or structure which could be associated with the fault*).

Other:

- DEM: Lidar based models of the Czech Republic (DMR4g and 5g; ČÚZK 2013, 2016) and Lower Austria
- Drill survey: mainly shallow drilling (mostly from CGS/Geofond archive, see references in Špaček et al. 2015b)

Other notes

Ongoing research and possible future work to be done:

- EM conductivity mapping of fault and covering sediments south of Hostěradice (Fojt and Špaček, ongoing), near Ivančice, Lesonice and Bořitov (planned)
- studies on cross structures

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… (the list of references is intentionally reduced here. See Web encyclopedia for complete version.)

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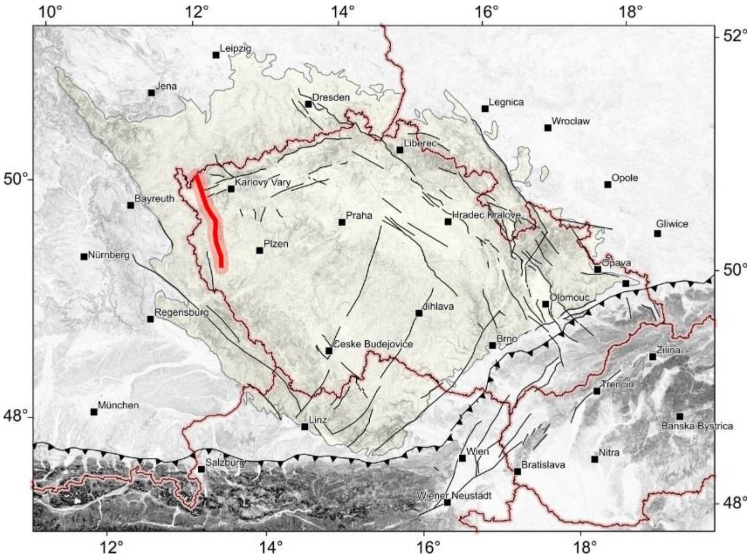
Mariánské Lázně Fault



Structure ID: MLF

Fault Section IDs: MLF_1-30; MLF_c1-20

Related terms: *cze*: mariánskolázeňský zlom)

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General description

The Mariánské Lázně Fault is a prominent tectonic structure in Western Bohemia. It is about 150 km long and it has the prevailing orientation NNW-SSE. The fault itself is a bounding structure of several distinctive geological units of the Bohemian Massif: the Saxo-Thuringian unit in the NW, Moldanubian unit in the S and SW and Teplá-Barrandian unit in the E (Zoubek et al., 1963). It is morphologically pronounced and controls the eastern limit of Cheb-Domažlice Graben at the length of 100 km. In its northern part it controls the eastern limit of Cenozoic Cheb basin. The uplifted footwall of the MLF truncates the Krušné hory Mts. (Erzgebirge) and the Eger rift including the Sokolov basin (Fig. 1).

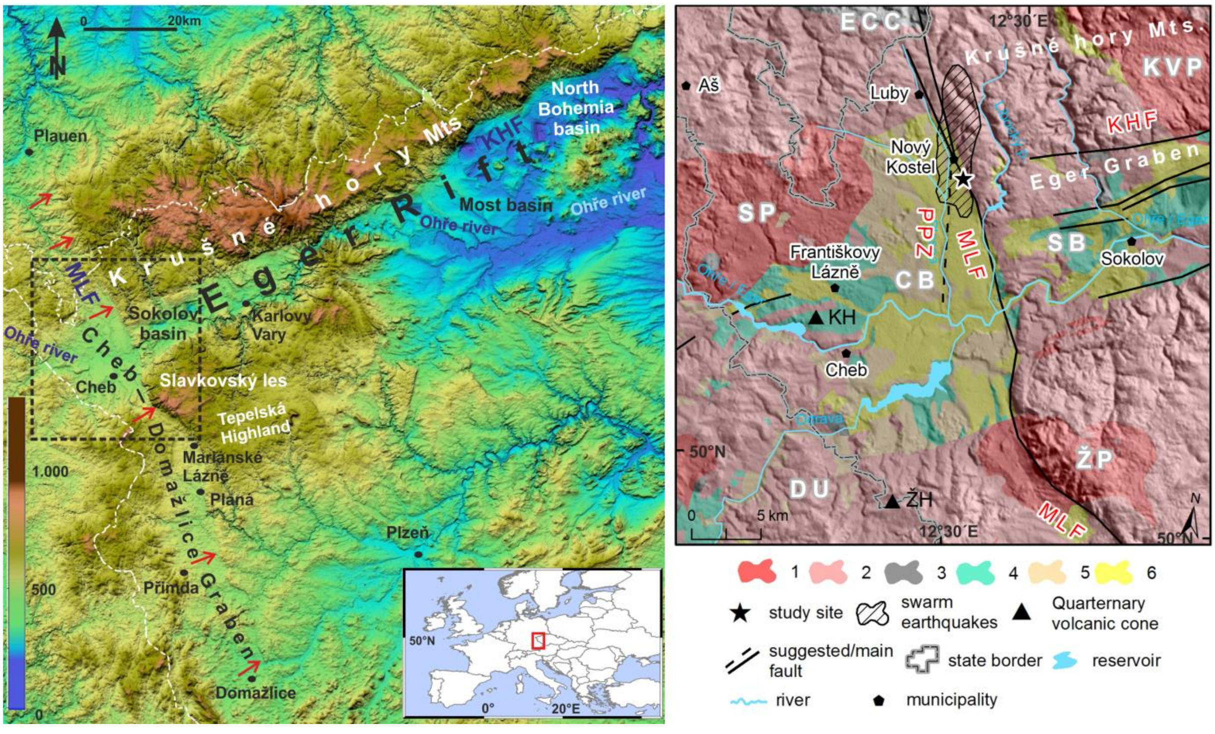

Fig. 1. Left panel: relief map fromSRTM3 data with the main morphotectonic structures; red arrows – Mariánské Lázně fault (MLF), KHF – Krušné hory fault, dashed rectangle – extent of right panel. Right panel: geological map simplified after Babuška et al. (2010), Mlčoch (2003), Peterek et al. (2011), and Zulauf et al. (2002). Hatched area defines territory with the highest density of swarm epicentres 1997-2017. Geology: 1 – Late Variscan granites and granitoids; 2 – Variscan metamorphic units; 3 – Volcanics (mainly Oligo-/Miocene); 4 – Miocene (Cypris

Formation); 5 – Plio-/Pleistocene (Vildštejn Formation); 6 – Quaternary. Saxothuringian: ECC – Erzgebirge (Krušnéhory) Crystalline Complex, DU – Dyleň Unit; Variscan granitoids: SP – Smrčiny (Fichtlgebirge) Pluton, KVP – Karlovy Vary Pluton, ŽP – Žandov Pluton; CHB – Cheb basin, SB – Sokolov Basin; KHF – Krušné hory Fault zone, MLF – Mariánské Lázně Fault zone, PPZ – Počátky-Plesná Fault zone. Quarternary volcanic cones: KH – Komorní Hůrka volcano, ŽH – Železná Hůrka volcano. After Štěpančíková et al. (2019).

The course of the fault is not properly geologically proved in the NW part between the CZE-GER state border and the Nový Kostel and it is traced only morphologically. However, the fault is crosscutting the bodies of phyllites in the NNW-SSE direction and their displacement suggests the dextral movement on this part of the fault (Müller et al., 1997). The sedimentary Cheb Basin is bounded by the MLF in the segment between Nový Kostel and Milíkov. The youngest gravels, sands and clays of Vildštejn formation (Pliocene-Pleistocene) or clays and claystones of an older Cypris formation (Miocene) can be found on the surface to the west of the fault. Holocene cover of various thickness (e.g. loess) can be found there as well (Teodoridis et al., 2016). Older formations - Staré Sedlo formation, Nové Sedlo formation (Eocene) or Sokolov formation (Oligocene-Miocene) are known only form wells and are not exposed on the surface (Müller et al., 1997). However, the Tertiary infill of the basin is in the sharp contrast with the schists and other crystalline rocks laying to the east of the MLF (Chlupáč et al., 2002). The part of the MLF between Milíkov and Mariánské Lázně is not forming any distinct lithological boundary. The fault is crosscutting mainly the granitic rocks or other crystalline rocks of saxo-thuringian unit (Cháb et al., 2008). Also, the fault orientation NW-SE in this part is different from the prevailing NNW-SSE direction. There is complicated lithological situation in the surroundings of Mariánské Lázně: the fault itself is forming the fault zone with diverse lithological blocks between fault branches. The orientation of MLF is changing to typical NNW-SSE direction to the south of Mariánské Lázně, also the fault is forming a boundary between granitic and metamorphic rocks of Teplá-Barrandian. MLF is formed by two or more parallel branches in this segment (Seifert a Straka, 1998). There are two main deviations from the prevailing orientation of the fault: the short segment near Kočov, where is the orientation almost W-E and the segment between Boječnice and Staré sedlo (NW-SE) (Seifert a Straka, 1998). To the south of Staré Sedlo, there is mostly only simple course of the fault (without branching) of NNW-SSE orientation. The fault is separating the Sedmihoří granitic massif from the major body of moldanubian batholite and further to the south it is crosscutting the paragneisses of moldanubian. In the part between granitic massifs, the MLF is accompanied with the zone of the weak hydrothermal alteration (Vejnar et al., 1980). According to faults parallel to the MLF, the main fault should have a steep dip to WSW Vejnar et al., 1978). The fault is gradually fading out south to the Horšovský Týn and it cannot be detected in lithology or morphology south to the Blížejov (Vejnar et al., 1978b).

Fault structure and dip

The MLF fault structure is complex and has been described by several authors differently, also depending on the various geological period of its activity (Špičáková et al. 2000, Peterek et al. 2011). Due to lack of the outcrops, the boreholes, geophysics and trenching survey that covers only very superficial part, are the only source of information. In a 100 m long trench across the most morphologically pronounced sections of the MLF near Kopanina village, the paleoseismic trenching survey revealed several fault strands with repeated movements and migrating activity towards the basin within a ~28 m-wide zone, which most probably form a single fault at the depth and which displaced Oligocene to Holocene sediments (Blecha et al. 2018, Štěpančíková et al. 2019) (Fig. 2). These faults appeared to dip towards the SW to the basin, usually 80°, which was also confirmed by the shallow geophysical survey (Fischer et al. 2012) as well as deeper geophysics (Blecha et al. 2018) (Fig. 2). Those geophysical surveys show the area of expected MLF position as an up to 100 m wide zone of low resistivity, low density and low seismic velocity, which could indicate a zone of intensively fractured and weathered rocks along the fault zone. The dip of the MLF was then shown as generally steeply dipping towards SW with dip 60° near the surface to 80° in the deeper parts. The normal dragging along the boundary fault of the MLF in the same area near Kopanina site was also confirmed by the seismic reflection by Halpaap et al. (2018).

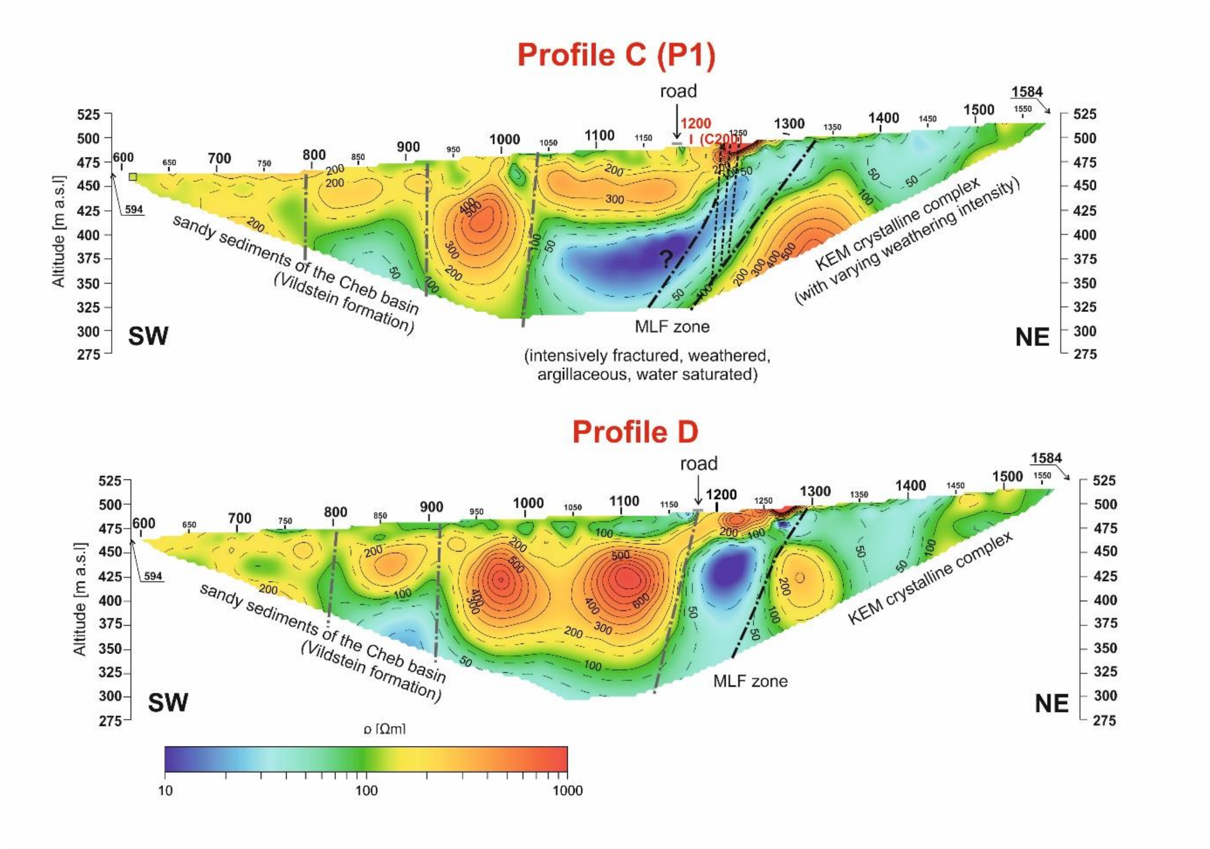

Fig. 2 Example of ressults of geophyiscal survey, namely electrical resistivity tomography (ERT) across the MLF near Kopanina site. Black dashed lines represent MLF zone, probably fractured and/or intensively weathered and water saturated as shown by higher conductivity. The dotted lines on profile C represent a splay of faults revealed by trenching and ERT by Fischer et al. (2012) and Štěpančíková et al. (2019). Adopted from Blecha et al. (2018).

Cross structures and Segmentation

The segmentation of the MLF was made for the purpose of the Fault database and further calculations, based on 1:50000 scale geological maps (CGS) and supplementary topographic data (DMR 4G; ČÚZK 2017). For the numerical purpose the strike changes of the fault trace were the leading information for segmentation (making sections), and 53 sections were distinguished.

Moreover, about 20 major cross structures were found along the MLF and were incorporated to the database with a proper code. Most of these structures are in the central and southern part of the MLF (to the south of Mariánské Lázně). Some of them are elongated step-overs of the main fault. The general direction of the MLF (besides 3 short parts, see above) is NNW-SSE. Therefore, the orientation of the cross structures is varying between WNW-ESE to SW-NE.

Large parts of the MLF are formed of two or more branches, only the parts between Milíkov and Kynžvart, and further to the south to Staré Sedlo, seem to be a simple course of the fault without branching.

Scarp morphology

The MLF is expressed in morphology by more or less pronounced fault scarp at the length of 120 km from Plauen in Germany to Horšovský Týn despite the lack of any fault outcrops (Fig. 1). In the northern part the fault is expressed by a linear arrangement of saddles and by 40-130 m high slope (fault scarp), which divides Smrčiny (Fichtelgebirge) from Krušné hory Mts (Erzgebirge) on the Czech territory. Around Nový Kostel, the fault splays into two scarps, where one is expressed by linear arrangement of places where enhanced headward erosion starts and several valleys change their character or direction, and the second by a steeper slope. This segment is proved also by geophysics and paleoseismic trenching (Fischer et al. 2012, Štěpančíková et al. 2018). From Milíkov the fault is bent and controls the highest elevated area, Slavkovský les by up to 300 m high fault scarp. The scarp is expressed by pronounced trapezoidal to triangular facets. From Mariánské Lázně the fault scarp strikes again NW to NNW and it steps over to the right near Planá, from where is rectilinear to Kočov, where the main river Mže antecedently flows into the fault scarp of about 100 m height. More to the south, almost up to Bor, the fault steps over to the left and is almost N-S striking expressed by two parallel gentle fault scarps, 10-15 m high. This segment seems to be morphologically the youngest one. Near Nová Hospoda (3 km north of Bor) Neogene fluvio-lacustrine sediments are ceased by the fault. From Bor to Staré Sedlo the fault/fault scarp is bending twice from N-S direction to WNW-ESE and reaches the height 15-35 m. From Horšovský Týn, the fault is not expressed in morphology any more.

Seismicity

The Cheb basin, which is controlled by the MLF at its eastern limit, is a part of one of the neotectonically most active regions in central Europe and overlaps with the West Bohemia/Vogtland earthquake swarm region that is characterized by persistent weak to moderate seismic activity (Fischer et al., 2014). The earthquake swarms are related mainly to the Nový Kostel focal zone, which dominates the seismicity of the whole West Bohemia/Vogtland area (Fig. 1, right panel). This is the location of all the $M_L \geq 3$ swarms during the past 30 years (one swarm in 1985 and 6 others between 1997 and 2018). Recent earthquake swarms usually consist of several thousands of earthquakes with prevailing focal depths between 6 and 15 km. The NK focal zone is formed by a steeply dipping narrow NNW striking belt of about 12 km length and by several intersecting fault planes with prevailing N-S orientation, which are step-wise activated. It crosscuts the MLF, suggesting no relation of the present earthquake swarms with the MLF (Fischer et al., 2014).

Pre-Miocene evolution

The MLF originated already in the late-Variscan as a normal fault with a dextral component and which alternated several different kinematics (Pitra, 1999). The fault itself is a bounding structure of several distinctive geological units of the Bohemian Massif at the surface: the Saxo-Thuringian unit in the NW, Moldanubian unit in the S and SW and Teplá-Barrandian unit in the E (Zoubek et al. 1963). The MLF is parallel to the West Bohemian Shear Zone to the West (Zulauf et al. 2002) which separates the Teplá-Barrandian in the East from the Moldanubian in the West and probably roots in the lithospheric mantle (Babuška et al. 2007). According to Zoubek et al. (1963) the MLF originated probably during the Asturian phase of the Variscan orogeny. During pre-mesozoic period the vertical position of the blocks on the both sides of the MLF was opposite to the present-day one. This could have lasted probably still during the beginning of the Tertiary sedimentation in the basins when Cheb basin (western block) was at higher position than the adjacent Sokolov basin (eastern block) as it is suggested by the lack of the oldest formations of Sokolov basin in the Cheb basin.

Fault activity in late Cenozoic

Tertiary

The evolution of the MLF started to have its great importance later with the Late Cenozoic Eger rift formation. It has been studied and known only due to Cheb basin formation controlled by the northern section of the MLF. So, the MLF evolution is related to the Cheb basin evolution.

The stratigraphy in the Cheb basin can be simplified and divided into three intervals (Malkovský, 1995; Špičáková et al., 2000). The Pre-Cypris strata (Late Oligocene to Early Miocene, ca. 26-21 Ma) group together the Lower Clay and Sand Formation, including volcanics and volcanoclastics and the coal seam formation, which fill several small depocenters associated with E-W trending normal faults. The Cypris Formation (Early to Middle Miocene, ca. 21-17 Ma) is characterized by widespread lacustrine conditions with dominant clay lithologies. This depositional period was terminated by partial uplift and erosion. The Vildštejn Formation (Late Pliocene-Pleistocene, ca. 4.5-1.4 Ma; Teodoridis et al., 2017) was deposited discordantly after a hiatus of 12 Ma duration. Its fluvio-lacustrine sediments consist of kaolinic clays, sands and gravels. During this period the NW-trending faults controlled the shape of the basin depocenters, especially the MLF as a master fault. Špičáková et al. (2000) proposed that the MLF acted as a sinistral strike-slip fault under transtension, although they mentioned also some contradictions (see also Rojík et al., 2014). The asymmetric subsidence was accompanied or followed by the uplift of the footwall with the Krušné hory Mts., which resulted in separate evolution of the formerly united Cheb and Sokolov basins (Špičáková et al., 2000; Pešek et al., 2014).

Quaternary

The Quaternary activity of the fault can be inferred from the morphology of the fault scarp controlled by the MLF as well as from the boreholes in the Cheb basin and paleoseismic trenching survey.

Geomorphology

The fault scarp controlled by the MLF at the lenght of around 100 km is one of the most prominent fault scarp in the Bohemian massif with several antecedent valleys of the largest rivers in the region, with anomalies of longitudinal river profiles analysed by morphometric methods, rectangular drainage network, tectonic valley assymmetry etc. In the Cheb basin sections, rapid changes in erosion intensity are present in the MLF zone related to the uplift. While in the Krušné hory Mts. well-preserved and deep V-shaped valleys are present, in the Cheb Basin, valleys are shallow and U-shaped.

Quaternary tectonic activity of the MLF is evidenced also by **offset of the fluvial terraces** of the Ohře/Eger river in the Cheb basin. Newly published work shows their vertical offset within the longitudinal profiles when crossing the Mariánské Lázně fault, which limits the Cheb basin towards the Chlum horst (Balatka et al. 2019). The vertical offset of the oldest terraces, which are ascribed to the early Pleistocene in age, is 15-20 m, with diminishing offset in progressively younger terraces, so it shows that the MLF has been active through the entire Pleistocene (Fig. 3).

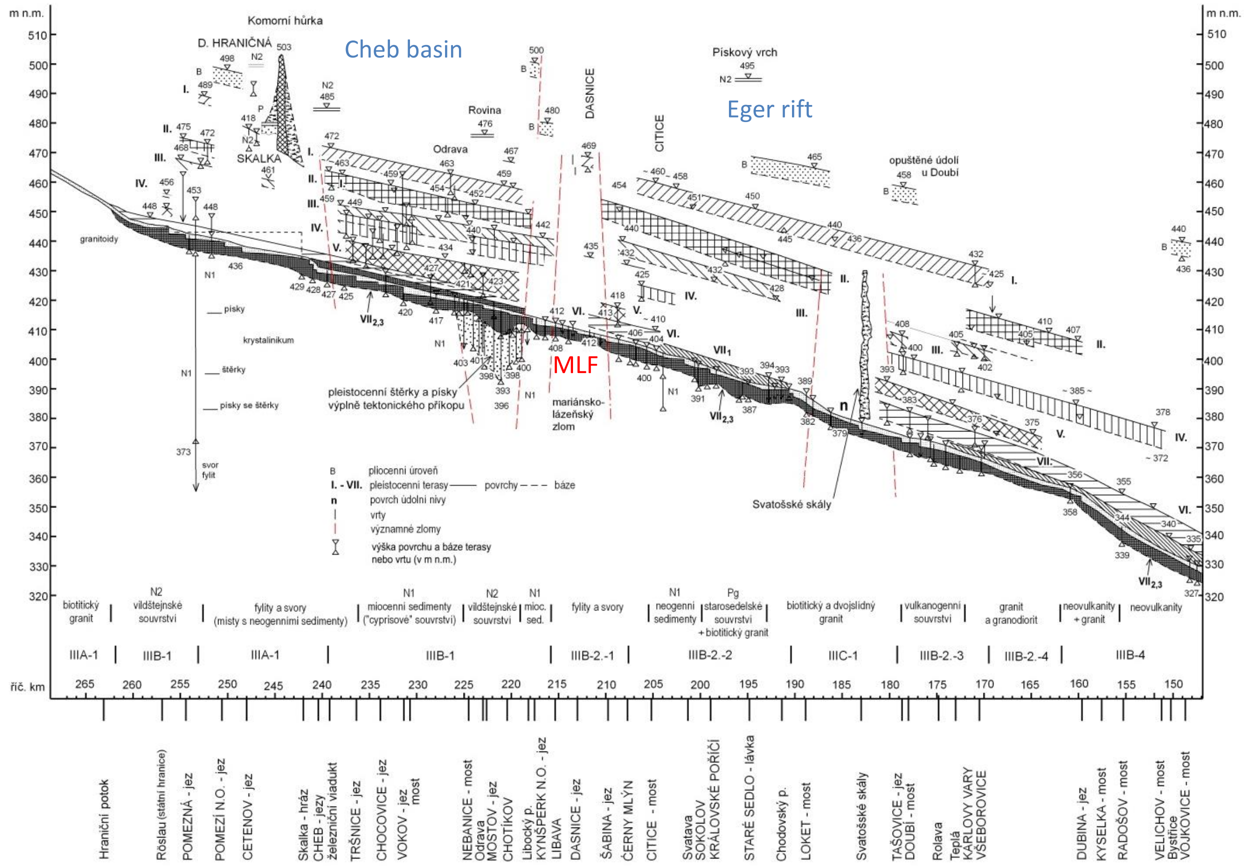

Fig. 3. A longitudinal profile of the Eger River terraces between the Smrčiny Mountains and the Doupovské hory Mountains. The red dotted lines – significant faults. The terraces of I., II., III. are uplifted along the MLF and can be found at higher position on the footwall than in the Cheb basin. Adopted from Balatka et al. (2019).

Continuity of overlying strata

The activity of the MLF during Quaternary has been documented based on Plio-Pleistocene Vildštejn Formation, whose depocenter with >100 m thickness is related to the MLF.

Oligocene to Holocene strata displaced by several strands of the MLF zone were documented in the paleoseismic trenches in the Cheb basin close to the Kopanina village (Štěpančíková et al. 2019). The topsoil was the only layer that was demonstrably non deformed, while the underlaying Holocene units of the age 4-1 ka have been displaced twice (Fig. 4).

Seismicity and paleoseismicity

Historical records show several earthquakes that could be associated with the southern continuation of the MLF within the Cheb Domažlice graben. These are the earthquakes in 1688 near Domažlice, in 1787, 1788, 1855 and in 1915 near Planá, and 1902 near Přimda (Procházková and Šimůnek, 1999; Leydecker, 2011) with intensity I_0 from 4.5° to 6.5° MSK. The unknown focal mechanisms of these pre-instrumental earthquakes, however, prevent us from verifying their tectonic relation to the MLF.

The paleoseismic studies at the Kopanina site, close to Nový Kostel village, revealed that the MLF was reactivated during several ground-breaking earthquakes during late Quaternary, with mid-Pleistocene normal faulting and two M6.5+ events in the late Holocene of right-lateral strike-slip character under transpression with maximum vertical displacement of 0.4 m (Štěpančíková et al. 2017, 2019). The youngest event dated by radiocarbon dating into the interval of about 792 to 1020 AD, which is even the historical event (Fig. 4). The fast seismic character of the movements documented in the trenches is indicated by the fault scarp, folds, push-up, and fissures, by faulted and folded strata, as well as by microstructural analysis of grain samples taken from the fault zone and showing different orientations of the grains within the fault and outside.

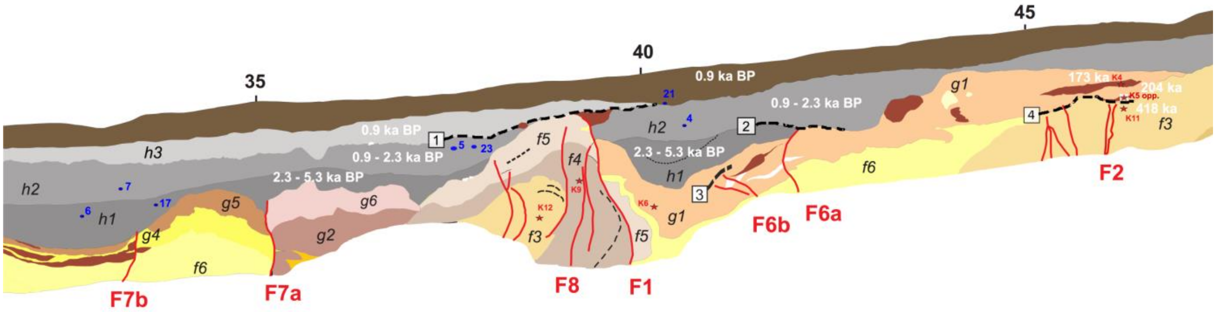

Fig. 4. Simplified chronological scheme of the faulting revealed in the Kopanina A trench. Calibrated radiocarbon (dots for samples) and OSL ages (asterisks for samples) of the strata in the area of the faults F1, F2, F6, F7, and F8 are indicated in white; dash bold lines mark the event horizons of the events 1, 2, 3 and 4. Adopted from Štěpančíková et al. (2019).

Based on the empirical relationships between moment magnitude, rupture length and surface displacement described by Wells and Coppersmith (1994), the extensively used magnitude scaling relationships in paleoseismology, a probable minimum earthquake magnitude for the recorded events on the MLF were approached. The surface rupture length was consider to be at least 10 km, identified by using LiDAR images and vertical fault displacements, which points to a minimum moment magnitude up to Mw=6.3 to 6.5. The values of Mw based on displacements were similar ranging from Mw=6.1 to 6.6 (Štěpančíková et al. 2019).

Related local evidence

The local evidence of the activity of the MLF was documented in the paleoseismic trenches at the Kopanina site, close to Nový Kostel village, by deformed and displaced Oligocene to Holocene stratigraphy (Fig. 5) (Štěpančíková et al. 2017, 2019).

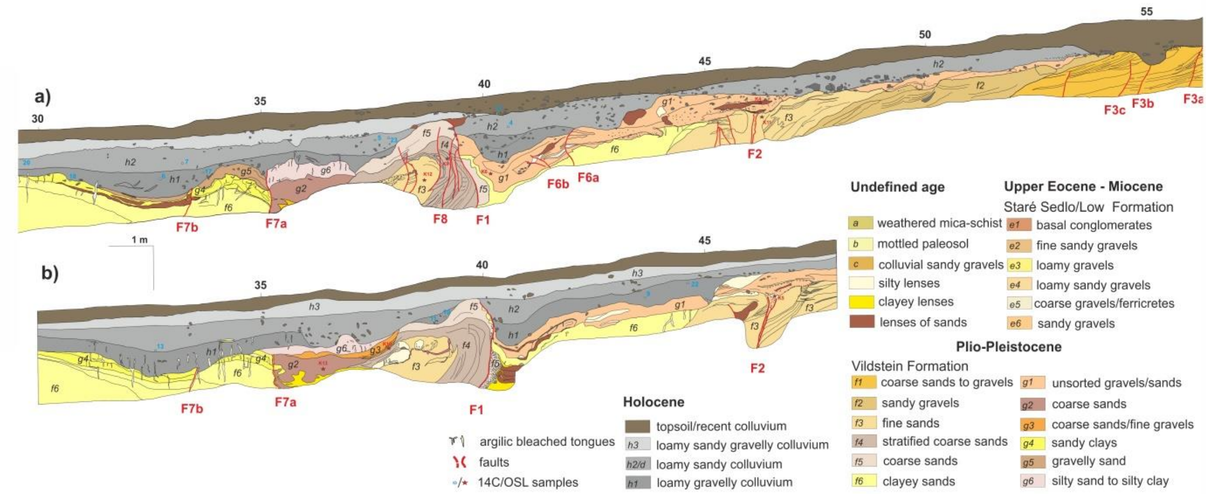

Fig. 5. Paleoseismological log of the Kopanina A trench with geological information. a) – southern part of the log of SE-facing wall, b) - flipped NW-facing wall. Adopted from Štěpančíková et al. (2019).

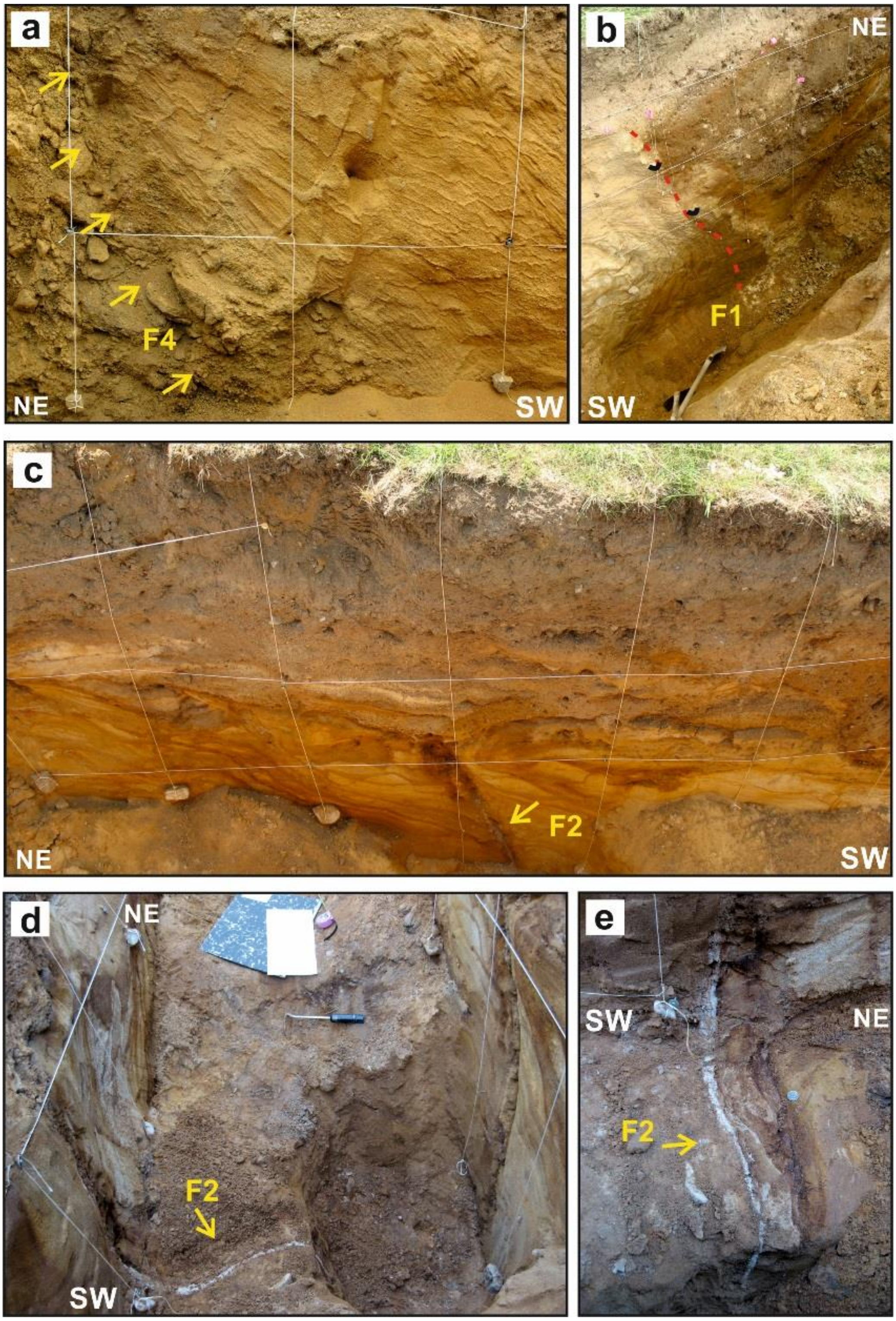

Fig. 6. Photographs from the trench Kopanina A, see the 0.5 m grid on the walls for scale. (a) Deformation bands around fault F4, NW-facing wall, X=58 m at the log – fig. 5 (b) Fault F1 with folded sandy layers (left block) and downwarped beige clay, sand and Holocene loamy colluvium (right block) sealed by upper 0.5 m of topsoil and unit h3, black marks – matching points, SE-facing wall, X=39-41 m, (c) Fault F2 with normal drag of unit f3 sandy layers (left block) pigmented by iron oxyde-hydroxides, NW-facing wall, X=44-46 m, (d) Fault F2 filled with white silty clay and (e) accompanied by distinctive iron mineralization that hardened the fault zone and by structures reminding Riedel shears on the trench floor indicating a horizontal component. Adopted from Štěpančíková et al. (2019).

Main data sources for fault map

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