HIKE GeoERA GEO-ENERGY

Hazard and Impact Knowledge for Europe

Deliverable D2.2b

Final fault data collection report and database: Annex 1

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1 INTRODUCTION

This Annex to the main report D2.2b – "Final fault data collection report and database" contains the individual reports from the partners with a geological background to the provided national and regional fault data.

1.1 Overview of HIKE partners and contributing authors

Chapter	Participant Legal Name	Institution	Country	Authors
2	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO	TNO (coordinator)	Netherlands	Serge van Gessel, Johan ten Veen, Hans Doornenbal, Maryke den Dulk
3	Albanian Geological Survey	AGS	Albania	Siri Hamiti, Ndoc Vukzaj, Rushan Çako, Elisa Prendi, Maga Ceroni, Alfred Mara
4	Geologische Bundesanstalt	GBA	Austria	Esther Hintersberger
5	Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium	RBINS-GSB	Belgium	Renata Barros and Alejandra Tovar
6	Geological Survey of Denmark and Greenland	GEUS	Denmark	Peter Britze
7	Bureau de Recherches Géologiques et Minières	BRGM	France	Thierry Baudin
8	Bundesanstalt für Geowissenschaften und Rohstoffe	BGR	Germany	Heidrun Louise Stück, Fabian Jähne-Klingberg
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10	Landesamt für Geologie und Bergwesen Sachsen-Anhalt	LAGB	Germany	Alexander Malz
11	Bayerisches Landesamt für Umwelt	LfU	Germany	Gerold W. Diepolder
12	Islenskar orkurannsoknir - Iceland GeoSurvey	ISOR	Iceland	Sigríður Kristjánsdóttir Albert Þorbergsson
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	Agenzia Regionale per la Protezione Ambientale del Piemonte	ARPAP		
14	Lietuvos Geologijos Tarnyba prie Aplinkos Ministerijos	LGT	Lithuania	Jurga Lazauskienė, Gintarė Andriuškevičienė, Artūras Baliukevičius
15	Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy	PIG-PIB	Poland	Marek Jarosiński, Tomasz Gogołek, Urszula Stępień, Ewa Krzemińska, Sylwester Salwa, Ryszard Habryn, Paweł Aleksandrowski, Ewa Szynkaruk, Monika Konieczyńska
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17	Geološki zavod Slovenije	GeoZS	Slovenia	Bogomir Celarc. Jure Atanackov, Petra Jamšek Rupnik
18	State Research and Development Enterprise State Information Geological Fund of Ukraine	GEOINFORM	Ukraine	Alexandr Shevchenko, Igor Melnyk, Alisa Lapshyna

2 TNO – NETHERLANDS

2.1 Introduction

This country report provides a summary of the tectonic structuration and fault developments in the Netherlands, based on the following three key publications:

- De Jager, J., 2007. Geological Development. In: Wong, Th.E, Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (Amsterdam):
- Duin, E., Doornenbal, J.C., Rijkers, R.H.B., Verbeek, J.W. & Wong, T.E. 2006. Subsurface structure of the Netherlands; results of recent onshore and offshore mapping. Netherlands Journal of Geosciences, 85, 245-276.
- Kombrink, H., Doornenbal, J.C., Duin, E.J.T., den Dulk, M, van Gessel, S.F., ten Veen, J.H. and Witmans, N., 2012, New insights into the geological structure of the Netherlands; results of a detailed mapping project. Neth., J. Geol., 91(4), 419-446.

The predominantly flat topology of the Netherlands reveals only sparse evidence of faults and tectonic activity at surface. In the south-eastern part of the country it is possible to detect some surface to near-surface faults defining the boundaries of the Roer-Valley Graben. In many other parts of the Netherlands, faults are covered by a thick and tectonically undisturbed sediment cover.

At larger depths (below 1 km), the subsurface of the Netherlands is characterized by a complex structuration and a dense network of faults dominated by SE-NW orientations. The different tectonic styles in the Netherlands are related to various phases including the Palaeozoic assembly of the Pangea super-continent (Caledonian and Variscan orogenies), the Mesozoic rifting and break-up of Pangea (Kimmerian phases), and the Alpine collision during the Late Cretaceous and Cenozoic. The dominant tectonic structuration of the Dutch subsurface mainly developed during the Mesozoic, yet many of the larger fault systems and structural elements are believed to be associated to older (pre-Devonian) structures. Due to deep burial (ca. 10 km) it is difficult to directly link faults to the basement in most parts of the Netherlands.

In the northern part of the country, massive Permian rock salt formations of the Zechstein Group generally act as a detachment zone separating deeper fault systems from shallower (post-Permian) faults (see Figure 1). Towards the south and west complex fault systems are present in Late Jurassic and Early Cretaceous extensional and trans-tensional rift basins such as the West Netherlands Basin (onshore) and the Central Dutch Graben (offshore). Many of these faults have been reactivated during various tectonic phases.

2.2 Structural elements

The map in Figure 2 shows the structural elements that define the present-day geological and tectonic framework of the Netherlands. The term 'structural element' is assigned to regional structures with a uniform deformation history in terms of subsidence, faulting, uplift and erosion during a specific time interval. The insights are the result of ca. 40 years of geological research in which the subsurface has been systematically mapped at regional and national scale (1:250.000). Definitions and names of structural elements have significantly changed during this period.

The main structural elements in the Netherlands are subdivided into basins, highs, and platforms. Each element has a distinct burial and erosion history. The structures have mainly developed during the Mesozoic (Triassic, Early Jurassic and Late Jurassic/Early Cretaceous) rifting followed by Late Cretaceous/Early Cenozoic compression and uplift). The origins and trends of these structures are probably underpinned by Paleozoic tectonic structures and fault systems. Kombrink et al. 2012 defines the structural elements as follows:

- **High**: an area with significant non-deposition and erosion down to Carboniferous or Permian strata (Rotliegend and Zechstein).
- **Platform**: areas characterized by the absence of Lower and Upper Jurassic strata due to Late Jurassic erosion down to the Triassic. A further subdivision is made into areas where Cretaceous rocks overlie Triassic rocks and areas where Cretaceous rocks lie directly on top of Permian sediments
- **Basin or Graben**: a fault-bounded basin with preservation of Jurassic sediments. Further subdivision is made into strongly inverted basins (erosion of Cretaceous and possibly also Jurassic intervals) and mildly inverted basins (Some erosion yet Lower and Upper Cretaceous intervals are mainly preserved).

Structural elements have tectonically defined boundaries. In most cases these boundaries are aligned with large-scale fault zones. In some areas the boundaries are defined by the wedging-out of major stratigraphic intervals (groups) due to tectonic tilting. The following four maps provide further insight in the geological development of the structural elements during the Paleozoic, Mesozoic and Cenozoic.

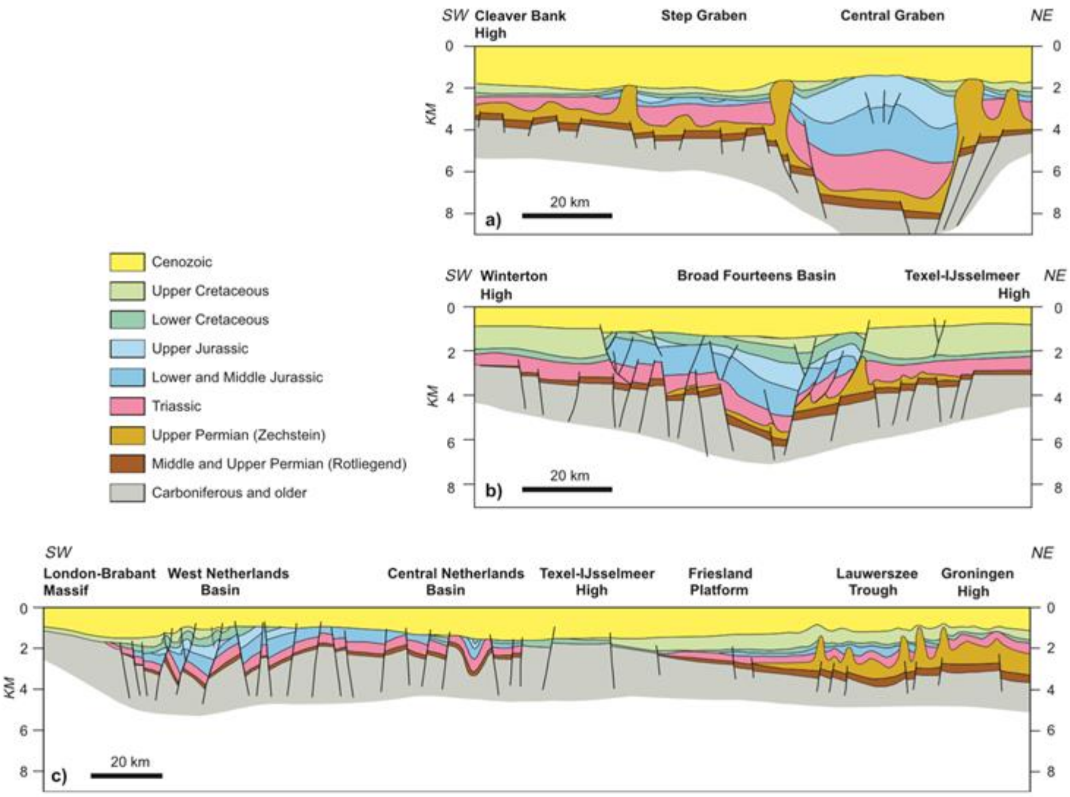


Figure 1: From de Jager, 2007: Cross-sections showing the different tectonic styles in the Netherlands. Late Jurassic and Early Cretaceous rift basins (West Netherlands, Broad Fourteens) exhibit complex structural styles with inverted and reversed faults. Salt pillars in the Central Graben flank the basin margins and are rooted by large offset faults. In the NE onshore, Carboniferous and Permian faults are detached from the shallower strata by the thick Permian rock salt interval.

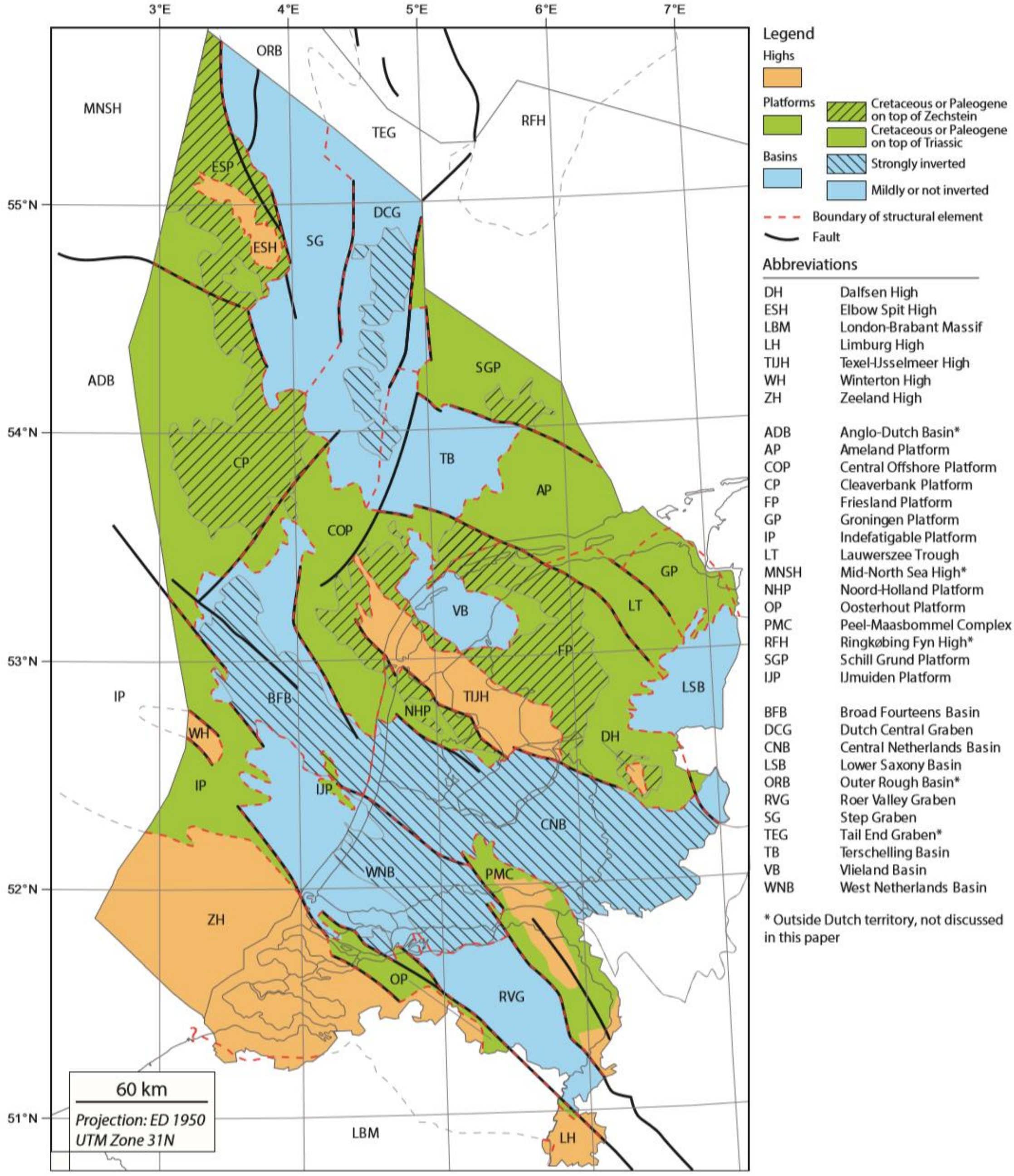


Figure 2: From Kombrink et al, 2012. Late Jurassic - Early Cretaceous structural elements of the Netherlands. The information from the border-regions is based on Best et al. (1983); De Jager (2007); Drozdzewski et al. (1985); Japsen et al. (2003); Langenaeker (2000); Lyngsie et al. (2006); Pharaoh et al. (2010) and Verniers & Grootel (1991).

2.2.1 Variscan structural elements (after Duin et al., 2006 and De Jager – 2007)

Many of the Mesozoic structural elements are rooted in structures that developed during the pre-Permian period. During this period three continental plates (Laurentia, Baltica, Avalonia and Gondwana) amalgamated into the supercontinent Pangea through closure of the Iapetus Ocean.

Figure 3 shows the Variscan structural elements map: Duin et al. 2006 distinguish the following elements:

- the Campine Basin (CB), Roer Valley Graben (RVG), Ems Low (EL) and the Cleaver Bank High (CBH) which have developed in response to Permo-Carboniferous wrench tectonics.
- The Brabant Massif and the Zuid-Limburg Block which evolved as highs and remained a high during the Mesozoic tectonic evolution.

During the Permo-Carboniferous many NW-SE to WNW-ESE trending fault systems have developed, outlining the above mentioned elements (among others Hantum Fault Zone - HFZ, Gronau Fault Zone - GFZ, Raalte Boundary Fault – RBF and Peel Boundary Fault - PBF). These faults have played a major role during the later Mesozoic period during which they were re-activated (both normal and reversed faulting). This is also visible in the orientation and demarcation of the Mesozoic basins and highs.

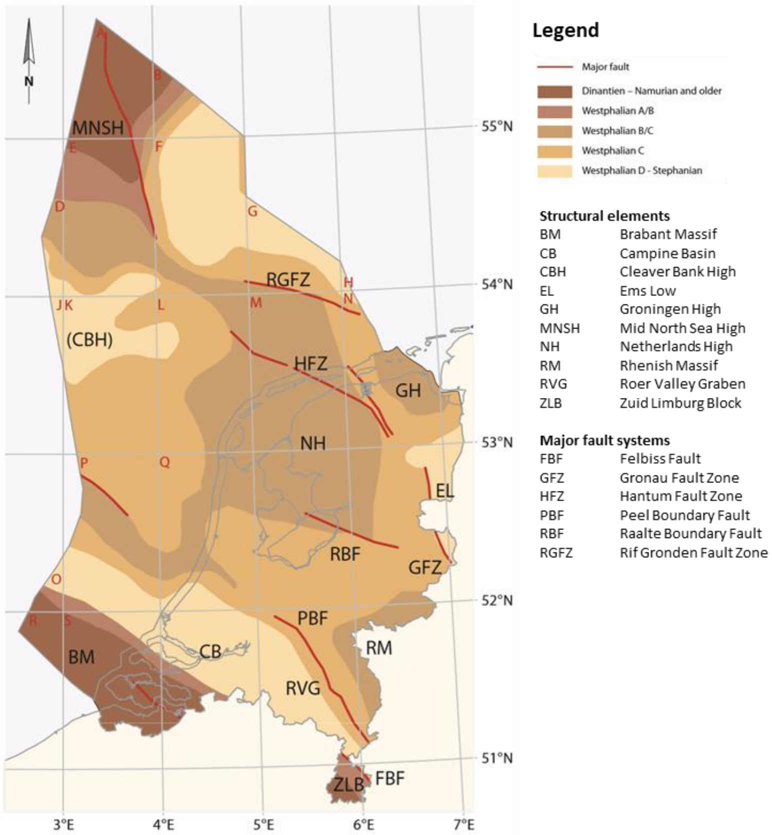


Figure 3: Development of the Variscan (Carboniferous and Early Permian) structural elements. After Duin et al. (2006)

2.2.2 Late Jurassic and Early Cretaceous structural elements (after Duin et al., 2006 and De Jager – 2007)

The main present-day structural elements were defined by the end of the Mesozoic. During the early Triassic, the North Sea area became influenced by rift tectonics as the Pangea supercontinent began to break up. This period was characterized by thermal uplift in the northern part of the Dutch onshore. Development of new faults and reactivation of older faults resulted in the tectonically induced emplacement of rock salt deposits in the underlying Permian strata (Zechstein Group) and the development of salt domes and pillars. Often these structures are aligned with the main fault zones and therefore align the main rift basins (e.g. Dutch Central Graben (Remmelts, 1995, 1996; ten Veen et al., 2012). During the Jurassic and Early Cretaceous several subsidence, rifting and uplift phases took place, resulting in major transtensional and extensional basins and grabens. These basins were geographically separated by (non-depositional) platforms and highs in between (see Figure 4).

Together these features define the present-day structuration of the Netherlands. The older NW-SE Paleozoic structural trend dominates while the Dutch Central Graben has a marked N-S orientation. Repeated reactivation of faults makes it difficult to determine sense of displacements (e.g. oblique, strike-slip). Local faults such as the Rifgronden Fault Zone seem to indicate dextral movements.

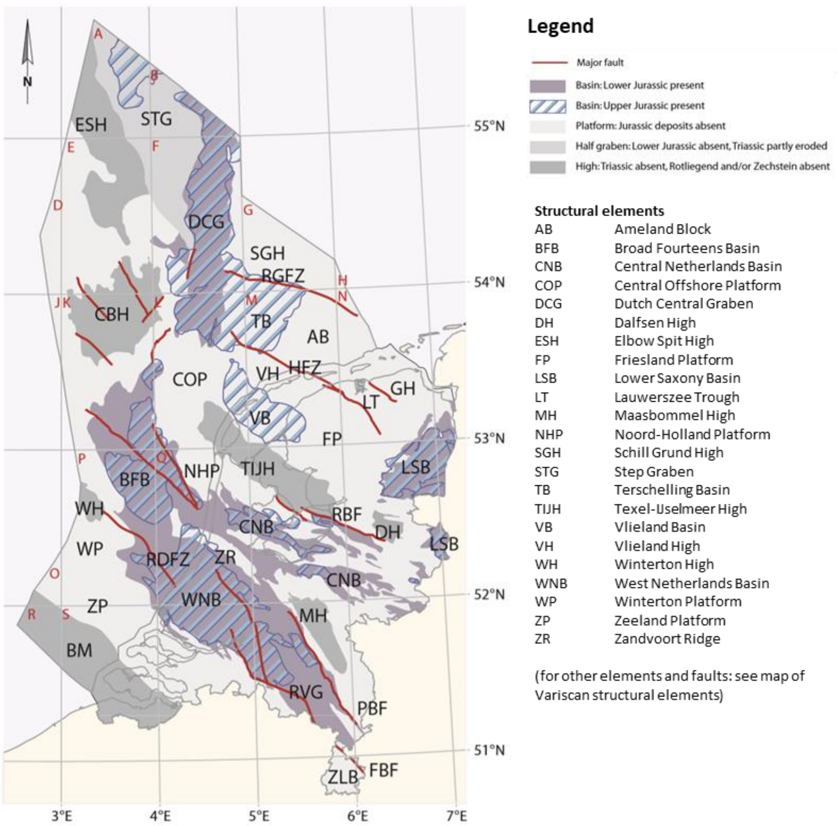


Figure 4: Development of Kimmerian (Late Jurassic – Early Cretaceous) structural elements. After Duin et al. (2006)

2.2.3 Late Cretaceous – Early Cenozoic structural elements (after Duin et al., 2006 and De Jager – 2007)

Rifting ended in the Netherlands during the Early Cretaceous and was followed by regional thermal subsidence in the Late Cretaceous. Towards the Paleocene the Alpine orogenic system began to develop which resulted in a compressional regime in the Netherlands. As a result, the boundary faults and internal faults of the Mesozoic rift basins (among others the Roer-Valley

Graben, West Netherlands Basin, Broad Fourteens Basin, Central Netherlands Basin, Dutch Central Graben) were re-activated and the basins started to invert. The main inversion axis are shown in Figure 5. The manifestation of basin inversion was strongly influenced by the presence of Permian rock salt deposits (e.g. flower structures in the south where no salt is present vs. detached faults in the northern parts of the Netherlands). Due to the sometimes huge uplift, hundreds of meters of Late Mesozoic strata were eroded. The amount of uplift differs per basin. In some cases the entire Cretaceous and Upper Jurassic intervals eroded.

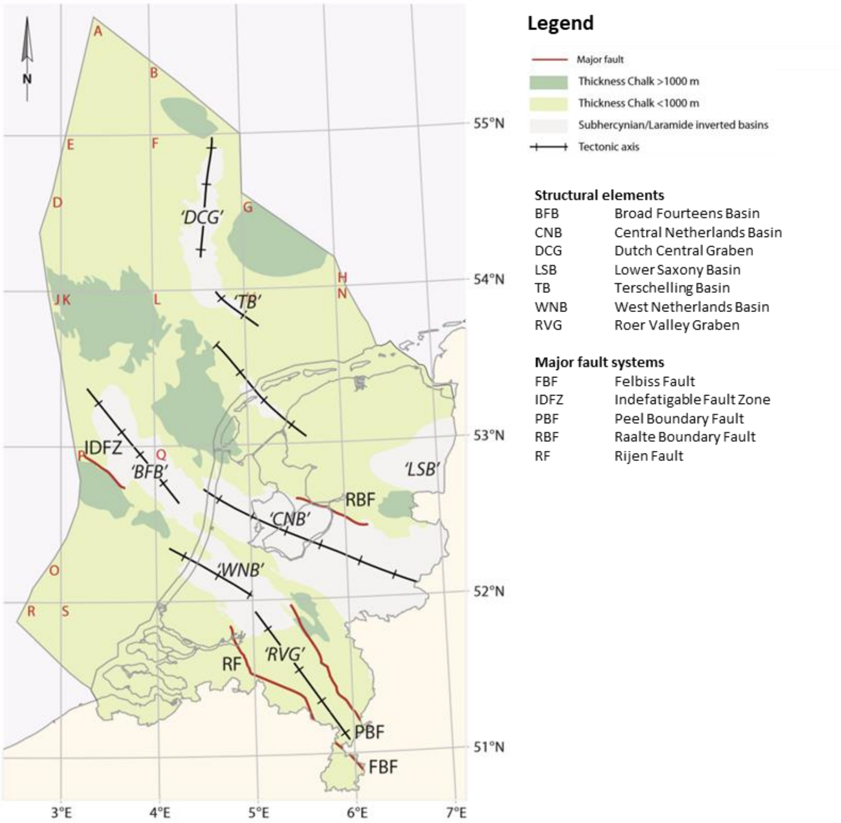


Figure 5: Development of Late Cretaceous – Early Cenozoic structural elements. After Duin et al. (2006)

2.2.4 Cenozoic structural elements (after Duin et al., 2006 and De Jager – 2007)

During the Cenozoic the Roer-Valley Graben was again influenced by strong subsidence as rifting took place in the adjacent Lower Rhine Graben (further to the south east in Germany). Occurrence of natural seismicity and earthquakes in the south-eastern part of the Netherlands indicate that this region is still tectonically active (mainly boundary faults of the Roer-Valley Graben). This area rises as a result of uplift in the Rhenish Massif (Germany). The rest of the Netherlands and Dutch North Sea slowly subsides. Main elements are shown in Figure 6.

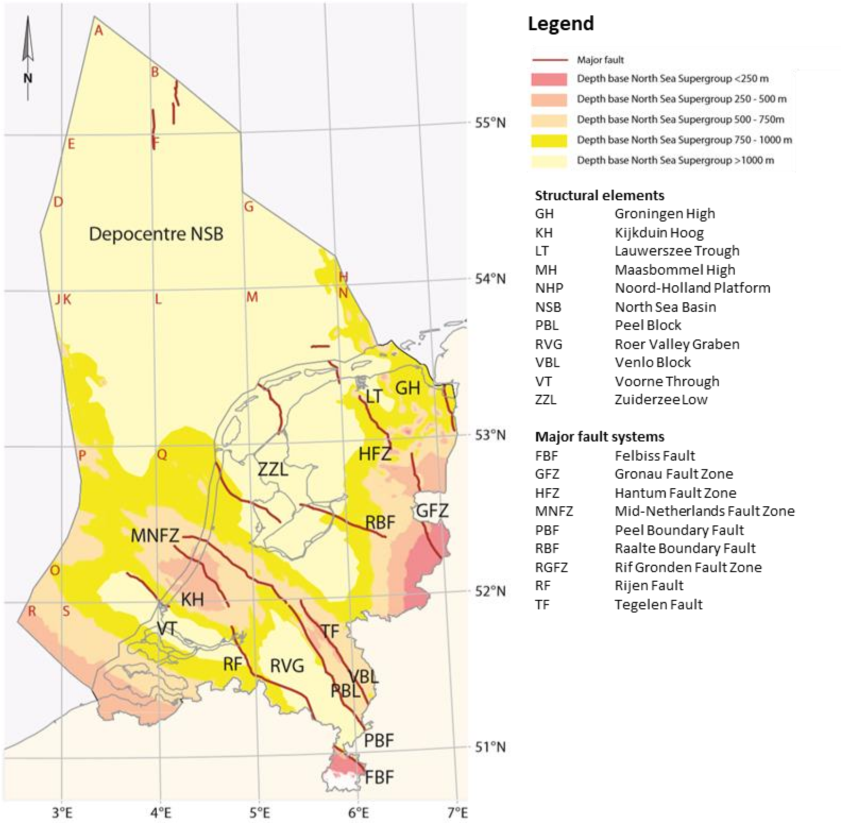


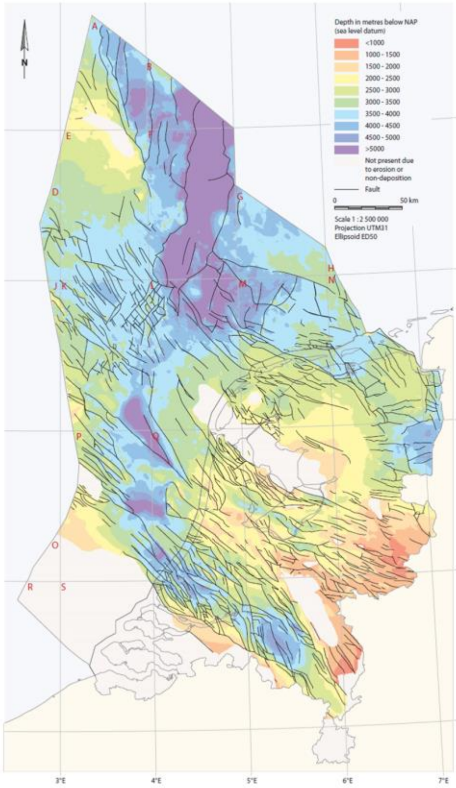
Figure 6: Development of Cenozoic structural elements. After Duin et al. (2006)

2.3 Fault patterns and characteristics (after Duin et al., 2006 and De Jager – 2007)

The main fault patterns and fault styles in the Dutch subsurface originate from the structural developments described earlier. As shown in the fault maps for individual stratigraphic intervals (Figures 7 – 10), the general fault orientation remained roughly NW-SE throughout the Late Permian to the Neogene despite changing tectonic regimes and rotations of the stress field. Following main trends are observed:

- Most faults and structural elements follow the Paleozoic NW-SE basement trends (e.g. Hantum Fault Zone, Gronau Fault Zone).
- A second NW-SE to ENE-WSW trend is observed from Early Permian tectonic phases.
- An anastomosing pattern of dominant WNW-ESE and NNW-SSE, and secondary N-S and E-W directions exists in the West Netherlands Basin.
- A N-S orientation exists along the Dutch Central Graben in the North (Jurassic rifting)
- NW-SE and NE-SW fault trends at Rotliegend level in the northern sector of the Broad Fourteens Basin and on adjacent platform areas, with secondary faults trending WNW-ESE and N-S
- NW-SE, NE-SW and WNW-ESE trends in pop-up structures (Late Cretaceous and Early Cenozoic reactivation) on the Cleaver Bank High
  NNW-SSE and ENE-WSW trends in the north-east of the Netherlands (deviating from the dominant WNW-ESE trend towards the west)
- E-W trending faults are common in the Lower Saxony Basin

De Jager et al (2007) mention that present-day fault trends cannot be linked to preferentially re-activated orientations. These faults are difficult to interpret in terms of paleo-stress directions. It is not possible to determine the sense and amount of displacement during the various evolutionary phases of individual faults due to accumulation of many re-activation phases and lack of reliable indicators for lateral displacement, etc.



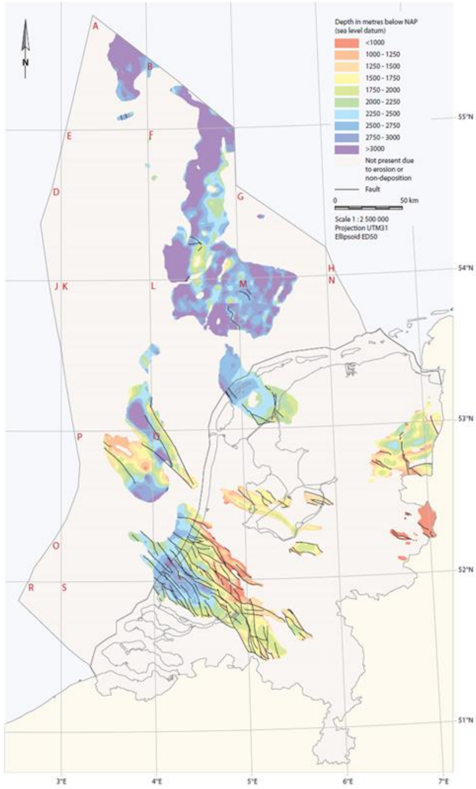
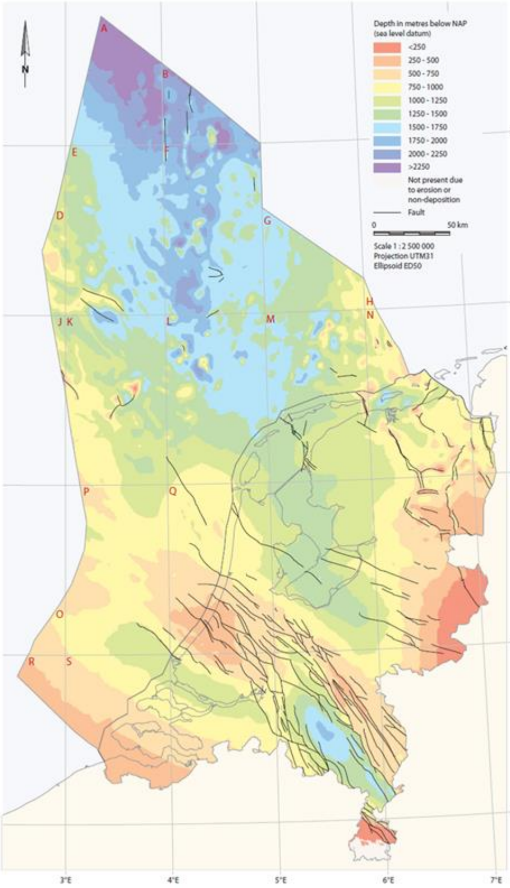


Figure 7 (left): From Duin et al 2006. Major regional faults and depth map of base Zechstein Group (Late Permian)
Figure 8 (right): From Duin et al 2006. Major regional faults and depth map of base Schieland, Scruff and Niedersachsen Groups (Late Jurassic)

Finally, the map on the next page shows the most shallow (Pleistocene and Holocene) faults. These faults are active at present (registered quakes and movements) or can be considered as likely active (movements during recent geological history).



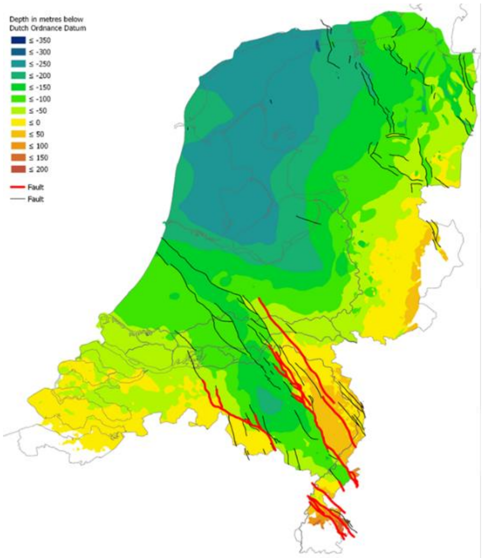


Figure 9 (left): Major regional faults and depth map of Base Lower North Sea Group (Early Cenozoic)
Figure 10 (right): Mapped faults at Pleistocene (black lines) and Holocene – surface levels (red lines. The red faults are proven to be active to date.

2.4 Data quality, origin and publication

The Geological Survey of the Netherlands (TNO) carried out several major mapping projects over the last decades in order to better understand the depositional history and structural geology of the shallow (0 – 500m) and deep (>500m) subsurface of both on- and offshore areas. For reasons of economic value (oil/gas), legal status (Mining Act) and data origins (E&P industry seismic and boreholes vs. geological Survey shallow drilling programs) the shallow and deep subsurface have traditionally been addressed by separate mapping programs. In the past few years both programs are gradually being merged into one consistent 3D model.

2.4.1 Deep subsurface (500 – 5000m) (after Kombrink et al. 2012)

In 2004 an overview of onshore mapping was published as a result of many mapping projects carried out since 1985 (TNO-NITG, 2004). First maps for the offshore region were established during 2004 – 2006 and finally published in Duin et al., 2006. A comprehensive update and integration of both the onshore and offshore has been published in Kombrink et al., 2012. Since 2012, the 3D mapping of the deep subsurface has been updated on a two-yearly basis; the latest version (DGM 5.0) was published in 2019.

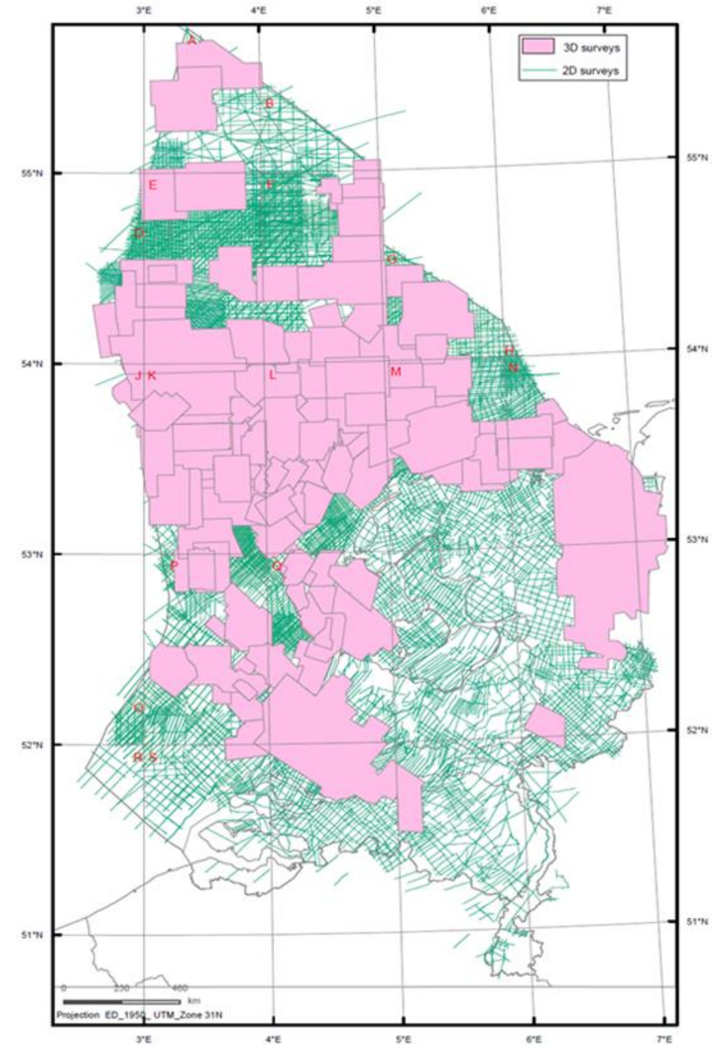


Figure 11: Overview of 2D and 3D seismic surveys used for the national deep subsurface mapping programs (stratigraphic horizons and faults)

3D seismic surveys are the main source of information for mapping the deep subsurface stratigraphic horizons and faults. 2D data are mainly used in areas that are not prolific for oil and gas (see Figure 11). Well logs and cores from several thousand exploration boreholes are used to identify the stratigraphic intervals and to convert the interpreted data from two-way-time to depth domain. Faults are interpreted from vertical seismic in- and crosslines resulting in a representation of fault sticks. The sticks are modelled into surfaces. In some key areas both fault surfaces and stratigraphic horizons are combined into a fully consistent 3D structural model.

Uncertainties and confidence levels are largely determined by the quality of seismic data (e.g. 2D vs 3D, decreasing resolution with depth) and reliable time-depth conversion data. Horizontally and vertically, mapping errors range between tens to several hundreds of meters. Interpreted 3D seismic lines are typically spaced at 250-500 m intervals. For 2D lines these distances can be significantly larger while the images may suffer from data acquisition and processing artefacts. The vertical precision largely depends on the presence of borehole data to tie the stratigraphic horizons.

Besides the national and regional maps and models, faults are studied in high detail in specific study areas (e.g. reservoir models for gas fields, local hazard studies). In these cases high levels of detail can be obtained from 3D seismic attribute analyses which reveal faults at sub-seismic resolutions (Figure 12). These results are often treated confidentially.

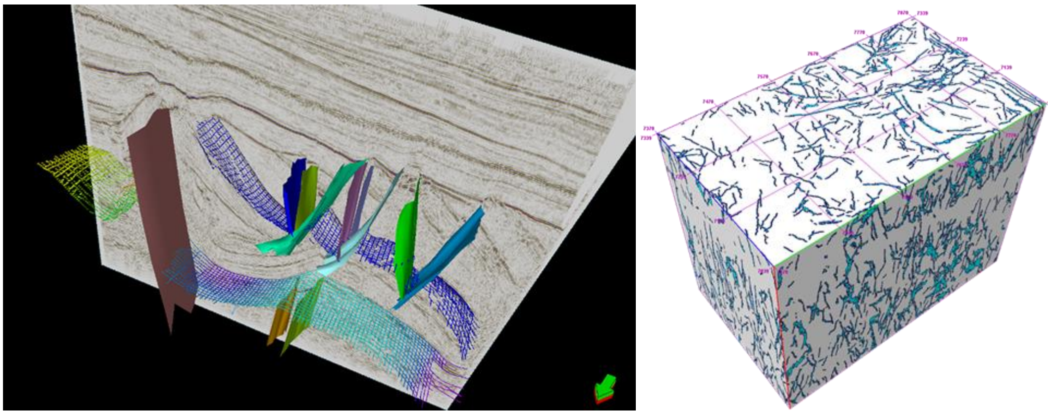


Figure 12 (left): Example of fault surfaces and horizons interpreted from 3D seismic data; (right): Example of detailed fault data obtained from 3D seismic attribute analysis

2.4.2 Shallow subsurface (0 – 500 m)

The mapping of the shallow subsurface already dates back to some 100 years ago. Since 1999 the traditional hand-contoured mapping has been replaced by digital 3D modelling techniques which have resulted in a 1:250.000 national coverage for over 20 Cenozoic formations (DGM v2.2; see Gunnink et al., 2013) and even greater detail for the Pleistocene and Holocene formations and members in the upper 30-50 meters (GeoTop v1.3; see Stafleu et al., 2011).

The faults in the shallow subsurface are observed from surface observations (only the currently active faults) and shallow seismic sections. For the majority of the country however, faults have been inferred from correlation and interpolation of borehole data (Figure 13). This has been possible given the very high drilling density as shown on the map. Observations and models from deep subsurface seismic data have assisted the identification of shallower faults.

Contrary to the deep subsurface, faults are represented as vertical planes in the shallow subsurface. Towards the surface level, the faults typically steepen. As the vertical interval (ca. 500m) is relatively small, the inclination is hardly noticeable at the used mapping scales. Consequently the shallow and deep sections of faults are disconnected and may show minor spatial discrepancies. Current mapping programs (e.g. the H3O project) are focusing on solving these issues by modelling one fault surface for the entire depth range (Figure 14).

Figure 13: Coverage of boreholes used for the shallow subsurface digital model of the Netherlands (DGM v2.2). The GeoTop models uses over 100.000 boreholes for the upper 30-50 meters

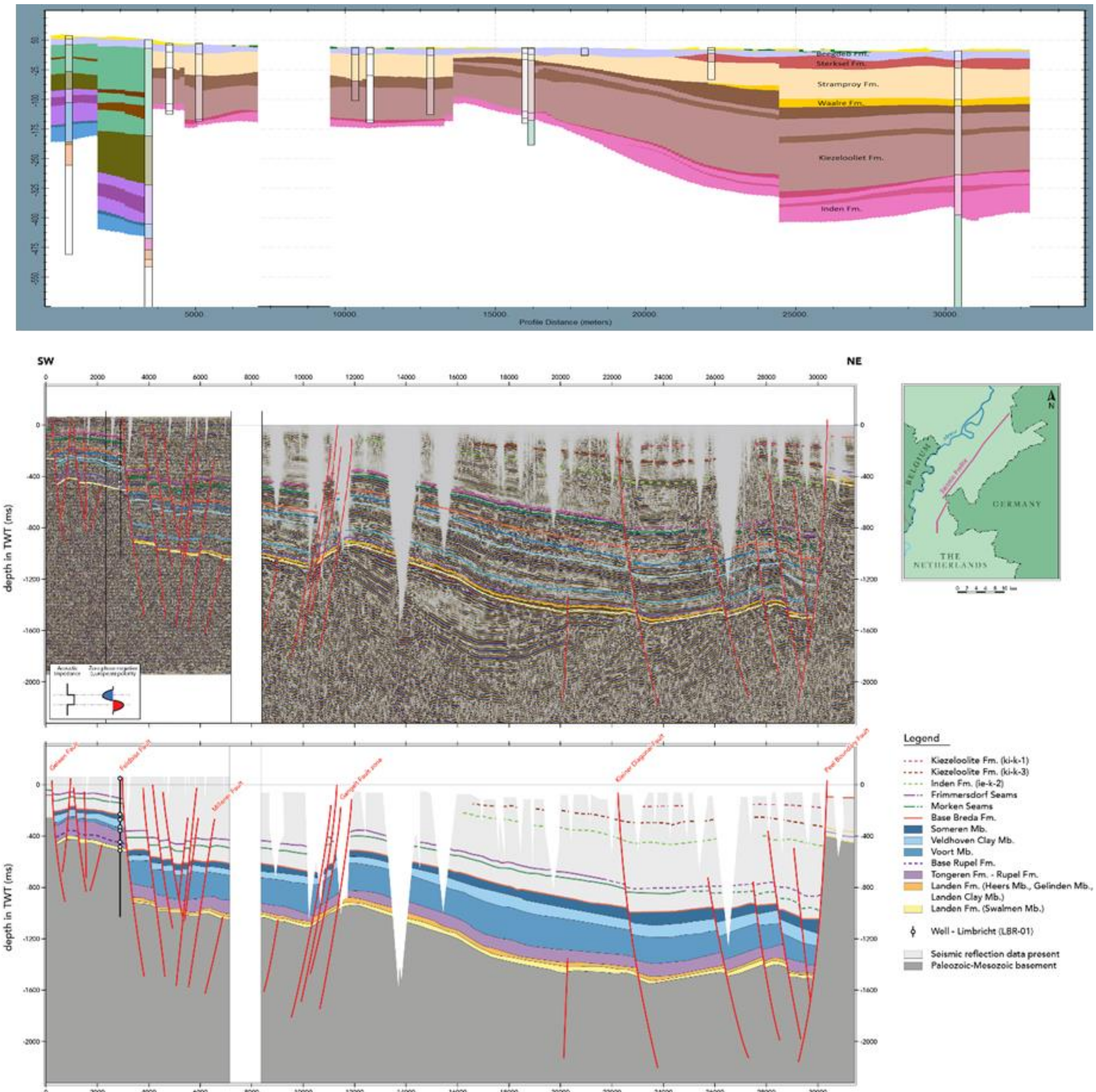


Figure 14: cross-sections showing the difference between mapped faults in the shallow and deep subsurface domains. The deep subsurface faults (lower two sections) cover the interval below 500 m. In this interval, faults clearly appear as inclined surfaces in seismic profiles. The shallow subsurface faults (upper section) provide more detail in the upper 500 m. Here the faults are represented as vertical surfaces. The sections are taken from the south-eastern part of the Netherlands (Limburg) where active faults are also visible at surface level.

2.5 Local fault relevance and application

2.5.1 Natural seismicity

The southeastern part of the Netherlands is known for the occurrence of small to moderate natural earthquakes in an area extending into Belgium and Germany. The largest event registered to date is the M 5.8 earthquake of 1992 under the city of Roermond.

2.5.2 Induced seismicity (gas production, geothermal)

Especially in the northeastern part of the country, many compaction-induced earthquakes have been registered in deep faults at the level of Permian natural gas reservoirs. Despite moderate magnitudes (max. M 3.6), these earthquakes have caused significant damage due to relatively high peak ground accelerations that result from the shallow depths of earthquake hypocenters in combination with amplification effects in the weaker soil.
Two geothermal systems in the Roer Valley Graben used to produce from faulted and fractured carbonates of Carboniferous age. Production was put on hold after minor seismicity (≤ M1.7) was registered in the vicinity of these systems. Thus far, no seismicity has been recorded near other geothermal systems, most of which are mainly producing from permeable reservoirs of Permian to Cretaceous age.

Seismicity associated with onshore gas production has led to more stringent legislation in order to reduce seismic hazards and risks for all deep onshore subsurface activities, including underground natural gas or CO2 storage and geothermal energy production.
As part of the subsurface license procedure, operators are now required to submit a production (oil/gas, geothermal) or storage plan for their field/system, consisting of a seismic hazard and risk assessment. In these assessments faults play an important role and the following aspects are included: fault dimensions and possible hydraulic connection to the basement, presence of faults in the vicinity of injection wells and orientation of faults in relation to the stress field. A national fault database could be a helpful tool to support these seismic risk assessments.

2.5.3 Groundwater

Faults are important for groundwater extraction and -flow. Especially in the southern part of the Netherlands, groundwater seepage at the surface occurs when the groundwater encounters impermeable clay layers in fault zones. Faults play a role in the delimiting groundwater aquifer as well.

2.6 Fault data included in HIKE fault database

For the Netherlands, all fault data from the deep and shallow national geological mapping programs has been included as one dataset (Figure 15). The faults for the deep subsurface are delivered as 2D intersection lines with the main stratigraphic horizons. For the shallow subsurface, faults are represented as (near) vertical structures due to the limited inclination in this interval and the limited thickness, which minimizes the misfit.
The main faults, fault systems and fault zones are classified according to the generic semantic framework in HIKE. This includes a correlation link with the faults in neighboring countries (in particular Germany and Belgium). Fault attributes are still mainly limited to geometric aspects (length, strike, dip, surface area), fault type (normal, reversed, etc.), timing of fault activity (youngest surface affected) and observation/evaluation method (seismic interpretation, inferred modelling, etc.).

The data are being applied to an example use case for geothermal seismic hazard assessment. Furthermore the data are tailored to highlight the structuration of the Dutch subsurface.

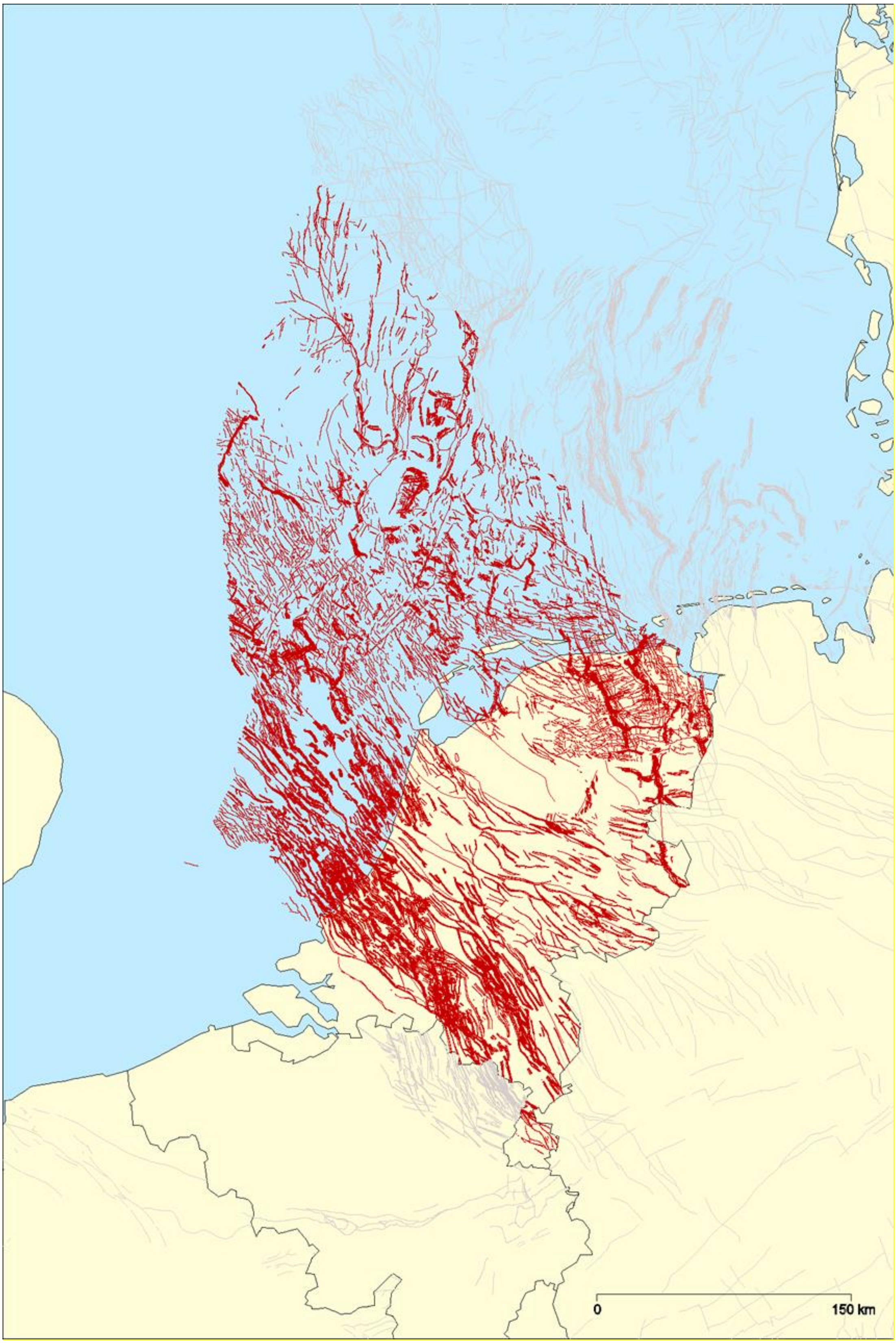


Figure 15: Location of mapped national faults and fault systems in the Netherlands contributed to the HIKE-Fault Database, reference depth Upper Permian, base Zechstein Group.

2.7 References

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3 AGS – ALBANIA

3.1 Introduction

General information about the Albanides

Albania lies in the western part of the Balkan Peninsula. From the geomorphologic point of view, the Albanian territory is represented by different types of relief such as plain, hilly, and mountainous. The hilly and mountainous terrains in their entirety appear broken. The causes of the formation of rugged and extremely rugged terrains are mostly related to the numerous tectogenic movements that have affected the Albanian territory at different times. First we are describing the structural elements of the Albanides and their position in the Dinarido-Helenic arc. Albania's geological structure is represented by rocks that range in age from Paleozoic to Quaternary. Albania is part of the "Alpine Mediterranean" wrinkled belt in the Dinarido - Albanido - Helenic arch. The Albanides express the wrinkled ensembles of different rock types on both sides of the Shkodra-Peja normal fault. In most sectors of the Albanides the formations (deposits) have discontinuities and the absence of these formations is clear by the lack of facies in the stratigraphic sections, the existence of transgressions and structural discontinuities. There are only a few sectors where the formations are continuous. The transition from Dinarides to Helenide takes place in the territory of Albania, where most of it enters the northern part of Helenides, a territory which Albanian geologists have named with the term "Albanide" (Peza L. 1967). Albanides as a territory, in recent years, based on the names and new concepts of global tectonics, constitute a tectono-stratigraphic unit. Based on numerous studies carried out over a period of nearly 70 years as geological surveys of various scales such (1: 500; 1: 1 000; 1: 2,000; 1: 5,000; 1: 10,000; 1: 25 000; 1: 50,000; 1: 100,000; 1: 200 000), altered and with geophysical works (seismic, gravimetry, electrical sounding, etc.), the zones and subzones that are evidenced in Albanides correspond to different microblocks such as: a) The eastern part of the Adria plate (Apulia), b) The western part of the Korab - Pelagonian micro continent.

- The distribution of faults

The tectonic zones are separated from each other by major Tertiary tectonic contacts which are quite well traced and mapped in the field during geological surveys. These tectonic zones differ from each other due to their different structural characteristics. Albanides are divided into two basic groups:

A) External Albanides, which include:

a) External Western Zones

   1) Sazani
   2) Periadriatic Basin
   3) Ionian
   4) Kruja

The representation of these areas from the lithological point of view begins with the Triasic Evaporites, the Triasic-Eocene carbonates and the Oligocene-Miocene flysch. These deposits are affected by paraeocenic orogenies.

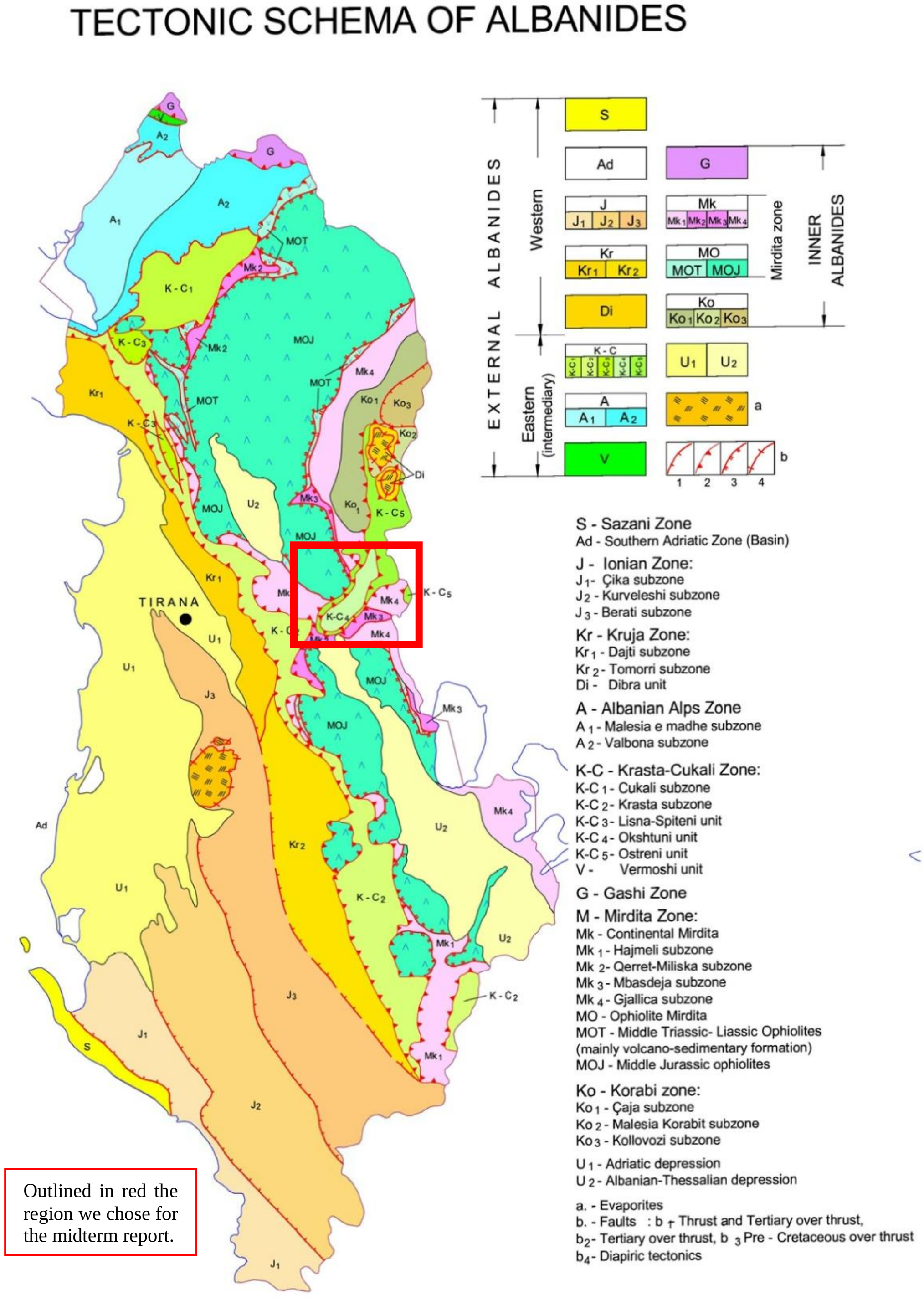
b) External Eastern Zones

   1) Krasta – Cukali

2) Albanin Alps
3) Ostren Unit
4) Vermosh Unit

In contrast to the western external zones, flysch deposits in the eastern external zones begin in the Late Cretaceous.

B) Internal Albanides, include tectonic zones such as:
   1) Mirdita
   2) Korabi
   3) Gashi



Outlined in red the region we chose for the midterm report.

A common feature of these areas is the size of the Jurassic and Triassic-Lias ophiolitic deposits and the continental deposits (bauxides) affected by strong tectogenesis occurring during the Jurassic, Cretaceous and Tertiary. The presence in these areas of sedimentary deposits, their metamorphism, underwater leaching, transgressions and structural inconsistencies clearly shows the activity of the above mentioned tectogenesis.

In the territory of the Albanides, is documented the presence of two cycles of tectogenesis:

- Hercynian orogeny
- Alpine orogeny

<u>Hercynian orogeny</u>

The significant structural elements of this cycle are found in the tectonic zones of Korab and Mirdita. The beginning of this orogeny coincides with the Late Paleozoic and is expressed in the transgressive extension of reddish sandy conglomerates over the Lower Paleozoic deposits. Further work is required regarding its intensity.

<u>Alpine orogeny</u>

This one is quite well documented in both the Internal and the External Albanides. At the beginning of the Alpine cycle, occur important tectonic structuring under conditions of a retreating geodynamic regime preceded by Alpine orogeny. (Fig. No.1) The study area, where the authors of this project have carried out research and mapping on a scale of 1: 25 000 coincides with the formations of the Upper Triassic to the Neogene. Based on this fact, the structures (basin and platform structures) will be named from this age towards the younger ones. In the study region, the formations that build the surface geology are given in the map below. (Fig. No.1)

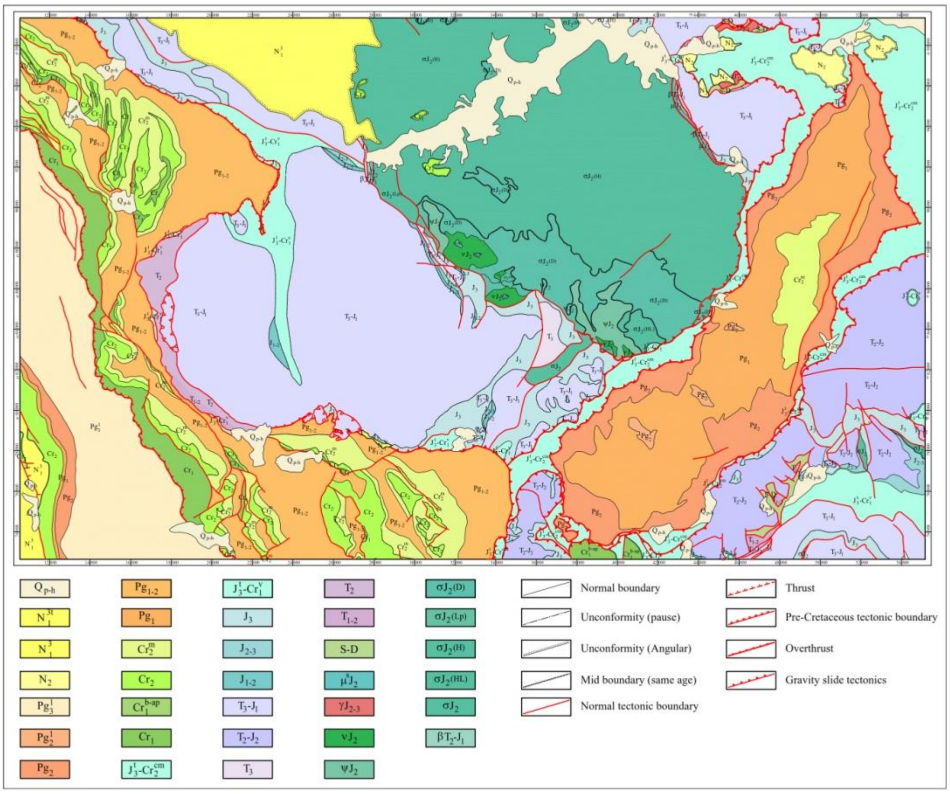


Fig. No.1 Geological map of the region under study

Period (Age of structure formation) (Fig. No.2)

During the Lower Triassic-Jurassic period Z.T.K.C formed with Z.T.M and Z.T.K a joint bend of a shallow sea where neritic carbonate formations (platform structures) were created.

In the upper and middle Liasik, Doger - Malm occurs a deepening of the basin and in the conditions of a pelagic sea occurred the deposition of pelagic sediments (basin structure). In addition to the deepening of the basin, begins the differentiation of tectonic zones. At this time, due to the oceanic expansion with the passive continental edges with low speed of expansion, occurred the expansion of Mirdita and the formation of western-type ophiolites (MOR) representing associations of the slightly poor ultramafic plutonic gabbro sequence of the troctolite type and the volcanic one with MORB type basalts. From this moment on, the basin leads a troubled and very active life, where the sides of the carbonate platform formations are involved by a whole system of tectonics with a vertical displacement character as a result of the force aplied by the intrusion of the ophiolites on these formations.

During the Jurassic-Cretaceous period in the Z.T.M the sea advanced eastward, forming in this case the formations of the early flysch transgressive series on the carbonate and magmatic bases. During this period both carbonate formations (platform structures) and pelagic ones (basin structures) placed transgressively on them are affected by numerous movements of a vertical character, giving these formations the Horst-Graben nature.

In the Late Jurassic (Titonian) after the sedimentation of radiolaritic silicaries (basin structures) at the head of the ophiolitic sequences continued the tectonic displacement of the ophiolites, their fragmentary elevation and partly of the continental periphery (platform structures); the formation of a very accidental Horst-Graben topography and the partial closure of the oceanic basin of Mirdita, the intensive leaching of ophiolitic and partly continental elevated sectors and the deposition in the basin sectors of the ophiolitic melange-colored formation, after homogenous ophiolite melange from the flysidal conglomerate-sandstone-marl formation of the Upper Titonian - Valanghian (Hoterivian) (basin structure).

During the Late Eocene - Oligocene (basin structure) due to the convergence of lithospheric plates occurred major collision, complete closure of the Mirdita Ocean and the overthrust of surrounding ophiolites and terrestrial terrains to the westernmost continental terrains, accompanied by sedimentation of the Piggy type extension.

During this period we have strong tectonic movements, a combination of vertical and horizontal forces that make it possible to raise areas in the form of a plateau, which move from east to west. In continuation of this tectonic process, other powerful tectonic impulses which constitute the last strong tectogenesis of the Eocene close this cycle, giving this sector the form it has today.

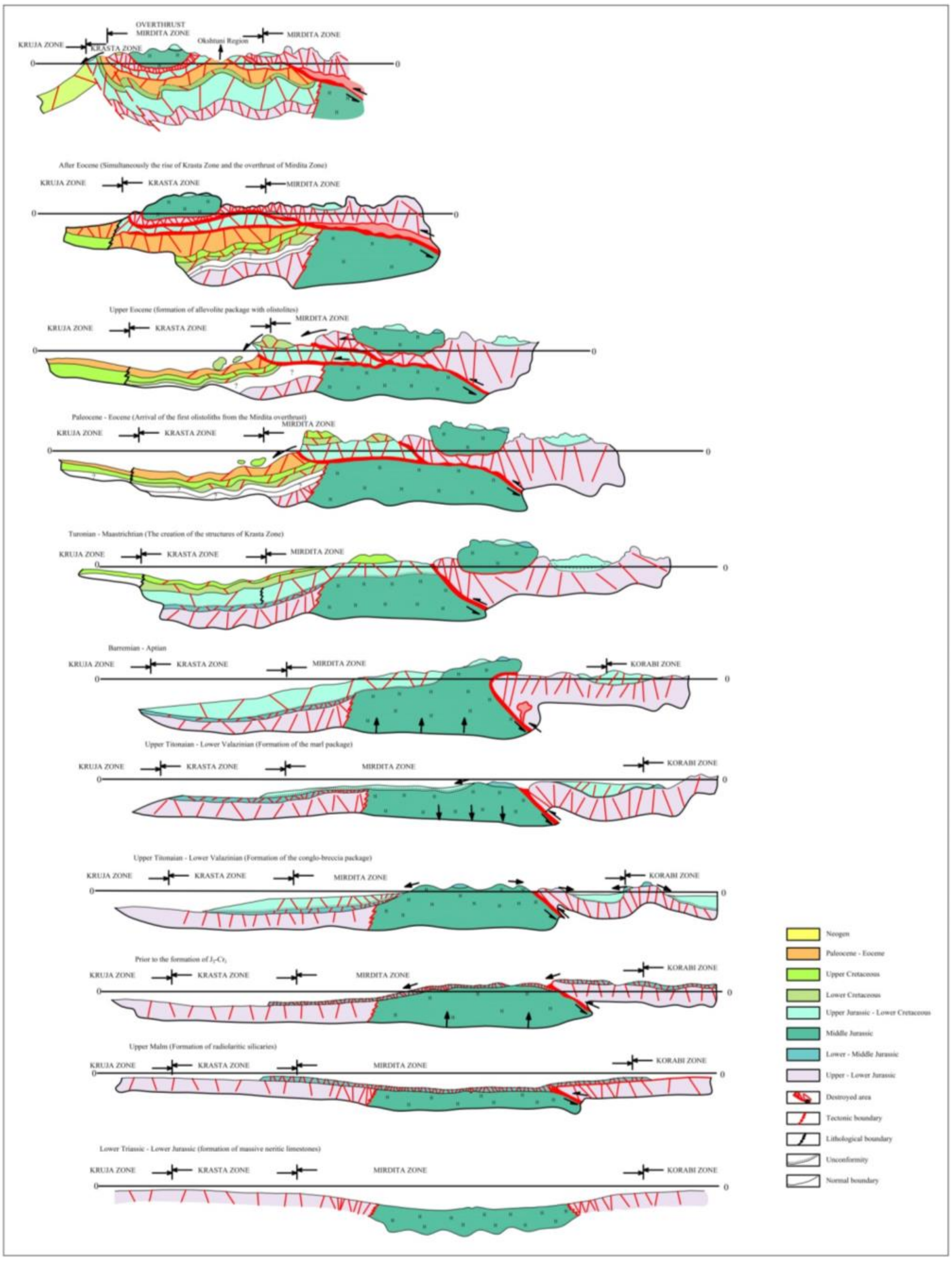


Fig. No.2 Ages of creation of basin and platform structures of the region under study

3.2 Structural Elements

For the tectonic zoning that is expressed by the separation of zones or structural sub-zones, several criteria have been used such as: ***Facial, structural, age of tectogenesis, intensity of magmatism, relationships between different tectonic units, etc.***

The map below (Fig. No.3) shows the structural elements of the current geological and tectonic framework of the region taken in study. The term 'structural element' is the name given to regional structures with a history of landing, tectonics, uplift and erosion over a period of time. The determination of the structural elements of this region has been done on the basis of several years of work done in the field by the authors of this project and other authors. A platform structure (S.P.M.G) has been defined in this sector, that sector which is characterized by formations of neritic facies and lack of Upper Jurassic and Lower Cretaceous formations. Basin structural elements are characterized by the presence in them of pelagic formations. In this region, with this name are named all formations starting from those of the Jurassic border to those of the Middle Eocene. Here we have the presence of these tectonic zones:

1. Mirdita (Z.T.M)
2. Krasta – Cukali (Z.T.Kr)
3. Kruja (Z.T.K)

This sector is built from the formations of three tectonic zones according to the following map.

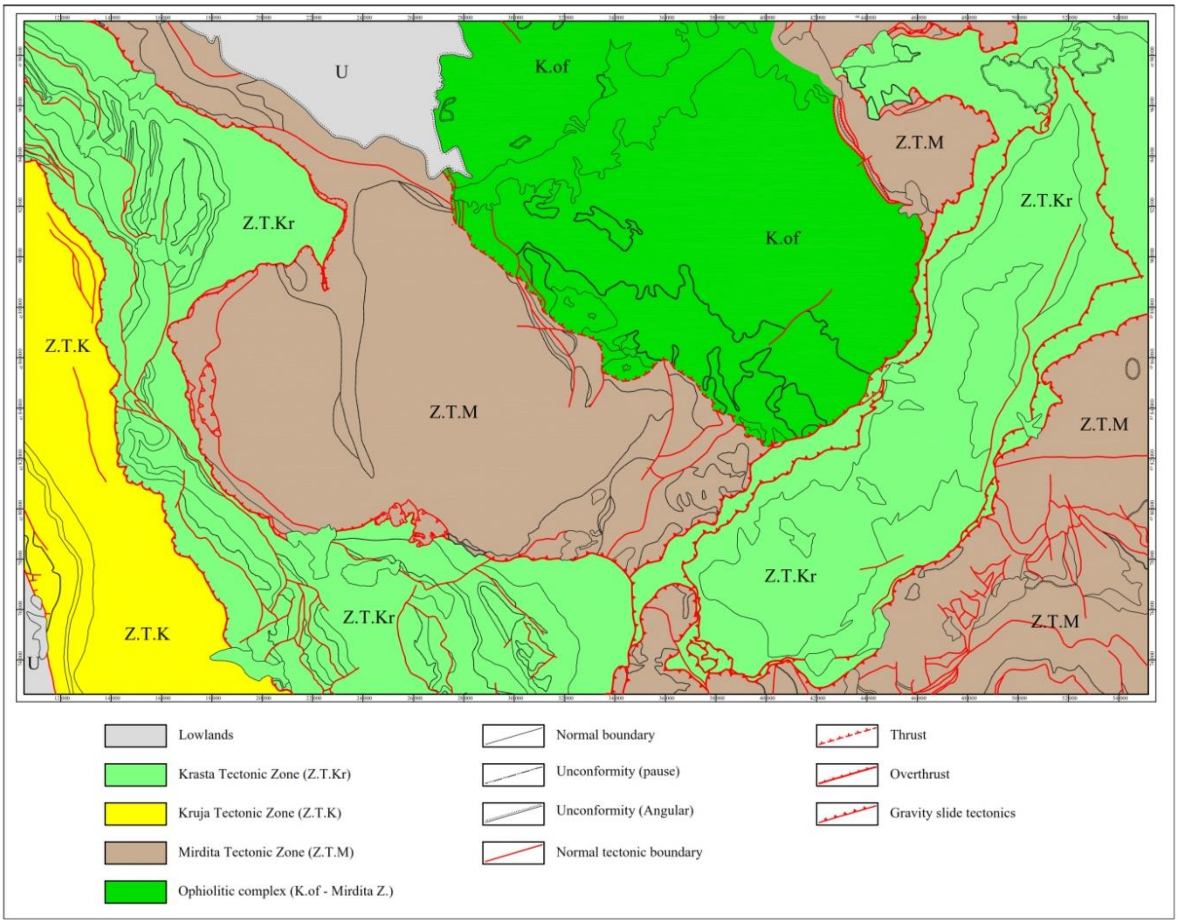


Fig. No.3 Geological - tectonic map of the region

1. **Mirdita Tectonic Zone (Z.T.M) –** It occupies a large part of the territory of this region and is bordered on the East by the tectonic zone of Korab, with which, it has complicated relations due to detached tectonics. For the most part it borders with Krasta - Cukali zone, with which there are tectonic relations with a thrust to overthrust character, this is emphasized in their western contact. Based on the facial criteria in this area, the ophiolitic subzone of Mirdita and the carbonate subzone of Mirdita have been singled out.

Ophiolitic Subzone of Mirdita – It builds the central part of (Z.T.M) and occupies most of its surface. In most of the range it is tectonically bounded by carbonate rocks of the carbonate subzone, in particular sectors it contacts tectonically with the Early Titon-Cretaceous flysch in the flysch tongue. The ophiolitic formations in our sector are represented by the ultrabasic rock formation that builds the lower and larger part of the ophiolitic section and consists of:
a) tectonite ultrabasic rocks (rare dunitic tectonite harzburgite) that consitute most of ultrabasic rock crosscut the bottom of it
b) ultrabasic cumulate rocks (dunitic, harcburgitic, lercolithic-verlitic cumulates of plagiarized, pyroxenitic, troktolitic ultrabasics). The structural relationships of ultrabasic rock tectonics with those cumulatives are of a normal and transgresive nature, however the problem of their dividing boundary and structural relations is the subject of more in-depth special studies in the future. The thickness of this formation is accepted from 2-3km to 10-14km.
The detachment tectonics in the ophiolites of the Mirdita zone are quite developed. In addition to the longitudinal tectonics, with dinaric extension, with thrust and overthrust nature, mainly in the southwest-west direction, there are also longitudinal and northeastern fractures of the type of normal detachment, upward placement, and even overlaping. Many of the faults are of pre-Cretaceous age. (Photo No. 4)

Photo Nr. 4 View of the fault plane with strike 295° and dip angle 70°

From the structural point of view, the ophiolitic subzone is characterized by the extensive development of folded structures and detachment faults; predominates the afromeridonal extension of folded structures and detached faults; folded structures in almost-transverse extension, transverse flexion, and almost-transverse detachment are less frequently observed. The ophiolitic subzone has thrusting tectonic relations with the periphery, up to the overthrusting through afrovertical tectonic faults with the peripheral carbonate subzone which apparently relate to the phenomenon of ophiolite obduction in the age range of the Jurassic-Cretaceous border. (Photo No.5). The structural elements of the tectonic planes are as follows: strike 40° and dip angle 35° - 45° - 55° - 69° - 70°.

Photo. no.5 View from tectonic contact with thrusting character between ultrabasic rocks and Triassic carbonates.

Carbonate subzone of Mirdita

This subzone builds the peripheral parts of the Mirdita zone and lies as a carbonate belt to the west of the ophiolites. The old carbonate formation Triassic Upper - Lower Jurassic participates in the construction of the Mirdita carbonate subzone. Above the carbonate formation follow with slight or normally stratigraphic and structural inconsistencies, the flyschoid formation and the ophiolitic mixture (melange) that are usually stored in the nuclei of syncline structures. The thickness of the carbonate formation, for this sector, is constituted of neritic facie that goes up to 1000m. In the study area, neritic carbonate formations are part of the Hajmeli tectonic subzone. Folded structures and detachments are widely developed in

this sub-area. Detachment faults are one step away from each other (observed in the field) 50 - 70m. In general, the structural elements of tectonic planes in this case have an strike of 230° and dip angle 30-35°. These faults are caused by ophiolite (intrusion) emergence processes during the Middle Jurassic. At the same time after the compression phase these faults are highly activated. The geological structure of the Hajmel subzone is quite complex. To the west it is branched over the flysch of the external zones, mainly of the Krasta-Cukali zone. (Fig. No. 6)

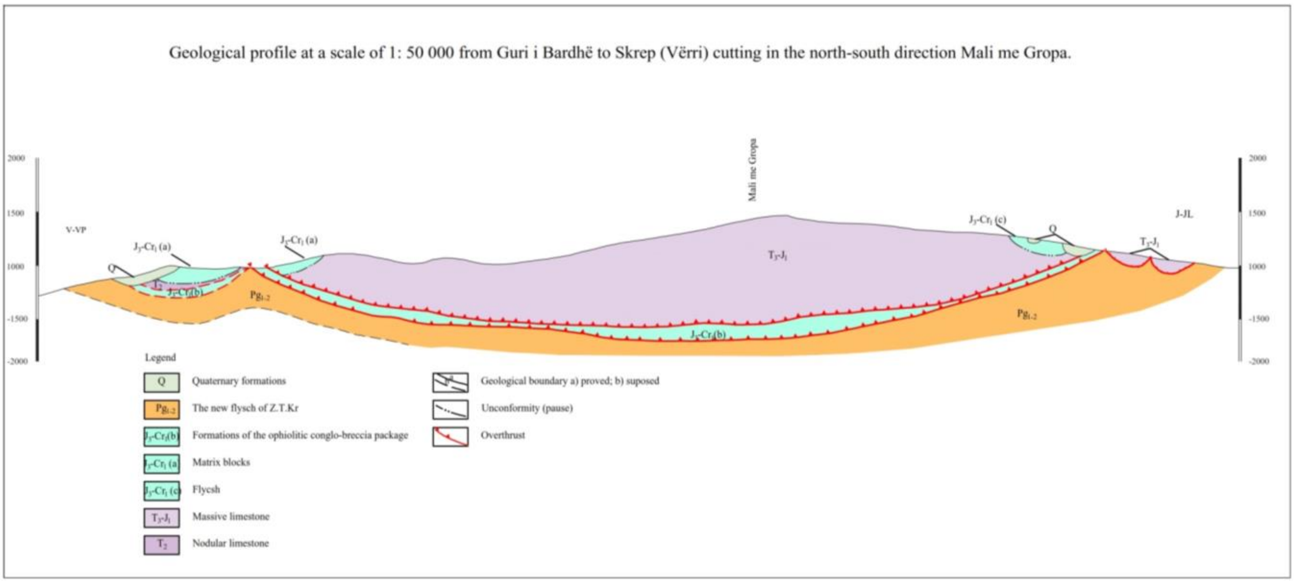


Fig. No. 6 Geological-structural section showing the nappe character of Z.T.M formations on Z.T.Kr formations.

This border in large regions is presented with pronounced oscillations, which supports the interpretations of the pronounced thrusting nappe character of the Mirdita area. In the Hajmel subzone there are numerous examples of evidence of sinedimentary tectonics as at Triassic levels as well as the Jurassic levels (Godroli 1992, Hoxha E. 1996, Kodra, etc. 1994). Sinsedimentary listric Paleo-Ruptures, sliding of blocks and their rotation during sliding have been documented in the sector of Derstiles, Stavec, Biza, etc. (Godroli 1992, Hoxha E., etc. 1996). In most cases as a result of later suppressive tectonics, which occurred during the later Jurassic, listric paleo-ruptures have shifted to reversed faults to overthrust which has complicated the structure of these regions. The processes of thinning of the continental crust (continental rifting) are assumed to be related to many subcontinental mantle diapiric outcrops. In the subzone of Hajmeli, are distinguished a series of folded structures such as the anticline structures of Mali me Gropa, etc. (Photo. No.7)

Photo No.7 View of the faults in the carbonate frame of Z.T.M.

In general, the afromeridional orientation is observed and the structure is extremely folded and is characterized by a displacement of its axis towards an inverted fold with western vergence. This has come as a result of the relocation following the restructuring of zones from east to west.

2. Tectonic zone of Krasta - Cukali (Z.T.Kr)

It is one of the tectonic zones that make the transition from the internal to the external zones. In the study area, we have the tectonic unit of the Krasta subzone which includes the territory where the carbonate-terrigenous formations are spread west of the Triassic-Jurassic carbonate framework. In the north, it has its origins from the village of Çerenec where the formations of this unit build the so-called flysch tongue and the western part of the zone we studied; it lies Q.Shtamë, Cudhi - Bruz - Q.Mollë - Fag - Benë - Labinot, mountain and plain, in Krasta e Madhe. A branch of this subzone is the corridor or the tongue of Labinot - Debar, which has a direction extending from southwest to northeast. It divides it through the ophiolitic zone of Mirdita from Labinot through the Okshtun grit in the direction of Dibra - Peshkopia and beyond. In the first phase of development during the Triassic - Jurassic this area formed with the internal zones of Mirdita - Korab a joint bend complicated by partial elevation. It can therefore be included in the internal zones. But starting from the end of the Jurassic, after the easternmost zones underwent the tectogenesis of the Jurassic-Cretaceous border and underwent fragmentary uplift and folding from the former wide, complex Krasta-Cukali-Mirdita-Korabi bend it continued the path of geosynclinal development as a trough inherited together with the flysch tongue of Labinot -

Dibra until the end of the Eocene. At the end of this period, it is for the first time affected by folding movements and turns into a cordilier thus joining the internal zones. Throughout Neogen (starting with Oligocene) this has been elevated with the exception of the Tortonian period when from the edge of the Pre-Adriatic Lowland ingressive tongues extended over the lowered (graben) parts of this area.

Krasta Subzone

It lies in the form of a narrow belt composed mainly of Paleogene flysch, which is located between the zone of Kruja and that of Mirdita and which enters like a tongue in Martanesh from Labinot to Debar and Peshkopi between the internal zones. In Greece, it is called the Pindi zone while in Serbia it is known as the Budva zone. The western and eastern boundary of the Krasta subzone is tectonic everywhere. In the east, it is thrust from the zone of Mirdita while in the west it thrusts the zone of Kruja. The plan of overthrusting of the Krasta zone over the Kruja zone in some sectors is also confirmed through seismic and it should be said that it is generally smooth with angles ranging from 20-30° of any special sector up to 40°, in the sector Cudhi - Q.Shtamë reaches up to 40°, in the sector of Shupal Kllojka 25-30° etc. Seismic information for the Krasta zone itself, where works were carried out (Zadrimë) Cudhi Q.Shtamë- Shupal- Kllojkë, Elbasan - Librazhd, is poor and there are almost no seismic reflections which in our opinion is related to deep complications both with frequent formal changes and with intense folding of formations. This subzone, due to the significant advancement of the Mirdita area in the west, is extremely narrow in a very narrow belt. The Krasta subzone is composed of three main formations that overlap each other in this order, the early Albian-Cenomanian marl flysch, the Upper Cretaceous limestone, and the late Mastriktian-Eocene terrigenous flysch, which has a large surface distribution. The structures of the Krasta subzone, as a whole, have a northwestern extension represented by numerous almost isoclinal anticlines with southwestern inversion and overthrust to the southwest or are monoclinic (with the eastern wing) or asymmetrical or even refreshing as can be seen in the north and south of Mali me Gropa, where this subzone also reaches the maximum width. In some cases the direction of the structures is northeastern as in Labinot - Fushë. Characteristic is the presence of many tectonic scales based on the early flysch that are placed in the form of monoclinic bundles that are repeated several times in the crosscut. In the Krasta subzone, there are narrow, upside-down folds that are complicated by many thrusts and scales. It is not ruled out that these scales, especially those of the front towards the contact with the Kruja zone, may be branches of a larger provincial detachment with a very mild decline, according to which a good part of the Krasta unit will cover the paleogenic formations of the Kruja zone. Due to the formational, structural, and denudation contruction, a rugged, asymmetrical relief is formed in this area with steep western carbonate slopes and slightly steep eastern slopes coinciding with the dip of the strata and are built mainly of Paleogene flysch. The structures are usually constructed of Albian-Cenomanian flysch formations, upper Cretaceous carbonates, and the late Mastriktian-Paleogenic flysch. They develop in parallel rows and in some regions we find several structures. They have a width of 25-30km, while their width is usually small and does not exceed 2km, but is usually 200-500m according to the contour of the limestone. Another characteristic feature of the structures of this subzone is that in most anticline cases they are represented only by the northeastern wings. (Fig. No.8)

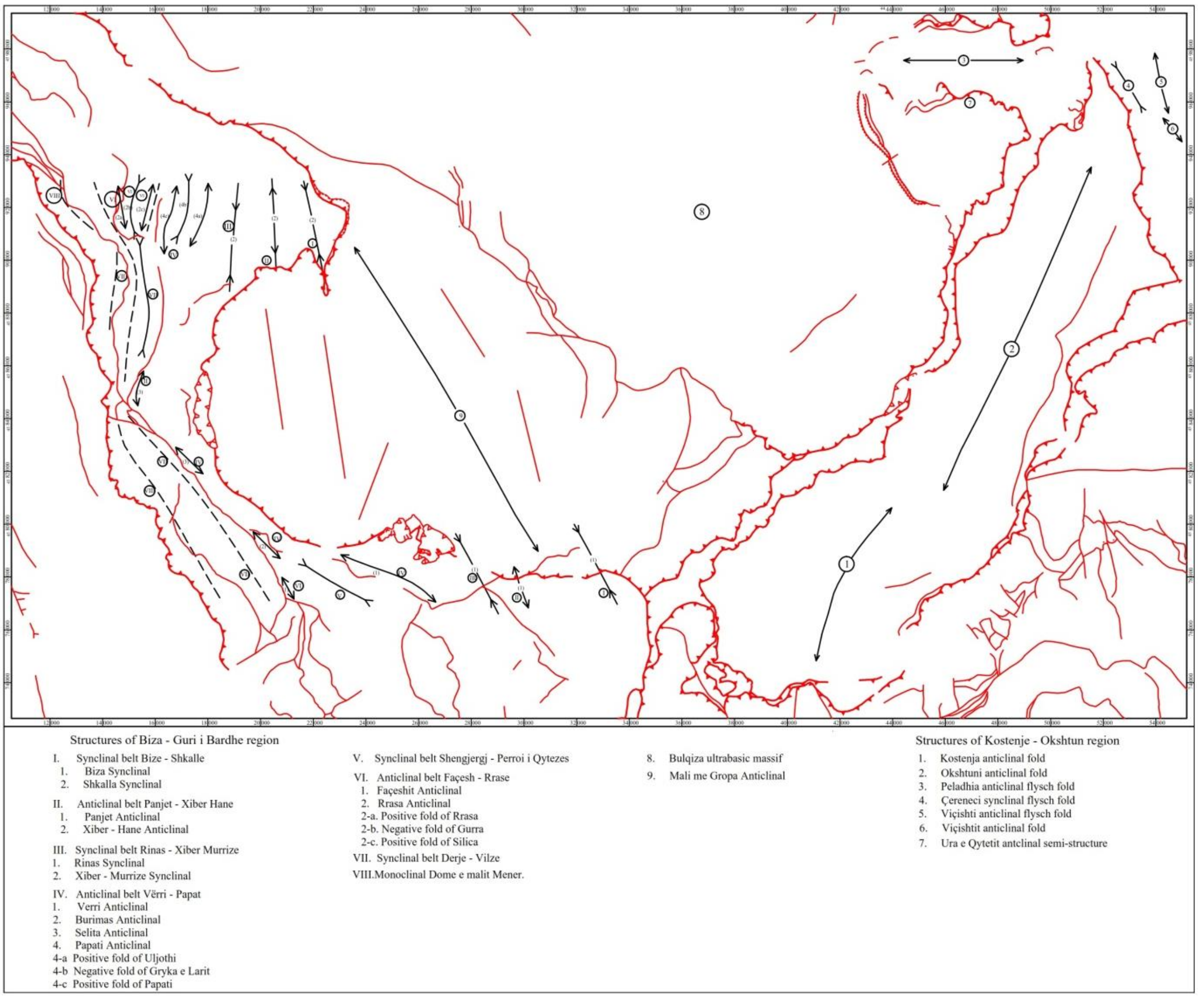


Fig.no.8 Structural Map of the Region

3.3 Fault patterns and characteristics in the region under study

In the proposed tectonic zoning, for a series of units (tectonic zones and sub-zones), the boundaries are clear, which in most cases are represented by overthrusts, but in rare cases, these boundaries are accepted as conventional. In the division of tectonic zones, we notice that a number of problems arise, such as the use of racial criteria creates problems over the affiliation of specific sectors, on which zone they belong, such as the case of the inclusion of the carbonate sub-zone in the Mirdita zone. In particular, in this region we group the different types of faults as follows:

1. Normal faults (afro-vertical)
2. Overthrusts
3. Detachment faults (gravity slide tectonics)
4. Horizontal faults (nappe)

1. <u>Normal faults.</u> The Mirdita tectonic zone and the Krasta sub-zone, where both the ultrabasics and carbonates as well as the Jurassic-Cretaceous boundary deposits have been affected by very

strong tectonic movements according to different tectogenesis. In this case, the effects of afro-vertical tectonic movements make possible the formation of two tectonic blocks:

a. Footwall
b. Hanging wall

In general, the extension of Afro-vertical tectonic types has an almost meridional orientation and the structural elements of the tectonic planes are: strike which varies from 230 - 240° and dip angle 55-65°. At the same time, we have tectonic lines that extend in the direction of WE, NW-SE, etc., where is noticed the high value of the dip angle of the tectonic plane that goes up to 70°. From the field measurements it results that the elevation of the block in verticality varies from 5-50-150 m. While the extension of afro-vertical tectonic lines in the field varies from 100 - 200 m up to several kilometers.

2. Overthrust. The elements of this fault are observed quite clearly, especially in the tectonic overthrust (nappe) contact between Z.T.Kr and Z.T.K. In this case, between these two zones are formed highly destroyed areas with a width varying from 300 - 500 - 1500m. The structural elements of the planes of the tectonic zone are: strike 50° and dip angle 30-35°. The extension of the overthrust plane has an almost meridional direction. (Photo. No.9)

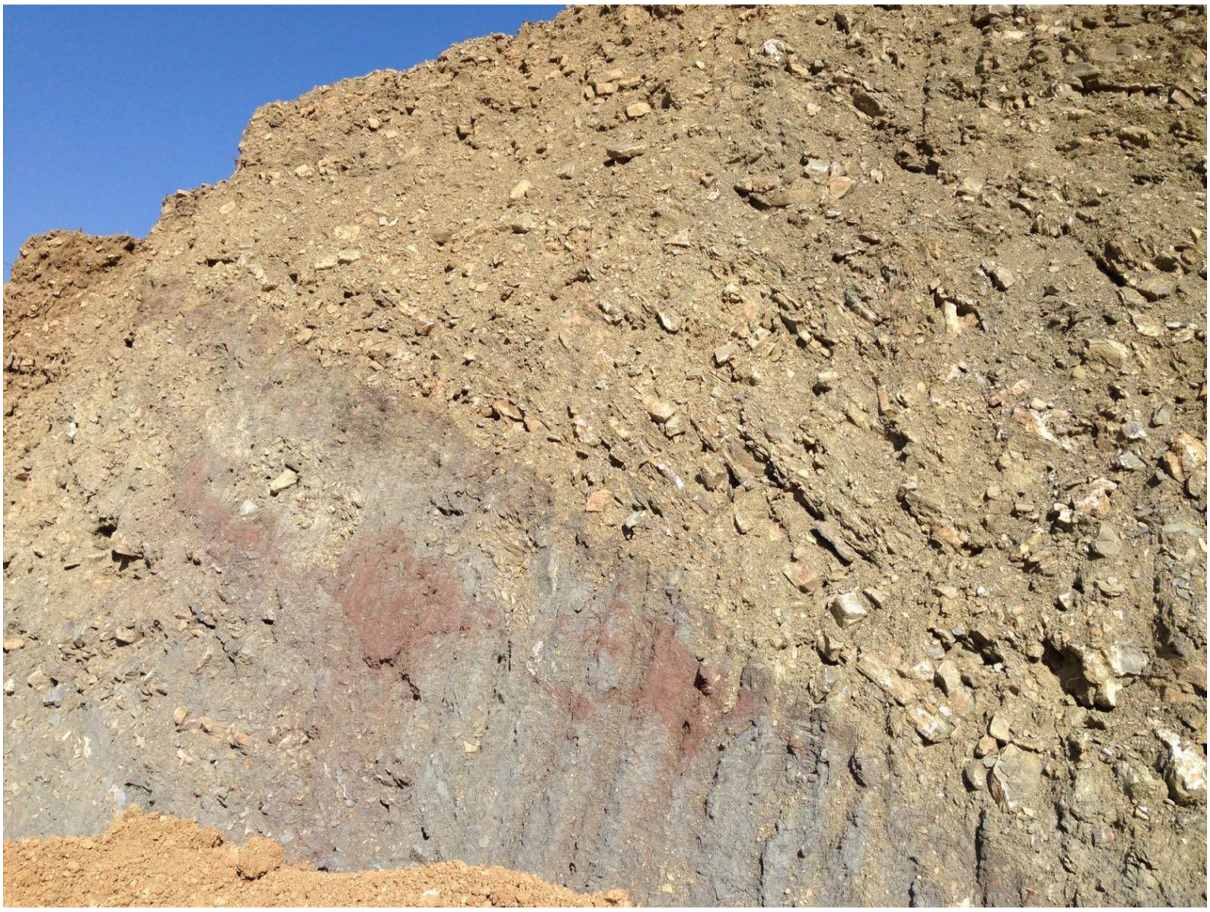


Photo No.9 Kontakti tektonik mbihypës midis Z.T.Kr dhe Z.T.K

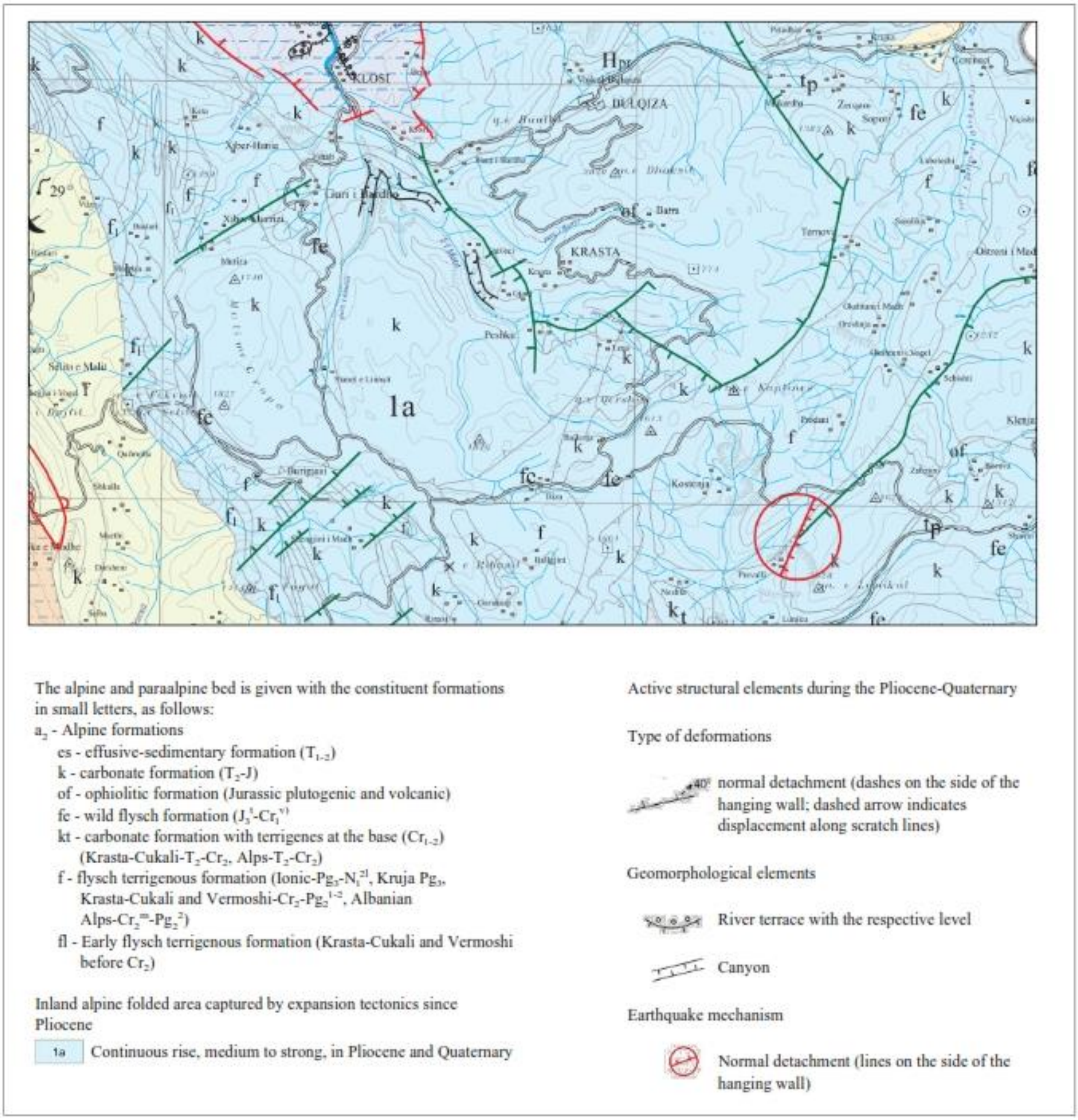
A very strong fault, in the region under study, with an overthrust character, is that between the ultrabasic rocks of K.of with carbonate formations of Z.T.M.
The structural elements of the planes of the tectonic zone are: strike 70° and dip angle 50°.
3. Detachment faults (gravity slide tectonics). The elements of this fault are present in the area under study and are represented by gravitational blocks of various sizes, this is especially evident in the western periphery of Mali me Gropa, part of Z.T.M. The blocks have dimensions of several hundred meters lie on the Eocene basin formations.
4. Horizontal faults (nappe). In the region under study this type of fault is widely evidenced and in the concept of horizontal displacement from bottom to top is represented by 2 different generations:

b. The horizontal displacement of the formations of the Jurassic-Cretaceous border
c. The horizontal displacement of Triassic carbonate formations

These displacements occurred as a result of the concluding phase of post-Eocene tectogenesis and both formations of these generations extend almost horizontally over the deposits of Z.T.Kr. The structural elements of the nape plane are: strike 30 - 35° and dip angle 15-25°. The presence of Cr_2^{mas} - Pg_{1-2} flysch formations below the Jurassic - Cretaceous boundary formations best confirms the presence of this nappe fault.

Neotectonic movements

The new movements which have caused the present appearance of the geomorphology of the Albanides began at the end of the Neogene which coincides with Pliocene. At this time the formation of new Pliocene third generation hollows began, which due to the sliding detachments that limit them, formed at this stage, gave them a prominent Graben character while the surrounding mountain blocks have Horst character. The new neo-tectonic stage of the Plio-quaternary, on the one hand, formed a morphostructural ensemble characterized by graben structures with diving regime during this time or at its intervals, and with Horst shaped blocks that later uplifted. Thus in the northwestern sector of this region Neogenic deposits were formed. Also as a result of new movements in the sector of Stavec, Vali Valley, Stanet e Linosit, we have the formation of canyons and the phenomenon of Horst - Graben. In general, the Pliocene - Quaternary formations are affected by normal detachments where their dip angle varies from 35-40° with NE-SW extension. In the Preval sector, on November 30, 1967, there was an earthquake with Ms = 6.6 and intensity I0 = IX (MSK-64) that caused 20 killed, 214 injured and great damage (Sulstarova, Koçiaj, 1980).
In this sector, the detachment created as a result of the earthquake, of flysch and carbonate formations in a length of about 2km, where the southeast side represents the hanging wall, is quite well observed. The extension of the created falut is NE-SW. The length of the sliding plane goes up to 2 -3m.



3.4 Data quality, origin and publication

The data of the presented report are divided into two categories:

a. Cartographic works at a scale of 1: 25 000 for sedimentary formations.
b. Cartographic works in scale 1: 5 000, 1: 10 000, 1: 25 000 accompanied by drilling to a depth of 1000m, electro-vertical probing, chemical and petrological studies, mineralogical, magnetometric, etc.

3.5 The importance of local faults

The study of local tectonics in the region under study is of great importance for the following aspects:

1. Protection of the territory from possible landslides
2. Collection of data on natural seismicity caused by earthquakes that occurred at different times, which will be used to predict the places where different socio-cultural objects can be built.
3. Accurate data are obtained on the possible exploration of useful minerals such as: Chromium, Oil, Gas, etc.
4. Preservation of surface water sources emerging in the nappe tectonic contacts between carbonate deposits which serve as a collector and flysch deposits which serve as a screen.

3.6 Fault data included in the report

In this midterm report the data presented above, grouped are:

a. This region taken under study is represented by the tectonic zone Mirdita (Z.T.M), the tectonic zone Krasta (Z.T.Kr), and the tectonic zone Kruja (Z.T.K). Note: For Z.T.K we have not presented data in this midterm report.

b.

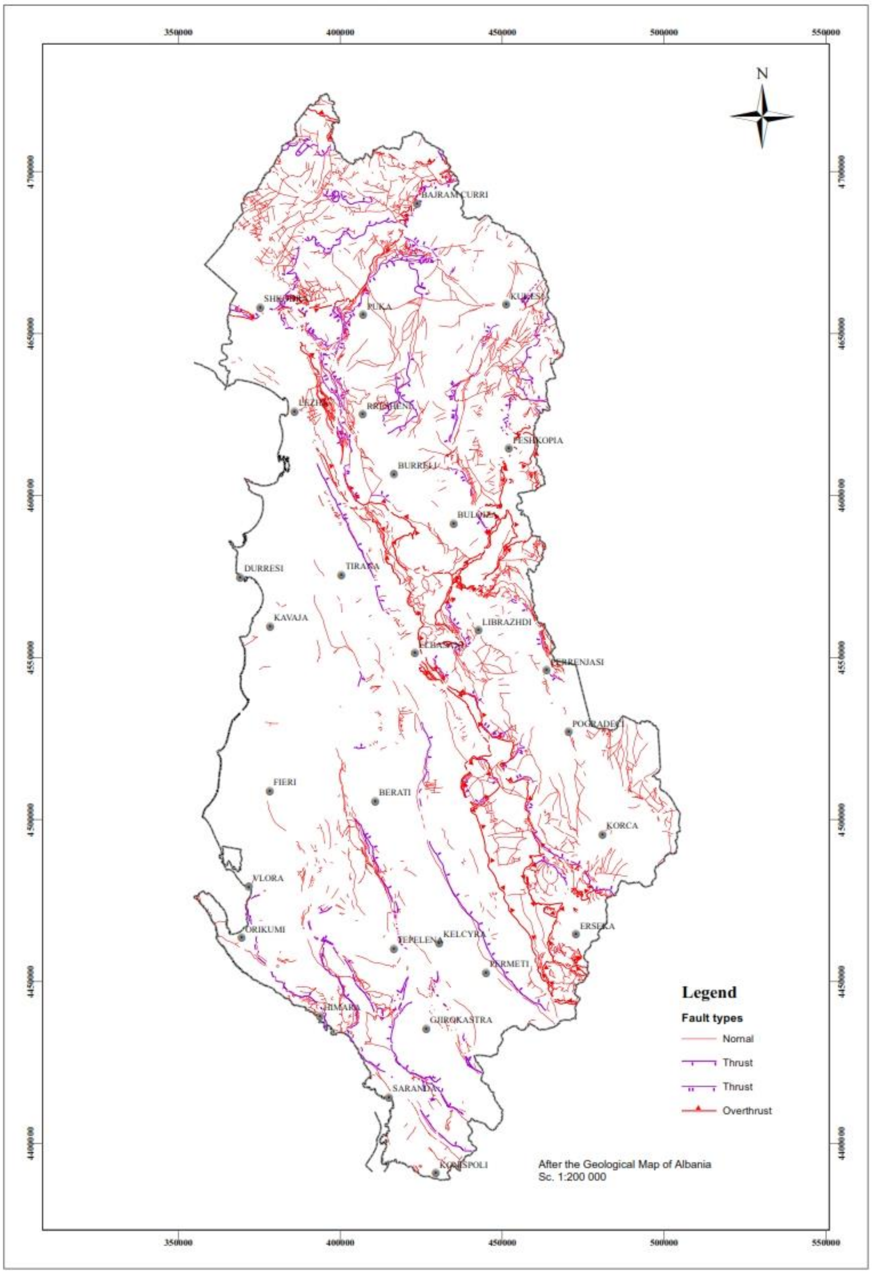
c. Structural elements according to our interpretation are classified in two terms:

   I. The term "Platform" is defined by the presence of neritic formations. The representative deposit that serves for the definition of the term Platform are the neritic carbonate deposits with Upper Triassic - Lower Jurassic age (T_3-J_1), this structural element is found in Z.T.M.

   II. The term "basin" is defined by the presence of pelagic formations. The representative deposit that serves for the definition of the term Basin are those deposits aged from the Upper Jurassic to the Lower and Middle Eocene.

Both platforms and basins are affected by tectonics, normal faults (almost normal; 50°-60°), overthrusts, detachment faults (gravity slide tectonics) and horizontal faults (nappe). The time of fault formation begins from the Triassic until today. The extension of the faults in general is North-South, but there are many other cases where the extension of the axis of faults goes from east to west, northeast-southwest, etc.

3.7 Tectonic map of Albania



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4 GBA – AUSTRIA

Authors: Esther Hintersberger, Christoph Iglseder

4.1 Introduction

The topography and also the deformation history in Austria is dominated by the Alpine orogeny. In total, more than 70% of Austria is considered mountainous, lying higher than 500 m a.s.l. Thus, with the majority of the tectonic boundaries cropping out at the surface, tectonic structures are generally well studied, mostly revealing detailed multi-phase deformation history.

Historically, tectonic structures in Austria are differentiated into two major groups (Figure 1): large almost horizontal thrust faults transporting nappes towards the north over large distances (nappe boundaries) and steeply dipping faults with strike-slip or normal sense of shear. In general, the steeply dipping faults post-date and displace the nappe boundaries.

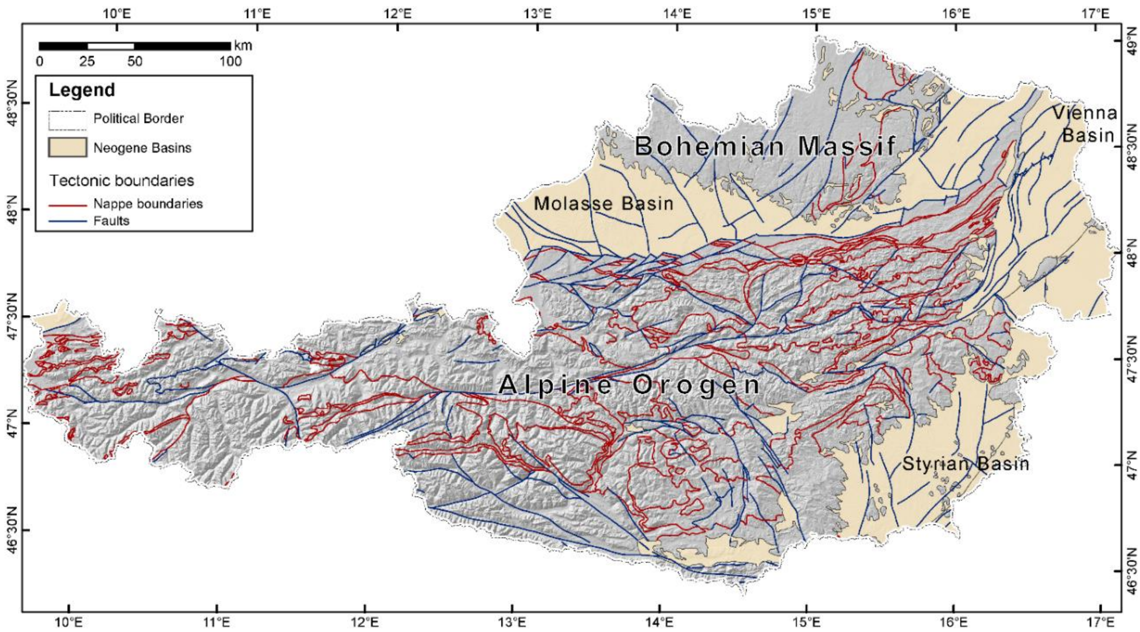

Figure 1: Tectonic lines in Austria at the scale 1:1.000.000, differentiated between steeply dipping strike-slip and normal faults (blue) and mostly gently dipping nappe boundaries (red) showing large thrusting. Neogene Basins are shown in light beige color.

In general, Austria can be subdivided into three major paleogeographic areas with distinct fault patterns

a) The Bohemian Massive, mostly north of the Danube at the border to the Czech Republic and Bavaria. This region is part of the European tectonic plate and is dominated by Variscan deformation and contains the oldest rocks of Austria (Lindner et al., 2021). The major structures have been reactivated during the Alpine orogeny.
b) The Alpine orogen, with the Eastern Alps as the most dominant geological superunit in Austria. Here, the fault pattern is dominated by thrusting along nappe boundaries. Since

Miocene times, the dominant features are steeply dipping strike-slip faults accommodating the lateral extrusion of the Eastern Alps towards the east.
c) The group of Neogene Basins comprises the North Alpine foreland molasse basin, the Vienna Basin with its adjacent subbasins, and the Styrian Basin which is tectonically linked to the larger Pannonian Basin further east, , and a number of smaller intramontanous basins (i.e. Fohnsdorf and Tamsweg basins). Even though the deformation histories of these basins are not identical, they all contain buried faults that were active during the Neogene and have been partly reactivated during the Pleistocene and Holocene.

4.2 Data quality, origin and publication

The tectonic boundaries of Austria presented in the GeoERA HIKE European Fault Database are based geological map of Austria at the scale of 1:1.000.000 published by Schuster et al. (2014), consisting on a generalized compilation of the ongoing 1:50.000 mapping program.
The first map of the Eastern Alps was published in 1832 by Sedgwick & Murchison. During the second half of the 19th century, a campaign was started to publish geological maps of the Austro-Hungarian empire at the scale of 1:75.000 based on systematic geological mapping. After WWII, modern geological mapping started at the scale of 1:50.000 and continues until today. In areas not covered yet with modern geological maps, digital compilations of the available manuscripts and local maps are provided (called GeoFAST, Figure 2). In addition, regional compilations at the scales of 1:200.000 and 1:100.000 are available for several counties but not yet completed on national level. These provide the base for the generalized geological map of Austria at the scale of 1:1.000.000 and the tectonic boundaries provided for the EFD.

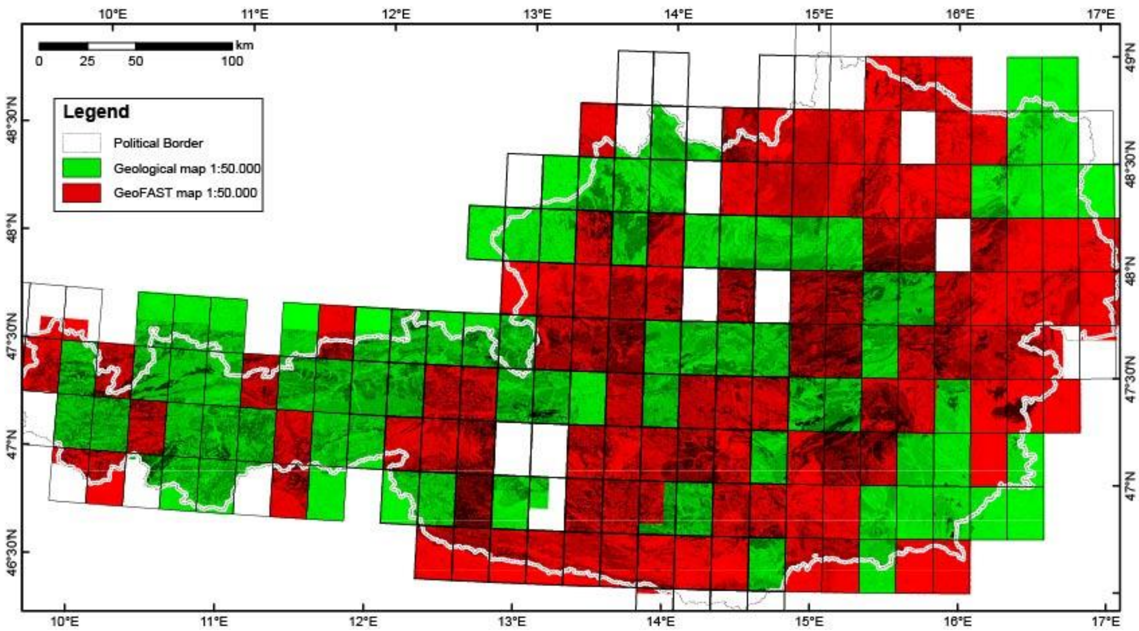

Figure 2: Coverage of Austria with geological maps at the scale of 1:50.000 (red) and with digitally compiled manuscript maps at the same scale (green).

Information shown in the EFD is an excerpt of the GBA fault data base (Hintersberger et al., 2017), which was extended to include also information on nappe boundaries (Hintersberger et al., 2019). As tectonic studies regarding single regions and/or structures are abundant, information is widespread. However, the level of information on faults is patchy, some faults are well studied and there is evidence for detailed multi-phase deformation history, others are only lines on maps with no kinematic information. In order to at least partly smooth this difference, faults in the GBA fault data base are hierarchically sorted into fault systems, which could be subdivided into sub-fault systems or grouped into large-scale fault systems. In Figure 3, all named fault systems in Austria are shown.

The Neogene basins, especially the Vienna and Molasse basins have been investigated by industrial 2D and 3D industry seismic exploration campaigns. Therefore, detailed information on the location and the deformation history of the faults in this regions is available not only at the surface, but also at the crystalline base of the basins (Kröll & Wessely, 1993, Kröll et al., 2001, 2006).

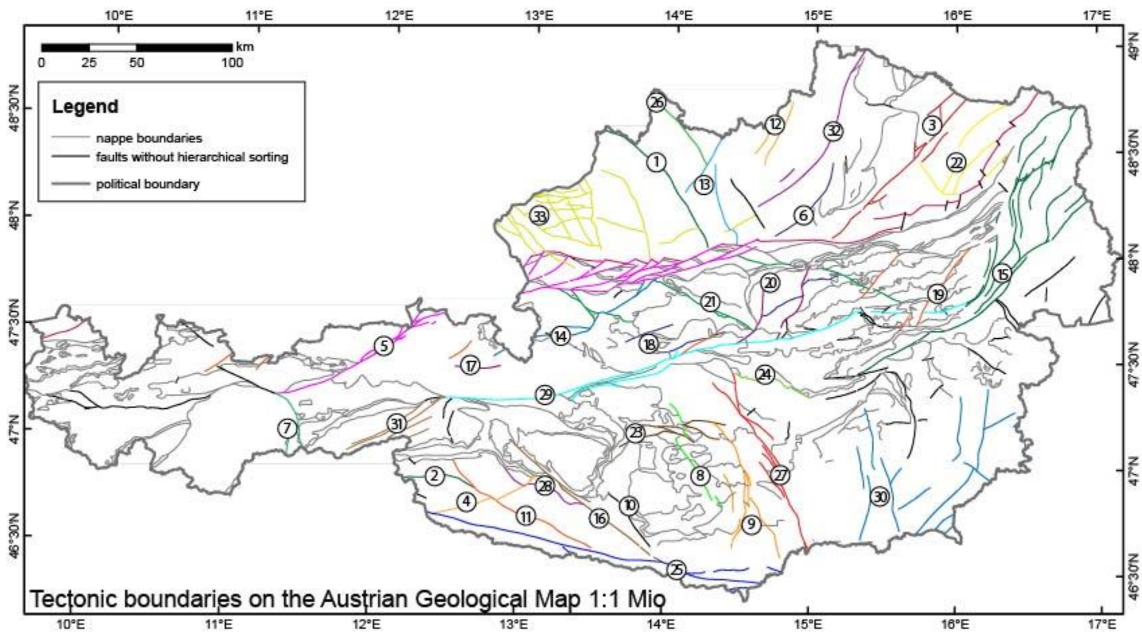

Figure 3: Figure 3: Tectonic boundaries in Austria at the scale 1:1.000.000, differentiated between steeply dipping strike-slip and normal faults (black and colors) and mostly gently dipping nappe boundaries (grey) showing large thrusting. The numbers indicate the respective (large-scale) fault systems and fault sets: 1 - Danube Fault System, 2 - Defereggen-Antholz-Vals Fault System, 3 - Diendorf-Boskovice-Cebin Large-scale Fault System, 4 - Drautal-Zwischenbergen-Wöllatratten Fault System, 5 - Engadin-Inntal-Innsbruck-Salzburg-Amstetten Large-scale Fault System, 6 - Freyenstein Fault System, 7 - Giudicarie-Brenner-Silltal Large-scale Fault System, 8 - Gurktal Alps Subfault System, 9 -Görtschitztal Fault System, 10 - Hochstuhl-Gegendtal Fault System, 11 - Iseltal Fault System, 12 - Karlstift Fault System, 13 - Kourim-Blanice-Rodl-Kaplice Large-scale Fault System, 14 - Königsee-Lammertal-Traunsee Subfault System, 15 - Mur-Mürz-Vienna Basin-Vah Large-scale Fault System, 16 -Mölltal Fault System, 17 – Northern Calcareous Alps (NCA) E-W Fault Set, 18 - NCA ENE-WSW Fault Set, 19 - NCA NE-SW Fault Set, 20 - NCA NNE-SSW Fault Set, 21 - NCA NW-SE Fault Set, 22 - NE Molasse Fault Set, 23 - Lower Tauern Southern Margin Fault System, 24 - Palten-Liesing Fault System, 25 - Periadriatic-Mid-Hungarian Large-scale Fault System, 26 - Pfahl Fault System, 27 - Pöls-Lavanttal Fault System, 28 - Ragga-Teuchl Fault System, 29 - Salzach-Ennstal-Mariazell-Puchberg (SEMP) Fault System, 30 - Styrian Basin Fault Set, 31 - Tauern Window Subfault System, 32 - Vitis-Pribyslav Fault System, 33 - West Molasse Fault Set

4.3 Fault data included in the HIKE project

The tectonic boundaries of Austria included in the GeoERA HIKE European Fault Database project are taken from a generalized compilation at the scale of 1:1.000.000 published in Schuster et al. (2014) and used as main overview map for Austria. An earlier version of the fault geometries but without additional information has been provided in the OneGeology-Europe project[1], which now is incorporated in the EGDI platform. The Austrian multi-thematic geological map was the first online source that includes kinematic and temporal information on Austrian faults (Hintersberger et al., 2016). Further complete nationwide compilations for 1:500.000 and 1:200.000 are in the making and will be included in the future when finalized.

The main faults, fault systems and fault zones are classified according to the generic semantic framework in HIKE. This includes a correlation link with the faults in neighboring countries (in particular Germany). Fault attributes are still mainly limited to geometric aspects (length, strike, dip, surface area), fault type (normal, reversed, etc.), timing of fault activity (youngest surface affected) and observation/evaluation method (seismic interpretation, inferred modelling, etc.).

4.4 A brief introduction to the geology and the major deformation events observed in Austria and included in the EFD

The Eurasian plate and the Alpine orogene build the geology of Austria. Latter includes a number of superunits and nappe systems, reflecting the Jurassic-Cretaceous paleogeographic situation with two oceans (Neotethys and Penninic oceans) and two continents (European and Adriatic plate) connected with a small continental bridge, the so-called Adriatic spur (Schuster, 2015). During geologic times, geological processes determined by a certain period, concluded in so-called geoevents or Geologic Events (CGI, 2017), which reorganize geologic units.

In Austria, four main deformation events can be distinguished and characterized (based on Schuster, 2015, modified after Hintersberger et al., 2017):

1. The **Devonian to Carboniferous Variscan Event** characterizes processes of the Variscan orogeny, formed during collision of Gondwana and Laurussia followed by orogenic collapse and plate reorganization (Kroner and Romer, 2013). In Austria, nappe stacking and thrusting in the Bohemian Massif as well as Palaeozoic areas within the "later Eastern Alps", the activation of major shear zones and faults with strike-slip kinematics and formation of intramontanous basins referred to this event.
2. The **Permian to Triassic Extensional Event** marks lithospheric thinning, intense magmatism within the Pangaean supercontinent (Schuster & Stüwe, 2010) and tectonic activity within the Central European Basin System (Scheck-Wenderoth et al., 2008). In Austria, the reactivation of major strike-slip faults in the Bohemian Massif is in context with this event.
3. The **Cretaceous Eo-Alpine Event** characterizes the formation of the Alpine orogenic-wedge and exhumation of the Eo-Alpine metamorphic belt respectively during ongoing Alpine subduction along the northern part of the Adriatic spur (Schuster, 2015). In Austria, thrusting along nappe boundaries and normal faulting along detachments within the Eastern Alps, partly reactivating preexisting Variscan and Permo-Triassic structures as well as major strike-slip faults in the Bohemian Massif are accompanying this event. In addition, the formation

[1] https://www.eurogeosurveys.org/projects/onegeology-europe

of the Cretaceous Gosau basin and activity within the Central European Basin System (Scheck-Wenderoth et al., 2008) is in close contact to this event.

4. The Palaeogene-Neogene Neo-Alpine Event can be characterized by subsequent collision of the Adriatic and European plate with ongoing subduction of the Penninic Ocean, formation of an accretionary wedge and exhumation of Neo-Alpine high-pressure rocks, as well as indentation of the Adriatic microplate. At ca. 23 Ma, it led to onset of lateral extrusion (Ratschbacher et al., 1989) within the Alpine orogen. In Austria, the development of laterally displacing E-W trending fault systems, such as the SEMP FS (Semmering-Enns Valley-Mariazell-Puchberg), and N-S trending normal faults, e.g. the Brenner and Katschberg Normal Fault Systems (Figure 3). Tectonic windows, with the Tauern window being the most prominent, opened along these fault systems (Genser & Neubauer, 1989; Fügenschuh et al., 1997; Dunkl et al., 1998; Luth & Willingshofer, 2008).

4.5 Geometry and origin of fault patterns and their characteristics

Next to the geographic zonation (or structural elements), historically, tectonic structures in Austria are differentiated into two major groups (Figure 1): large, almost horizontal thrust faults transporting nappes over large distances (nappe boundaries) and steeply dipping faults with strike-slip or normal sense of shear. In general, the steeply dipping faults post-date and displace the nappe boundaries. In the following, an overview of the different fault patterns that can be observed in Austria and the respective general deformation history is provided:

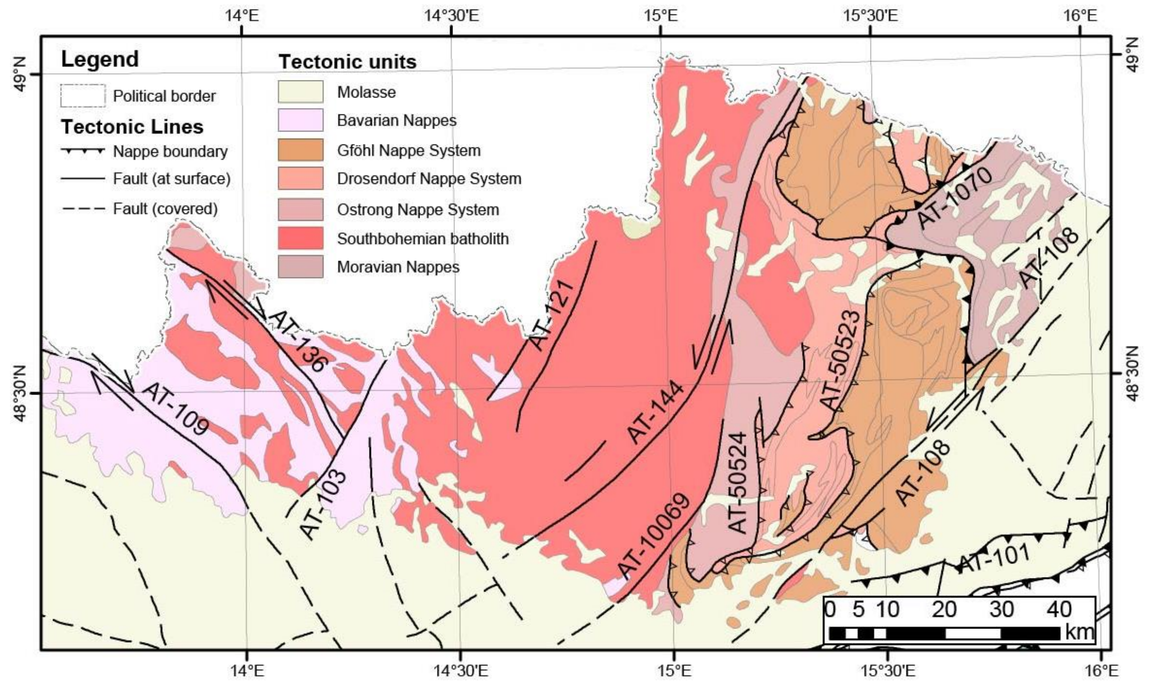

Figure 4: Fault pattern in the Bohemian Massif

1. The **Bohemian Massif** is dominated by N-S-trending, gentle thrust faults dipping to the E which mark the nappe boundaries within the Moldanubian superunit and the W-dipping Moldanubian thrust system onto the Moravian superunit were active during the Carboniferous (340-325Ma). They show often N-directed kinematics. Conjugated set of steeply dipping NW-SE striking right-lateral older faults (e.g. Pfahl and Danube fault, IDs AT-

136 and AT-109 in Figure 4) and NE-SW striking, left-lateral younger faults (e.g. Rodl and Diendorf fault, IDs AT-144 and AT-108) cross cut the Moldanubian superunit (Figure 4). They origin as ductile to ductile-brittle shear zones during the Late Variscan to Permian (~310-280 Ma), and were later reactivated during the Late Cretaceous and the Miocene. Partly Quaternary reactivation and sparse seismicity is observed.

2. **The Eastern Alps**, the most prominent geological superunit in Austria, are subdivided into three groups showing distinct fault patterns:
   a) **Penninic Units (including Rhenodanubian Nappe System) and Helvetic Units**: EW-trending to the south dipping faults with N-directed kinematics along nappe boundaries were active during Paleogene to Neogene times. They are closely spaced, steeply dipping thrust faults, mostly indicating out-of-sequence thrusting (Figure 5). They are displaced by younger NE-SW left-lateral strike-slip faults active during upper Oligocene to recent times. The most prominent is the ISAM (Inn valley-Salzburg-Amstetten) left-lateral fault system (Egger & Peresson, 1997, part of #5 in Figure 3). Partly Quaternary reactivation and sparse seismicity is observed.
   b) **Northern Calcareous Alps,** representing cover nappes of the Tyrolian, Juvavian and Bajuvarian Nappe systems: Here, large south-vergent nappe boundaries are present. They follow mostly E-W-trending sometimes-preexisting structures like half-graben of Jurassic times reactivated during the Cretaceaous to Paleogene Eo- and Neo-Alpine Events. They are postdated by a complex pattern of steeply, almost vertical conjugated strike-slip fault sets that have accommodated different phases of N-S shortening since the Oligocene and later on the lateral extrusion of the Eastern Alps. Earlier NW-SE striking left lateral faults, NNE-SSW trending strike-slip faults and EW-striking reverse faults were active during Late Eocene to Oligocene times. They were cut by NE-SW striking right lateral faults, NNE-SSW to EW trending normal faults and ENE-WSW striking left lateral faults during Miocene times (Figure 5, Hintersberger et al., 2017 and references therein).

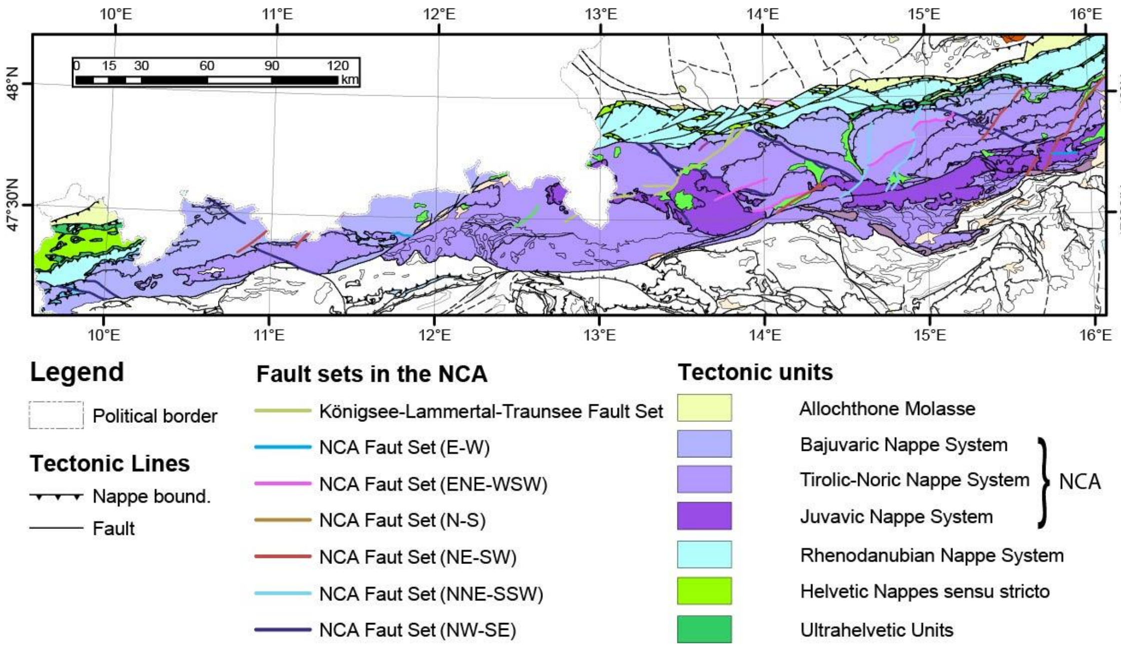

Figure 5: Fault pattern in the Northern Calcareous Alps.

c) **Austroalpine Units south of the SEMP fault system** representing basement nappes of the Silvretta-Seckau-, Koralpe-Wölz, Drauzug-Gurktal and Tirolic-Noric Nappe systems: Main structures in this area are formed by (N)E-(S)W-trending nappe boundaries, sometimes following preexisting Variscan and Permo-Triassic structures active during Cretaceous Eoalpine Event. Subsequent thrust faults with kinematics to the (W)NW are overprinted by normal faults with (E)SE directed kinematics. These earlier structure are reactivated and crosscut by Neo-Alpine strike-slip faults with mainly right-lateral kinematics. Earlier W/NW-E/SE –trending fault systems (e.g. Defereggen-Antholz, Kalkstein-Vallarga, Ragga-Teuchl, Gurktal Alps and Lower Tauern Southern Margin FS) of Palaeogene times followed by NE-SW-trending left- lateral faults (e.g. Drautal-Zwischenbergen-Wöllatratten FS). The most dominant fault pattern are NW-SE to NNW-SSE trending right- lateral faults active during late Oligocene to Miocene times (e.g. Möll valley, Isel valley, Pöls-Lavant valley and Götschitz valley FS) (Figure 3). Partly Quaternary reactivation and sparse seismicity is observed.

A general overprint affecting most of the Austrian Alps are **structures related to the lateral extrusion of the Eastern Alps** (Ratschbacher et al. 1989) since the Miocene (Linzer et al., 2002). The most prominent structures are E(NE) –W(SW) trending steep strike-slip faults with left-lateral (e.g. SEMP FS, #29 in Figure 1) and right-lateral (e.g. Periadriatic FS, part of #25) kinematics. In addition, Early Miocene N-S trending shear zones and normal faults along the western (Brenner subfault system) and eastern edge of the Tauern window cause the opening of the Tauern window (Schmidt et al., 2013). In a later stage, WSW-ENE left-lateral (Mur-Mürz FS, part of #15) and right-lateral (Pöls-Lavantal FS, #27) strike-slip faults are the active structures (Brückl et al., 2010). In addition, the opening of the Vienna Basin (part of #15) and N(NE)-S(SW) striking normal faults in the Styrian basin (#30) are caused by ongoing lateral extrusion (Decker et al., 2005). Ongoing moderate seismicity suggest Quaternary movement along the mentioned structures.

3. The **large Neogene basins** consist of the Molasse Basin, the Vienna Basin, and the Styrian Basin. Even though the deformation histories of these basins are not identical, they all contain mostly buried faults that were active during the Neogene and have been partly reactivated during the Pleistocene and Holocene. The North Alpine foreland molasse basin (comprising #22 and #33 in Figure 3) consists of NNW-SSE trending normal faults creating a horst-and-graben structure that overprints WSW-ENE trending thrusts. The Vienna Basin (part of #15) is characterized by the NE-SW striking left-lateral Vienna Basin Transfer Fault, from which N-S striking normal splay faults are branching of, compensating E-W extension. Ongoing moderate seismicity in the southern part and paleoseismological and geomorphic data suggest Quaternary movement along the mentioned structures (Decker et al, 2005, Weissl et al., 2017, Hintersberger et al., 2018). The Styrian Basin comprises mostly N-S striking normal faults related to the E-W extension caused by the roll-back at the eastern end of the Pannonian basin. Quaternary reactivation in the Pannonian basin shows mainly wrench and thrusting deformation along the faults (Horvath & Cloething, 1996 and citations therein).

4.6 Local fault relevance and application

4.6.1 Natural seismicity

Austria is characterized by moderate seismicity moment magnitudes (Mw) up to 6.0 documented since the 13th century (Figure below). More than half of the recorded earthquakes occurred in Tyrol and Lower Austria, especially in the area of the Inn Valley and its tributaries, the Mur and Mürz valleys and the Vienna Basin (e.g. Lenhard et al., 2007). Whereas most earthquakes are too small to be felt by people, earthquakes causing damages occur every 2-3 years on average (ZAMG, 2019). In general, most of the damages are rather minor, such as cracks and toppling of rooftop tiles, corresponding to epicentral intensities (Io) of VI-VII. Earthquakes with Io = VIII and higher causing heavy damages occur every 100 or more years, with the most recent ones occurring in the southern Vienna Basin (with more than 25% of Austrian population), close to Schwadorf in 1927 (Io = VIII) and in Seebenstein in 1972 (Io = VII) (Figure 6). Even though many efforts have been undertaken to assess the seismic hazard in Austria and on European level during the last decades (e.g., Grünthal et al., 1999, Giardiani et al., 2013), the sparsity of available data regarding stronger, mostly historic, earthquakes prevents more detailed assessment for specific regions. Therefore, even though the statistical view on the overall earthquake occurrence in Austria is well documented, the linkage to the origin of earthquakes, i.e. active faults, is not yet well established.

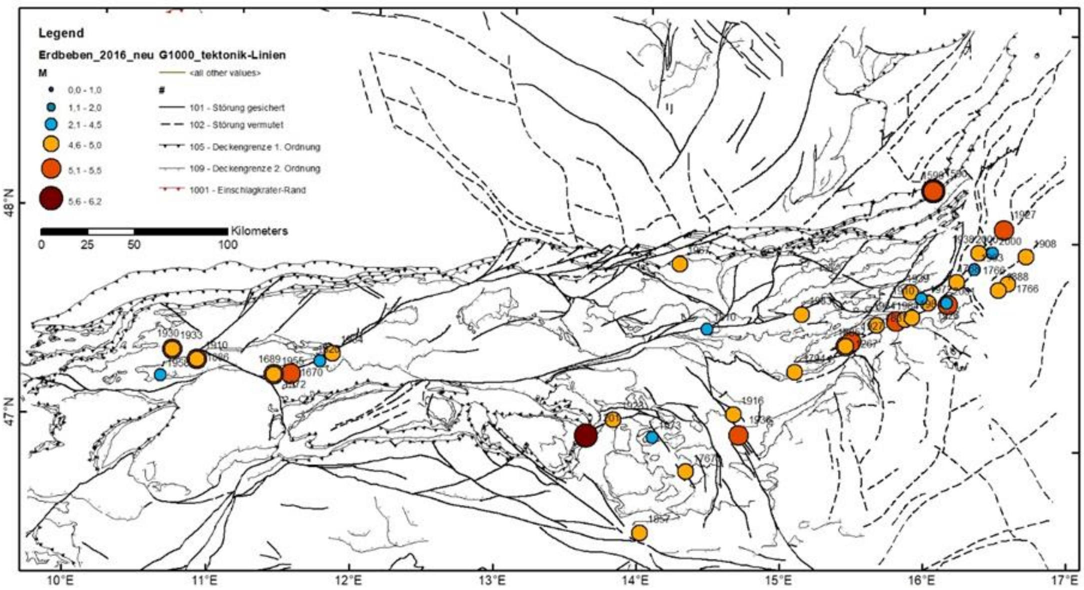

Figure 6: Earthquakes with magnitudes of 4.5 and larger in Austria during the last 850 years. Fault data are based on Schuster et al. (2014), earthquake information extracted from the Austrian catalogue of felt earthquakes (ZAMG, 2019).

4.6.2 Oil production

Ongoing oil and gas production since the 1960s in the Vienna Basin and the Molasse Basin in Upper Austria has provided detailed information on the geometry of faults within these basins. Especially in the Vienna Basin, faults play an important role regarding the location of oil and gas fields (see Figure below). The field can be mostly found in the small NNE-SSW striking graben structures as indicated by the thickness of the Quaternary sediments. Even though induced seismicity has not been observed or systematically documented, Quaternary reactivation of the faults might have an effect on the preservation of the oil and gas fields as well on the related infrastructure, such as major gas pipelines crossing the basin (see red line in Figure7).

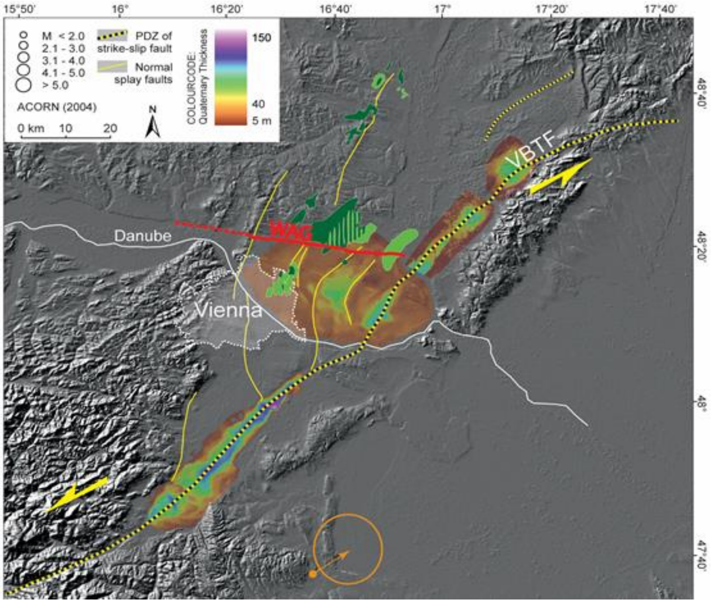

Figure 7: Approximate location of oil and gas fields in the Vienna Basin (light and dark green, respectively)

4.6.3 Hydrothermal usage

The existence of thermal water and springs is widespread in Austria and has been exploited since Roman times. Even though the direct linkage between the existence of faults and sources of thermal water has not yet systematically investigated, a close connection between both phenomena is assumed. For example, the most famous alignment of thermal springs at the western margin of the Vienna Basin is called “Thermenlinie” (thermal line) and coincides with the basin margin faults in the subsurface.

Geothermal energy generation in Austria is concentrated on the Molasse Basin in Upper Austria and the Styrian Basin in the Southeast of Austria. Here, the conditions are favorable for the usage of geothermal energy exploration, even though the potential is far greater than the actual exploitation. As faults provide normally an easy gateway for water to be transported into the depth and up to the surface again, the knowledge of their location is of vital interest. In the Vienna Basin, the potential and the risks of geothermal energy exploitation is currently assessed (www.geotiefwien.at). As the faults in the Vienna Basin are known to be active during the Quaternary, the potential for induced seismicity is an important factor in the assessment.

4.6.4 Groundwater and water supply

The influence of faults on aquifers plays a major role in the Neogene basins, where groundwater depth can change significantly across faults or can be bounded by faults. However, the interplay between faults and groundwater is complex and must be investigated for each fault and aquifer separately. Therefore, good knowledge of the fault location is important.

Since 1910, Vienna, the capital of Austria, receives a major part of its freshwater supply from the karstic plateau region of the Hochschwab. Water of several springs at the base of the plateau are collected and then transferred via aqueducts to Vienna. The understanding of the fault network within the Hochschwab and its connection to the springs is important for a sustainable and reliable water management of Vienna (Bauer et al., 2016).

4.6.5 Infrastructure

Austrian mountainous landscape demands the construction of several tunnels or bridges for both, cars and trains along European trunk sections. Due to the complex geological situation at most of the construction sites, intensive geological investigations are part of these large projects and generally started 10 years before construction. In the case of the Brenner basis tunnel between Austria and Italy, the tunnel is planned to run parallel to a major fault system, the Brenner-Silltal Fault System (e.g., Bergmeister, 2019). Other large construction projects include those of the Koralm tunnel cutting the Lavanttal fault (e.g., Schubert et al., 2010) and the Semmering base tunnel (e.g., Holzer et al, 2020). In addition, the construction of reservoir dams was and is necessary for a self-sustaining energy management in Austria. Therefore planning and construction is in a close connect to the local tectonic situation including faults (Clar & Horninger, 1964). In all cases, detailed understanding of the local fault inventory is of utmost importance (e.g., Lenz et al., 2017). Information of fault occurrences in advance helps significantly in order to plan the needed amount of geological investigations and to foresee difficulties associated with possible fault occurrences, such as the degree of disintegration or the hydrogeological properties of the rocks (e.g., Saugruber & Brandner, 2001).

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5 RBINS-GSB – BELGIUM

5.1 Overview

Within its relatively small territory (~30.5 km²), a large part of the geological timescale is covered in Belgium with minor hiatuses, from the Lower Paleozoic to the Quaternary. Sedimentary rocks predominate in the subsurface of Belgium, with subordinate magmatism and metamorphism.

Lower Paleozoic basement

The Belgian basement is split into two different geotectonic domains: the southern part belongs to the Variscan Rhenohercynian Zone, and the northern part to the Anglo-Brabant Fold Belt (e.g. Verniers et al., 2002).

The Cambrian-Silurian basement was consolidated during the two main events of the Caledonian Orogen, resulting from the closure of the Iapetus Ocean. The first collisional stage between the Avalonia microplate, where Belgium is located, and Baltica during the Middle and Late Ordovician resulted in the Ardenne deformation phase. Throughout the end of the Silurian, the Avalonia-Baltica composite collided with Laurentia located to the north, resulting in the Brabantian deformation phase (Boulvain & Vandenberghe, 2017). Paleozoic inliers from this cycle include, from north to south, the Brabant Massif, the Condroz Inlier, and the Ardenne Inliers (**Fig. 1**). They record different supersequences of sedimentation spanning from the Lower Cambrian to the Silurian, starting from littoral or platform sandstones and ending with deep hemipelagic or turbiditic deposits (Boulvain & Vandenberghe, 2017).

Structurally, the Caledonian deformation in these sequences can be identified as following (after Debacker et al., 2005, and Boulvain & Vandenberghe, 2017):

- Steeply dipping folds associated with a subvertical schistosity in the Cambrian core and moderately dipping folds with a north-dipping schistosity in the Ordovician-Silurian border of the Brabant Massif.
- South-verging folds associated with a north-dipping schistosity in the Condroz Inlier.
- Thrust sheets and tight north-verging folds in the Ardenne Inliers.

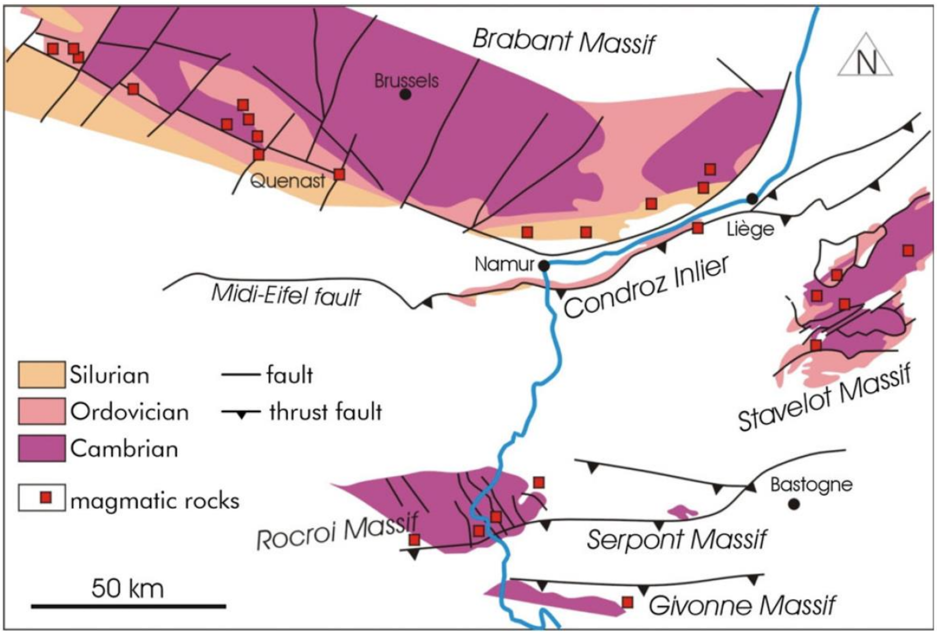

Fig. 1: Simplified geological map of the Belgian Lower Paleozoic inliers with magmatic rocks (after Boulvain & Vandenberghe, 2017).

Devonian-Carboniferous sedimentary-tectonic cycle

The basement is unconformably covered by a thick Devonian-Carboniferous series consolidated during the Variscan Orogeny, which also reworked the Lower Palaeozoic rocks of the Ardenne Allochton (Cambier & Dejonghe, 2010).
The Devonian sedimentation cycle is marked by the Devono-Dinantian transgression event of the Rhenohercynian Sea. Detrital sedimentation during the lower Devonian marked the first of three successive pulses, when the sea receded to the south, eroding the lower Paleozoic basement. Towards the Middle Devonian, a transgressive regime is resumed, giving way to the first carbonated platforms over southern Belgium. The entire Brabant massif was flooded during the third pulsation (Upper Devonian), establishing a new carbonate platform shifted northward (Pirson et al. 2008).

Carbonate production continued throughout the early Carboniferous until Variscan deformation began, forcing the uplift of the Variscan mountain belt and the retreat of the sea to the north. Consequently, the sediments previously deposited by the transgression event were highly deformed (Boulvain & Vandenberghe, 2017).
The Variscan orogeny is a result from the closure of the Rheic Ocean during the Late Carboniferous, and consequent continental collision between Laurussia and Gondwana. The Variscan tectonics shapes the general structure of Belgium (**Fig. 2**), with the major Midi-Eifel thrust fault separating the Rheno-Hercynian fold-and-thrust belt (Ardenne allochthon) to the south from the Variscan foreland (Brabant parautochthon) to the north (Boulvain & Vandenberghe, 2017).
The Ardenne Allochthonous is structured in large-scale anticlines and synclines that extend eastward into Luxembourg. The Lower Paleozoic foreland (Brabant Massif) and its Devono-Carboniferous cover (Namur Synclinorium) are overlaid by this allochthon. The rocks situated north of this thrust complex belong to the Brabant Parautochthonous (Cambier & Dejonghe, 2010).

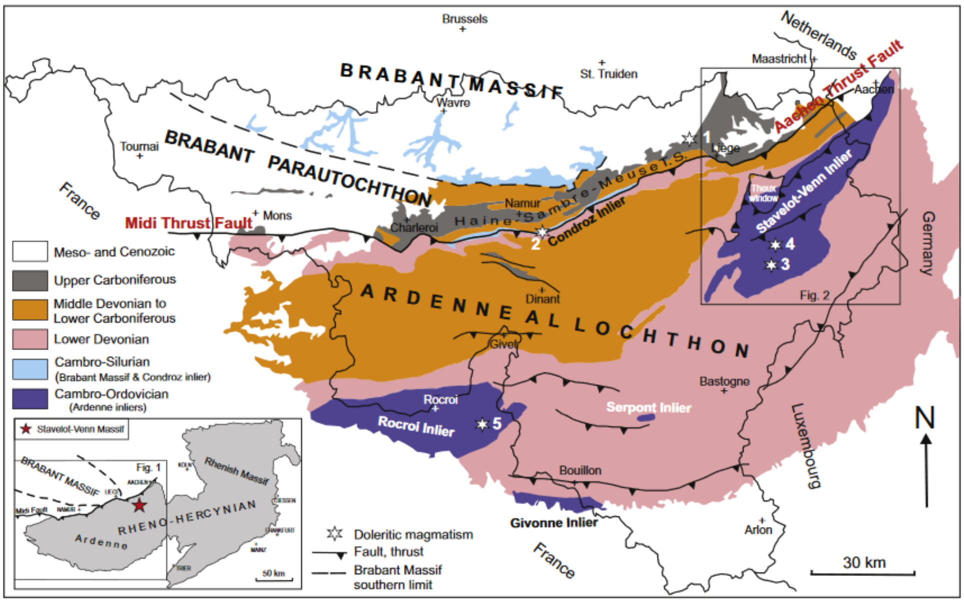

Fig. 2: Simplified geological map of the Variscan front, with indication of the main tectonostratigraphic units (after Herbosch et al., 2020).

Post–orogenic times

Limited brittle deformation and epeirogenic movements in the Belgian region followed the Variscan orogeny. From the Permian to the present, further sediment accumulation was made possible by subsidence (Boulvain & Vandenberghe, 2017).

Permian formations are scarce in Belgium due to generalized continental conditions when Pangea transitioned into an arid climate induced by its vast surface. Alluvial fan conglomerates crop out in the Stavelot-Malmédy area and Permian marine deposits were cored in the deep subsurface in the Campine Basin (Boulvain & Vandenberghe, 2017).

Triassic-Jurassic sediments

The Triassic and Jurassic series are defined by the break-up of Pangea and the epicontinental seas periodically flooding Belgium, The Netherlands and Germany. The climate was still warm and the erosion of the Variscan mountain belt supplied large amounts of detrital material into the seas. Marine Triassic-Jurassic series are restricted to the Belgian Lorraine in southeast Belgium. Boreholes in the Campine Basin also registered rocks from that period (Pirson et al., 2008).

Cretaceous cover

During the Cretaceous, Pangea was completely broken up. Large part of Belgium was progressively flooded until reaching very high sea levels in the Late Cretaceous. Deposits of (mostly) marine and unconsolidated sediments that may reach several hundred meters of thickness, resulted from relative sea-level fluctuations and sea migration to the N/NW. Cretaceous units crop out in the Liège-Maastricht area and in the Mons Basin (Boulvain & Vandenberghe, 2017).

The Cenozoic

Most of the northern area of the Sambre-Meuse drainage line is covered in Cenozoic sedimentary deposits and only minor outliers occur over the Condroz and Ardenne. These deposits were formed at the southern rim of the North Sea basin when the sea was a shallow area subsiding due to thermal cooling over a failed Mid-Mesozoic rift (Boulvain & Vandenberghe, 2017).

During the Paleogene and Neogene, the sea episodically invaded Belgium, mostly from the North. Marine sediments reach several hundreds of meters in northern Belgium. However, these sediments were progressively more distant from the Sambre and Meuse axis, which was linked with the generalized uplift of the Ardenne and the subsidence of the Netherlands Basin (Pirson et al., 2008).

In southern Belgium, the Eocene-Oligocene sea made few incursions that rarely crossed over the Sambre and Meuse line. Evidence of these invasions are found in residual superficial deposits in the Liège and Namur areas as well as marine sands trapped in karstic sinkholes in the Condroz. However, the subsiding Mons Basin kept trapping marine deposits during the first part of Paleogene. Neogene marine sediments are absent in southern Belgium (Pirson et al., 2008).

A thin layer of Quaternary deposits covers northern Belgium. The coastal plain deposits belong to the early Pleistocene and the series along the coast belongs to the later Pleistocene. Other Quaternary layers are mainly fluviatile sediments and aeolian loam and cover sands. These sediments display periglacial structures that were acquired during glacial periods. The presence of river terraces is due to the interaction of tectonic uplift and river erosion and deposition during glacial–interglacial cycles. Middle Pleistocene Rhine and Meuse deposits constitute the Campine Plateau, which are bordered to the west by the Mol-Rauw Fault. Considerably thick Holocene deposits are found along the present coast and in the river valleys (Boulvain & Vandenberghe, 2017).

The geology of Belgium is summarized in **Fig. 3**. As described earlier, in the Flemish Region in northern Belgium, Cenozoic deposits are predominant. In the Walloon Region in southern Belgium, there are predominant consolidated Paleozoic rocks, strongly deformed at the end of the Carboniferous during the Variscan Orogeny; Mesozoic rocks are less abundant, and Cenozoic rocks are restricted to the Mons Basin.

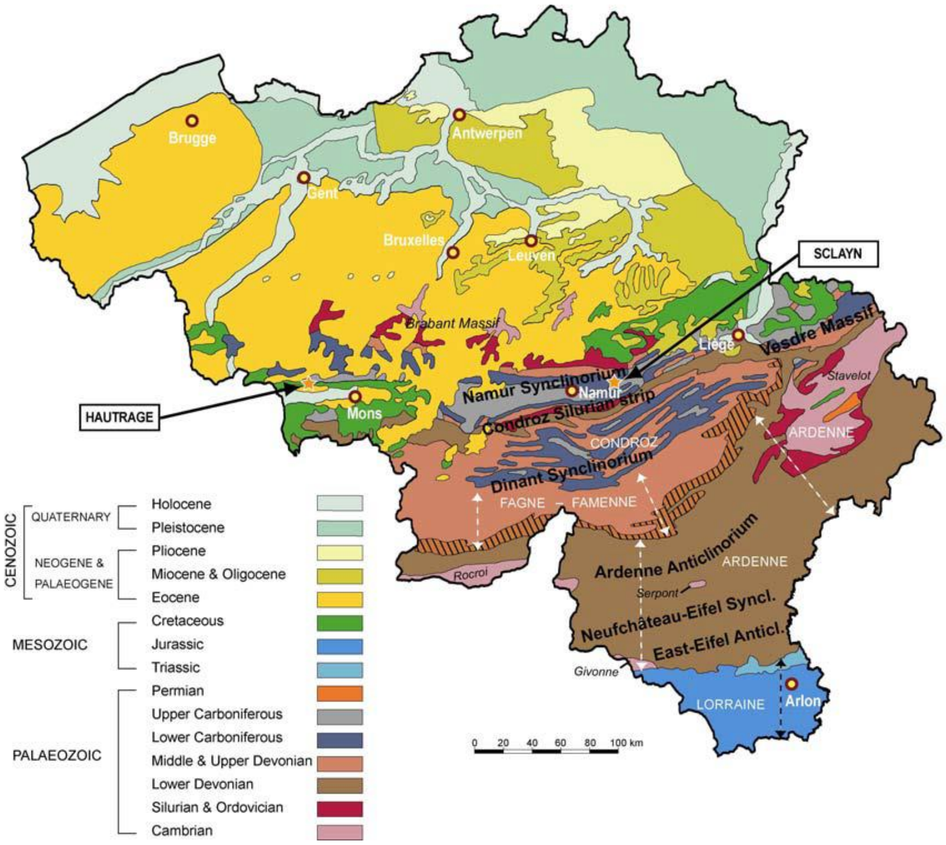

Fig. 3: Simplified geology of Belgium. After Pirson et al. (2008).

5.2 Fault patterns and characteristics

The main fault patterns in Belgium originate from its geological history described earlier. As it is the case with the country's geology, main fault styles can be broadly divided into two different domains in the south and in the north. The following information is compiled from Cambier & Dejonghe (2010; 2012).

The **southern domain** corresponds to a geotectonic region of the Variscan area in Europe, where faults follow NE-SW to WNW-ESE trends resulting from the Variscan Orogen. The Variscan front thrust (**Fig. 4**) is subdivided into several connected segments that are from west to east: The Midi Fault, the Sambre and Meuse inlier, the Eifelian Fault, and the Aachen Fault.

The frontal fault system of the Ardenne Allochthon comprises the Dinant Synclinorium and the Vesdre Nappe to the NE as its lateral equivalent, of Devonian-Carboniferous age. An association of longitudinal faults (north-vergent folds and south-dipping reverse faults) was developed during the Variscan compression and are abundant in the Dinant Synclinorium.

The inner part of the Ardenne Allochthon comprises the Ardenne Anticlinorium and the Neufchâteau-Eifel Synclinorium, which form the High-Ardenne slate belt. These Lower

Devonian pelitic rocks present a dominant slaty cleavage developed in response to the Variscan compression.

In the axial part of the Ardenne Anticlinorium, three main Lower Paleozoic inliers crop out: the Rocroi, the Serpont and the Stavelot-Venn Massifs. The Cambric Givonne Massif is located to the south of the Eifel Synclinorium. The interpretation of the faults crosscutting these Cambrian-Ordovician basement inliers is unresolved due to possible links to either Caledonian and/or Variscan orogenies.

The Belgian Lorraine, of Triassic-Jurassic age, is in the southernmost part of Belgium and corresponds to the northeast border of the Paris Basin. The rocks found here are displayed slightly dipping south and are unconformably covering the southern limb of the folded Variscan Eifel Synclinorium. Many NNE-striking and subvertical faults crosscut this Mesozoic cover.

The **northern domain** belongs to the Lower Paleozoic Brabant Massif and it forms the eastern termination of the British-Belgian Caledonides. Because of an extended, mainly Eocene cover, most of the Brabant Massif does not outcrop.

Comprising the Brabant Parautochthon are the Brabant Massif to the north and the "Namur Synclinorium" and Liège Syncline to the south. The latter is located in the footwall of the Midi-Eifelian Fault and constitute the unconformable Upper Paleozoic cover of the Brabant Massif. The Namur and Liège units are part of the foreland Variscan basin over which the Ardenne Allochthon is thrust. The southern part of the Brabant Parautochthon is disrupted by many longitudinal, south-dipping thrust faults linked to the Variscan front thrust.

The Campine Basin, of Devonian-Carboniferous age, covers the northeastern flank of the Brabant Massif. Several NW-SE striking normal faults are found in this region and were mostly reactivated in a contractional way. The formations of the Campine Basin are overlaid by rocks of Permian to Jurassic age.

Four major subsidence stages and synsedimentary tectonics associated with temporary contractional events enable the filling and structuring of the Mons Basin. This Cretaceous to Paleogene sedimentary filling is in the western Belgian Variscan front zone. Several networks of differently striking normal faults are related to that tectonics.

The northeast corner of Belgium corresponds to the Roer Valley Graben, a seismically active subsiding area of the Rhine Graben rift system (**Fig. 4**). Two sets of antithetic, normal and NNW-SSE striking faults of Quaternary age bound this graben. However, only the Feldbiss Fault to the west is partly in Belgium.

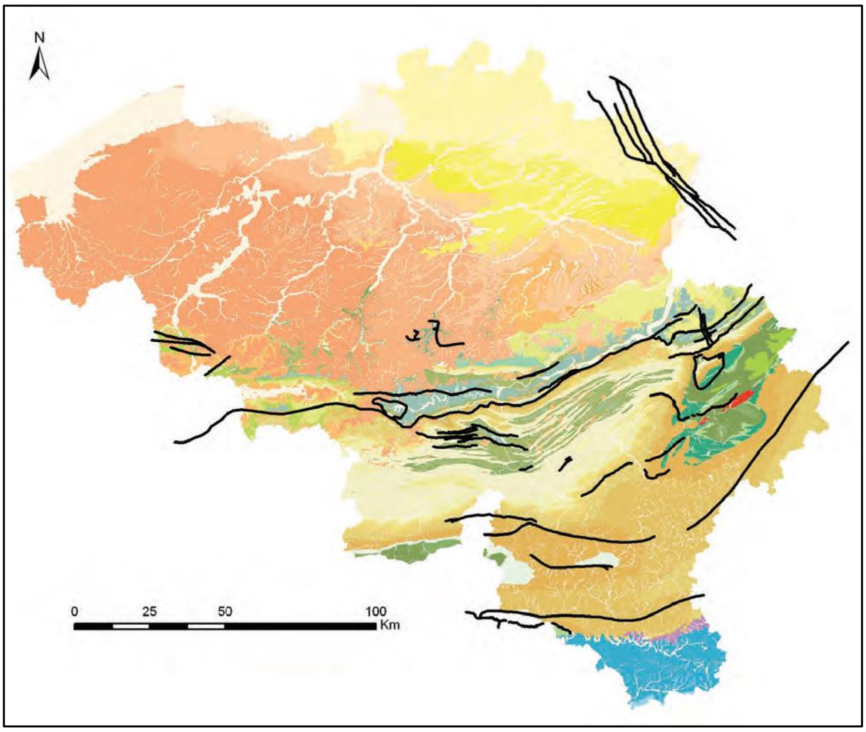

Fig. 4: Main faults in Belgium represented in black. Legend of the lithostratigraphic background corresponds to the International Stratigraphic Chart. After Cambier & Dejonghe (2012).

5.3 Structural framework

The structural framework of Belgium (**Fig. 5**) developed as part of the GeoConnect³d project (https://geoera.eu/projects/geoconnect3d6/) summarizes the main geologic and tectonic elements in the country. In the structural framework model, faults and other planar surfaces (e.g. contacts and unconformities) are treated as geological *limits* that often define geological *units*.

Based on the geological history of Belgium, the geological limits identified include regional *unconformities* and *contacts*, the Variscan *deformation front*, and various *faults*. The regional units then follow:

Lower Palaeozoic basement:

- The Brabant Massif, limited by the unconformity between late Silurian-Lower Devonian deep marine deposits and Middle Devonian conglomerates (Linnemann et al., 2012).
- The Condroz inlier, limited by the contact between its more competent rocks and surrounding Upper Devonian shales (Thorez et al., 2006).
- The Ardenne inliers Stavelot and Rocroi Massifs, limited by angular unconformities between the inliers and Pridoli-Lochkovian deposits (Sintubin et al., 2009; Herbosch et al., 2020).

Devonian-Carboniferous sedimentary-tectonic cycle:

- The deformed rocks of the Ardenne Allochthon, the northernmost thrust nappe of the Rhenohercynian foreland fold-and-thrust belt, limited in the north by the Variscan deformation front (Sintubin et al., 2009)
- The foreland Namur Basin, part of the regional Rhenish Massif, between the Variscan deformation front and the Brabantian unconformity.

  Triassic-Jurassic sediments:
- The Paris Basin, defined by the unconformity between its flat-lying, gently south-dipping Triassic-Jurassic sedimentary sequence covering the southern limb of the Ardenne Allochton.

  Cretaceous-Cenozoic sediments:
- Sedimentary sequences in the Campine Basin and Roer Valley Graben, mostly defined by normal faults.

  The complete structural framework model, covering different scale ranges, will be available for free consultation in the EGDI platform from October 2021.

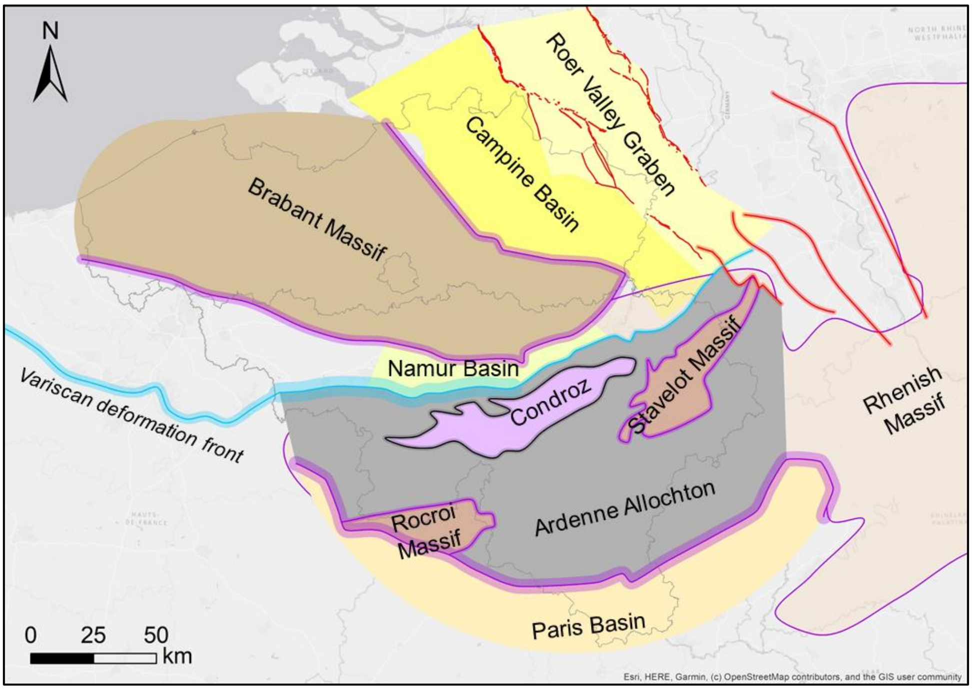

Fig. 5: GeoConnect³d structural framework highlighting main limits and units in Belgium. Geological limits represented: unconformities in purple, contact in black, deformation front in light blue, and faults in red.

5.4 Data availability and quality

Data availability varies for the different regions in Belgium.

For the southern domain, data was compiled from the recently completed geological mapping campaign by the Geological Survey of the Walloon Region. These maps are on the scale of 1/25,000, and structural maps available for some areas are on the scale of 1/75,000. Although the campaign is complete, not all maps are available for consultation and download as of December 2020 (**Fig. 6**). For a complete coverage of this region, publications on specific areas (e.g. Belanger et al., 2012) and the geological maps published in the early 1900s on the scale 1/40,000 were used.

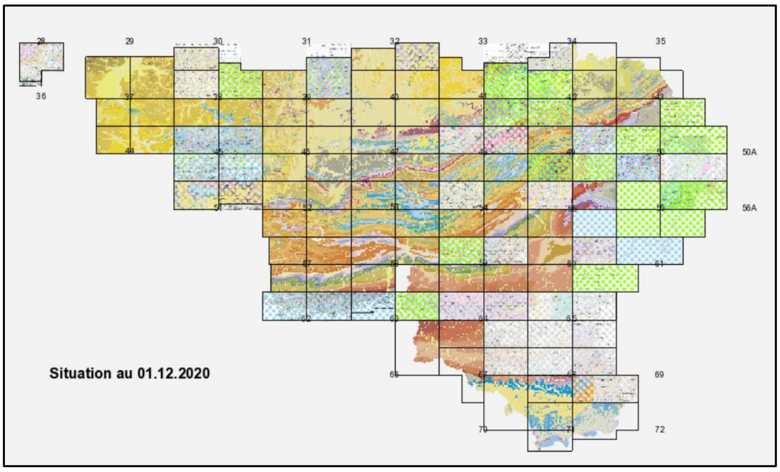

Fig. 6: Coverage of the geological mapping of the Walloon Region. Areas hatched in green, blue and grey are not yet available for consultation and download. (http://geologie.wallonie.be/home.html)

For the northern domain, 2D seismic surveys are the main source of information for mapping the stratigraphic horizons and faults in the subsurface. Data from the residual Bouguer gravity anomaly map of Belgium and wells complete the source material. Uncertainties and confidence levels are largely determined by the scale at which elements were mapped and quality of seismic data (e.g. decreasing resolution with depth). Horizontally and vertically, mapping errors range between tens to a few hundreds of meters.

5.5 Fault data included in HIKE fault database

For Belgium, the data included in the fault database (**Fig. 7**) is derived from the structural framework model of the Roer-to-Rhine area of interest (https://geoera.eu/projects/geoconnect3d6/roer-to-rhine-case-study-r2r/). This means the result is not a fault inventory of the whole country, but a highlight of faults of regional geological importance inside the area of interest.

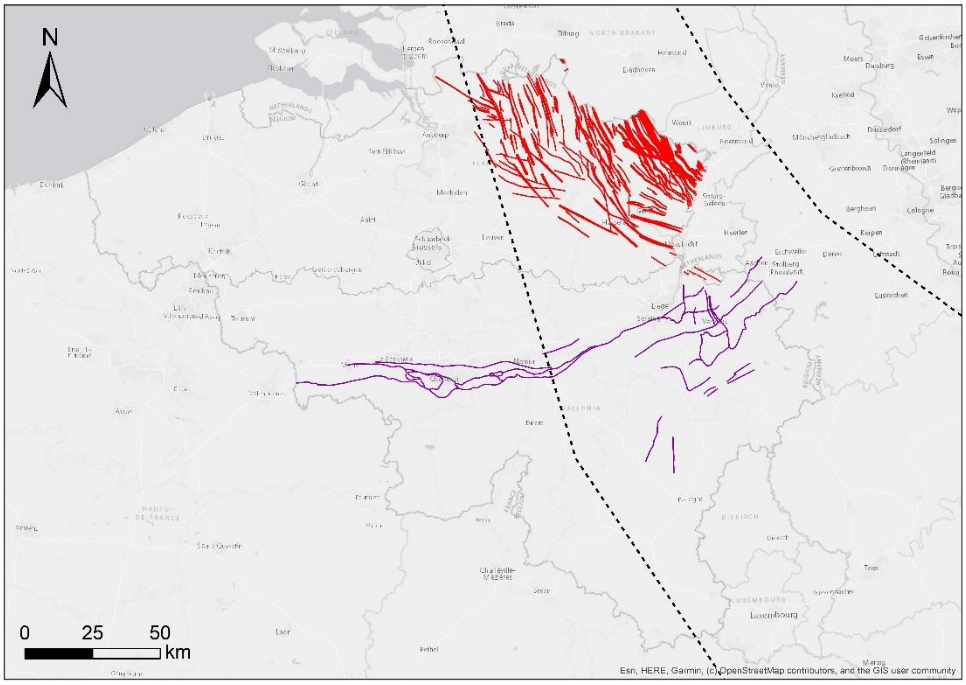

Fig. 7: Fault traces from the GeoConnect³d structural framework of the Roer-to-Rhine are of interested (inside dashed line) included in HIKE fault database. In purple: data from GSB; in red: data from VITO.

For fault data in the Walloon Region to the south, faults are mapped at surface. For fault data in the Flemish Region to the north, faults are represented as lines intercepting relevant reference surfaces at depth, namely the bases of Quaternary, Neogene, Paleogene, Cretaceous, Jurassic and Permian-Triassic, as well as the top of the Dinantian. Fault data are therefore being delivered as 2D intersection lines with the topography or main stratigraphic horizons at depth.

The faults are classified according to the hierarchical semantic framework of GeoConnect³d, which is similar to that of HIKE. This includes a correlation link with the faults in neighboring countries (in particular the Netherlands). Fault attributes covered in GeoConnect³d include basic information on geometric and timing aspects, as well as reference surface for the trace, fault type, and observation/evaluation method.

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6 GEUS - DENMARK

6.1 Top pre-Zechstein Tectonic structures and Fault zones in Denmark

The fault zones presented in the Danish territory are published in “Geological map of Denmark, 1:750 000” 1994: Ole Valdemar Vejbæk & Peter Britze (eds). The 'Top pre-Zechstein' is the deepest regional surface, which can be mapped seismically throughout the Danish area, and all Late Paleozoic to Mesozoic major tectonic structural elements and fault zones in Denmark are represented in this surface.

The mapped 'Top pre-Zechstein' surface represents the top of the youngest pre-Zechstein Palaeozoic deposits, where Palaeozoic deposits are present, or else the top of the Precambrian rocks. The surface also represents the base of the Zechstein Group, where Zechstein is present, or else the base of the Mesozoic/Cenozoic. The subcrop against the Quaternary is an angular unconformity, which is continuously identified along the northeastern boundary from the Stavanger Platform area to the Hano Bay Basin (cf Jensen & Schmidt 1991, Jensen & Michelsen 1992, Japsen 1992). The mapping of this boundary is locally based on published information, notably in the Skagerrak and Kattegat areas (Ro et al. 1990, Lykke-Andersen 1993, **H.** Lykke-Andersen, pers. comm. 1993).

Due to cooperation with Lars N. Jensen (STATOIL, Stavanger), and Mikael Erlstrom and Ulf Sivhed (SGU, Lund) the final map extends beyond the borders of the Danish area. Lars N. Jensen has contributed with the interpretation of the bordering Norwegian area and Mikael Erlstrom and Ulf Sivhed with the Swedish landscape of Skåne (Scania) and adjacent Swedish waters. Fault trends are extended into Polish waters southeast of the Bornholm area in the Baltic Sea based on maps published by Dadlez (1990) and maps made available by Inge Nering-Lehfelt (pers. comm.). Fault trends north of the German island of Rugen are based on Thomas et al. (1993) (see also Piske & Neumann 1993). Fault trends are extended into Schleswig-Holstein and the German North Sea based on Best et al. (1983), Best (1989) and Franz Kockel (pers. comm.).

6.2 Database

Mapping using all 1993 public domain seismic and well data (Nielsen & Japsen 1991) in Denmark is the basis for this fault zone map. The database comprise all released reflection seismic data in the Danish area, seismic data owned by STATOIL in the Norwegian area, and all data available to the SGU in the Swedish area. The seismic data vary in quality from single fold analogue sections to 3D data. Where reflection seismic data are sparse or poor in quality, other geophysical methods (refraction seismic data, magnetic data and gravity modelling) have been used to improve the map. In areas with very high data coverage, especially where 3D seismic surveys were available , only the best quality data were used.;.

Structural elements

The major structural elements found within the Danish area are given on the structural faults of Europe Web GIS and shown on the structural element map (figure 1). These major structural elements are, from northeast to southwest: The Skagerak-Kattegat Platform (EUGENO-S working group 1988), the Sorgenfrei-Tornquist Zone (EUGENO-S working group 1988), The Norwegian - Danish Basin, The Ringkøbing-Fyn High (Sorgenfrei & Buch 1964), and the North German Basin (Rasmussen 1978). The Central Graben defines the termination of the Ringkøbing-Fyn High to the west (Rasmussen 1978). The names of minor elements and fault zones affecting the mapped surface, as abbreviated on the structural element map (figure 1), are listed below in alphabetical order with literature references:

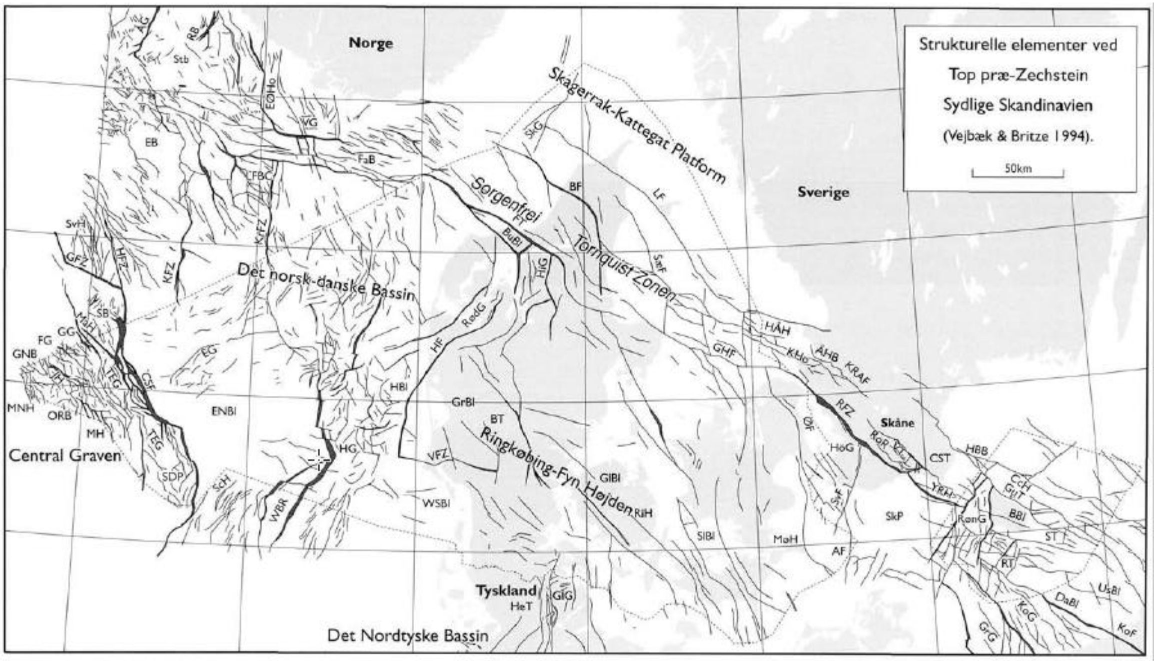

Figure 1: Danish structural elements at Top pre-Zechstein level. (from Vejbæk & Britze, 1994)

ASB	Arnager-Sose Block	(Gravesen et al.1982)
AF	Agricola Fault	(Thomas et al.1993)
BBI	Bornholm Block	(Andersen et al. 1975)
BF	Børglum Fault	(Liboriussen et al. 1987)
BT	Brande Trough	(Rasmussen 1978, EUGENO-S working group 1988)
BuBI	Bulbjerg Block	(Vejbæk & Britze 1994)
ChH	Christians Ø High	(Andersen et al. 1975)
CSF	Coffee Soil Fault	(Gowers & Sæbøe 1985)
CST	Colonus Shale Trough	(Bergstrom et al. 1982)
DaBI	Darlowo Block	(Dadlez 1974, 1976, 1977, 1990)
EB	Egersund Basin	(Brekke et al. 1989)
EG	Else Graben	(Cartwright 1990)
ENBI	East North Sea Block	(Rasmussen 1978)
EØHo	Eigerøy Horst	(Brekke et al. 1989)
FaB	Farsund Basin	(Hamar et al. 1983, Jensen & Schmidt 1991)
FG	Feda Graben	(Gowers & Sæbøe 1985, Brekke et al. 1989)
FT	Fjerritslev Trough	(Vejbæk 1990)
GFZ	Gyda Fault Zone	(Brekke et al. 1989)
GG	Gertrud Graben	(Møller 1986, Vejbæk 1986, Brekke et al. 1989)

GHF	Grenå - Helsingborg	(Mogensen & Jensen 1994)
GlG	Glückstadt Graben	(Best et al. 1983)
GIB!	Glamsbjerg Block	(Rasmussen 1978)
GNB	Grensen Nose Basin	(Gowers & Sæbøe 1985)
GrBl	Grindsted Block	(Rasmussen 1978)
GrG	Gryfice Graben	(Dadlez 1974, 1976, 1977, 1990, Thomsen et al. 1987)
GuT	Gudhjem Trough	(Vejbæk 1985)
HBl	Holmsland Block	(Rasmussen 1978)
HBB	Hano Bay Basin	(Kumpas 1980)
HeT	Helgoland Trough	(Best 1989)
HFZ	Hummer Fault Zone	(Brekke et al. 1989)
HiG	Himmerland Graben	(Vejbæk 1990)
HF	Holmsland Fault	(Rasmussen 1978)
HG	Horn Graben	(Rasmussen 1978, Best et al. 1983, Vejbæk 1990)
HoG	Hollvik Graben	(Bjelm et al. 1979)
HÅH	Hallands Ås High	(mod. Bergstrom et al. 1982)
IH	Inge High	(Møller 1986, Vejbæk 1986)
KFZ	Krabbe Fault Zone	(Brekke et al. 1989)
KoF	Koszalin Fault	(Dadlez 1990, Thomsen et al. 1987)
KoG	Kolobrzeg Graben	(Dadlez 1974, 1976, 1977, 1990)
KRAF	Kullen Ringsjon Andrarum Fault	(Norling & Bergstrom 1987)
KrFZ	Krebs Fault Zone	(Brekke et al. 1989)
KHo	Kullen Horst	(Bjelm et al. 1979).
LF	Læsø Fault	(J. M. Hansen pers.comm.)
LFBC	Lista Fault Block Complex	(Brekke et al. 1989)
MaH	Mandal High	(Rasmussen 1978, Hamar et al. 1983, Gowers & Sæbøe 1985, Brekke et al. 1989)
MH	Mads High	(Møller 1986, Vejbæk 1986)
MNH	Mid North Sea High	(Rasmussen 1978)
MøH	Møn High	(mod. Rasmussen 1978)
ORB	Outer Rough Basin	(Gowers & Sæbøe 1985)
RB	Rott Basin	(Brekke et al. 1989)
RFZ	Romele Fault Zone	(Bergstrom et al. 1982)
RiH	Ringe High	(Vejbæk & Britze 1994)
RoR	Romele Ridge	(Norling & Bergstrom 1987)
RT	Risebæk Trough	(Thomsen et al. 1987)
RødG	Røding Graben	(Madirazza et al. 1989)
RønG	Rønne Graben	(Andersen et al. 1975)
SB	Søgne Basin	(Gowers & Sæbøe 1985, Brekke et al. 1989)
ScH	Schillergrund High	(Best et al. 1983)
SDP	Salt Dorne Province	(Møller 1986)

SkG	Skagerrak Graben	(Ro et al. 1990)
SkP	Skurup Platform	(Bjelm et al. 1979, Bergstrom et al. 1982)
ST	Svaneke Trough	(Thomsen et al. 1987)
StBI	Stigsnæs Block	(mod. from Rasmussen 1978)
StP	Stavanger Platform	(Sørensen & Martinsen 1987, Brekke et al. 1989)
SvF	Svedala Fault	(mod. from Bjelm et al. 1979, Bergstrom et al. 1982)
SvH	Sørvestlandet High	(Gowers & Sæbøe 1985, Brekke et al. 1989)
SæF	Sæby Fault	(Vejbæk & Britze 1994)
TEG	Tail End Graben	(Andersen et al. 1982)
UsBI	Ustka Block	(Dadlez 1990, Thomsen et al. 1987)
VFZ	Varde Fault Zone	(Vejbæk & Britze 1994)
VG	Varnes Graben	(Brekke et al. 1989)
VT	Vomb Trough	(Bjelm et al. 1979, Bergstrom et al. 1982)
WBR	Weisse Bank Ramp	(kockel, pers. Comm.1993)
WSBI	West Schleswig Block	(Best et al. 1983)
YRH	Ystad - Rønne High	(Vejbæk & Britze 1994)
ÄHB	Ängelholm Basin	(Bergström et al. 1982)
ØF	Øresund Fault	(Bjelm et al. 1979.)
ÅG	Åsta Graben	Brekke et al. 1989)

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7 BRGM – FRANCE

7.1 Pyrenees domain

The Pyrenees, at the border between France and Spain, constitutes a typical example of an intraplate orogen. Only the northern part of the Pyrenean chain and its (retro-)foreland basin, the Aquitain Basin, belong to the French territory.

The history of the Pyrenees results from the different opening stages of the Atlantic Ocean. First, the central Atlantic opening reactivated inherited Permian faults, NE-SW (CAMP) and mainly WNW-ESE oriented, forming a basin, which connected the Central Atlantic to the Thethys during Triassic to Jurassic times. Then, the opening of North Atlantic produced the well-known hyper-extended Albo-Cenomanian rifting leading, thanks to detachment faults, to sub continental mantle exhumation. Finally, the South Atlantic opening induced a northward displacement of the African plate causing, from the Campanian to Oligocene, to the inversion of the Albo-Cenomanian basins and their margins, the result being the Pyrenean orogeny.

In this context, all the faults belonging to the Pyrenean domain were created during this period of convergence between the Iberian microplate and the European plate, from Upper Santonian (84 Ma) to the Lower Miocene (20Ma), interrupted by a quiescent stage during late Maastrichtian - Paleocene.

Most of the major (crustal) faults identified in the Pyrenees result from the inversion of preexisting normal or detachment faults that limited the edges of the rift-basins. These extensional faults themselves originated from the reactivation of dextrous (transpressive and/or transtensive) faults generated at the end of the Variscan orogeny (Permo-Carboniferous, from 320 to 270 Ma) in the core of the Ibero-Armorican arc.

3 of these major faults limit the main current tectonic zones of the northern part (French part) of the Pyrenees. Are distinguished from South to North : the North Pyrenean Fault (NPF), The North Pyrenean Frontal Thrust (NPFT) and Sub-Pyrenean Thrust (SPT).

The northernmost fault thrust is the Sub-Pyrenean thrust which is a blind thrusting evidenced by seismic profiles. This fault constitute the limit between the Pyrenean domain and the Aquitain Basin.

The North Pyrenean Frontal Thrust (NPFT) corresponds to northwards inversion of the North Pyrenean rift basins. In the eastern part the NPFT joins the Corbière Thrust showing a westwards kinematics.

The North Pyrenean Fault (NPF) is a crustal upright fault putting in contact high-T metamorphic Mesozoic marbles of the North Pyrenean Zone with the Paleozoic sediments of the Axial Zone. This fault, seismically active, is located in the Central and Eastern part of Pyrenees and disappears in the Western Pyrenees, replaced by South verging thrustings such as Barousse, Bigorre, Ferrière or Lakhoura thrusts. All these thrust faults corresponds to the southward inversion of the southern part of the Cretaceous rift-basins.

To the South of the latters, the Axial Zone (ZA) corresponds to the south margin of the cretaceous rift-basins. The ZA is also structured by southwards thrust sheets as the famous Gavarnie or Eaux-Chardes thrust sheets, in the western part, or Aspres and Canigou thrusts, in the East. All these faults are also inherited from late-Variscan and Cretaceous tectonics.

8 BGR - GERMANY

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8.1 Introduction

The present picture of Germany's subsurface and distribution of different lithologies at the surface originates from multiple, tectonic phases, accompanied by the formation of e.g. several basins (*Error! Reference source not found.**Fig. 1a***) and complex fault systems (*Error! Reference source not found.**b, c***). Today's knowledge about the structure of the deeper subsurface has been developed over decades, is based on geological and geophysical data that differ in type, density and quality. After a short presentation of the origin, basis and data responsibility of fault-related data (*chapter 8.2*), superordinate structural styles (*chapter 8.3*) as well as the essential characteristics of individual structural areas are presented (*chapter 8.4*). Finally, due to their great importance for today's structural appearance of Germany, the Cenozoic rift valley system (*Chapter 0*) as well as the characteristics of salt structures are presented (*Chapter 8.6*). Finally, we briefly present the concept of how we proceeded with the hierarchical differentiation of the faults for the fault database (*chapter 0*).

8.2 Data base & data responsibility in Germany

8.2.1 Data base

The data provided by the Federal Institute for Geosciences and Natural Resources (BGR) in the GeoEra HIKE fault database are, with exception for the offshore area of the North and Baltic sea, based on data compiled within the Geothermal Atlas (Schulz et al. 2013). This dataset is made up by different map series (***Fig. 2***), such as e.g. the Geological surface map of Germany (1993, GÜK1000, ***Fig.1b***), the Geotectonic Atlas of North West Germany and the German North Sea (Baldschuhn et al. 2001), the Southern Permian Basin Atlas (Doornenbal & Stevenson 2010) and several more, which were collected, merged and generalized within the frame of the Geothermal Atlas (Schulz et al. 2013). In *Figure 1d* illustrates the generalized faults and fault zones presented in the Geothermal Atlas, which also are delivered for the HIKE-fault data base (for illustration of higher resolution see also Appendix 8.9.1 bis **Error! Reference source not f ound.**).
At this point it should be noted that the generalization of the Geothermal Atlas not includes a comparison of data available at the geological state authorities. The necessary generalization and harmonization of faults in an overview scale may differ in details from detailed data hosted by geological state authorities of Germany. Individual sections of a structure can also have different local or regional names, but in the following description they are only named in a superordinate manner.
For the offshore area (***Fig. 1a***, see also Appendix 0 bis **Error! Reference source not found.**), fault d ata provided for the Central German North Sea originate on Baldschuhn (2001). These data consist of generalized fault intersections with 13 Mesozoic to Cenozoic horizons and the Late Paleozoic Base Zechstein (Baldschuhn et al. 2001). For the northwestern part of the German North Sea, the Entenschabel, faults originate from interpretation of 3D-seismic data from the GPDN-Project (https://www.gpdn.de/; Arfai et al. 2014). Those faults are defined by vertical and horizontal fault-polyline seismic picks. Fault data of the Baltic Sea are based on the studies of Seidel et al. (2018), Seidel (2019) and fault intersections of 13 Mesozoic to Cenozoic horizons as well as the base Zechstein and base Upper Rotliegend from Doornenbal & Stevenson (2010). For

the HIKE-fault data base these fault intersections were assigned, where useful, to individual faults or fault systems due to their orientation, length or spatial proximity in the map view. Even if fault intersections spatially overlap, a direct linkage of a Meso-Cenozoic fault with the Pre-Zechstein must be questioned, as salt often acts as a decoupling element between the overburden and basement.

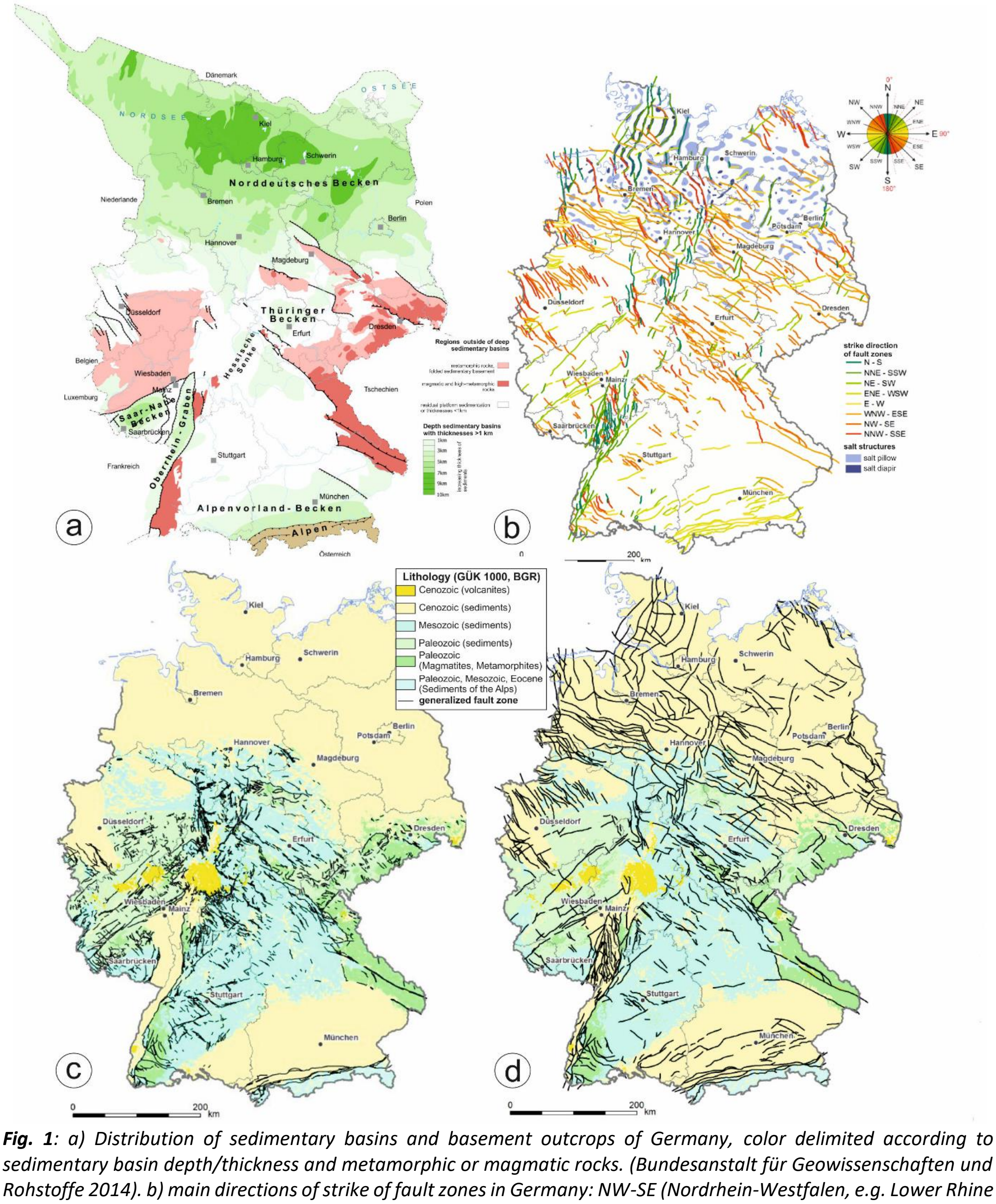


***Fig. 1**: a) Distribution of sedimentary basins and basement outcrops of Germany, color delimited according to sedimentary basin depth/thickness and metamorphic or magmatic rocks. (Bundesanstalt für Geowissenschaften und Rohstoffe 2014). b) main directions of strike of fault zones in Germany: NW-SE (Nordrhein-Westfalen, e.g. Lower Rhine Graben), WNW-ESE (southern North German Basin and Mid-German uplands), NNE-SSW (e.g. Upper Rhine Graben; Glücksstadt Graben, Horn Graben), WSW-ENE (Alps and Molasse Basin), NE-SW (Variscan deformed basement outcrops) (modified from Schulz et al. 2013). c) Fault inventory from the GÜK1000 (Bundesanstalt für Geowissenschaften & Rohstoffe 1993) of mapped faults at the surface, illustrating one of the database used within the Geothermal Atlas (modified from Schulz et al. 2013). d) Shows the map of important and generalized fault zones*

in Germany, compiled in the Geothermal Atlas (modified from Schulz et al. 2013) and delivered within the present fault database for GeoEra-HIKE.

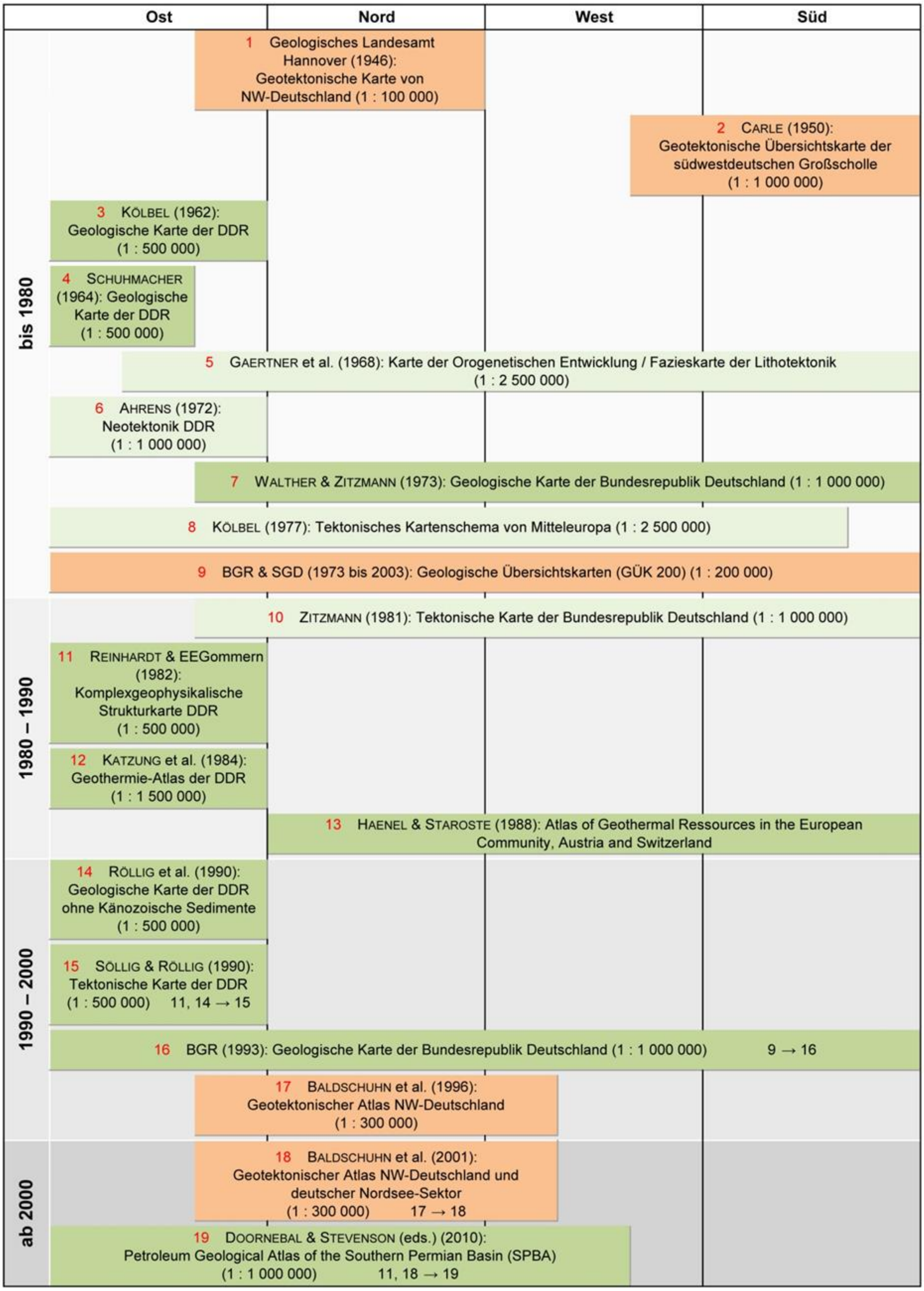


Fig. 2: *Overview of regional and supra-regional maps and map series with fault related data in onshore-Germany that were generalized and incorporated in the course of creating the Geothermal Atlas (Schulz et al. 2013).*

8.2.2 *Information of geological data responsibility in Germany*

In Germany the federal states and their respective state geological survey organisations (GSO) are responsible for matters, tasks and data relating to the geological subsurface up to the earth's surface in their area of responsibility. However, a nationwide planning of a safe and sustainable use of the underground requires geologically relevant data of the federal states harmonized, summarized and evaluated uniform across national and international borders.
This task is performed by the Federal Institute for Geosciences and Natural Resources (BGR), under reconciliation of the State Geological Surveys of the Federal States. On a supraregional scale, the BGR produces maps on a smaller scale between 1:1 000 000 to 1:200 000. For the production of supraregional maps with scales of 1:200,000 or larger, the SGD of the federal states are involved. For the Economic exclusive zone EEZs (and continental shelves) of the North Sea and Baltic Sea, these tasks fell to the BGR when the Geological Data Act (GeolDG) came into force in July 2020 (ttp://www.gesetze-im-internet.de/geoldg/).

8.2.2.1 Data base of the deeper subsurface in Germany

The knowledge about the deeper subsurface and in consequence on faults and fault systems is not only based on outcrop analysis, but especially on seismic and well data analysis. *Fig. 3* shows that both data types are mainly concentrated on three areas, the North German Basin, the South German Molasse basin and the Upper Rhine graben due to the exploration of oil and gas, salt mining and geothermal exploration respectively (***Fig. 3 a & b***, from BGR 2014, compiled from Müller & Reinhold (2011), Doornenbal & Stevenson (2010) and NIBIS-Kartenserver: https://nibis.lbeg.de/cardomap3/).
To understand the structure of the sedimentary basement, reflection seismic data and well data are often sufficient. However, gravimetric and magnetic data can often show the bedrock

geology as well as deep fault structures. Overview maps of the Bouguer anomaly (

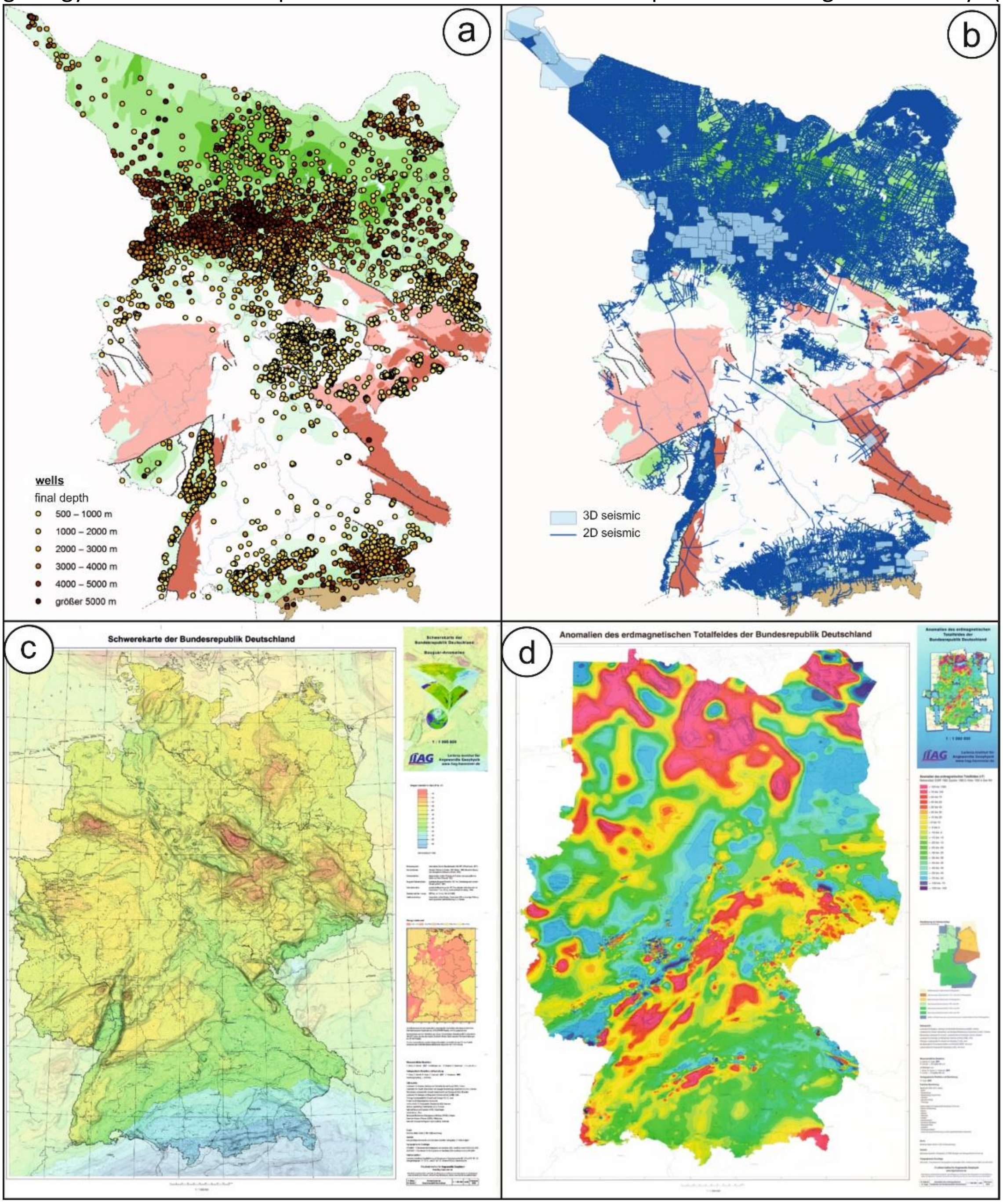


***Fig. 3: Overview maps of a) wells** with drilling depths over 500 m and b) 2D and 3D seismic sections in Germany (Bundesanstalt für Geowissenschaften und Rohstoffe 2014). Overview maps in a scale of 1:1000.000 of (c) the bouguer anomaly (Bouguer anomalies, GRS80, 0 m amsl) of Germany (Skiba et al., 2010) (d) and the Earth's total magnetic field (ΔT–anomalies, DGRF 1980.0, 1000 m a.s.l) of Germany (Gabriel et al., 2010). The maps are compiled and provided by the LIAG (Leibniz institute for applied Geophysics).*

c; Skiba et al. 2010) and the Earth's total magnetic field of Germany (***Fig. 3Fig. 3d***; Gabriel et al. 2010) in a scale of 1:1000.000 are provided by the LIAG (Leibniz institute for Applied Geophysics). The Bouguer anomaly map is based on more than 275000 data points, recorded in recent decades by State Geological Surveys of the Federal States, research institutes and industry. The database for the map of the total magnetic field of Germany consists of 67 marine, surface and aerogeophysical survey campaigns carried out between 1961 and 2008. More information about these data can be found at: https://www.leibniz-liag.de/en/research/projects/internal-projects/analysis-and-interpretation-of-potential-field-data.html

For most of the federal states there are also gravimetric data sets with a much higher resolution. These are managed State Geological Surveys of the Federal States.

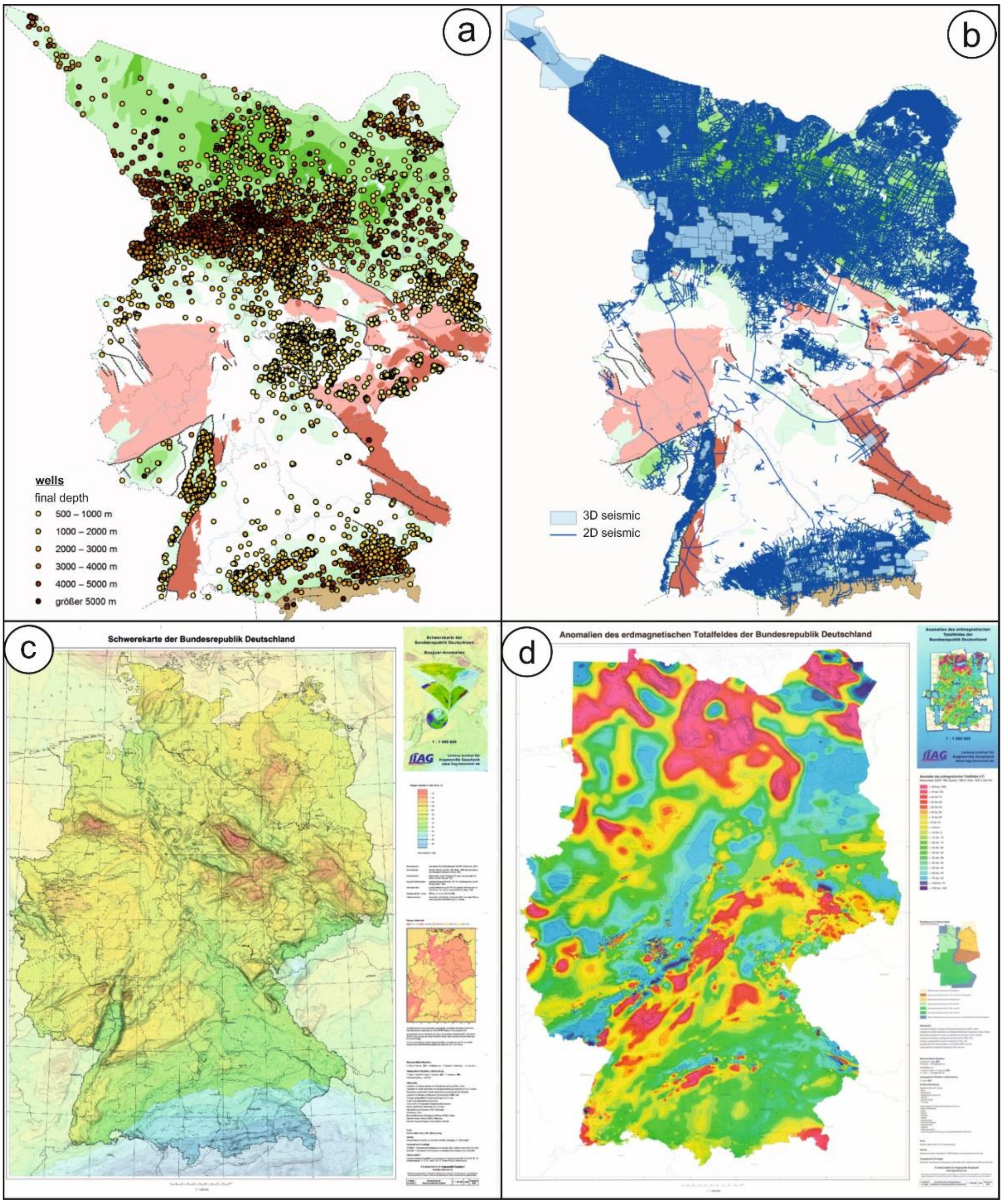


Fig. 3: *Overview maps of a) wells with drilling depths over 500 m and b) 2D and 3D seismic sections in Germany (Bundesanstalt für Geowissenschaften und Rohstoffe 2014). Overview maps in a scale of 1:1000.000 of (c) the bouguer anomaly (Bouguer anomalies, GRS80, 0 m amsl) of Germany (Skiba et al., 2010) (d) and the Earth's total magnetic field (ΔT–anomalies, DGRF 1980.0, 1000 m a.s.l) of Germany (Gabriel et al., 2010). The maps are compiled and provided by the LIAG (Leibniz institute for applied Geophysics).*

8.3 From superordinate structures to structural regions

8.3.1 Main structural styles in Germany

The earth's crust of Central Europe including Germany is composed of an undefined number of crustal segments that aggregated during the Paleozoic. Crust formation was almost completed with the end of the Variscan orogeny. Since the Rotliegend, the Central and Western European structural development was characterized by intraplate tectonics and associated processes such as the formation of several sedimentary basins and graben structures.
The sedimentary basins and grabens respectively of Germany have a varied appearance due to their different structural histories and can be broken down regionally into the following characteristics and structural styles:

① Deep-reaching Mesozoic, often reactivated or partly inverted rift zones can be found in the North German Basin and adjacent areas of the German North Sea

② In Northern Germany and within the German North Sea the Mesozoic and Cenozoic sedimentary evolution and the structural style is determined by halotectonic processes since the Lower Triassic. As a result large areas of the North German Basin and the German North Sea are marked by thin-skinned faulting in the Mesozoic and Cenozoic strataabove the Zechstein and Upper Rotliegend salt layers.

② Narrow, complexly structured normal to oblique fault zones are found in Central Germany. These "young" rifts are witnesses of the European, Cenozoic rift system (Upper Rhine Rift, Eger Rift)

③ Fold and thrust belts are characteristic for the Northern Alpine and parts of the Molasse basin in the northern foreland.

④ Complex fold and thrust tectonics, meshed with a complex pattern of different degrees of metamorphism and intrusion shape the image of the Paleozoic Variscan surface outcrops but as well dominate the seismic image of the basement from Southern to Northern Germany.

⑤ Several German low mountain ranges, such as the “Harz” or the “Thüringer Wald” are bordered by Late Variscan to Rotliegend faults, which are partially reactivated during the Late Cretaceous, or newly formed steep basement reverse faults.

⑥ Narrow complex graben-systems occuring in Mesozoic outcrops, which resulted from several rifting phase from the Triassic to the Lower Cretaceous and are partly inverted during the Late Cretaceous, dominate the structure of Mid-Germany (Mitteldeutschland).

Regarding the fault pattern, the predominant structural direction (*Error! Reference source not found.**b**,* S chulz et al. 2013) and the structural style of important fault zones, several main structural elements and subsequent regions can be distinguished. Although the boundaries between these regions are mostly not to be considered as sharp transitions, there are some prominent fault zones, such as the “Harznordrand fault”, the “Osning thrust fault” or the “Franconian lineament”, which separate individual structural areas clearly from each other.

8.3.2 *The Pre-Rotliegend Basement of Germany*

The Pre-Rotliegend basement of Germany is mainly formed by the Variscan orogeny (***Fig. 4***). The German Variscides can be subdivided into following units:

- Rhenohercynian Zone (Rhenoherzynikum) with the northern Phyllite Zone in the south (Southern Rhenish Massif and SE Harz),
- The Saxothuringian Zone (Saxothuringikum) with the Mid-German Crystalline High (Mitteldeutsche Kristallinzone)
- and the Moldanubian Zone (Moldanubikum).

Into the south the Moldanubian Zone is covered by the Molasse Basin and further south overprinted by Alpine orogeny with a ENE-WSW main strike of thrust faults in Germany. Especially the basement outcrops in the surrounding of Bohemian Massif and the Black Forest show sporadic older Precambrian units, which also have partly overprints of older orogenies. The northern Variscan thrust front runs within the basement of the North German Basin. The exact course of the deformation front is only in parts well documented. The NE-SW main strike of Variscan domains is also the dominating strike of thrust faults in the basement outcrops of German basement highs.

The basement of most of the North German Basin (NGB) and the German North Sea is defined by the Avalonia basement Terrane, which is partly overprinted by the Caledonian orogeny. Avalonia broke off from the northern edge of the southern continent Gondwana in the Lower Ordovician, and collided with Baltica in the Upper Ordovician. Depending on the model conception, the transition to the adjoining Baltica to the north is defined in parts clearly differently (e.g. Smit et al. 2016, Blundell et al. 1992, Pharaoh 1999). One important fault system that is roughly aligned along the transition to Baltica is the Tornquist – Teisseyre – Zone.

Especially below the Late Permian - Mesozoic North German Basin, the crystalline & metamorphic Variscan to Pre-Variscan basement is superimposed by Carboniferous sediments of the North-West Carboniferous Basin (***Fig. 5***). This was formed during the final amalgamation of Pangea in the Carboniferous as a foreland basin of the Variscan mountain belt. The North-West Carboniferous Basin can be regarded as a precursor of the Southern Permian Basin (Doornenbal & Stevenson 2010). To the south in Mid-Germany, the Variscan basement is also overlaid by the Permo-Carboniferous basin and platform sediments (e.g. Saar-Nahe Basin, Ilfeld Basin, Saale Trough, NW Saxony). Because of the often thick sediments of the Permo-Carboniferous with partly massive volcanism and the typical structural patterns of the Permo-Carboniferous in comparison to the Pre-Rotliegend basement and the Mesozoic to Cenozoic structural evolution, the Permo-Carboniferous is often combined into a separate tectonic basement unit in Germany.

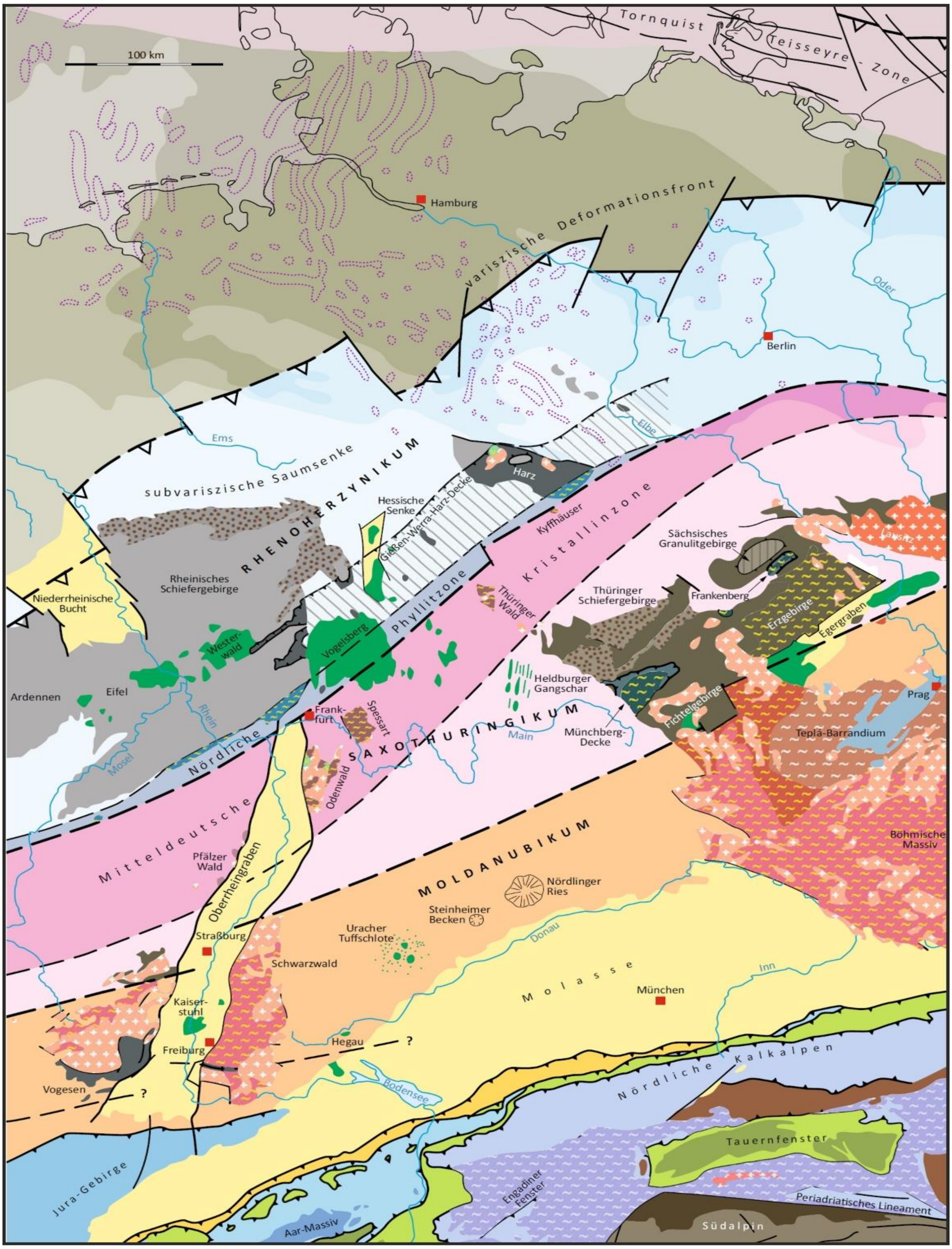


Fig. 4: *Tectonic map of Germany in relation to provided faults and lineaments from the Geothermal Atlas (Schulz et al. 2013). The tectonic map was redrawn & edited by Meschede (2015) after Bundell et al. (1992). Beside the main zones of the Variscan orogen, the Cenozoic rifts and the Alpine Molasse Basin are also shown.*

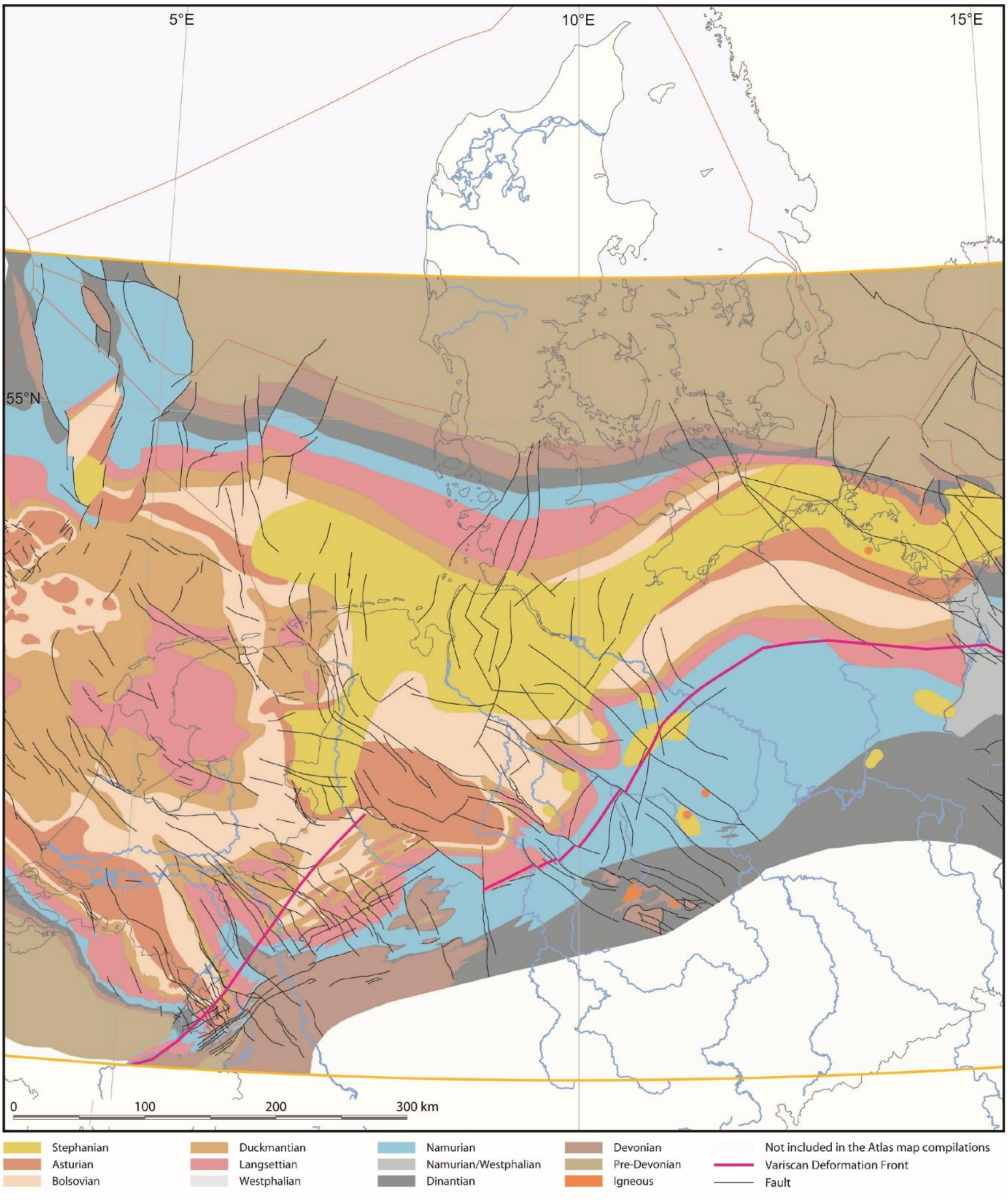


Fig. 5: *The Pre-Permian of Northern Germany and the German EEC edited on the base of Doornenbal & Stevenson (2010).*

8.3.3 Central European Basin System

Major parts of Germany belong to the complex Central European Basin system (CEBS; Ziegler 1990, Scheck-Wenderoth & Lamarche 2005, Littke et al. 2008) including several sub-basins like the North German Basin and therein the e.g. Thuringian Basin or Lower Saxony basin. The structural evolution of the Central European Basin System is related to four main tectonic phases from the Late Carboniferous until today, and resulting structural features can be attributed to changing kinematic and dynamic regimes (Kley et al. 2008):

Stage 1: Transtension in Latest Carboniferous to Permian time (

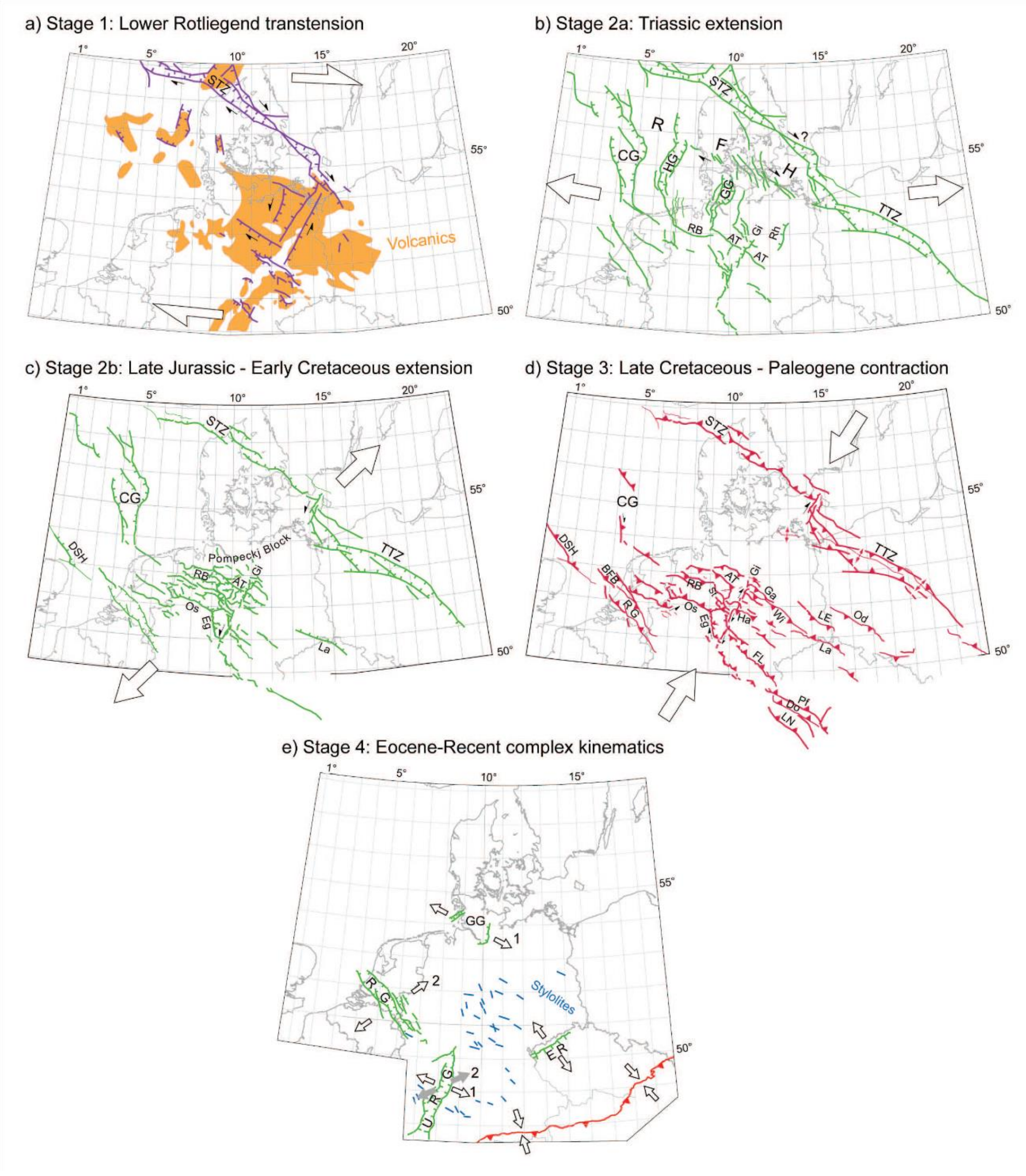


Fig. a):

- characterized by extensive volcanic activity, accompanied by formation of normal and strike-slip faults as well as associated formation of sedimentary basins (e.g. Gast & Gundlach, 2006).

Stage 2 a: Early to Late Triassic (to a lesser extent up to the Middle Jurassic) extension (

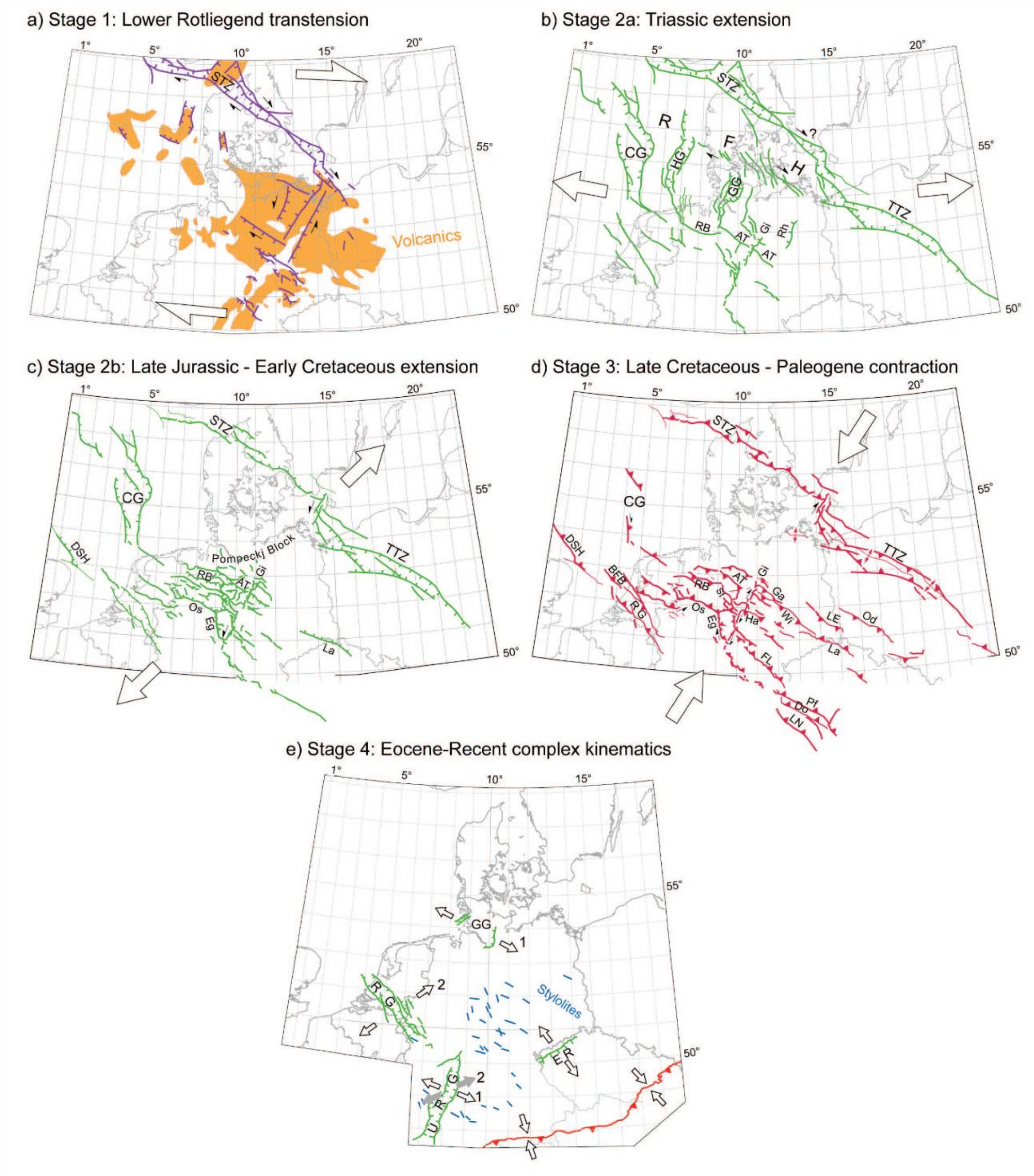


Fig. b):

- Formation of the North Sea Central, Horn and Glückstadt Graben, as well as the Weser and Rheinsberg troughs through significant E-W extension on N-S trending normal faults. Thereby, NW-trending faults are partly linked with the N-trending graben.

Stage 2 b: Late Jurassic to early Late Cretaceous extension (

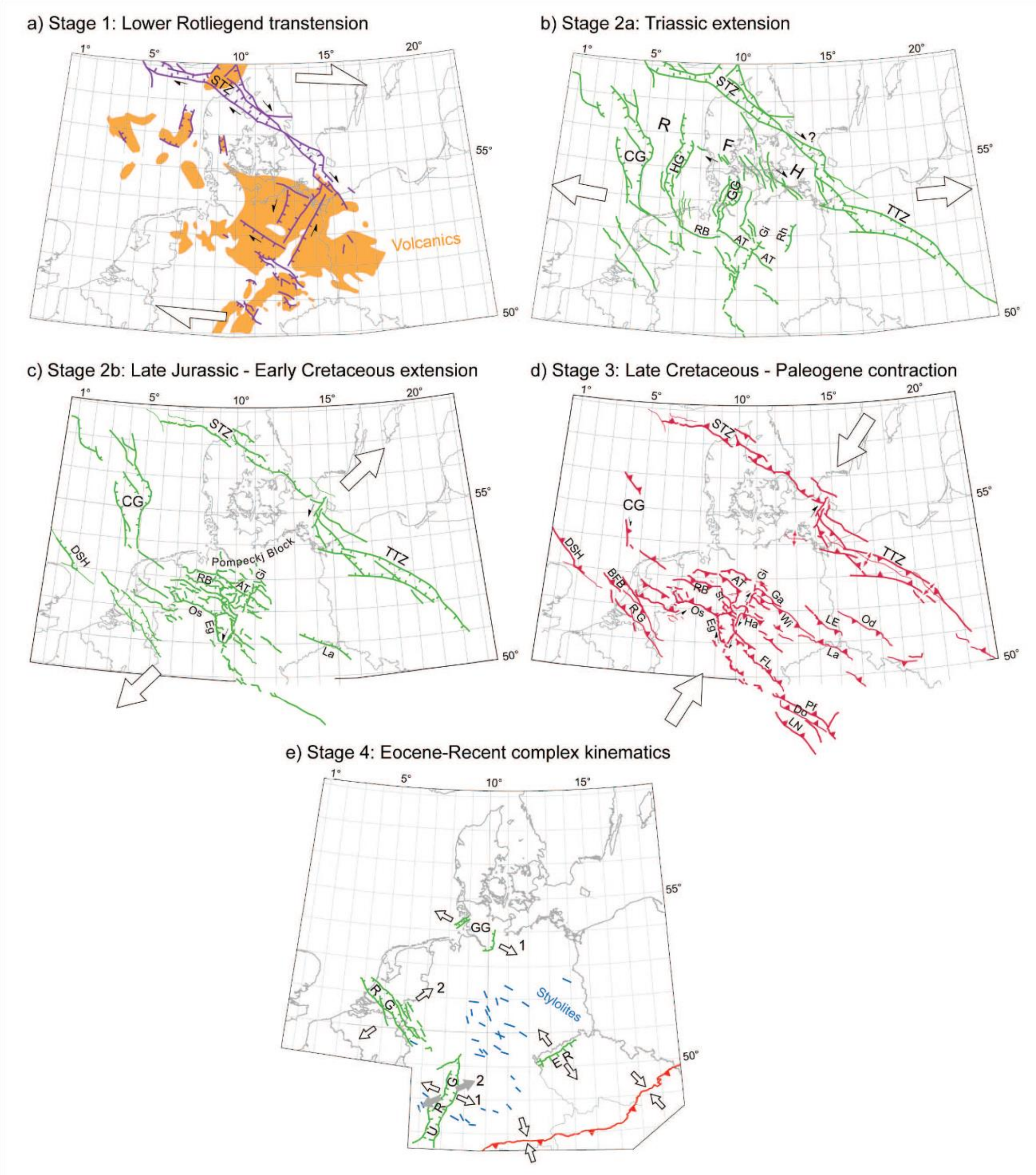


Fig. c):

- Formation of the Lower Saxony Basin (LSB) south of the Rheder Moor and Allertal fault zones and west of the Gifhorn system caused by pronounced extension. The rest of the North German Basin especially the eastern basin part shows no obvious large normal faults during this time interval. The switch from the dominantly N-S trend of the Triassic grabens to the NW/WNW-SE/ESE structural trend of the LSB suggests an anticlockwise rotation of the extension direction.

Stage 3: Contraction and inversion in latest Cretaceous to Late Oligocene time (

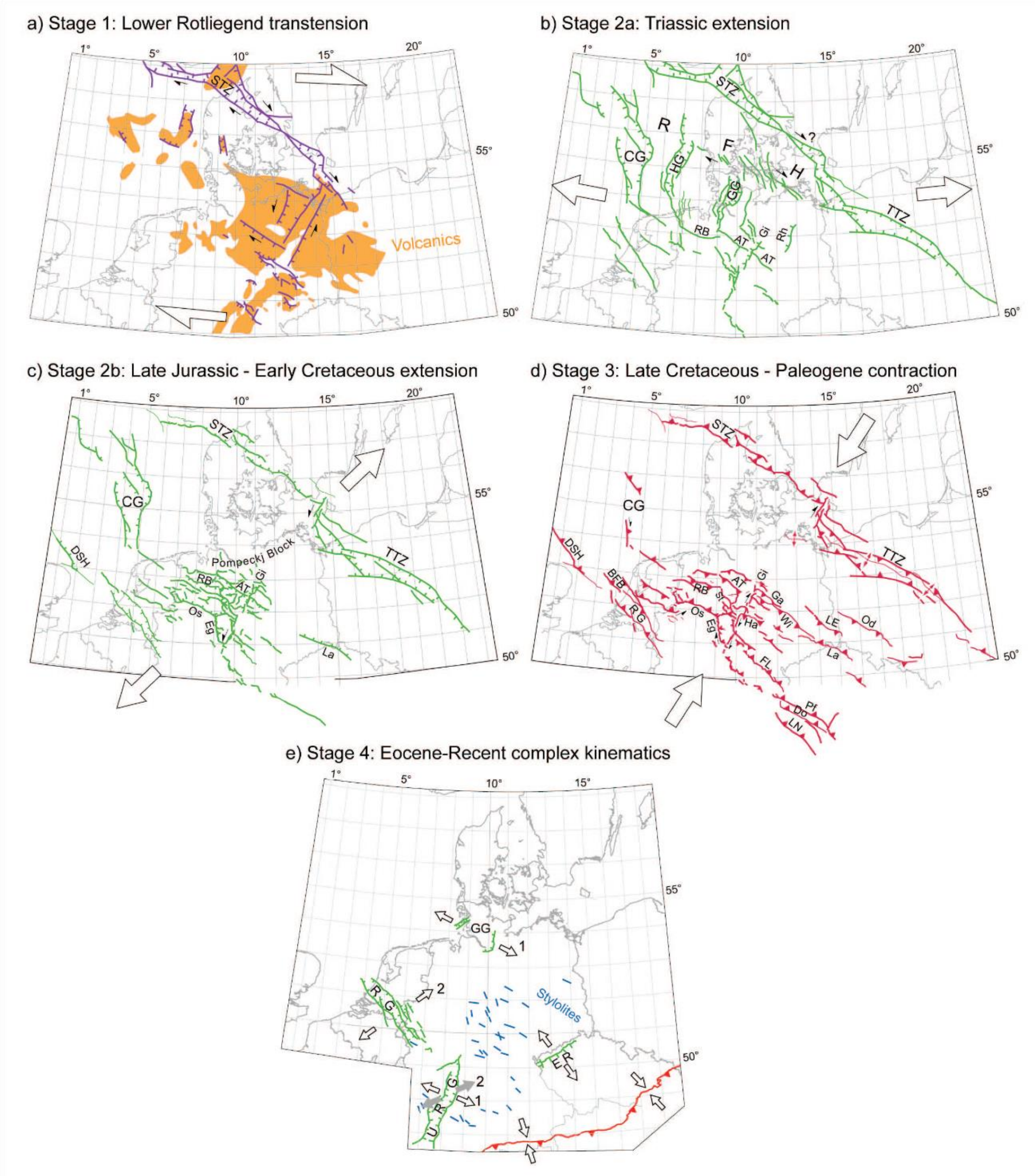


Fig. d):

- The extensional systems of afore formed structural elements become reactivated as reverse faults. Thus, e.g. the LSB is inverted and basement reverse faults dissect and raise the southern margin of the eastern North German Basin (e.g. Harz, Thuringian forest). The general direction of contraction at the beginning of this phase is SSW-NNE. By coeval W-E to NW-SE directed extension during the late phases of inversion in the Eocene the Upper Rhine and Eger rifts were formed as part of the European Cenozoic Rift system (ECRS; Ziegler 1990, Dézes et al. 2004).

Stage 4: Complex kinematics during the Neogene (

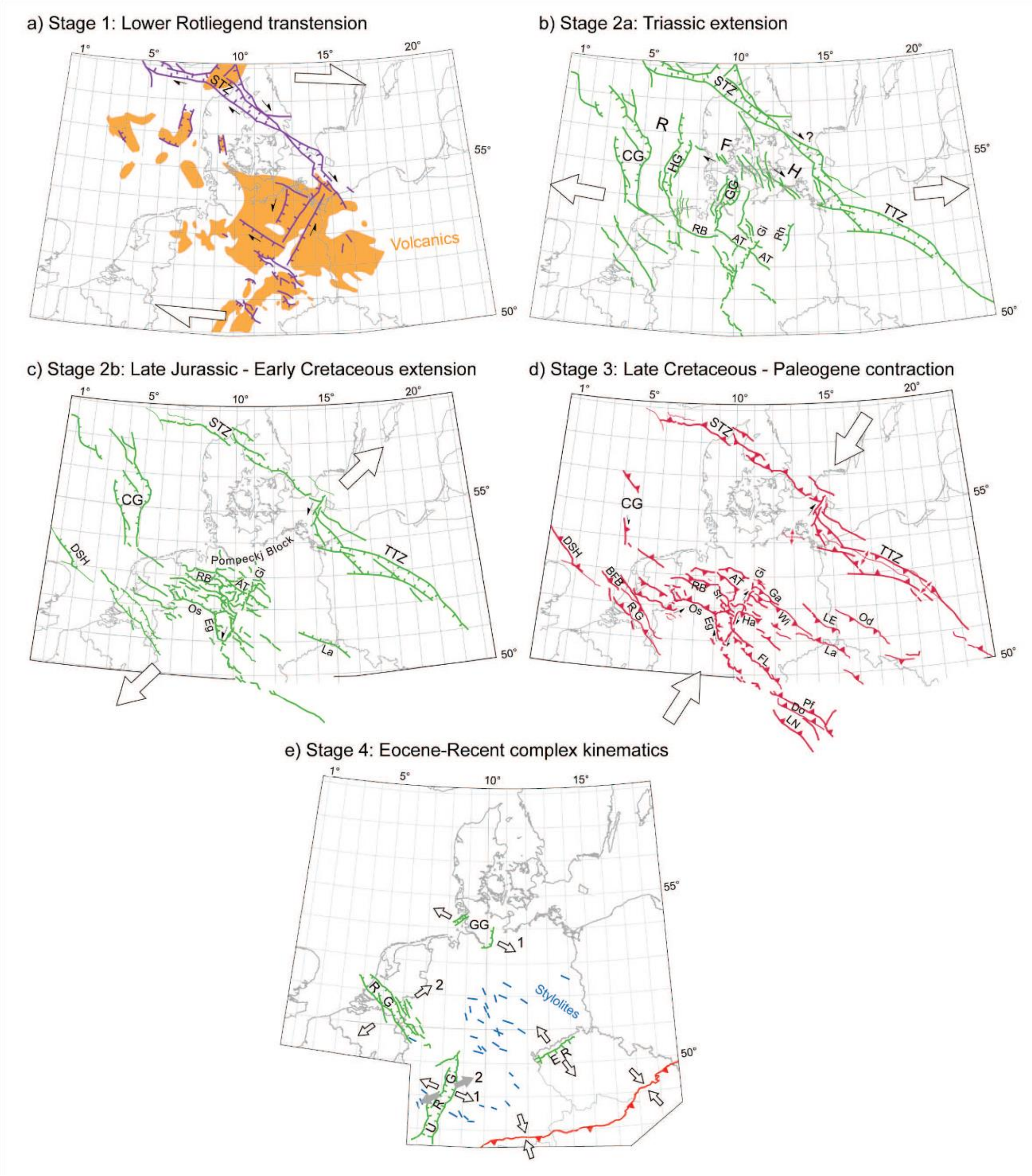


Fig. e)

- In between the late Eocene and Middle Miocene the stress field rotates from NE-SW into its present NW-SE direction (e.g. Hinzen 2003). With exception at the Alpine front, this rotation is not evident by fault evolution.

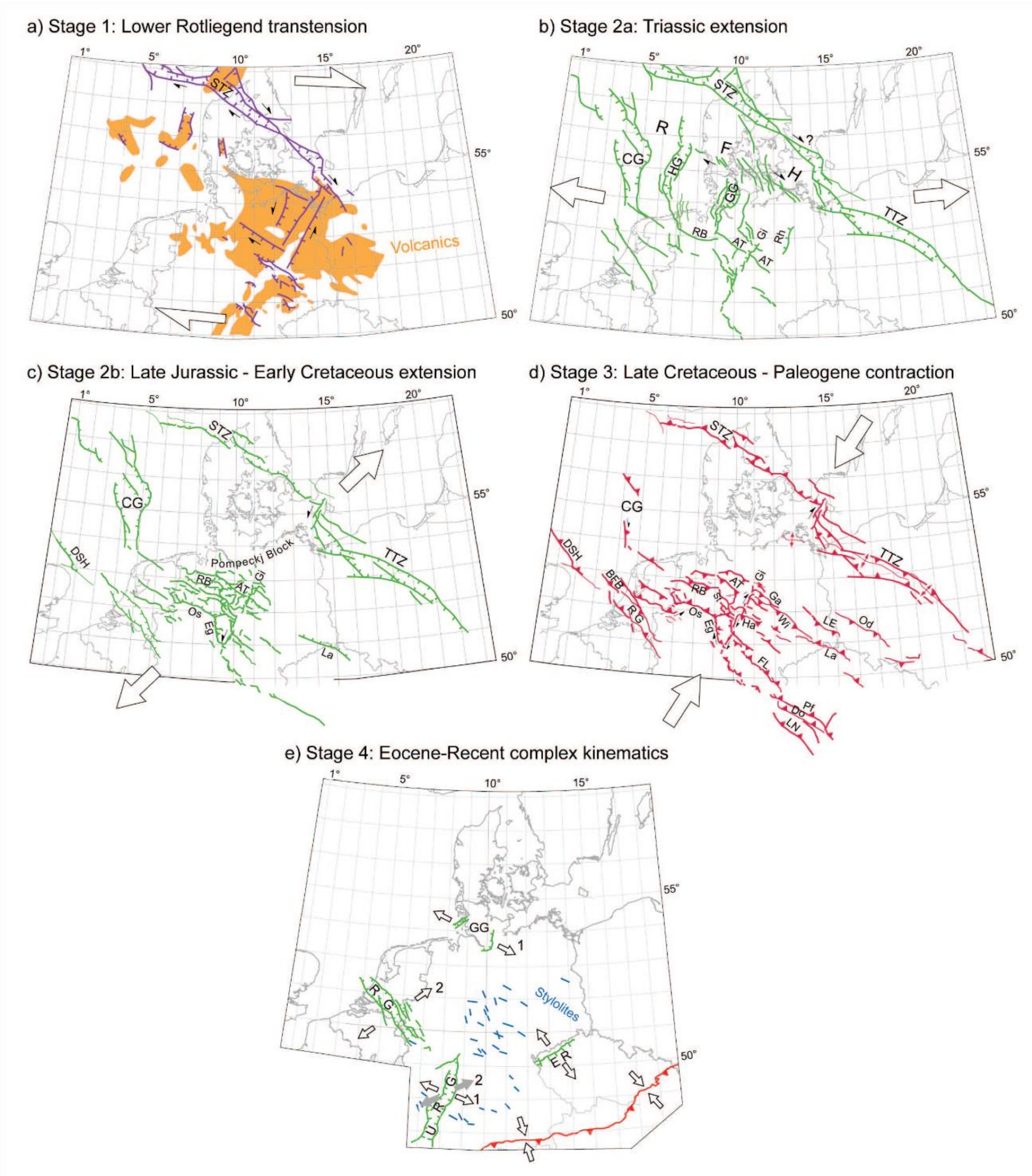


Fig. 6: *Main structural stages of structural evolution within the Central European Basin (from Kley et al. 2008), differentiated in a) a Lower Rotliegend transtension, b) Triassic extension, c) Late Jurassic – Early Cretaceous extension and d) a Late Cretaceous – Paleogene contraction. AT= Allertal lineament, CG= Central Graben, ER= Eger Rift, GG= Glückstadt Graben, RG= Rhein Graben, URG= Upper Rhine Graben, OS= Osning thrust.*

8.4 Structural regions

In the following description of structural regions as well as associated faults and fault systems we focus on Mesozoic-Cenozoic sedimentary basins and graben systems, underpinned by a table listing the key features and further reading.

8.4.1 North German Basin (NGB)

- <u>Western and Central part of the NGB</u>

The western and central part of the North German Basin (*Error! Reference source not found.*, ***Fig. 8***) is characterized by a very complex pattern of grabens and structural highs, while the south is dominated by compressional structures. Due to pronounced overprint by salt tectonics, the causal tectonic influences on the structural genesis, however, is difficult to determine (Müller et al. 2016). The northern part of the NGB, especially in the German North Sea sector and in Schleswig-Holstein, is significantly influenced by the N-S-running Glückstadt Graben, Horn Graben (***Fig. 8a***) and - in the very northwest - bordered by the Central Graben within the so called Entenschnabel area (***Fig. 7a***). The latter is moreover limited to the Central German North Sea by the Schillgrund and Coffee Soil faults. The formation of these large intracontinental rifts and the system of interconnected smaller Lower Rotliegend graben structures, as assumed by Gast (2006), is directly related in time to the disintegration of Pangaea and the development of large rift structures in the area of today's North Atlantic (i.a. Rockall-Faeroe Rift; Ziegler 1990). As structural highs, platform areas and sedimentary basin areas with only minor tectonic activity respectively, e.g. the Schillgrund High, G+L-platform, the Hunte- and Eichsfeld-Altmark swell (Röhling 1991, 2013) characterize the western and central part of the North German basin.

Towards the south, the structures of the German North Sea Sector and the Glückstadt Graben continuously merge into a not clear distinct structural region the "Pompeckj Scholle" (or Pompeck´sche Block; ***Fig. 8b***). This Jurassic to Cretaceous structural region of mixed platform, respecivelly structural high characteristic is dissected by several, mostly Triassic, fault zones, such as the Leer-Bremen lineament or the Uelzen lineament. As this structural region cannot be distinguished from neighboring parts of the basin in north-eastern Germany, neither in terms of facial nor structural aspects, the necessity of this structural division is questioned in recent literature (Müller et al. 2016). The fault zones within the "Pompeckj Scholle" have been reactivated several times. During the Upper Cretaceous pre-existing faults were locally compressive overprinted and basins and graben partly inverted (e.g. Bremen Graben) but to a much lesser extent than the adjacent Lower Saxony Basin to the south and associated structural features.

Aside from these afore mentioned structural elements, a significant proportion of structural characteristics in the North German basin, especially in this western and central part, lays on salt structures and their associated faults (*see chapter 8.6*).

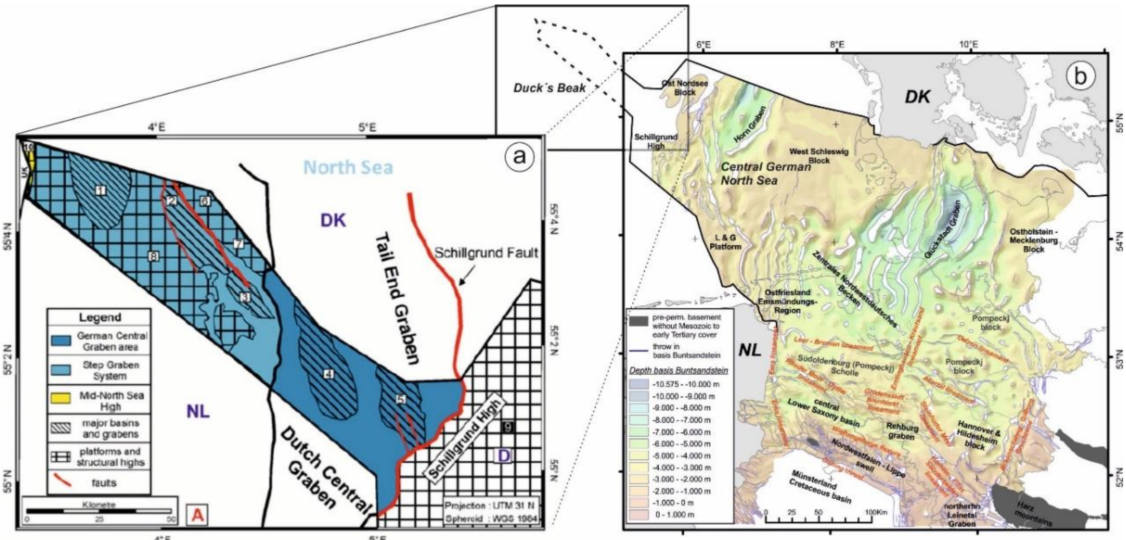


Fig. 7: *Mesozoic Structural elements of the a) Entenschnabel area, representing the north western part of the German offshore area (modified after Arfai et al. 2014) and b) of the Central German North Sea sector and the central part of the North German Basin covering the onshore area. Depicted are main structural units, salt structures, grabens, lineaments (narrow to broad long elongated fault systems) (modified from Müller et al. 2016).*

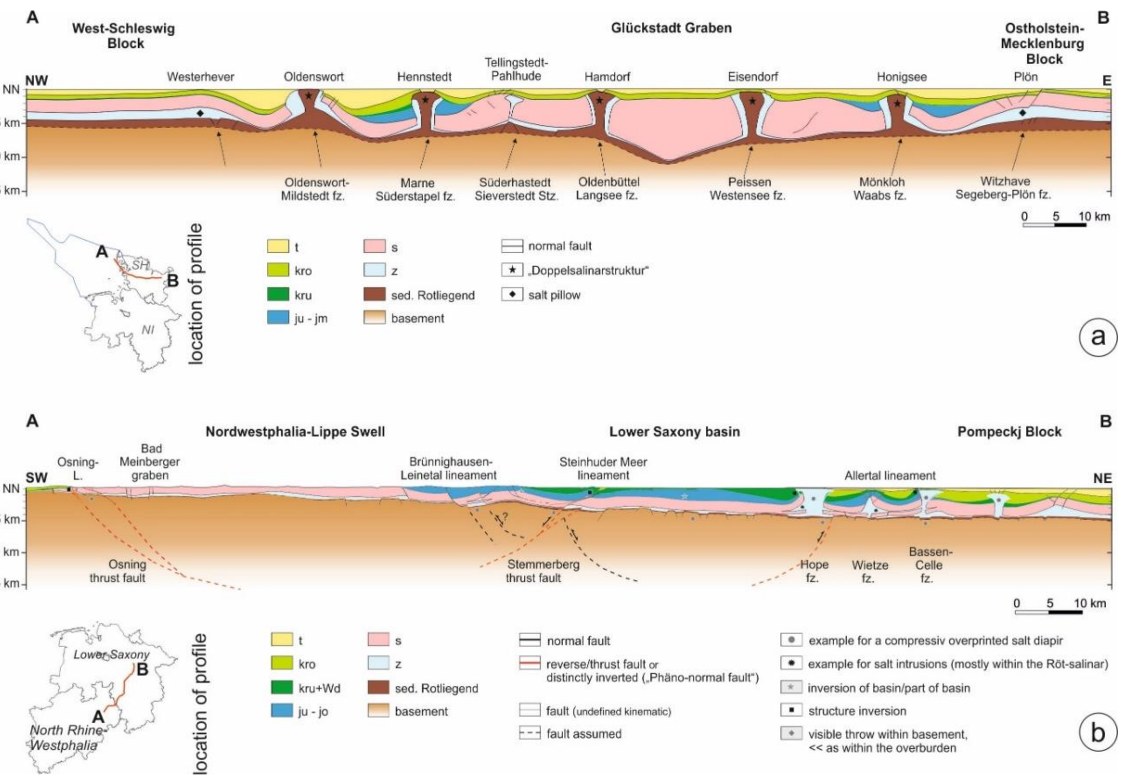


Fig. 8: *Subsurface structures within the western and central part of the North German Basin, interpreted profiles based on Baldschuhn et al. (2001) and redrawn from Müller et al. (2016): a) From the West Schleswig Block in the German North Sea Sector across the Glückstadt Graben to the Ostholstein-Mecklenburg Block; b.) from the southern rim of the Lower Saxony Basin with the Osning thrust to NE crossing uplifted Nordwestfalen-Lippe swell area, the Central Lower Saxony Basin to the Pompeckj block.*

Table 1: Main Characteristics and elements of the Western and Central parts of the North German basin

Kinematics/style	*Mainly normal dip slip faults/extension, most of the Mesozoic and Cenozoic time strike-slip movement is subordinate, along the southern rim often dip slip inverted features, partly Late Cretaceous strike-slip tectonics along N to NNW striking faults, transtensional Rotliegend faults, mainly thin-skinned tectonics in the Mesozoic Supra-Salt overburden*
Main characteristics	*Most of faults in the Mesozoic to Cenozoic overburden are influenced by halotectonic processes; salt walls and diapirs*
Predominant strike of Late Paleozoic to Cenozoic structural elements	*N-S; NNE-SSE; WNW-ESE*
Examples of prominent/characteristic structures, sub basins, fault zones, lineaments or graben	*Entenschnabel: Step graben system, Central graben, Schillgrund fault, Coffee soil fault* *Central German North Sea: Schillgrund High, G+L-platform, Horn graben, West Schleswig Block* *Western part of the North German basin (onshore): Lower Saxony Basin, Thuringian Basin, Allertal lineament, Leer-Bremen lineament, Ems lineament, Osning thrust*
Further literature	*e.g. Kockel (1995), Baldschuhn et al. (2001), Brückner-Röhling et al. (2002, 2004), Littke et al. (2008), Arfai et al. (2014), Müller et al. (2016)*

- <u>Eastern part of the NGB</u>

Compared to the western and central part of the NGB, the eastern section of the basin shows a clearly reduced structuring of the Mesozoic-Cenozoic overburden by halotectonic structures (**Error! Reference source not found.**). In contrast to the northwestern part of the NGB - with the exception of the Altmark-Fläming depression and the southwestern Mecklenburg-Brandenburg depression - salt diapirs do not dominate here, but salt pillows. The northern and southern edges of this basin part are particularly markedly structured. Thus, in the north of the Mecklenburg Brandenburg depression a system of prominent, NW/NNW-SE/SSE running fault zones has developed, which is also called the "Vorpommern fault system" (Krauss & Mayer 2004). The largest of these fault zones is the Möckow-Dargibeller fault zone, which is about 50 km long and show Old Cimmerian development (e.g. Gluško et al. 1976, Mayer et al. 2000).
North of the Grimmener Wall (***Fig. 10***; profile C-D), the NGB gradually changes to an elevated zone with significantly reduced Mesozoic-Cenozoic cover. The Møn-Arkona High (or Rügen Swell; Franke 1990, among others), in interaction with the Ringkøbing-Fyn High, has repeatedly been a swell region in CEBS' Paleozoic-Mesozoic development (Doornenbal & Stevenson 2010). In the outer NE of the German Baltic Sea sector runs the Skurup-Adler-Kamien fault, another important fault zone, which belongs to the Sorgenfrei-Tornquist Zone and the Teisseyre Tornquist Zone. The eastern part of the NGB merges to the east into the East Brandenburg Swell (Ostbrandenburg Schwelle), which delimits the NGB from the eastwardly adjoining Mid-Polish Trough (***Fig. 9***).

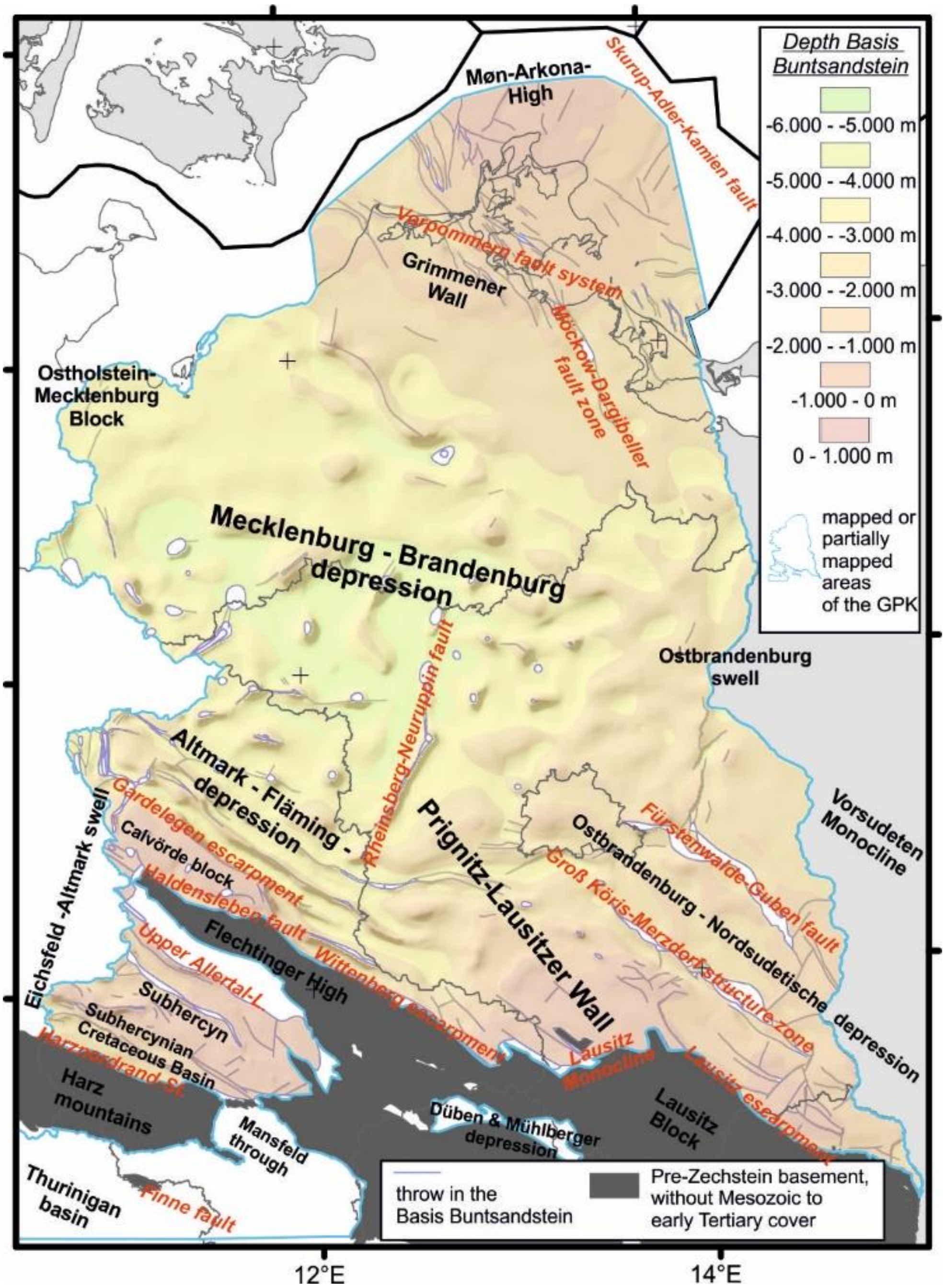


***Fig. 9**: Structural map of eastern part of the North German Basin, illustrating the main structural elements, such as faults, salt structures and highs/depressions (modified from Müller et al. (2016) based on Doornenbal and Stevenson (2010), structure and nomenclature based on Katzung & Ehmke (1993) and Franke (2015)).*

The compressive/transpressive event during the Upper Cretaceous (e.g. Kley & Voigt 2008) is even more clearly visible in the southern part of the eastern NGB (***Fig. 7***). Along an en-echelon NW-SE running band of basement faults and basement flexures (e.g. *Gardelegen Escarpement/ Gardelegen Abbruch*; Benox et al. 1997, Kossow 2002) and further steep basement reverse faults (*Haldenslebener and Wittenberger "Abbruch"*; e.g. Otto 2003), large parts of the former southern Permo-Triassic NGB were raised several kilometres and, with the exception of smaller basin relics (*Dübener and Mühlberger depressions*), were eroded down to the Paleozoic (*Flechtinger Höhenzug*), partly even the Proterozoic basement (Lausitz Block).

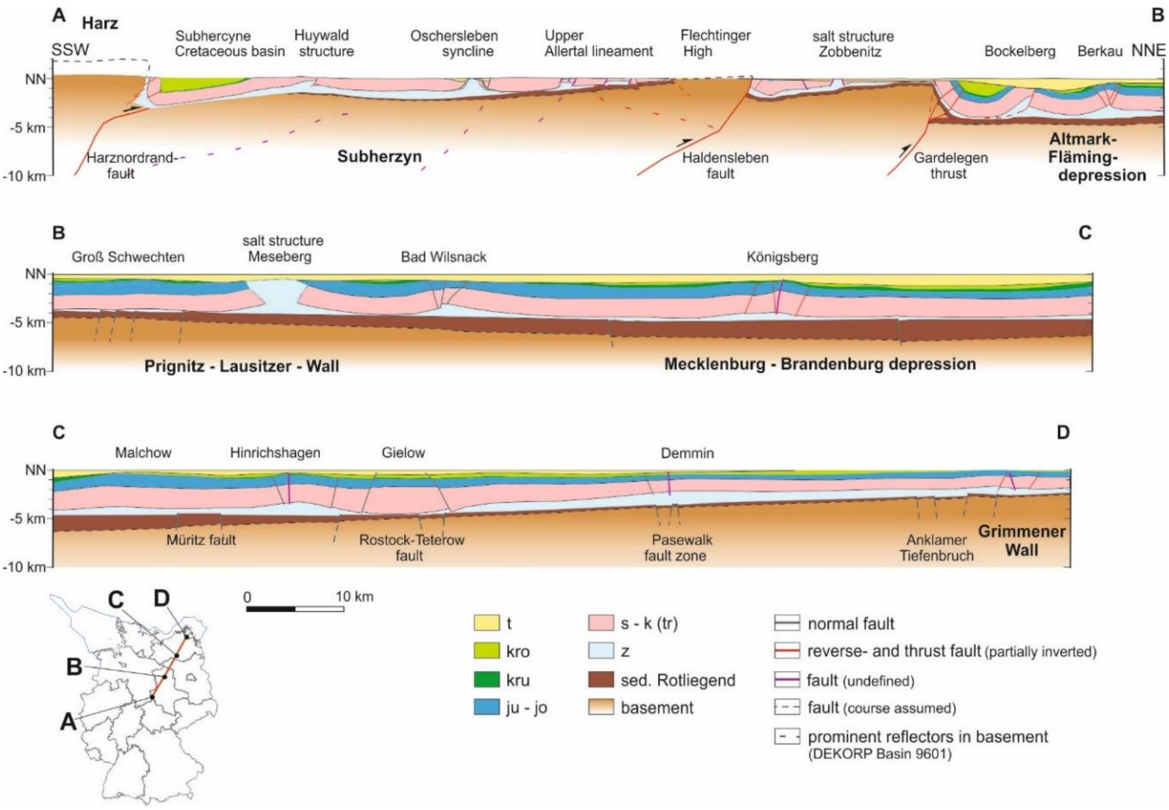


Fig. 10: *Supraregional geological profile based on seismic data of the DEKORP BASIN 9601, modified from Müller et al. (2016). The profile cover the area from the Harz in the southwest to the northern rim of the North German Basin along the Grimmener Wall and the Vorpommern Fault system.*

Table 2: Main Characteristics and elements of the Eastern North German Basin.

Kinematics/style	*Mainly normal dip slip faults/extension, mainly thin-skinned or soft-linked tectonics of the Mesozoic to Cenozoic overburden, mainly thick-skinned tectonics along the uplifted rims of the basin*
Main characteristics	*Salt pillows, strongly uplifted basement blocks in the southern basin part (e.g. Flechtinger High, Harz, Thuringian Forest)*
Predominant strike of Late Paleozoic to Cenozoic structural elements	*WNW-ESE; NW-SE (faults along the northern rim similar to regional strike of elements of the TTZ)*
Examples of prominent/characteristically structures, subbasins, fault zones, lineaments or graben	*Vorpommern fault system, Gardelegen „Abbruch" Haldenslebener and Wittenberger "Abbruch", Subhercynian Basin, Harz, Grimmen Wall*
Further literature	*Katzung & Ehmke (1993), Kossow (2002a, b), Otto (2003), Krauss & Mayer (2004)* *Rügen/Baltic Sea: Deutschmann et al. (2018), Seidel et al. (2018), Seidel (2019)*

8.4.2 Selected Sub features of the North German Basin

- *Lower Saxony Basin (LSB)*

The NW-SE-striking Lower Saxony Basin, as part of the North German Basin, is a 300 km long and 65 km wide Late Jurassic to Early Cretaceous trough, which is bordered to the south by the Osning lineament and the Münsterland Cretaceous Basin, and to the north by the Aller lineament (Adriasola Muñoz (2007), Baldschuhn & Kockel (1999), Lohr 2007; ***Fig. 7b***, ***Fig. 8***). Along the southern rim of the basin the most important fault zone creates as much as 7 km of vertical offset. Due to structural inversion during the Upper Cretaceous and associated deep erosion, these high vertical offsets are not obvious in the today's geological maps.
The basin can be divided into a central part in the west and several individual structural areas such as the Hannover and Hildesheim Scholle in the east. Several fault zones in-between run from NW to SE, but to the east and west, this basin is again limited by structural lineaments running from N to NNE (e.g. *Ems lineament, Braunschweig-Gifhorn fault zone,* ***Fig. 7b***). Pronounced deformation occurs at the rim of the basin parts, e.g. along the structural lineaments shown in *Fig. 7b* (including the *Rheder Moor-Oythe-Lineament*) (e.g. Betz et al. 1987). During the Jurassic to Cretaceous several sub-grabens and half-grabens were formed within the Lower Saxony basin, which again were strongly overprinted and inverted during the Upper Cretaceous in a compressive/partly transpressive manner. The central part of the Lower Saxony Basin, on the other hand, is only slightly dissected by faults and was inverted over a large area during the Upper Cretaceous, corresponding to the "Broad Fourteens Basin" and the Middle Polish Trough, in the form of a broad "bulge" extending from NW to SE.

Table 3: Main Characteristics and elements of the Lower Saxony Basin.

Main characteristics	*Jurassic to Lower Cretaceous WNW-ENE elongated graben, The graben axis is strongly raised by structural inversion*
Kinematics/style	*Normal faults/extension, dip-slip structural inversion, partly oblique slip along N/NNE striking elements*
Main strike directions	*Mainly WNW-ESE; N/NNE-S/SSW at western and eastern end; partly NW-SE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Rheder Moor-Oythe-Lineament, Ems lineament, Braunschweig-Gifhorn fault zone; Osning thrust, gravimetric anomaly of Bramsche*
Further Literature	*Gramann et al. 1997, Baldschuhn & Kockel (1999), Adriasola Muñoz (2007), Brink (2013), Bruns et al. 2013*

- *North-Westphalia-Lippe Swell*

The inverted Lower Saxony Basin merges towards the south via a broad flexure (*Wiehengebirge and Wesergebirge flexure*) into a strongly structured, inverted intra basin high, on which predominantly only Triassic sediments are preserved. This elevation, known as the *North Westphalia-Lippe Swell* (***Fig. 7b***, ***Fig. 8b***), is separated in the south by a few kilometers wide structural element along a steep, partly overturned and broken flexure, with steeply dipping chalk (similar to parts of the Harz foreland – "Teufelsmauer"), from the south bordering Münsterland Basin.

Table 4: Main Characteristics and elements of the North-Westphalia-Lippe Swell.

Main strike direction	*NW-SE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Bad Meinberger Graben, Brünninghausen-Leinetal lineament*

- *Thuringian Depression*

The Thuringian Depression (***Fig. 9, Fig. 11***) is an uplifted and deeply eroded marginal area of the North German Basin in Thuringia. During the Late Cretaceous (Santonian to Campanian) this basin part of the SPB/NGB (uplift after Beyer (2015) 1500 m to 3700 m) as well as the surrounding basement highs (uplift up to 5000 m and more) were uplifted. The main structure representing a NW-SE striking syncline which is located in between the more strongly uplifted Variscian to Rotliegend basement of the Thuringian forest (***Fig. 4***) and Thuringian Schiefergebirge in the south and of the Palaeozoic outcrops of the Harz in the North (***Fig. 9, Fig. 11***). The basin is limited in the West by the *Eichsfeld-Altmark Swell* and further west by NNE-SSW striking grabens (e.g. *Leinetal Graben, Altmorschener Graben*) within the northern Hessian depression. To the NE the basin is limited by several smaller highs (*Kyffhäuser, Bottendorfer Höhenzug*) along the Kyffhäuser-Crimmitschauer fault zones. The uplifted basin part north of this fault zone is called the Mansfelder Mulde, which in turn is limited to the north by the Halle fault.
Accompanying to the broad uplift of this region several NW-SE striking Late Triassic to Jurassic (maybe Early Cretaceous) small grabens were structurally inverted during the Late Cretaceous. Prominent examples for faults and fault zones are the *Finne fault,* the *Kyffhäuser-Crimitschauer* or the *Eichenberg-Gotha-Saalfelder fault zone*. These grabens and fault zones dominate the structural pattern of the Thuringian “Syncline”with the exception of a few NNE-SSW striking elements (e.g. Ohmgebirge graben) and WNW-ESE elongated minor oval uplifts.

Table 5: Main Characteristics and elements of the structural area Thuringian Depression (“Thuringian Basin”).

Main characteristics	*WNW-ESE elongated Late Cretaceous syncline, deeply eroded marginal areas of the North German Basin*
kinematics	*Late Paleozoic until Lower Cretaceous mainly extensional; during Late Cretaceous mainly dip-slip contraction; thick-skinned tectonics as well as in minor degree thin-skinned tectonics;*
Main strike directions	*NW-SE/ WNW-ESE, especially along the western rim of the syncline NNE-SSW*
Prominent/characteristically structures, fault zones, lineaments or graben	*Finne fault zone, Kyffhäuser-Crimitschauer, Eichenberg-Gotha-Saalfeld fault system, Thuringian forest NE boundary fault*
Further literature	*Seidel (2003), Franke (2011), Voigt & Kober (2015), Malz (2014)*

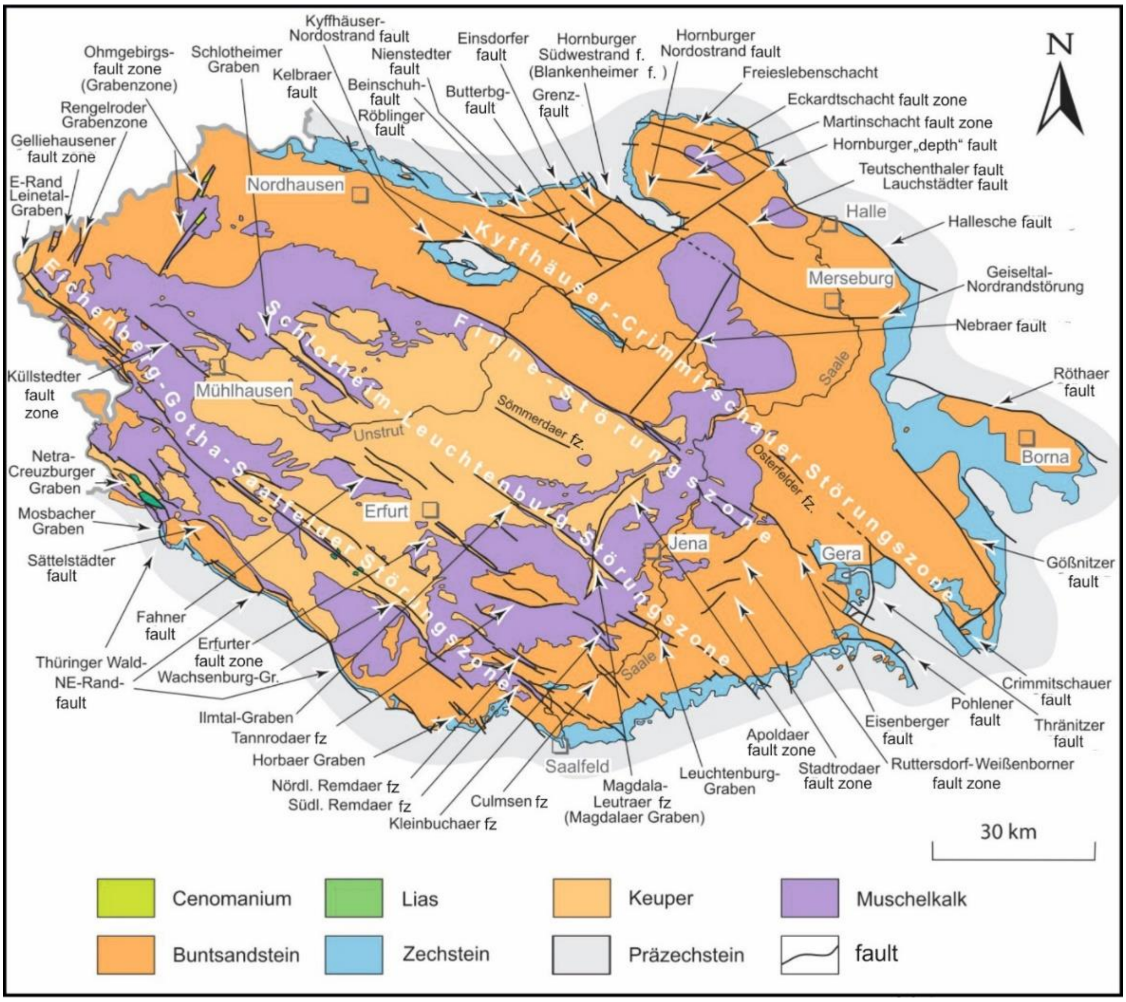


Fig. 11: *Structural map of the Thuringian syncline, illustrating the main faults and fault zones; "Störungszone" in white font = fault zone (modified from Franke (2011)).*

- <u>*Hessian Depression*</u>

The Hessian Depression is a NNE-SSW elongated sub-basin of the North German Basin (NGB), located in the northern continuation of the Upper Rhine graben and is more or less aligned and controlled during the Triassic - Jurassic(?) by surrounding swells (such as the Eichsfeld-Altmark swell) (***Fig. 12)***. As a result, this sub-basin of the North German Basin exhibits a Triassic basin evolution, as well as in parts graben tectonics (e.g. Leinetal Graben) and a Late Cretaceous contractional/transpressional overprint. During Jurassic times, fault zones or grabens were newly created. They mainly strike N-S, NNW-SSE (e.g. Egge fault system), NNE-SSW (e.g. eastern part of the Leine valley graben), NW-SE and WSE-ESE. The southern part of the Hessian Depression is also influenced by Tertiary evolution of the European Rift system and is partly covered by Tertiary basin sediments. The region is also characterized by intense volcanic activity during the Tertiary period. The Vogelsberg, in the south of the Hessian depression for example lies in the continuation of the Upper Rhine Graben and is the largest Tertiary volcanic complex known in Germany (Vogelsberg complex). In addition, smaller volcanic structures NNE of the Vogelsberg are also located in the strike of the Upper Rhine Graben.

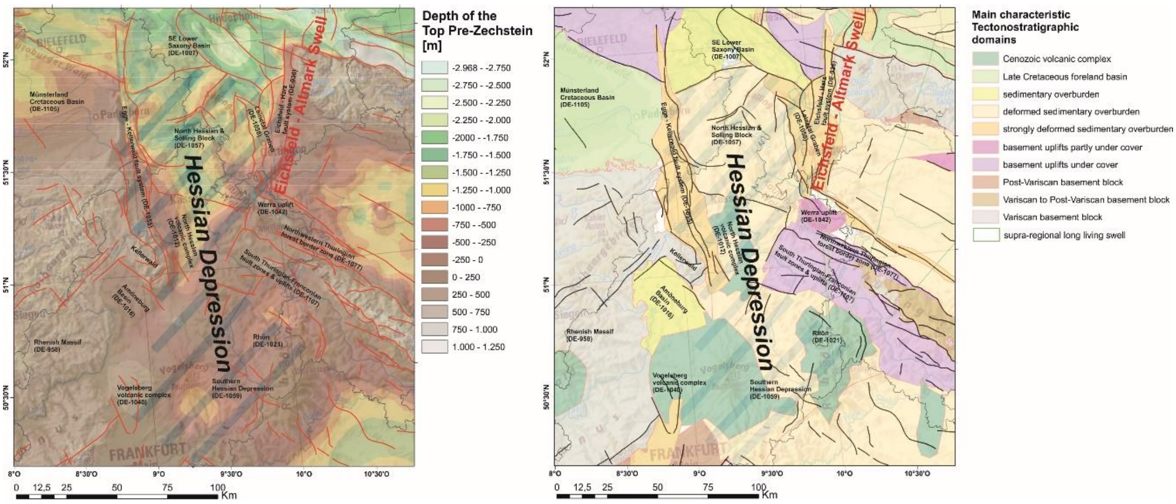


Fig. 12: *The structural domain of Hessian depression and surrounding (sub-) domains represented within the HIKE-fault database, left side illustrating the depth of the top of pre-Zechstein and right side illustrating the mains characteristic tectonistratigraphic domains defined in the frame of the HIKE fault database. Background: Oroghydrographic map with a scale of 1:2,500,000 (www.bkg.bund.de).*

Table 6: Main Characteristics and elements of the structural area Hessian Depression.

Kinematics	*Normal faults, strike slip*
main strike directions	*NNE-SSW, NNW-SSE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Egge-Kellerwald fault system, Leinetal Graben, Altmorschen-Neuenkirchen fault system*
Further Literature	*Thews (1996)*

8.4.3 Late Cretaceous basins and basement uplifts in the south of the North German Basin

The Subhercynian (***Fig. 9, Fig. 10***: profile A-B), also part of the NGB, was strongly uplifted during the Upper Cretaceous, with exception of the Subhercynian Cretaceous Basin. This basin is a Late Cretaceous foreland basin of the Harz (Voigt et al. 2004) similar to the Münsterland Cretaceous Basin as foreland basins of the Osning or the Cretaceous Basin in front of the Lausitz thrust in transition to Czech Republic. The Harz, as well as the Flechtinger Höhenzug, the Lausitz-Riesengebirgs Anticlinal Zone and the Thuringian Forest present deep eroded basement highs (e.g. Schröder 1987, Andreas & Lützner 2009, Voigt et al. 2009), which were thrusted along larger basement faults formed during Upper Cretaceous or partly reactivated Permo-Carboniferous fault zones.

Table 7: Main Characteristics and elements of the Late Cretaceous basins and basement uplifts in the south of the North German Basin.

kinematics	*Foreland basins in front of faulted/thrusted flexural basement uplifts (comparable to American Laramide uplifts; e.g. Erslev 1986)*
main strike directions	*WNW-ESE, NW-SE*
Associated, characteristically structures, fault zones, lineaments or graben	*Harz, Harznordrand fault, Lusatia-Krkonose High, Lausitz-Riesengebirgs Anticlinal Zone, Lausitz thrust, Prignitz-Lausitz Wall, Münsterland Basin*
Further Literature	*Voigt et al. (2004), von Eynatten et al. (2008), Voigt (2009), Voigt et al. (2009), Wilmsen et al. (2014), Wilmsen et al. (2019)*

8.4.4 Münsterländer Cretaceous Basin

The Münsterland Cretaceous Basin is located south of the Lower Saxony basin and is characterized by nearly flat lying massive Upper Cretaceous limestones near the surface and residual preserved Lower Cretaceous, which lie directly on Paleozoic rocks (***Fig. 7b, Fig. 13***). The bedding conditions of the Upper Cretaceous of the central Münsterland are considered relatively undisturbed (Dölling & Juch 2009). The rocks below the Upper Cretaceous (locally also Lower Cretaceous) form the coal-bearing strata of the Upper Carboniferous and are intensively folded as a result of the Variscan orogeny (Drozdzweski & Wrede 1994). The SW-NE striking Variscan folds are displaced by NNW-SSE striking cross faults, such as the Rheinpreußen or Fliericher Sprung, Sekundus-, Teritus- or the Drevenacker fault (***Fig. 13b***).
A discrete boundary of the Münsterland basin cannot be clearly identified, why the depicted outline of the Münsterland Cretaceous Basin in the fault database overlaps with other structural areas: To the Lower Saxony Basin, the boundary of the basin runs along the Osning thrust (see also *sub-chapter* □○–“Lower Saxony Basin”). Because of that, the outline of the Münsterland Basin overlaps with the outline of the Lower Saxony Basin in this region. To the east, this tectonostratigraphic unit overlaps with the “Egge – Kellerwald” fault system, which in turn belongs to the “Hessian Depression”. The extent to the west and south is defined by the today distribution of the Cretaceous deposits.

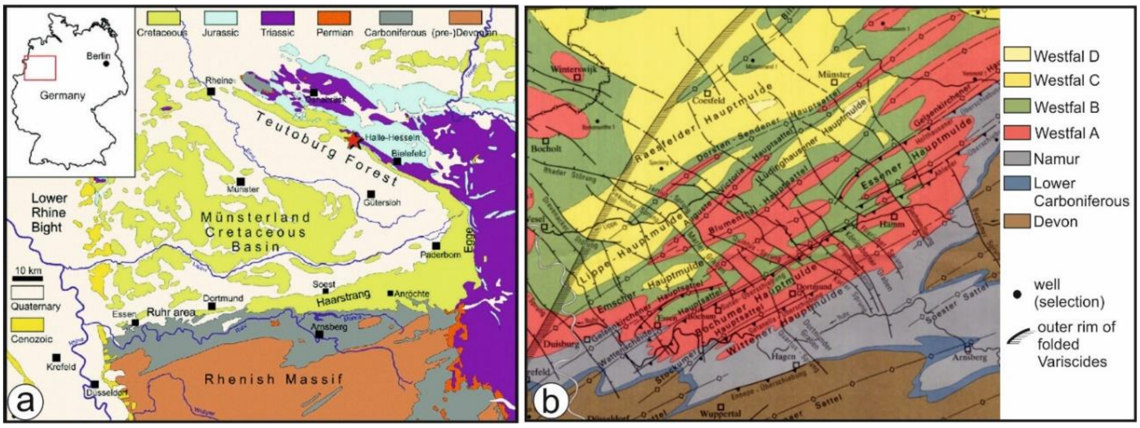


Fig. 13: *a) Geological map illustrating the Münsterland Cretaceous Basin and surrounding structural areas (modified from Wilmsen et al. (2019) after Drozdzewski et al. (1995)), b) Part of structural geological map illustrating faults of the Münsterland Cretaceous Basin (Drozdzewski et al. 1995).*

Table 8: Main Characteristics and elements of the structural area Münsterländer Cretaceous Basin.

Main characteristics	*Strata of Upper Cretaceous nearly undisturbed, variscan SW-NE running faults displaced by NNE-SSE faults*
main strike directions	*NNW-SSE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Drevenacker fault, Rheinpreußen-, Münster-, Hervester- or Fliericher-Sprung, Sekundus-, Teritus Sprung, Haltern fault*
Further literature	*Drozdzewski & Wrede (1994), Drozdzewski et al. (1995), Dölling & Juch (2009)*

8.4.5 Upper Rhine Graben

The Upper Rhine graben belongs to the Cenozoic rift system (Ziegler 1992; ECRIS; see also *chapter 0*) and is oriented predominantly NE-SW, in the line from Frankfurt to Basel. The graben is differentiated in three segments, each up to 100 km long (Grimmer et al. 2017). The evolution of the graben was controlled by multiple change of the stress field and a reactivation of Permo-Carbonifereous crustal discontinuities (Illies 1975, Schuhmacher 2002).

The formation and subsidence of the Upper Rhine Graben starts in the south during Lower Eocene by NNW-SSE-extension, in the north during the Upper Eocene. The main rift stage began in the Lower Oligocene with continuous northward movements of the Alps (Dézes et al. 2004). A major reorientation of the regional stress field during the Early Miocene is assumed to cause the main subsidence phase within the northern parts of the Upper Rhine Graben (Schuhmacher 2002). Along with this change of stress field, a counterclockwise rotation and a northeastward shift of the depocenter axis takes placed, followed later by Middle Miocene uplift and erosion within the southern parts of the Upper Rhine Graben (Schuhmacher 2002). The fault throw in the south is about 5000 m and in the northern part above 4000 m. The offset of the eastern flank is up to 1000 m higher than on the western side. With rotation of the stress field from NNE-SSW to NW-SE within the Eocene, transtensive strike-slip movements characterize the recent activity of the Upper Rhine graben. Today´s morphology of the flanks and the graben itself is characterized by great amount of normal faults or stepped faults and strike slip faults. After e.g. Derer et al. (2005) the fault pattern might be complex as illustrated in ***Error! Reference source not found.****a*, where tilted fault blocks are bounded by growth faults. The complex, internal structural inventory of the graben is also revealed when looking at ***Error! Reference source not found.***b, which Grimmer et al. (2017) compiled and (re-)interpreted from numerous studies. The geological profile from the Saarland in the Northwest across the Upper Rhine graben, the Schwarzwald, Schwäbische Alb to the Alps gives an overview of the changing structural style in this part of Germany (*Error! Reference source not found.****c***; modified from Schreiner 2013).

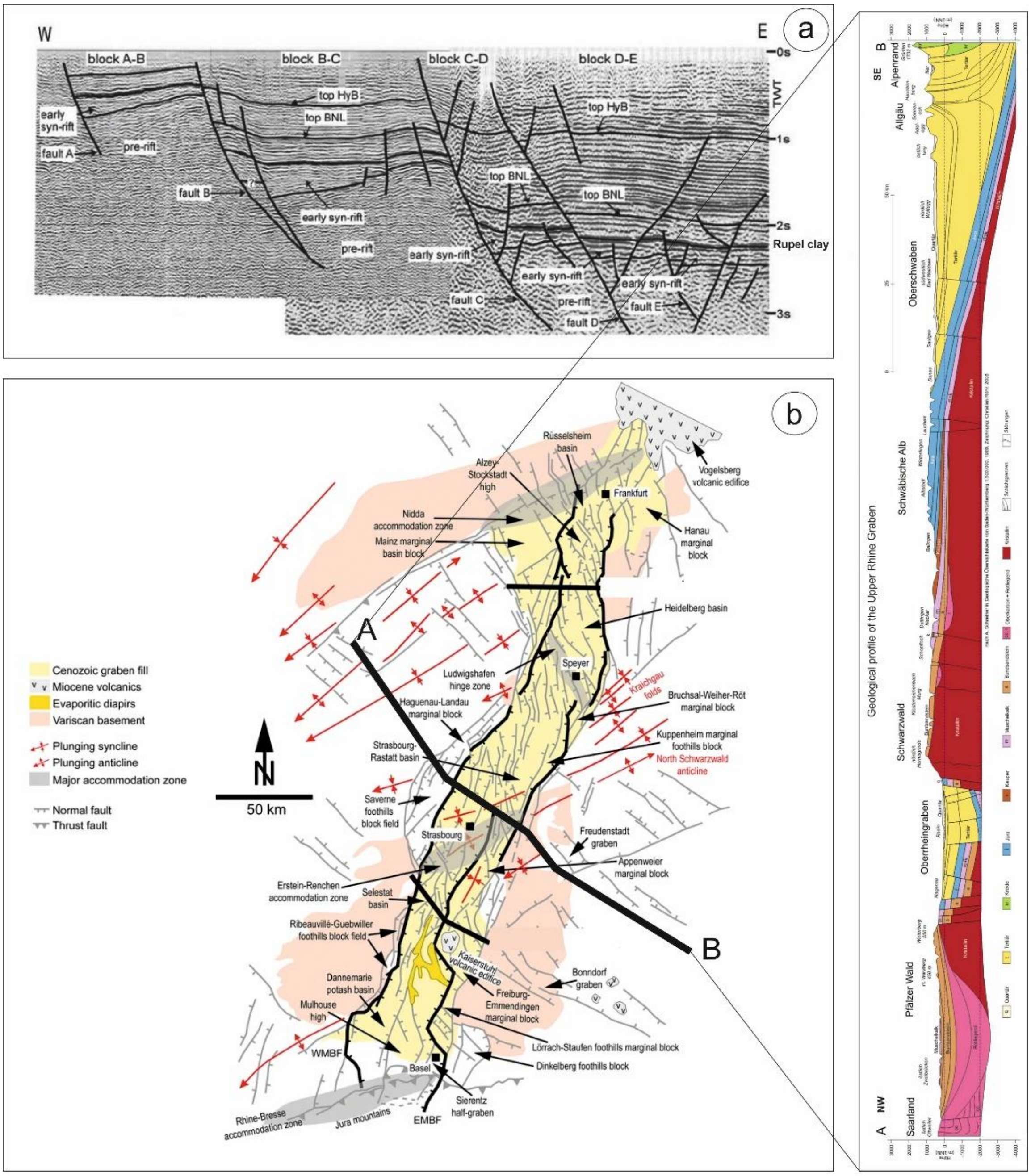


Fig. 14: *a) Interpreted seismic section located in the Upper Rhine graben, illustrating exemplarily the complex fault pattern by tilted fault blocks bounded by growth faults (modified from Derer et al. 2005). b) Structural map of the Upper Rhine Graben (modified from Grimmer et al. 2017); c) Geological profile from the Upper Rhine Graben in the NW across the Schwarzwald and the Schwäbische Alb to the rim of the Alps in the SE (modified from Schreiner 2013).*

Table 9: Main Characteristics and elements of the Upper Rhine Graben.

Main activity / formation	Early Oligocene
Main Kinematics / Style	Normal faults, strike slip
main strike directions	NNE-SSW
Prominent/characteristically structures, fault zones, lineaments or graben	Ilfeld-Bruchsal fault system
Further literature	Illies (1975), Schuhmacher (2002), Derer et al. (2005), Grimmer et al. (2017), GEORG project team (2013)

8.4.6 *Lower Rhine Bight/Graben*

The NW-SE striking lower Rhine bight, a recently seismically active zone, is bordered in the West and South by the Eifel and the Westerwald respectively, and rises up into the Rheinisches Schiefergebirge (***Fig. 15a***). The formation of the still subsiding graben structure started in the Early Oligocene at around 36 Ma (Zijerveld et al. 1992) and therefore is younger than the Upper Rhine graben. Several major blocks characterize the area, each bounded by NW-SE striking faults, such as the Krefeld Block, the Köln Block or the Erft Block (***Fig. 15b***). According to Ahorner (1975) the initiation of rifting along NW-SE oriented basement faults probably was caused by a counterclockwise rotation of the regional stress field from NE-SW to NW-SE (Ahorner 1975). Recently recorded earthquakes indicate a stress field that is characterized by a subvertical σ1 and a subhorizontal NE-SW oriented σ3 indicating almost pure dip-slip for the predominately NW-SE striking normal faults (Hinzen 2003). Additionally to NW-SE striking fault zones and, to a lesser extent, WNW-ESE ones, large strike-slip faults characterize the recent structural style of the active graben. Highest fault offsets are found at the Erft and Rurrand faults with 100 -180 m (Hinzen 2003).

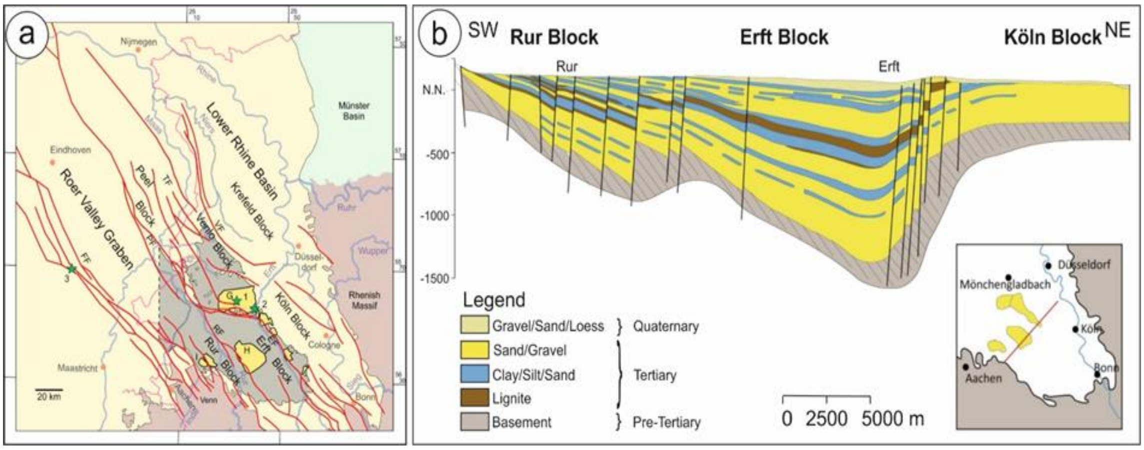


Fig. 15: *a) Structural map of the Lower Rhine embayment (from Prinz & McCann 2019), illustrating the arrangement and orientation of NW-SE oriented blocks and faults, b) Geological profile across the Lower Rhine Bight from southwest to Northeast (modified from Kothen 1997).*

Table 10: Main Characteristics and elements of the Lower Rhine Bight/Graben.

Main activity / formation	*Early Oligocene*
Main Kinematics	*Normal faults; extension/dip-slip*
Main strike direction	*NW-SE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Erft fault, Ruhrrand fault, Viersen fault* *Krefeld Block, Köln Block, Erft Block*
Further literature	*Ahorner 1975, Hinzen 2007, Prinz & McCann 2019, Zijerveld et al. (1992)*

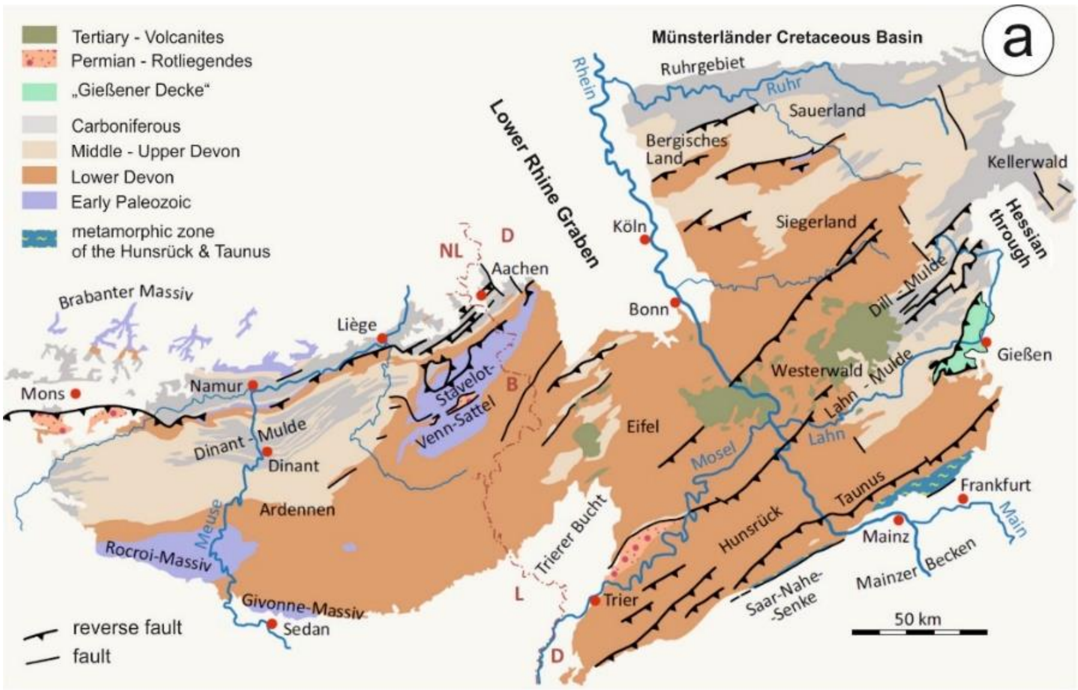
8.4.7 Rhenish Massif / Schiefergebirge & Saar-Nahe Basin

The predominantly low metamorphic Paleozoic rocks of the Rhenish Massif were folded during the Variscan orogeny and belong to the Rhenohercyan (***Fig. 16a***). It is part of the variscian Molasse, which was formed in the sub-variscian depression during the variscian orogeny and represents a long-living basement high from the Mesozoic to Tertiary. Larger thrust faults determine the structural picture, NE-SW striking thrust faults and WNW-ESE striking strike-slip faults dominate the recent fault pattern (***Fig. 16a***). It is bordered to the south by the Hunsrück southern rim fault and Taunuskamm thrust and to the North by the Münsterland Cretaceous basin.

The tectonic development of the Saar-Nahe Basin as a large Late Variscan molasse basin began simultaneously with the sedimentation of the oldest Upper Carboniferous (border between Namur and Westphalia) and was completed at the end of the Rotliegend. After Henk (1993) the basin is formed in the hanging wall of a major detachment which soles out about a depth of 16 km. The structural style of the basin is characterized by normal faults running parallel NE-SW oriented basin axis and orthogonal to this by transfer fault zones (***Fig. 16b***). In the course of the postvariscan tectonic development older NE-SW striking faults seem to have been reactivated (Rein et al. 2011).

Table 11: Main Characteristics and elements of the Rhenish Massif / Schiefergebirge & Saar-Nahe Basin.

Kinematics	*Rhenish Schiefergebirge: thrust tectonics*
Main strike sirections	*Rhenish Schiefergebirge: NNE-SSW/ NE-SW; 2nd: NW-SE; Saar-Nahe basin: NNW-SSE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Bopparder thrust fault, Taunuskamm thrust fault, Siegen thrust fault, Ennepe thrust fault, Hunsrück southern rim fault, Lothringen fault, Saar fault, Lauter fault, Odenbach fault*
Further literature	*Henk (1992); Rein et al. (2011), Toloczyki et al. (2006), Muraswki et al. (1983), Franke et al. (1990), Königshof et al. (2016), Dittmar et al. (1994), Trautwein-Bruns (2011)*



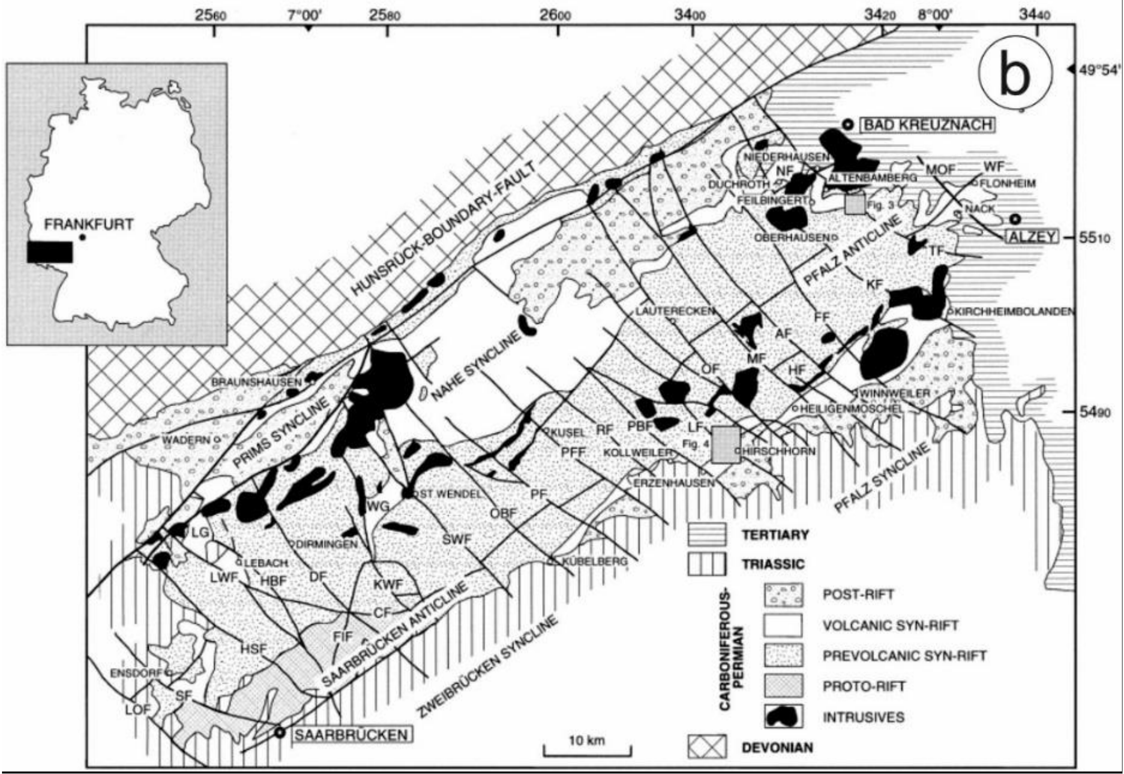


Fig. 16: *Geological overview maps of a) the "Rhenish Schiefergebirge" (modified from Meschede (2015)) and b) the Saar-Nahe-Basin with its tectono-sedimentary units (Stollhofen 1998).*

8.4.8 Mid-German basement highs and the surrounding of the Bohemian Massif

These areas include the Harz, the Flechtinger Höhenzug (***Fig. 7b**, **Fig**. 8*), the Thuringian Forest, the Saxon "Granulitgebirge", the Lausitz Block, the Erzgebirge, the Thuringian-Franconian-Voigtland Schiefergebirge, the Fichtelgebirge, the Oberpfälzer Wald and the Bavarian Forest. They are mainly part of the Central European Variscides and consist of Variscan folded Paleozoic sediments as well as plutonites, magmatites and metamorphites as well as of Pre-Variscan metamorphic remnants. Late to Post-Variscan tectonic development, the partially structural inversion and uplift during the Late Cretaceous and Cenozoic to recent tectonics resulted in the fragmentation and uplift of the basement along the western edge of the Bohemian Massif along fault systems mostly striking NW-SE and NNW-SSE (Walter 1992). According to Franzke et al. (2004) and Franze & Rauche (1991), major faults such as the "northern Harz fault" (Harznordrandstörung) or the Franconian Line separate these areas from the neighboring structural areas.

8.4.9 South German Molasse Basin

The European Molasse Basin is a Tertiary thrust foreland basin at the northern front of the Alps and extends over parts of France, Switzerland, Germany and Austria. The main part of this Basin lies within Germany. The development started some 35 Million years ago. This large asymmetrical syncline is filled with mostly clastic sediments originating from erosion of the Alpine orogen, and is underlain by Mesozoic sedimentary successions. The typically wedge shape of the basin evolved in consequence of the Euro-Adriatic continental collision and the rise of the Alps (Berge and Veal 2005). Those sediments are partly overrun and folded (Folded Molasse) due to the ongoing plate movement of the Euro-Adriatic continental collision (Schmid et al. 2008). In general, foreland basins are known to contain complex fault pattern due to the tectonic development (Beaumont 1981, Decelles & Giles 1996) and are characterized by thrusts close to the deformation front (Folded Molasse) due to plate convergence and normal faults at the foreland, due to extensional stresses, which lead to basin subsidence foreland bulge development (Bergerat 1987, Bradley & Kidd 1991). An example for this complexity in fault pattern within the South German Molasse basin is illustrated by recent studies on a 3D seismic cube around Munich (von Hartmann et al. 2016). Here, large normal faults displacing the Molasse sediments show lateral alternating dips. Although they are disconnected, they strike parallel to fault lineaments of the underlying carbonate platform. Von Hartmann et al. (2016) suggest that these faults grew both upward and downward from the middle of the Molasse package, are newly initiated within the Molasse sediments and not caused by reactivation of the faults in the carbonate platform and/or crystalline basement.
Aside from these locally observed characteristics, main structural elements in the South German Molasse (***Fig. 17a***) are found in the north the "Folded Molasse" (directly in front of the Alps and therefore involved within the nappes), which is bordered by the Alpen Randstörung. North of this fault the so called "Foreland Molasse" is located, which is characterized by nearby horizontal bedding, flexures and joints. Prominent fault elements are the Landshut-Neuöttinger fault, Donaurandabbruch and the Keilberg fault (***Fig. 17b***).

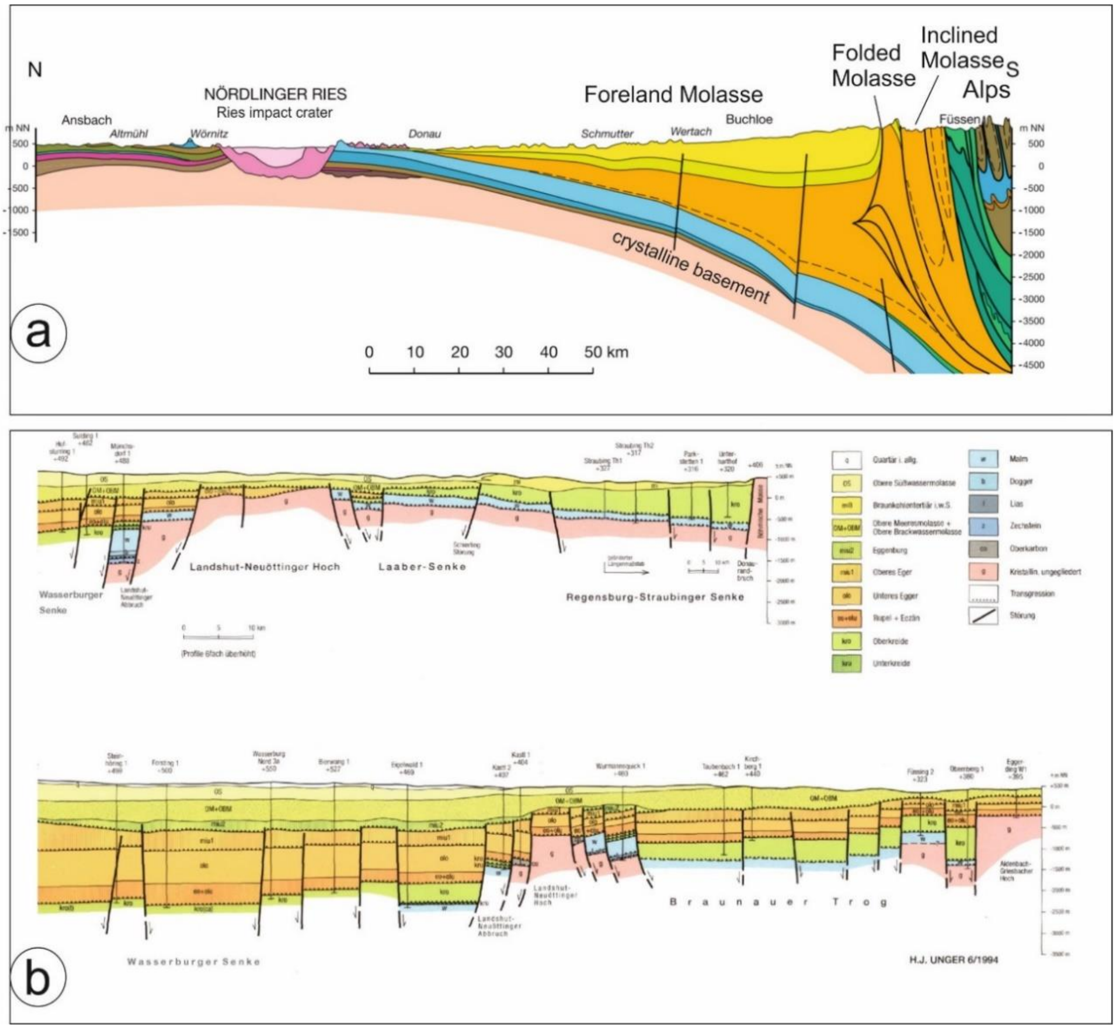


Fig. 17: a) Geological profile through the Molasse basin, illustrating the main strutural units such as the foreland molasse and folded molasse (10x exageration; modified from Glaser et al. (2014). b) Geological profiles across the Molasse basin: (https://www.lfu.bayern.de/geologie/geologie_bayerns/tektonik/molasse/index.htm).

Table 12: Main characteristics and elements of the South German Molasse Basin.

Main activity / formation	*Stages: Eo-Alpine (Cretaceous), Paleocene-Eocene, Oligocene-Miocene, Quaternary* *Main collisional phase Paleocene-Eocene: upper crust of the Adriatic plate was thrusted over European crust*
Main kinematics	*Foreland Molasse Basin: extension* *Folded Molasse: thrust tectonics/ previous extensional tectonics*
Main strike direction	*ENE – WSW*
Prominent/characteristically structures, fault zones, lineaments or graben	*Structural units: folded molasse (part of the alps), foreland molasse, inclined molasse* *Faults: Donaurand fault, Keilberg fault, Landshut–Neuöttinger fault*
Further Literature	*Unger (1996), Kuhlemann & Kempf (2002), Bachmann & Müller (1992), Von Hartmann et al. (2016), Abele et al. (1955), Glaser et al. (2014)*

8.4.10 German Alps

The structural units of the European Alps consist of the Helvetic, the Penninic, the Austroalpine and the South Alpine superunits. The Bavarian Alps consist of the superordinate units of Folded Molasse (Faltenmolasse), the Helveticum, the Ultra-Helveticum, the Feuerstätter Flysch, the Rhenodanubikum, the Arosa zone and the Northern Calcareous Alps (Nördliche Kalkalpen) (***Fig. 18***). Due to Upper Cretaceous´ nappe and flake tectonics, reverse-and thrust faults, strike slip but also normal faults were formed, separating the nappes. The W-E to WSE-ENE running fault zones separate the individual nappes, and often are transferred by NW-SE and NE-SW running strike slip fault. At diagonal and transverse fault systems (lateral ramps, strike-slip faults) the geometry of folds and thrusts often changes abruptly in the strike, whereby the amount of the total shortening between individually often differently deformed segments within an thrust belt (transfer faults) remain preserved and fault offset amounts of up to several kilometers can add up. Further characteristics for the structural style are strike-slip fault systems and associated compressional- and extensional structures. These were formed during Oligocene-Miocene N-S compression caused by eastward directed shift of the central East-Alp block. Examples for these fault systems are Innsbruck-Salzburg-Amstetten fault, Salzach–Ennstal fault, Königsee–Traunsee fault.

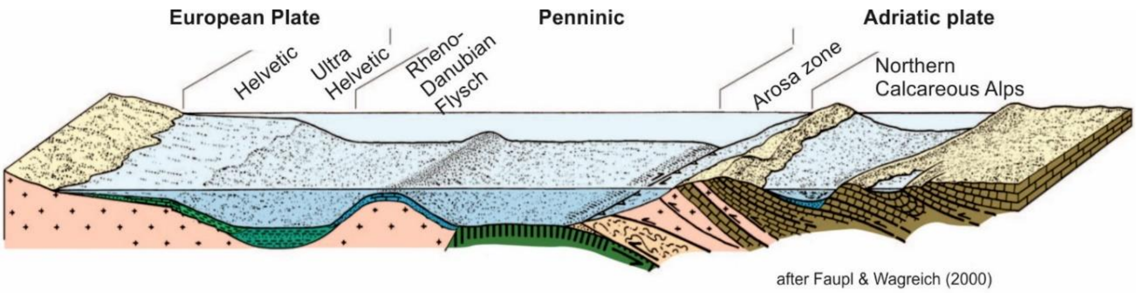


Fig. 18: Schematic illustration of the Alps with its main elements such as the folded Molasse (Faltenmolasse), Ultra-Helvetic, the Helvetic, Rheno-danubian Flysch, the Arosa zone and the Northern Calcareous Alps (Nördliche Kalkalpen), modified from Faupl & Wagreich (2000).

Table 13: Main characteristics and elements of the German Alps.

Main activity / formation	*30-35 Ma - Recent*
Main kinematics	*contractional, fold/thrust tectonics*
Main strike of prominent thrusts	*WSW-ENE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Nappes and flake tectonics: W-E to WSW-ENE running fault zones separate the individual nappes, often are transferred by NW-SE/NE-SW running strike slip faults* *Innsbruck-Salzburg-Amstetten fault, Salzach–Ennstal fault, Königsee–Traunsee fault*
Further literature	*Glaser et al. (2014), Faupl & Wagreich (2000), Schwerd (1996)*

8.5 Cenozoic Rift System, Seismicity & Volcanism

Today's structural pattern of Germany is largely defined by the European Cenozoic Rift system (ECRIS; Ziegler (1992), Ziegler & Dézes (2005), Reicherter et al. 2008) as it overprinted the afore formed structures within the Meso-Cenozoic times and offset major fold and thrust belts of the Variscan basement or mask those basement features below thick Cenozoic to Quaternary sediments. The rift system is thought to have formed in response to compression of the lithosphere in front of the zones of collision that formed the Alps and Pyrenees (Ziegler 1992). Rift initiation starts by an ESE-WNE directed extension during Late Eocene to Oligocene and initial rift propagated northwards as the collision along the Alps intensified and the western part of France moved to the west.

Ongoing active structures responsible for recently earth movements are the Hohenzollern Graben, the Ruhr Graben in the Lower Rhine Bight and the Eger Graben (***Fig. 19a***). However, the Upper Rhine Graben as the largest and geomorphologically most prominent structure in southwestern Germany has not shown major activity for the last 6-7 million years.

To the north, the ECRI system branches off to the north-east into the Hessian Tertiary Basin (see also *Chapter* ⍰ο–-), and to the east, into various smaller depressions, which merge into the Southern Lower Saxony Basin, and the Lower Rhine Bight, which branches off to the north-west via several smaller Quaternary basins in the Middle Rhine (e.g. Neuwieder Becken). Below the Mainz Basin is the triple point for this branching (Rhenish triple point), which was already recognized by Cloos (1938). The northwestern branch continues in the rift structures of the North Sea.

Accompanied with the formation of the ECRIS an up to 1200 km wide intraplate magmatism developed, also known as European Cenozoic Volcanic province (ECVP). Only few centers of volcanism formed in the context of ECRIS are located directly within the graben. Instead, some are located up to 200 km away from the rift structures. In Germany the main centers are the Vogelsberg, Eifel, Westerwald and Rhön (***Fig. 19a***).

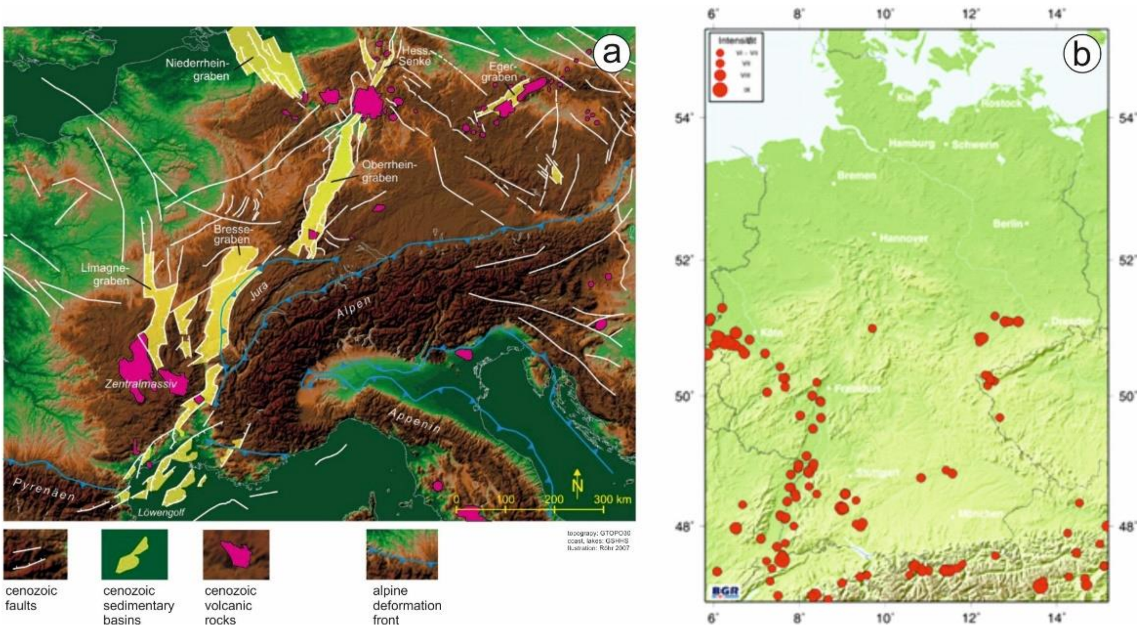


Fig. 19: a) Topographic map illustrating the European Cenozoic Rift system with e.g. the Upper and Lower Rhine graben and associated centers of volcanism in Germany, e.g. the Vogelsberg, Eifel, Westerwald and Rhön (modified

after Röhr 2007). b) Damage earthquakes in Germany since the year 800 (epicentral intensity), Bundesanstalt für Geowissenschaften und Rohstoffe, www.bgr.bund.de

Table 14: Main characteristics and elements of the ECRIS.

Main activity / formation	*Tertiary*
Main kinematics	*Normal faults, extensional/transtensive*
Prominent strike directions	*NNE-SSW; NNW-SSE; NW-SE*
Prominent/characteristically structures, fault zones, lineaments or graben	*Recently active grabens: Hohenzollern Graben, Ruhr Graben in the Lower Rhine Bight and Eger Graben* *Volcanism: e.g. Vogelsberg, Kaiserstuhl*
Further Literature	*Ziegler 1992, Ziegler & Dézes (2005), Reicherter et al. 2008, Schuhmacher 2002*

8.6 Salt structures & faults associated to salt tectonics

Most of salt structures of Germany belong to Southern Permian Basin, respectively the North German Basin therein. These structures and their formation contribute significantly to the current structural appearance of Germany, in particular, northern Germany. While the western and central part of the NGB is characterized by complex salt diapirs and walls, in the eastern part of the NGB salt pillows dominate. In the Mesozoic overburden e.g. of the Horn- and Glückstadt Graben (***Fig. 7b***) elongated salt walls dominate, which often are associated to larger normal faults in the basement and whose formation is probably mostly due to movements along these faults during the Keuper (Jaritz 1973, Frisch & Kockel 1997, 1998, Brückner-Röhling et al. 2005). Additionally, very complex crestal graben systems are found in top of the salt structures, affecting the Upper Cretaceous to Cenozoic.
A first structural pre-drawing of the salt walls, e.g. at least for the Glückstadt Graben, probably took place with the formation of salt pillow already during the Buntsandstein to Muschelkalk (Warsitzka et al. 2016, or see ***Fig. 20 & Fig. 21a***). Due to intensive extensional movements together with a high primary thickness of Zechstein- and Rotliegend salt, a decoupling of overburden and basement can be observed. In consequence, thick-skinned tectonics can only be observed at few places (e.g. structure Langsee, Looft and Itzehoe fault). Besides that a lot of salt structures are aligned along normal faults with major vertical offsets, the predominant part of salt structures show soft-linked (thick-skinned) to unlinked (thin-skinned) relations to the basement fault pattern (Warsitzka et al. 2019, ten Veen 2012). Based on these observations, it can be concluded that not only the activity at basement faults played a role in the formation of the salt structures and associated fault patterns of the Mesozoic-Cenozoic sedimentary cover (Warsitzka et al. 2019).
The relatively symmetrical and rather "simply" built salt walls, which dominate in the north, are replaced to the south by WNW/NW-ESE/SE striking complex, partly salt-filled fault zones or salt diapirs, which often change their characteristics along strike (Müller et al. 2016).
A summary of prominent tectonic phases, phases of initiation and main activity of salt structure growth within the North German Basin and surrounding is illustrated in the tectonostratigraphic chart of *figure Fig.* ***20*** and the maps of *figure Fig.* ***21***.

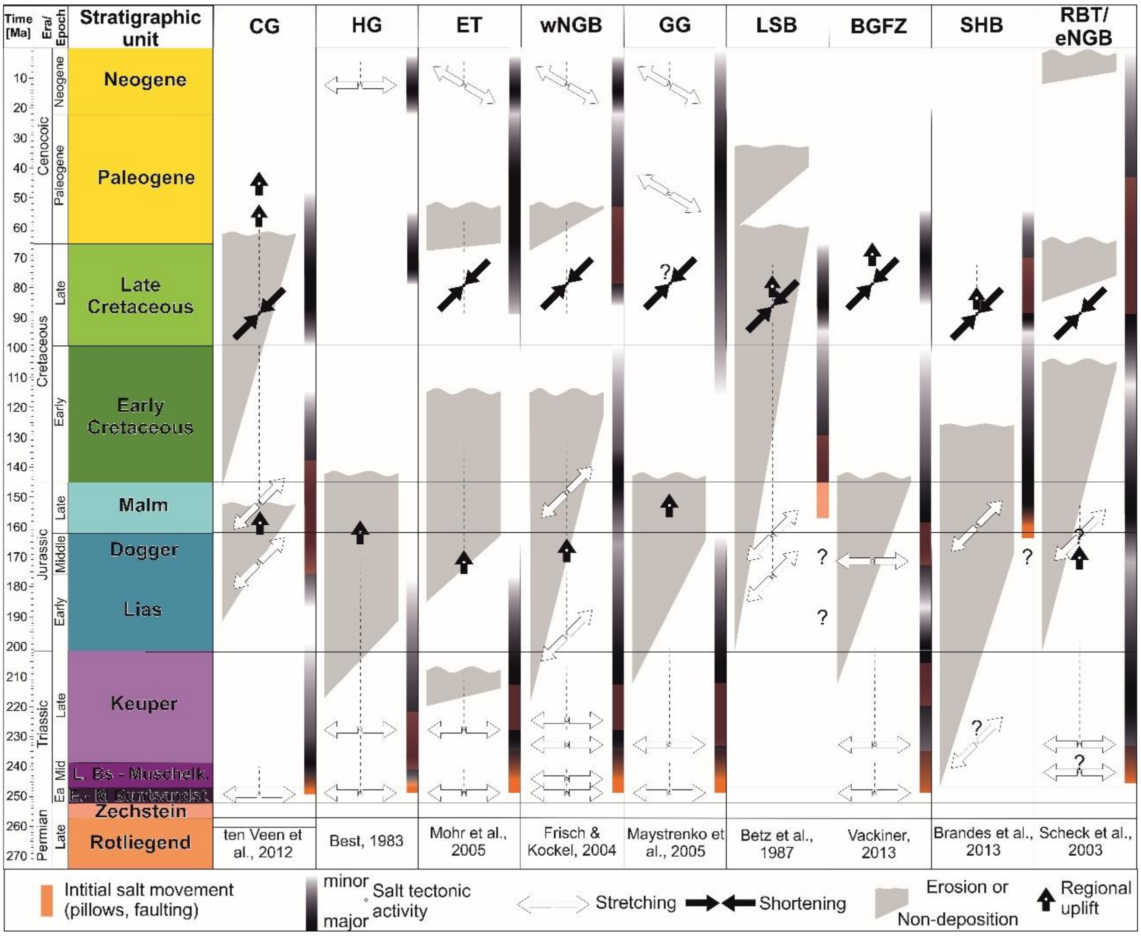


Fig. 20: Tectonostratigraphic chart of the main sub-basins of the North German basin and surrounding areas including prominent tectonic phases and phases of initiation and main activity of salt structure growth (edited from Warsitzka et al. (2018)). *BGFZ - Braunschweig-Gifhorn fault zone, CG - Central Graben, eNGB – eastern part of North German Basin, ET - Ems Trough, HG - Horn Graben, GG - Glückstadt Graben, LSB - Lower Saxony Basin, RBT - Rheinsberg Trough, SHB - Subhercynian Basin, wNGB - western part of North German Basin.*

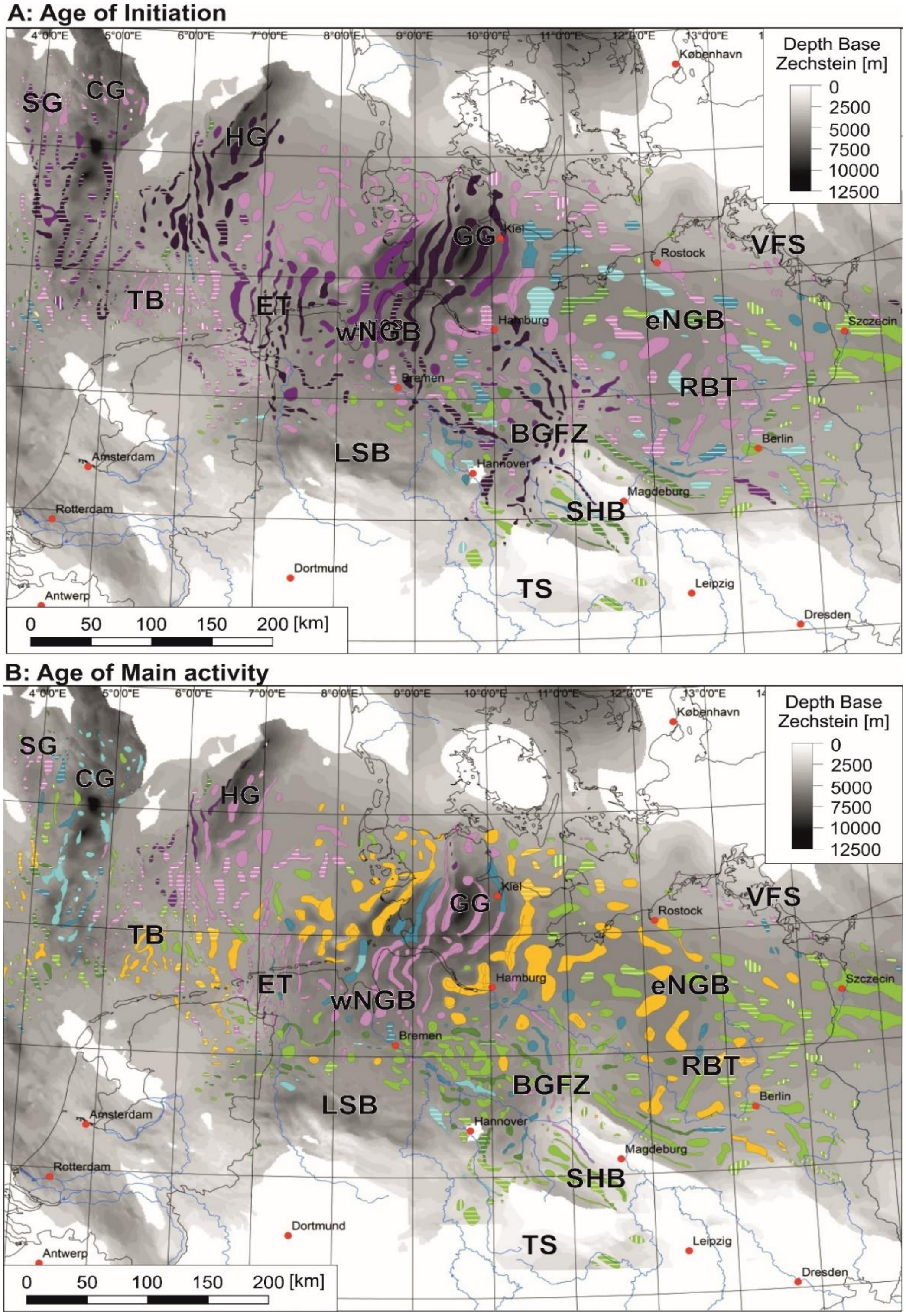


Fig. 21: **A:** Initiation phase of salt structures, **B:** Main activity phase of salt structures. Hatched structures are only assumed without a clear reference. See figure *Fig.* ***20*** for abbreviations and colour coding (edited from Warsitzka et al. (2018)). *SG - Step Graben, TB - Terschelling Basin, ET – Ems Trough, WNGB – western part of Central North German basin, TS - Thuringian Syncline, VFS - Vorpommern fault system, BGFZ - Braunschweig-Gifhorn fault zone, CG - Central Graben, eNGB – eastern part of Central North German Basin, HG - Horn Graben, GG - Glückstadt Graben, LSB - Lower Saxony Basin, RBT - Rheinsberg Trough, SHB - Subhercynian Basin.*

8.7 Preparation of German fault data: Concept and characteristics

The concepts of principal and overarching tectonic boundaries presented for entire Germany by the BGR are in an overview scale and are named by the notation "DE". For some German Federal States, more detailed concepts are available prefixed DE-<ISO 3166-2 code>. The fault data considered are characterized by regional variations in density and detail, different degree of generalization and origin. For this reason, different display scales are recommended for the respective data sets: 1.) German onshore (1: 2,500,000 - 1: 500,000), 2.) Baltic Sea (1:1,000,000 - 1:250,000), 3.) Central German North Sea (1:1,000,000 - 1:100,000), 4.) Entenschnabel region - The northwestern German North Sea sector (1:1,000,000 - 1:50,000).

The focus of the concept presented here follows the idea of assigning faults (i.e. if faults cross, lie within or border the domain) to different structural domains or subdomains (***Fig. 22***), each characterized by a specific tectonic-sedimentary development. The breakdown of Germany into different structural domains follows the idea of building a structural framework for an overview scale (see also van Daele et al. (2021) – GeoConnect 3D Deliverable 5.2c).

The delivered fault attributes are currently mainly limited to geometric aspects (such as length, strike). Some of them also include information on regional names as well as fault type, although most are marked as "unknown". For more detailed information on the definition of the individual structural domains and subdomains, their essential characteristics, and on selected faults themselves, please refer to the HIKE fault database itself.

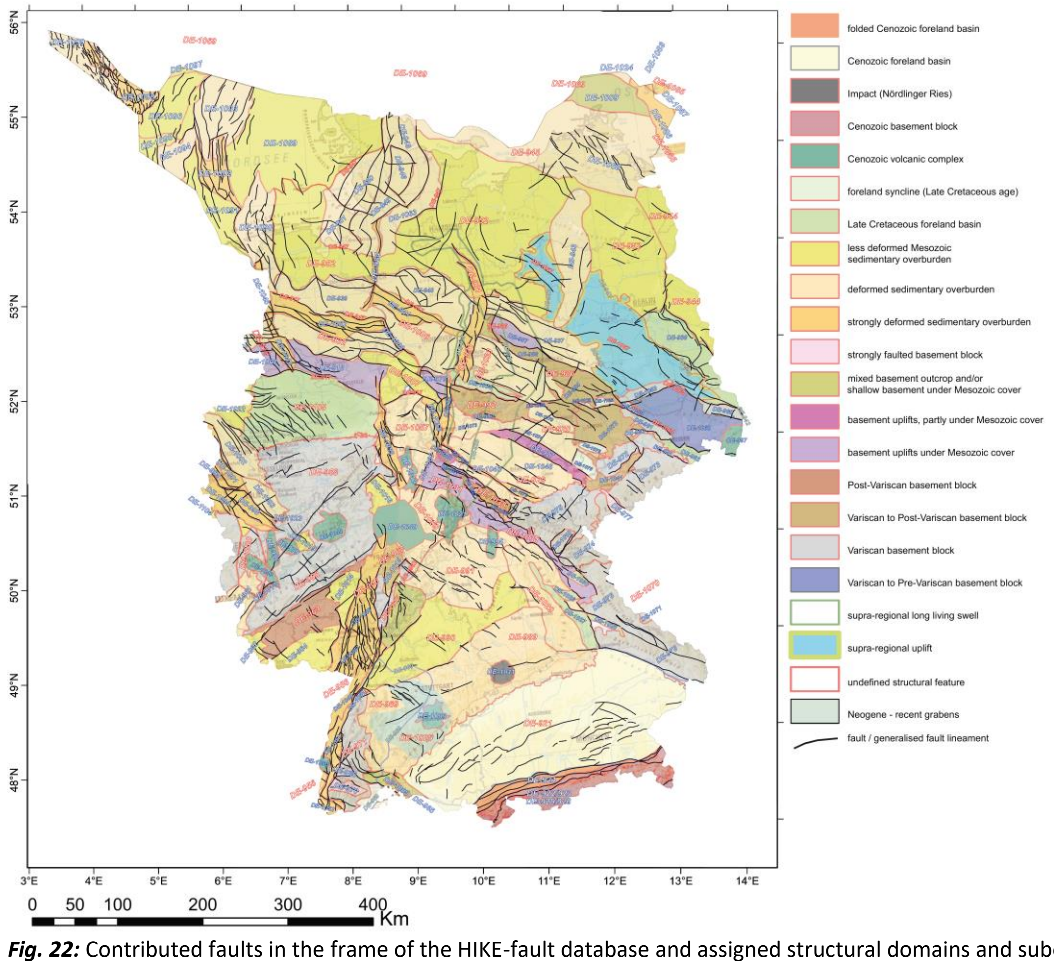


Fig. 22: Contributed faults in the frame of the HIKE-fault database and assigned structural domains and subdomains. For a higher resolution of this figure and for a tabular representation of the hierarchy of the defined structural domains and subdomains, see also Appendix **Error! Reference source not found.**: A-VIII.

8.8 References

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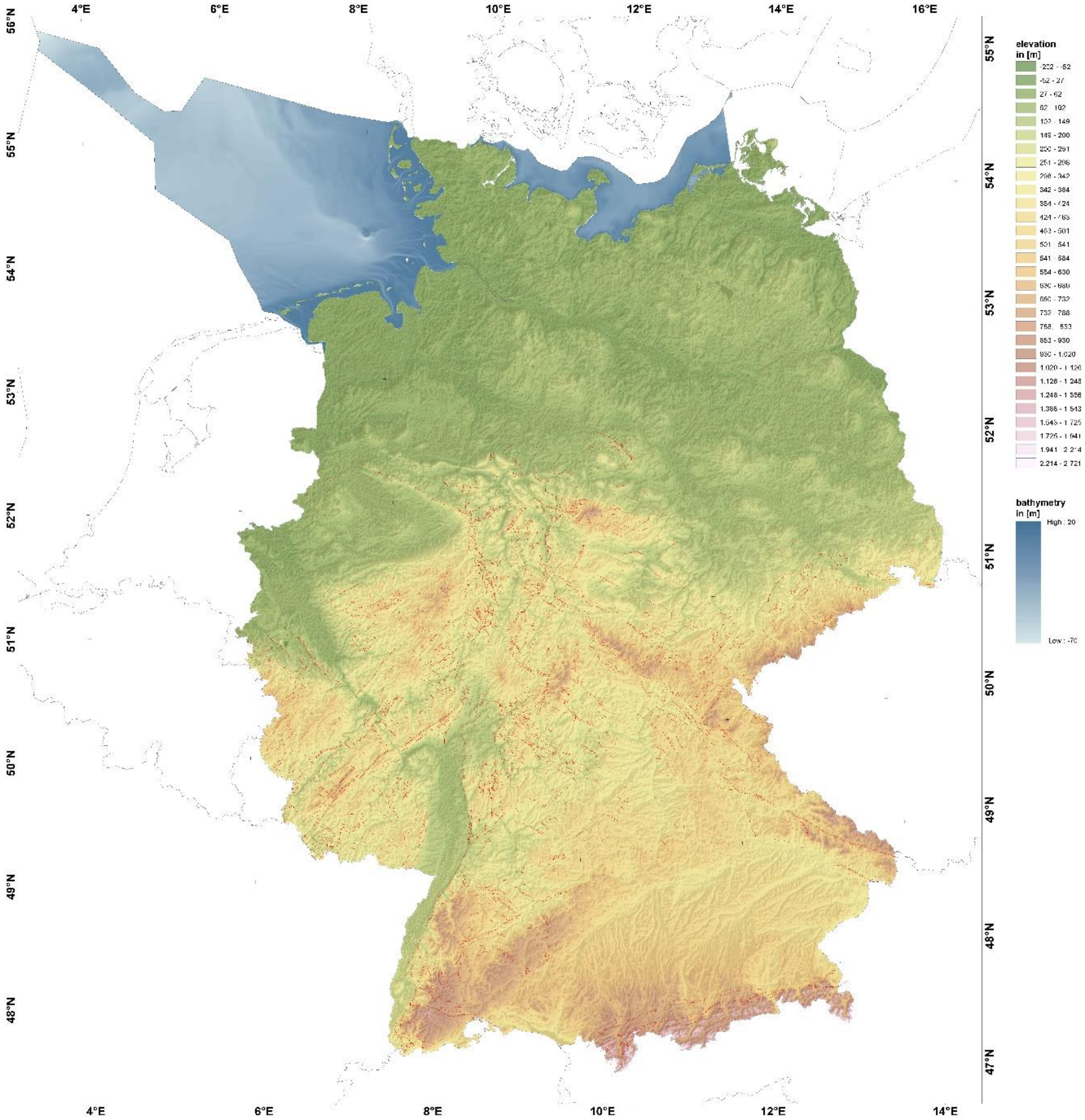
8.9 Appendix

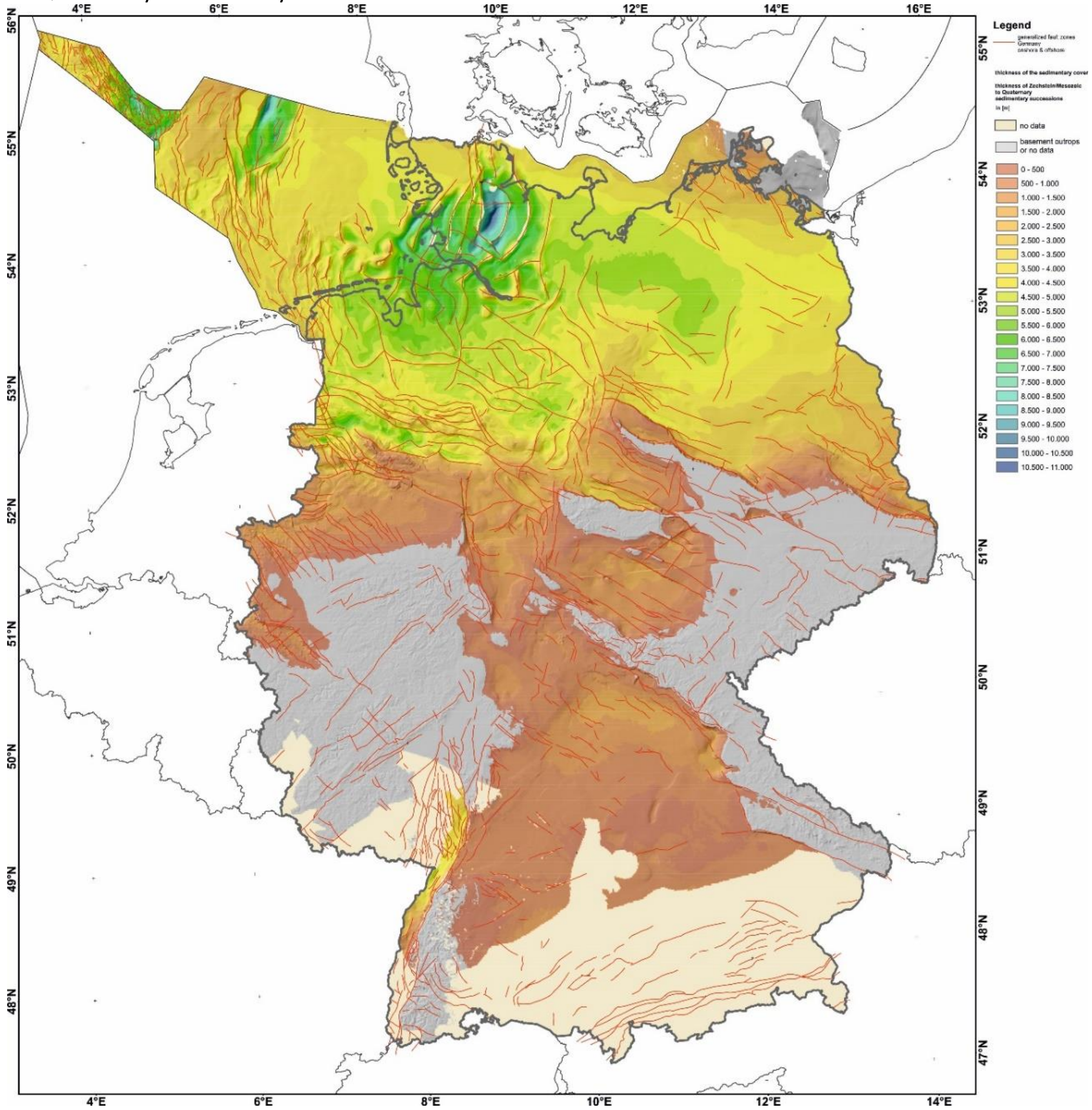
8.9.1 A-I: topography & faults at the surface

Topography and hillshade based on SRTM 90m & bathymetry of Germany. Faults at the surface after GÜK1000 (BGR 1993) are highlighted as thin red lines. Especially in areas with thin or absent Neogene to Quaternary sedimentary cover, fault traces are visible in the topography and captured by several outcrops. Furthermore, also for central and southern Germany, the definition of geological structural regions often correlates with changes in the topographical profile (e.g. Upper & Lower Rhine Graben, Nördlinger Ries, Harz, Münsterland Basin).



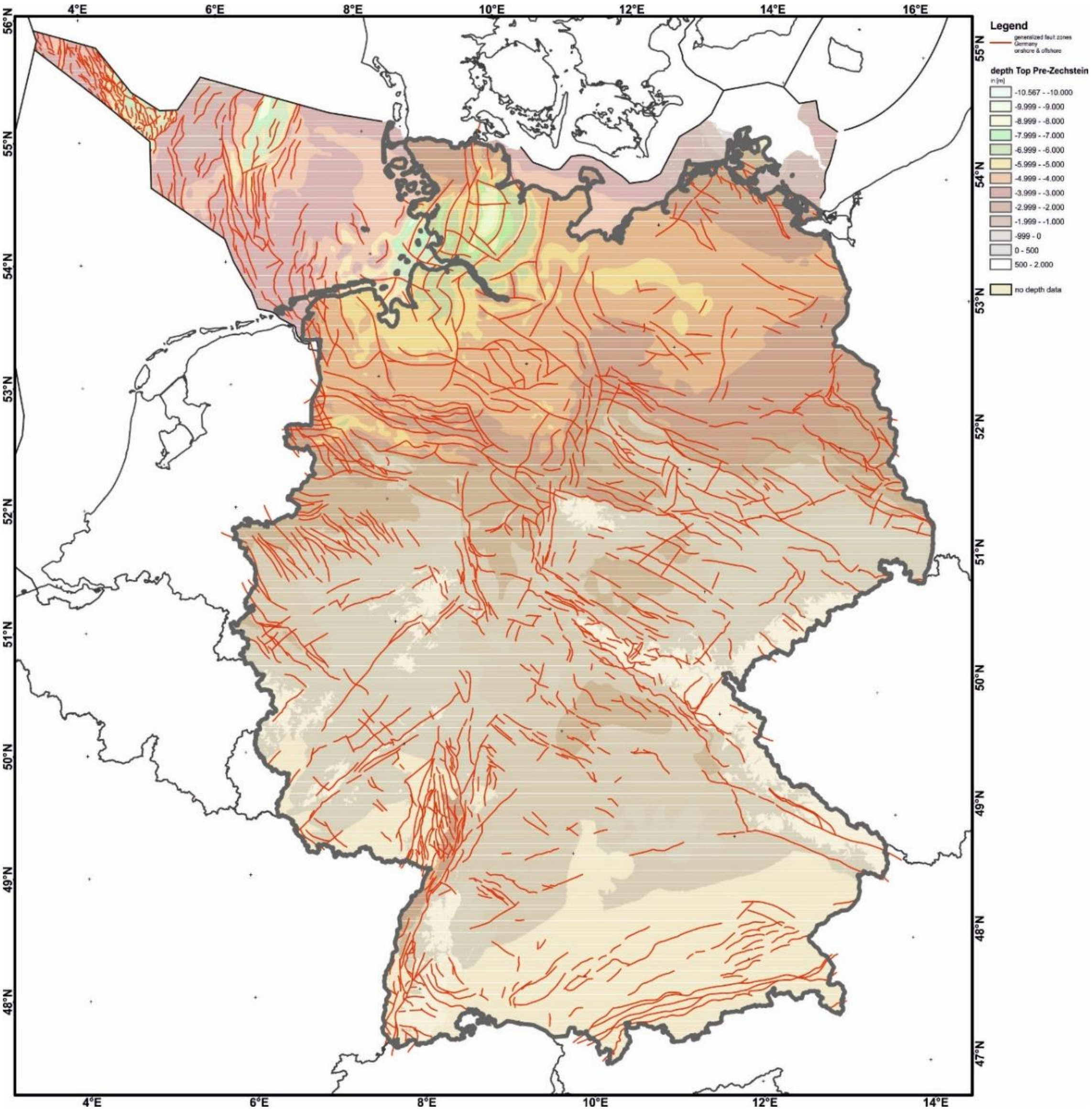
8.9.2 A-II: faults and their impact on thickness distribution of Late Paleozoic to Tertiary sedimentary cover

Faults and generalized fault zones in on- and offshore Germany in relation to thickness of the Zechstein to Quaternary sedimentary cover.



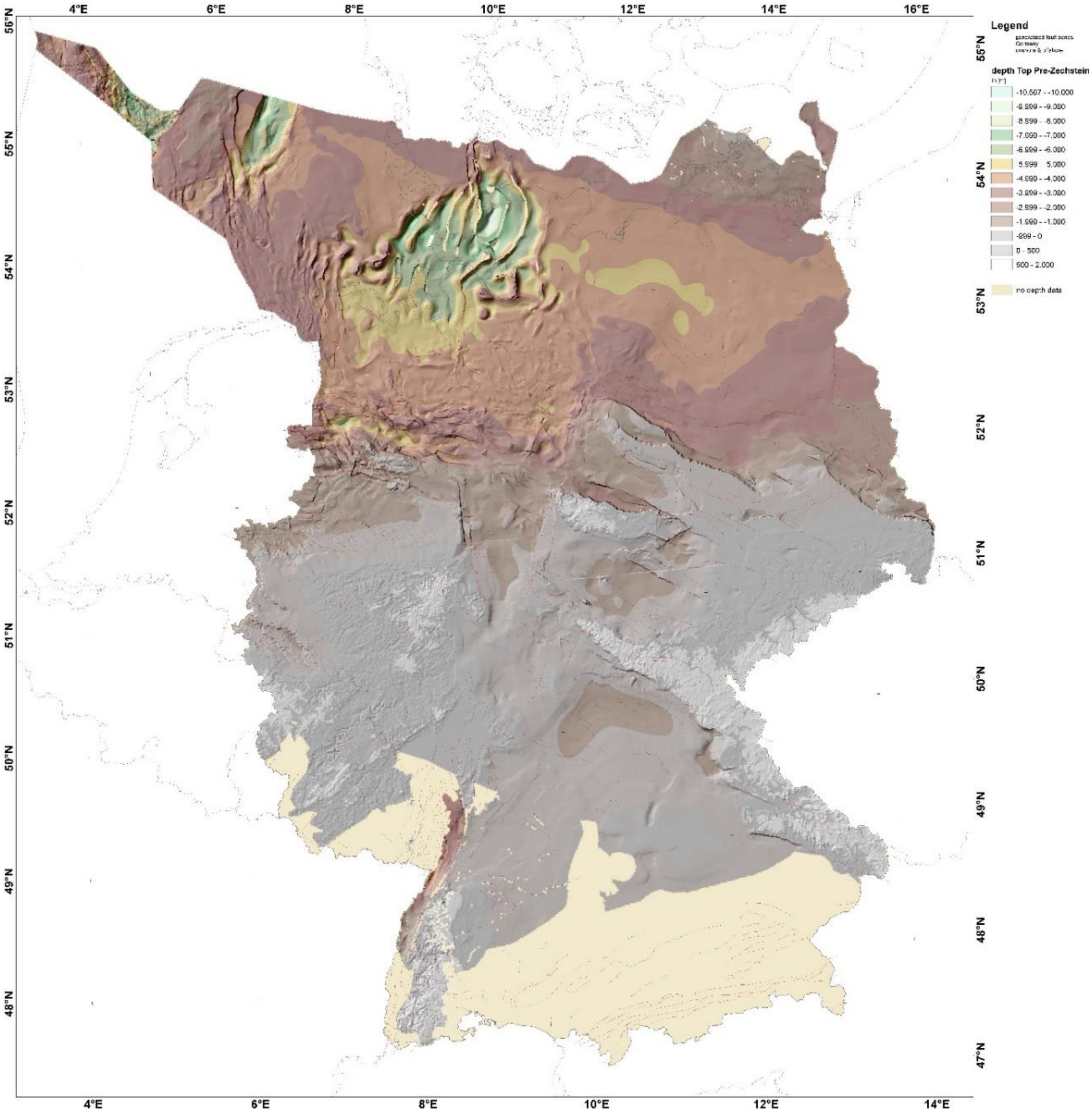
In grey a hillshade of the Pre-Zechstein topography. The grey areas represent regions without or only residual Zechstein to Cenozoic sedimentary cover. The fault compilation after Schulz et al. (2013) is highlighted in red.

8.9.3 A-III: Faults and generalized fault zones in on- and offshore Germany in relation to the depth of the Top Pre-Zechstein.



The fault compilation after Schulz et al. (2013) is highlighted in red.

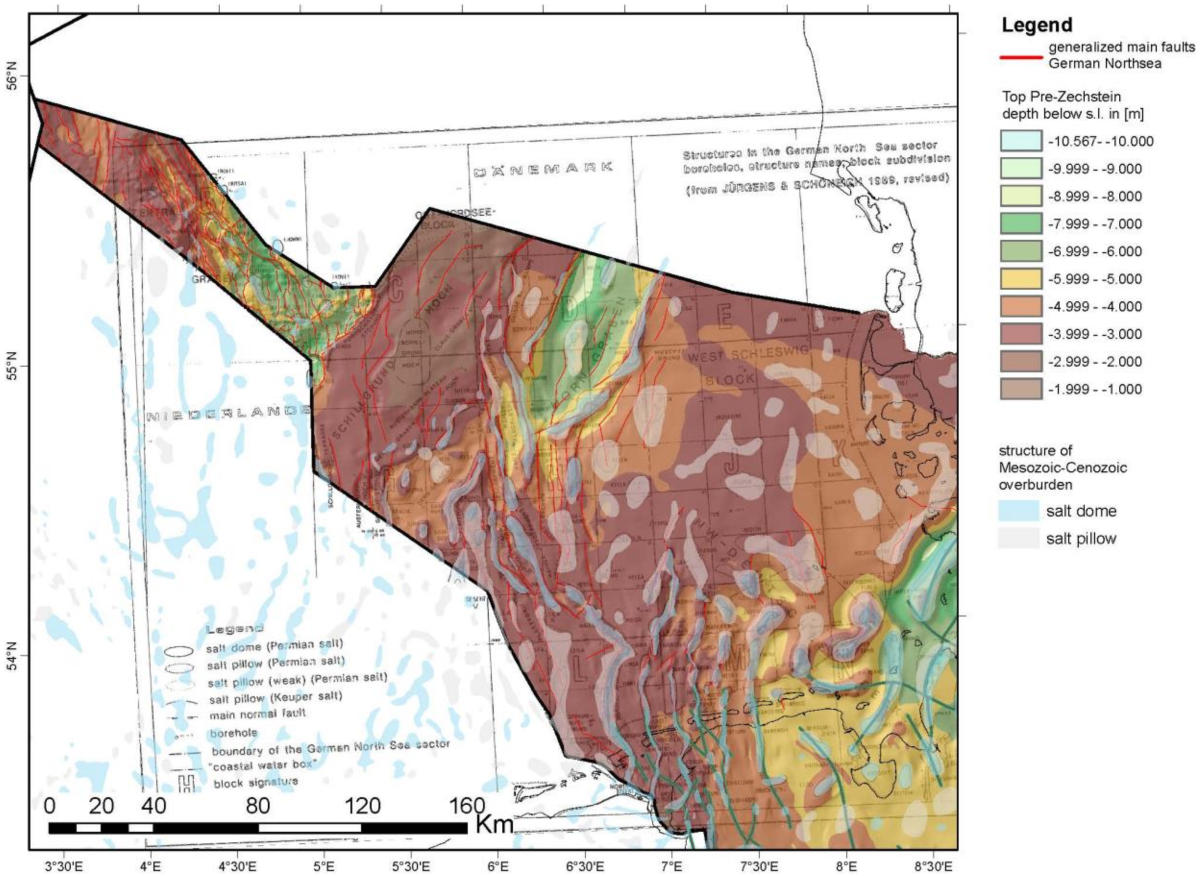
8.9.4 A-IV: Faults and generalized fault zones in on- and offshore Germany in relation to a map of the Top Pre-Zechstein with hillshade effect.



The Top Pre-Zechstein is shown together with a hillshade of the Pre-Zechstein topography in the background (in grey) to highlight the topographical differences and structure of this horizon. The fault compilation after Schulz et al. (2013) is highlighted in as red thin lines.

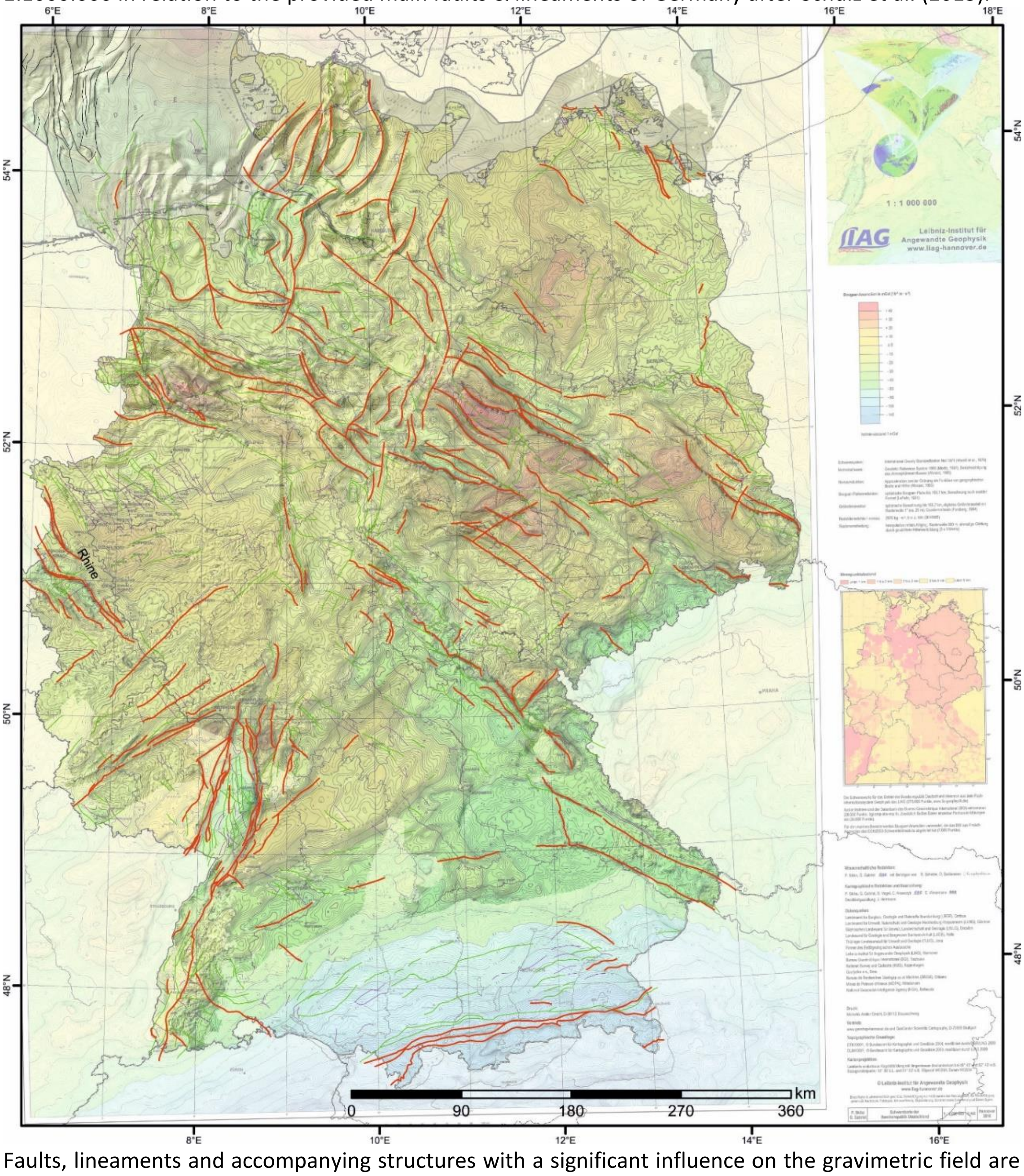
8.9.5 *A-V: fault pattern of the German North Sea*

Generalized main faults in the German North Sea in relation to the Top Pre-Zechstein topography. In addition a structure map from Jürgens & Schöneich (1989) and outlines of salt structures after Warsitzka et al. (2019) are shown.



8.9.6 *A-VI: major faults with influence on the bouger anomaly*

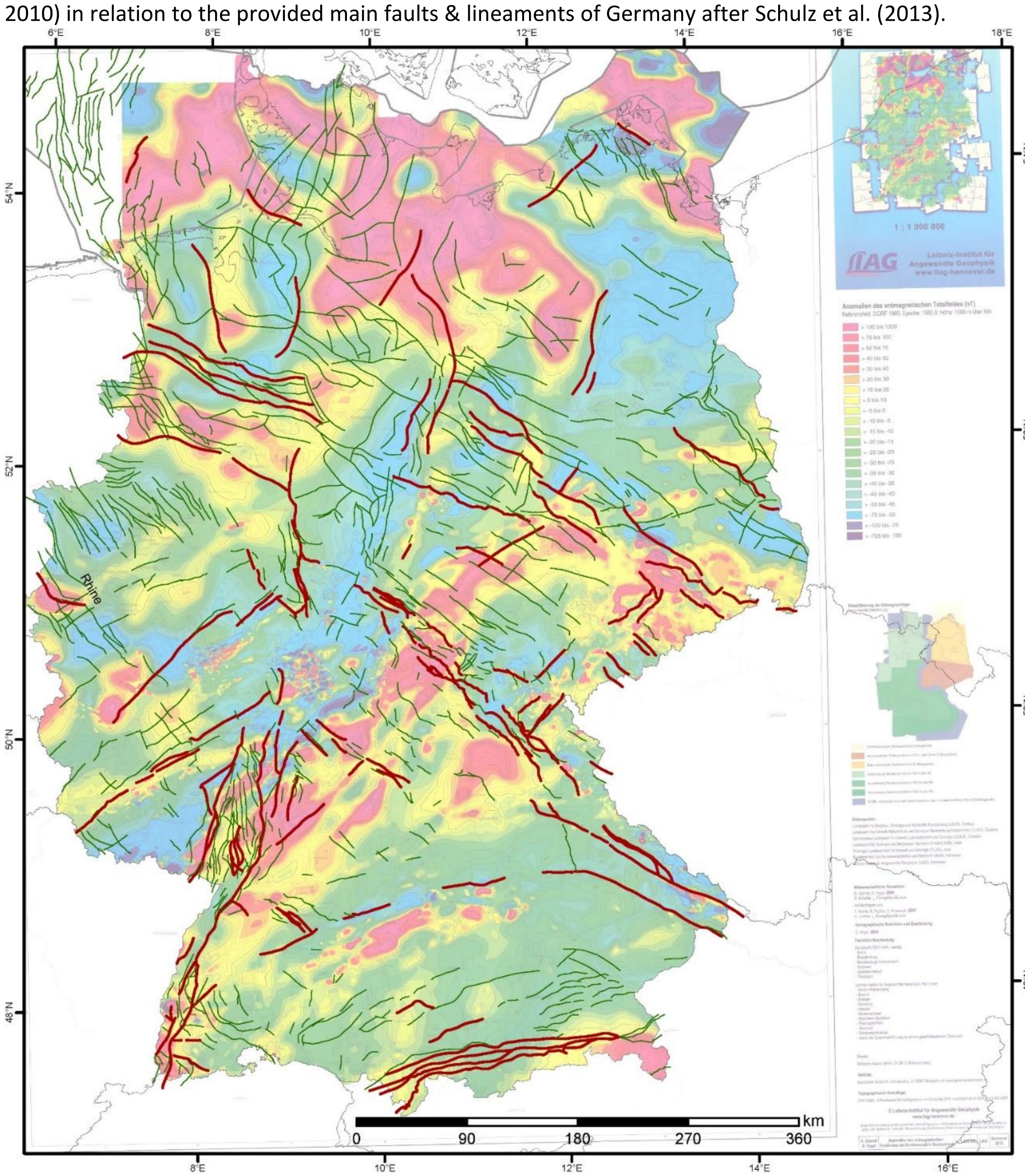
The bouguer anomaly (Bouguer anomalies, GRS80, 0 m amsl) of Germany (Skiba et al. 2010) in a scale of 1:1000.000 in relation to the provided main faults & lineaments of Germany after Schulz et al. (2013).



Faults, lineaments and accompanying structures with a significant influence on the gravimetric field are shown in red. Faults that presumably also show a correlation to the regional gravimetric field are shown in green. Faults which were not visible in gravimetric overview data in a scale of 1: 1000.000 are shown in purple. Faults in black were not analyzed.

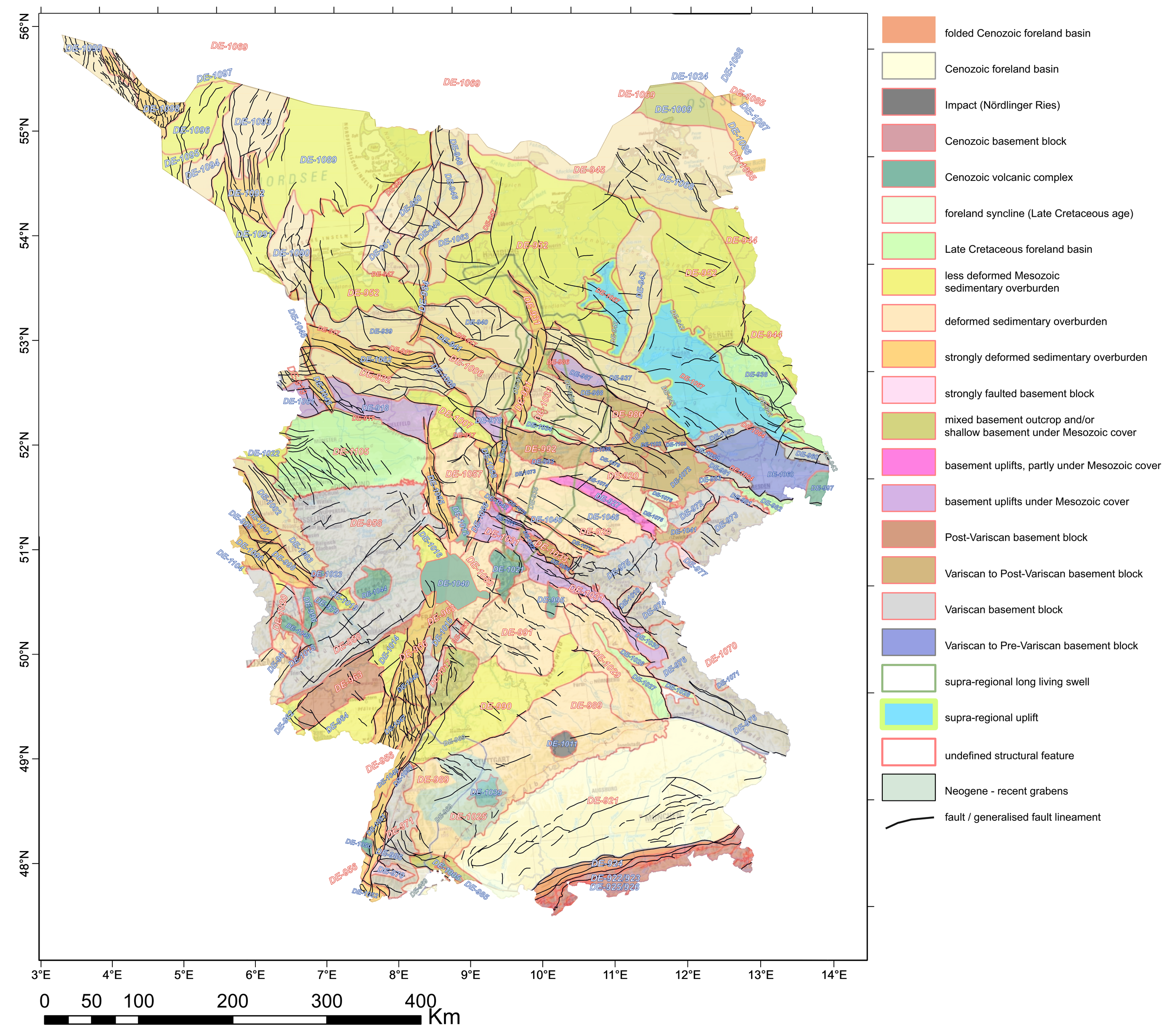
8.9.7 *A-VII: major faults with influence on the Earth's total magnetic field*

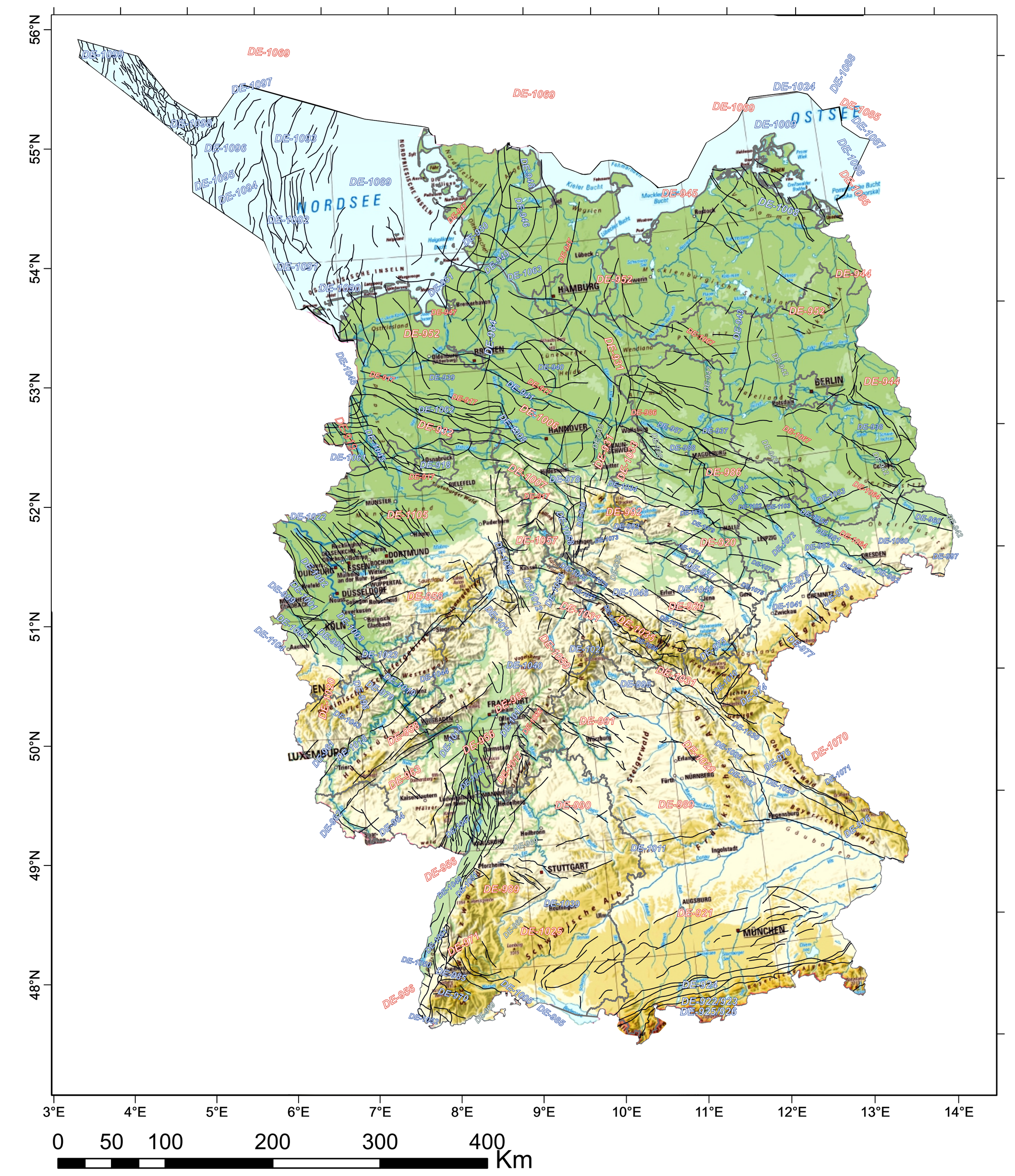
The Earth's total magnetic field (ΔT–anomalies, DGRF 1980.0, 1000 m a.s.l) of Germany (Gabriel et al. 2010) in relation to the provided main faults & lineaments of Germany after Schulz et al. (2013).



Faults, lineaments and accompanying structures with the same strike with significant influence on the magnetic field are shown in reddish brown. Faults that presumably also show a correlation to the regional magnetic field are shown in green.

8.9.8 A-VIII: The Structural Framework of Germany in an overview scale, based on structural domains & sub-domains





North German Plain

North German Basin - domain I: North German Plain & Central German North Sea				DE-1065
	Lower Saxony Basin			DE-917
		Central Lower Saxony Basin		DE-932
			Central Lower Saxony Basin fault system	DE-1062
		NE Lower Saxony Basin		DE-1006
			Allertal fault system	DE-941
		SE Lower Saxony Basin		DE-1007
		Steinhuder Meer-Stemmer Berg-Limberg fault system		DE-1008
		Western Lower Saxony Basin		DE-919
			Gronau-Waldhügel-Nordhorn thrust unit/	DE-1061
		Osning-Wiehengebirge thrust unit/ uplift		DE-918
		Dipping Harz structure & Sack depression		DE-978
	Ems Lineament			DE-1045
	Braunschweig-Gifhorn-Lüneburg fault system			DE-931
	Thrusted Central North German Basin sub-domains			DE-1106
		Altmark Fläming Depression		DE-937
		East-Brandenburg - North Sudetes Depression		DE-938
		Südoldenburg & Hoya Block		DE-939
		Rotenburg-Soltau-Eldingen Block		DE-940
	Emtinghausen-Krautsand fault system			DE-984
	Rheinsberg Trough			DE-943
	Prignitz-Lausitz-Riesengebirge Anticline			DE-942
		Prignitz Wall		DE-1067
		Rheinsberg Trough		DE-943
	Eastern rim of the North German Basin/ Szczecin-			DE-944
	Northeastern rim of the North German Basin			DE-945
		Vorpommeranian fault system - Grimmen Wall		DE-1068
	Glückstadt Graben			DE-947
		Central Glückstadt Graben		DE-946
		Mittelschleswig-Neumünster Block		DE-948
		Southern Glückstadt Graben - Krummendeich - Hohenlockstedt Graben		DE-949
		Western branch Glückstadt Graben		DE-950
		Southwestern Glückstadt Graben		DE-951
		Eastern branch Glückstadt Graben		DE-1063
		Emtinghausen-Krautsand fault system		DE-984
	Central North German Basin			DE-952
		Central NWGB - Ostholstein-West-Mecklenburg Block - Mecklenburg-		DE-953

Northern rim of North German Basin

Rynkøbing-Fyn-Møn-Arkona Highs				DE-1069
	Møn-Arkona High			DE-1009
Skurup Block				DE-1024
Teisseyre-Tornquist zone (TTZ)				DE-1085
	Gryfice Block			DE-1086
	Kolobrzeg Block			DE-1087
	Rønne Graben			DE-1088

Upper Rhine Graben & Lower Rhine Bight

Upper Rhine Graben				DE-956
	Western segment subdomain			DE-1047
	Northern segment subdomain			DE-1048
	Ilfeld-Bruchsal fault system			DE-1049
	Kaiserstuhl Block subdomain			DE-1050
	Southern segment subdomain			DE-1052
	Eastern border zone subdomain			DE-1051
	Northern marginal area subdomain			
		Mainz Basin		DE-1014
		Hanau-Seligenstadt Basin		DE-1015
		Amöneburg Basin		DE-1016
Lower Rhine Bight				DE-957
	Erft Block			DE-998
	Peel Horst			DE-999
	Roer Valley Graben subdomain			DE-1000
	Venlo graben			DE-1001
	Krefeld Block			DE-1002
	Cologne Block			DE-1003
	South Limburg Block			DE-1104
SE Central Netherlands Basin domain				DE-1022

W/SW Germany - Rhenish Massif and surrounding

Münsterland Cretaceous Basin				DE-1105
Rhenish Massif				DE-958
	Wittlich Depression			DE-1018
	Neuwieder Basin			DE-1019
	Eifel North - South zone			DE-1020
Trier Bight & Gulf of Luxembourg domain				DE-961
Saar-Nahe Basin domain				DE-963
Merziger Graben & SW Saarland Triassic platform domain				DE-962
Pfalz-Pirmasens-Nancy Trough				DE-964

uplifted/inverted southern regions of the NGB

North German Basin - domain II: "uplifted and/ or inverted southern regions of the North German Basin"				DE-1066
	Prignitz-Lausitz-Riesengebirge Anticline			DE-942
		Lausitz Block		DE-1064
			Görlitz Synclinorium	DE-960
			Torgau-Doberlug Synclinorium	DE-1053
			Mühlberg Depression	DE-1054
			Lausitz Anticlinorium	DE-1060
	Northwestern Saxony Basement Block			DE-1072
	Southern Eichsfeld-Altmark Swell			DE-935
		Werra Uplift		DE-1042
	Thuringian Depression			DE-920
		Thuringian Syncline		DE-1046
			Eichenberg-Gotha-Saalfeld fault system	DE-1078
			Northwestern Thuringian forest border zone	DE-1077
		Hermundurian Block		DE-927
		Mansfeld Syncline		DE-1079
		NW Thuringian Depression (Ohmgebirge, Leinefeld Anticline, Bleicherode Depression)		DE-1073
		Sangerhausen & Querfurt depression		DE-1074
		Zeitz-Schmölln depression		DE-1075
		Borna depression		DE-1076
	Halle-Wittenberg Block			DE-954
		Bitterfeld Graben		DE-1102
		Düben Depression		DE-1103
	Gardelegen-Flechtingen-Rosslau Uplift			DE-986
		Gardelegen uplift		DE-987
		Haldensleben-Wittenberg uplift		DE-988
	Subhercynian Basin			DE-1033
		Subhercynian Cretaceous Basin		DE-1034
	Hessian Depression			
		Egge-Kellerwald fault system		DE-1055
		Altmorschen-Neukirchen fault system		DE-1056
		North Hessian & Solling Block		DE-1057
		Leinetal Graben		DE-1058
		Southern Hessian Depression		DE-1059
	Harz			DE-992
		Ilfeld Basin		DE-993
	Thuringian Forest			DE-1035
		Schiefergebirge nappe of Schmiedefeld Vesser		DE-1036
		Ruhla Crystalline Complex		DE-1037
	Southwestern fringe of Bohemian Massif &			DE-1031
		South Thuringian-Franconian fault zones & uplifts		DE-1031
	Northern Kraichgau & Grabfeld Depression			DE-991

Franconian Platform & Black Forest

Black Forest				DE-969
	Badenweiler-Lenzkirch fault system			DE-970
	Black Forest basement high subdomain			DE-971
	Freiburg-Bonndorf-Bodensee fault system			DE-985
Swabian - Franconian - South Thuringian Block				
	Southern Franconian - Swabian Escarpments			DE-989
		Freudenstadt-Hohenzollern-Filder-Bodensee Graben system		DE-1025
	Southern Kraichgau Depression & Franconian			DE-990
	Northern Kraichgau & Grabfeld Depression			DE-991
	southwestern fringe of the Bohemian Massif & the Thuringian Forest subdomains			
		South Thuringian-Franconian fault zones & uplifts		DE-1031
		Franconian Jurassic-Cretaceous Depression		DE-1029
			Vilseck Depression	DE-1026
			Hollfeld-Veldenstein-Sulzbach-Kallmünz	DE-1027
		Bodenwöhr half-graben		DE-1028
		Weiden Basin		DE-1030

Alps & Molasse Basin

South German Molasse Basin				DE-921
German Alps				
	Folded Molasse Basin			DE-924
	Königsee-Traunsee fault system			DE-201
	Northern Calcerous Alps (Bavarian Nappe System)			DE-922, DE-923
	Helveticum			DE-926
	Rhenodanubian Flysch			DE-925

Bohemian Massif and surrounding East German basement highs

Bohemian Massif & East German Variscan to Pre-Variscan basement highs				
	Granulitgebirge			DE-972
	Erzgebirge			DE-973
		Gera-Jachimov fault system		DE-977
	Fichtelgebirge			DE-974
	Münchberg Crystalline complex			DE-1010
	Thuringian-Franconian-Voigtland Schiefergebirge			DE-975
	Bavarian - Bohemian Moldanubian			DE-976
	Bavarian - Bohemian Teplá-Barrandian			DE-1070
		Marienbad-Complex / Western Bohemian Shearzone / Teplá-Domazlice zone		DE-1071
	Elbe Zone (Basement outcrops)			DE-981
	Lausitz Block			DE-1064
		Görlitz Synclinorium		DE-960
		Torgau-Doberlug Synclinorium		DE-1053
		Lausitz Anticlinorium		DE-1060

Cenozoic volcanic regions & Impacts

German Cenozoic Volcanic regions				DE-994
	Siebengebirge volcanic field			DE-1023
	East Eifel volcanic field			DE-979
	West Eifel volcanic field			DE-1043
	Vogelsberg volcanic complex			DE-1040
	Hegau Volcanic field			DE-1005
	Heldburg Gangschar			DE-995
	Hocheifel Volcanic field			DE-996
	Lausitz Volcanic complex			DE-997
	North Hessian volcanic complex			DE-1012
	Urach Volcanic field			DE-1039
	Westerwald Volcanic field			DE-1044
	Rhön Volcanic field			DE-1021
Cenozoic impact - Nördlinger Ries				DE-1011

German Basement Highs

German basement highs				
	Tectonostratigraphic Permo-Caboniferous			
		Northwestern Saxony Basement Block		DE-1072
		Vorerzgebirge depression & Nossen-Wilsdruff Schiefergebirge		DE-1041
		Thuringian Forest		DE-1035
		Saar-Nahe Basin		DE-963
		Wittlicher depression		DE-1018
	Moldanubian basement domain			
		Bavarian-Bohemian Moldanubian		DE-976
		Black Forest domain		DE-969
			Badenweiler-Lenzkirch fault system	DE-970
			Black Forest basement high	DE-971
			Freiburg-Bonndorf-Bodensee fault system	DE-985
	Teplá-Barrandium domain			
		Bohemian Massif		
			Marienbad-Complex / Western Bohemian	DE-1071
			Tirschenreuth-Mähring Zone	DE-1081
			Erbendorf-Vohenstrauss Zone	DE-1080
			Münchberg Crystalline complex	DE-1010
	Saxothuringian basement domain			
		Bohemian Massif & Variscan to Pre-Variscan fringe of the Bohemian Massif		
			Granulitgebirge	DE-972
			Erzgebirge	DE-973
			Fichtelgebirge	DE-974
			Thuringian-Franconian-Voigtland Schiefergebirge	DE-975
		Schiefergebirge nappe of Schmiedefeld Vesser		DE-1036
		Elbe zone		DE-980
			Basement outcrops	DE-981
			Saxonian Bohemian Cretaceous Basin	DE-982
			Mügeln depression	DE-983
		Lausitz Block		
			Görlitz Synclinorium	DE-960
			Torgau-Doberlug Synclinorium	DE-1053
			Lausitz Anticlinorium	DE-1060
		Northwestern Saxony Basement Block		DE-1072
	Mid-German Crystalline High			
		Halle-Wittenberg Block		DE-954
		Thuringian Forest		DE-1035
			Ruhla Crystalline Complex	DE-1037
		Odenwald		DE-1017
		Spessart		DE-1032
	Rhenohercynian basement domain			
		Harz		DE-992
		Werra Uplift		DE-1042
		Transition Harz - Halle-Wittenberg Block (Hettstedter Sattel)		DE-1038
		Haldensleben-Wittenberg uplift		DE-988
		Rhenish Massif		DE-958
			Wittlicher depression	DE-1018
			Neuwieder Basin	DE-1019
			Eifel North - South zone	DE-1020

German Baltic Sea and surrounding

North German Basin - domain I: North German Plain & Central German North Sea			DE-1065
	Northeastern rim of the North German Basin		DE-945
		Vorpommern Fault System-Arkona High - Grimmen High	DE-1068
Rynkøbing-Fyn-Møn-Arkona highs			DE-1069
	Møn-Arkona High		DE-1009
Skurup Block			DE-1024
Teisseyre-Tornquist Zone (TTZ)			DE-1085
	Gryfice Block		DE-1086
	Kolobrzeg Block		DE-1087

German North Sea and surrounding

North German Basin - domain I: North German Plain & Central German North Sea			DE-1065
	West Schleswig Block		DE-1089
	Glückstadt Graben		DE-947
		Southwestern Glückstadt Graben	DE-951
		Southern Glückstadt Graben - Krummendeich - Hohenlockstedt Graben	DE-949
		Western branch Glückstadt Graben	DE-950
	southern branch Horn Graben		DE-1092
	Horn Graben		DE-1093
	East Frisia – Ems Estuary Region		DE-1090
	Central North German Basin		DE-952
transition North German Basin/ Anglo Dutch Basin			
	southwestern branch Horn Graben		DE-1094
	Schillgrund Platform		DE-1095
	Schillgrund High		DE-1096
	G+L Platform		DE-1091
Anglo-Dutch Basin			DE-1101
	Central Graben		DE-1100
		central parts of the Central Graben	DE-1098
		Step Graben	DE-1099
East North Sea - Rynkøbing-Fyn - Møn-Arkona highs			DE-1069
	East North Sea High		DE-1097

9 LBGR – GERMANY

9.1 Introduction – Principle geological situation and data base

The area of Brandenburg is situated in the South Eastern part of the North German Basin ("NGB", a part of the Central European Basin System, see Fig. 1). The North Eastern part of Brandenburg is in close contact to the border zone of the NGB and the Polish Trough.

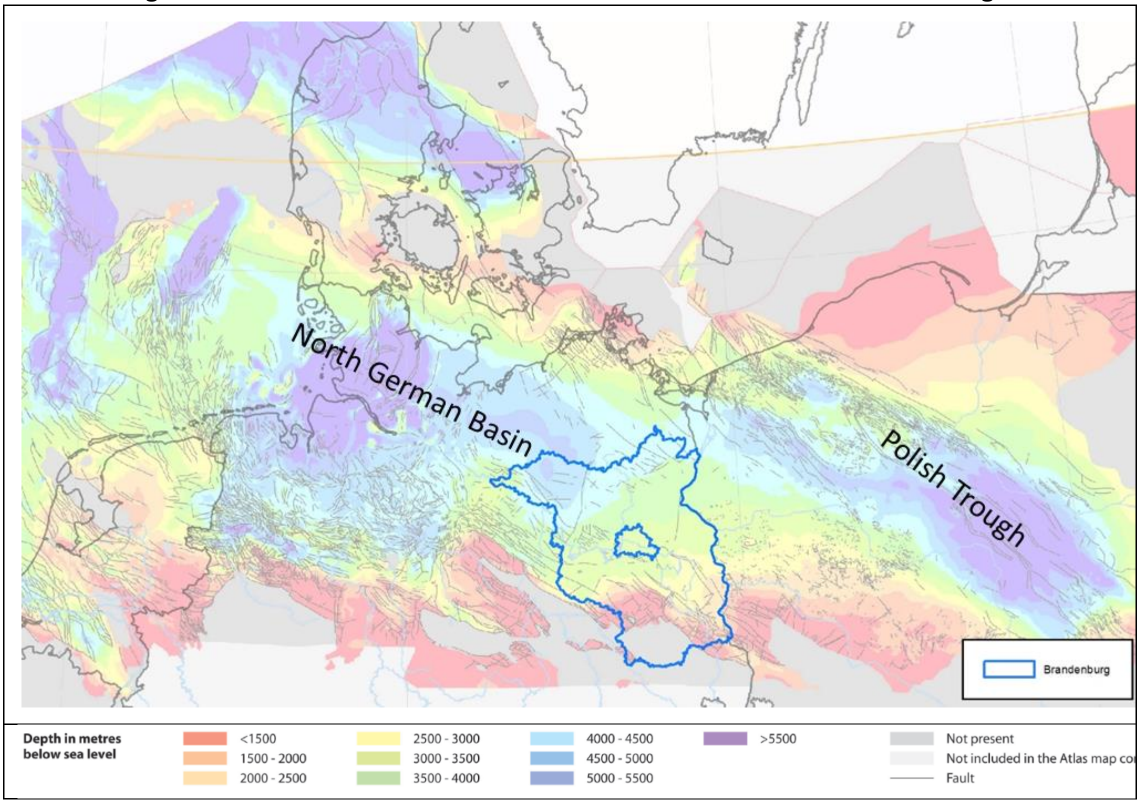


Fig. 1: Position of Brandenburg in the Central European Basin (Map after Doornenbal & Stevenson 2010, Fig. 8.2 depth of the base of the Zechstein)

The evolution of the North German Basin in Brandenburg took place in different phases (Stackebrandt 2010):

- initial rifting phase — Carboniferous to Rotliegend
- major subsidence phase — Upper Rotliegend to Upper Triassic
- differentiation phase (synalpidic extension phase) — Upper Triassic to Upper Cretaceous
- inversion phase (synalpidic contraction phase) — Upper Cretaceous to Paleogen
- stabilization phase — Eocene to recent

These phases were related to different structural stages and stress conditions and developed specific fault patterns and fault activities.

The principle structure of the sedimentary filling from Carboniferous to Cenozoic is shown in the cross-section of Fig. 2. The basin evolution starts in the initial rifting phase with Permocarboniferous volcanics and sediments (Variscian Molasse). In the major subsidence phase sedimentary series with thicknesses up to more than 3.000 m were deposited from the Upper Rotliegend to the Upper Triassic. The basin configuration in the Upper Permian (Base of Zechstein salt) is shown in Fig. 1. The Young Palaeozoic Zechstein salt was of special importance for the further basin evolution in Mesozoic and Cenozoic because halokinesis of Permian salt starting in the Late Triassic led to the development of local sinks during Jurassic, Cretaceous and Tertiary and to a decoupling of the tectonics of the Pre-Zechstein strata and the Mesozoic/Cenozoic succession. The stress field changed in this period from an E-W-extension (Triassic) to NE-SW-extension (Jurassic to Cretaceous) (Kley at al. 2008). From Late Cretaceous to Early Tertiary a stress regime with a NE-SW contraction developed that results inversion of fault structures (especially a partial back-thrusting at the Central German Main Escarpments). Basement blocks at the southern margin of the NGB basin were uplifted (Lusatian Massif or "Lausitz Block") and the Paleozoic-Mesozoic succession was eroded in these areas.

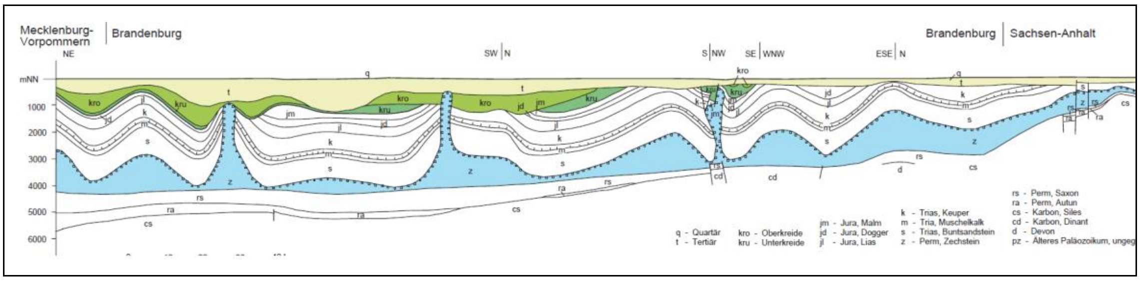


Fig. 2: Geological section (S/SW-N/NE) through the Sedimentary cover of the North German Basin in Brandenburg and the neighbouring Federal States Sachsen-Anhalt in the Southwest and Mecklenburg – Western Pommerania in the Northeast. (after Stackebrandt 2010, blue signature: Zechstein Salt, green signature: Cretaceous, yellow signature: Tertiary)

The basement in the area of Brandenburg was formed in the Variscian period (Fig. 3: Geotectonic situation in Central Europe at the end of the Variscian Orogensis).

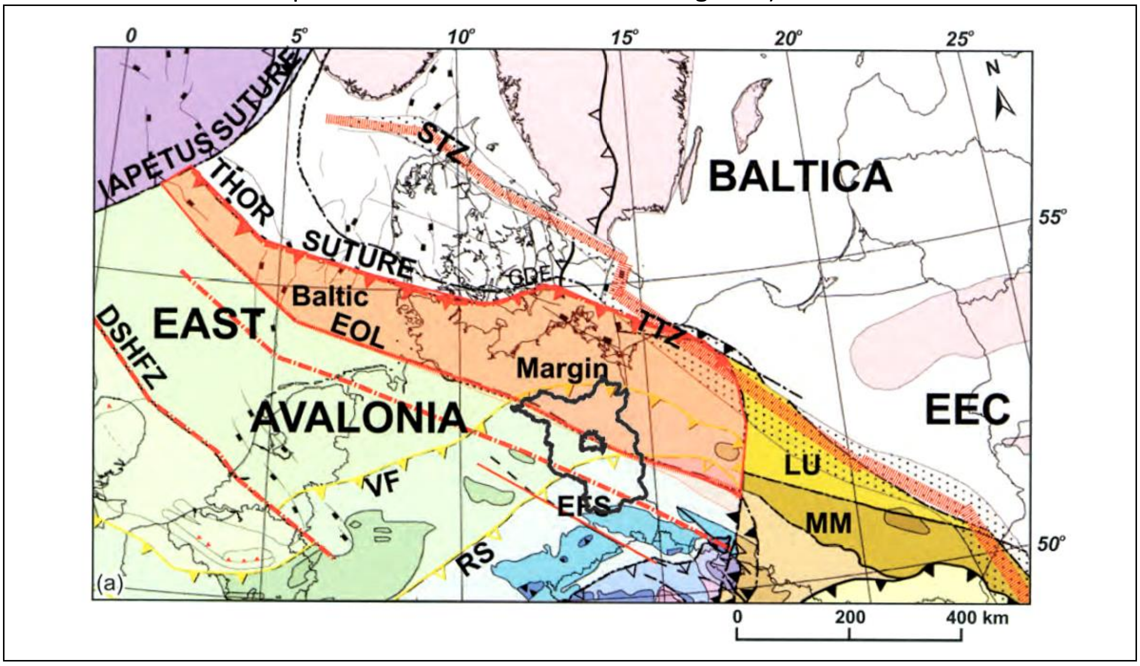


Fig. 3: Geotectonic situation in Central Europe at the end of the Variscian Orogensis (Maystrenko et al. 2008, modified by Stackebrandt & Manhenke 2010). Selected abbreviations : EEC: East European Kraton, TTZ: Tornquist-Teysseure Zone, EOL: Elbe-Odra Lineament, VF: Variscian Front , EFS: Elbe Fault System, RS: Rheic Suture)

After the current interpretations of geophysical and geological data (Maystrenko et al. 2008, Franke et al. 2015) Brandenburg is crossed in crustal level by the NW-SE striking border zone of East-Avalonia and the Baltic Margin Zone (Fig. 3, EOL: Elbe-Odra Lineament) and parallel structures (Fig. 3, EFS: Elbe-Fault System). The Variscian Deformation Front is situated close to the Northern border of Brandenburg. The area between the Variscian Front and the Rheic Suture belongs to the Variscian Rhenohercynian Zone (folded and thrusted Paleozoic). The Rheic Suture is represented by the Mid-German-Crystalline-Rise (a metamorphic succession of Para-Gneises). The Southern part belongs to the Variscian Saxothuringian Zone (Late Proteroczoic to Early Paleozoic units of the Lusatian Block).

The Pre-Cenozoic strata and the related tectonic inventory are covered by Cenozoic loose sediments and only at a few points Pre-Cenozoic strata reach the surface (related to salt domes). The knowledge about the Mesozoic and Paleozoic succession and the tectonic inventory of Brandenburg was gained primarily from deep drillings and 2D-seismic surveys (Fig. 4). The configuration of the deep basement structures were derived from gravimetrical and magnetical data (Conrad 1996, Gabriel et al. 2015) and deep 2D-seismic (DEKORP BASIN Research Group 1998). The major exploration phases of the deep subsurface in Brandenburg were from the 1960th to the early 1990th.

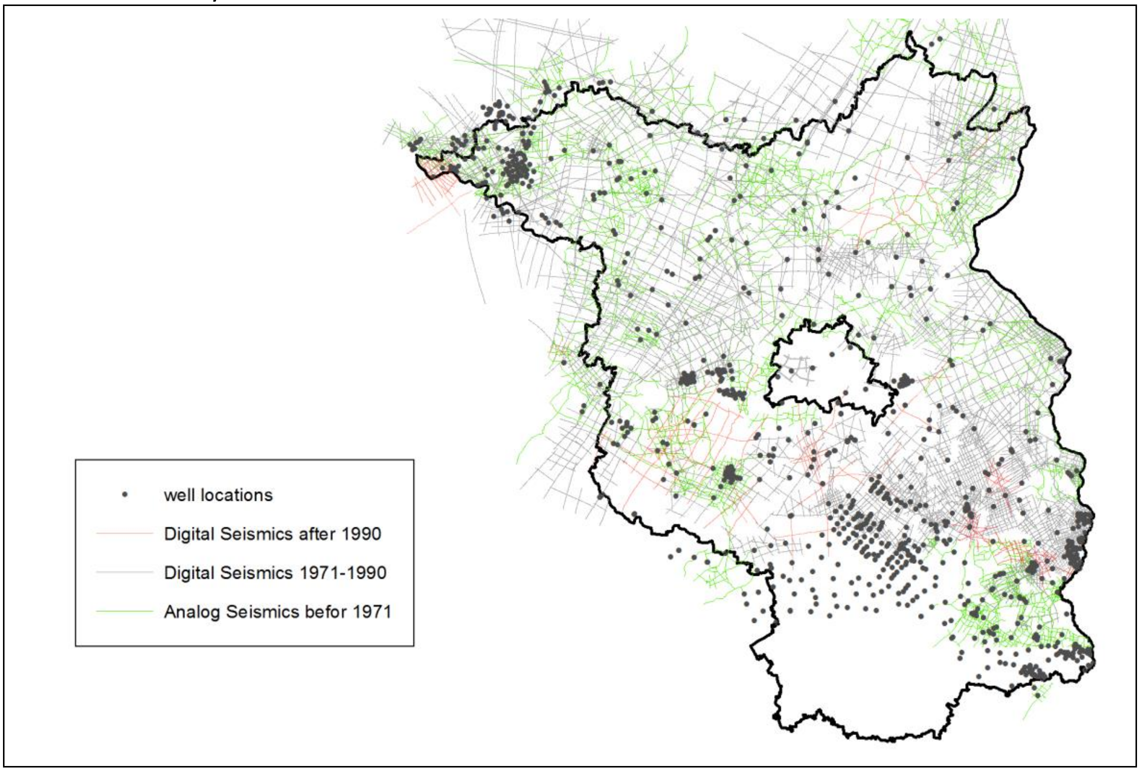


Fig. 4: database 2D-seismics and deep wells in the North German Basin in Brandenburg

9.2 Structural domains and related fault systems in Brandenburg

The tectonic inventory of Brandenburg can be differentiated according to structural domains with characteristic fault pattern (Fig. 5):

- Southeastern border of the North German Basin (NGB) and Lusatian Block (DE-BB-1)
  - Subdomain of the Lusatian Block (DE-BB-11) (details see section 9.2.1)
- Central part of the Eastern North German Basin (DE-BB-2)
- Northeastern margin of the North German Basin (DE-BB-3)

The ID in brackets (DE-BB-…) refers to the internal ID of the fault. This ID follow a hierarchical order of a semantic framework (Hintersberger et al. 2017) in 4 levels with the following structure:

1. Structural domain	e.g. “DE-BB-1”
2. Fault sets and subdomains	e.g. “DE-BB-12”
3. Fault zones	e.g. „DE-BB-1201“
4. Sub-zones and faults	e.g. “DE-BB-120101”

(DE: ID for Germany ; BB: ID for the Federal State Brandenburg).

The fault traces shown in Fig. 5 are generalized in a scale of ≈ 1:500.000. They were compiled by a review of several maps and publications from the last decades (Geophysical Atlas of the GDR 1975-1990, Lange et al. 1990, Röllig et al. 1990, Göthel & Grunert 1996, Stackebrandt & Beer 2010, Benek & Hoth 2010, Kopp et al. 2010, Beutler & Stackebrandt 2012).

The fault inventory of the domains is presented and explained basing on the second hierarchical level (fault sets and subdomains) in the following sub-chapters 9.2.1 to 9.2.3. For further information to the individual faults see the GIS-web-application of the HIKE - fault data base.

More detailed fault geometries (fault planes in 3D, scale 1:100.000, without naming and hierarchical order) can be obtained at the following web-pages:

- www.brandenburg.de/Brandenburg_3D/client/portal/index.html
  Web-presentation of the deep-subsurface 3D model of Brandenburg (Schilling et al. 2018) including 12 major seismic reflectors from base of Cenozoic to Upper Rotliegend and the fault network (differentiated in sub-salinar faults and post-salinar faults).
- https://gst.bgr.de
  Web-presentation of the TUNB-Model. 3D-Model of German part of the North German Basin including 14 stratigraphic horizons and the fault network developed by the Geological Surveys of the German Federal States Lower Saxony, Schleswig-Holstein, Mecklenburg-Western Pommerania, Sachsen-Anhalt and Brandenburg in co-operation with BGR.

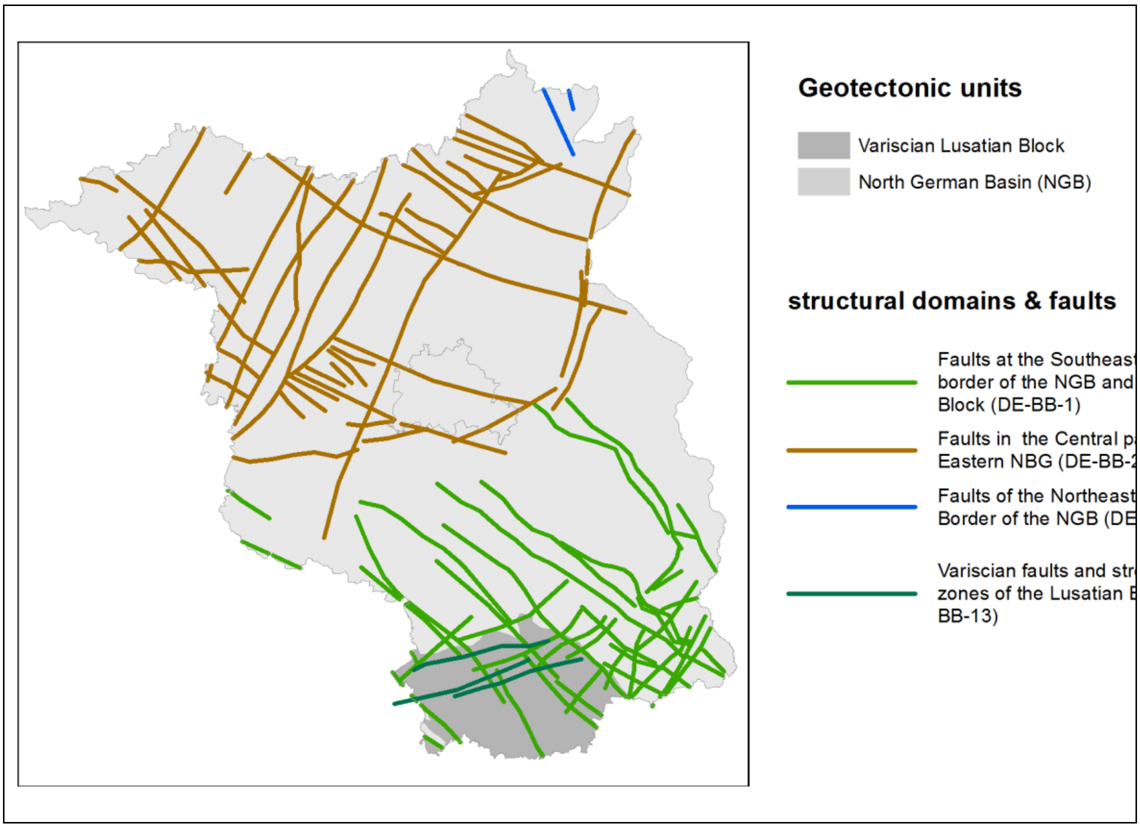


Fig. 5: Geotectonic units, structural domains and related faults in Brandenburg (compiled from: Geophysical Atlas of the GDR 1975-1990, Lange et al. 1990, Röllig et al. 1990, Göthel & Grunert 1996, Stackebrandt & Beer 2010, Benek & Hoth 2010, Kopp et al. 2010, Beutler & Stackebrandt 2012).

9.2.1 Structural domain: Southeastern border of the North German Basin and Lusatian Block (DE-BB-1)

The fault sets and structural sub-domain of the second hierarchical level (DE-BB-11, 12, 13) at the Southeastern Border of the NGB are shown in Fig. 6. The fault often reach up to the base of Cenozoic and are mostly well tracked by drillings and geophysical methods (seismic, gravimetrical data). Some authors (e.g. Kopp et al. 2010) postulate an extension of the fault set DE-BB-11 to the Northwest in deeper parts of the basin and a connection to faults in the central part (structural domain DE-BB-2, fault set DE-BB-22), but this is not proved at the time.
The ID in brackets (DE-BB-…) refers to the hierarchical ID of the semantic concept.

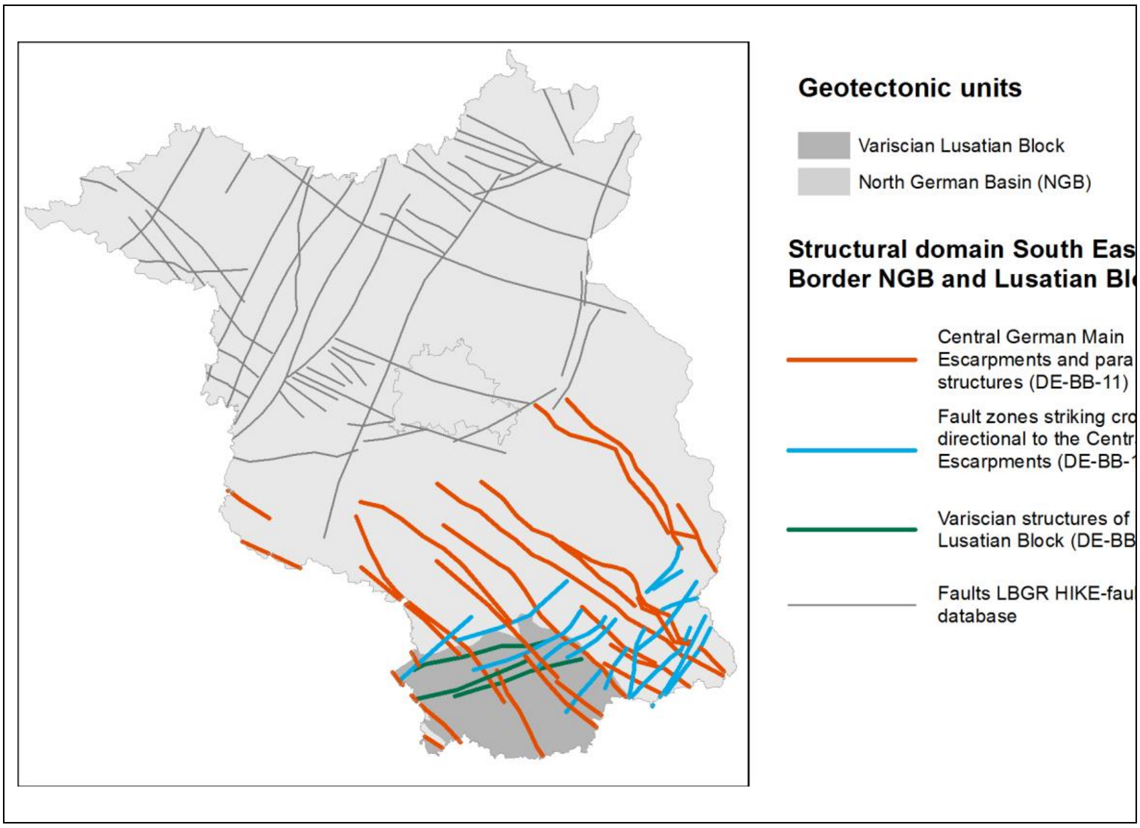


Fig. 6: Structural domain of the Southeastern border of the North German Basin (NGB) and Lusatian Block (DE-BB-1) with related faults sets

- Central German Main Escarpments and parallel structures. Fault set striking NW-SE (DE-BB-11)
  Fault zones at the Southeastern border of the North German Basin and related parallel structures striking NW-SE. The structures were formed after the Variscian Orogeny as dextral strike-slip faults of a crustal wrench-system and were re-activated in different phases of the tectonic development of the NGB under varying stress regimes ("Saxonian" Tectonics from Permian to Tertiary). Extensional regimes (E-W and NE-SW direction) with normal faulting from Triassic to Early Cretaceous. Inversion in the Upper Cretaceous (contraction in NE-SW direction) with the development of compression structures (back-thrusting, anticlines).

- Cross-directional structures of the Central German Main Escarpments. Fault set striking NE-SW (DE-BB-12)
  Fault and fracture zones at the Southern border of the North German Basin striking cross-directional to the Central German main escarpments (SW/WSW-NE/ENE). Post-variscian origin ("Saxonian" Tectonics from Permian to Tertiary). Partially re-activation of Variscian structures. Activity especially since the inversion phase (normal faulting and Graben structures).

- Variscian structures of the Lusatian Massif (Lusatian Anticline and the Torgau-Doberlug Syncline). Structural subdomain with fault set striking ENE-WSW (DE-BB-13)
  Variscian structure zones of the Lusatian Massif Striking ENE-WSW. Partially re-activated during the different phases of the post-variscian development under varying stress regimes.

9.2.2 *Structural domain: Central part of the Eastern North German Basin (DE-BB-2)*

The fault sets and structural sub-domain of the second hierarchical level (DE-BB-21, 22, 23) in the Central part of the Eastern NGB are shown in Fig. 7. The fault zones in the Central part are observed in Pre-Zechstein strata and often reach down to crustal level. Faults of fault sets DE-BB-21 and DE-BB-23 also reach the Post-Permian strata (Buckow-Oderhaff fault zone, Kotzen-Zechlin Structural Zone, Potsdam fault zone, Barenthin Fault) and influenced the formation of salt structures and the sedimentation of the Post-Permian succession (see section 9.3). The fault traces partially are postulated based on gravimetrical and geomagnetic data and sedimentation pattern in the overburden.
The fault sets DE-BB-21 and DE-BB-22 are forming a cross-directional system. The third fault set DE-BB-23 striking ± E-W differs from these directions. Some authors (Kopp et al. 2010) postulate an extension of the fault set DE-BB-21 to Southeast and a connection to faults of the set DE-BB-21, but this not proved at the time.
The ID in brackets (DE-BB-...) refers to the hierarchical ID of the semantic concept.

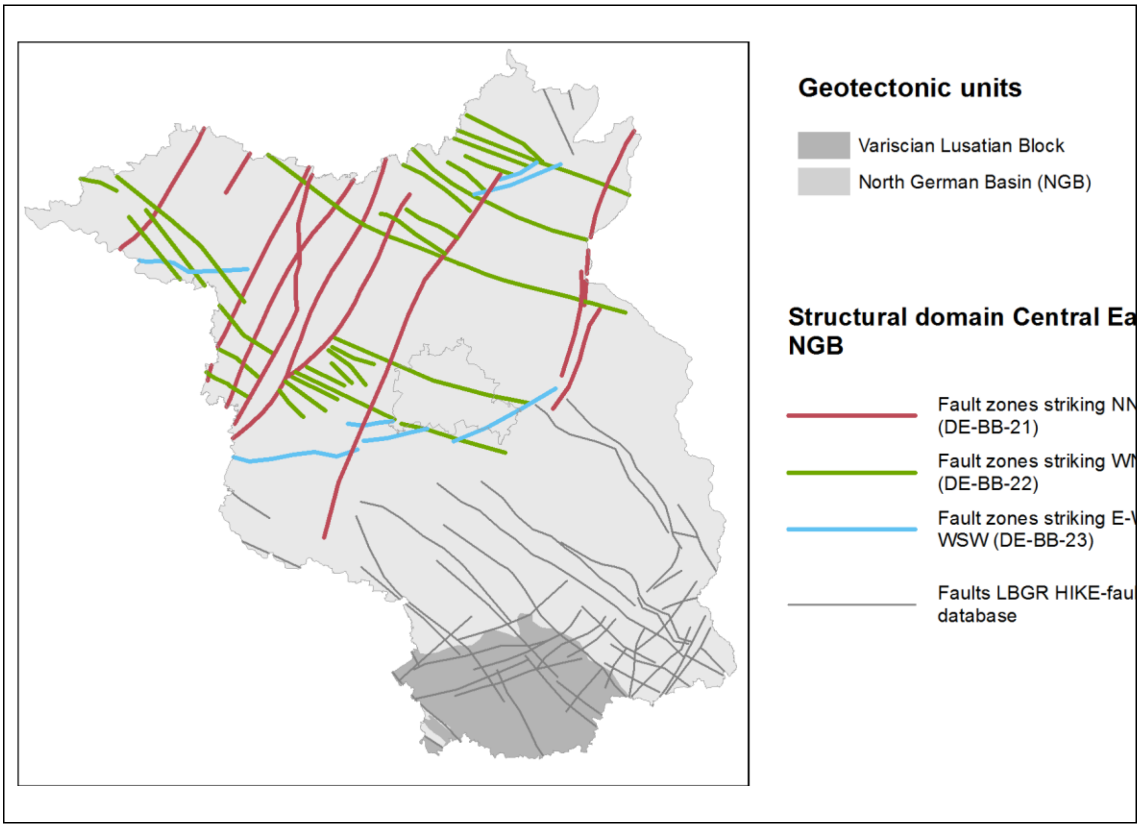


Fig. 7: Structural domain of the Central part of the Eastern North German Basin (DE-BB-2) and related faults sets

- Fault Zones of the Central Eastern North German Basin, striking NNE-SSW (DE-BB-21)
  Fault zones and structure zones in the central eastern part of the North German Basin striking NNE-SSW. Deep reaching basement faults formed after the Variscian Orogeny in the Lower Rotliegend transtension of the Central European Basin (Kley et al. 2008). With effects up to the Mesozoic.

- Fault Zones of the Central Eastern North German Basin, striking WNW-ESE (DE-BB-22)
  Fault zones and fault sets in the Central Eastern part of the North German Basin striking NW-SE (perpendicular to DE-BB-21). Active in the Permocarboniferous.

- Fault Zones of the Central Eastern North German Basin, striking E-W to ENE-WSW (DE-BB-23)
  Complex fault zones (containing sub-faults) in the central eastern part of the North German Basin striking approximately E-W. Reaching from Permocarboniferous to Mesozoic.

9.2.3 Structural domain: Northeastern border of North German Basin (DE-BB-3)

The fault sets of the structural domain DE-BB-3 are shown in Fig. 8. Only one fault zone reaches the northeastern part of Brandenburg.

- Fault zones of the Northeastern border of the North German Basin (DE-BB-31)
  NNW-SSE striking fault zones at the Northeastern border of the North German Basin. Southern extension of the Western Pommerania Fault system (possibly an extension of the Möckow-Dargibell fault zone).

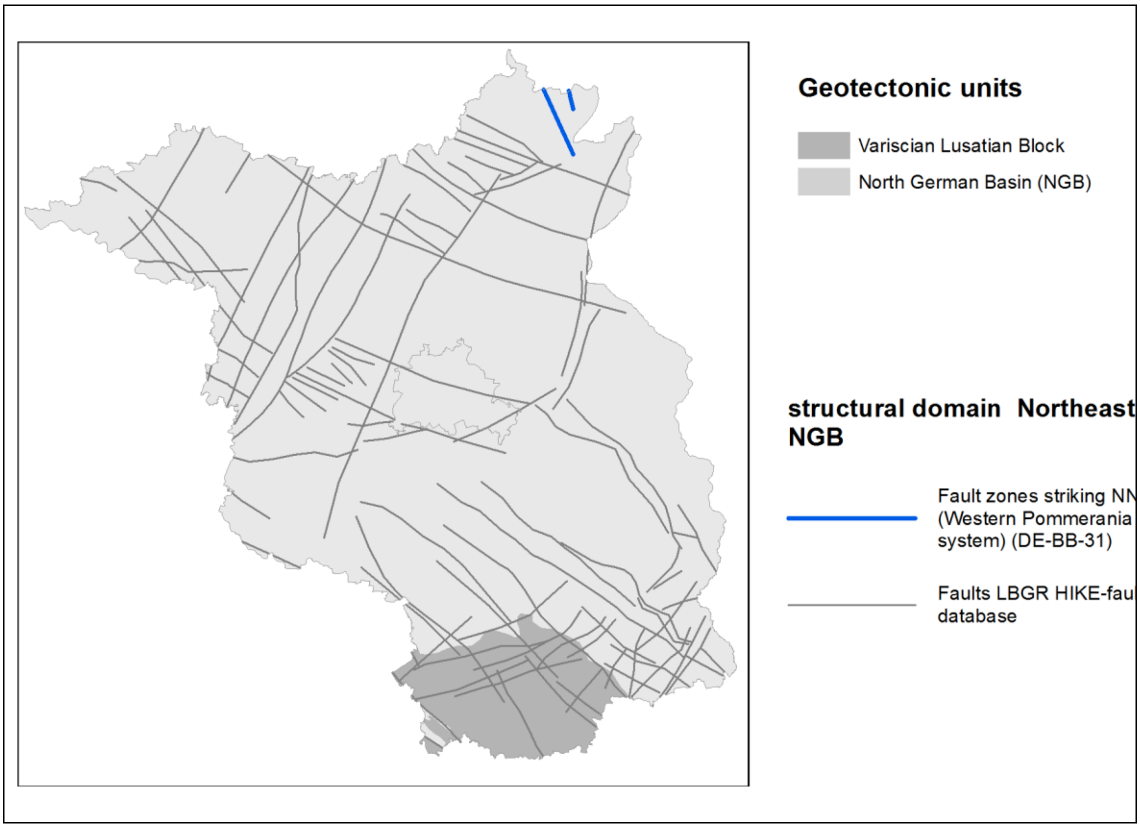


Fig. 8: Structural domain of the Northeastern border of the Eastern North German Basin (DE-BB-3) and related faults sets

The ID in brackets (DE-BB-…) refers to the hierarchical ID of the semantic concept.

9.3 Halokinesis and faults

9.3.1 Fault-induced halokinesis

As shortly discussed in section 9.1 and shown in Fig. 2 the Zechstein salt is of special importance for the development of the Mesozoic and Cenozoic strata. The primary thickness of the Permian salt in Brandenburg ranges from <500m at the southern border of the basin and >1.500m in basin center in the Northwest (Stackebrandt 2015). The current thickness distribution in the Central European Basin System is shown in Fig. 9 and documents strong local variations between <200m and >2000m due to halokinesis. Today the thickness of the Zechstein succession in Brandenburg ranges in the central basin between <200 m in regions of halotectonic salt depletion and >3.000 m in diapirs. At the southern margin of the basin the halokinesis is of minor importance cause of reduced primary thickness. The thickness is here further reduced due to erosion and subrosion especially since the inversion phase in Late Cretaceous (see Fig. 2). The uplifted Lusatian Block (see Fig. 5) is today free of Permian and Mesozoic deposits.

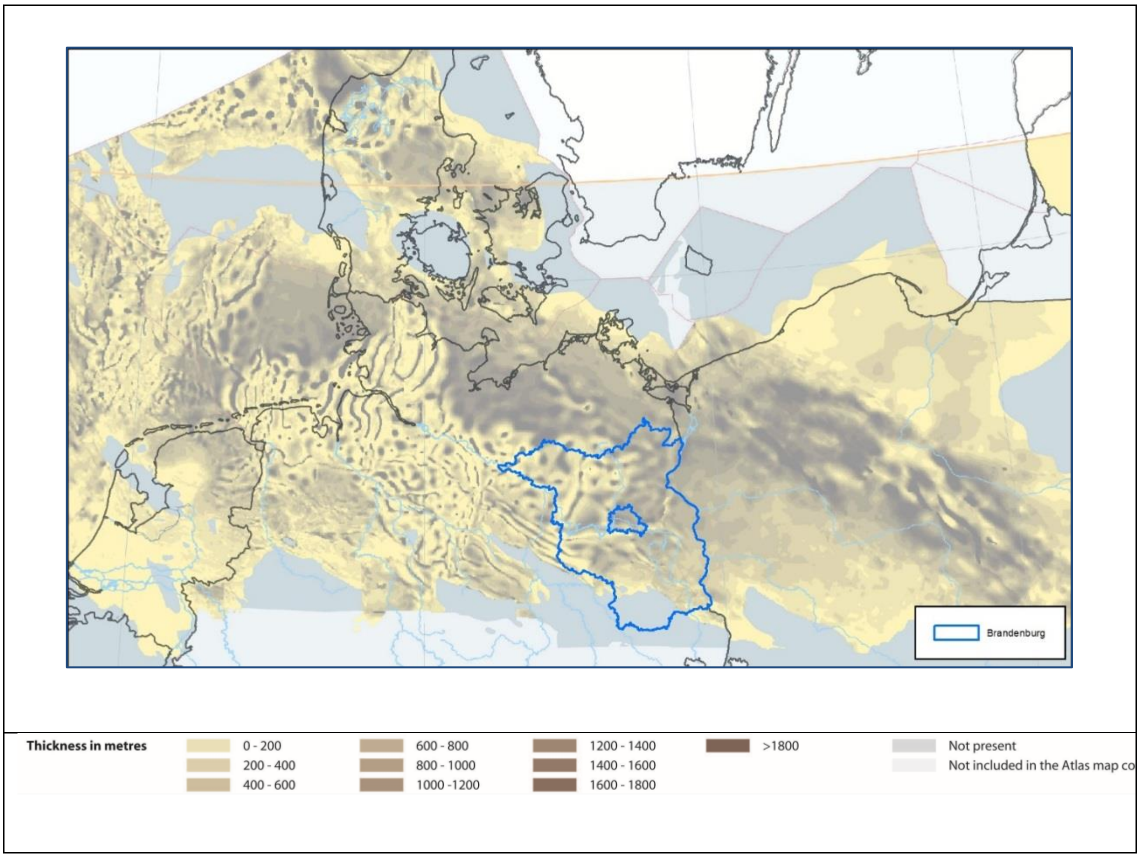


Fig. 9: Position of Brandenburg in the Central European Basin (Map after Doornenbal & Stevenson 2010, Fig. 8.3 Thickness of the Zechstein)

Stackebrandt (2010, 2015) differentiates the halokinetic structures in Brandenburg in a tectonic and a gravitational type. The tectonic type is related to subsalinar faults and shows an elongation along the faults (Stackebrandt 2015). The non-tectonic, gravitational typ is only related to buoyancy and gravitational forces. Also other authors postulate relations between subsalinar faults and halotectonic structures in Brandenburg (e.g. Elicki & Göthel 2019).

In Fig. 10 several aspects of halokinesis are shown in relation to the fault inventory:

a) areas of salt accumulation
   - diapirs
   - salt pillows (differentiated in tectonic and gravitational type after Stackebrandt 2010)
b) areas of intense salt depletion (up to the total loss of the NaCl-components in the Zechstein succession)
c) zones with intense faulting of the Zechstein succession

Elongated salt structures or salt structures in close neighborhood along the striking of faults, areas of intense faulting of the salt and elongated areas of salt depletion are concentrated in some characteristic zones and indicate a triggering of halokinesis by faults in these regions (Fig. 10).

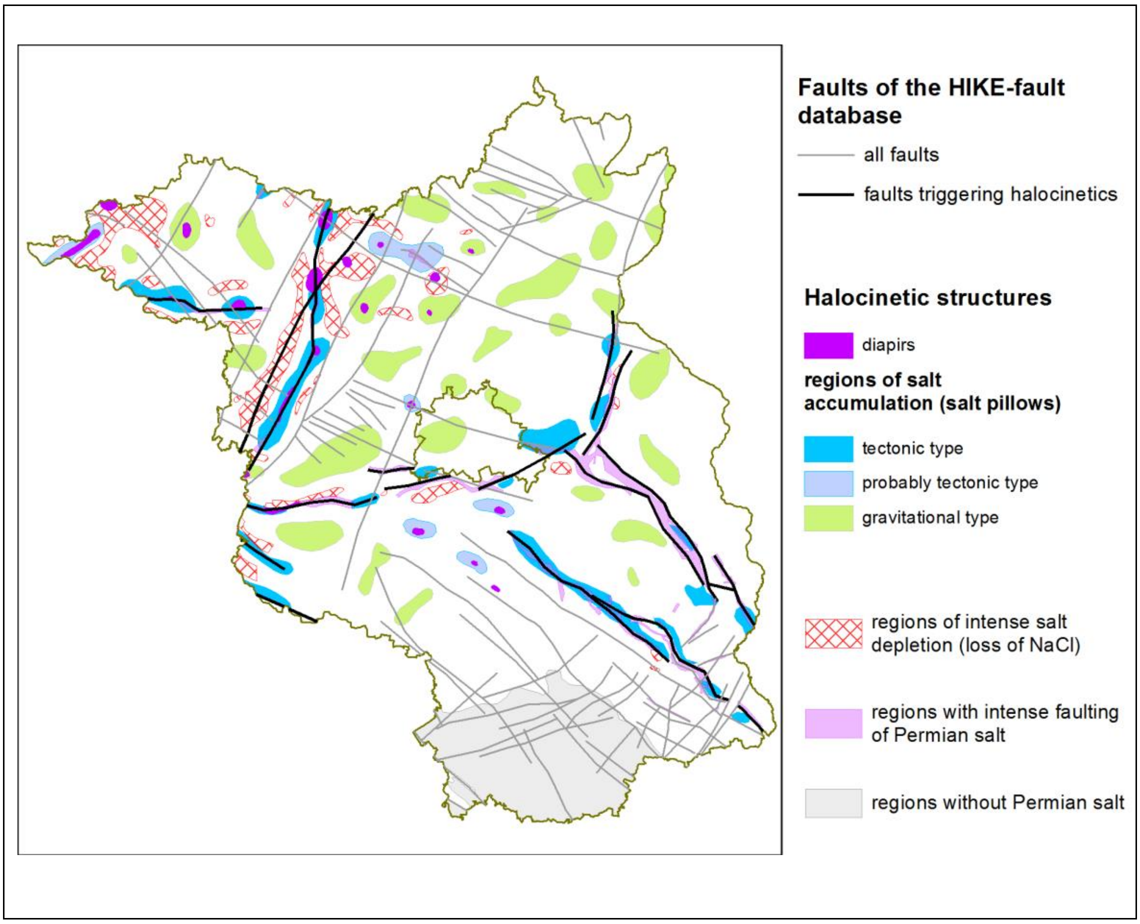


Fig. 10: Salt structures of Brandenburg. Compiled and modified after Geophysical Atlas of GDR (seismic reflector X1), Lange et al. 1990, Stackebrandt & Beer 2010, Stackebrandt 2015.

A comparison with the fault sets in the structural domains (discussed in section 9.2) show that especially the following fault sets and faults triggered halocinetics:

- Central German Main Escarpments and parallel structures, striking NW-SE (DE-BB-11)
  - Groß-Köris – Dissen - Merzdorf fault zone
  - Fürstenwalde-Guben Structural Zone

- Zerben-Belzig Structural Zone
    - Setzsteig Structural Zone
- Fault Zones of the central eastern North German Basin, striking NNE-SSW (DE-BB-21)
    - Rheinsberg Deep Fracture System / Kotzen-Zechliner Structural zone
    - Buckow Fault Zone
- Fault Zones of the central eastern North German Basin, striking E-W to ENE-WSW (DE-BB-23)
    - Potsdam fault zone
    - Barenthin fault zone

The other fault sets in Brandenburg in regions with Zechstein deposits have no or only minor importance for the salt dynamics:

- At the Southern border the fault set DE-BB-12 show no influence to halokinesis (what is probably related to reduced thickness of the salt at the southeastern margin).
- In the central part of the basin – a region with increased primary thickness of the Permian salt – the WNW-ESE striking fault zones DE-BB-22 have no or only minor influence to the salt dynamics. This fault set was only active in the Permocarboniferous (up to Rotliegend).
- The fault set DE-BB-13 is detectable only in the Rotliegend of Brandenburg. In the northern extension of the faults zone (Western Pommerania fault system) several salt structures exist.

9.3.2 Local tectonics at salt structures

In the top of ascending salt structures (of both - tectonic and gravitational - types) local faults developed in the overburden (crestal graben systems). These structures are related to the local stress field (that can differ from the regional situation) and have usually only a low lateral extend of some km and are not included in this collection at national/trans-national scale.

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10 LAGB – GERMANY

10.1 Introduction

The structural framework of Saxony-Anhalt can only sparsely be revealed at the surface. An over wide areas flat topography in the north is caused by a huge amount of Cenozoic subsidence and a Quaternary glacial overprint. Older tectonic structures only crop out in the south of Saxony-Anhalt while the north and northeast is widely covered by up to 500 m thick Cenozoic sediments.

Structures of the deep subsurface comprise Mesozoic brittle faults in the sedimentary cover as well as Variscan and post-Variscan structures in the Harz and the Flechtingen-Rosslau Blocks (Fig. 1).

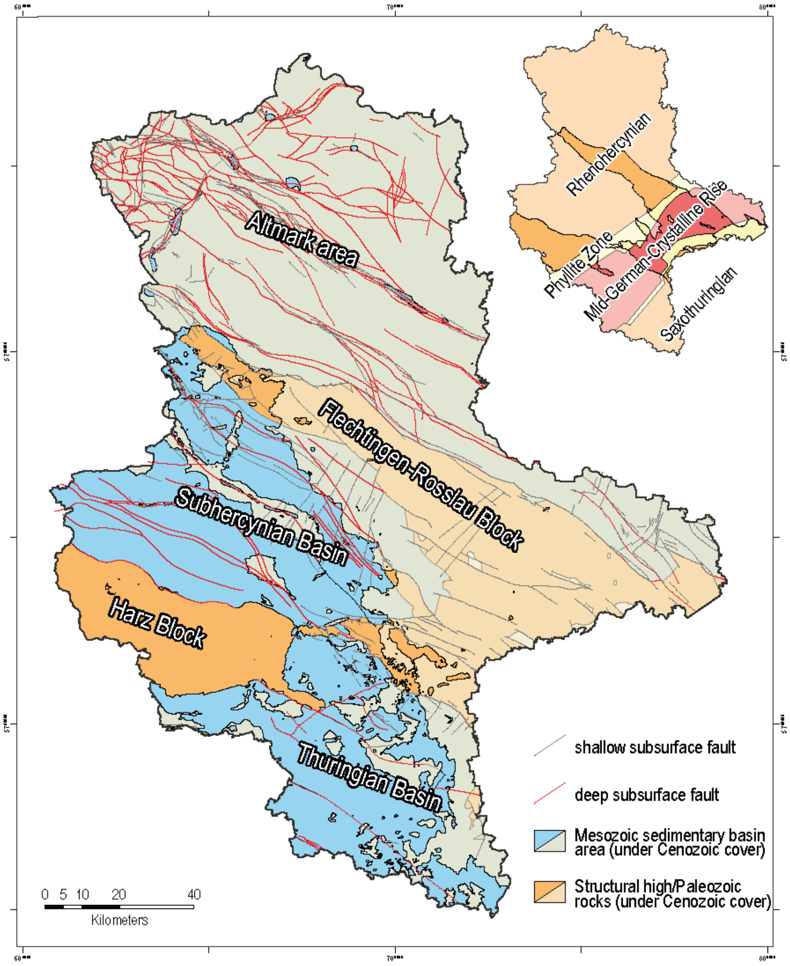

Fig. 1: Structural overview of Saxony-Anhalt (without Quaternary cover) with major regional geologic units as well as major deep and shallow subsurface faults (regional faults in the fault database). Inset map on the upper right corner shows the Palaeozoic segmentation of the basement [modified from *Reinhold*, 2005].

In many parts of Saxony-Anhalt, faults at larger depths are only known from extensive geological and geophysical exploration campaigns, which reveal a highly complex structural framework at larger depths (below 1 km). The different tectonic styles are related to various phases of deformation. The assemblage of the super-continent Pangaea during the Variscan orogeny (Devonian to Carboniferous) affected various NE-SW trending thrust faults northwest and southeast to the Rheic suture zone, which is represented by the Mid-German-Crystalline-Zone straddling the southeastern part of Saxony-Anhalt.

Synchronously to plate convergence synkinematic sediments were deposited and compressed in the realm of closing oceanic basins. In parts, these sediments were affected by low-grade metamorphism and contact metamorphism where syn-orogenic igneous rocks intruded. After the end of the Variscan orogeny, extensive igneous activity, extension [*Bayer et al.*, 1999; *Ziegler*, 1990] and right-lateral transtension along E-W to NW-SE-trending shear zones [*Arthaud and Matte*, 1977] affected the thermal and structural destabilisation of the Central European crust [*Scheck and Bayer*, 1999]. Since Late Palaeozoic times the area of Saxony-Anhalt became a part of the Central European Basin System [also named 'Southern Permain Basin'; cf. *Doornenbal and Stevenson*, 2010; *Ziegler*, 1990]. Differential subsidence during Latest Permian to Middle Triassic times affected various areas that are in parts delimited by earlier deep ranging shear zones [e.g. the Elbe Fault Zone or the Arendsee Lineament; *Franke*, 1990a; b].

In the Late Triassic (Karnian to Norian) a phase of E-W-directed extension initiated basin differentiation and the activation of rapidly subsiding NNE-SSW-trending troughs, where locally more than 1.5 km synkinematic strata were deposited [*Barnasch et al.*, 2005; *Beutler et al.*, 2012]. Subsequent tectonic quiescence lasted until the Late Jurassic [*Ziegler*, 1990] when NE-SW-directed tensional stress [*Navabpour et al.*, 2017; *Rauche and Franzke*, 1990; *Sippel et al.*, 2009] caused the structural subdivision of the Saxony-Anhalt realm into several sub-basins and local (half-)graben systems. During the middle Late Cretaceous (i.e., Turonian to Santonian) a short (20 myr) incident of contraction resulted in uplift of several kilometres wide basement-cored blocks [the Harz Mountains and the Flechtingen High; *Stackebrandt*, 1986; *Thomson et al.*, 1997; *v. Eynatten et al.*, 2019; *Voigt et al.*, 2004; *Wienholz*, 1964 and references therein], reverse reactivation of inherited normal faults [*Malz and Kley*, 2012; *Stackebrandt and Franzke*, 1989] and inversion of earlier sub-basins [*Malz et al.*, 2020].

Later vertical movements rather indicate plate-wide stress relaxation [*Nielsen et al.*, 2005] or large-scale uplift of entire basin areas [*Kley*, 2018], but some authors even argue that faulting at large structures remained active during Neogene times [*Wrede*, 2008]. More recent studies imply that local stress variations associated with Pleistocene glacial loading locally initiated the reactivation of deep-ranging basement faults [*Brandes et al.*, 2015; *Brandes et al.*, 2018].

10.2 Structural segmentation and classification

The realm of Saxony-Anhalt can roughly be subdivided into a northern (Altmark area), central (Subhercynian Depression) and a southern part (northeastern part of the Thuringian Syncline), where Mesozoic and Cenozoic sedimentary rocks specify the deep (below 1 km) geologic structure. Two structural blocks of uplifted Palaeozoic crystalline and sedimentary basement rocks, the Flechtingen High and the Harz Mountains, respectively, separate these areas (Fig. 1).

In contrast, the near surface geology can be subdivided in a northern area (north of the Subhercynian Depression) with flat topography, which is widely covered with Cenozoic sediments, and a southern realm with smooth morphology and in parts deep river incisions due to Pleistocene uplift and lithospheric buckling (Fig. 1).

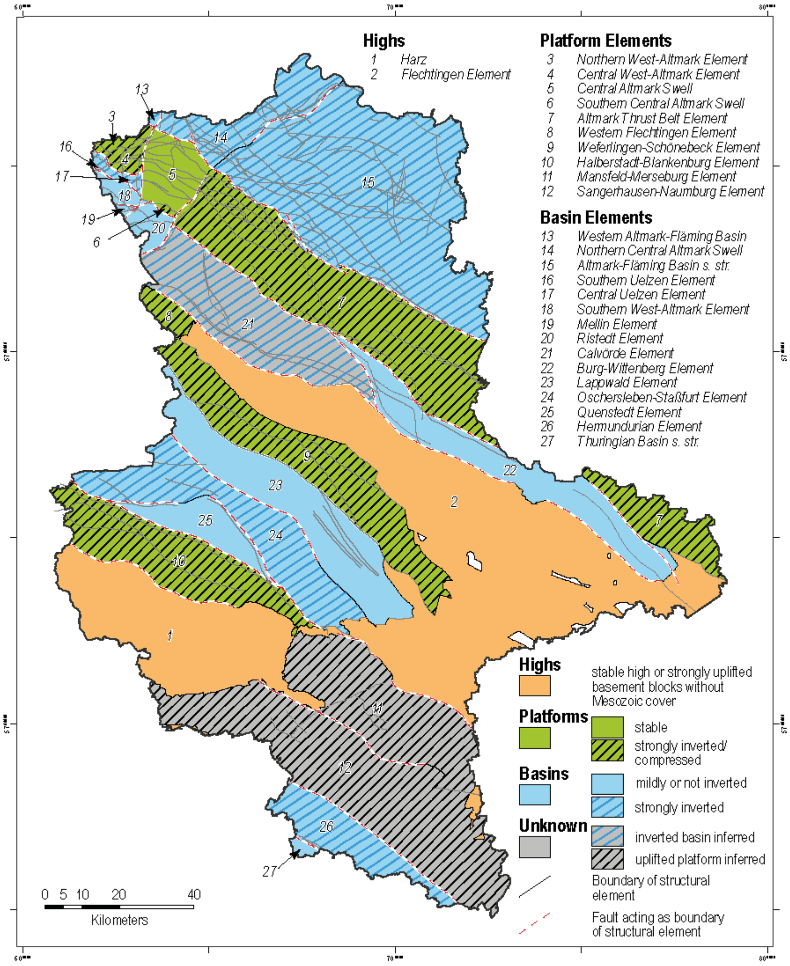

Fig. 2: Regional and local structural elements of Saxony-Anhalt as defined in the fault database [Structural configuration of the Subhercynian and Thuringian Basins slightly modified from *Katzung and Ehmke*, 1993; *Malz*, 2014; segmentation of the Altmark area is based on kinematic interpretations of *Malz et al.*, 2020].

Various NW-SE- and NNE-SSW-striking faults, structural domains, uplifted blocks and local depressions define the present day structural inventory and segmentation of Saxony-Anhalt (Fig. 2). During the past decades this regional subdivision into areas of similar tectonic evolution was made based on bordering faults, distribution outlines or lithological variations [*Katzung and Ehmke*, 1993; *TGL-34331/01*, 1983]. Later various attempts to refine this regional classification [e.g., *Beutler and Stackebrandt*, 2012; *Beutler et al.*, 2012] suggested very detailed small-scale structural elements with an individual tectonic history. Due to the fact that these compilations tried to integrate all structural elements (e.g.; deep crustal shear zones vs. surface faults) into one classification scheme, fault traces of various scales or investigated by different observation methods were combined (e.g., refraction seismics and gravity modelling for crustal anomalies combined with near-surface seismics and analysis of satellite images). Thereby local fault kinematics, mechanics and the integration into the regional geologic context often got lost [see *Kley*, 2013 for a discussion]. Hence, in the following only areas, structural elements and fault zones of regional importance subdividing the realm of Saxony-Anhalt will be described. For the northern part of Saxony-Anhalt (Altmark area) these descriptions mainly emerge from the more recent interpretations of *Malz et al.* [2020] while explanations for the southern part are based on recent and still on-going structural mapping, 3D modelling and map homogenisation[*Malz et al.*, 2019; *Martiklos et al.*, 2001] campaigns carried out at the Geological Survey of Saxony-Anhalt (Landesamt für Geologie und Bergwesen; LAGB).

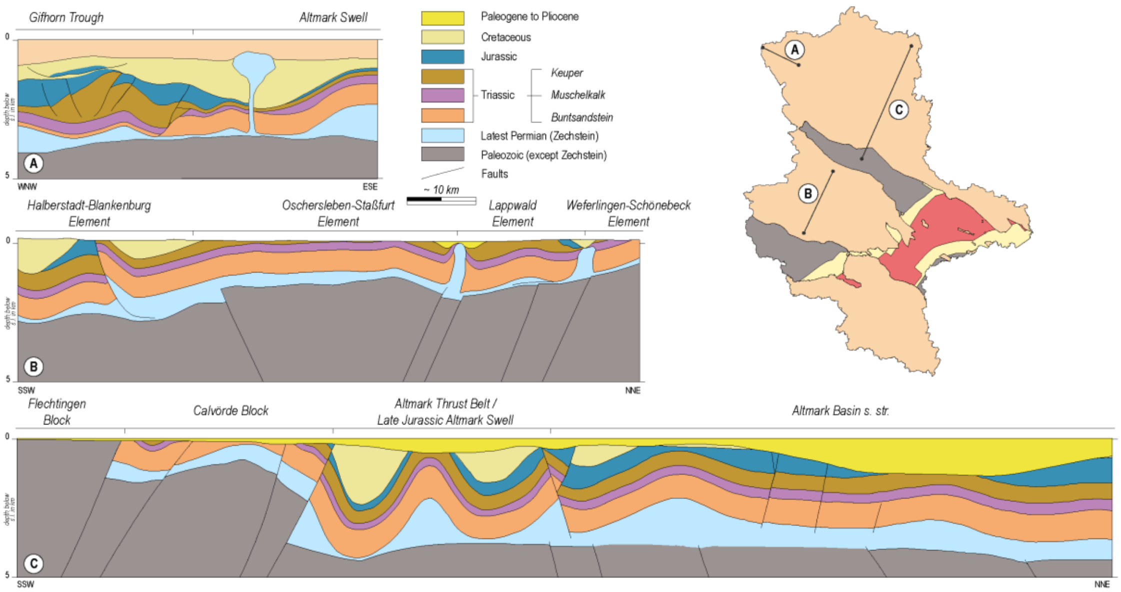

Fig. 3: Three simplified cross-sections (2x exaggerated) showing the structural framework of the Central European Basin System in Saxony-Anhalt.

The recent structural configuration of Saxony-Anhalt is the result of a complex tectonic history reaching from Palaeozoic times until the Pleistocene. Below the Mesozoic infill of the Central European Basin System a heterogeneous crystalline and sedimentary basement deformed during the Variscan orogeny is preserved (cf. inset in Fig. 1). Today, it is subdivided by large crustal fault zones (e.g. the Harz Northern Boundary Thrust or the Gardelegen and Haldensleben Thrusts), which became (re-)activated during Mesozoic times. While the large basement uplifts (Harz Mountains and Flechtingen High) form the most obvious results of Mesozoic deformation, even areas with preserved Mesozoic strata show a strong segmentation by NNE-SSW and NW-SE striking fault zones resulting in various blocks acting as platforms or basins over geologic timespans (Fig. 3).

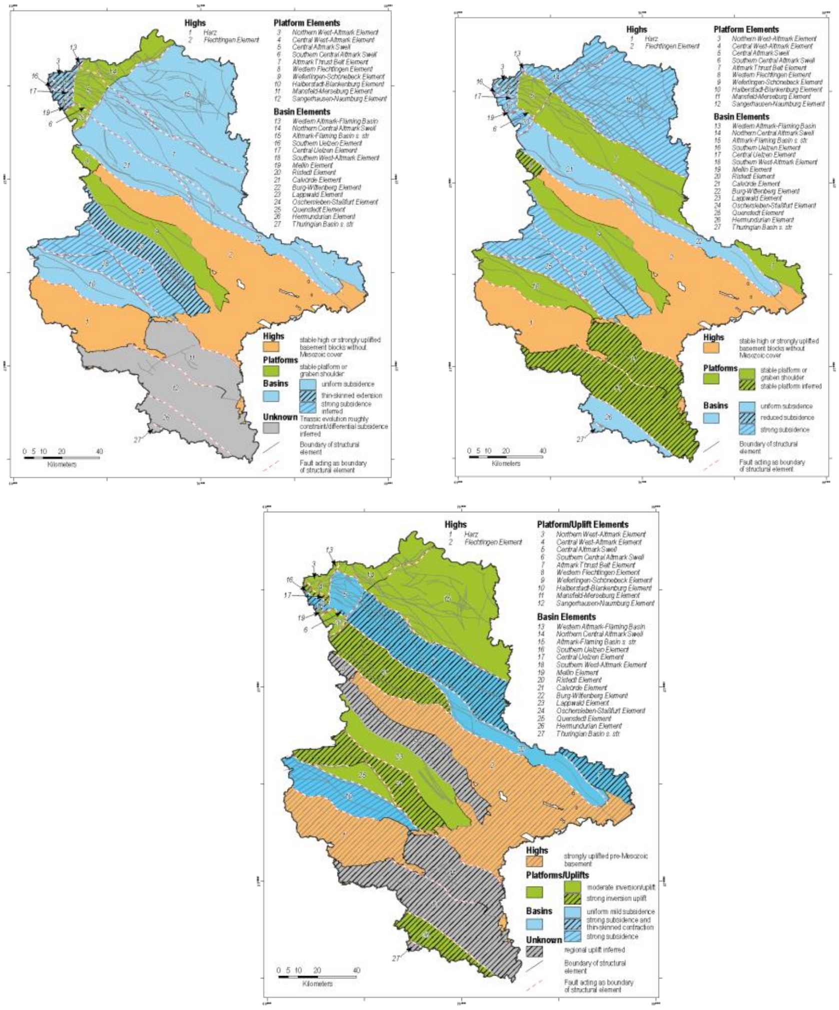

Fig. 4: Structural elements of Saxony-Anhalt and style of deformation during Late Triassic WNW-ESE extension (left), Late Jurassic to Early Cretaceous NE-SW extension (middle) and Late Cretaceous contraction and basin inversion (right)

10.3 The Altmark area

The northern part of Saxony-Anhalt (Altmark area) forms the southern rim of the Central European Basin System. It underwent continuous subsidence since Permian times. The major tectonic blocks trend either NNE-SSW or NW-SE. Hence, in earlier classifications [e.g., *Katzung and Ehmke*, 1993] the entire area was named 'Altmark-Fläming Depression'. Based on more recent investigations based on extensive reflection seismic data and several hundreds of boreholes, which were combined in a homogeneous 3D geological model [*Malz et al.*, 2020], the Altmark area can be subdivided into six major tectonic units (Fig. 3): (1) The eastern part of the Gifhorn Trough is located in the outer northwest and forms a NNE-SSW-trending Mesozoic (trans-)tensional graben. (2) The (Eichsfeld-) Altmark Swell to the east of the Gifhorn Trough is an approximately 50 km wide NNE-SSW to NE-SW-striking structural high [*Wienholz*, 1964] initially emerged during the latest Permian to Triassic [*Paul*, 1993].

It is interpreted as the former graben shoulder of the western adjacent Gifhorn Trough [*Malz et al.*, 2020] and is bordered by a deep crustal shear zone (Arendsee Lineament) to the east

[*Franke*, 1990a; b]. (3) In the northeast of the Altmark structures of similar trending direction (NNE-SSW) are associated with the Rheinsberg Trough located at the eastern border of Saxony-Anhalt. In these areas (Gifhorn Trough, Altmark Swell and Rheinsberg Trough) associated fault zones are difficult to detect due to the complex interplay of synkinematic erosion and deposition, extensive diapirism as well as crosscutting NW-SE-striking normal and reverse faults. (4) The inverted Altmark-Fläming Basin s. str. is located between the Altmark Swell and the Rheinsberg Trough (Fig. 2). Narrow NW-SE-striking, in parts reverse reactivated normal faults and long wavelength folds, salt pillows and diapirs characterize this area. (5) The 'Late Jurassic Altmark Swell' borders the Altmark-Fläming Basin s. str. to the south. It forms the southern graben shoulder of the northern adjacent basin and is mostly characterized by several tens of kilometres long, Late Cretaceous short-wavelength thin-skinned folds and thrust faults. The Altmersleben-Demker Fault zone defines the border fault between the latter mentioned structural blocks. (6) The Calvörde Block in the south and southwest forms a basement uplift of Late Cretaceous age. It is covered by older Mesozoic rocks, which were uplifted and folded in a flexure above a large basement fault, the Gardelegen Fault, respectively. To the south the Haldensleben and Wittenberg Fault separate the Altmark area against the Flechtingen High.

10.4 The Flechtingen High

The Flechtingen High, often referred to as the Flechtingen-Rosslau Block (cf. Fig. 1), forms the approx. 100 km long and 20 km wide, NW-SE trending surface outcrop of Palaeozoic rocks in central Saxony-Anhalt. In wide areas Cenozoic strata cover that basement block. The outcropping rocks were low-grade metamorphic, moderately deformed foreland sediments of the Rhenohercynian Zone as well as high-grade metamorphic and intrusive rocks in the Mid-German-Crystalline Rise. They are widely covered by Late Carboniferous to Early Permian sedimentary rocks. After the Variscan orogeny, the border faults of the Flechtingen High evolved as large dextral strike-slip faults forming the southern Elbe Zone, a crustal-scale wrench system ranging from the Bohemian Massif in the southeast to the North Sea in the northwest. It is supposed that sedimentary rocks of the Central European Basin System covered the Flechtingen High during Mesozoic times. The border faults, i.e. parts of the Elbe Zone, were probably reactivated under extension during the Jurassic to Early Cretaceous. Late Cretaceous contraction lead to the uplift of the Flechtingen High and probably affected later large-scale crustal movements as revealed by the distribution of Cenozoic strata [*Stackebrandt*, 1986].

10.5 The Subhercynian Basin

The Subhercynian Depression is that area of Saxony-Anhalt, which is located between the basement uplifts of the Flechtingen High and the Harz Mountains. To the north (Flechtingen High) its border forms the mostly continuous transition from Mesozoic and Late Palaeozoic (Zechstein) strata to Palaeozoic crystalline and sedimentary rocks of the Flechtingen High. To the south the northern border fault of the Harz Mountains and steep-dipping Zechstein strata associated with basement faulting form the structural border of the Subhercynian Depression. The internal structure of the Subhercynian Depression is mostly characterized by NW-SE-trending fault zones, which are in parts accompanied with the intrusion of mechanically weak (Zechstein) salt (e.g. salt structure 'Oberes Allertal', 'Offleben-Oschersleben-Staßfurter Salzsattel'), local thin-skinned anticlines (e.g., 'Quedlinburger Sattel', long-wavelength fault-related folds and deep synclines. Although the entire Subhercynian Depression underwent uplift in Late Mesozoic to Cenozoic times, relicts of older (Mesozoic) strata indicate a similar structural evolution like in the Altmark area further north. The Subhercynian Depression can be subdivided into several smaller blocks [*Martiklos et al.*, 2001; from north to south]: (1) The 'Weferlingen-Schönebeck Block' north of the Allertal fault is characterized by small, low-offset normal and reverse faults and a gentle dip (less than 3°) towards the southwest. The Allertal Fault separates it to the (2) 'Lappwald Block' further south. Although fault kinematics of the Allertal Fault are still matter of debate [*Best and Zirngast*, 2000; *Stottmeister et al.*, 1998], it can be summarized to form a Late Triassic/Late Jurassic-Early Cretaceous high-offset (> 2.5 km) normal fault, which probably formed as an extensional detachment fault and later underwent mild contraction and inversion. To the south the 'Offleben-Oschersleben-Staßfurt Salzsattel' forms the border between the 'Lappwald Block' and the (3) central part of the Subhercynian Depression. There various E-W- and NW-SE-striking fault zones occur. In parts these faults are accompanied with long-wavelength basement uplifts in the deeper subsurface. (4) The southern part of the Subhercynian Depression is characterized by two deep synclines filled with up to 1.5 km thick synkinematic, Late Cretaceous sediments [*v. Eynatten et al.*, 2008; *Voigt et al.*, 2006]. The 'Quedlinburger Sattel', a thin-skinned reverse fault, separates both against each other.

10.6 The Harz Mountains

Together with the Palaeozoic rocks of the Flechtingen High the Harz Mountains form the outcropping units of the Rhenohercynian Zone in Saxony-Anhalt (inset map in Fig. 1). The internal structure of the Harz Block comprises NE-SW trending folds and faults formed in the evolving foreland basin of the Variscan orogen. The southeastern margin of the Harz is characterized by Rheic Suture Zone, where high-grade metamorphic rocks of the Mid German Crystalline Rise occur. During Mesozoic times the Harz Mountains was covered by Mesozoic sediments as revealed by low-temperature chronology [*Thomson et al.*, 1997] and maturity measurements. During the Latest Cretaceous, NE-SW contraction leads to the uplift of the Harz Block along its northern boundary fault.

10.7 The northeastern Thuringian Syncline

NW-SE- and subordinated NNE-SSW-striking fault zones, long-wavelength folds and local Cenozoic depressions characterize the southern part of Saxony-Anhalt. The deep Palaeozoic structure comprises NE-SW-trending faults and folds of the Rhenohercynian Zone in the west and the Saxothuringian Zone in the southeast of the former Rheic Suture Zone (Mid-German Crystalline Rise; cf. Fig. 1). This crystalline to low-grade metamorphic basement is segmented by the NE-SW-striking, Permocarboniferous 'Saale Depression' [*Kuhnert*, 1995; *Schneider et al.*, 2005]. Faults and structures of Mesozoic age dominantly strike NW-SE and subdivide the northeastern Thuringian Syncline. In parts these faults border small basement uplifts (e.g., the Kyffhäuser Mountains, the Bottendorf High and the Hornburg Anticline) or separate local depressions in the Mesozoic cover against each other [*Katzung and Ehmke*, 1993]. Thereby, faults of the Thuringian Syncline typically show low normal or reverse offsets, which is probably due to reverse reactivation of former normal faults [cf. *Kley*, 2013; *Malz*, 2014 and references therein].

10.8 Data quality, origin and publication

Fault data of Saxony-Anhalt was collected and compiled by several geological and geophysical exploration companies and institutions over the past decades for reasons of raw material exploration and exploitation.

Since the early 1990s the Geological Survey of Saxony-Anhalt (LAGB; formerly Geologisches Landesamt Sachsen-Anhalt, GLA) used the enormous fundus of existing data, reports and structural maps [e.g., *Reinhardt and Gruppe Regionales Kartenwerk*, 1968-1991] to carry out local and countrywide structural mapping and compilation projects [*Fuchs et al.*, 1995; *Martiklos et al.*, 2001]. More recently, these datasets in combination with over 100 reflection seismic exploration reports was used for countrywide 3D geological modelling in the framework of the TUNB (Subsurface Potentials for Storage and Economic Use in the North German Basin) and 3DGEO-EU (3D Geomodeling for Europe) projects. Within the scope of these projects all used data and according meta-information were collected in a Fault Information and Documentation System at the LAGB. These datasets were now generalized, processed and transferred into the HIKE (Hazard and Impact Knowledge Europe) fault database concept. In areas and stratigraphic levels, which were yet not finally processed during 3D modelling projects, datasets were completed with existing fault information from regional to local maps [*Fuchs et al.*, 1995; *Malz et al.*, 2019; *Martiklos et al.*, 2001; 2002].

Fault mapping and documentation of the deep subsurface (500 - 5000 m) during 3D modelling

The systematic fault mapping and documentation during 3D modelling was performed to ensure the better confirmability of provided information and to allow for investigating raw data if more detailed and local analysis becomes necessary. Until now, approximately half of Saxony-Anhalt (Altmark area and Subhercynian Basin) was mapped by use of 3D modelling.

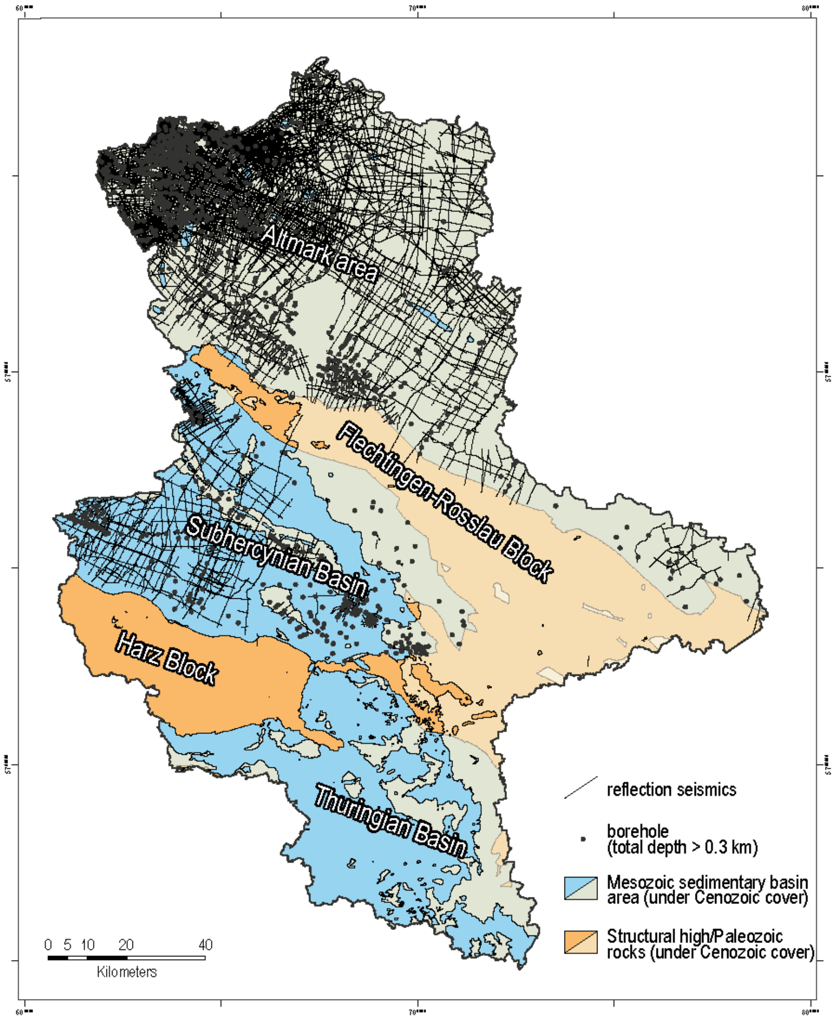

Fig. 5: Overview map of 2D seismic sections and boreholes used for national deep subsurface mapping projects (stratigraphic horizons and faults) in the northern part of Saxony-Anhalt [Altmark area; figure from *Malz et al.*, 2020]

For that reason over 700 depth-converted reflection seismic sections were inspected (Fig. 5). Interpreted fault sticks were digitized and compiled into a consistent fault network for the whole area of investigation. For every digitized fault stick the original reflection seismic section and the report of the geophysical survey was documented. Afterwards, all fault sticks were transferred into three-dimensional fault surfaces. During that step of modelling the fault classification and documentation of fault attributes was performed. Single fault strands, which are arranged in a dense pattern, were summarized to fault systems or fault zones. The major faults of these zones were determined based on their regional relevance, connectivity and length; i.e. the longest faults with similar properties (e.g., dip, offset and timing) were classified as 'major fault'. All other faults of one fault zone were classified as 'secondary faults' (

Fig. 6). In some cases (e.g. in the vicinity of salt structures) it became necessary to provide a third ‘subordinated’ class of faults. These faults are only of local relevance for the further modelling process.
The intersecting points of modelled faults with approximately 350 boreholes were extracted and corrected based on the original geologic profile of the boreholes. All these raw data information was transferred into the Fault Information and Documentation System of the LAGB and became completed with fault information, properties and kinematics derived from the regional 3D model.

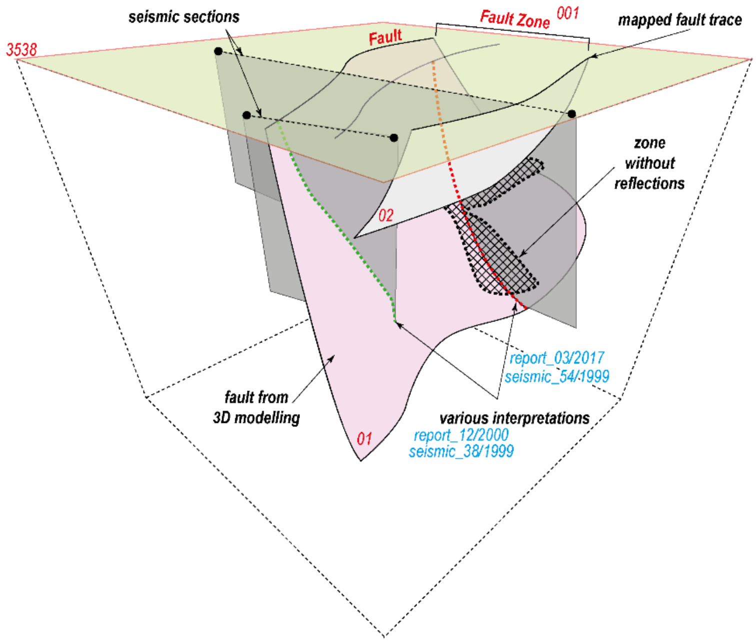

Fig. 6: Schematic visualisation of the fault mapping and documentation concept during 3D modelling. The fault zone (001) consists of one ‘major fault’ (01) and one ‘subordinated fault’ (02). The modelled surfaces are taken from various seismic sections (red and green line) and are documented in individual reports (blue letters).

During further 3D modelling and parameterization efforts fault traces will become systematically collected for map sheets in the scale of 1:50’000. Thereby, the intersecting lines of faults with regional geologically and economically relevant stratigraphic horizons (footwall and hanging wall cutoff lines) will be derived from these detailed models (Fig. 7). These fault data will be available from the HIKE fault database in scales of up to 1:50’000. Furthermore, it becomes possible to derive further information (e.g. hydraulic and mechanic properties) from adjacent stratigraphic formations to the fault lines and surfaces.

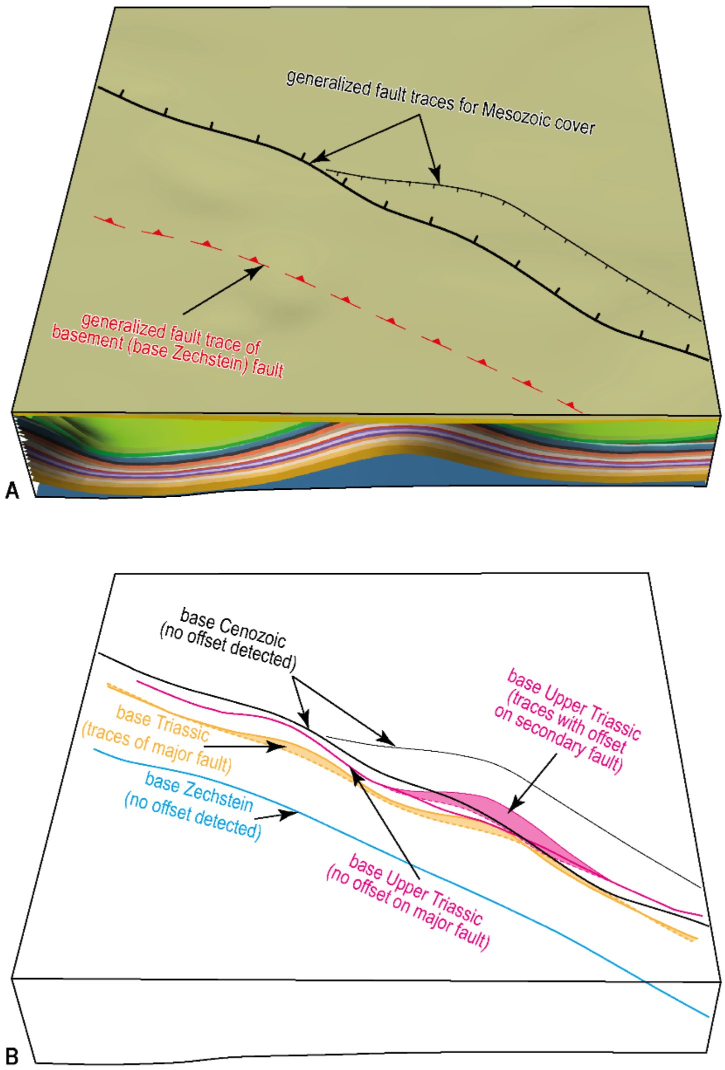

Fig. 7: Detailed 3D model (A) with derived fault lines (B; footwall and hanging wall cutoff lines) for selected regional geologically and economically relevant stratigraphic horizons

10.9 Generalization for countrywide fault data

For regional observations and investigations as well as for homogenization with surrounding countries and geological surveys a compilation and generalization of existing fault data was performed. Therefore, generalized fault lines of detailed 3D models were generated for two stratigraphic levels, the base Late Permian Zechstein, representing the mechanical top basement in tectonic sense, and approximately the top Mesozoic for faults in the sedimentary cover (Fig. 7 A). For areas were yet no 3D model exists, these data were completed with existing fault traces from local and yet unpublished investigation reports, still on-going 3D modelling campaigns and from the regional geologic map of Saxony-Anhalt available in the scale of 1:400’000 [*Martiklos et al.*, 2001]. These datasets were integrated into the HIKE fault database in scales greater than 1:50’000.

10.10 Faults of the shallow subsurface (< 500 m)

Faults of the shallow subsurface that have no surface expression were taken from various local and regional reports. These reports dominantly handle with the structure of local exploration campaigns associated with brown coal deposits but even comprise regional studies [*Fuchs et al.*, 1995] or countrywide maps [*Martiklos et al.*, 2002] of the base Cenozoic and younger hydraulically or economically relevant stratigraphic horizons (e.g., the top of the Rupelian acting as the major hydraulic barrier for shallow groundwater reservoirs). This information was available for scales of 1:50’000 to 1:400’000.

Shallow subsurface faults are classified and assigned to regionally relevant fault zones of the deep subsurface (see chapter Generalization for countrywide fault data) based on their spatial position. Due to the fact that these faults are based on separate regional to local compilations their position can vary with respect to the regional faults for the deep subsurface. However, these faults most often do not contain any information about fault geometries (e.g.; dips) or kinematics (e.g., normal or reverse fault). In the concept for data available in the HIKE fault database these shallow subsurface faults form an optional layer of fault information in regional scale (larger than 1:50’000).

10.11 Fault surface mapping and documentation of surface faults

In the area of Saxony-Anhalt surface expressions of faults are relatively rare. They only occur in the southern part of the country, where pre-Cenozoic strata crop out at the surface. In northern Saxony-Anhalt faults are difficult to detect due to the Pleistocene glacial overprint. Here, only faults associated with deformation occurring at the glacier’s front are detectable and mappable, if huge stratigraphic offsets (larger than few tens of meters) occur.

Surface expressions of faults for the whole area of Saxony-Anhalt were derived in map view from the digital Preliminary Geologic Map of Saxony-Anhalt [*Malz et al.*, 2019]. For generating that fault dataset all stratigraphic units of the digital map were classified and attributed by total ages referring to the hierarchical Stratigraphic Column of Germany [*German Stratigraphic Commission*, 2016]. This information enabled an automatic extraction of polyline features for adjoining polygons, where the stratigraphic column was intact; i.e. where the limiting borders represent the uniform chronostratigraphic transition from one geologic era to another. Where these contacts are not intact; the limiting border is interpreted to represent either an unconformity or a fault, which was attributed and classified by regional geologic observations of the entire research area. For those stratigraphic units, which have been deposited with a transgression at their base, limiting polylines were classified to represent an unconformity. Thus, the resulting discontinuity lines were interpreted to represent faults of different classification (suspected, inferred or well-known faults).

Due to the fact that surface expressions stem from geological maps and do not contain any hierarchical or semantic link to deep faults, additional attributes became necessary. Hence, surface faults were additionally linked to structural elements and fault zones by transmitting these attributes based on the position of single fault lines. Therefore regional geologic parameters of generalized fault lines (cf. chapter ‘Generalization for countrywide fault data) were transferred to mapped faults.

10.12 Fault data included in HIKE fault database

For Saxony-Anhalt, all yet available fault data from the deep and shallow subsurface will be included in the HIKE fault database. The dataset will become complemented with additional surface expressions of faults. For the deep subsurface fault geometries of a detailed scale (approximately 1:50’000) are delivered as 2D intersection lines (footwall and hanging wall cutoff lines) with the main stratigraphic horizons. 3D surface models (optional downloads) will complement this information. For regional reasons (scales larger than 1:50’000) as well as for the shallow subsurface and surface expressions faults are represented as polylines. If possible to determine, these faults are attributed with a dip direction and azimuth. Otherwise, this information is left blank to minimize unconfirmed attributes.

Detailed faults for the deep subsurface are classified according to a generic semantic framework. This includes a correlation link with the faults in neighbouring countries (in particular faults from the Geological Survey of Brandenburg; LBGR).

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11 LfU – GERMANY

Tectonic Boundaries in Bavaria

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11.1 Rationale

All tectonic boundaries of Bavaria, as revised in HIKE project and uploaded to the European Fault Data Base, are linked to a detailed description in the Tectonic Boundaries in Bavaria linked open data vocabulary https://data.geoscience.earth/ncl/geoera/hike/faults/7378. Rather than giving a full inventory of principal tectonic features, that compilation aims at stressing the contextual relationship of the fault network in Bavaria. To avoid repetitions, this report textually is kept concise, but well illustrated with the pictorial attachments of the vocabulary. It mainly focuses on background information and scope notes, the overarching concepts and the structural framework.

11.2 Overview of regional geological setting and structural framework of Bavaria

Situated at the southern margin of the European Plate Bavaria is characterized by a Mesozoic sedimentary sequence, overlying and framed by Paleozoic rock suites of the Variscan basement and the Alpine Orogen to the south (Figure 1). Four structural domains can be distinguished: the Alps,the Molasse Basin, the Scarpland (Cuesta Region) and the Varicscan basement terrain (Figure 3). Quaternary sediments are common to all regions.

The Alpine-Carpathian Orogen evolved owing to the collision of the Adriatic and European plates during Cretaceous and Tertiary, bequeathing four principal tectonic units on Bavarian territory. The nappes of the Northern Calcareous Alps, built up of Adriatic plate shelf formations, over thrusted the oceanic trench fill (Flysch), the European plate shelf sediments (Helveticum), and the southern rim of the foreland basin fill, the Subalpine or Folded Molasse (Figure 2).

Along the forefront of the emerging orogenic belt, due to the large-scale downwarping of the European plate, a foreland basin developed progressively infilled with 'Molasse' sediments eroded off the northward thrusting Alps during Tertiary. In the south and west of the Alpine piedmont the top of the Molasse is shaped by several phases of Pleistocene glaciation.

Jurassic and Triassic sedimentary sequences make up the footwall of the, up to 5 km deep, Molasse Basin.

Hosting central Europe's most prolific hydrothermal aquifer at great depth, the karstified carbonate rocks of the Upper Jurassic on the surface feature the 14.6 Ma old Ries asteroid impact crater (Figure 2), and form the uppermost escarpment of the Scarpland revealing increasingly older strata towards the northwest. The lowermost cuesta forming sequence, Buntsandstein, rests upon non-metamorphic Permian sediments in post-Variscan troughs or directly overlays older low-grade to high-grade metamorphic rocks associated with plutonic rocks, both formed during Variscan orogenesis.

This Varican basement, made up of two stratigraphic-lithologic-tectonic zones, the Saxothuringian and Moldanubian Zones in terms of Kossmat (1927) crops out in the very northwest of Bavaria and along its eastern border (Figures 1 and 3).

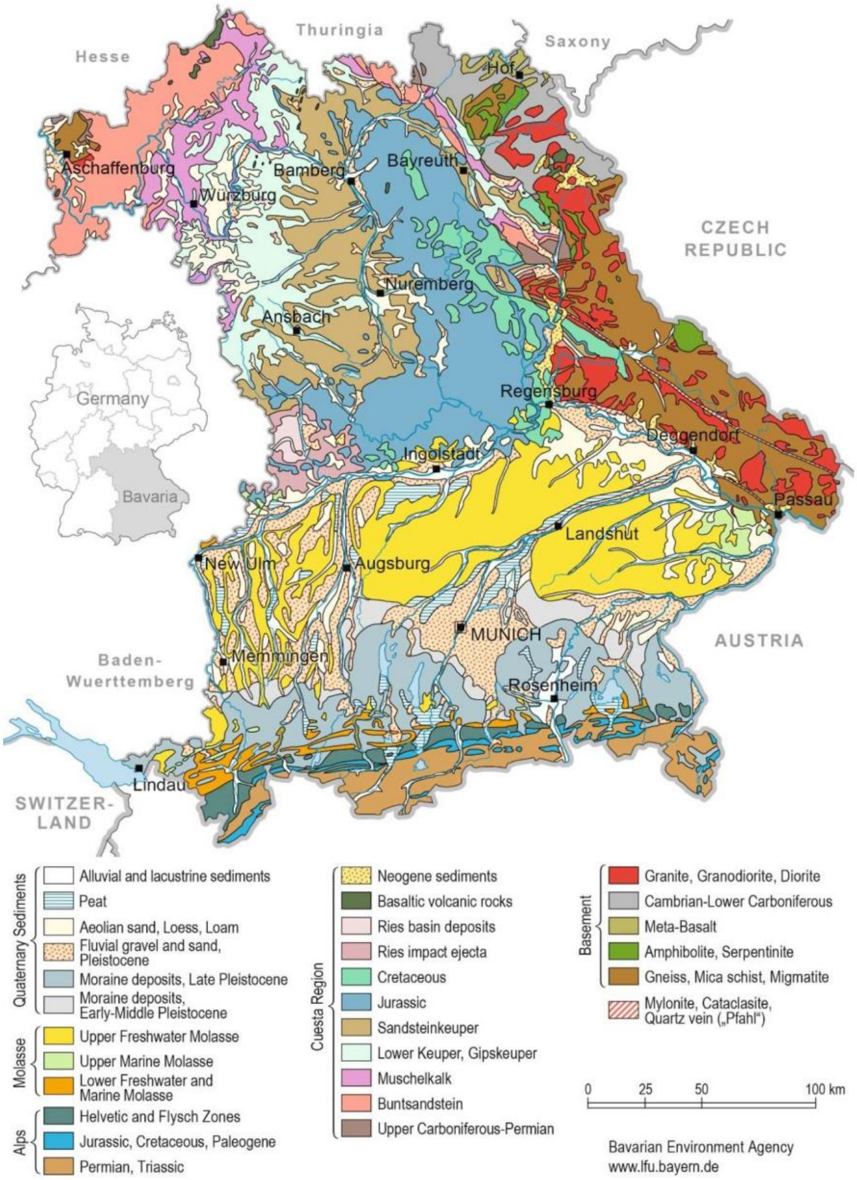

Fig. 1: Geological overview of Bavaria portraying the principal geological units and the location of Bavaria within Germany (inset). See text for discussion.

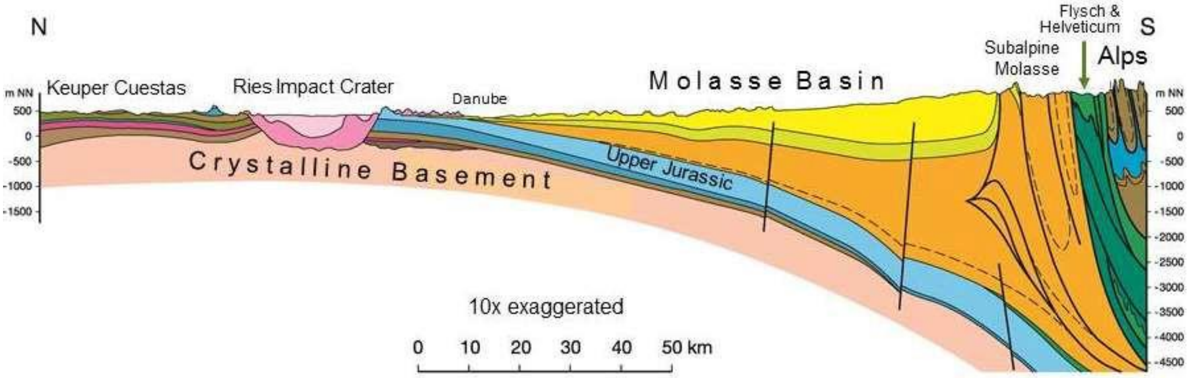

Fig.2: Geological section across the southern Cuesta Region, the Alpine Foreland and the Pre-Alps in western Bavaria (from Diepolder et al. 2019 after Doppler et al. 2004, modified); color coding refers to Figure 1.

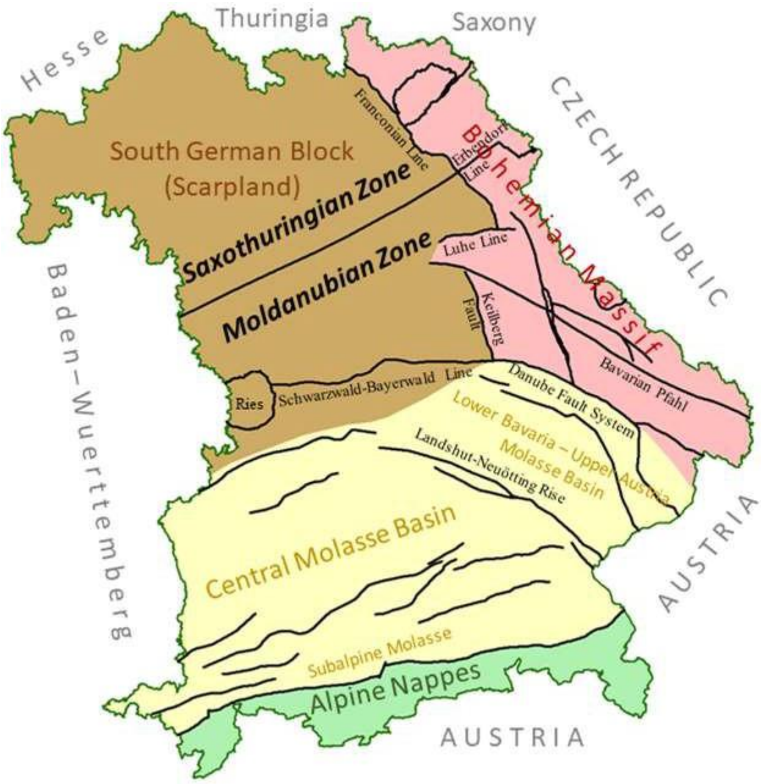

Fig. 3: Principal geo-tectonic domains of Bavaria and their boundaries and subdividing lines represented by major fault systems or lineaments (after Bayerisches Geologisches Landesamt 1996, modified). The basement of the domains, emerging in the Bohemian Massif, is made up of rock suites of the Variscan collision orogeny, subdivided into two stratigraphic-lithologic-tectonic zones, the Saxothuringian and Moldanubian Zones (Kossmat 1927). The boundary between these zones has been evidenced directly in the Bohemian massif only (Erbendorf Line).

11.3 Tectonic boundaries in Bavaria revised in HIKE and uploaded to EFDB

Within the scope of HIKE project the tectonic boundary concepts in Bavaria have been re-evaluated, revised and, state 12-2020, uploaded to the European Fault Data Base. A connected Semantic Web vocabulary describes the faults and their overarching concepts in detail. Considered are major faults and fault systems from all geological units / structural domains of Bavaria, except for the Alpine Domain (cf. Figure 3), as mapped in various scales or inferred from indirect evidence using various methods deemed appropriate in the respective geological settings. Rather than giving a full inventory of principal tectonic features, this compilation aims at stressing the contextual relationship of the fault network in order to elucidate the regional tectonic regime as the result of large-scale crustal movements. In Bavaria, tectonic boundary objects detection and contextual classification is an ongoing process. Hence, this inventory is subject to future upgrading and change.

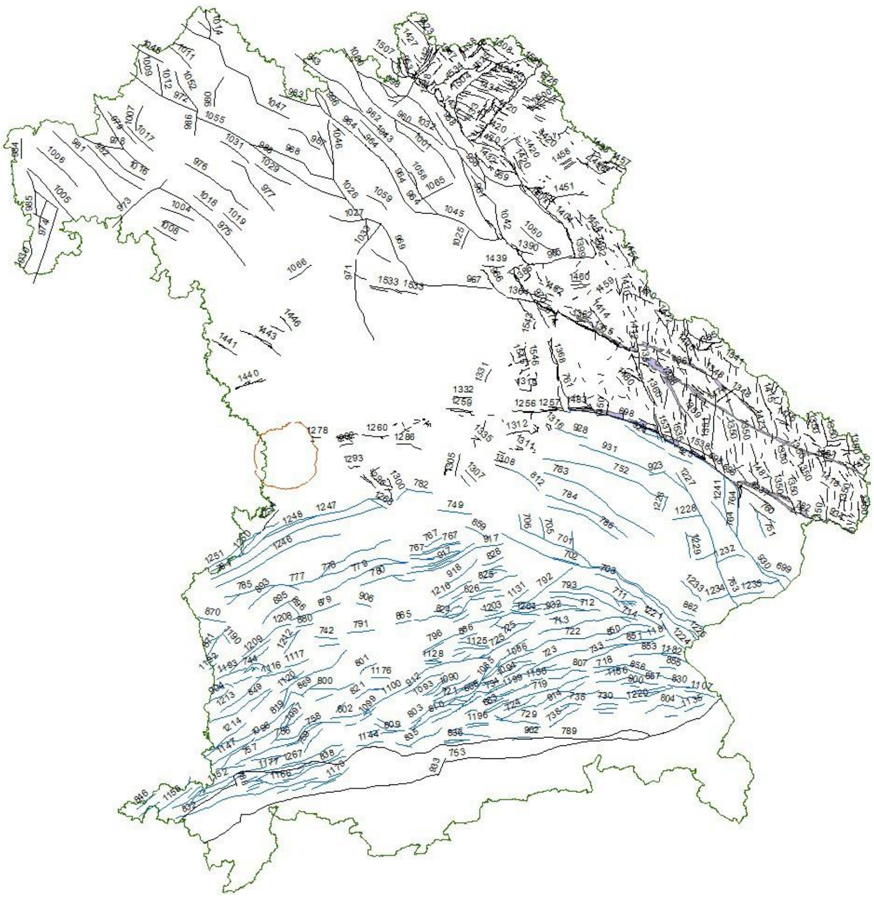

Fig. 4: Synopsis of the faults and shear zone as stored in and retrievable from the European Fault DataBase, and described in the connected vocabulary https://data.geoscience.earth/ncl/geoera/hike/faults/7378.
Black: surficial faults, blue: traces of blind faults at the top of Upper Jurassic Molasse Basin footwall, orange: Ries Impact crater rim.

11.4 Faults of the central part of the North Alpine Molasse Basin and northward adjoining areas

All faults of the Central Molasse Basin are blind faults 3D modelled based on evidence of seismic surveys and deep drillings. The fault geometries and concepts refer to the fault traces on the top of Upper Jurassic carbonate sequence (resp. the top of Purbeck) as one of the principal reflectors in seismic surveys.

The Upper Jurassic Molasse Basin footwall continues northward emerging in the Swabian-Franconian Alb, there forming the uppermost cuesta of the scarpland. As hydraulically connected to the Molasse Basin bedrock, the Swabian-Franconian Alb is considered an extension of the Central Molasse Basin and accordingly described in that structural domain.

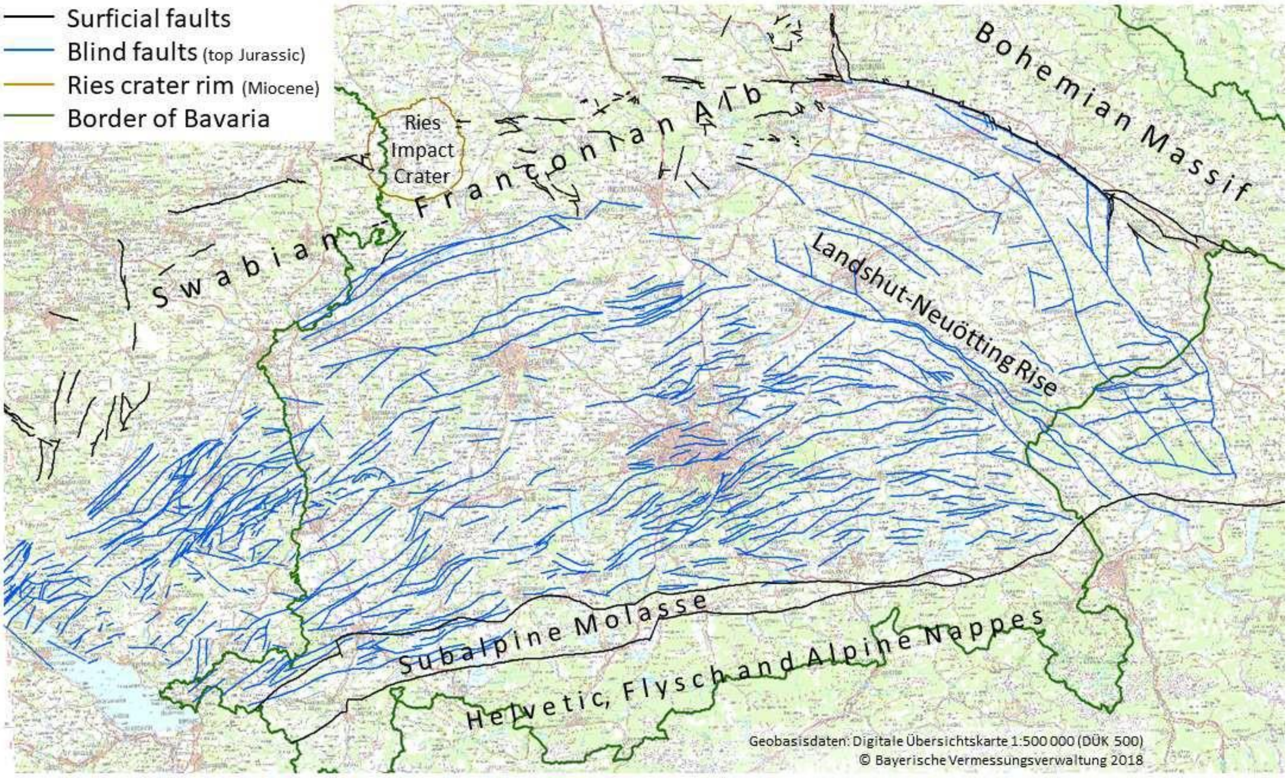

Fig. 5: Areal coverage of the "Central part of the North Alpine Molasse Basin and northward adjoining areas" faults as regarded in HotLime project case study 1. HIKE considers faults and concepts of the Bavarian share only. For a cross-section (omitting most faults) refer to Figure 2.

11.5 Molasse Basin fault domain

Separated by the Landshut-Neuötting Rise, a swell of Variscan basement, two principal tectonic sub- domains can de distinguished in the central part of the North Alpine Molasse Basin (cf. Figure 5).

The central part of the South German Molasse Basin, overlapping the territories of Baden-Württem- berg and Bavaria, is characterized by syn- and antithetic normal faults related to flexure-like strain of the foreland basin. Faults, often arranged as trains of faults, predominantly trend subparallel to the basin's centerline and the Alpine Thrust Front. Close to the Landshut-Neuötting Rise the faults' strike is deflected subparallel to the counterfort of the northward Alpine thrust, the Bohemian Massif. All faults of the basin are blind faults, active until Badenian of mid-Miocene at the latest, solely evidenced by seismic surveys and deep drillings.
The Lower Bavaria - Upper Austria Molasse Basin fault domain, overlapping the Austrian-German border, takes up the space in between the southwestern scarp of the buried Landshut-Neuötting Rise or Central Swell Zone to the southwest, the Franconian Alb to the northwest, the outcropping basement rock suites of the Bohemian Massif to the north and northeast, and, on Austrian territory, the Alpine thrust front to the south. It is characterized by syn- and antithetic normal faults running subparallel to the counterfort of the Alpine thrust formed by the Bohemian Massif, southwards increasingly crossed by faults subparallel to the Alpine Thrust Front. The roughly NW-SE trending (Variscan strike) reactivated Permo-Carboniferous lineaments subdivide specifically the Lower Bavaria Molasse Basin into sub-basins and troughs. All faults within the basin are blind faults, active until Badenian of mid-Miocene at the latest, solely evidenced by geophysical surveys and few drillings.

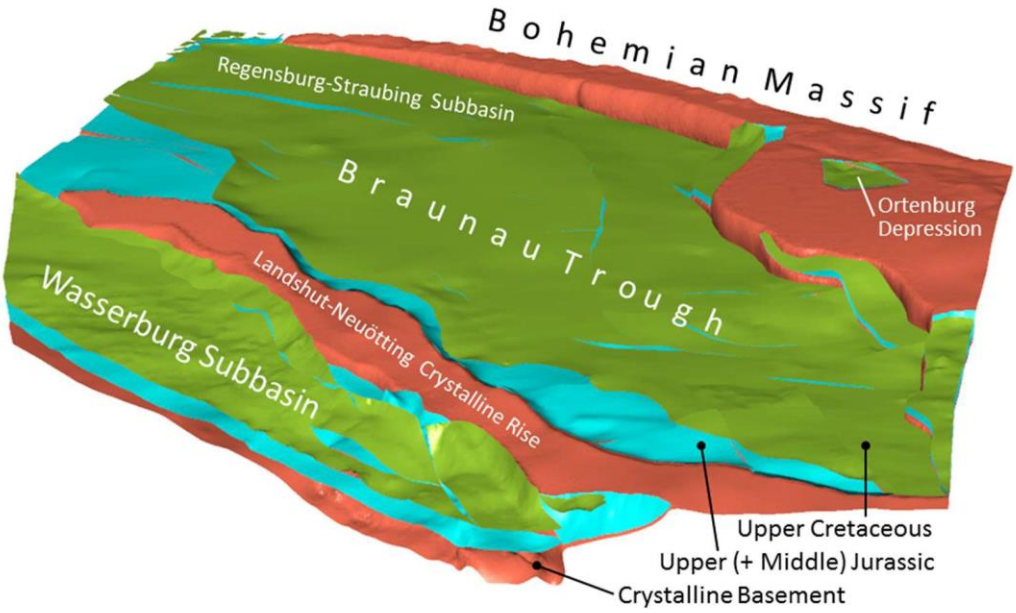

Figure 5: 3D geological model Niederbayern (Lower Bavaria), including a small share of Upper Austria, view from SW, Tertiary layers omitted for clarity. Due to the lack of hydrocarbon prospectivity and a low geo-thermal potential few seismic surveys have been carried out in the southern (deeper) part of this shallow to medium- deep portion of the Molasse Basin only. Hence, a Bouguer gravity residual anomalies map was used to accentuate the structure of the pre-Mesozoic basement and the >1,000 m throw fault system along the edge of the Bohemian Massif basement complex (Danube Fault System in figures 3 and 8). (From Diepolder et al. 2019)

Scope note: As discussed, all basinal faults are blind faults 3D modelled based on evidence of seismic surveys and deep drillings. Tectonic boundaries featuring throws of less than approximately 10 m, likewise soft links between faults, like relay ramps or horsetail splays, commonly are subseismic in legacy surveys and detectable only in novel 3D-seismics as carried out in few focus areas only. The inventory of concepts, thus, cannot be complete with respect to these features. It reflects the state of knowledge as of 2020 and is subject to future amendments.

Due to these constrains the actual geometries of the faults are deemed much more complex than representable in an overview inventory. Figures 6 and 7 depict examples of in-depth studies carried out in small areas covered by up-to-date 3D seismic surveys.

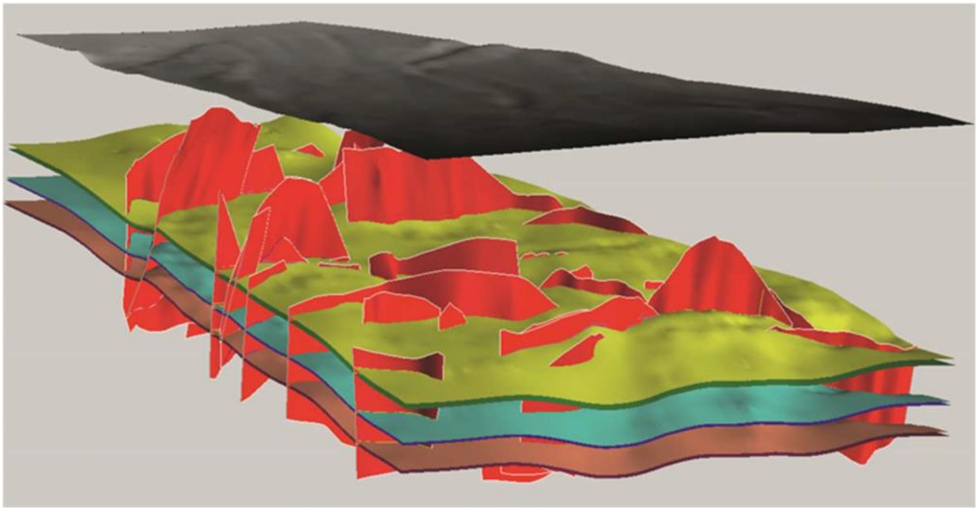

Fig. 6: 2,000 km^2 tile of GeoMol Ost pilot area model, vertical extension approx. 5,400 m, view from SW. Depicted are six Mesozoic layer surfaces of the south dipping footwall sedimentary sequence and the fault network reflecting the complex tectonic evolution of the basin. Tertiary units are omitted for clarity. (From Diepolder et al. 2019)

Fig. 7: Horsetail splay structure at the southeastern end of Velden Fault. Such branching out at the termination of faults seems to be quite common but is detectable in high-resolution up-to-date 3D seismic surveys only (cf. HotLime Factsheet Faults (europe-geology.eu)).

11.6 Swabian-Franconian Alb fault domain

The Swabian-Franconian Alb is made of Upper Jurassic carbonate rocks forming the uppermost cuesta of the South German Scarpland. In its southern part, the elongated, SW-NE trending ridge overlapping the territories of Baden-Württemberg and Bavaria forms a gently SE dipping platform submerging underneath the Tertiary sedimentary sequence of the Molasse Basin.

Except for the faults and flexures relatable to the Schwarzwald-Bayerwald Line (cf. Figure 3) no prevailing tectonic structures are obvious. The predominant strike directions of micro-tectonics SSW-NNE (Rhenish) and SE-NW (Variscan/Hercynian) are conspicuous in the fault network of few areas only. The most striking structural feature of Swabian-Franconian Alb is atectonic: the almost perfectly circular crater rim of the 14.6 Ma old Ries asteroid impact (cf. Figures 2 to 5).

11.7 Molasse Basin southern margin fault systems

Between Lake Constance in the west and Chiemsee in the east, the southern boundary of the Foreland Molasse is formed by the northern boundary of Subalpine (Folded) Molasse. East of Chiemsee, where the Subalpine Molasse is overthrusted by Alpine units, the Alpine Basal Thrust (Thrust Front of Helvetic, Penninic and Austroalpine Nappes) represents the southern boundary of the Foreland Molasse (cf. Figure 5).

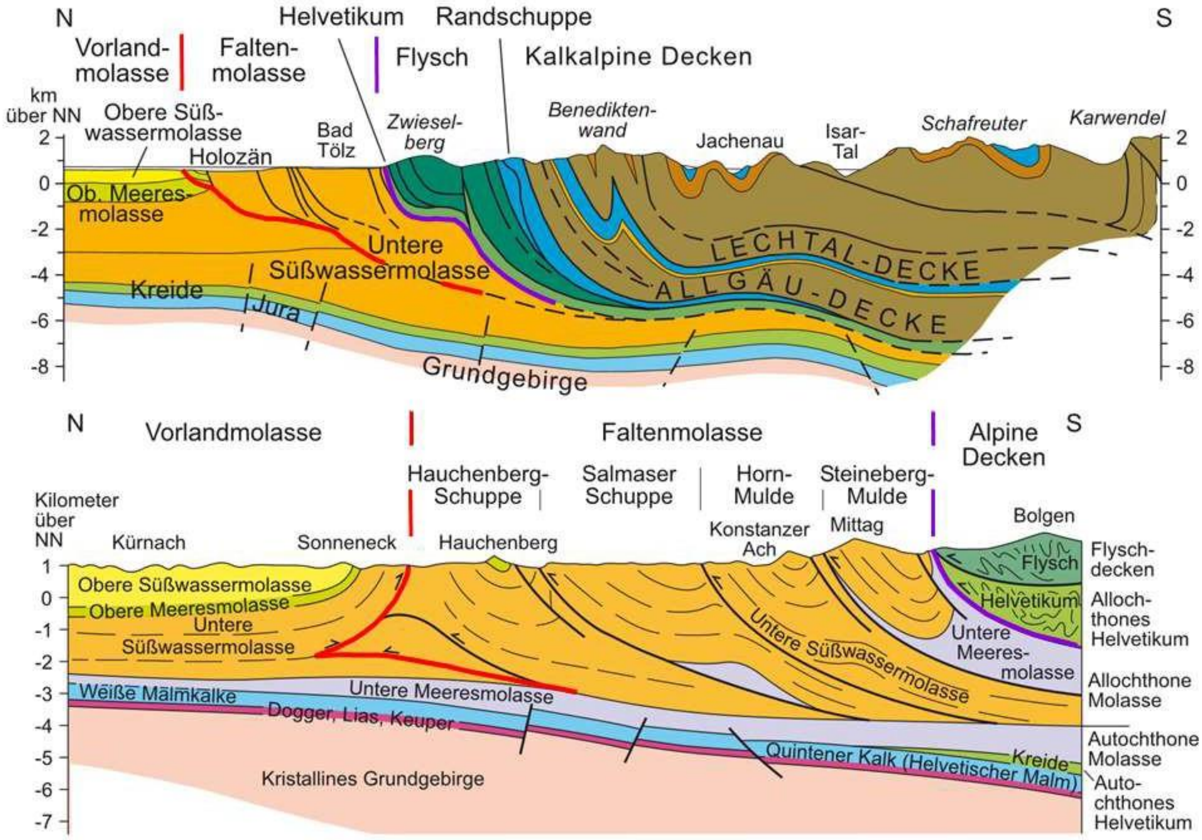

Fig. 8: Schematic geological N-S sections across the Bavarian Pre-Alps and the northern fringe of the Alps illustrating in red the northern boundary of the Subalpine or Folded Molasse (Faltenmolasse) towards the Foreland Molasse and in violet its southern boundary, the Alpine Basal Thrust, top: ± along the 11.5°E longitude in central Bavaria (from Glaser et al. 2008, p. 135), bottom: ± along the 10°E longitude west of Iller river (from Lagally et al. 2009, p. 148).

Scope note: Regarding the Molasse Basin southern margin fault systems the HIKE fault inventory includes only the outer boundaries of the Subalpine Molasse and the Alpine Basal Thrust, highlighted in red and violet in figure 8. The complex internal build-up and faulting is not considered.

11.8 Molasse Basin eastern margin fault systems

The Danube Fault System, featuring a throw of up to more than 1 km, represents the borderline where the blind faults of the Lower Bavaria - Upper Austria Molasse Basin and exposed resp. subcropping faults of the Bohemian Massif converge.

Scope note: The basinal faults, as 3D modelled based on evidence in seismic and gravity surveys and scarce deep drillings, are described as traced on the top of Upper Jurassic strata or its marginal facies equivalents. Conditioned by methodology, fault tips, horsetail splays etc. commonly are subseismic, non-detectable features (cf. Figure 7 and HotLime Factsheet Faults (europe-geology.eu)).

The inferred subcropping and mapped rarely outcropping tectonic boundaries of the Bohemian Massif, including the wide shear zones made up of mylonites and cataclastites, are compiled generalized equivalent to an approximately 1:100,000 scale.

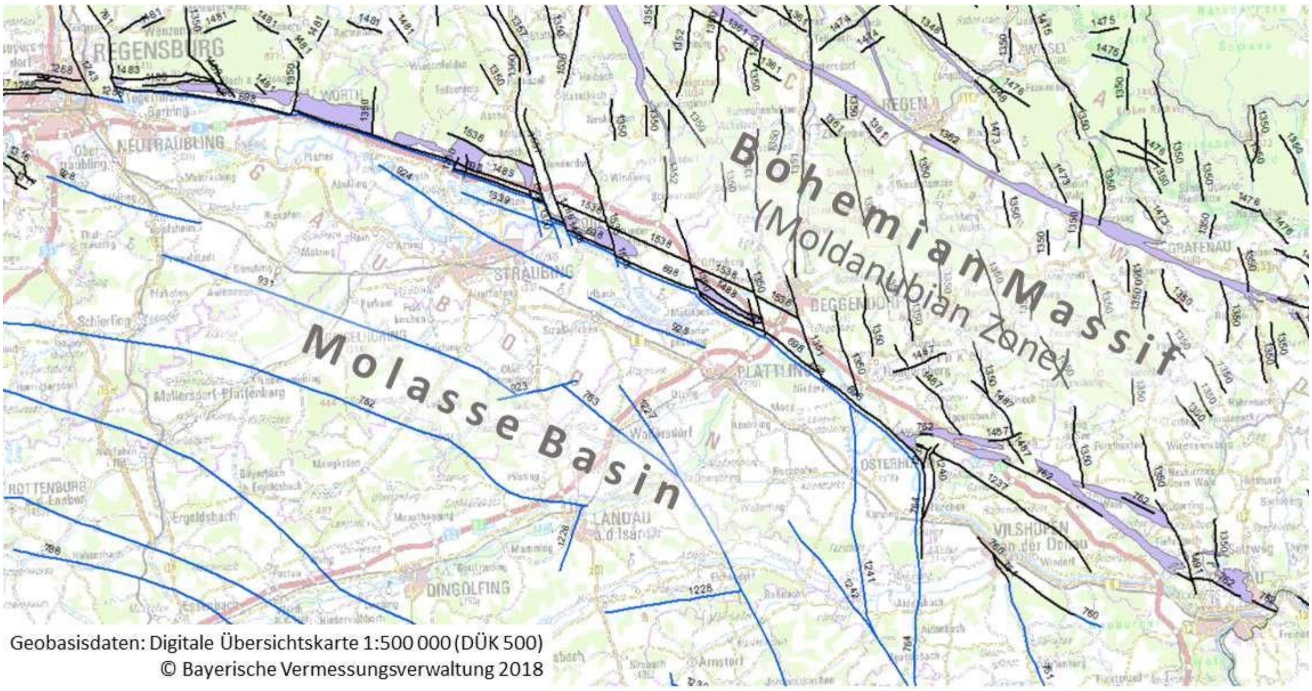

Fig. 8: Eastern Margin of Lower Bavaria Molasse Basin towards the Bohemian Massif (blue: blind basinal faults at the top of Upper Jurassic carbonate rocks, black: subcropping faults of the Variscan basement exposed in the Bohemian Massif, bluish-grey: mylonitic shear zones of the Variscan basement. The steeply S to SW dipping border fault systems subparallel to the Danube River features a throw up to more than 1 km.

11.9 Bohemian Massif fault domain

Overlapping the principal stratigraphic-lithologic-tectonic zones of the Bohemian Massif in Bavaria, Saxothuringian Zone, Moldanubian Zone and Münchberg Klippe (a Teplá-Barrandian thrust outlier), roughly NW-SE, flat-angle Hercynian (100-120°) to high-angle Hercynian (130-140°) trending faults or fault zones prevail the tectonic boundaries pattern, particularly in the Moldanubian Zone forming large-scale polyphase shear zones (Figure 8) partially protruding into the Permo-mesozoic foreland. Transverse faults, predominantly ± N-S trending in the south, prevalently ± SW-NE in the north, resuming the orientation of accreted terranes sutures, complement the overall picture.

Scope Note: The tectonic boundary inventory within the verdant Bohemian Massif rock suites, apart from larger scale faults manifested in fractured zones and tectonites or evidence in scarce quarries, only rarely can be observed directly. Fault pattern are inferred mostly from indirect field evidence such as conspicuous lithological changes, joint system measurements, linear features like quartz veins, aligned with remote sensing data and geophysical surveys in few areas. By nature, these investigations do not allow for exact information on the dip angle and vertical displacement. Accordingly, most of the concepts' statements on these parameters shall be considered an assumption.

Small-scale faults and fractures of fragmented plutonic complexes (granite tectonics) are not considered. Both principal stratigraphic-lithologic-tectonic zones making up the Varican basement of the Bohe- mian Massif, the Saxothuringian and Moldanubian, feature exotic blocks of high-grade metamorphic rocks (amphibolite, eclogite) thrusted over and into the Saxothuringian and Moldanubian rock suites. The most conspicuous of these Bohemian Zone (Teplá-Barrandian) thrust zones is the Münchberg Klippe, a thrust outlier bowl-like resting upon the anchimetamorphic Saxothuringian basement. Münchberg Klippe features an inverse stack of nappes with the highest-grade metamorphic rocks on top, piled up by thrusting during Devonian and Early Carboniferous (Mississippian).

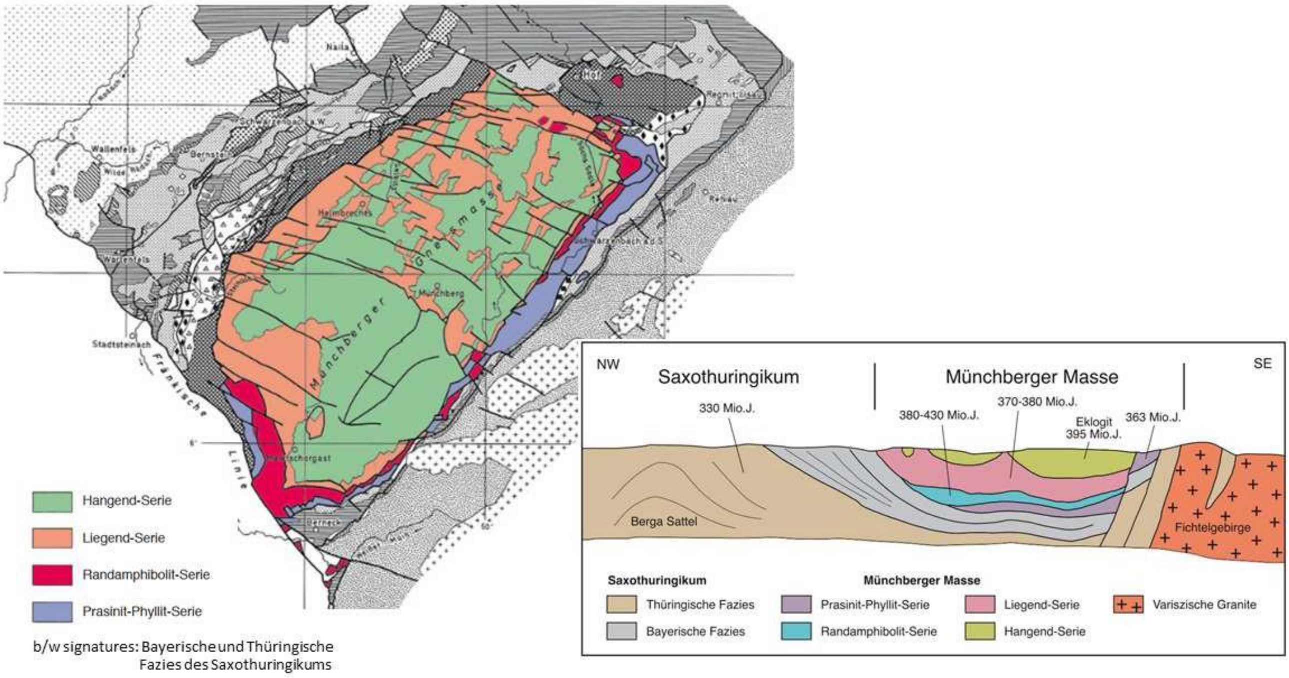

Fig. 10: Schematic sketch map and cross-section indicating the principle tectonic boundaries of the Münchberg Klippe, a thrust-outlier of high grade metamorphic rocks bowl-like resting in and upon anchimetamorphic rock suites of the Saxothuringian Zone (slightly modified from Eichhorn et al. 2003)

11.10 Bohemian Massif western margin tectonic boundaries

Traversing Bavarian territory for more than 150 km, the overall NW-SE trending borderline separating the Bohemian Massif to the east from the South German Scarpland to the west, primarily forms a ± E dipping reverse or thrust fault (system), multiply displaced by transverse fault systems and is in sections obscured by younger deposits. In the south, it is truncated / deflected by the Danube Fault System towards the east and southeast (Figure 3). Evolving during Variscan orogeny, afterwards multiply reactivated, the main phase of the uplift of the Bohemian Massif western marginal zone, overthrusting the Permo-mesozoic foreland, took place during Upper Cretaceous and Paleogene (Bayerisches Geologisches Landesamt 1996).

Scope note: The Bohemian Massif Western Margin tectonic boundaries can be directly observed only in very few segments. In most cases, the faults' trends are inferred from contour lines pattern of the Permo-Mesozoic foreland and/or extrapolated from outcrop evidence, aligned with geophysical surveys interpretations or remote sensing data in few areas. As a rule, the top of the Variscan basement serves as the reference horizon for the indication of the vertical displacement (throw). As the exposed Bohemian Massive has been subject to intense peneplanation during Tertiary, the figures given, thus, represent the present-day "residual" throw.

The Bohemian Massif western margin is made up of four principal segments, from north to south, the Franconian Line, Luhe Line, the northwestern limb of the Bavarian Pfahl, and Keilberg Fault System (cf. Figure 3). Even though many segments form a physiographically conspicuous scarp, its NE to N dipping large throw reverse faults are mappable in certain parts only, as covered by thick debris. Figures 11 and 12 provide an impression of the variable conformation of the Bohemian Massif western margin even on a short distance.

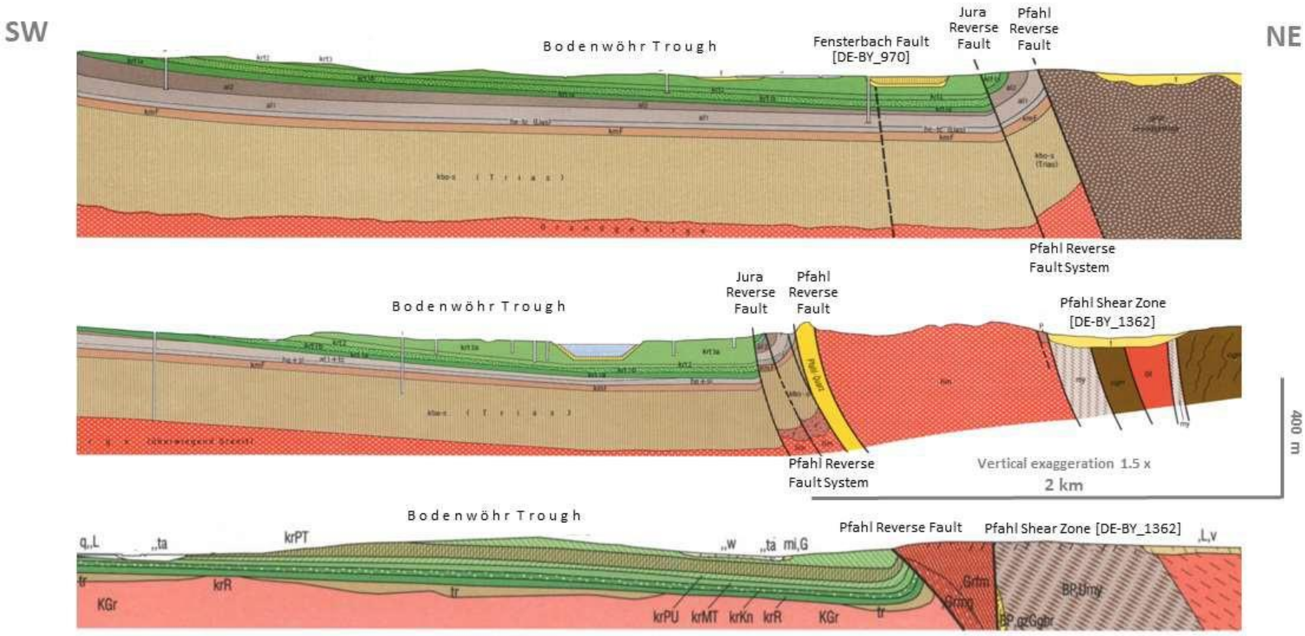

Fig. 11: Compilation of geological SW-NE sections across the Pfahl Reverse Zone System, the northwestern limb of the Bavarian Pfahl , from NW to SE (adjusted true to scale from, top: Meyer 2000, middle: Meyer & Mielke 1993, bottom: Teipel et al. 2007).

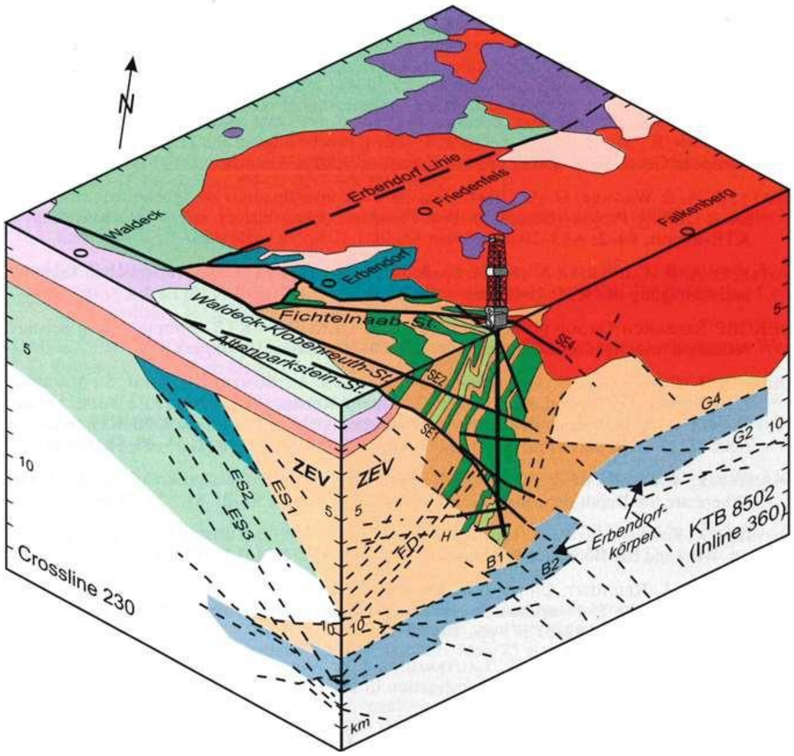

Fig. 12: Block diagram depicting the geological situation of the KTB (German Continental Deep Drilling Program) northern surround illustrating the spatial relationship of Erbendorf Line, the boundary between Saxothuringian and Moldanubian zones, the two branches of the Franconian Line, forming the Bohemian Massif western margin, (namely Altenparkstein Fault and Waldeck-Klobenreuth Fault, featuring a cumulative throw of about 5 km), as well as Fichtelnaab and Nottersdorf Fault Zones, confining the Teplá-Barrandian thrust outlier (ZEV) to the east (from Hirschmann 1996).

11.11 Bavarian Scarpland domain

The tectonic elements of the South German block are wide-span bulges and depressions, as well as long-range fault zones. The tectonic boundaries of its sedimentary cover, the Bavarian Scarpland, mostly strike in flat-angle Hercynian (WNW-ESE) or high-angle Hercynian aka Franconian (NW-SE) direction (Figure 4) and show indications of multiple extensional and compressional events (graben and horst). The deformation structures show folding, normal faulting, reverse faulting and thrusting. An example if a major fault system in the eastern part of the scarpland, Freihung Fault System featuring a throw of up to 1.2 km.

Scope note: The tectonic boundaries of the sedimentary cover of the South German block, the Bavarian Scarpland, in parts can be directly observed, otherwise are extrapolated from outcrop evidence or inferred from contour lines pattern. The tectonic boundary inventory of the Scarpland presently is under revision and contextual classification. Many faults and fault zones, thus, are represented and described generalized, resembling a 1:1 m scale.

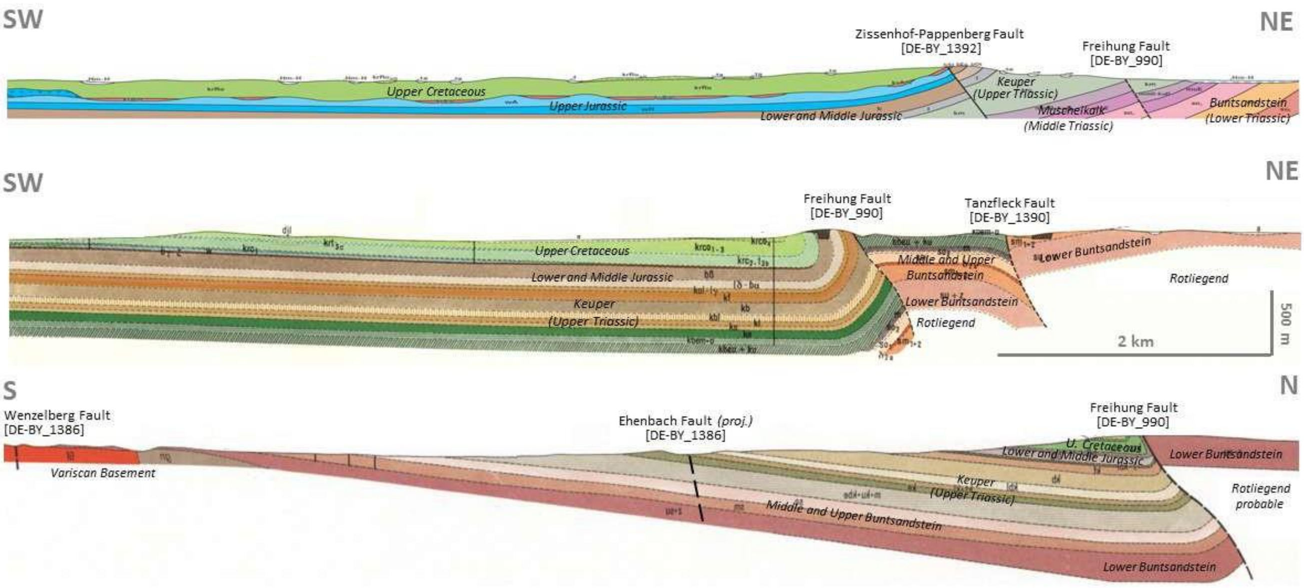

Fig. 13: Compilation of geological sections across the Freihung Fault System, from NNW to SS, (slightly modified and adjusted true to scale and direction from, top: Raum 2014, middle: Tillmann 1958, bottom: Bauberger et al. 1960).

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12 ISOR – ICELAND

Iceland
Fault Data Country Report

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Albert Þorbergsson

Short report
ÍSOR-20034
Project no.: 18-0131
20.10.2020

Project manager's signature

12.1 Introduction

Iceland is a volcanic island located in the North Atlantic. It is forged by the interaction of excessive volcanic activity and plate spreading. The excessive volcanism is due to a mantle plume situated underneath the island and the spreading is the manifestation of the Mid Atlantic Ridge, a divergent plate boundary which runs along the Atlantic ocean sea floor separating the North America and Eurasia plates. Geological features on the surface are heavily influenced by the plate spreading. The volcanic zones which run through the center of the island from southwest to northeast along the plate boundary are the most active areas on the island, both volcanically and tectonically. Within them we find the youngest rock formations which are predominantly basalts. The oldest rock formation onshore are found in the West- and Eastfjords, 16-17 million years old.

The plate boundary that crosses Iceland is offset to the east from the Mid-Atlantic Ridge, towards the Iceland plume. This results in an unstable plate boundary with reoccurring rift transfers in the geological history (Einarsson, 2008; Sigmundsson et al., 2018). These plate boundary offsets are accommodated by transform zones that manifest as highly oblique rift systems and seismic zones, such as the Reykjanes Oblique Rift, the South Iceland Seismic Zone, and the Tjörnes Fracture Zone. According to the NUVEL-1A plate velocity model (DeMets et al., 2010) the velocity of plate spreading in Iceland is on average 18- 19mm/yr and the plate velocity direction is N105°E. Most of the spreading is taken up by diking events and normal and strike slip faulting in the volcanic zones.

Figure 1. *Normal faults in Þingvellir. They are formed by divergent plate movement and are a part of the Western Volcanic Zone*

12.2 Categories

The three main types of plate boundaries in Iceland are volcanic zones, transform faults, and oblique rifts. Each subzone has its own characteristics which are described in the following sections.

12.2.1 Volcanic zones

The volcanic zones and their structural elements are the surface expression of a divergent plate boundary. The main structural elements are normal faulting, extension fractures, rift-parallel strike-slip faulting, and volcanic fissures (e.g. Karson, 2017; Tibaldi et al., 2020). Volcanic systems are the principal geological features in the volcanic zones. These volcanic systems consist of several large central volcanos that each form their own sets of faults and fissures extending on each side of the volcano. These fault and fissure swarms are aligned sub-parallel to the axis of the hosting volcanic zone (Thordarson and Höskuldsson, 2008), which accommodate for the active plate spreading and extension and dyke emplacements along the plate boundary.

The volcanic zones that are defined are (from Einarsson, 2008):
The Western Volcanic Zone
The Central Volcanic Zone
The Eastern Volcanic Zone
The Northern Volcanic Zone

Figure 5 shows the location of each zone. There are between two and nine volcanic systems in each zone, the Central Volcanic Zone has two and the Eastern Volcanic Zone has nine. We note that the exact number and boundaries of active volcanic systems are often hard to determine and are still being investigated.

Figure 2. *Normal fault in Námafjall in the Northern Volcanic Zone*

12.2.2 Transform fault zones

The direction of plate spreading in transform fault zones is parallel or close to parallel to the overall orientation of the zone. Strike-slip faulting is dominant and volcanism insignificant.

The active transform zones are:
The South Iceland Seismic Zone
The Húsavík-Flatey Fault Zone

The two transform fault zones exhibit different behavior. The main faults in the South Iceland Seismic Zone belong to a system of bookshelf faults, N-S striking strike-slip faults which lie near-perpendicular to the E-W oriented transform fault zone. The Húsavík- Flatey fault zone is oriented WNW-ESE and is more mature than the South Iceland Seismic Zone. The Húsavík-Flatey Fault Zone is part of the Tjörnes Fracture Zone.

12.2.3 Oblique rifts

The oblique rifts share many characteristics with the volcanic zones. The main difference is that they are aligned highly oblique to the direction of spreading. The oblique opening of the rift zone is accommodated by en-echelon normal faulting and strike-slip faulting, where the strike-slip faults are oriented transverse to the zone.

The oblique rift zones are:
The Reykjanes Oblique Rift
The Grímsey Oblique Rift

Like the Húsavík-Flatey Fault zone, the Grímsey Oblique Rift is a part of the Tjörnes Fracture Zone.

Figure 3. *In the foreground is the Kambar hyaloclastite ridge in the Eastern Volcanic Zone. Lake Þórisvatn in the center of the image*

12.3 Icelandic fault dataset

As described in the previous sections we define several subzones within the plate boundary. Out of ten subzones within the plate boundary eight are active, and were named in earlier sections, and two are inactive. These are the Snæfellsnes Volcanic Zone and the Borgarfjörður Zone.

Most faults submitted by ISOR are located within the plate boundaries. Areas outside the boundaries have not been mapped as extensively and surface features have been eroded by glaciers and weathering. The faults are from the institute's 1:600,000 catalogue (Hjartarson and Sæmundsson, 2014). Faults have been mapped either in the field or by examining aerial photographs. The catalogue is the result of decades of work, mainly done by geologists Haukur Jóhannesson and Kristján Sæmundsson at ÍSOR and its forerunner, the Research and Development department of the National Energy Authority.

Additionally we submit offshore data which has been mapped within the EMODnet project using primarily seafloor bathymetry (Hjartarson and Erlendsson, 2018).

The main type of structural elements in Iceland are normal and strike- slip faults. The normal faults are mainly found in the volcanic zones, accommodating the main rift extension in association with volcanic systems. The strike-slip faults are mainly found in the transform zones and the largest magnitude events in recent history have taken place along these strike-slip faults. Fissures and volcanic crater rows are also included in our database. The fissures and crater rows tend to have a near-parallel alignment as the normal faults and are usually connected to the volcanic systems. Figure 5 and 6 show the faults and fissures in the Icelandic dataset.

Figure 4. *Volcanic fissures in Krafla in the Northern Volcanic Zone*

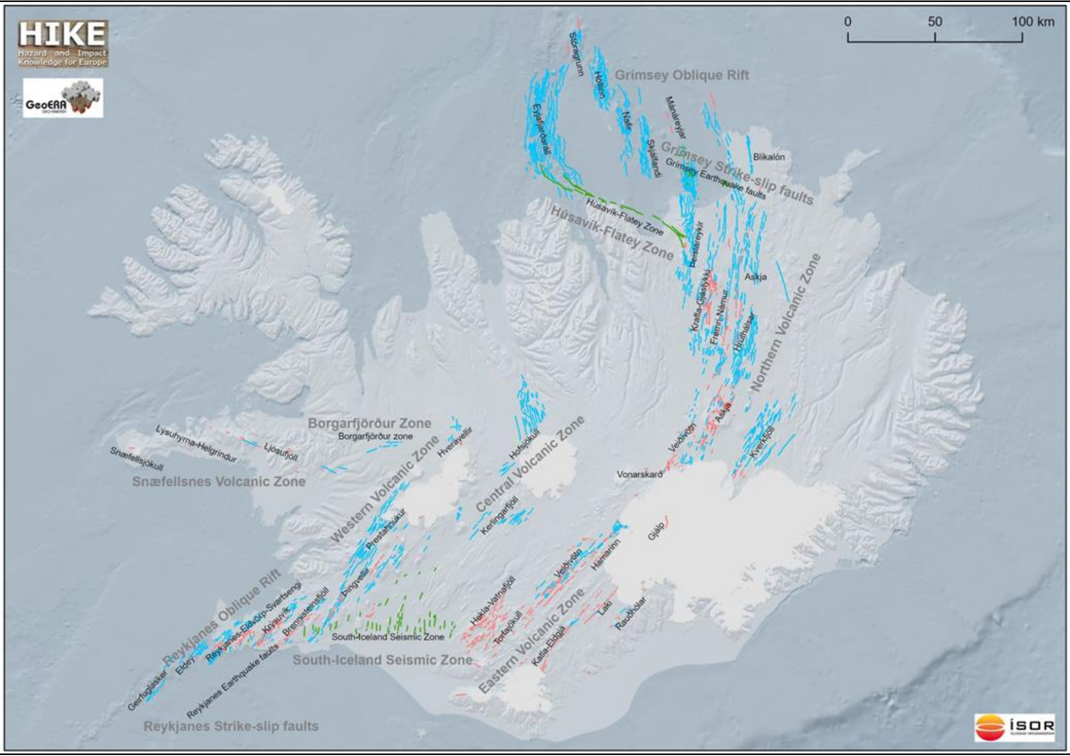

Figure 5. Map of fault and fissure sets of the Icelandic dataset. Normal faults are coloured in blue, fissures in red, and strike-slip faults in green.

12.4 Iceland subcategories

This map shows the location of the defined subzones in Iceland. Each subzone contains sets of faults and/or fissures which in the cases of the volcanic zones belong to volcanic systems. The fault and fissure sets of each volcanic system is coloured with the same colour.

We give all faults and all fissures within the same volcanis system the same strike in the fault attributes table. The given strike is the average strike of the subset. This is not strictly true for all volcanic systems and should be rectified in future projects.

The South Iceland Seismic Zone differs from the volcanic zones. The faults in this zone are N-S striking strike-slip faults which have been formed in earthquakes. A closer look at the faults in the SISZ reveals a series of en-echelon fractures with right-lateral movement arranged in a N-S trending system (Einarsson, 1991).

The age of the faults and fissures is hard to determine precisely, but we conclude that all faults in the ÍSOR database that are placed within the active plate boundary are from Holocene.

One fault in our data set stands out. This is the Kerlingarfault, which is located in the northeast of Iceland, along the edge of the Northern Volcanic Zone and the Tertiary Eastern Fjords Block (Hjartardóttir et al., 2010). This is a Holocene normal fault which likely formed as a result of stress changes during the last deglaciation, although other explanations have not been excluded.

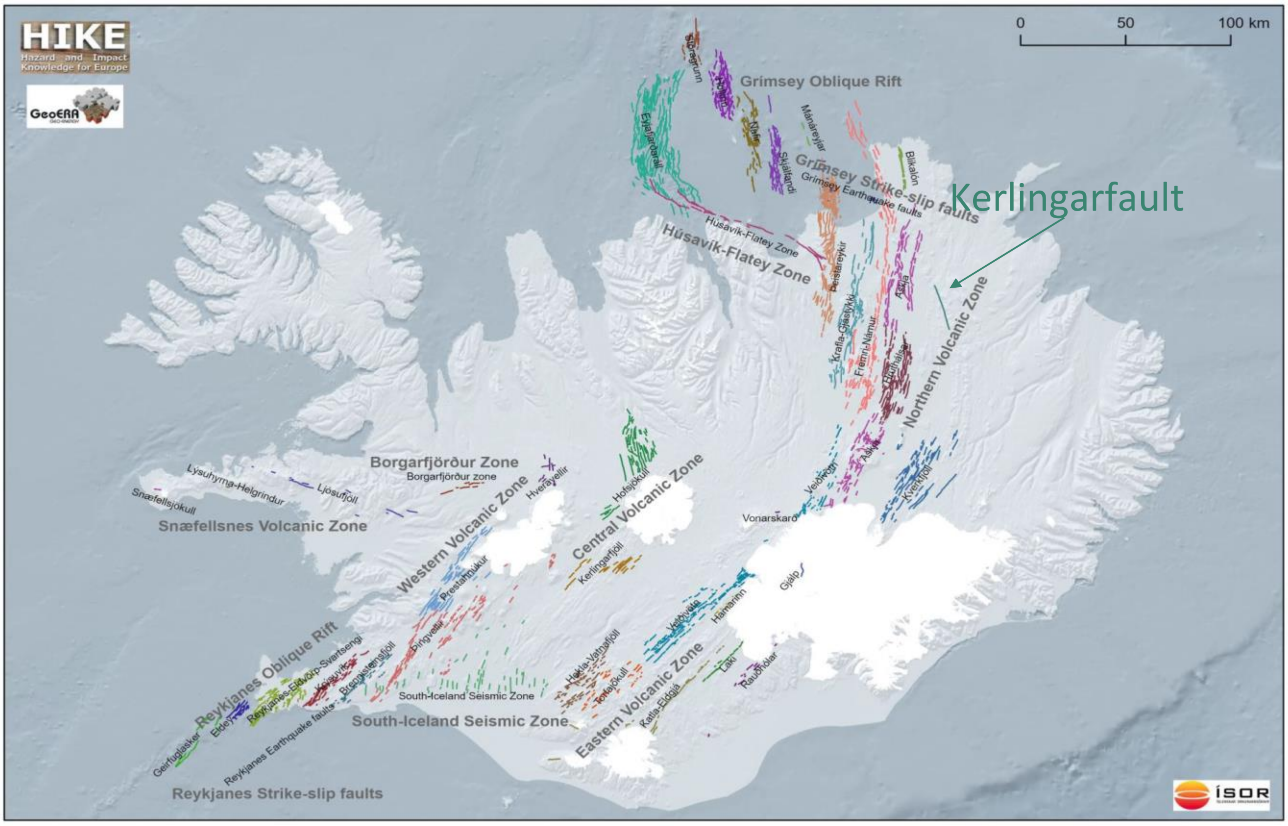

Figure 6. Map of the faults and fissures submitted to the HIKE database by ÍSOR. Fault and fissure sets which belong to a distinct volcanic system are coloured with the same colour.

12.5 Seismic activity

Seismicity in Iceland is largely confined to the plate boundaries. The majority takes place in the oblique rift zones and transform zones with less activity in the volcanic zones. Occasional intense seismic periods are associated with volcanic eruptions. The seismicity occurs on pre- existing faults which are re-activated when the built-up stress exceeds the strength of the rock.

Most of the seismicity in Iceland is natural seismicity due to the spreading of the plates. Recorded examples of induced seismicity are all related to the exploitation of geothermal systems (Flóvenz et al., 2015).

The probability of damage or injury due to an earthquake in Iceland is very low. Building codes are strict, population density is low, and the possible earthquake magnitude is limited to around 7. Despite this it is important to account for seismic risk when planning exploitation of natural resources. In Iceland, the biggest natural resources are hydrothermal and geothermal power which has been harnessed with great success. With rising energy demand and increase in population care must be taken to evaluate the hazard properly and the fault database is valuable for that process.

A new method for the sequestration of CO2 has been developed in Iceland within the Carbfix project (www.carbfix.com). The highly successful method pumps CO2 into the subsurface where it is turned into stone. It is likely that this method will gain more ground in the future. A reliable fault database is crucial both for finding suitable faults to pump the fluid into and to estimate hazard due to the injection.

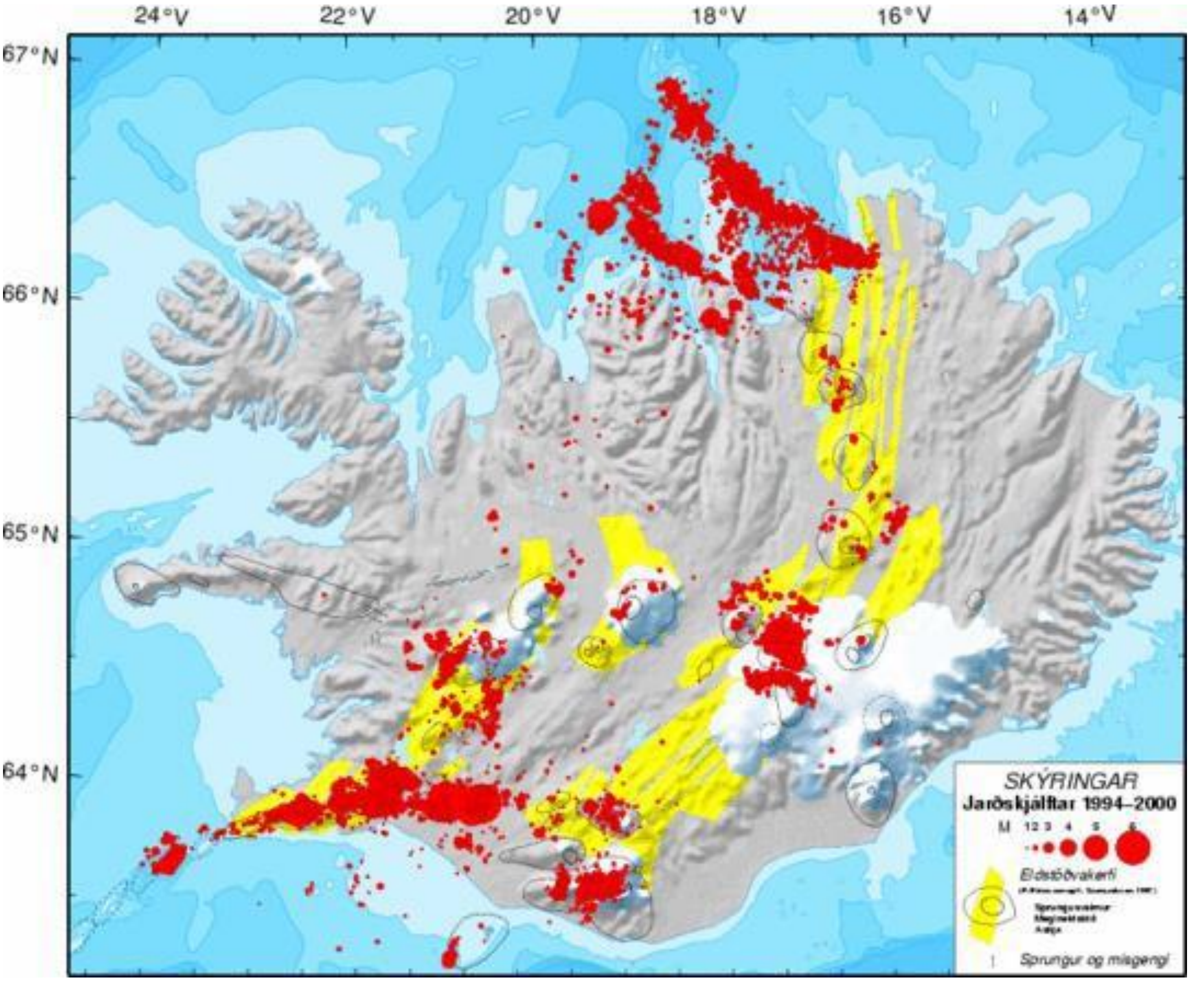

Figure 7. *Seismicity in Iceland from 1994 to 2000. Red circles are earthquakes and the size of the circle is relative to magnitude. Volcanic systems are shown by yellow areas. The seismic activity is confined to the plate boundaries. Image from vedur.is, Gunnar B. Guðmundsson (2001).*

12.6 Future work

The dataset that we submit to the HIKE fault database is limited to ISOR's 1:600.000 catalogue. Several areas in Iceland have been mapped in greater detail and those datasets are preserved in ISOR's database. Those datasets are mainly from geothermal areas all over the country and have been gathered as a part of preparations for geothermal exploitation. Other institutes in Iceland, e.g. the University of Iceland and the Icelandic Institute of Natural History, possess additional fault datasets. All these datasets would be a valuable contribution to the European fault database created within HIKE.

Considerable work needs to be done to harmonize the various fault data sets that exist in Iceland. The definition of the plate boundaries has been under reconsideration in the last years, but some discrepancies still exist in the literature. Sigmundsson et al. (2018) and Sæmundsson et al. (2020) show a very similar definition of plate boundaries but the naming conventions are inconsistent. The figure to the right is taken from Sigmundsson et al. (2018). The general picture is the same as ours, with the distinction of the oblique rift and volcanic rifts being categorized as two subcategories of volcanic rift zones. Additionally, three volcanic flank zones are described which traditionally have not been included in the work at ÍSOR.

Furthermore, more detailed analysis needs to be done on the individual volcanic systems. We assigned an average strike to all faults and fissures within a single volcanic system, but there are clear examples where this is not applicable (see figures 9-10 on p. 11).

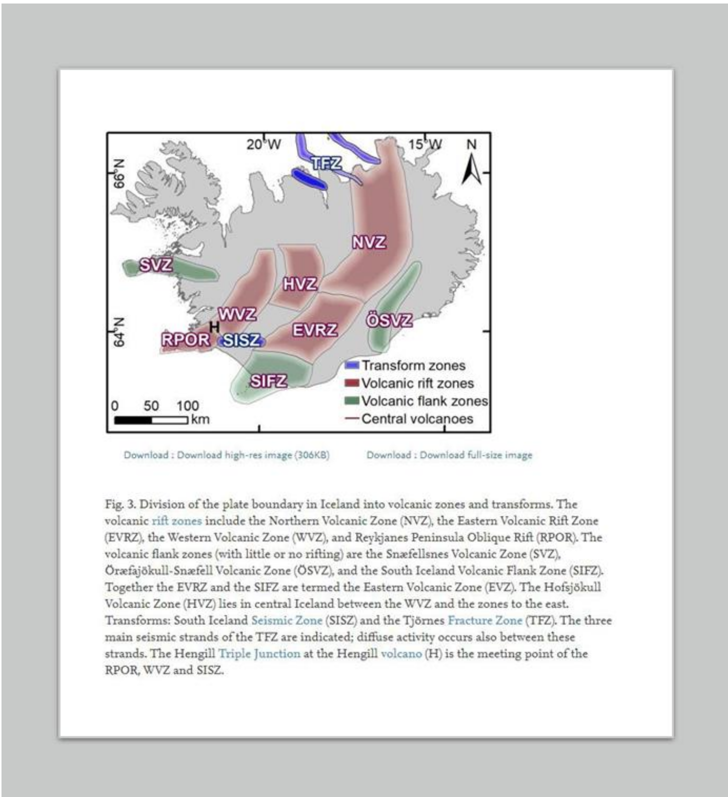

Figure 8. *Map from Sigmundsson et al. (2018) of the plate boundaries in Iceland as they are defined in their paper.*

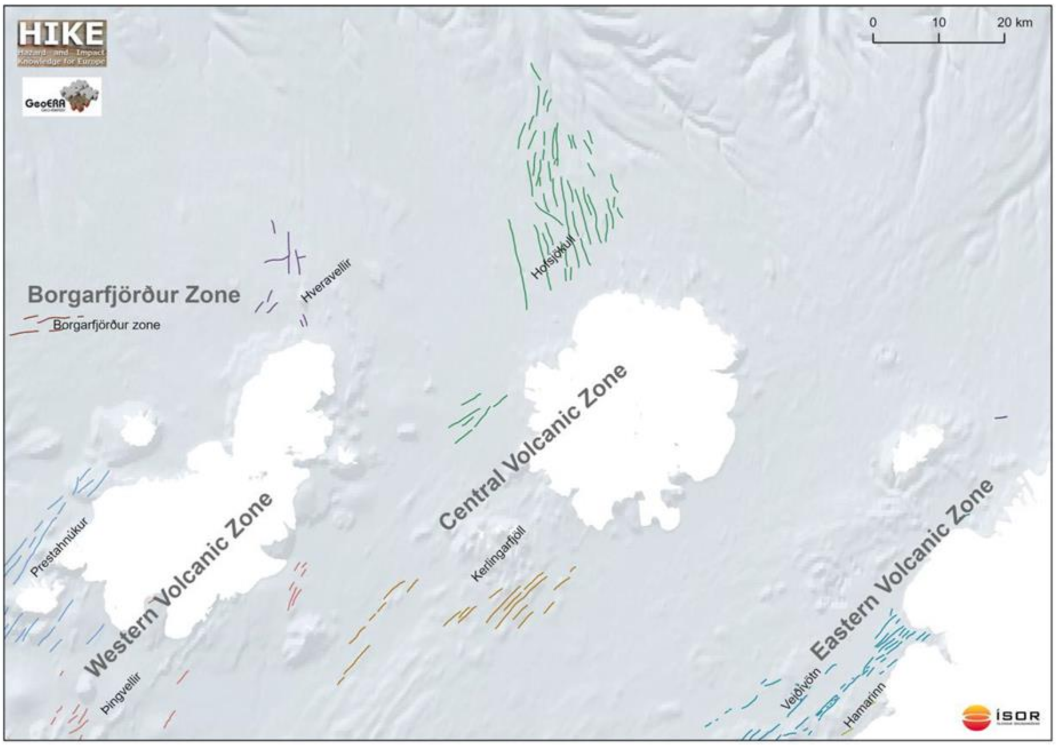

Figure 9. Close up view of the Central Volcanic Zone. Faults and fissures in this system are coloured green. The different strike of the faults in the Hofsjökull volcanic system are evident. This should be addressed in future projects.

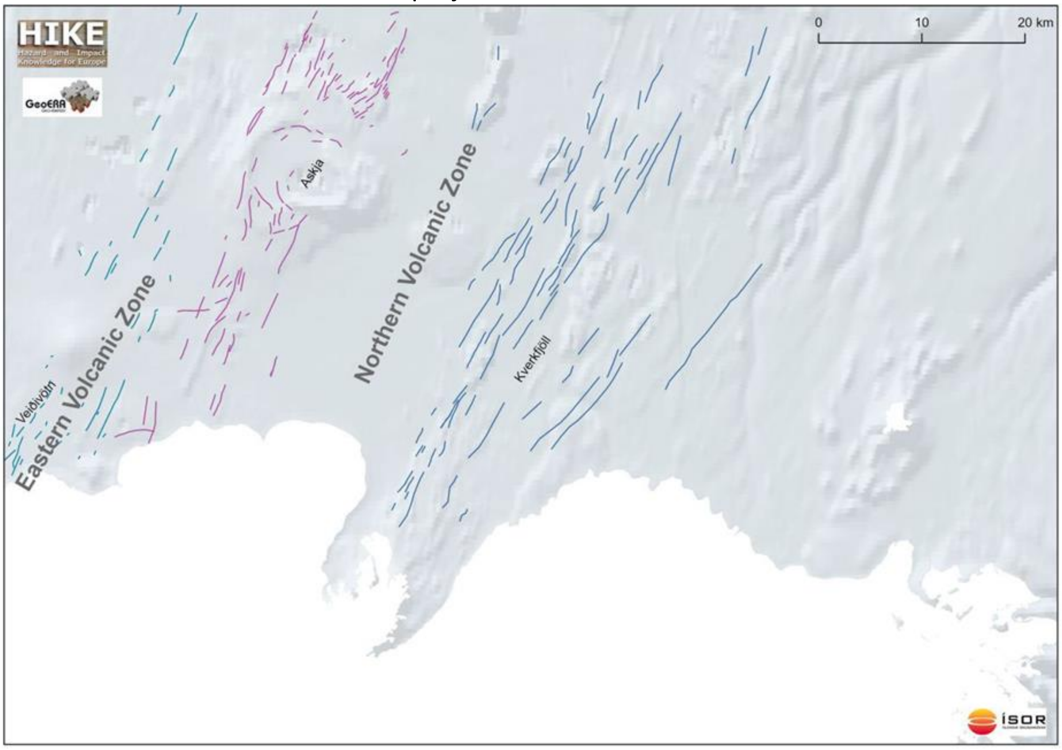

Figure 10. Close up view of the Askja and Kverkfjöll volcanic systems north of Vatnajökull. Faults and fissures in these system are coloured purple and dark blue. The variability in strike within the Askja system is obvious and should be addressed in future projects.

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13 ISPRA – ITALY

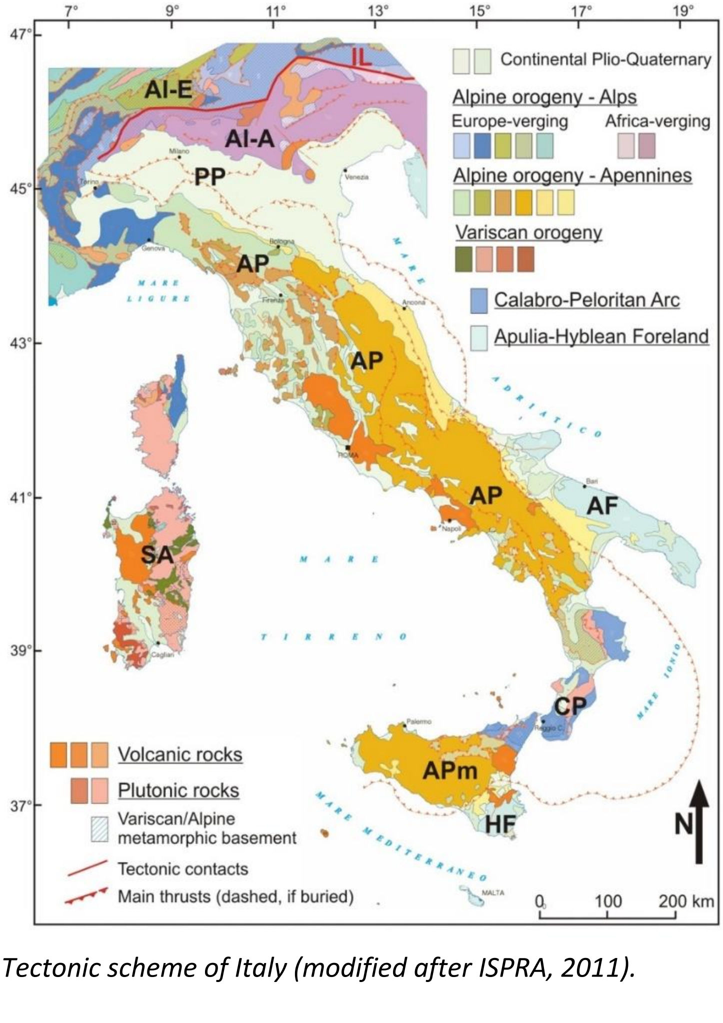
13.1 Introduction - Regional Geological Setting

The complex pattern of faults that characterize the surface and subsurface of the Italian territory is the result of a long series of geological events: i) the evolution of the passive margin of the Gondwana continent (Precambrian–Ordovician); ii) the opening and closure of the Rheic ocean (Ordovician–Devonian); iii) the Variscan (or Hercynian) orogeny and the following creation of Pangea (Carboniferous–Triassic); iv) the opening of the Tethys ocean and its closure due to Alpine orogeny, that generated both the Alps (Jurassic–Oligocene) and the Apennines - Maghrebides chains (Upper Oligocene-Present); v) the opening of the Liguro-Provençal and Corsica basins (Lower Miocene); and vi) the opening of the Tyrrhenian basin (Late Miocene).

These events drove and controlled the overall tectonic framework of Italy; on this basis, the Italian territory can be subdivided, from north to south into the following tectonic regions, with a common history characterized by more than one tectonic event: the Alps, the Po Plain, the Apennines, the Apulia and Hyblean foreland, the Calabrian-Peloritan arc, and the Sardinia. Sardinia (SA), in the western Tyrrhenian Sea, has preserved the oldest rocks outcropping in Italy, Precambrian-Carboniferous in age, and faults related to the pre-Variscan orogenic history (**Sardinia Variscan basement Domain**). Normal faults affected the Sardinia Variscan basement, starting from the Oligocene up to Miocene, as a result of the extensional regime that acted on the Iberian-Europe region (**Sardinia Graben and Campidano system Domains**). In the other parts of Italy, the Variscan orogeny has been overprinted by the Alpine orogeny. The Italian portion of the Alps mountain chain extends from the Gulf of Genova, in the west, to the boundary with Austria and Slovenia, in the east. It can be subdivided into two belts, according to the sense of tectonic transport toward the foreland: a Europe-vergent belt (Al-E) and an Africa-vergent belt (Al-A), named the Southern Alps (Dal Piaz 2010). The Europe-vergent belt includes units deriving both from European and African continental crusts and Tethyan ocean domain, displaced towards the Molasse foredeep and European foreland. The Europe-vergent portion of the Alps is subdivided into the following tectonic domains: **Helvetic, Penninic, Austroalpine**.

The Africa-vergent belt consists of **Southalpine Domain**, constituted by units of non-metamorphic, ophiolite-free, African continental crust, developed inside the Alpine hinterland. The two belts are juxtaposed along with the **Insubric** (or Periadriatic) **Fault System** (IL). Normal faults pertaining to the (Africa) **Adriatic plate passive continental margin Domain** are still preserved at depth under a pile of clastic sediments in the Po Plain area (PP).
The **Po Plain-Adriatic foreland basin Domain** (PP), developed between the Alps and the Apennines, represents the common foreland of these oppositely verging fold-and-thrust belts. The external fronts of the Southern Alps, to the north, and Northern Apennines, to the south, are buried and/or blind below more than 7,000 m thick pile of Plio-Quaternary marine-to-continental sediments (Fantoni and Franciosi 2010).
The Apennines geographically extend the length of the Italian peninsula, from north to south (AP/APm); this belt is the result of the convergence between the Alpine orogen and the continental crust of the Africa plate (Adria promontory or Adria microplate). The deformations of the Apennines are superimposed on previous compressional events, responsible for the formation of the Alps during the Late Oligocene-Early Miocene counter-clockwise rotation of the

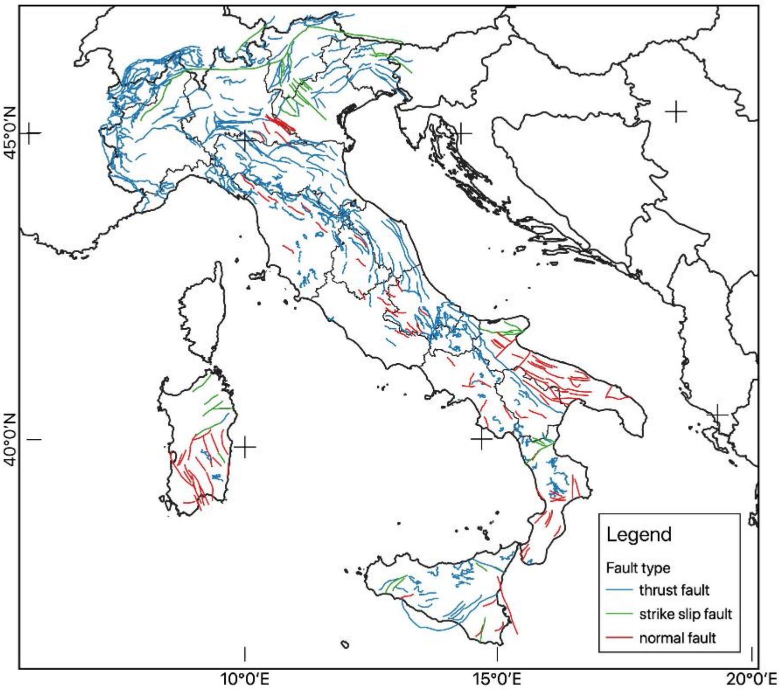
Corsica-Sardinia block. The Apennines also include units of African continental crust derived from the Mesozoic Tethys ocean (**Ligurian Domain**). In the Apennines since the Miocene the eastward migration of compression (i.e. **Northern Apennines, Southern Apennines, Sicilian-Maghrebides Domains**) has been followed and coupled by the activity and migration of a co-axial extension (in the hinterland), due to the counter-clockwise rotation of the Corsica-Sardinia block, the opening of Tyrrhenian Sea, the foreland flexural process, and the fast overall uplift of the Apennines chain (**Apennines extensional Domain**). The extension has been accompanied and post-dated by magmatic activity.
Toward the south, the Apennines chain is separated by its still poorly deformed foreland (**Apulia foreland**-AF and **Hyblean foreland –** HF **Domains**) by the **Bradanic Trough** and **Catania-Gela foredeep Domains**. Finally, the **Calabride-Peloritan arc Domain** (CP), interpreted as a fragment of the Alpine chain migrated toward the SE and overlay the Apennines-Maghrebides belt, where some sectors preserve nearly entire segments of Variscan continental crust, unaffected by Alpine metamorphism.



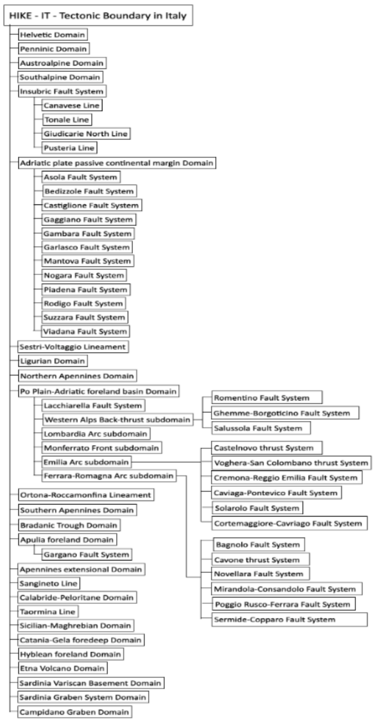
Tectonic scheme of Italy (modified after ISPRA, 2011).

13.2 Database structure and semantic vocabulary concepts

The faults collected in the database are organized according to a hierarchical scheme based on concepts. The top concept is the Tectonic Domain - a region with a typical fault pattern and arrangement of geological units related to well-defined geological history/evolution. In some cases, Tectonic Domains are divided in sub-domains. Subordinate concepts are Fault System and Lineament. According to the pan-EU view of the HIKE project, a large effort has been done to simplify the Italian structural setting, grouping the faults in 20 main Tectonic Domains, 5 Subdomains, 30 Fault Systems and 8 major Lineaments.



Map of the Italian fault database showing the distribution of the faults with a length ≥20 km; thrust faults, strike slip faults and normal faults are represented only



Semantic vocabulary scheme

13.3 Tectonic boundaries

The Europe-vergent portion of the Alps belt includes three major tectonic domains characterized by ductile deformations and thrusts bounding nappes and tectonic windows, affecting units deriving both from European and African continental crusts and Tethyan ocean domain. The overall tectonic transport is towards the Molasse foredeep and European foreland (Dal Piaz et al., 2003). The boundary with the Africa-vergent portion of the belt, namely Southern Alps, corresponds with the Insubric Fault System.

13.3.1 Helvetic Domain

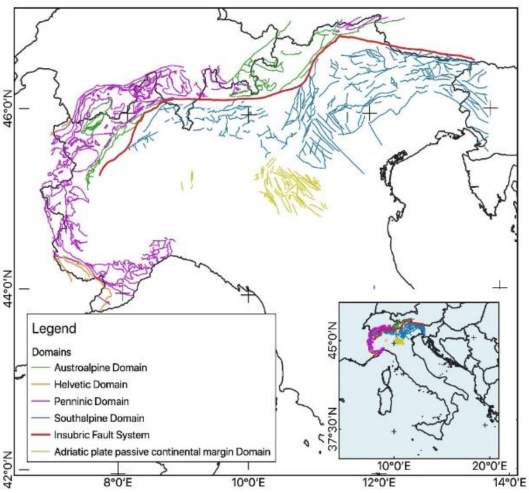
The Helvetic domain, part of the Alpine chain, is characterized by Europe-vergent (N and NW) nappes derived from the proximal part of the European continental margin, imbricated from the Oligocene onwards. The faults pertaining to this domain crop out limited to the border with France.

13.3.2 Penninic Domain

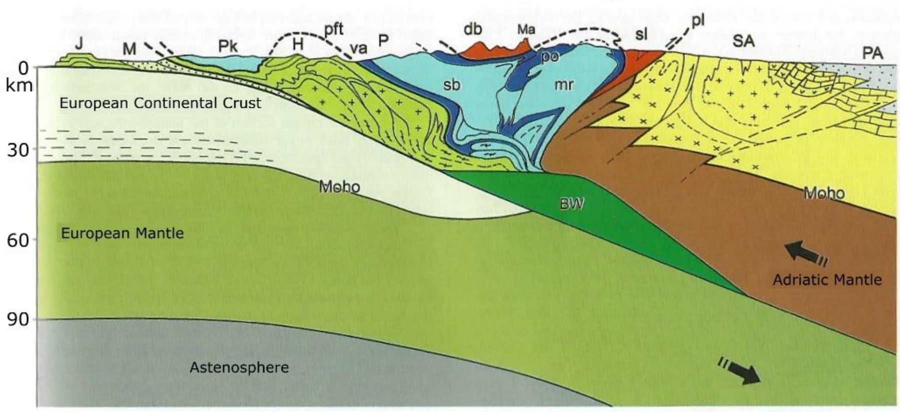
The Penninic domain, part of the Alpine chain, groups the continental and oceanic nappes which issued from the distal European continental margin and Mesozoic ocean, characterized by ductile deformations and Europe-vergent thrust faults, bounding the tectonic windows or separating units, mainly stacked during Paleogene. The domain is marked by a severe Alpine metamorphic overprint with the exception of pre-Alpine klippen. The faults of this domain crop out in the western part of the Alps.

13.3.3 Austroalpine Domain

The Austroalpine domain, descending from the Africa ocean-facing continental margin, overlies the Penninic domain, as part of the Alpine chain. The faults are the boundaries of the main nappes and tectonic windows showing the Penninic domain units. The activity is dated to pre-Late Cretaceous (pre-collisional phase - eoalpine) for the eastern part and to Late Cretaceous-Eocene (collisional - mesoalpine) for the western part. The faults of the Austroalpine domain crop out in the central and western part of the Alps, mainly at the border with Switzerland and Austria.



Map of the Italian fault database showing the main structural domains identified in the Alpine area.



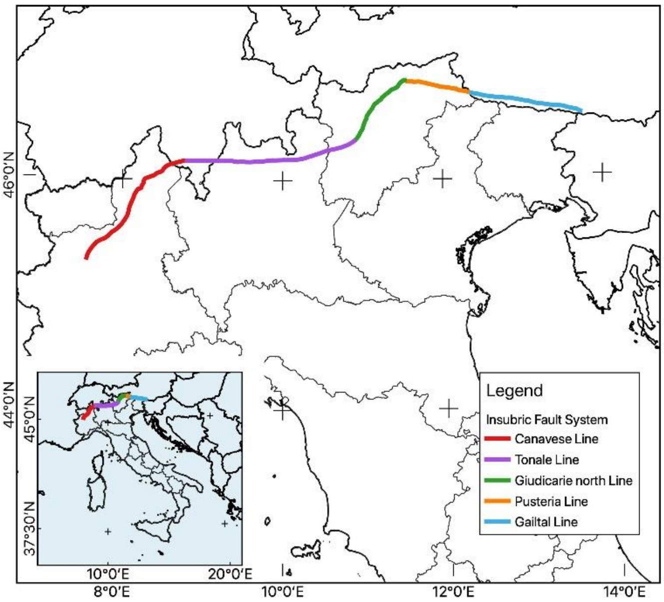
Lithospheric section of the north-western Alps - Austroalpine: Sesia-Lanzo (sl), Dent Blanche nappe (db), Matterhorn (Ma); Penninic domain (P): Piedmont ophiolitic units (po), Monte Rosa (mr) and Gran S. Bernardo (sb) nappes, Valais zone (va), P klippen (Pk), P frontal thrust (ptf); Helvetic domain (H); Molasse foredeep (M); Jura belt (J); buried wedge of European mantle (BW) (modified after Dal Piaz et al., 2003).

13.3.4 Insubric Fault System

This fault system demarcates the boundary between Africa and Europe plates. It is the original suture, potentially dating back to the Hercynian orogeny, which separates the S-verging Southalpine from the N-verging Penninic and Austroalpine domains (Schmid et al., 1987). It is constituted, from west to east, by the SW-NE Canavese Line and the W-E Tonale Line, with important dextral strike-slip movements (60-100 km along the Tonale Fault) (Schmid et al., 1987, Biino and Compagnoni, 1989, Guillaume, 1978), the SW-NE Giudicarie North Line, a transfer zone acting first with a sinistral strike-slip displacement of some tens kilometers, then inverted as thrust with a western domain overthrusting the eastern one (Castellarin et al., 2006; Prosser, 2000), and the NNW-SSE Pusteria (Frisch et al., 2000) and Gailtal Lines, with transpressive dextral kinematic. The Insubric Fault System is part of the regional Periadriatic Large Scale Fault System.

13.3.5 Southalpine Domain

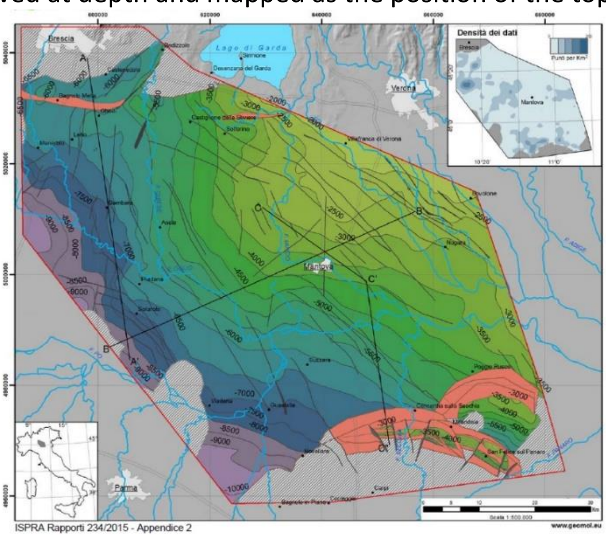
The Southalpine domain, as part of the Alpine chain, is characterized by large scale thrusting and folding, mainly E-W and NE-SW trending, with dominant vergence toward the south. Besides, extensional faults, antithetic and synthetic mainly NW-SE trending, related to Upper Triassic-Middle Jurassic rifting are preserved within large inverted compressional structures. Some areas still preserve the record of Variscan/Hercynian deformations with limited metamorphic overprint. The compressional activity (post-collisional - neoalpine) started during the Tertiary (Oligocene) and progressively propagated towards the foreland; in the western sector evidence of Cretaceous compressional phases are known (Castellarin & Transalp Working Group, 2004). The northern boundary of this domain is represented by the Insubric Fault System.



Map of the Italian fault database showing the Insubric Fault System segmentation; this lineament represents the western termination of the Periadriatic – Mid –Hungarian Large Scale Fault System as identified in HIKE.

13.3.6 Adriatic plate passive continental margin domain

The Adriatic plate passive continental margin domain is characterized by faults related to the rifting phase affecting the Adriatic plate margin during Late Triassic and from Early Jurassic to Early Cretaceous (Masetti et al, 2012). They are normal faults, mainly NNW-SSE and N-S oriented, steeply W- and E-dipping. Minor W-E and NE-SW faults are present. Based on their orientation and relationship, the faults of this domain are further subdivided in fault systems. The occurrence of these faults is based on seismic interpretation and derived 3D geological models realized in the frame of GeoMol Project and GeoERA – HotLimeProject. All the faults in this domain are observed at depth and mapped as the position of the top of the fault.



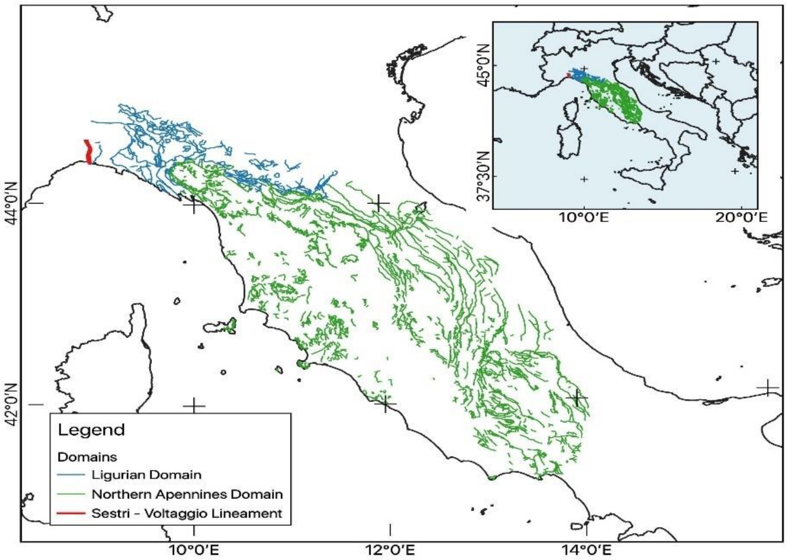
Depth map of the Lower Jurassic horizon and position of normal faults (black lines), red polygons represent the thrust fault planes in map view (GeoMol Project; D'Ambrogi et al, 2015).

13.3.7 Sestri-Voltaggio Lineament

The Sestri-Voltaggio lineament is a N-S lineament acting as the boundary between Alps and Apennines chains with opposite vergence, it was active, as transform fault (Scholle, 1970), during the eo- and meso-alpine tectonic phases.

13.3.8 Ligurian Domain

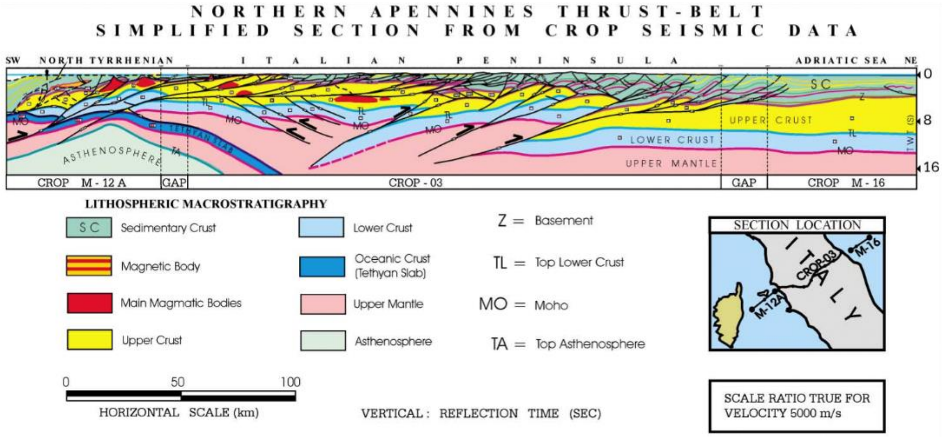
The Ligurian domain is characterized by thrusts active during the collisional mesoalpine underthrusting and underplating (Late Cretaceous-Middle Eocene); furtherly active during post-collisional neoalpine eastward overthrusting (Oligocene-early Pliocene or Pleistocene - Sillaro e Marecchia) (Barchi et al., 2001; Cerrina Feroni et al., 2004). Both ductile and fragile deformations are recorded. Due to the final phase of the deformation, the overall regional vergence of the Ligurian thrusts is toward NE, both for high-angle thrusts and low-angle overthrusts.



Map of the Italian fault database showing the Ligurian and Northern Apennines Domains; in red is marked the Sestri-Voltaggio Lineament separating Alps from Apennines.

13.3.9 Northern Apennines Domain

The Northern Apennines domain is characterized by thrust fault imbricated structures, mainly E-vergent, related to the Apenninic orogenic phase (post-collisional - neoalpine) active from Chattian (Cerrina Feroni et al., 2004). Several decollement low-competence levels are recognized (the deeper at the top of the Triassic Anidriti di Burano, the shallower located on Lower Jurassic Rosso Ammonitico, Lower Cretaceous Marne a Fucoidi, Eocene-Lower Miocene Scaglia cinerea or Messinian Evaporites) (Barchi et al., 2001). Back-thrusts are associated with the main structures. The boundary between Northern and Southern Apennines domains is the Ortona-Roccamonfina lineament.

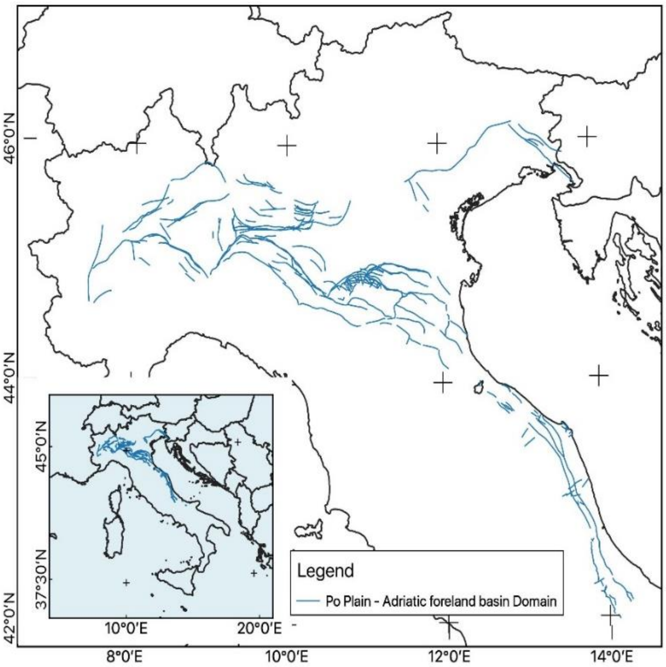


Simplified version of Geological Cross-Section along the interpreted seismic sections CROP M-12A/CROP-03/M-16 (Finetti et al., 2001).

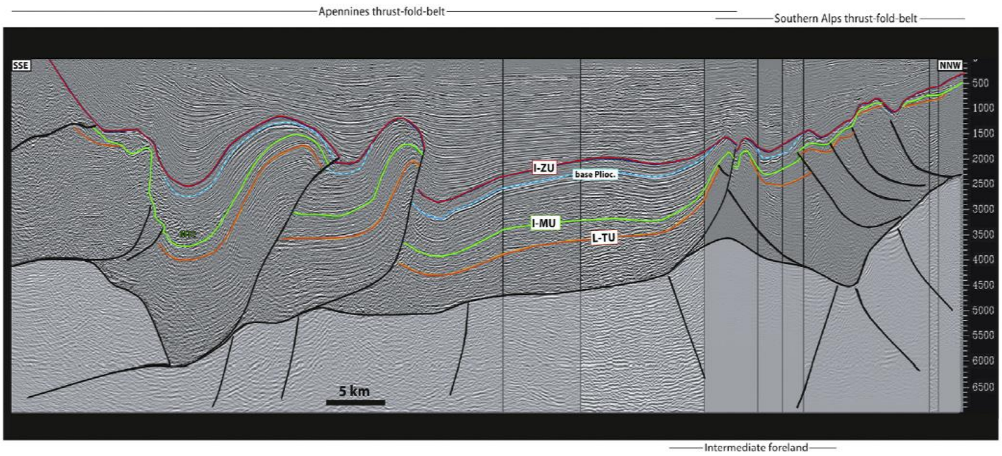
13.3.10 Po Plain - Adriatic foreland basin Domain

The Po Plain-Adriatic foreland basin domain is characterized by buried and/or blind thrusts solely evidenced by seismic surveys and deep drillings. It represented the common foreland basin of both Alps (retroforeland) and Northern Apennines fold-and-thrust belts; for this reason, the thrusts are N-dipping S-vergent and S- to SW-dipping N- to NE-vergent, respectively those of the retro-belt of the Alps (Southern Alps) and the Apennines front.

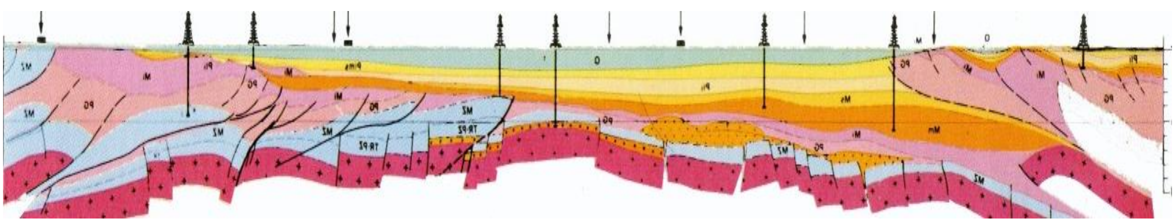
Their activity ranges from Chattian to present. The main thrust fronts are characterized by an arched shape with the following trend, moving from west to east and south-east: mainly E-W (Western and Southern Alps, Monferrato Front and Emilia arc), SE-NW (Ferrara-Romagna arc) and SSE-NNW the Adriatic thrusts (Rossi et al., 2015). Some minor isolated thrusts NE-vergent are also recognized. The faults of this domain, for the Po Plain region, are further subdivided in subdomains and fault systems. The occurrence of these faults, in the Po Plain region, is based on seismic interpretation and derived 3D geological models realized in the frame of GeoMol Project and GeoERA – HotLimeProject. All the faults in this domain are observed at depth and mapped as the position of the top of the fault.



Map of the Italian fault database showing the Po Plain- Adriatic basin Domain.



Regional seismic profile from the Northern Apennines to the Southern Alps. Gray shade: pre-collision Permian-Eocene succession; L-TU: latest Tortonian unconformity; I-MU: intra-Messinian unconformity; I-ZU: intra-Zanclean unconformity (after Rossi et al., 2015).



N-S oriented geological cross-section (Cassano et al., 1986) showing the complex structural framework of Po Plain – Adriatic foreland basin domain and the superimposition on the normal faults of Adriatic plate passive continental margin domain. On the left: Southern Alps S-vergent thrusts, on the right: Northern Apennines N-vergent thrusts.

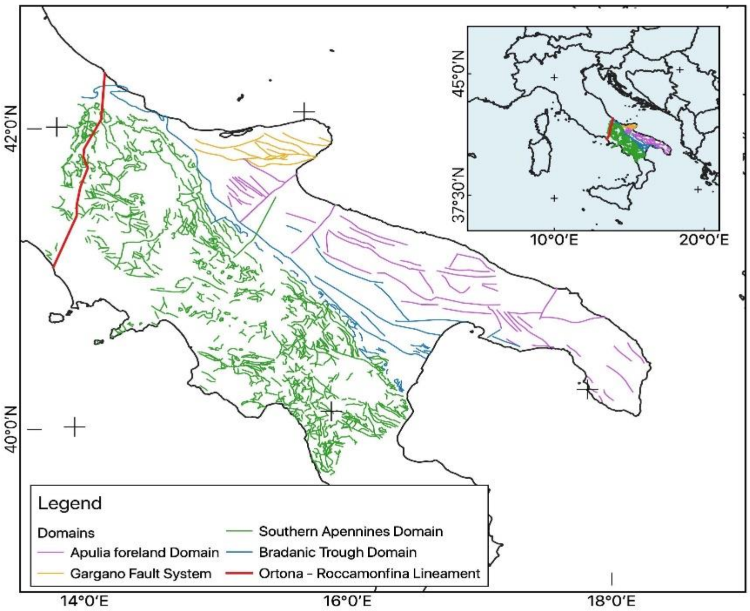
13.3.11 Ortona-Roccamonfina Lineament

The Ortona-Roccamonfina (or Sangro-Volturno) lineament is considered the tectonic separation between the northern Apennines and Southern Apennines (Patacca & Scandone, 2007 and references therein).

The Ortona-Roccamonfina transversal structure can be interpreted as a crustal oblique thrust ramp, trending NNE-SSW, with right-lateral transpressive kinematic involving the Apulian carbonate platform and the slope-to-basin paleodomains. Thrusts and related folds of the Ortona-Roccamonfina oblique ramp also involve the basal thrust and the left-lateral oblique ramp of the Molise Allocthonous Units (Satolli et al., 2014).

13.3.12 Southern Apennines Domain

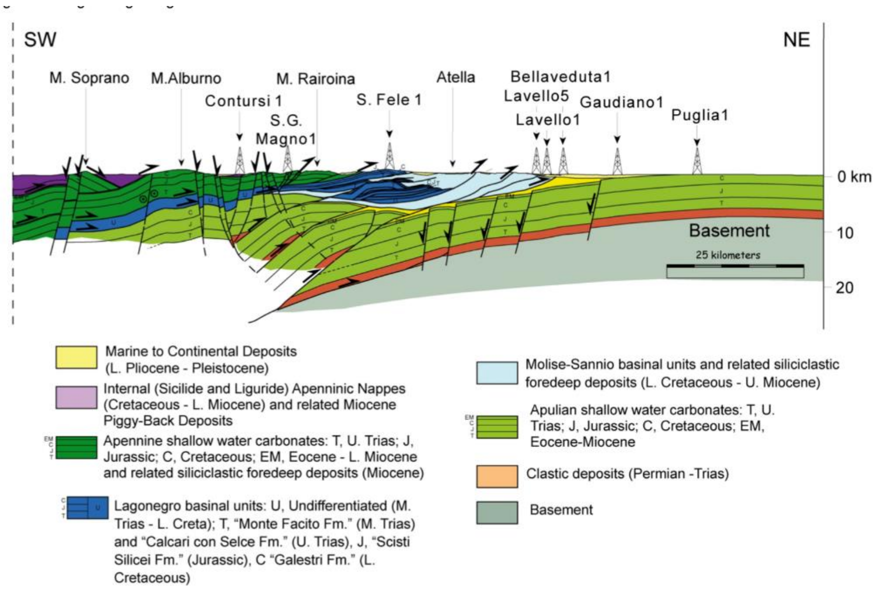
The Southern Apennines Domain developed through the deformation of the thinned oceanic-transitional to continental crust of the Liguria-Piedmont Ocean and the Africa continental passive margin, starting in the Late Cretaceous. The accretion of the fold-and-thrust belt is strictly linked to the continental collision and post-collisional activity, ranging from late Oligocene to early Pleistocene, with eastward migration of the deformation and piling and out-of-sequence thrusting. The Southern Apennine mountain chain is formed by a deep-seated carbonate duplex system tectonically overlain by a thick pile of NE-verging rootless nappes derived from basin and platform domains (Patacca & Scandone, 2007). Each tectonic-sedimentary unit (nappe) is bordered by major thrusts or, more frequently, by a group of thrusts. The internal nappe geometry is complicated by second order of folds and thrusts mainly NE-verging. In addition, some allochthonous units, locally placed up as gravitative flows, constitute the easternmost and more advanced thrust sheets outcropping in the Southern Apennines.This complex NE-verging thrust belt developed during Neogene and Quaternary times along the eastward-retreating west-directed subduction of the Apulo-Adriatic lithosphere (Scrocca, 2010).



Map of the Italian fault database showing the fault distribution for the Southern Apennines Domain, Bradanic Trough Domain, Apulia foreland Domain, and Gargano Fault System; the about NE-SW trending Ortona-Roccamonfina lineament is also reported.

13.3.13 Bradanic Trough Domain

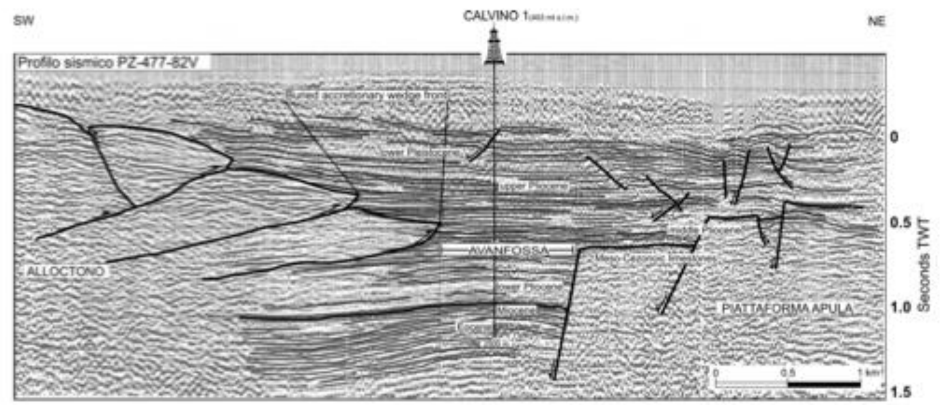
The Bradanic Trough represents the Pliocene-present-day southern Apennines foredeep. It is a NW-SE elongated foreland basin separating the Apennine chain from the Apulia foreland. This flexural depression developed at the front of the Apennine thrust belt and has been filled by Pliocene-Pleistocene deposits. This domain is mainly characterized by the presence of NW-SE trending E-verging thrusts due to the involvement in the Apennines thrust front deformation or to the Apennine blind thrust propagation. At the same time, syn-depositional extensional structures are present as a result of the propagation of the deep extensional tectonic pattern affecting the buried foreland.



Regional geological cross-section built along the CROP-04 seismic reflection profile (Scrocca, 2010).

13.3.14 Apulia foreland Domain

The Apulia foreland domain represents the outcropping portion of the Southern Apennines foreland. This structural domain is characterized by NW-SE striking normal faults linked to the early Middle Pleistocene flexural tectonics and the following Middle-Upper Pleistocene extensional tectonics. These faults affected mainly the foreland buried below the front of the chain and the foredeep deposits. The outcropping Apulia sector (Apulia foreland) exhibits a regional pattern of large-scale deformation which is manifested through a system of NW-SE extensional structures affecting both its smoothly flexure along the contact with the Bradanic foredeep and its eastern sector; locally minor striking NE-SW normal faults are also present.
The northern border of this structural Domain is marked by the E-W trending Mattinata fault and in general by the Gargano Fault System.



Geological interpretation of the migrated seismic profile across Arcieri 1 deep well (Lazzari, 2008). The seismic line shows the relationship between the allochthonous units of the Apennines thrust front and the Apulia Platform, both covered by the terrigenous units of the Bradanic foredeep; the Mesozoic limestones of the Apulia platform are displaced toward SW by the extensional tectonic pattern of the depocentral foredeep basin interesting also the overlapped Miocene-Pliocene deposits.

13.3.15 Gargano Fault System

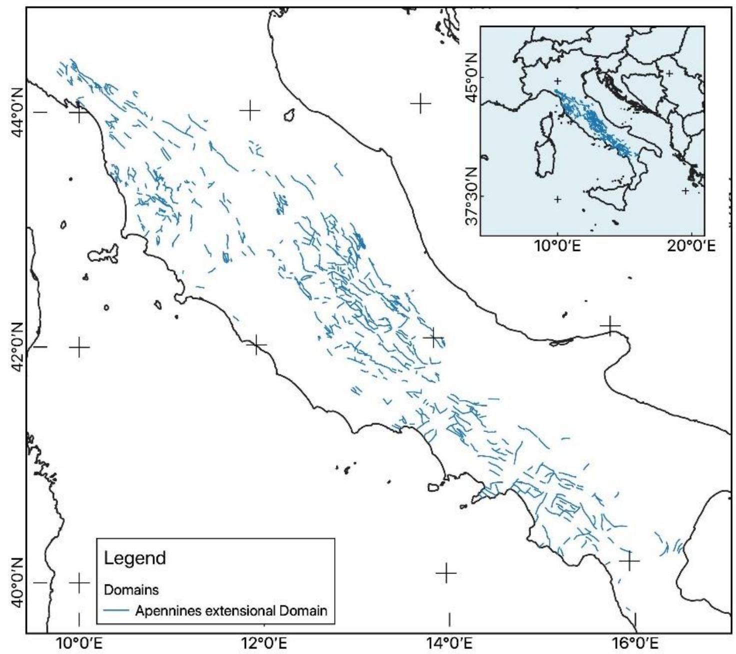
The Gargano Fault System characterizes the Gargano Promontory, which represents the northern portion of the Apulian foreland emerging from the Adriatic Sea. The promontory shows E-W elongated anticline morphology and it is affected by NW-SE and E-W trending main faults and by NE-SW trending minor faults. The major structure is the E-W trending, south-dipping, Mattinata Fault cutting cross the southern border of the Gargano Promontory (Funiciello et al., 1988). Many Authors suggest that the Gargano faults might have experienced different activity and a different sense of motion in different tectonic regimes and they propose multi-phase kinematics (Patacca & Scandone, 2004 and references therein). Major evidence are in favor of a dextral strike-slip kinematics along the Mattinata Fault from Late Pliocene to the present (Piccardi, et al., 2004).

13.3.16 Apennines extensional Domain

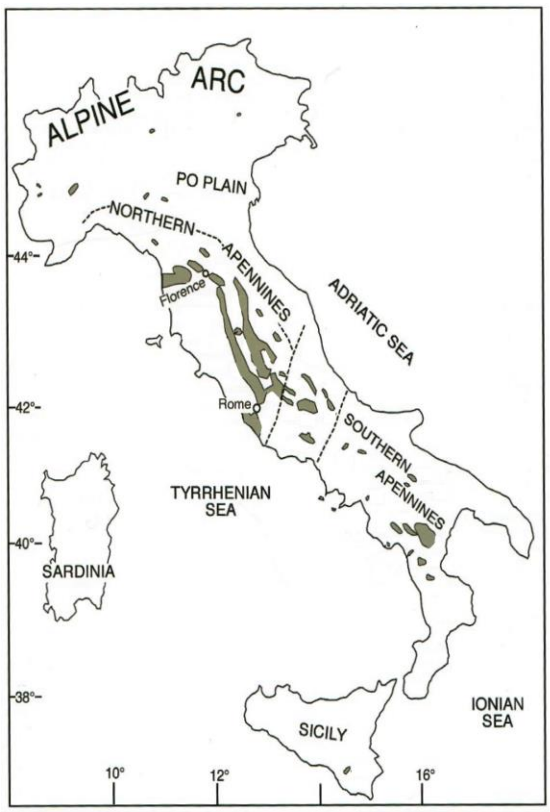
The domain is characterized by normal faults, mainly NW-SE and NNW-SSE oriented, related to the extensional regime active from the Middle-Upper Miocene due to the counter-clockwise rotation of the Corsica-Sardinia block, the opening of Tyrrhenian Sea, the foreland flexural process, and the fast overall uplift of the Apennines chain. The age of inception rejuvenates from west to east superimposing on the compressional phases. In the Northern

Apennines extensional kinematic is associated with minor transtensional, with master faults are often E-dipping with antithetic W-dipping faults; in the Southern Apennines both right- and left-strike-slip faults are observed, related to counter- and clockwise rotation respectively (Peter Martini et al., 2001).

The faults of the Apennines extensional domain mainly controlled the formation of the intramontane basins.



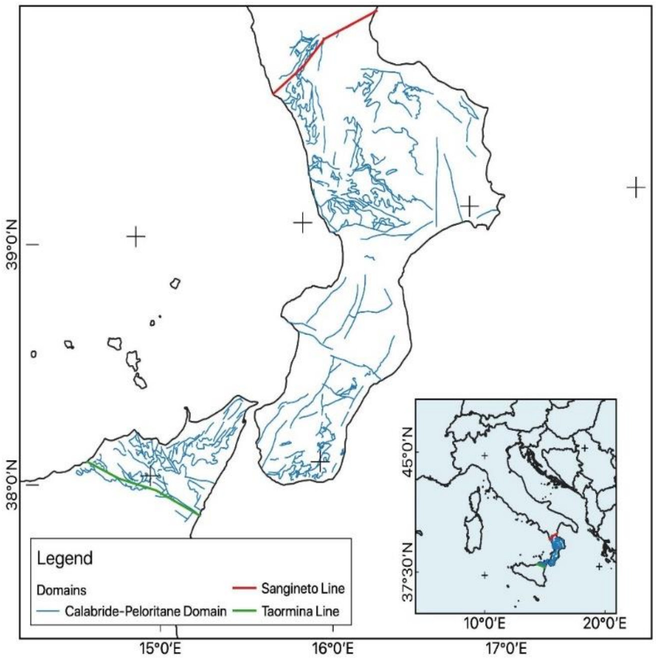
Map of the Italian fault database showing Apennines extensional domain.



Main Italian Quaternary extensional basins (after Bosi, 2004).

13.3.17 Sangineto Line

The Sangineto Line marks the northern border of the Calabride-Peloritane domain. T the Sangineto line seems to be a complex fault system with a left-lateral strike-slip component (Bonardi et al., 2001).



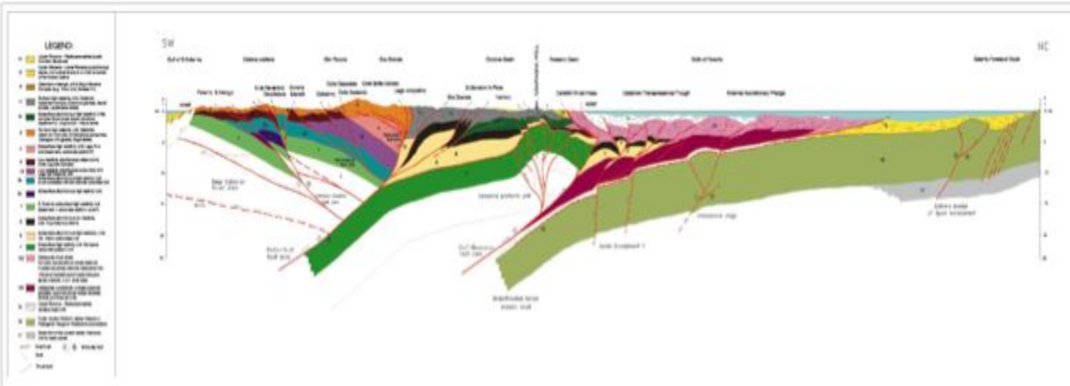
Map of the Italian fault database showing the fault pattern for the Calabride-Peloritane Domain; the Sangineto Line and the Taormina Line mark respectively the northern and the southern border of the Domain.

13.3.18 Calabride-Peloritane Domain

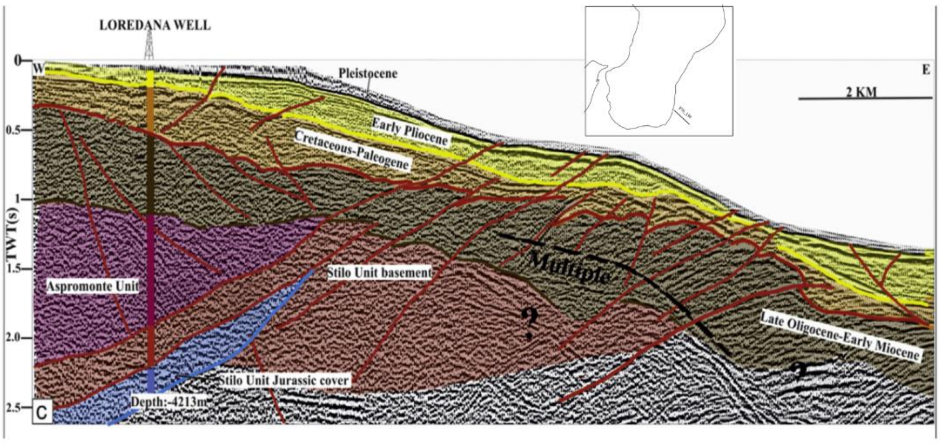
The Calabride-Peloritane domain is a fault-bounded exotic terrane located at the intersection between the NW-SE-trending Southern Apennines and the E-W-trending Sicilian Maghrebides, characterized by i) pre-Mesozoic crystalline basement with ductile deformations (Hercynian Orogeny), ii) Alpine (Apennines) Oligo-Miocene reverse faults (Bonardi et al., 2001) associated with shear zones, and iii) post-orogenic extensional, sub-vertical and sub-parallel N-S, NE-SW, and NW-SE, with minor NNE-SSW and E-W, normal faults (upper Miocene and upper Pleistocene-Holocene). At its N and S margins, the Calabride-Peloritane domain is bounded by the Sangineto and Taormina lines.

13.3.19 Taormina Line

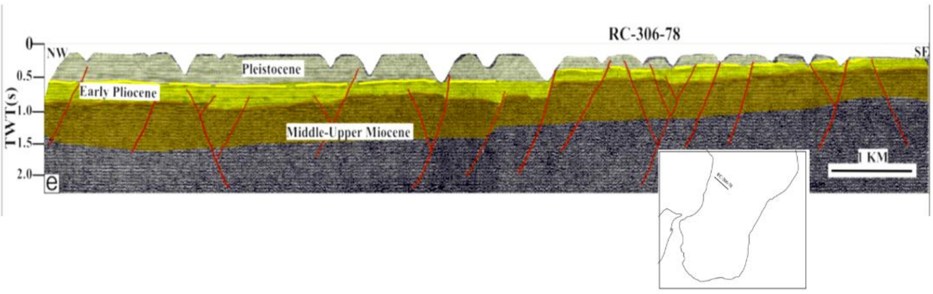
The Taormina Line identifies the southern border of the Calabride-Peloritane domain. This Tectonic Line is interpreted to be a NNE dipping thrust fault (Bonardi et al., 2001).



Structural model for Northern Calabria. The section is based on the interpretation of the available compiled seismic section indicated and shows the complex structural style of the Calabride Domain. The depth conversion of the section was performed using the data from the wells and the results of the magnetotelluric survey (Van Dijk et al., 2000).



The Line F76_139 is oriented NW-SE just offshore the southeastern Ionian border of the Calabria. This seismic profile further gives information on the general attitude of the sedimentary succession and the Lower Pliocene unconformity is evidenced. In this seismic line is evidenced the main thrust that tilts the basement and the sedimentary succession (Tripodi et al., 2018). Despite the offshore faults are not reported in the Italian contribution of HIKE fault database, this seismic line allows representing the complexity of the structural setting of the Calabride–Peloritane Domain.



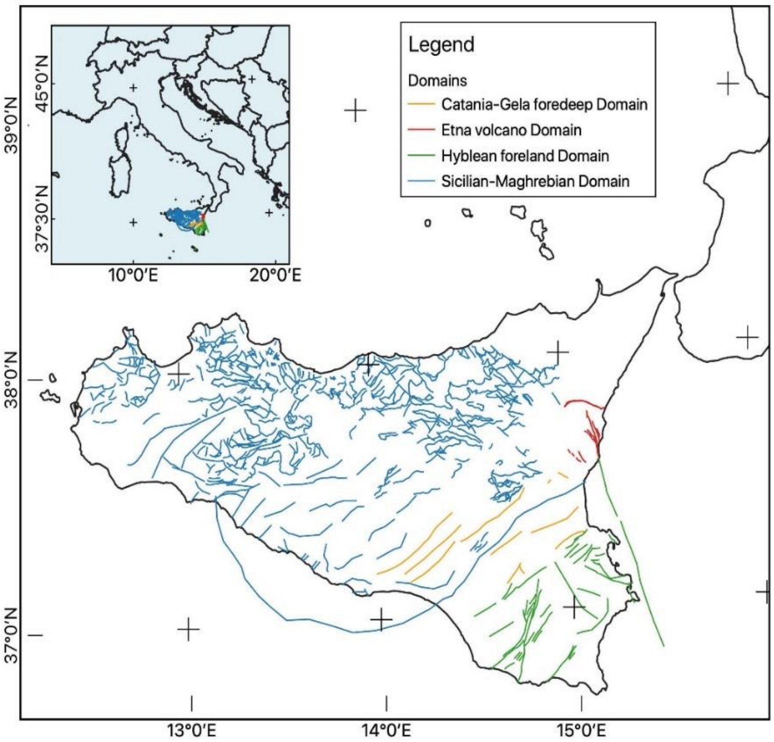
The seismic lines RC-306-78 is located onland in the western margin of the Calabria and it is oriented NW-SE, perpendicular to the coast. The seismic line clearly shows the general attitude of the Pliocene-Pleistocene sedimentary succession and the main fault systems that characterize the Tyrrhenian side of the Calabria with NE striking normal faults west predominant and subordinately east dipping (Tripodi et al., 2018).

13.3.20 Sicilian-Maghrebian Domain

The Sicilian-Maghrebian domain extends in the whole Sicily west of the Etna volcano and the Calabro- Peloritane Units and north of the Catania-Gela Foredeep. This structural domain is related to the complex Sicilian Fold and Thrust Belt system deriving from the Miocene-Pliocene deformation of the Northern African Continental Margin. On the whole, the domain is characterized by prevalently E-W trending, S- and locally SE-verging thrust tectonic related structures that show variable shortening and rotational rates. Compressive structures are locally dislocated by strike-slip faults mainly related to the rotational Plio-Pleistocene phase. High-angle normal fault systems related to early Pliocene-Present extensional tectonics are also present.

13.3.21 Catania-Gela foredeep Domain

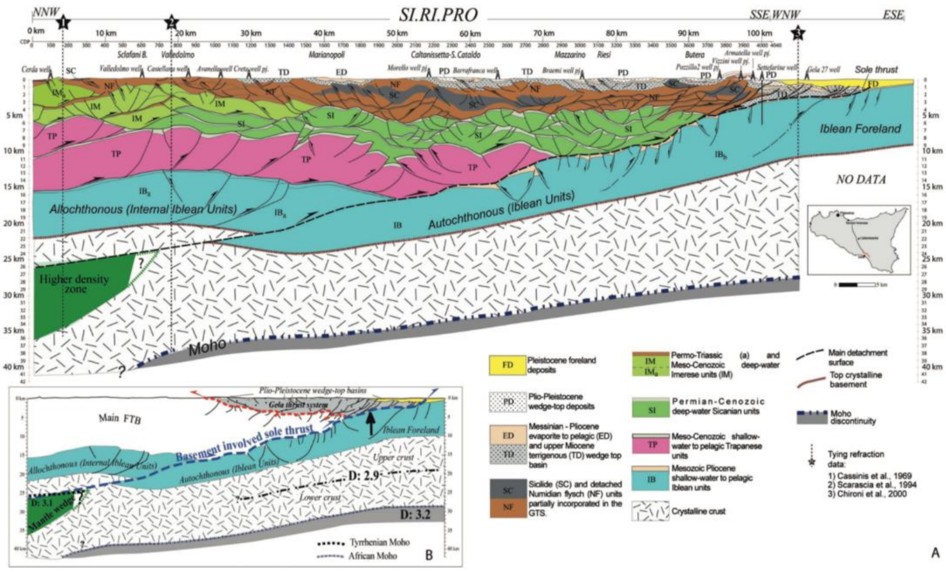
The Catania-Gela Foredeep domain extends between the front of the Apenninic-Maghrebides Belt and the Hyblean Plateau (foreland). The depression starts developing in the Late Pliocene from the inflection of the carbonate substrate related also to the frontal nappe loading (Catalano et al., 1993). The north-western sector of the Catania-Gela Foredeep is fully occupied by the allochthonous units of the frontal wedge of the chain, the Gela Nappe, of which the S and SE verging front represents the main structural feature. A system of NE-SW trending normal faults identifies its south-eastern border and the separation with the Hyblean Foreland domain, partially flexured below the foredeep. Minor extensional elements mainly NE-SW striking locally deform the Upper Pliocene-Pleistocene sedimentary succession.



Map of the Italian fault database showing the main structural domains identified in Sicily; the Etna Volcano Domain is also included.

13.3.22 Hyblean foreland Domain

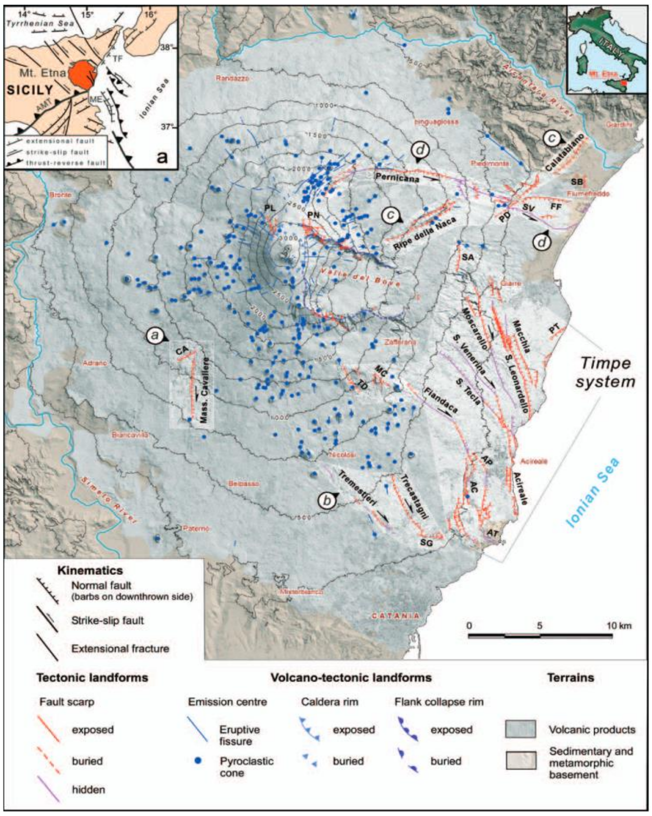
The Hyblean foreland is characterized by sub-parallel normal faults, mainly NE-SW oriented and NW dipping, related to the Mesozoic extensional phase (Patacca et al., 1979; Lentini et al., 1987) and a Plio-Quaternary collapse as a response to the migration of the thrust front. Besides, Plio-Pleistocene NW-SE oriented normal faults and NNE-SSW strike-slip faults, with dextral movement, occur (Ghisetti & Vezzani, 1981; Lentini et al., 1984).



a) Geological cross-section resulting from the interpretation of the seismic stack section of the SI.RI.PRO. crustal profile and its southeastern commercial multichannel seismic extension; b) Geological sketch illustrating the regional monocline that underlies the whole orogenic wedge (after Catalano et al., 2013). The cross-section highlights the structural complexity of the tectonic domains identified in Sicily (especially for the Sicilian-Maghrebian Domain) and the relationship among them.

13.3.23 Etna volcano Domain

The Etna volcano, in eastern Sicily, is the largest and most active stratovolcano in Europe. Its eruptive activity started during the middle Pleistocene on the structural domain of the Gela–Catania Foredeep in the front of the Apennine–Maghrebian thrust belt at the intersection of two active regional master faults, the Hyblean–Malta Escarpment and the Messina–Fiumefreddo line (Branca et al., 2011). The Etna structural setting represents the result of the interaction of regional tectonics, volcano-tectonic processes, and local scale volcano-related and gravitative processes (Lo Giudice et al., 1982). The northern termination of the Malta Escarpment dissects the base of the eastern flank of Etna volcano through a set of NNW–SSE normal faults called Timpe fault system (Lo Giudice et al. 1982). The most active faults in this system are the Moscarello, San Leonardello, and Acireale faults. The E-W trending Pernicana-Fiumefreddo fault system and the NW-SE trending Tremestieri and Trecastagni faults represent the northern and the southern border of a sliding sector. Both these faults systems are characterized by seismic and aseismic (creep) activity.



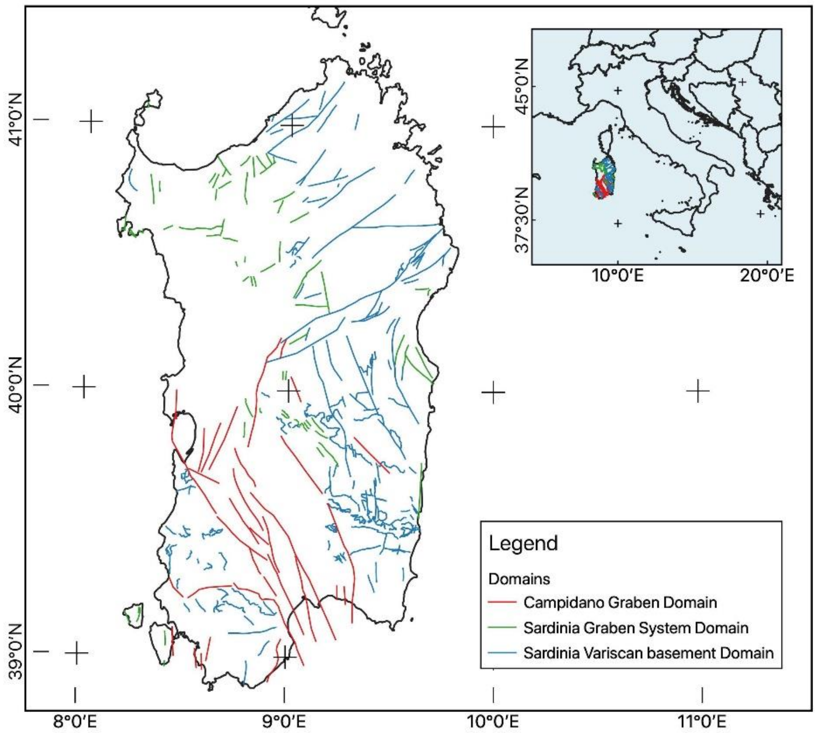
Volcano-tectonic map of Mt. Etna with the main faults characterizing the Eastern flank of the volcano (Azzaro et al., 2012)

13.3.24 Sardinia Variscan basement Domain

The largest part of Sardinia consists of a Variscan basement, composed of different tectonic units deformed and emplaced with a tectonic transport direction toward SW during the Early Carboniferous and of a Permo-Carboniferous batholith emplaced between 340 and 280 Ma (Carmignani et al., 2001). The main tectonic features are ductile and brittle-ductile overthrusts developed during the continental collision between Gondwana and the Armorica Terranes Assemblage. Low- to high-angle normal faults developed during the collapse of the thickened crust in the final stages of the Variscan orogeny, in part during emplacement of the plutonic complex, the dyke complex, and development of a volcano-sedimentary complex of Upper Carboniferous–Lower Triassic age (Carmignani et al., 2015). The External zone, cropping out in the SW sector (Iglesiente and Sulcis), is the less metamorphosed and deformed portion of the Sardinia Variscan chain allowing to distinguish fold and thrust (Carmignani et al., 2004). The Variscan tectonic structures are locally cut or reactivated by the most recent normal faults related to the extensional phase responsible for the Oligocene-Miocene Sardinia Rifting System.

13.3.25 Sardinia Graben system Domain

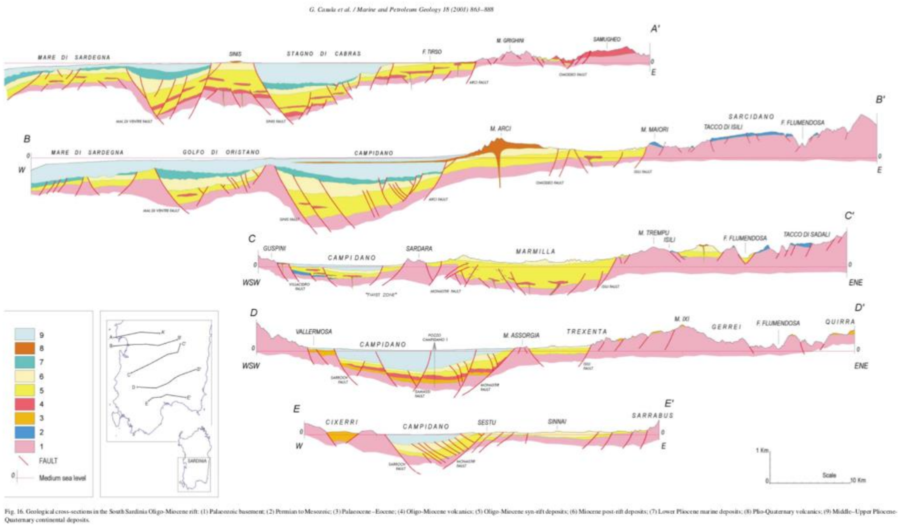
The Sardinia Graben System characterizes the western sector of the Sardinia block with a roughly N-S elongated depression running from the Gulf of Asinara to the North and the Gulf of Cagliari to the south (Carmignani et al., 2001; 2015). The system started developing since the Oligocene up to Miocene upon the Variscan metamorphic and plutonic basement as a result of the extensional regime that affected the Iberian-Europe Region at about 34 Ma (Casula et al., 2001). The present-day structure of the Sardinia Graben System consists of large graben whose margins are well exposed and bordered by major N-S striking normal faults with associated minor parallel and transverse structures (Casula et al., 2001; Carmignani et al., 2015).



Map of the Italian fault database showing the fault pattern for the main structural domains identified in Sardinia.

13.3.26 Campidano Graben Domain

The Campidano Graben domain corresponds to a NW-SE elongated Plio-Quaternary depression that lies on the SW sector of the Sardinia block and extends from the Gulf of Oristano to the NW and the Gulf of Cagliari to the South. The graben is probably related to the coeval extension in the Tyrrhenian Sea; it is in part superimposed on the Oligo-Miocene rift system and involves mostly reactivated normal faults (Casula et al., 2001; Carmignani et al., 2001; 2015). This domain is characterized by prevalently NW-SE striking normal faults organized in half-graben geometry. In the central and southern sectors of the basin, two main longitudinal master faults (i.e.: Isili fault, and Monastir fault) are along the eastern side. Several associated second-order synthetic and antithetic structures are present in the subsurface of the Campidano basin. In the same way, minor extensional tectonic features related to the Plio-Quaternary extensional phase have been also mapped affecting the Variscan basement out of the borders of the Campidano valley.



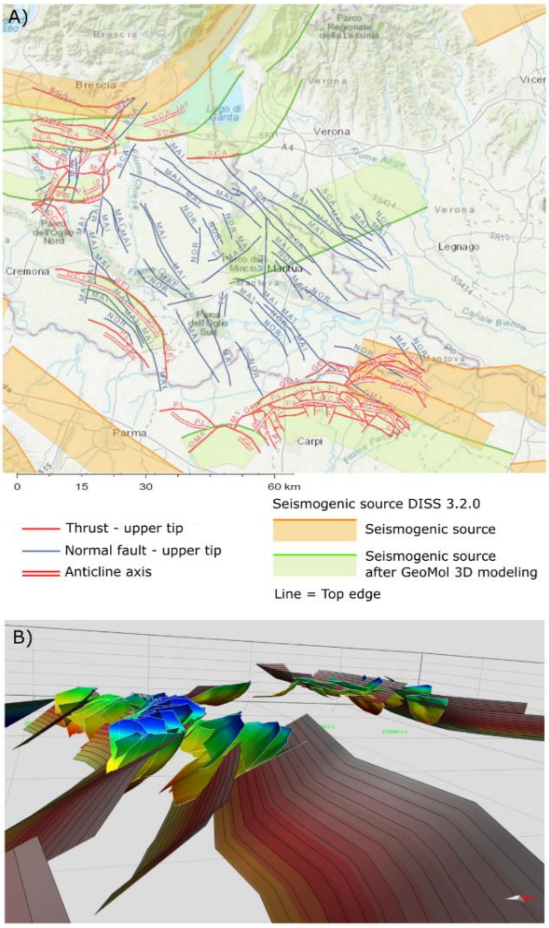
Geological cross-sections in the South Sardinia Oligo-Miocene rift: 1) Palaeozoic basement; 2) Permian to Mesozoic; 3) Palaeocene-Eocene; 4) Oligo-Miocene volcanics; 5) Oligo-Miocene syn-rift deposits; 6) Miocene post-rift deposits; 7) Lower Pliocene marine deposits; 8) Plio-Quaternary volcanics; 9) Middle/Upper Pliocene-Quaternary continental deposits (after Casula et al., 2001).

13.4 Match within Italian HIKE fault database and other Italian fault databases: DISS and ITHACA

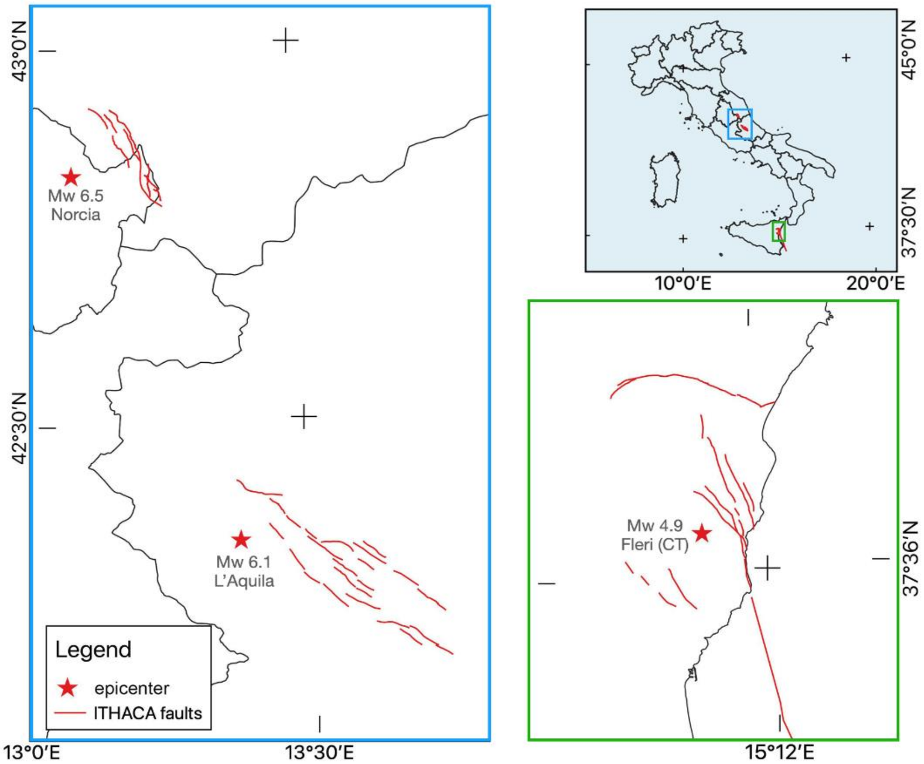
Italy is characterized by a high level of seismicity connected both to compressional and extensional tectonic processes as a consequence of the geodynamic evolution of the Mediterranean region. Seismogenic sources of the Italian territory are collected and characterized in the DISS - Database of Individual Seismogenic Sources: a compilation of potential sources for earthquakes larger than M 5.5 (DISS Working Group, 2018). Some of these seismogenic sources have been modified or better defined according to improvements derived from 3D geological modeling projects.

In some cases, it has been possible to establish a relationship between the DISS sources and the faults mapped in the HIKE database and deriving from these 3D geological modeling projects (e.g. GeoMol and GeoERA – HotLime). This relationship has been defined for some faults in the Po Plain foreland basin domain, as an example of the interaction among the two databases. Italy experimented many events of surface faulting as a consequence of historical and recent earthquakes with M ≈ 7 (1783 Calabria, 1915 Fucino, 1980 Irpinia, 2009 L'Aquila; 2016-2017 Central Italy). In the world, surface faulting is documented for crustal earthquakes with at least M 5.5-6.0 and less than 5 in the volcanic areas. This is also the case of the Etna volcano, where surface faulting can occur for earthquakes with magnitude around 4, due to the less deep hypocentral depth (frequently 0.5-2 km).

ITHACA Project is aimed to collect and characterize the capable faults in the Italian territory, those data are suitable for seismic risk assessment, support site analysis for relevant projects, and are important tools for land planning (ITHACA Working Group, 2019). The matches between the ITHACA faults and the HIKE faults are provided for the areas affected by the last earthquakes occurred in Italy: 6 April 2009, Mw 6.1 L'Aquila; 2016-17 - Central Italy seismic sequence with the main shock of 30 October 2016, Mw 6.5 Norcia; 26 December 2018, Mw 4.9 Fleri (CT)- Etna earthquake.



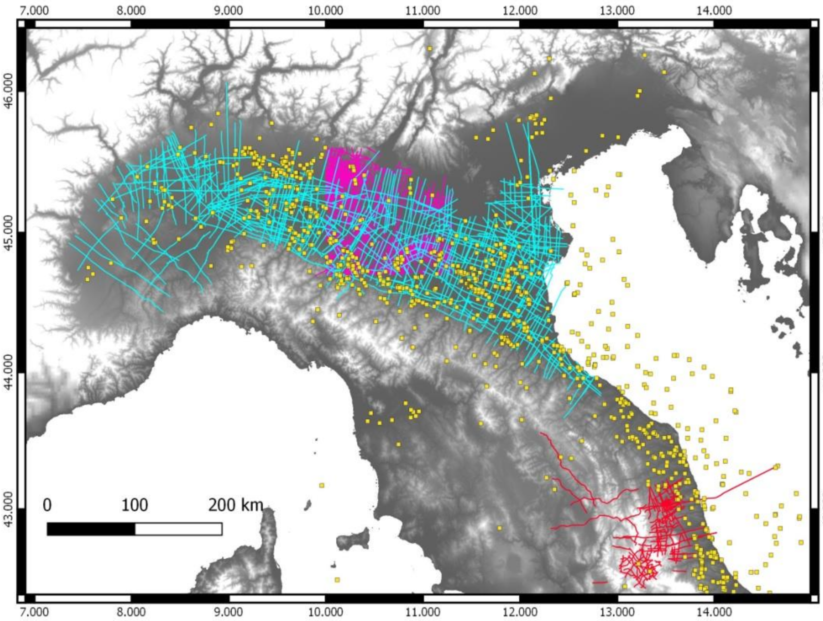
Po Plain foreland basin domain: comparison between position and geometry of seismogenic sources (DISS Working Group, 2018) and 3D geologically modeled faults. A) map showing location of modeled faults and seismogenic sources; B) seismogenic sources represented as squared surfaces with contour lines, and 3D faults, surface coloured from blue to yellow and bounded by white line (GeoMol Project, D'Ambrogi et al., 2015).



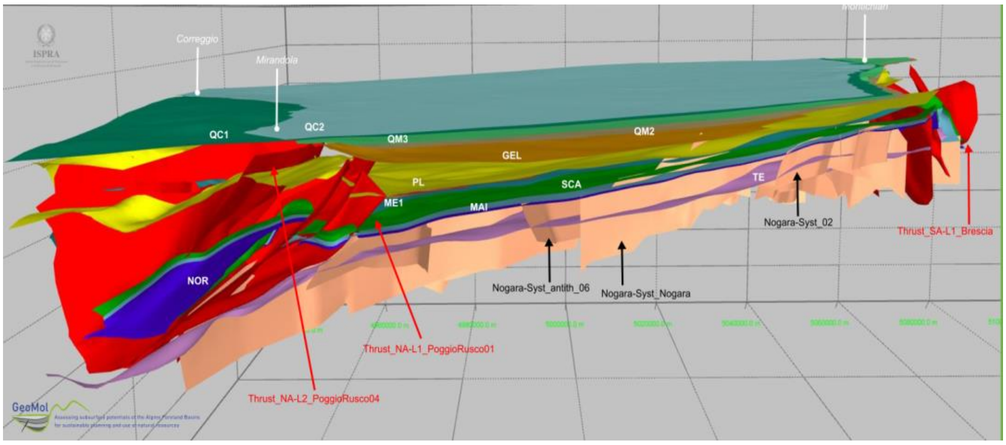
Maps of the Italian fault database showing some of the faults mapped in the ITHACA Catalogue (ITHACA Working Group, 2019) for the areas affected by coseismic surface faulting after the last major earthquake: 2009, Mw 6.1 L'Aquila earthquake, the 2016-2017 Central Italy seismic sequence with the Mw 6.5 Norcia event, the 26 December 2018, Mw 4.9 Fleri (CT) earthquake.

13.5 Data quality, origin and publication

The data used to obtain information on the position and characteristics of the faults are derived from the following sources: Geological Map of Italy 1:1,000,000 (ISPRA, 2011); Sheets of the Geological Mapping Program 1:50,000 scale (http://portalesgi.isprambiente.it/it); 3D geological models, with particular attention to the Po Plain area. In addition, for some areas, many papers and thematic scientific publications have been collected and consulted, in order to implement the description of the attributes of faults. The dataset also includes for the Po Plain area data coming from the GeoMol and HotLime projects. In the same area also the link between the HIKE fault database and the seismic sources collected in the DISS 3.2.1 is provided. Finally, just for the three areas affected by the last major earthquakes in Italy, the Italian contribution for the HIKE fault database includes also some capable faults from the ITHACA Catalog, mapped at detailed scale.



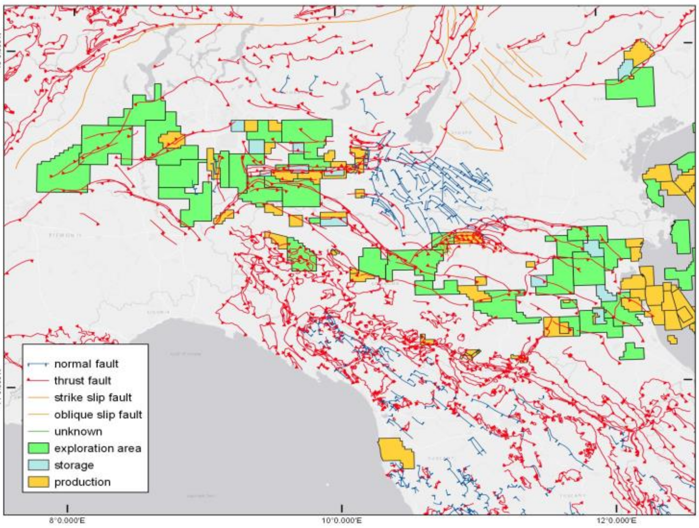
Overview of seismic reflection profiles and deep wells used in the production of the 3D geological model. Lines (confidential seismic reflection profiles): light blue - GeoERA HotLime project; pink - GeoMol project; red: RETRACE-3D project. Yellow squares: deep well logs.



Example of faults modeled after seismic interpretation; in red: main thrusts, in light pink: main normal faults.

13.6 Local fault relevance and application

The dataset follows the primary goal of the HIKE project providing better access to harmonized data and knowledge on fault characteristics and behavior. The integration of the database with other available data on active and inactive faults allows defining a more detailed geo-structural setting better supporting induced hazard studies. This is particularly true for Italy where a large number of active and capable faults are mapped close to inactive or passive faults in areas where anthropogenic activities are present and increasing.



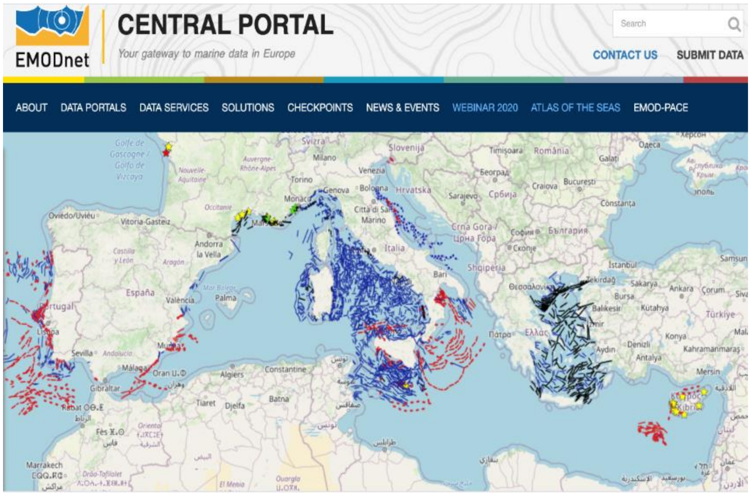
Map of the Italian fault database showing the occurrence of faults in the Po Plain together with anthropogenic activities related to exploration, production and storage of gas and oil

13.7 Fault data included in HIKE fault database

The faults included in the database are delivered as 2D lines representing the position of the fault at surface, derived from direct observation or inferred, or the position of the upper tip of the fault at depth. In some cases also the 3D surface models are available (optional download). The major tectonic domains, and faults include in them, and main fault systems are classified according to the semantic framework defined in HIKE. The fault attributes are mainly limited to the geometric characteristics (length, strike, dip direction and dip angle), fault kinematics, observation and evaluation method.

For the faults derived from 3D geological models also the age of the younger faulted unit is reported. In addition the link to external specialist databases are provided form some faults.

Finally, the Italian contribution for HIKE project fault database includes on land faults only, an extensive view of the offshore faults mapped in Italy is available and downloadable through the EMOdnet map viewer (https://www.emodnet.eu/geoviewer/) in the Layer "Geological events and probabilities/Tectonics - lines".



Screen shot of the EMODnet web portal showing the Tectonics lines mapped in the Mediterranean Sea

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14 LGT – LITHUANIA

14.1 Introduction

The territory of Lithuania is located in the central part of Baltic Basin (BB) – a Phanerozic sedimentary basin situated along the western edge of the East European Craton (EEC; Fig. 1). It consists of a Peri-Baltic sub-basin and a Peri-Tornquist sub-basin along the Tornquist-Teisseyre Zone (TTZ); (Poprawa et al., 1999, Lazauskiene et al., 2002). The south-eastern margin of the BB is flanked by the Mazury-Belarus High and the Fennoscandian Shield lies to the North-East and North (Paškevičius, 1997). Baltic Basin experienced the long-termed tectonic evolution – the main structuring phase took place during the latest Silurian – earliest Devonian, relating to far-field stress transmission from the Scandinavian Caledonides due to the hard coupling between Baltica and Laurentia, while soft collision along amalgamation zone of the Eastern Avalonia to the Baltica did not play any significant role in structuring, though was important for the basin subsidence (Poprawa et al., 1999, Lazauskienė et al., 2002). Subsidence prevailed during the Palaeozoic with occasional short-term uplift events, while non-deposition environment prevailed throughout Latest Palaeozoic–Cenozoic time span interrupted by shorter sedimentation events. The present extent of the Baltic Basin represents only the preserved part of an initial Early Palaeozoic basin that has been considerably diminished in succeeding periods by denudation processes, especially during Carboniferous-Early Permian times.

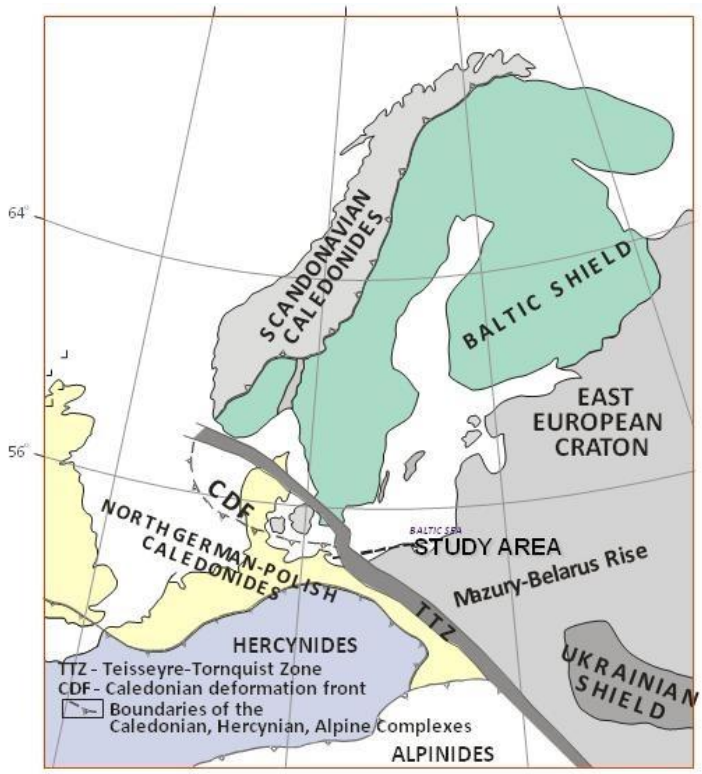

Fig. 1. Tectonic scheme of the Baltic sedimentary basin and adjacent territories, TTZ – Teisseyre–Tornquist zone, KDF – Caledonian deformation front, dotted line – the boundary of the distribution of Silurian strata, bold dotted line – limits of distribution of Caledonian, Hercynian and Alpine complexes (after Poprawa et a., 1999),

Two main factors are accounted for the subsidence history of the area: the location close to the craton margin, and the specific mechanical and rheological properties of the lithosphere. Due to marginal position, the territory of the region was more intensely affected by processes originated in the adjacent active tectonic zones along the plate margins, essentially during the Paleozoic time (Poprawa et al., 1999). It is evident from the close correlation of the shape of the basin to the Early Precambrian arcuate system of the accretional belts, the center of the basin overlying the weakest West Lithuanian granulite domain encountered by stronger East Lithuanian Belt (Skridlaite, Motuza, 2001). The Phanerozoic sedimentary succession represented by the Riphean-Vendian and all the systems of the Phanerozoic to Quaternary overlies the deeply eroded strongly faulted, displaced by steps and elevations Precambrian crystalline basement predominantly composed of magmatic and metamorphic rocks, gradually submerging to the southwest, from depths of 200 m to 2300 m.

14.2 Structural elements

Structuring of the territory of Lithuania was mostly related to the Late Caledonian-Hercynian movements at Late Silurian - Early Devonian times. The structural pattern of the territory mostly reflects the configuration of the underlying crystalline basement and features of the Caledonian Orogeny.

Several major structural units are distinguished based on the structure of the crystalline basement, thickness, stratigraphic continuity of the sedimentary cover and the facies distribution. These units include the Baltic Depression, the Latvian Saddle, the slope of the Belarus–Mazurian High, the southern slope of the Baltic Shield, the Central Baltic Depression, the Polish-Lithuanian Depression and the Latvian–Estonian Monocline (Suveizdis, 1979; Paškevičius, 1997; Fig. 2).

The first-order tectonic element of the crystalline basement is the N-S trending Middle Lithuanian Suture zone separating Western Lithuanian domain and East Lithuanian Domain, it also marks a considerable offset of Moho (Skridlaite, Motuza, 2001).

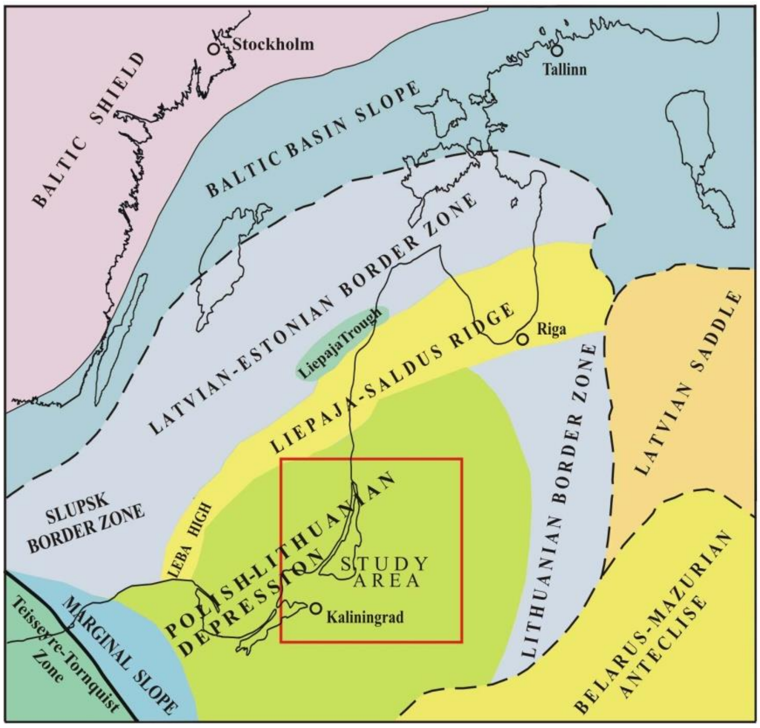

Fig. 2. Major tectonic structures of the central part of the Baltic Basin (after Zdanaviciute et al., 2012; *Paškevičius, 1997)*.

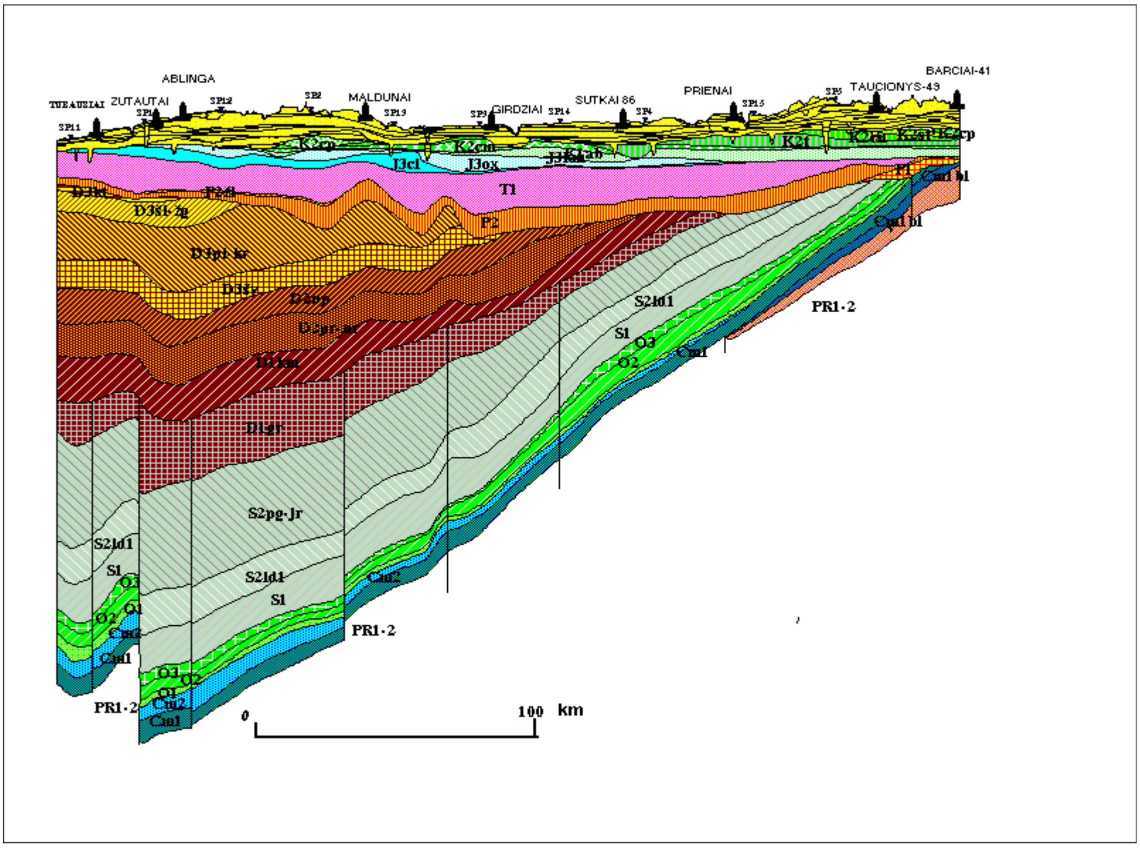

Fig 3. E-W trending geological cross-section

The most complete geological section is recorded in the western part of Lithuania, where the thickness of the sedimentary cover exceeds 2 km, gradually attenuating to the east towards the Mazury–Belarus High (Fig. 3). .The Palaeozoic, Mesozoic and Cenozoic successions are covered by 0.5–10 to 300 m thick (~150 m in average) Quaternary sediments.

The Baltic Depression is the largest traverse structure on the western edge of the EEC. It is an area of uneven crystalline basement (Fig. 4.) formed of Proterozoic rocks overlain by sedimentary succession. The surface of the basement rocks subsides from 300–500 m to 1200–1400 m, and the monoclinal pattern exhibits only rare and small anti- and syn-form structures (Paškevičius, 1997).

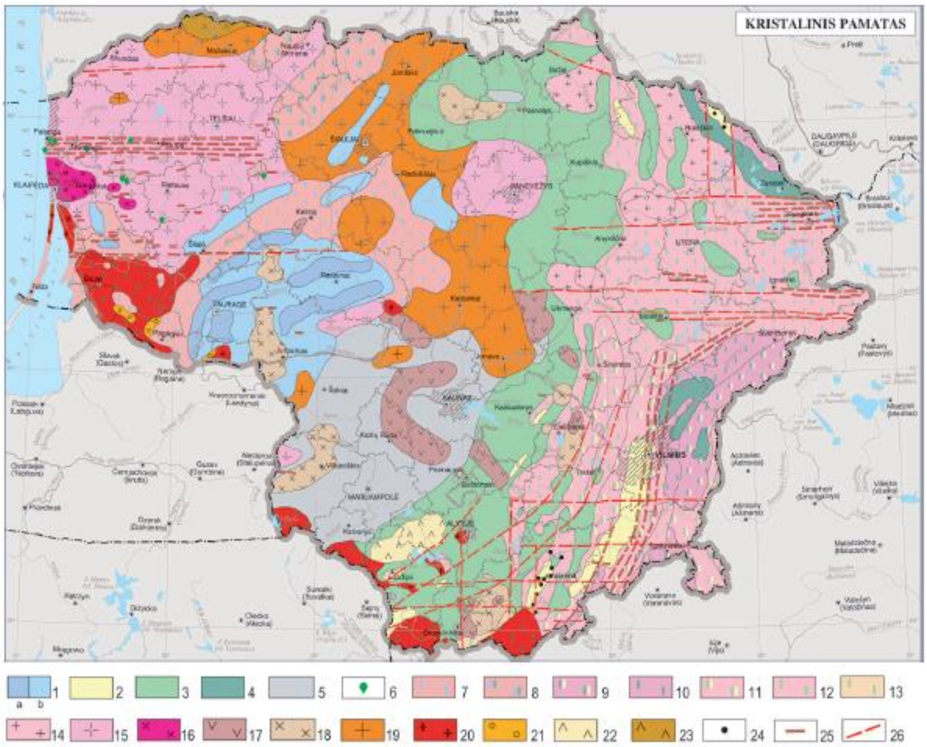

Fig. 4. Map of crystalline basement of Lithuania (Motuza, 2004, 2005). Legend:

The Belarus–Mazurian High edges the territory of Lithuania from the east and the south. The thickness of the sedimentary cover is less than 500–800 m due to syn-depositional and post-depositional (erosional) wedging of most strata. The most intense uplift of the high occurred during the latter part of the Hercynian time (more than 1 km).The Lithuanian Border Zone is the area of gently dipping crystalline basement and gentle subsidence of the overlying sedimentary succession. West of it, in the Polish–Lithuanian Depression, the dipping increases markedly. The surface of the basement rocks subsides from 500 to 1 200–1 400 m, and the monoclinal pattern exhibits only rare and small anti- and syn-form structures (Suveizdis, 2003; Paškevičius, 1997). The Polish–Lithuanian Depression is represented in the south-westernmost part of Lithuania only by its eastern edge.

It is the deepest of the tectonic features within the study area, and depth to crystalline basement reaches 2 km in Lithuania and ~5 km close to TTZ. The Latvian Saddle is the gently dipping area stretching in longitudinal and latitudinal directions. The crystalline basement occurs at the depth of 400–1050 m below sea level and the inclination of the surface is around 2–6.5 m/km. The sedimentary cover is composed of Vendian–Devonian strata (Paškevičius, 1997).

The dense family of compressional and transpersional faults (Fig. 5) was established in western Lithuania, while faulting was only scarce in the eastern part of Lithuania that is accounted to stronger lithosphere and longer distance the stress source (Šliaupa et al., in Baltrūnas (ed.), 2004).

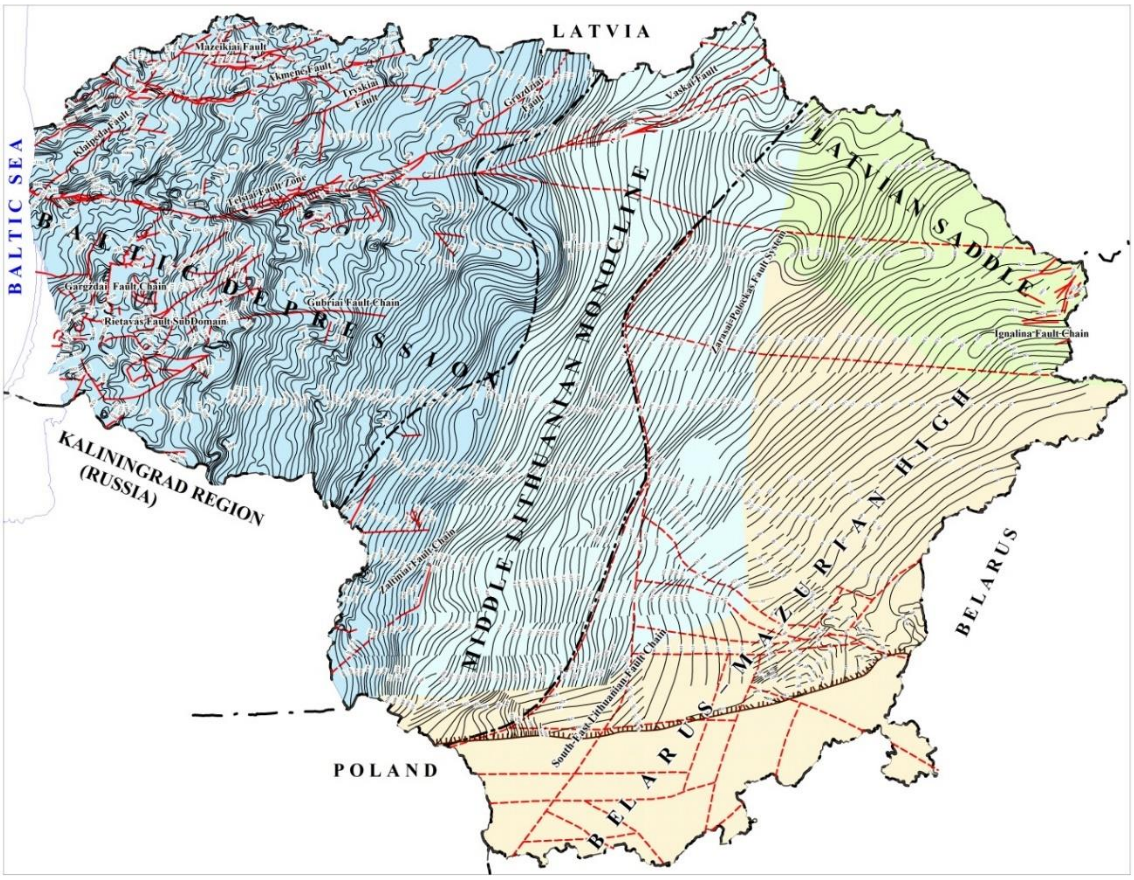

Fig. 5. Scheme of the distribution of faults and main structural elements of Lithuania (after Čyžiene et al, 1999, Paškevičius, 1997). Red solid and dashed lines indicate the distribution of faults; black lines – izohypses of the base of the Silurian.

The crystalline basement is comprised of metamorphic and magmatic rocks and has a block-like structure, strongly dissected by tectonic faulting, with two major types of faults prevailing: the oldest Precambrian and ones juxtaposed by younger Phanerozoic features. The former are defined in the crystalline basement and do not dissect the sedimentary cover, whereas the latter penetrate into the sedimentary succession overlying the crystalline basement. The faults are oriented N-S, W-E, NW-SE and NE-SW predominantly. Two major systems of late Caledonian reverse faults, oriented W-E (WSW-ENE) and SW-NE (SSW-NNE) prevail (Sliaupa et.al., 2002).

14.3 Fault patterns and characteristics

While adopting the concepts of HIKE project, three major fault domains have been distinguished in the territory of Lithuania also following the major features of the structural composition of area of interest – namely, West Lithuanian Fault Domain, Middle Lithuanian Share Zone and East Lithuanian Fault Domain. These major fault domains are compose of smaller subdomains, fault systems, fault chains, etc. (Fig. 6).

14.3.1 Middle Lithuanian Share zone

Roughly coincide with the major first-order tectonic elements of the crystalline basement – the N-S trending Middle Lithuanian Suture zone separating Western Lithuanian Granulite Domain and East Lithuanian Domain of the crystalline basement (Fig. 6.) A scattered character of related gravity and magnetic anomalies suggests establishment of this structural family in a rather ductile crustal environment.

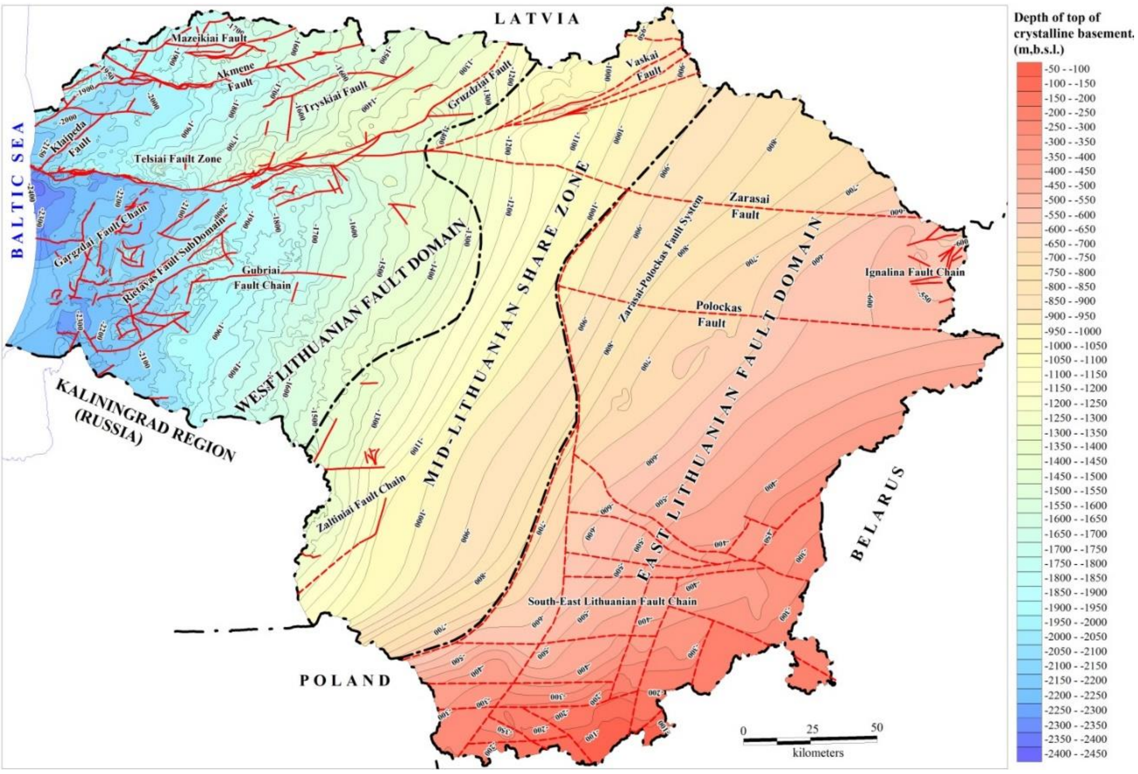

Fig. 6. Tectonic scheme of the territory of Lithuania at a scale of 1:500 000 with major foult domains. Red solid and dashed lines indicate the distribution of faults; black lines – izohypses of the top of the crystalline basement (top of the crystalline basement after Bitinas et al., 2019).

Within this area rather few reverse faults are indicated: SW-NE trending Vaskai fault is located in the Northern part of the Mid-Lithuanian Share zone. The fault is identified in the crystalline basement and penetrates the sedimentary succession up to Tournasian strata with an amplitude up to 25 m. Some segments of fault were identified by 2D seismic surveying data, whilst some - by gravity and magnetic and well data. Reverse faults of Zaltiniai Fault Chain are oriented in E-

W and NW-SE directions. They have been identified by 2D seismic data and by interpretation of the magnetic and gravity anomalies, and well data.

14.3.2 East Lithuanian Fault Domain

Comprises NNE-SSW and W-E trending faults' chains, coinciding predominantly with magnetic and gravity anomalies and implying lenticular tectonic fabric of the basement rocks. In the East Lithuanian Fault Domain the main faults/fault chains are Zarasai Fault, Polockas Fault and Ignalina Fault Chain, the first two are mainly identified by the interpretation of gravity and magnetic anomalies data, whilst Ignalina Fault Chain is well investigated also by 2D and 3D seismic surveying. Faults of East Lithuanian Fault Domain are identified in predominantly in the crystalline basement, very few of them, namely Ignalina Fault Chain penetrate also the Lower Paleozoic sedimentary cover up to the Silurian (Pridoli) strata. The differences in fault identification might be related to the level of the investigations of the domain and the availability of data - Ignalina Fault Chain is located in the vicinity of Ignalina Nuclear Power Plant, thus, is much more detail investigated by 2D and 3D seismic surveying and well data in comparance with the rest of the area of this domain. Zarasai and Polockas faults are reflected by negative correlation of gravity and magnetic fields (Šliaupa, 2003). The polyphase structuring of the crust during the Early Precambrian times is reflected in the gravity and magnetic anomalies maps (Figs. 8, 9).
The NNE-SSW structural trend is complicated by NW-SE, N-S and W-E directed fault populations. The NW-SE-trending structures form dense network imprinting the oldest structures only. In contrast, N-S and W-E-trending shear lineaments show more distinct concentrated character of associating anomalies. Some of these oldest tectonic zones were repeatedly reactivated in a brittle regime during Phanerozoic time. Nearly vertical Zarasai fault in the crystalline basement is oriented in W-E direction. The strike-slip movements are implied as occurring along the fault. Polockas fault is oriented in W-E direction and identified as share lineament inclined to the north at the angle 25^{o}. The dislocation amplitude at crystalline basement is up to 50 m.

14.3.3 West Lithuanian Domain

Comprises the most tectonically dislocated part of the territory of Lithuania and it is considerably more detail investigated by different mapping campaigns, and, mostly, due to the hydrocarbon exploration and production activities. Based on the different orientation, as well as deformation history, several types of fault chains could be distinguished, namely, Mazeikiai – Telsiai fault set, Gargzdai fault chain, Rietavas sub-domain and Gubriai fault chain.
Faults of West Lithuanian Domain were identified by 2D (predominantly) and 3D seismic surveying and deep well data, supported also by potential fields data. Faults of West Lithuanian Fault Domain are mainly assigned to the reverse fault type. The faults are identified in crystalline basement and penetrate also the Paleozoic sedimentary cover up to the Lower Devonian Gragzdai Group (Early Pragian time) and Tournasian succession of the Carboniferous in the Northern part of Mazeikiai-Telsiai fault set, which is also one of the dominant fault set of West Lithuanian Fault Domain. This fault set comprises Mazeikiai, Akmene, Klaipeda and few other smaller faults, and the major Telsiai fault zone. Telsiai fault zone is oriented in W-E direction its amplitude exceeds 300 m; the total length of onshore Telsiai fault zone is up to 270 km. The sub-faults are dipping at the angles 60-80^{o}. Fault zone is identified in the crystalline basement and penetrate Lower Paleozoic sedimentary cover up to Lower Devonian Gargzdai Group (Early Pragian). Akmene fault is oriented in NE-SW direction.. Mazeikiai fault is oriented in NE-SW direction and inclines to the north with amplitudes ranging from 25 to 50 meters. Both Akmene

and Mazeikiai faults are identified in the crystalline basement and could be traced in the sedimentary cover up to the Carboniferous (Tournaisian) strata.
In West Lithuanian Fault domain NNE-SSW striking Gargzdai Fault Chain is the other major fault chain that consists of a set of several reverse faults. It comprises the major Gargzdai Fault Zone and related satellite faults. Faults are identified in crystalline basement and penetrate Lower Paleozoic sedimentary cover up to Lower Devonian Gargzdai Group (Early Pragian). The amplitudes of faults range from a few dozen to 100 m. The NE-SW faults set shows rather simple compressional geometries dipping to the west at the angles 70-80^o (Šliaupa, 2003).
The recent data reveals no reliable evidence of faults and tectonic activity at surface.

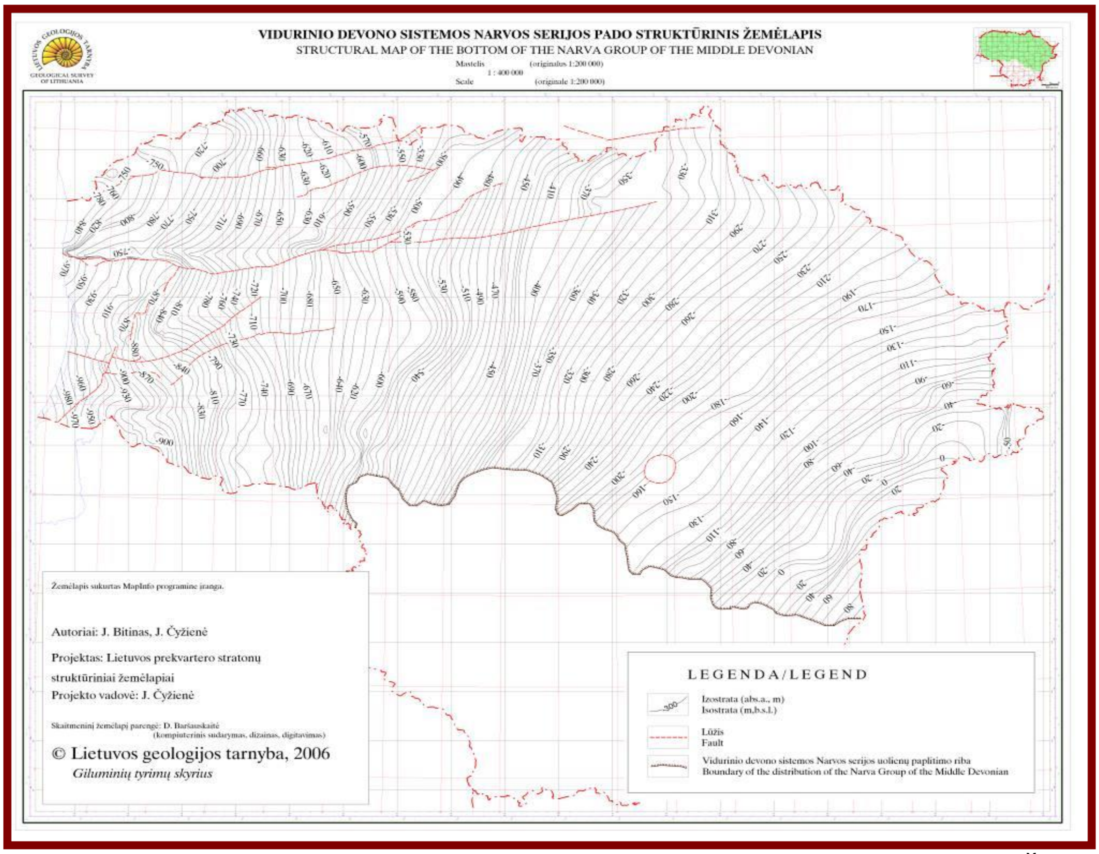

Fig. 7. *Structural map of the base of the Middle Devonian Narva Group (Pragina time;(Čyžienė et al., 2006).)*

14.4 Data quality, origin and publication

In Lithuania most comprehensive studies of fault tectonics were carried out by P. Suveizdis, (2003), A. Stirpeika (1999), G. Motuza (2004, 2005), S. Šliaupa (2003), J. Paškevičius (1997), J. Bitinas (2019), J. Čyžienė et al (2006). In 2019 Lithuanian Geological Survey collected the available fault data and information from the different type of sources. Collected data were summarized and interpreted, resulting in compilation of the upgraded structural map of the top of the crystalline basement and identification of the occurrence and distribution of the tectonic dislocations and compilation of new tectonic scheme of the territory of Lithuania at a scale of 1:500 000 (Bitinas et al., 2019, Fig. 6). The fault tectonics of the territory of Lithuania was analyzed applying various methods: 2D and 3D seismic data, interpretation of the gravity and magnetic fields anomalies, analysis of the faults' features on the Earths' surface, features of the deep fault within the shallower layers, correlation old stratigraphic data between wells etc.
The recognition of the structural fabric of the crystalline basement of the territory of Lithuania is mainly based to geophysical data (potential field data) for the Early Precambrian rocks are overlain by 0.2–5 km thick sedimentary pile and deep well data. Therefore, only scarce drilling data are available in the major part of the territory. Faults of the crystalline basement in East Lithuanian Fault Domain and Middle Lithuanian Share Zone are identified by interpretation of the magnetic and gravity anomalies and interpretation of well data. The level of reliability of faults was identified by establishing exclusion criteria. In Western part of Lithuania 2D and 3D seismic surveying data along with well data are the main source of information for mapping the deep subsurface stratigraphic horizons and faults. In the onshore areas of Lithuania, seismic data acquisition had seen a first phase of activity in the time period from 1952 to 1956, which was then resumed and increased from 1958 to 1994. Whilst during the first 30 years of activities major parts of the seismic were recorded by Soviet Union crews. The western part of the Lithuanian onshore has also been covered by refraction seismic (Zdanaviciute, Sakalauskas 2001). Since mid-1990ies, private oil companies are carrying out seismic surveys within their license blocks. They comprise 2D and 3D surveys employing up-to-date western equipment. A total of ~ 2,000 km 2D and 680 km2 3D data were acquired within the companies' license areas up to now (Fig. 8). The reverse faults formed during the Hercynian period are of rather small amplitudes and, therefore, are rather difficult to distinguish by 2D seismic exploration data. The formation of low-amplitude tectonic faults of this period was determined mostly by geological cross-sections' and thickness maps' analysis. According to the data of previous geological exploration and cross-sections, the formation of faults during the Alpine period is implied only in the eastern part of the territory of Lithuania. There is a lack of reliable data to support the Alpine tectonics processes in western part of Lithuania (Šliaupa, 2003). The most possibly fully cored wells (most of 286 of the wells in Western Lithuania) were drilled 1960-1990 predominantly (Fig. 7). Beside 2D and 3D seismic survey data, faults have been inferred from correlation and interpolation of borehole data

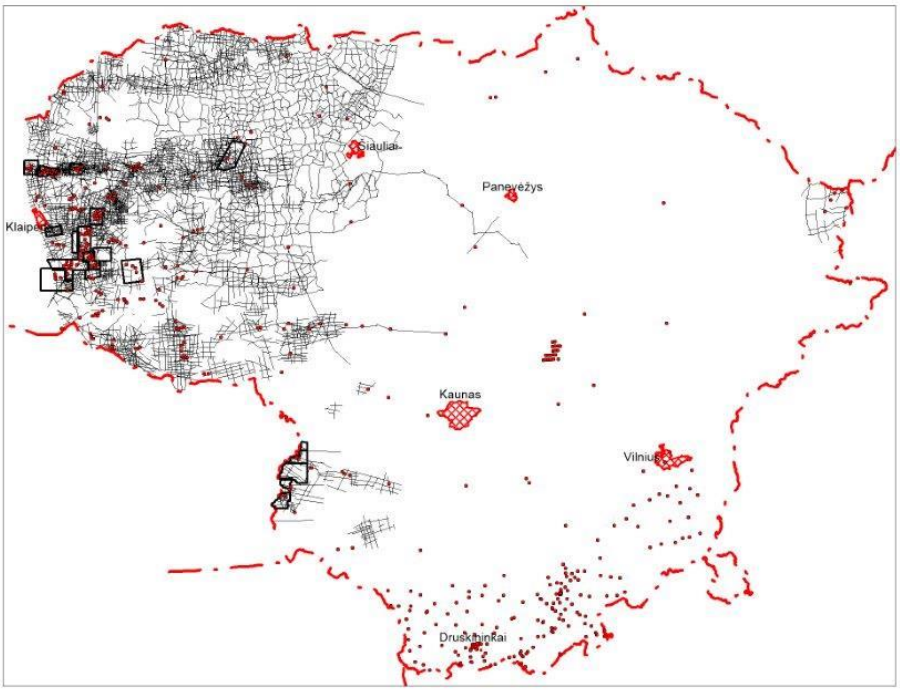

Fig. 8. The scheme of the distribution of 2D and 3D seismic surveys in Lithuania. Black lines indicates 2D reflection seismic profiles, black square – 3D seismic surveys, dots – drilled wells.

The entire territory of Lithuania is covered in a scale 1:200 000 gravity and magnetic mapping (Fig. 9, 10). All the processed and interpreted primary gravity and magnetic field surveying data resulted in compilation of local and regional gravity and magnetic field anomalies and horizontal gradient maps, the gravity and magnetic anomaly maps and their transformations‘ as well as shadow relief maps are compiled. Based on these data, the majority of the faults in the crystalline basement have been identified, particularly those in the areas not covered by well and seismic surveying data (Fig. 5, 6).

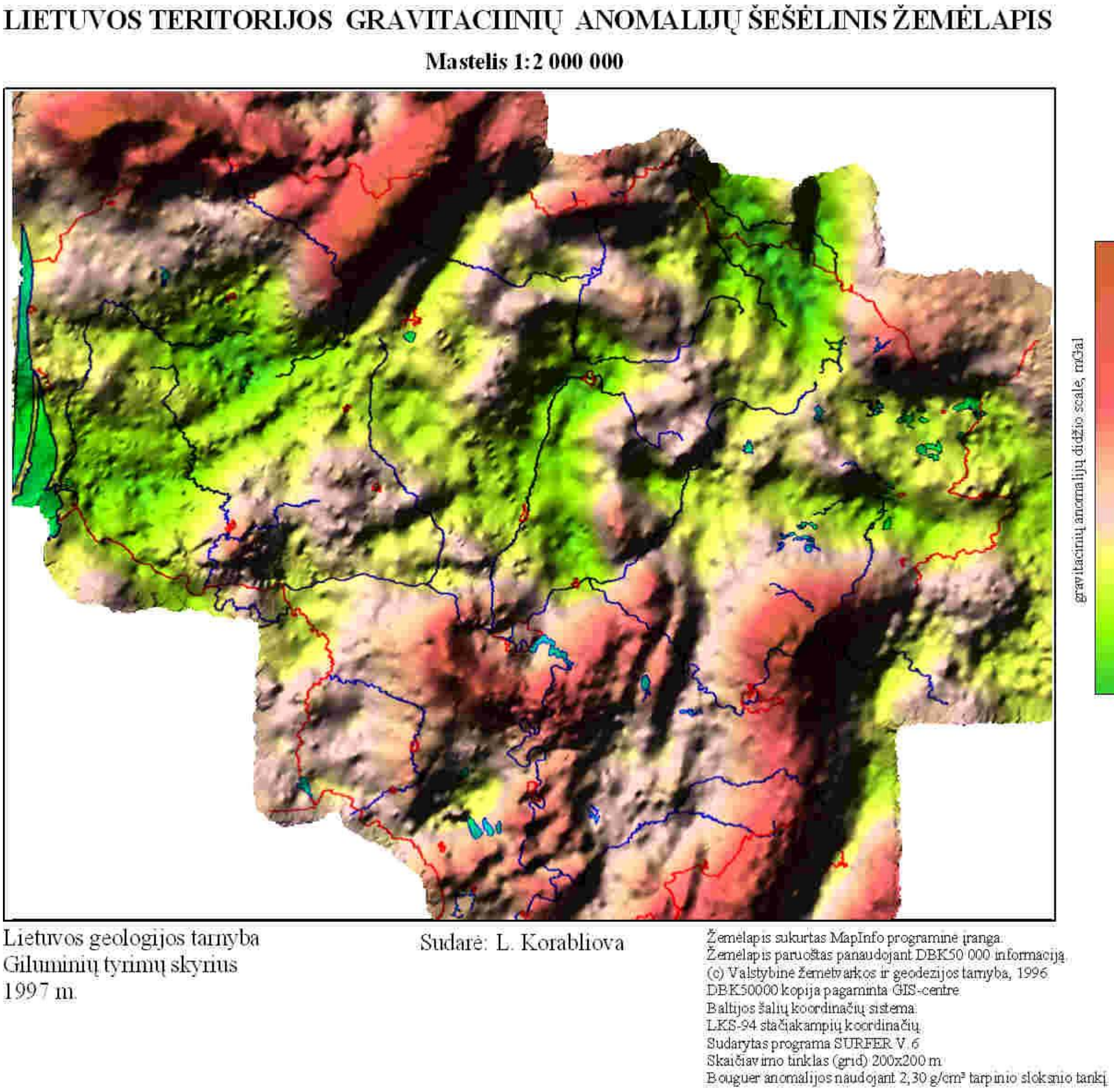

Fig.9. Gravity anomaly shadow map of Lithuania (Korabliova et al., 2000, LGT).

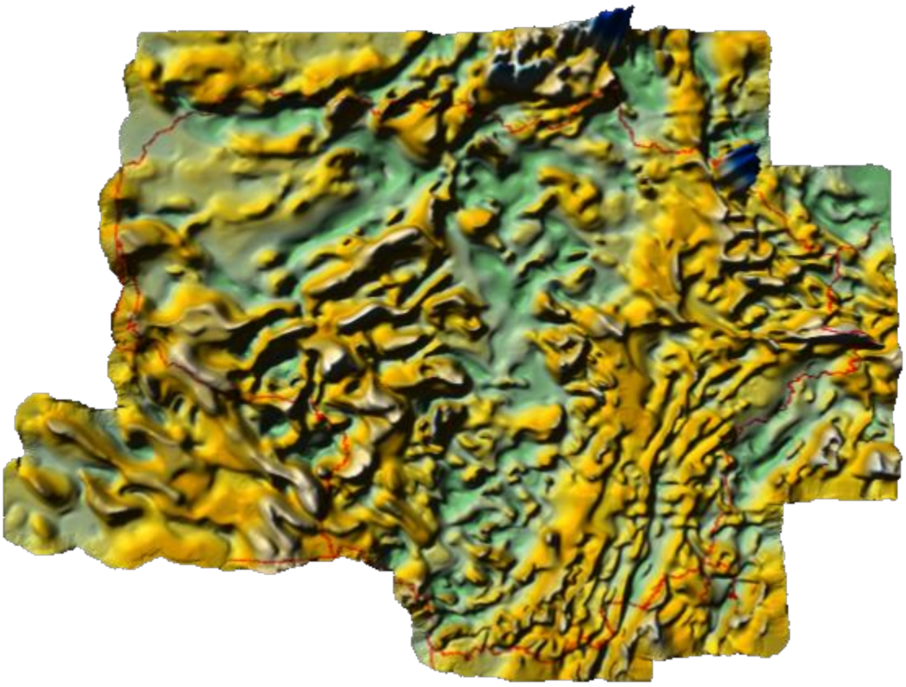

Fig. 10. Magnetic anomaly shadow map of Lithuania (Korabliova et. al., 2000, LGT).

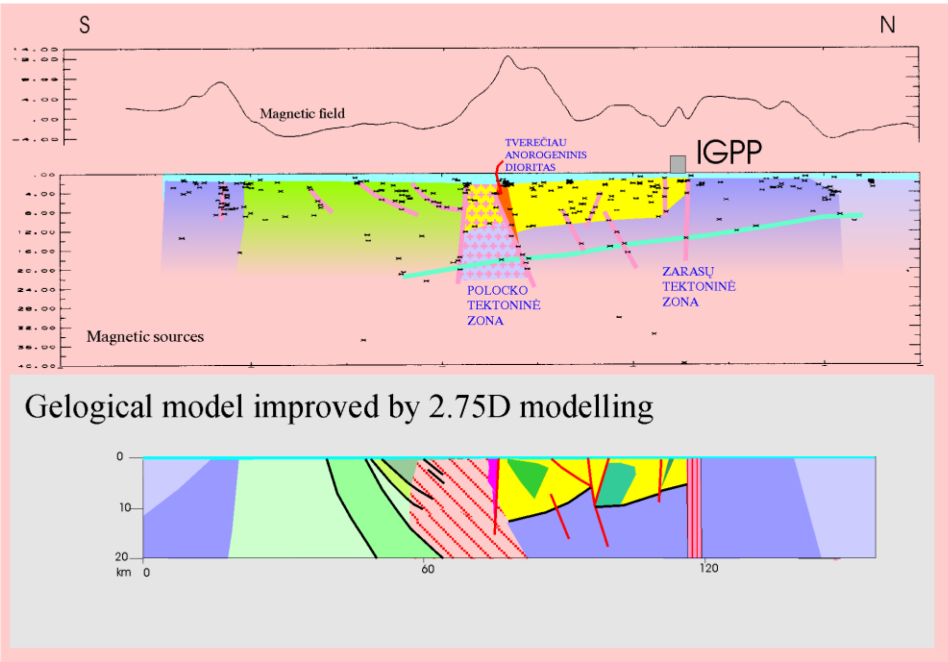

Fig. 11. 2.75D modelling of magnetic surveying data demonstrating Zarasai and Polockas faults (Zamžickas 2018, LGT).

14.5 Local fault relevance and application

Lithuania has several important industrial facilities, such as decommissioned Ignalina NPP, projected radioactive waste storages; Nemunas dam, nitrogen fertilizer factory “Achema” in Jonava, mineral fertilizer factory “Lifosa” in Kedainiai, oil refinery “Orlen” in Mazeikiai, liquefied natural gas floating storage and regasification unit terminal in Klaipeda; geothermal Power Plant in Klaipeda area; 15 producing oil fields in Western Lithuania, planned projects of Visaginas NPP and Syderiai underground gas storage (Fig. 12) that are dependent on the knowledge on distribution and characteristics of faulting and might be affected by the activity of faults.

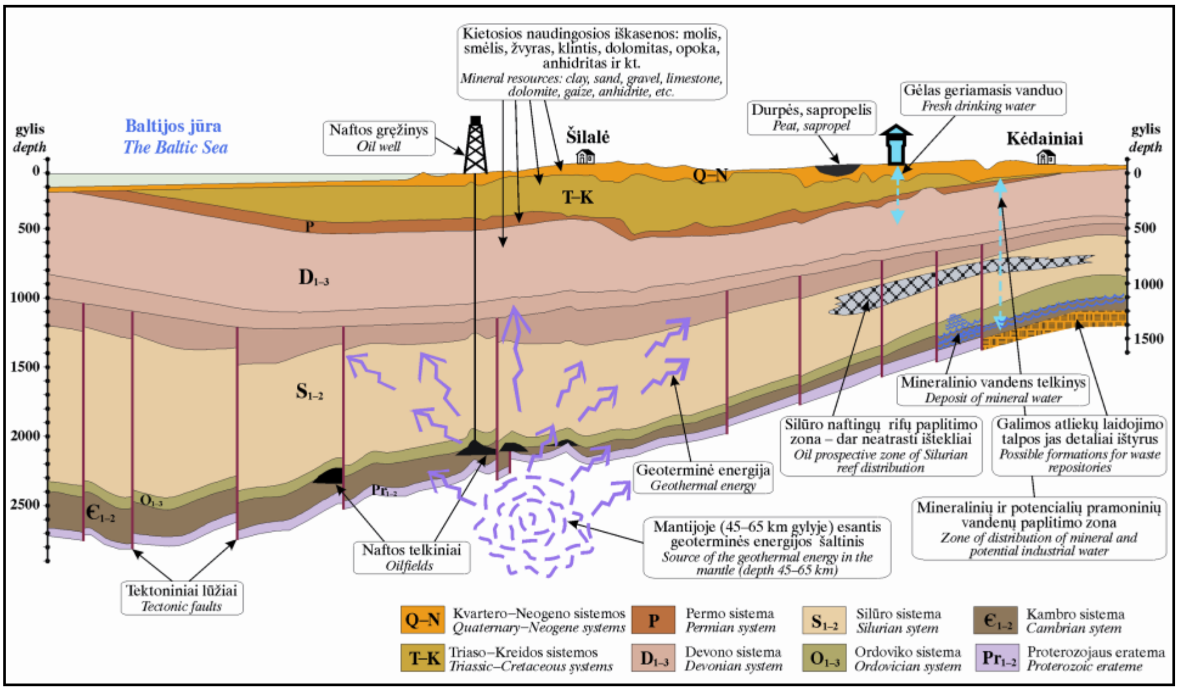

Fig. 12. W-E trending geological cross-section of the territory of Lithuania with indicated applicability of the Earth‘s subsurface and faults.

14.5.1 Nuclear objects

Lithuania has several strategic nuclear objects, such as decommissioned Ignalina NPP, several constructed and planned radioactive waste storages varying form low to high level radioactive waste; planned projects of Visaginas NPP. Following the IAEA requirements, one of the major aims of the geological investigations in the process of the NPP or radioactive waste storage site selection is to determine the capability of tectonic faults, especially determining the potential for- and rate of- fault displacement at the sites’ surface- and to identify conditions of potential geological instability of the sites’ areas. The presence (absence) of faults are of crucial importance and might be defined by analyzing by integrated approach all the available 2D and 3D seismic surveying and seismological data, potential fields interpretation data, lineament and morphotectonic data analysis and deep borehole information.

14.5.2 Underground energy storage potential

For underground energy storage facilities assessment the geological structure which ensures isolation of the Earths, subsurface, the distribution, tightness and activity of faults in the area are important parameters to be considered. Over 100 local structures in Lithuania were analyzed for their suitability suitable to be considered as prospective (Šliaupiene, Šliaupa. 2011). Syderiai structure investigated in detail by 2D and 3D seismic surveying and deep well data represents the local uplift bounded by the large-scale Telsiai fault in the south. Another prospective Vaskai uplift is limited by two faults trending W–E determined, but was abandoned due to uncertain tightness of the bounding faults.

14.5.3 Natural Seismicity

The territory of Lithuania feature low seismic activity that is determined by tectonic structure - Earth's crust of early Precambrian consolidation, specific properties of the lithosphere and significant distances to active tectonic zones. No natural earthquake has been reliably recorded is within the territory of Lithuania. Majority of seismic events in the central Baltic Basin region are historical ones. It is rather complicated to associate single earthquakes with some certain faults unambiguously due to significant errors of location of seismic events and faults location and the identification of the seismogenic faults. Not all the earthquakes are related to the faults' zones that strongly imply local seismogenic sources with diffused seismicity. The seismo-tectonic map of Lithuania shows that peak average ground acceleration (PGA) that can be exceeded within 50 years with probability of 10 % is 19.7 cm/s2 with standard deviation of 6.5 cm/s2. The highest seismic hazard with PGA of 32,6 cm/s^2 (0,0326 g) is recorded in Eastern Lithuania, whilst PGA of 25-30 cm/s2 (0,025-0,030 g) characterizes the Northern Lithuania (Pačėsa, Čečys, 2015).

14.5.4 Induced seismicity

The test site for the investigations was chosen to be the dolomite quarry of Petrašiūnai, where a portable seismic monitoring station was installed by the specialists of the LGT. The results of the analysis of the anthropogenic seismic events registered at the site of seismic observation showed that the maximum intensity of the ground surface vibrations at the village of Vaišvydžiai was ~4–5 times lower than the maximum values allowed by the Safety Requirements for Explosive Work (SDRS) norms (Andriuškevičienė et al., 2018). More investigation is needed in more faulted ares, where oil production is rather intensive.

14.6 Fault data included in HIKE fault database

All available not confidential fault data from the deep wells, national geological mapping programs, industrial reports, scientific publications and the other investigation projects are included to the HIKE fault database. The faults for the deep subsurface are delivered as 2D intersection lines with the oldest and youngest dissected stratigraphic horizons indicated. The main faults, fault domains, systems, chains, sets and fault zones are classified according to the generic semantic framework in HIKE. This includes a correlation link with the faults in neighboring countries (in particular Poland). Fault attributes are still mainly limited to geometric aspects (length, strike, dip, surface area), some of them - in fault type (normal, reversed, etc.) and observation/evaluation method (seismic interpretation, inferred modelling, etc.).

14.7 References

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15 PIG-PIB – POLAND

FAULT DATA REPORT – POLAND

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MAJOR FAULT ZONES IN POLAND

15.1 Introduction

The geological structure of the continental crust of Poland was formed in a course of Precambrian stages of primordial earth crust amalgamation, the Early Palaeozoic accretion of Eastern Avalonia, through the Late Palaeozoic accretion of Armorica and the Cainozoic accretion of ALCAPA. This accretion/collision phases, separated by rifting and/or basin subsidence led to the complex patchwork of crustal blocks in the basement (Fig. 1). The last tectonic phase, which significantly reshaped the structure of the sedimentary Mesozoic complex of the Polish Lowlands took place at the end of Cretaceous. This stage of the Alpine orogeny caused an inversion of the subsidence centre of the Polish Basin and a large-scale buckling of the upper crust. So-called troughs and swells were created which were later covered by Cainozoic sediments (Fig. 2). In the southern part of Poland the Cainozoic stage of the Alpine orogeny led to the creation of the thrust-and-fold belt of the Carpathians and caused major vertical movements related to the formation of the foredeep basin and the forebulge. The present-day tectonic structure of Poland differs greatly by structural levels, thus must be considered and described accordingly. The lower, consistently discernible level is the post-Variscan domain, where the differentiation of crustal blocks is best visible (Fig. 1). However, recognition of this level is limited due to the significant burial of Palaeozoic complex under Mesozoic and Cainozoic sedimentary cover in the vast part of Poland.

Much better surveyed is the post-Mesozoic structural level, which nonetheless reflects, at least to some extent, the post-Variscan block structure, however overprinted by Alpine deformations. In the great part of Poland, decoupling of tectonic deformations between the Palaeozoic and Mesozoic complexes across the Zechstein evaporite complex blurs expression of the basement structures at the upper structural level (Fig. 3). Such decoupling also makes the pattern of fault zones quite different at the Paleozoic and Mesozoic levels. In this Report, faults are presented in separate chapters (A–F) covering areas related to the main tectonic units of Poland (Fig. 4): (A) the East European Craton (EEC), (B) northern segment of the Trans-European Suture Zone (TESZ), (C) southern segment of the TESZ divided into the Holy Cross Mts. and the Małopolska Massif, (D) the Upper Silesia Block, (E) the Lower Silesia Block with the Fore-Sudetic Homocline (Monocline), and (F) the Inner Carpathians. Our study does not include thin-skinned structure of the thrust-and-fold belt of the Outer Carpathians.

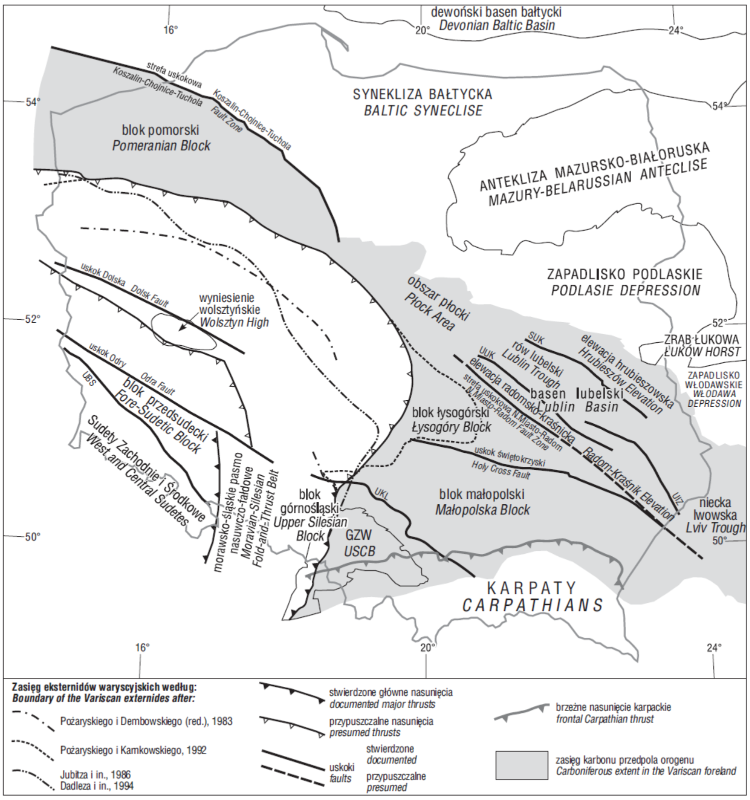


Fig. 1. Sketch of the hypothetical Variscan structures formed before Permian (after Narkiewicz and Dadlez, 2008).

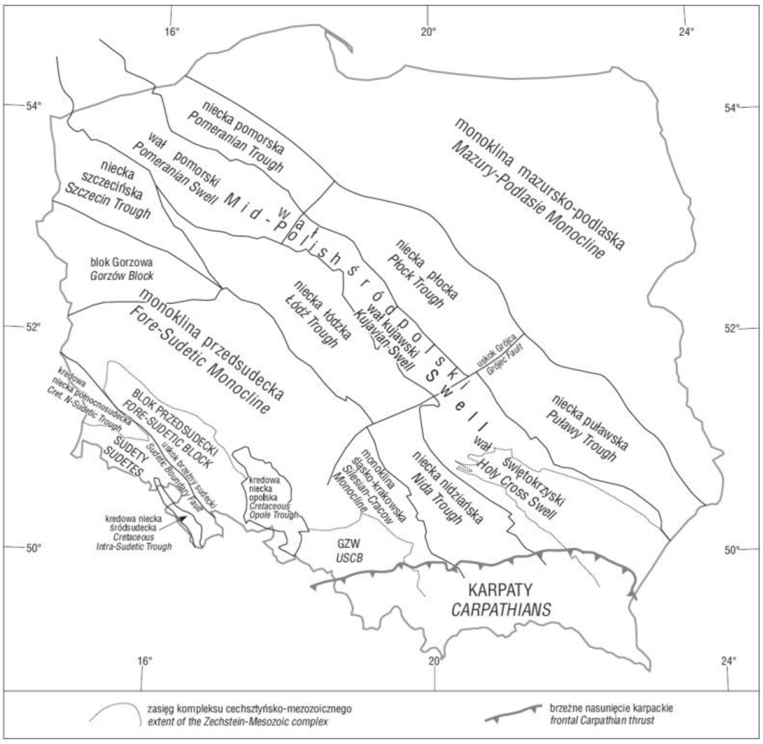


Fig. 2. Conventional structural units designated at the pre-Cenozoic surface, created in the course of the Late Cretaceous inversion of the Polish Basin (after Narkiewicz and Dadlez, 2008).

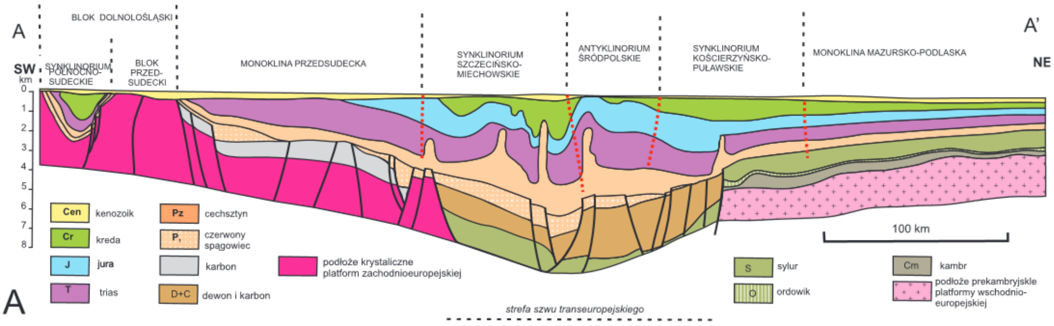


Fig. 3. Schematic profile across Poland (Żelaźniewicz et al., 2011) presenting the elevation of the crystalline basement in the Lower Silesian Block (blok dolnośląski), the slope of the peri-Sudetic Homocline (monoklina przedsudecka), the maximum thickness of sedimentary cover in the Mid-Polish Trough (synklinorium szczecińsko-miechowskie, kościerzyńsko-puławskie and antyklinorium śródpolskie) and decreasing thickness of sedimentary cover towards the interior of the East European Craton (monoklina mazursko-podlaska).

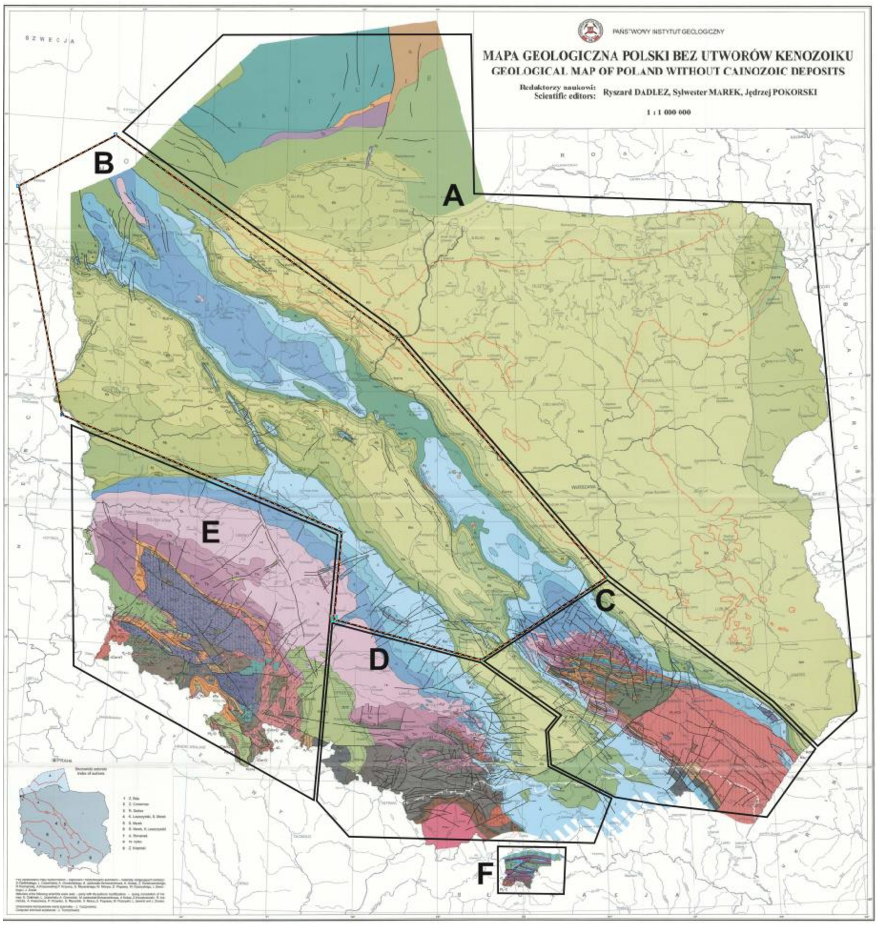


Fig. 4. The areas described within the Report chapters, on the background of the geological map of the sub-Cenozoic complex (Dadlez et al., 2000). Notice that the extent of these areas is not identical with the extent of tectonic units, used to name them.

15.2 A. East European Craton area

15.2.1 A.1. Tectonic evolution of the EEC

The basement beneath the northeastern Poland belongs to the Precambrian part of Europe known as the East European Craton (EEC). It includes the junction of two independent crustal segments of Fennoscandia and Sarmatia, that belonged to two different lithospheric plates which collided 1.80–1.78 Ga ago (Bogdanova et al., 2006). Subsequently, the Late Palaeoproterozoic crust of NE Poland was intruded (1.53–1.50 Ga) by several igneous bodies of anorthosite–mangerite–charnockite–granite suite (AMCG), forming a prominent Mazury Complex, and Warmia and Kościerzyna chain of A-type granite intrusions (Fig. A.1). The structure of crystalline basement was finally assembled during the Carboniferous (circa 345 Ma) with intrusions of at least four alkaline-ultramafic complexes localized close to Mława, Olsztynek, Ełk and Tajno. Main fault zones and single faults located in the hidden crystalline basement of NE Poland are sparsely documented. Following the interpretations from southern part of the EEC (Bogdanova et al., 2006, 2015) it is widely accepted that:

1) the main tectonic uplift of various crustal blocks, major deformation movements, faulting and metamorphism ceased at 1.79 Ga – 1.77 Ga, after Sarmatia – Fennoscandia collision.
2) Before 1.53 Ga – 1.50 Ga the new E–W and NW trending fault zones, accompanied by numerous AMCG intrusions, became dominant. The main belt of granitoids (A-type) and associated mafic and intermediate igneous rocks follows E–W trending lineament, extending from the Baltic Sea through northern Poland (Mazury), including southern Lithuania, to western Belarus.
3) Subsequent rifting of the Palaeoproterozoic basement led to development of the NW–SE oriented half-graben on the EEC margin – filled with a Neoproterozoic syn-rift volcano-sedimentary succession and being part of Late Mesoproterozoic (?)/Ediacaran structure of the Volyn–Orsha Aulacogen. The Neoproterozoic rift zones were either perpendicular (the Volyn– Orsha Aulacogen) or parallel (Tornquist Rift) to the EEC margin (Bogdanova et al., 1997; Bogdanova et al., 2008).
4) The last significant episode of crystalline basement faulting took place before the Early Carboniferous (before ~345 Ma). It was a very late stage of Middle Devonian – Early Carboniferous rifting, widespread on the EEC and its margin. In Poland it was marked by emplacement of a few prominent, deep sourced alkaline – ultramafic bodies close to Mława and Ełk and a smaller one in Tajno, with well preserved carbonatite volcanic pipe. This group of alkaline platform type intrusions (Fig. A.1) emphasize a potential zones of the local lithospheric thinning or/and discontinuity of crust, or deep faults.

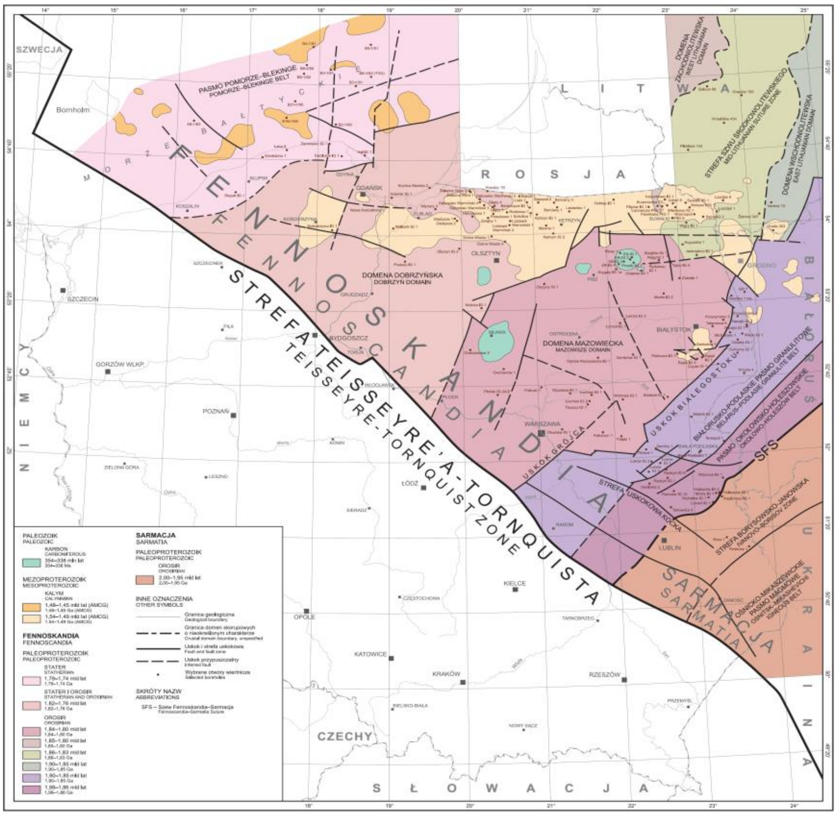
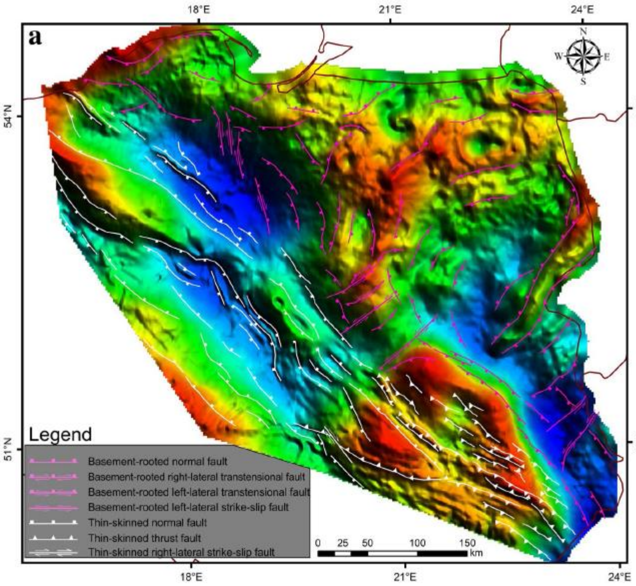


Fig. A.1. Major crustal domains of crystalline basement in the northeastern Poland (Krzemińska et al., 2017).

15.2.2 *A.2. Fault detection methods within crystalline basement.*

The A area (Fig. 4) is completely covered by Phanerozoic sedimentary rocks only 0.3–1 km thick in the region of the Mazury–Belarusian anteclize (high) in NE Poland, up to 7–8 km thick towards the south-west margin of the EEC. The fault zones in the basement have been investigated using combined geophysical surveying techniques. The location of faults and deformation zones was deduced from magnetic, gravity mapping (Wybraniec, 1999; Wybraniec and Cordell, 1994), magnetotelluric measurements (Stefaniuk et al., 2008), and seismic refraction and reflection profiles. Several deep seismic experiments have been carried out to identify the basement in NE Poland and adjacent areas: e.g. POLONAISE deep seismic sounding P3, P4 and P5 (Guterch et al., 1999) or CELEBRATION (Grad et al., 2006a). Recently this area was covered by the deep seismic reflection profiles of the ION Geophysical Poland SPAN™project. In 2012, 10 PolandSPAN™profiles (with a total length of 2200 km) were acquired in Poland over the marginal part of the EEC, east of the Teisseyre–Tornquist Zone (TTZ). Late tectonic phases (e.g. Ediacaran rifting, Caledonian orogeny) did not leave a clear signature in the deeper crust, however, some of the sub-horizontal reflectors below the basement may be linked to the Early Carboniferous magmatism (Krzywiec et al., 2018). The fault (or lineament) locations are visible on the maps of the depth to the crystalline basement and the top Neoproterozoic (Fig. A.2) – as evidenced on maps constructed with Barnes and Barraud (2012) method by Mikołajczak et al. (2019).
For EEC area including Mazury region, an integrated gravity and magnetic data modelling was performed along the refraction/wide-angle seismic reflection profile P4 (Fig. A.3).

The gravity and magnetic models of the crust and upper mantle, down to the depth of 60 km along the P4 profile, show several crustal discontinuities along the Mazury complex where fault zones bound crustal domains that differ in potential field character. Moreover a numerous drill cores (more than 100 deep boreholes) from the area of Suwałki Anorthosite massif show vestiges of tectonic activity.



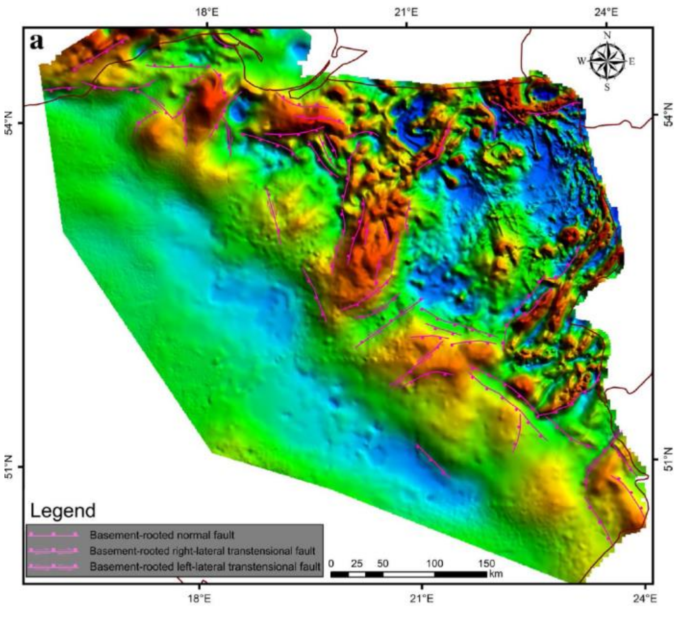


Fig. A.2. Two examples of qualitative interpretation of gravity and magnetic data (left: Bouger gravity) (right: magnetic anomaly map) (Mikołajczak et al., 2019).

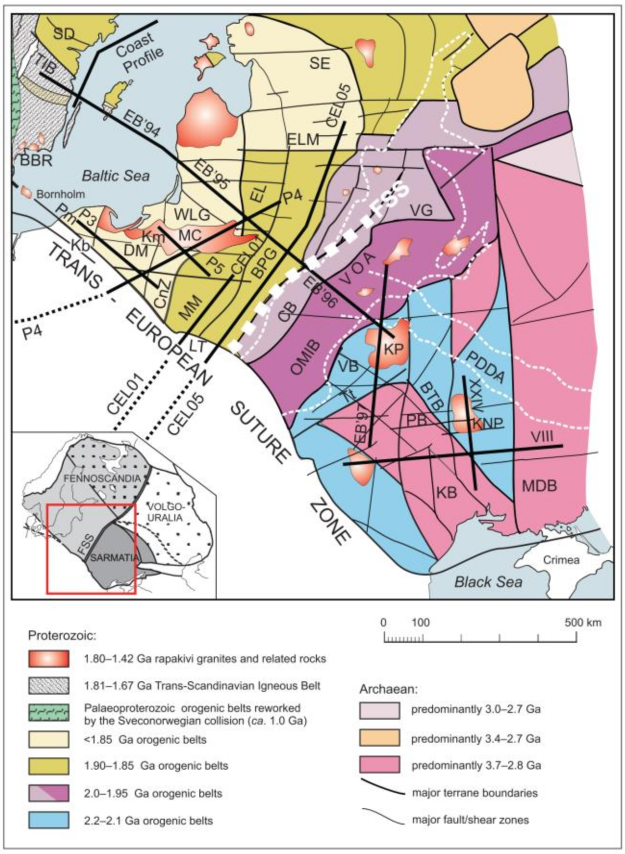


Fig. A.3. Location of refraction and wide-angle reflection deep seismic sounding profiles on a simplified tectonic map of EEC (Grad et al., 2006b).

15.2.3 A.3. Fault Zones and Fault Systems

Teisseyre–Tornquist Zone (TTZ) is the longest geophysical and tectonic NW–SE lineament in Europe, extending from the Skagerrak in the eastern North Sea Basin and Southern Baltic to the Black Sea. This lineament is divided into the Sorgenfrei–Tornquist Zone (STZ) to the NW and the Teisseyre–Tornquist Zone (TTZ) to the SE. The TTZ is a crustal boundary between Precambrian East European Platform (EEP) and the Palaeozoic West European Platform (included in the B section of this Report). Despite of several geophysical experiments, its course, geometry and origin are still poorly constrained. Deep seismic reflection profile POLCRUST-01, recently acquired in SE Poland, provided a more precise comparison of the Ediacaran and later tectonic patterns with the deep crustal features of the TTZ. The TTZ corresponds to the subvertical Tomaszów Fault separating the Radom–Kraśnik Elevation, composed of the typical EEP crust, from the Biłgoraj–Narol Block (BNB) to the SW. To the NW, the zone extends towards the Pomeranian part of the Caledonide fold-and-thrust belt related to the Avalonia–Baltica collision zone (Thor Suture). *The Baltic Sea faults* (Fig. A.4). Geological data derived from the basement-deep boreholes and the analyses of seismic reflection profiles led to the interpretation of the structure of southernmost Baltic Sea (off shore area). Reflection seismic investigations were focused on three major seismic boundaries, including the top of Proterozoic.

Consequently this area has been subdivided into several tectonic blocks, characterized by similar geological structure of the crystalline basement and its sedimentary cover, and separated by faults deeply rooted in the Late Palaeoproterozoic basement. The number of blocks resulting from the analysis and generalization of their tectonic activity differs in previous reports (Pokorski, 2010) but the fault systems and fault zones are almost the same. *Darłowo, Ustka, Smołdzino and Łeba Fault Zones.* The fault zones (or faults) Darłowo, Ustka and Łeba are almost parallel to the TTZ direction. The magnetotelluric investigations (Stefaniuk et al., 2008), performed on the profile running along the shore line (Smołdzino–Szczecin), show that the Ustka and Smołdzino Fault Zones are rooted in the crystalline basement to a depth of approximately 10 km (top of the basement is at ~3000 m). A similar pattern of the fault/fracture zones distribution was described in the exposed Bornholm area. The Bornholm horst block together with the surrounding fault blocks make up an integral part of the composite TTZ in the southern Baltic Sea. *Sambia, Żarnowiec, Kuźnica Fault zones.* The meridional, N–S-trending Smołdzino and Kuźnica fault zones and the longitudinal (E–W) Samlino Fault Zone and the Sambia Fault are rooted in the crystalline basement. All these faults controlled the Late Paleozoic evolution of the sedimentary cover (Pokorski and Modlinski, 2007). The westernmost border of *Mazowsze domain* (Fig. A.1) is visible as one of the most prominent Y-shaped magnetic and gravimetric anomalies north to the TTZ (Wybraniec, 1999). This area was penetrated by only a few deep boreholes, that document different evolution of crystalline rocks on both sides of the anomaly. Furthermore, the NE section of the deep seismic profile P4 (800-km long), that runs obliquely through the Mazowsze domain (MD) and adjacent Dobrzyń Domain, as well as short, perpendicular profile P5, allow to register discontinuities and differences of Moho depth boundary. An additional argument for this fault zone is an alkaline intrusion fed by deep mantle magmas. *Białystok Fault* is located in easternmost Poland along the border of Palaeoproterozoic structure known as Belarus Podlasie Granulite belt (BPG). The BPG is made up of several SW–NE trending large lens-shaped bodies of highly metamorphosed rocks (granulite facies), separated from each other by zones of shearing and faulting. In the regional context of EEC this NE-trending zone is also known as Grodno–Bialystok deformation zone, which defines the NW limit of the BPG and truncates obliquely the essentially NW–SE-trending array of various Fennoscandian belts and domains, which are bent and displaced in the vicinity of this boundary. It is interpreted as one of the major shear zones penetrating the entire crust within the suture zone, related to the 1.82 Ga – 1.80 Ga Fennoscandia – Sarmatia collision. The presence of Mazury Fault Zone in the crust was deduced from the linear chain of intrusions. A regional E–W-trending lineament in the northern Poland and southern Lithuania, detected by the magnetic and gravimetric mapping, is related to Mazury (Poland) and Veisiejai (Lithuania) complexes, which are made up of anorthosite, mangerite charnockite and granite series. The fault zones recognized within the East European Craton are presented in the Fig. A.8.

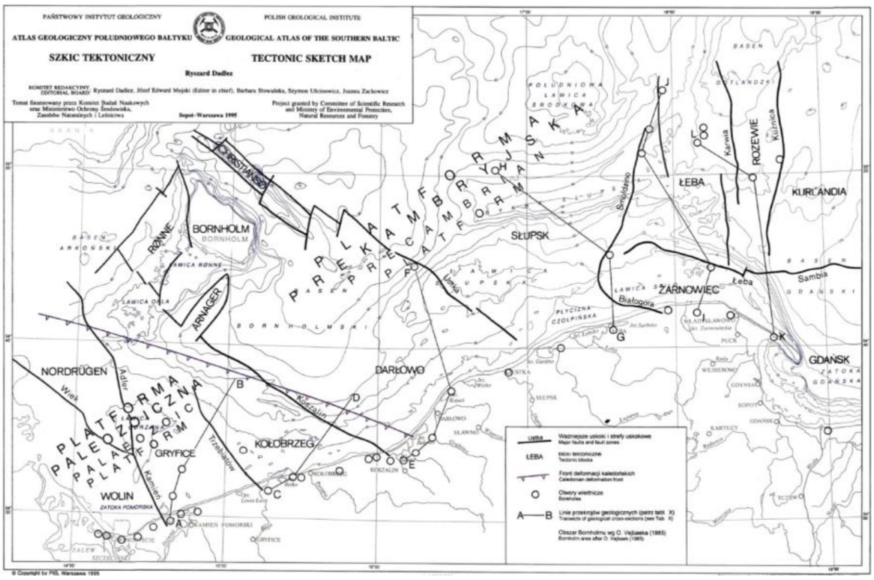


Fig. A.4. Fault zones in the bottom of the Baltic Sea according to: Dadlez, 1995 and Brzozowski, Domżalski, 2006.

15.2.4 A.4. Lublin Basin margin of the EEC

Lublin Basin, located at the edge of the East European Craton (EEC) is the Variscan structure. In the Early Palaeozoic this area was a marginal portion of the Baltica plate occupied by the proximal part of the foreland basin involved in the Caledonian collision with Avalonia (Poprawa, 2006). During the Variscan orogeny, the subsidence of the Lublin Basin developed in response to the multiphase collision occurring in the inner part of the Variscan belt. The mechanism of Variscan subsidence at the edge of Baltica and within the Lublin Basin and the role of main faults bounding and transecting the Lublin Basin are still a matter of discussion (Narkiewicz et al., 1998). Recent interpretations emphasize the role of the thin-skinned tectonics in the basin inversion stage (Fig. A.5), which overprints the basement-involving faults active in the previous basin subsidence stages (Fig. A.6). The recognition of faults in the Lublin Basin relays mostly on the 2D seismic profiling and the borehole data. Due to the overprint of thin-skinned compressive tectonics, within the basin you would find anticlinal zones that we omitted in this Report, which is focused on dislocations. Although the locations of fault zones are well established their kinematics is still disputable.

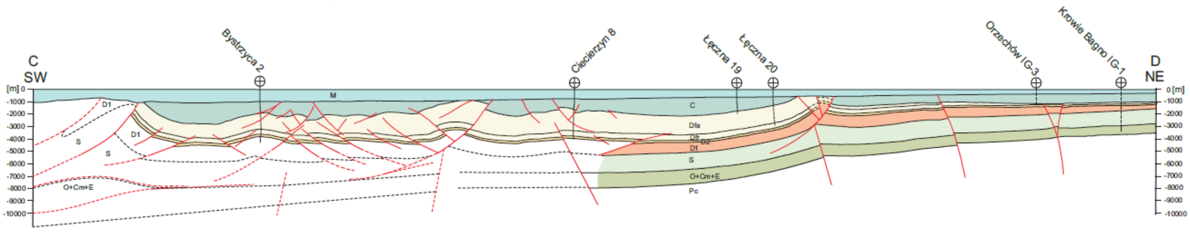


Fig. A.5. Interpretation of seismic profile across the Lublin Basin, after Tomaszczyk, 2016. For location see Fig. A.6 and Fig. A.7.

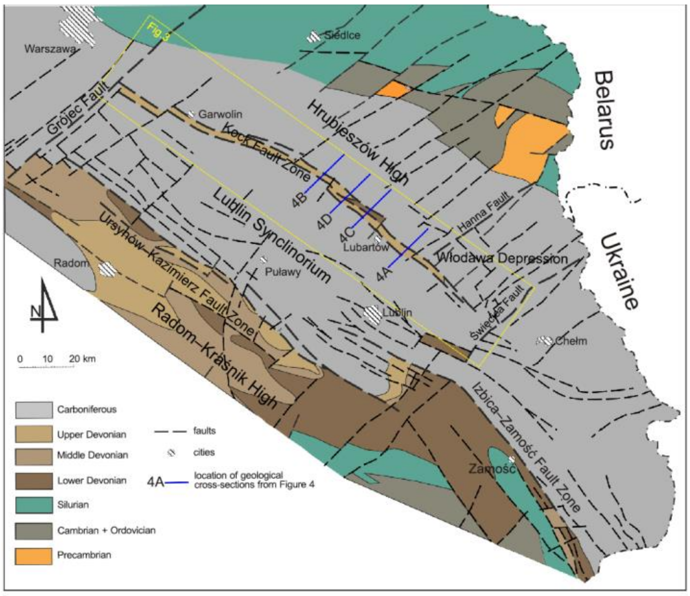


Fig. A.6. Tectonic map of the Lublin Basin after Żelichowski and Kozłowski, 1983, modified by Tomaszczyk and Jarosiński, 2017.

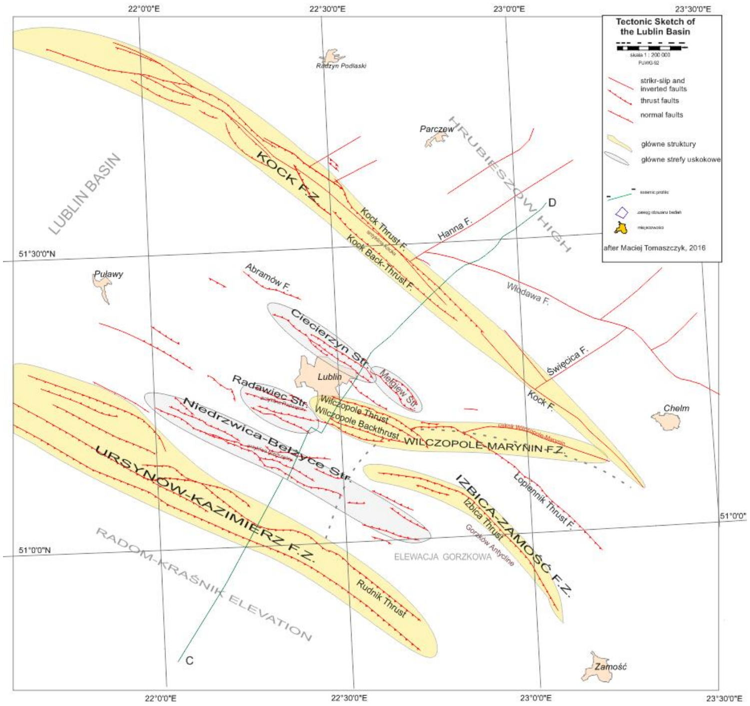


Fig. A.7. Fault zones of the Lublin Basin on the background of tectonic map of Tomaszczyk (2016).

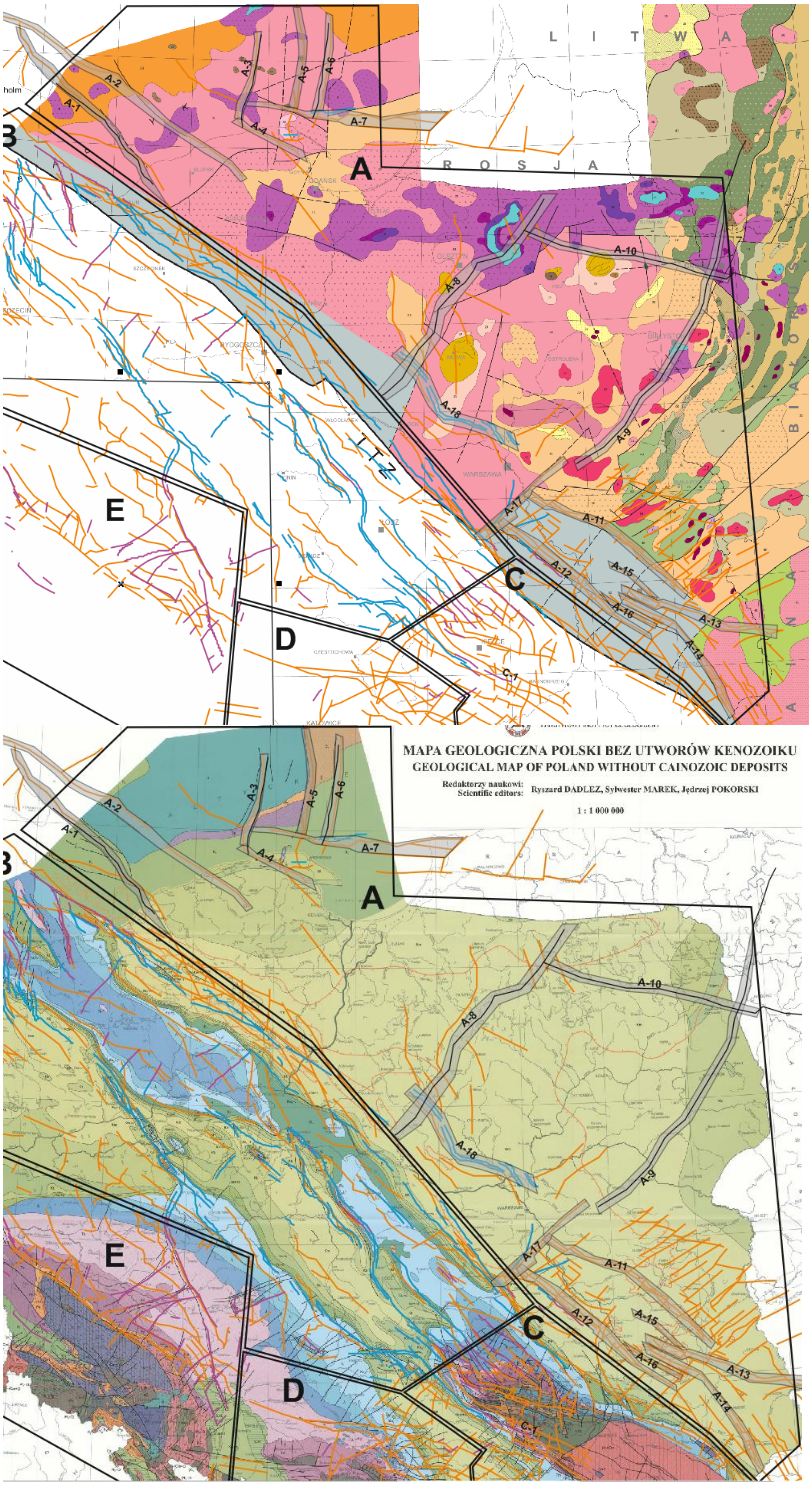


Fig. A.8. Fault zones (transparent grey) of the East European Craton area. Upper sketch: on the background of the geological map of Precambrian at the EEC after Krzemińska et al. (2017). Lower sketch: on the background of the geological map without Cainozoic after Dadlez et. al. (2000). Faults marked by orange, blue, purple and black are taken from different data sets.

15.3 B. Northern segment of the Trans-European Suture Zone (TESZ)

15.3.1 B.1. Tectonic evolution of the northern TESZ segment

The TESZ is a major polygenetic tectonic unit trending from the North Sea to the Black Sea (Pharaoh, 1999). In this chapter, we consider the northern, Polish segment of the TESZ, in which the thickness of the sediments reaches over 10 kilometres, as evidenced in deep seismic sounding data (Grad et al., 2002).

Pre-Zechstein basement formation. Due to the large thickness of the sedimentary cover in the TESZ area, the crystalline basement has not been reached by boreholes, so the origin of individual blocks of the substrate can only be presumed on the basis of geophysical data. The basement probably consists of tectonic blocks of the Baltica and Avalonia provenance (Mazur et al., 2018; Jarosiński and Dąbrowski, 2006). The oldest sediments and magmatic rocks at the edge of the EEC indicate the Neoproterozoic break-up of Panotia, resulting in development of the passive continental margin of Baltica and the Tornquist Ocean (Poprawa et al., 1999; Poprawa and Pacześna, 2002), at the place of the current TESZ. In the Ordovician and Silurian, the subduction of the Tornquist Ocean plate beneath the Eastern Avalonia initiated its collision with Baltica. The vast suture area of this collision, comprising blocks of the Baltica and Avalonia origin, is called the Trans-European Suture Zone (TESZ) (Thybo, 1997). This area, with tectonically and thermally weakened crust, in contrast to the adjacent rigid crust of the EEC, was prone to successive tectonic deformations. In the subsequent Variscan tectonic stage, the TESZ area was located in the distal foreland position with respect to the collision zone of Eastern Avalonia (being a part of the Laurussia plate) with Armorica. Scarce seismic data from the Palaeozoic basement of the northern part of the TESZ indicate large extensional episode coeval with the Carboniferous magmatic event in the East European Craton (EEC) (Poprawa, 2019). In the late Carboniferous, the Variscan thrust-and-fold belt covered the area of the Fore-Sudetic Homocline while the northern segment of TESZ was probably covered by the foredeep basin deposits, which are however sporadically reached by boreholes. As a result of the collision and the following wrenching event (Thybo, 1997; Pegrum, 1984), the ancient faults were reactivated and the basement block pattern was formed – similar to what we currently see in the area.

Zechstein–Mesozoic overprint. After the Permian stage of erosion and sedimentation in terrestrial conditions, a thick complex of Zechstein evaporites was deposited in the Southern Permian Basin (Doornenbal and Stevenson, 2010), eastern segment of which covered the majority of the current area of Poland. Thick salt rock complexes create mechanical decoupling horizons between the Palaeozoic basement and the Mesozoic cover strata. In the subsidence centre of the Polish Basin (Mid-Polish Trough) the Triassic, Jurassic and Cretaceous sediments reached a total thickness of up to 6 km. In the Mesozoic, multiple selective reactivation of basement faults took place, over which the Mesozoic cover was also deformed. The first, Early Triassic episode of faults reactivation caused the formation of normal faults and the initiation of the first salt pillows (Dadlez, 1980; Raczyńska, 1987; Krzywiec, 2006). Such a structure as the Krośniewice graben gave rise to the development of the largest salt structures in the Polish Lowlands. The next phase of faults reactivation dates back to the Late Triassic – Early Jurassic when the strike-slip displacement along the weakest basement fault zones led to the formation of transtensional grabens in the Mesozoic cover. Some of these structures initiated the breaking of the salt through the top of Zechstein, which in turn triggered successive raise of the salt diapirs. In Late Cretaceous, the multi-stage inversion of the Mid-Polish Trough (Dadlez, 1980; Krzywiec and Stachowska, 2016) resulted in the strike-slip and thrust fault reactivation of major basement faults, associated with buckling of the Mesozoic complex, compensated by salt pillows. This major tectonic phase (also called Laramide phase) shaped the present-day structure of the sub-Cenozoic surface.

Cenozoic modification. Major Cenozoic deformations were related to the collision in the Alps and the Carpathians, which culminated in the Oligocene and the Miocene (Jarosiński et al., 2009). As a result of plate bending and active stretching driven by slab pull mechanism, the Carpathian foredeep basin developed in the southern segment of TESZ. In the northern segment of the TESZ, selective reactivation of Mesozoic faults led to the development of grabens and minor reactivation of salt diapirs.

15.3.2 B.2. Faults in the northern TESZ segment

The efficacy of fault detection in the northern TESZ segment is largely determined by the intensity of industrial exploration, mainly by the oil industry. The most direct information about fault locations and geometry is obtained from seismic surveys. Most of the northern part of TESZ is covered by the network of 2D seismic profiles (Fig. B.1), which are easily used to survey the location of major faults. The geometry of individual fault surfaces can be determined from the 3D seismic images, which however, cover only a few percent of this area.

The present distribution of dislocations in the TESZ is the result of rifting and accretion of tectonic blocks and their relative displacement in subsequent tectonic phases. Large-scale displacement along the TESZ during the Caledonian collision, advocated by Brochwicz-Lewiński et al. (1981), can be correlated with the previously mentioned oblique collision of Avalonia with Baltica (Poprawa, 2006). The TESZ tectonic blocks assembled in the Caledonian times were also, most probably, displaced by the transcurrent faults during the Variscan collision, and on the minor scale, modified again by strike-slip faults in the Mesozoic. However the effects of this multiple wrenching have not yet been properly reconstructed, and the extent of the main tectonic blocks in the basement can only be presumed based on the shape of younger complexes, the density of the faults and clues given by low resolution deep seismic sounding data (Guterch and Grad, 2006). Fault pattern under Permian salt is much less recognized than in above-salt layers (Fig. B.2). The reason for this is the significant contrast of impedance within the Zechstein evaporites, which contribute to intense reflection of the seismic signal. Reliable seismic reflections from the Palaeozoic basement covered by the thick Zechstein complex are usually not recorded. The deepest reliable information about the basement faults is provided by the base of Zechstein seismic reflector, which is the last, clearly visible seismic horizon. In this case, however, seismic data record only faults that were reactivated in Permian and later. Despite these limitations, the fault network interpreted at the base of Zechstein is much denser than the Mesozoic fault network. The correctness of such an interpretation is indirectly proved by the observations of a dense faults system in the southern TESZ segment, where the Zechstein evaporites are absent. In both segments, most basement faults strike parallel to the trend of the TESZ. Thick Zechstein complex in the northern TESZ segment is the reason for mechanical decoupling of the Palaeozoic and Mesozoic complexes, that contributes to different character and shape of faults on both structural levels. E.g. en echelon array or horse-tail pattern of faults are observed in the Mesozoic complex where individual faults are oblique to the basement faults underneath. Such fault arrangement seems to result from compensation of strike-slip motion in the basement controlled by mechanical decoupling across the Zechstein salt layers. Due to the high salt mobility, salt pillows and domes were formed over the reactivated basement faults (Fig. B.3).

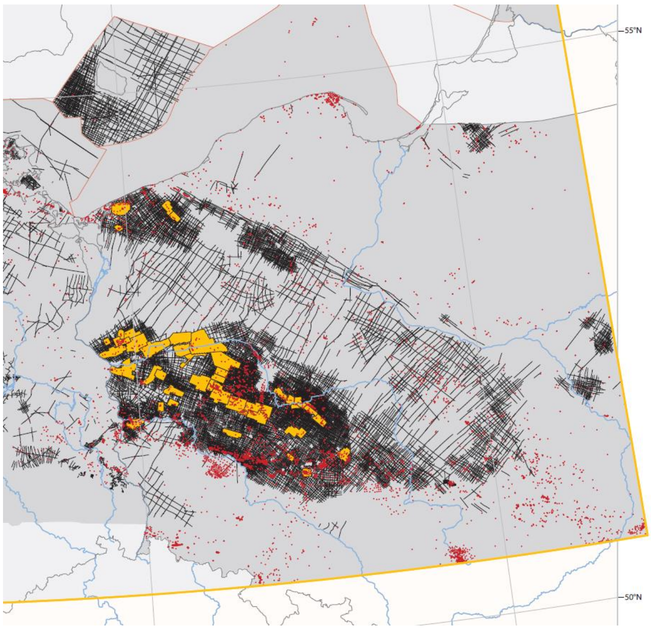


Fig. B.1. Distribution of seismic lines (black lines), 3D seismic images (yellow areas) and deep boreholes (red dots) in the northern TESZ segment (after Doornenbal and Stevenson, 2010*).*

In the map view, the TESZ fault zones often have sigmoidal shapes and create an anastomosing pattern, which is also reflected in gravimetric lineaments (Wybraniec, 1999). This pattern is characteristic of strike-slip shear zones in the basement (Fossen and Cavalcante, 2017). Such a shape of faults causes problems when determining the range of individual fault zones, which often split and merge around tectonic blocks. In this sense, the range of the fault zones (depicted in this Report) is subjective and often depends on the quantity and quality of seismic data.

Within the TESZ, 21 fault zones have been identified (Fig. B.4). All of them are rooted in the Palaeozoic basement. Almost all zones show signs of at least partial reactivation in Mesozoic and a few of them have also been reactivated in Cainozoic. Despite the large horizontal extent of these zones, usually exceeding 100 km, most of them reveal minor vertical offset, both at the base of Zechstein and in the Mesozoic complex. Vertical offsets exceeding 1 km are exceptional and are associated with mobility of the Zechstein salt. Small offset is an additional argument for predominance of strike-slip kinematics of their reactivation, which also results in the lack of the consistent direction of vertical offset in these fault zones.

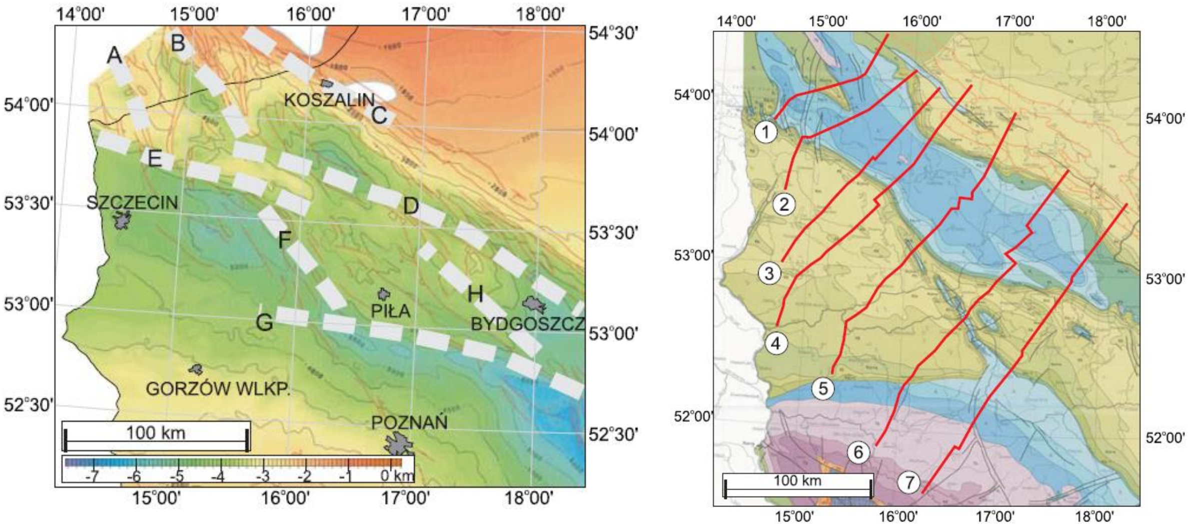


Fig. B.2. Left image – Major basement faults in the northern segment of TESZ distinguished by Krzywiec (2006); Right image – location of regional seismic lines presented in Fig. B.3 (Krzywiec, 2006).

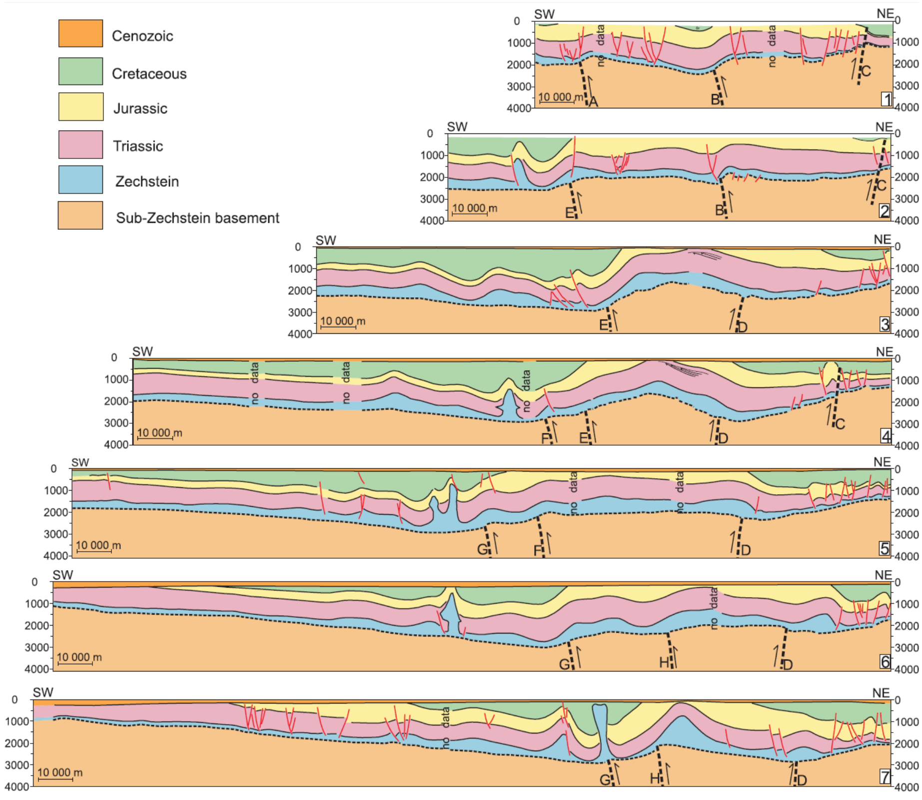
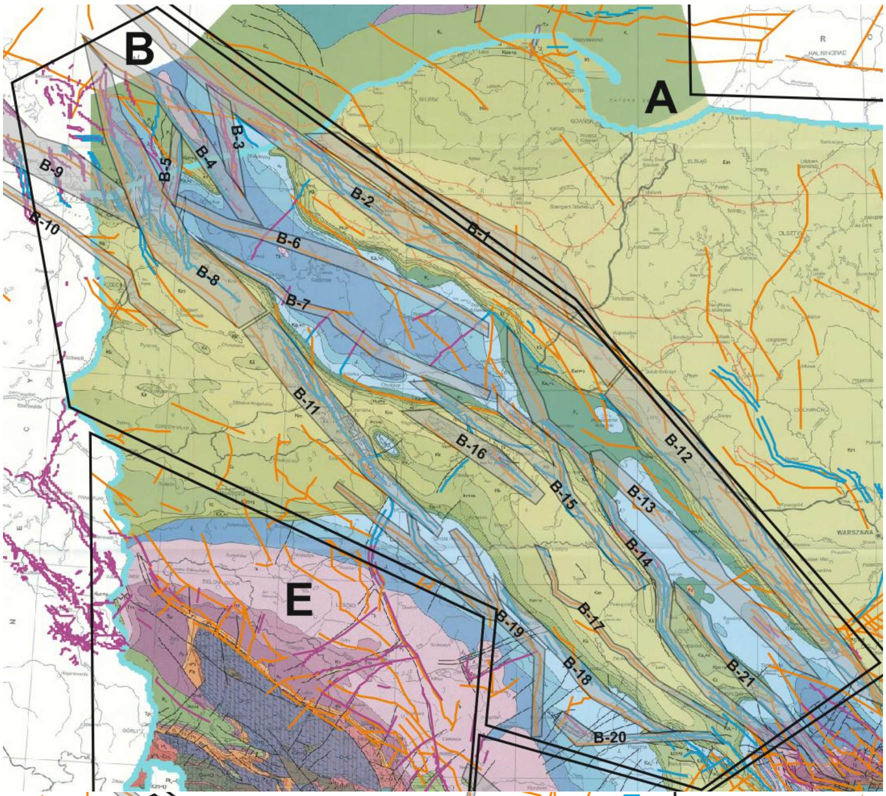


Fig. B.3. Interpretation of seismic profiles across the TESZ (Krzywiec, 2006). For location see Fig. B.2.



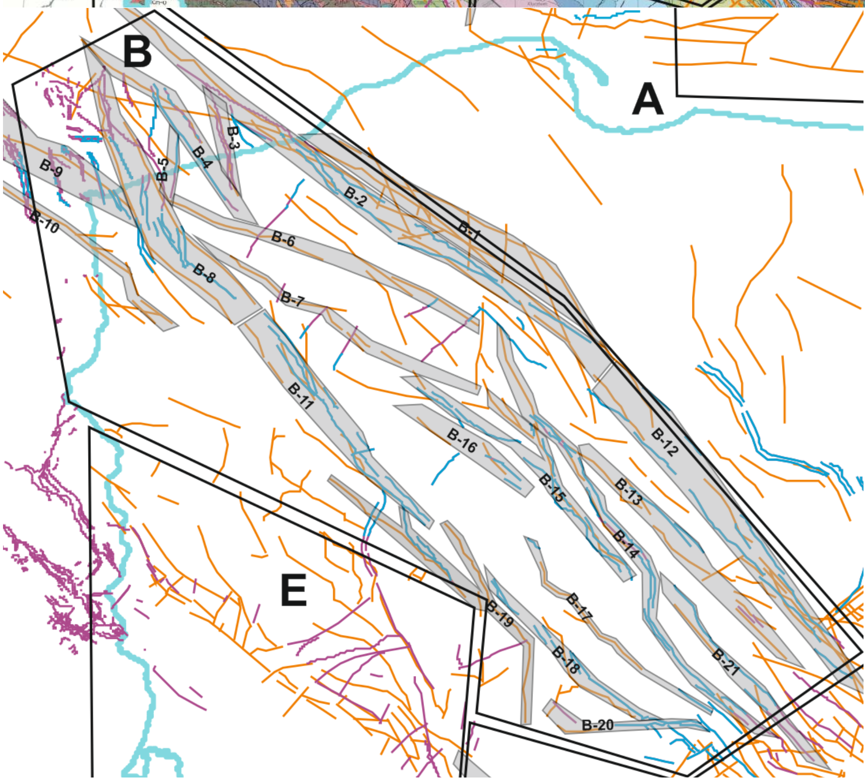


Fig B.4. Fault zones (transparent grey) of the northern TESZ segment. Upper sketch: on the background of the geological map without Cainozoic (after Dadlez et. al., 2000). Lower sketch: without background. The faults marked by orange, blue, purple and black are taken from different data sets.

15.4 C. Southern segment of the Trans-European Suture Zone

Tectonic evolution of the southern segment of the TESZ led to the formation of two distinct units: the Holy Cross Mountains (HCM) to the NW and the Małopolska Block to the SE (Fig. C.1 and C.2).

15.4.1 C.1. Holy Cross Mountains

The Holy Cross Mountains (HCM) consist of the Palaeozoic core and the surrounding Permian–Mesozoic cover. Two main tectonic units form the Palaeozoic core – the Łysogóry Unit to the N and the Kielce Unit to the S. The geotectonic character of the HCM crystalline basement is still under debate, mostly due to the lack of deep borehole data. The Palaeozoic basement of the HCM consists of folded Cambrian, Ordovician, Silurian, Devonian and Lower Carboniferous sedimentary rocks crosscut by numerous faults and meso-scale diabase and lamprophyre intrusions and metamorphic phyllites (Salwa, 2006; Salwa and Jarosiński, 2006). The main units are bounded by repeatedly reactivated WNW–ESE-trending Łysogóry Thrust (the Świętokrzyski Fault), which was a normal fault during the deposition of the Cambrian clastic rocks in the Middle to Late Cambrian and Tremadocian. The dominant trend of the oldest fold axes and faults is sub-latitudinal. Later Caledonian movements at the turn of Ordovician and Silurian and during Silurian and Devonian, led to the tight folding of the entire Lower Palaeozoic complex with the WNW–ESE trending axes. Both main tectonic units of the HCM came together at the end of Silurian. In the Caledonian geotectonic phase the Kielce Unit became part of the old-red land, while the northern Łysogóry Unit became part of the foredeep (Narkiewicz, 2002). During Ludlow and Early Devonian, the WNW–ESE strike-slip faults in Kielce Unit triggered intrusions of igneous rocks (Kowalczewski, 1974, 2004; Nawrocki, 1999). In the Middle Devonian, a system of sub-meridian normal faults was formed which controlled sedimentation of carbonates. In the Late Carboniferous, the Variscan folding and thrusting event took place in the HCM, that led to the overprint of WNW–ESE trending folds. The old, mainly longitudinal WNW–ESE fault zones, including the Łysogóry Thrust, were reactivated. Along it, the Cambrian rocks of the Łysogóry Unit overthrusted (by several kilometres) the Devonian and Carboniferous formations of the Kielce–Łagów Synclinorium in the Kielce Unit (Czarnocki, 1950, 1957; Kowalczewski, 2004). The folding stage finished with strike-slip motion along longitudinal and sub-meridian faults, some of them forming a characteristic horse-tail pattern. At that time, the next generation of diabase intrusions in the Łysogóry Unit and of lamprophyre intrusions in the Kielce Unit was emplaced (Kowalczewski, 1974, 2004; Nawrocki et al., 2014) and the HCM area was disintegrated by normal faults into horsts, grabens and half-grabens. In the northern part of the Łysogóry Unit, Skrzynna Fault was active, that bordered the HCM from the N and Odrzywół–Jastrząb–Ćmielów Graben (structural equivalent of the Lublin Basin) from the S (Kowalczewski, 2002). In the Zechstein, the HCM area was denudated (Kowalczewski and Rup 1989; Kuleta and Zbroja, 2006).The Permian–Mesozoic sedimentary cover of the HCM was deposited in the southern extension of the Mid-Polish Through. However, here the deposition of Zechstein, Triassic, Jurassic and Cretaceous sequences was interrupted by denudation. Old fault zones were reactivated and new faults were formed trending mainly in the NW–SE direction (Kutek and Głazek, 1972; Kutek, 1994; Hakenberg, 1978; Hakenberg and Świdrowska, 1998, 1999; Kowalczewski, 2004). At the end of Cretaceous, the Mesozoic complexes were slightly folded and uplifted, forming the southern segment of the Mid-Polish Swell (Znosko, 1966, 1984, 1992; Pożaryski, 1974) and the adjacent Nida and Puławy Trough.

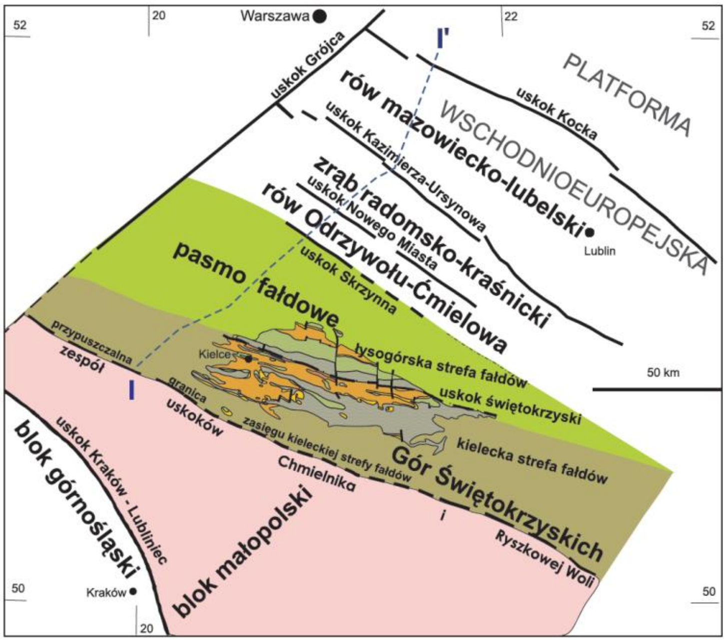


Fig. C.1. Tectonic blocks in the southern segment of the TESZ and the transition to the EEC (after Żelaźniewicz et al., 2011)

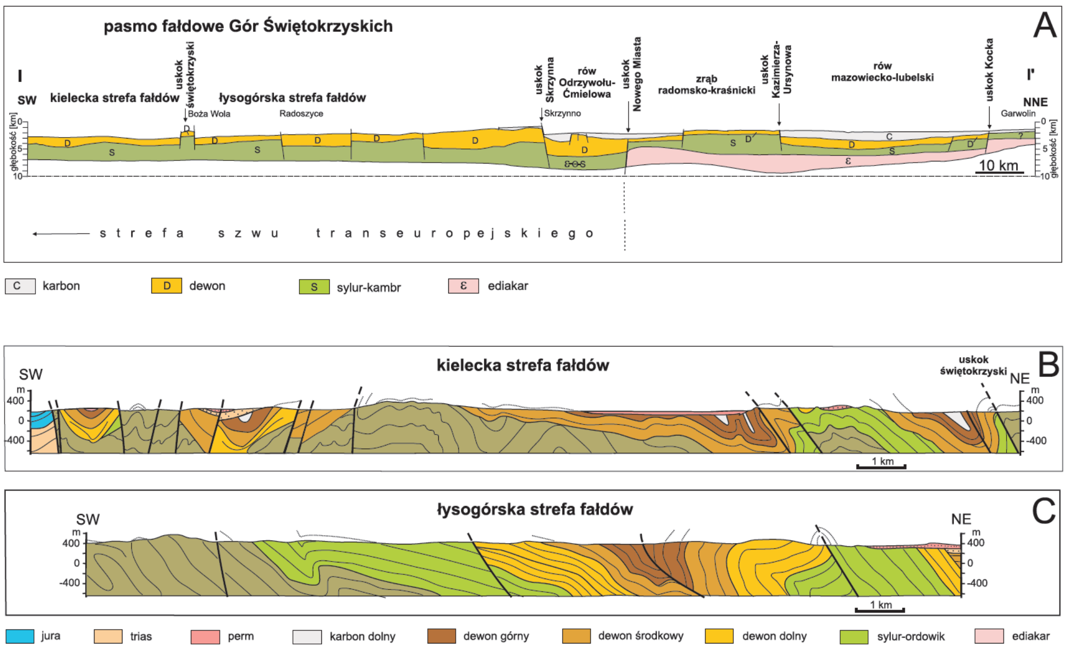
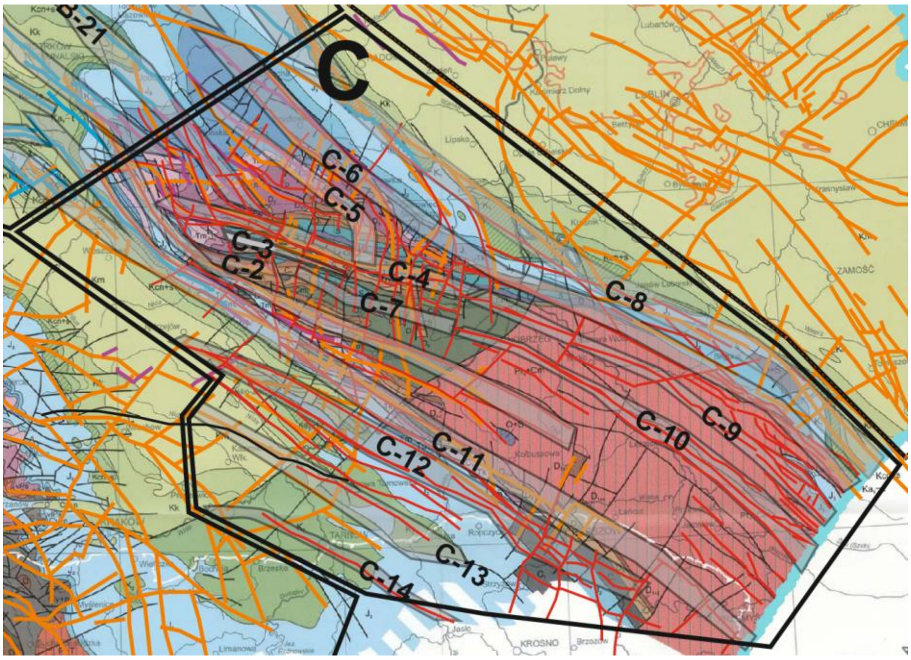


Fig. C.2. (A) Schematic cross-section through the Holy Cross Mts. and the EEC margin with major fault zones indicated; notice that internal structure of tectonic block is simplified to stratigraphic units representation. (B) tectonic cross sections through the Kielce and (C) Łysogóry unit; (all after Żelaźniewicz et al., 2011)

15.4.2 C.2. Małopolska Block

The Małopolska Block consists of the metamorphic core of the Małopolska Massif and the adjacent sedimentary complexes, which are all covered by the Miocene Carpathian Foredeep deposits. The Precambrian basement is made of of tectonically deformed Ediakarian flysch complexes that were folded in the Cadomian tectonic stage and mildly metamorphosed to the anchizone facies, in the centre of the massif (Żelaźniewicz et al., 2011). In the NE part of the Małopolska Block, the Ordovician and Silurian clastic and carbonate rocks cover the metamorphic core, while to the S, the Upper Palaeozoic complexes are present. The Paleozoic complexes on both sides of the Małopolska Massif were involved in multiple faulting stages which led to their disintegration and only local preservation in small tectonic blocks. The entire block was covered by different layers of the Mesozoic sedimentary sequences belonging to the Polish Basin, which, however, are preserved fragmentarily, mostly in the Nida Trough. During Cainozoic the Małopolska Block was initially uplifted and deeply eroded (the Meta-Carpathian Swell) due to lithosphere buckling related to the Carpathian compression (Jarosiński et. al., 2009).

Then, in the Miocene, the Carpathian Foredeep basin developed due to plate bending driven by subduction and collision in the Carpathians. In the Małopolska Block faults were surveyed by the dense network of industrial seismic profiles (Buła and Habryn, 2008), except for the metamorphic core of the massif, where faults are not detectable. The most visible are faults, which were reactivated during the foredeep stage of the block evolution. These faults indicate minor longitudinally distributed extension, related to plate bending. In general the high density of the fault network is observed, with dominant NW–SE and WNW–ESE trends which are characteristic of the TESZ. The wrenching kinematics of this major fault zone is expected, however, not sufficiently documented by data. The fault zones distinguished for the southern TESZ segment are presented in the Fig. C.3.



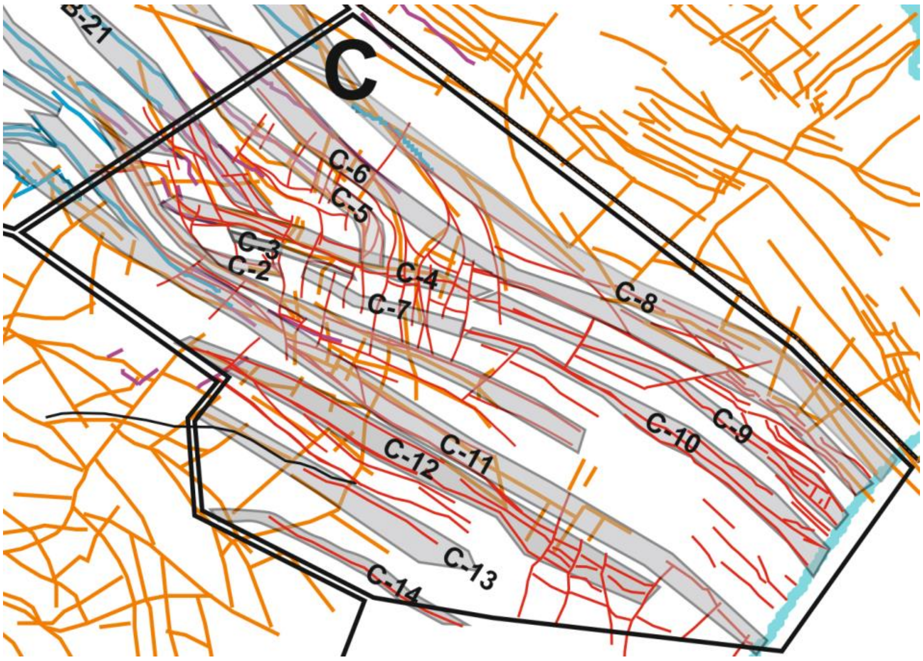


Fig. C.3. Fault zones (transparent grey) of the southern TESZ segment. Upper sketch: on the background of the geological map without Cainozoic (after Dadlez et. al., 2000). Lower sketch: without background. The faults marked by orange, blue, purple and black are taken from different data sets.

15.5 D. Upper Silesian area

15.5.1 D.1. Tectonics of the Upper Silesian Block (USB)

The D area (Fig. 4; Fig. D.1-3) featured in the central part of southern Poland covers the westernmost edge area of Małopolska Block and Polish fragment of the Upper Silesian Block of the Brunovistulicum Terrane complex (Dudek, 1980; Kotas, 1982, 1985; Finger et al., 2000; Buła and Żaba, 2008; Buła et al., 2008, 2015; Żelaźniewicz et al., 2009, 2011).

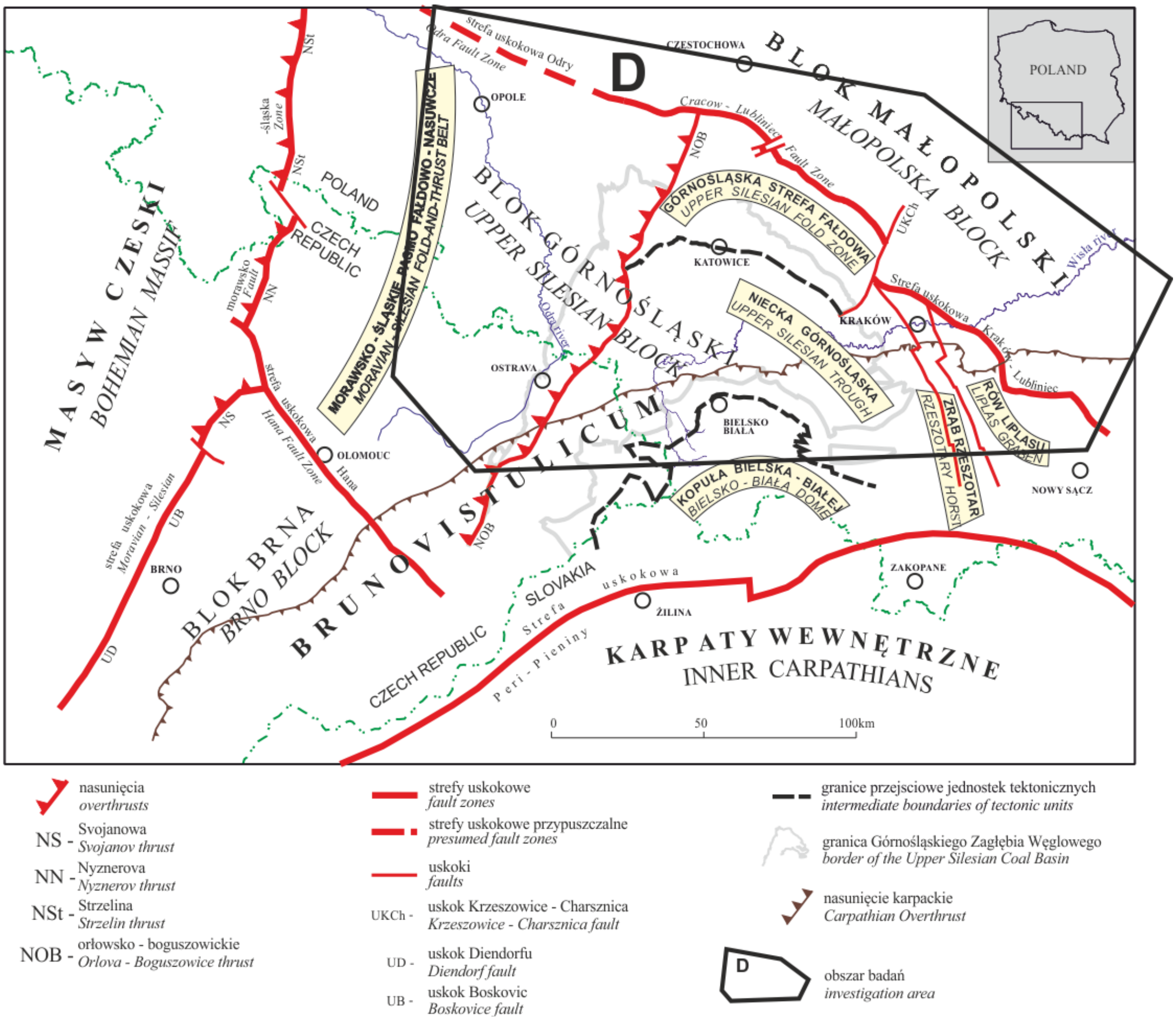


Fig. D.1. Tectonic regionalization of the Brunovistulicum Terrane (after Buła et al., 2008) with highlighted research area.

To the west, the Brunovistulicum Terrane borders on the Czech Massif. These two tectonic units are separated by the Moldanubian Thrust Zone stretching from around Vienna–Brno in the S to the Odra Fault Zone around Wrocław in the N. In the NE the Brunovistulicum Terrane borders on the Małopolska Block along the Cracow–Lubliniec Fault Zone (Buła and Żaba, 2008; Buła et al., 2008, 2015). From the S, part of the Brunovistulicum Terrane submerges underneath the Outer Carpathians, probably reaching the Pieniny Klippen Belt Suture Zone (Żaba, 1999).

The Precambrian basement of the Brunovistulicum Terrane subcrops locally on the base-Cenozoic surface in the western part of the Brno Block and in the area of the Jaseniki Massif and the Strzelin Massif (Buła and Żaba, 2008; Buła et al., 2008, 2015). In the NW part of the Brunovistulicum Terrane, within the Moravian–Silesian Fold-and-Thrust Belt (Fig. D.1), the Precambrian basement is covered by metamorphic successions of the Variscan accretionary prism (D.2. and D.3.). The prism contains fragments of the Cadomian Orogen and Upper Devonian – Lower Carboniferous flysch formations. In the Upper Silesian Foreland, the Precambrian basement submerges gradually from the S and SE to the NW underneath the sediment cover, with the sediment thickness rising from several hundred meters to over 6 kilometres. The sedimentary cover is built of the Cambrian–Ordovician sequence covered with the Variscan complex represented by Devonian–Carboniferous formations (Buła et al., 2015). This sedimentary cover underwent faulting and folding due to the Variscan collision, which took place in the adjacent Sudetic area. This deformation stage was accompanied by intense magmatism in the peripheral – NE and W part of the Upper Silesian Block. The Paleozoic complex is covered by laterally heterogeneous, discontinuous Permian–Mesozoic–Tertiary platform sediments. The Upper Silesian Block and Małopolska Block are in contact along the Cracow–Lubliniec Fault Zone, which is relatively well documented by numerous boreholes. These tectonic blocks differ in terms of the structure of their Precambrian basement and the Early Palaeozoic sedimentary cover, pointing to a major Late Palaeozoic motion between them (Buła et al., 2008).

15.5.2 D.2. Fault zones of the USB

The *Cracow–Lubliniec Fault Zone* (C-LFZ; D-1) is a long-lived shear zone, active from the Neoproterozoic to the Mesozoic with multiple records of brittle and semi-brittle deformations. Multi-phase strike-slip movements played dominant role, with sinistral transpression at the turn of the Silurian and Devonian and dextral in later periods (Żaba, 1999). The Late Carboniferous – Permian magmatism in the area (Nawrocki et al., 2010; Żelaźniewicz et al., 2009) and polymetallic mineralization (Markowiak, 2015; Oszczepalski et al., 2010) are related to the activity of Cracow–Lubliniec zone. The *Krzeszowice–Charsznica strike-slip fault* (D-2) (Żaba, 1999; Buła and Habryn, 2010) is a distinctive and well-documented fault. The sinistral strike-slip offset in a range of 12 km occured at the turn of Carboniferous and Permian. The *Tworóg–Zawiercie Fault Set* (D-3) limits the Upper Silesian Block from the north. These faults, of the Cadomian origin were being reactivated up to the end of the Mesozoic. The fault system separates the Brudzowice (Siewierza) elevation and the Permian Sławków Graben. Its maximum vertical displacement exceeds 1000 m (Markowiak and Habryn, 2020).

The *Reszotary Fault Set* (D-4) creates the horst structure in which Neoproterozoic metamorphic and igneous rocks (660–556 Ma) are elevated within the Permian complex. These faults are located at the contact of Precambrian terranes (Ryłko and Tomaś, 2010), the Archean – early Proterozoic rocks of the Reszotary horst are genetically- and age-diverse complex documented by drilling in the Cieszyn–Bielsko-Biała–Andrychów region (Buła and Żaba, 2008; Buła et al., 2015; Żelaźniewicz et al., 2009). The *Orlova–Boguszowice Thrust Fault Set* (D-6) separates structurally diverse areas within the Devonian–Carboniferous Moravian–Silesian Basin (Unrug and Dembowski, 1971). To the W of the frontal thrust are the Palaeozoic folded complexes of the Moravian–Silesian Fold-and-Thrust Belt. To the E there are the Upper Silesian foreland basin complexes. According to Kotas (1982, 1985), the structure of the Carboniferous deposits was formed as a result of the late Variscan phase (Asturian) and modified in the Alpine orogeny.The

Ruptawa and Jawiszowice Fault Set (D-7) is the W–E trending Variscan tectonic zone, accompanied by grabens and half-grabens. The southern block of this fault set, thrown down by 1000 m (Jureczka et al., 2005) with respect to the northern block, forms the northernmost extent of the Carpathian Foredeep Basin.

The *Żywiec–Nowy Sącz Fault Set* (D-8) is created by latitudinal faults of the Variscan origin, active up to the Cenozoic. The offset of the southern wall reaches 400–600 m. This fault set delineates the southern boundary of the Neoproterozoic Bielsko-Biała dome.

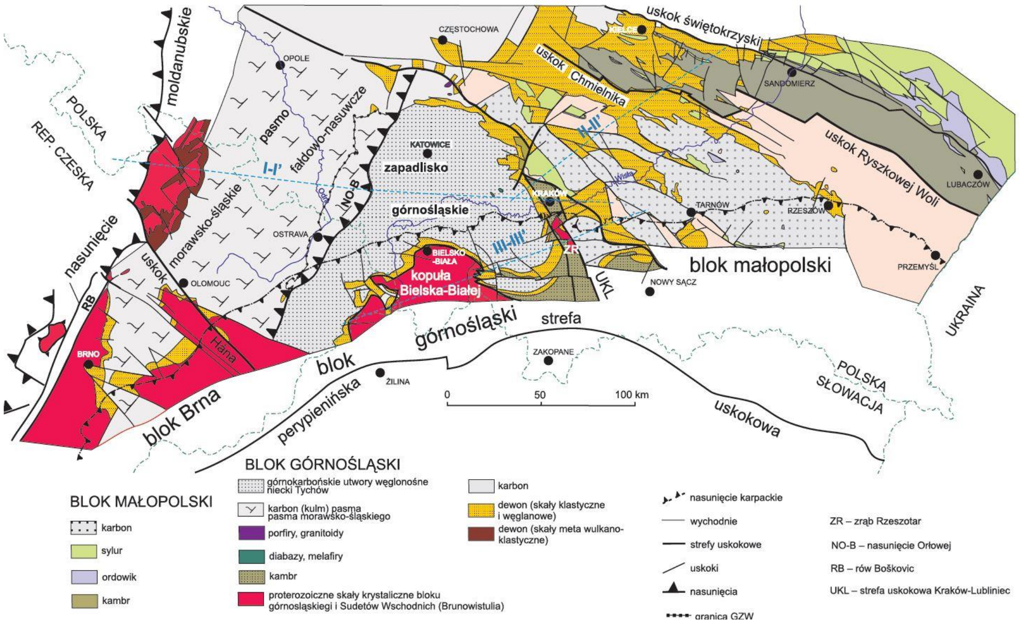


Fig. D.2 Tectonic sketch of the D area with cross-section lines presented in the Fig. D.3 (after Buła et al., 2008; Żelaźniewicz et al., 2011).

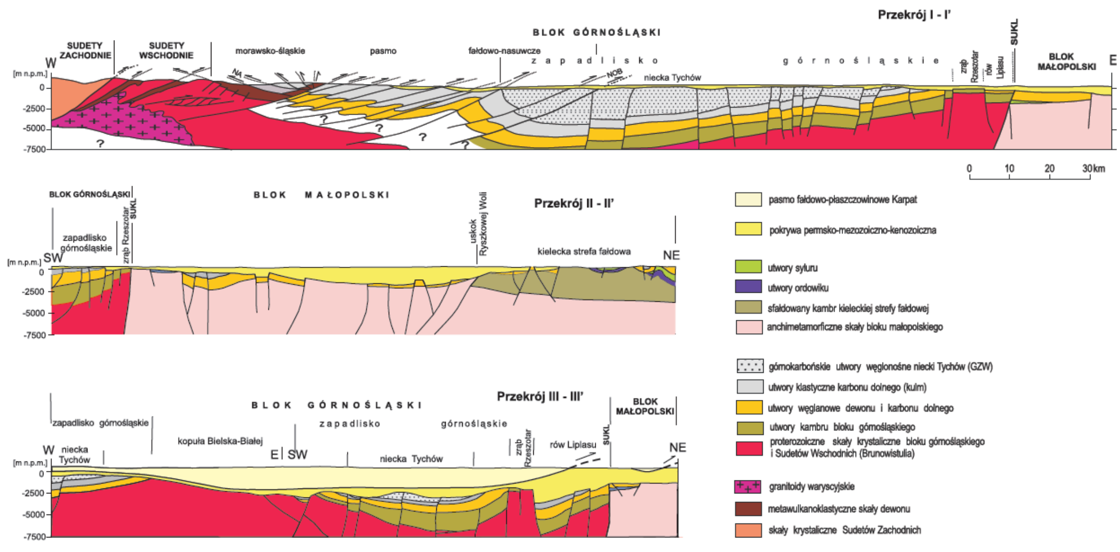


Fig. D.3 Geological profiles across the Upper Silesian Block after Buła et al. (2008) and Żelaźniewicz et al. (2011) (for location see Fig. D.2)

Major fault zones of the USB are presented in the Fig. D.4.

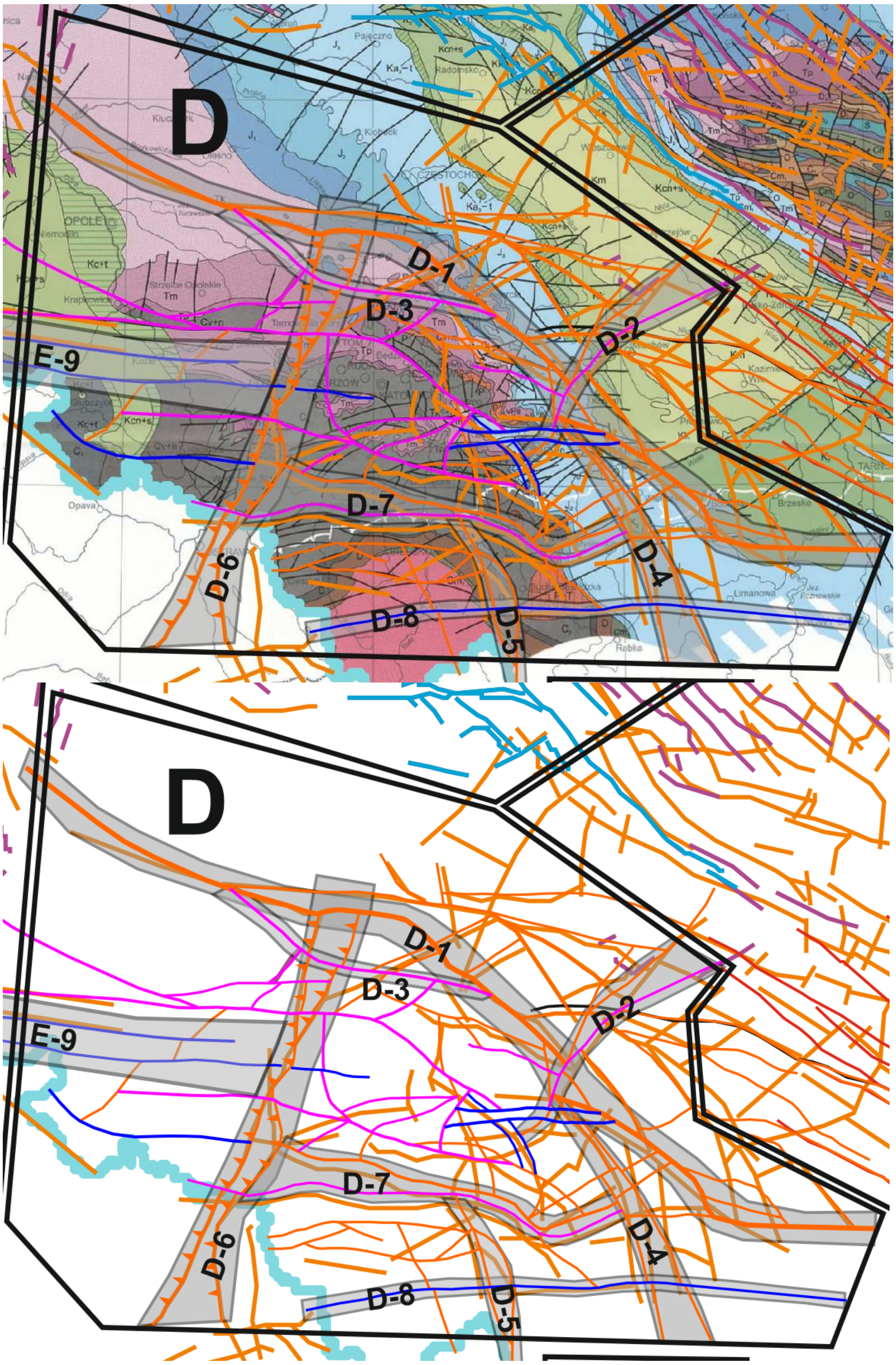


Fig. D.4. Fault zones (transparent grey) of the Upper Silesian area. Upper sketch: on the background of geological map without Cainozoic (after Dadlez et. al., 2000). Lower sketch: without background. The faults marked by orange, blue, purple and black are taken from different data sets.

15.6 E. Lower Silesian Block (LSB) and Fore-Sudetic Homocline (FSH)

15.6.1 E.1. Tectonic evolution of the LSB and FSH

The E area (Fig. 4) covers Lower Silesia and southern Wielkopolska up to the line of Pleszew – Nowy Tomyśl – Kostrzyn in the N and to the W of Opole in Upper Silesia. Geologically, the area can be divided into four tectonic units, partly representing major fault blocks (Fig. E.1). From the S to N these are the Sudetic and Fore-Sudetic blocks, followed by the Fore-Sudetic Homocline and the southernmost part of the so called Gorzów Block.

The Sudetic and Fore-Sudetic blocks expose at the surface a tectonised, mostly crystalline basement, consolidated before the end of Carboniferous and representing the internal part of the Variscan Orogen (Variscan internides). The Sudetic Block, in contrast to the Fore-Sudetic Block, is partly covered with Carboniferous–Mesozoic synclinorial basins. The Fore-Sudetic Homocline contains thick Permo-Mesozoic cover, unconformably resting on top of folded, syn- and late-orogenic, Carboniferous strata representing a piggy-back basin, incorporated into the Variscan orogen during the late stages of its development (Mazur et al., 2010, 2020). The Carboniferous is underlain with Devonian and older low-grade metamorphosed rocks, whose presence may point to a northward continuation of the Variscan internides up to this area. The part of the Fore-Sudetic Homocline located to the north of the buried Dolsk Fault Zone (**E-1** in the Fig. E.2) has its crystalline basement at depths too high to allow its direct examination through drilling. Deep seismic exploration (e.g. Grad et al., 2003) revealed a change in the crustal structure at the latter fault zone: from a 2-layer crust to the SW – typical of the Variscan belt, to a 3-layer one – considered as typical of Baltica to the NE. The latter characteristics may, however, also apply to the Avalonian type crust and it cannot be excluded that in the deep basement, the Dolsk Fault Zone marks the transition from the Armorican crust of the Variscan Sudetes into the Avalonian crust NE of it. This would imply a location of the Rhenohercynian suture along the Dolsk Fault Zone. Subsequent to the Variscan orogeny, the area in question was affected by Early Permian post-orogenic volcanism and continental sediment deposition in a regime of extension and presumed regional uplift, followed by Late Permian regional subsidence associated with setting up of the SW part of the Polish–German basin developing under mostly marine conditions. From Triassic to Late Cretaceous it underwent a number of extension pulses, subsidence and mostly marine deposition of Mesozoic strata. This was terminated with Late Cretaceous inversion and the end-Cretaceous compressional episode (cf. Kley and Voigt, 2008; Mazur et al., 2005). This episode uplifted the Fore-Sudetic Block with respect to the Sudetic one, which resulted in erosional removal of the Mesozoic deposits from the Fore-Sudetic Block and the deeper level of exposition of its erosionally uncovered crystalline complexes comparing to that level on the Sudetic Block. The Palaeogene witnessed a rather limited sedimentation over the area of SW Poland, mostly, but not exclusively, in continental conditions. The Late Miocene vigorous inversion of the Sudetes, with the Sudetic Block being uplifted and the Fore-Sudetic Block depressed, was due to the location of the Bohemian Massif within the forebulge area in front of the active orogenic fronts of the Alps and Carpathians. All the above mentioned changing tectonic conditions had their effects on the network of faults in the SW Poland, that developed and evolved from the end of Carboniferous until present.

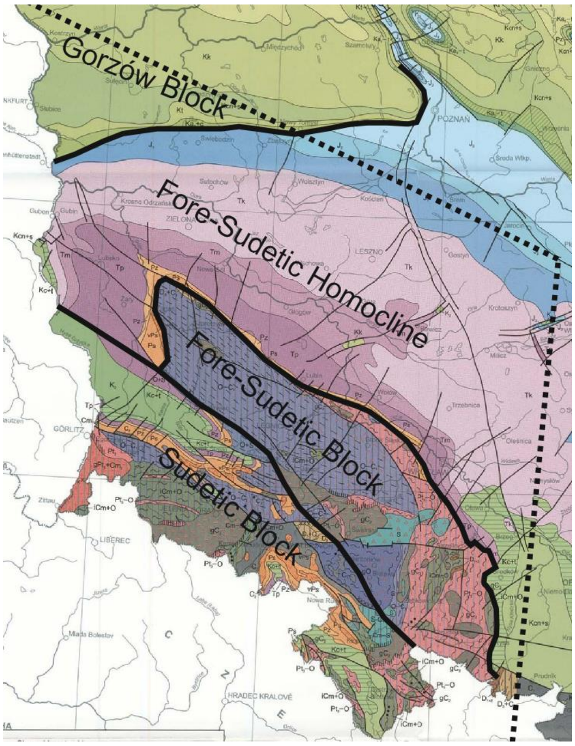


Fig. E.1. Main tectonic units of the E area on the background of the geological map without Cainozoic (after Dadlez et al., 2000). The Dotted line marks the border of the E area.

15.6.2 E.2. Fault zones of the LSB and FSH

The main fault systems of SW Poland (Fig. E.2) are in most part genetically related to the pre-Permian deep structural discontinuities in the crystalline basement (and/or in the heavily deformed Carboniferous sedimentary cover) which were either produced during the Variscan orogeny (in the Sudetes and their direct foreland) or, still, are older and presumably date back to the accretion of Armorican terranes to Avalonia (along the Dolsk Fault Zone **E-1**), by then already accreted to Baltica. The basement discontinuities, subsequently, controlled and affected the formation of overlying fault systems in the Permo–Mesozoic cover during the recurrent extensional and compressional events (cf. Ziegler and Dèzes, 2007; Jarosiński et al., 2009). In SW Poland, eight main fault systems/zones are distinguished. These are reviewed briefly below from the N to S. Roughly along the discussed area's northern boundary, below a depth of ~2-2.5 km the WNW–ESE-trending Dolsk Fault Zone (E-1) is known to subcrop at the base-Permian surface, as evidenced mainly by oil industry exploration data achieved with seismic and drillhole methods (Grad et al., 2003; Dadlez, 2006; Kiersnowski et al., 2010). This important fault zone is thus confined to the basement of the Fore-Sudetic Homocline and is bounding from the NE the Wolsztyn High that exposes pre-Carboniferous, low-grade metamorphosed Devonian and older rocks on the base Permian surface (cf. Mazur et al., 2010). Its origin is related to the Avalonia accretion to Laurasia, but better constrained is its Variscan, Carboniferous stage of development as a dextral strike-slip discontinuity (Mazur et al., 2010, 2020). It was probably reactivated in later times. The *Poznań–Oleśnica Fault System* (E-2) is a complex, extensive system of variously oriented Mezo- to Cenozoic tectonic grabens cutting across the entire Fore-Sudetic Homocline (Kasiński, 1984, 1991, 2000, 2004; Widera et al., 2008). The grabens branch off the main axis oriented roughly N–S and defined by the sigmoidal shaped (in map-view) Poznań–Oleśnica Graben. Apart from the latter graben, the system includes also branched Chruścina and Rawicz–

Chobienia–Legnica segments. This fault system follows the originally Triassic fault train, of possible Variscan antecedence (Kasiński, 1984), that evolved through Mesozoic extensional events, and Late Cenozoic extension which led to lignite deposits. Some smaller grabens located eastward of this system (not included in this report) have a similar origin (Fig. E.2). The *Middle Odra Fault System* (E-3) represents a highly complex pattern of faults in the Permo-Mezozoic cover and the underlying Variscan basement on the borderland between the Fore-Sudetic Block in the S and the Fore-Sudetic Homocline in the N and – as a whole – it shows a general trend of NW–SE to WNW–ESE. Believed by some to represent a fragment of the transcontinental "Hamburg–Kraków Fault Zone", or, using a more recent terms, a SE-ly extension of the 'Elbe fracture' of Arthaud and Matte (1977), which defines the NE boundary of the known extent of Variscan crystalline basement of the Sudetes (Mazur et al., 2020). The knowledge of the faults defining the E-3 System, is based mostly on borehole, potential field and sparse seismic data and, also, on spatially limited data from the KGHM copper mines. The Middle Odra Fault System (E-3) originated from a Variscan, Carboniferous dextral strike-slip major fault zone injected with Carboniferous granitoids (Aleksandrowski, 1995; Dörr et al., 2006; Mazur et al., 2020) and was next recurrently reactivated in the Permo–Mesozoic cover, mostly in dip-slip regime in the time span between the Permian and Present (Grzempowski et al., 2009), thus achieving a complex geometry. At present, it is buried below Quaternary deposits and does not show clear topographic effects of its youngest activity, except for its trace being followed by the Odra river. The *Sudetic Boundary (Marginal) Fault System* (E-4) of the NW–SE to NNW–SSE trend, is a high-angle to vertical, NE-dipping discontinuity. It is entirely exposed on the Earth's surface (but not the fault core itself), yielding prominent topographic effects (Oberc and Dyjor, 1969; Oberc, 1972; Grocholski, 1977; Badura et al., 2002, 2007). Reflected in potential field record and magnetotelluric data, it separates the uplifted Sudetic Block from the downthrown Fore-Sudetic Block. On the average, it appears to be a sub-vertical structure. Originally, a probable large-scale Riedel shear accompanying the Carboniferous displacement on the Intrasudetic Fault Zone (Aleksandrowski et al., 1997), it was subsequently reactivated with a dip-slip kinematics: (1) at the Cretaceous/Palaeogene turn, leading to an uplift of the Fore-Sudetic Block with respect to the Sudetic Block; (2) in the Late Miocene, reversing the position of the Sudetic vs Fore-Sudetic blocks. On the Sudetic Boundary Fault downthrown (NE) side, there occurs a chain of deep Cenozoic grabens (of Mokrzeszów, Paczków and Kędzierzyn; Dyjor and Kuszell, 1977; Dyjor et al., 1978; Krzyszkowski et al., 1995; Przybylski, 1998). The fault displays minor recent seismogenic activity (Guterch et al., 2002; Guterch, 2009).The NNW–ESE-trending *Intra-Sudetic Fault Zone* **(E-5;** e.g. Oberc, 1964, 1972; Aleksandrowski, 1995; Aleksandrowski et al., 1997) is the most conspicuous Variscan structural discontinuity in the Polish Sudetes (Mazur et al., 2020) that separates distinct tectonic units of the Sudetic Block on its southern side from unlike ones on its northern side. It is locally well exposed on the surface, mappable and reflected in potential field data. The main activity occurred in Early Carboniferous times under ductile conditions, with estimated dextral displacement of at least 50 km, possibly reaching even as much as ~300 km (Aleksandrowski, 1995). This was followed by Late Carboniferous reversal with a sinistral displacement of ~25 km and Permian to Neogene dip-slip reactivations at various segments of the fault zone, whose present-day topographic effects are, however difficult to verify. The *Turoszów–Żytawa Fault System* (E-6) is expressed by topographic effects related to Miocene brown coal-bearing depression of two basins, the Siekierczyn and Żytawa (Zittau) ones, separated and limited with intervening horsts (Kasiński, 1991, 2000; Badura and Aleksandrowski, 2013; Kasiński et al., 2015). It is geologically located within the Sudetic Block, on the borderland between the Karkonosze–Izera Massif to the E and the Lusatian Massif to the W. The component faults of the system show the NNE–SSW and WNW–ESE strikes and are normal ones in terms of their kinematics. The fault system in question occurs at the NE termination of the extensive SW–NE-directed Ohře (Eger) Graben of NW Czechia, related to Late Cenozoic abundant basaltoid volcanism and rifting. Over the *Karkonosze–Izera Massif* within the Sudetic Block there is the North Karkonosze Fault System (E-7), which is responsible for the fault-controlled subsidence of the Jelenia Góra Basin and the uplift of the Karkonosze main range by c. 1000 m above the floor of the basin, composed of the same granite as the Karkonosze range. This fault system seems also to define the tectonic boundary between the Jelenia Góra Basin and the Izera Mts further to the NW (as Wojcieszyce Fault). Related faults enter the interior of the Izera Mts as well, dividing them into the WNW–ESE-trending ranges and the intervening grabens (Oberc, 1975). The faults are young and clearly expressed in the topography (Sroka, 1991; Migoń, 1996; Kasprzak, Traczyk, 2010; Aleksandrowski et al., 2019). They show mostly the WNW–ESE strikes, but also those of the NE–SW and NW–SE direction.The *Upper Nysa Fault System* (E-8), whose name refers to the upper reach of the river Nysa Kłodzka, represents a relatively complex cluster of Cretaceous to sub-recent faults downthrowing the Kłodzko Basin and the N–S-trending Upper Nysa Graben, filled with Upper Cretaceous deposits. Kłodzko basin and Upper Nysa Graben are surrounded by mountain massifs of the Sudetic Block, that geologically represent the Orlica–Kłodzko Dome (including the Bystrzyca Mts and Śnieżnik metamorphic massifs and that of the Orlica Mts). Thus, the exposed faults have their clear topographic and geological mapping expression. The component faults trend NW–SE to N–S and, in general, form part of a larger-scale, trans-frontier fault system that continues to Czechia in the NW direction as the Pořiči–Hronov Fault Zone (Valenta et al., 2008; Wojewoda, 2009). The Upper Nysa Fault System developed from the end of Cretaceous through late Cenozoic, mimicking older Variscan NW–SE faults in the crystalline basement. Initially, some of its faults originated as end Cretaceous reverse structures but, subsequently, were transformed into normal faults downthrowing the Upper Nysa Graben and adjacent smaller depressions with respect to the surrounding mountain ranges (cf. Grocholski and Grocholska, 1958; Fistek, 1989; Sroka, 1992, 1997; Don, 1996; Kiełczawa and Teisseyre, 2000; Cymerman, 2004; Don and Wojewoda, 2005; Badura et al., 2005; Don and Gotowała, 2008; Badura and Rauch, 2014a, 2014b).

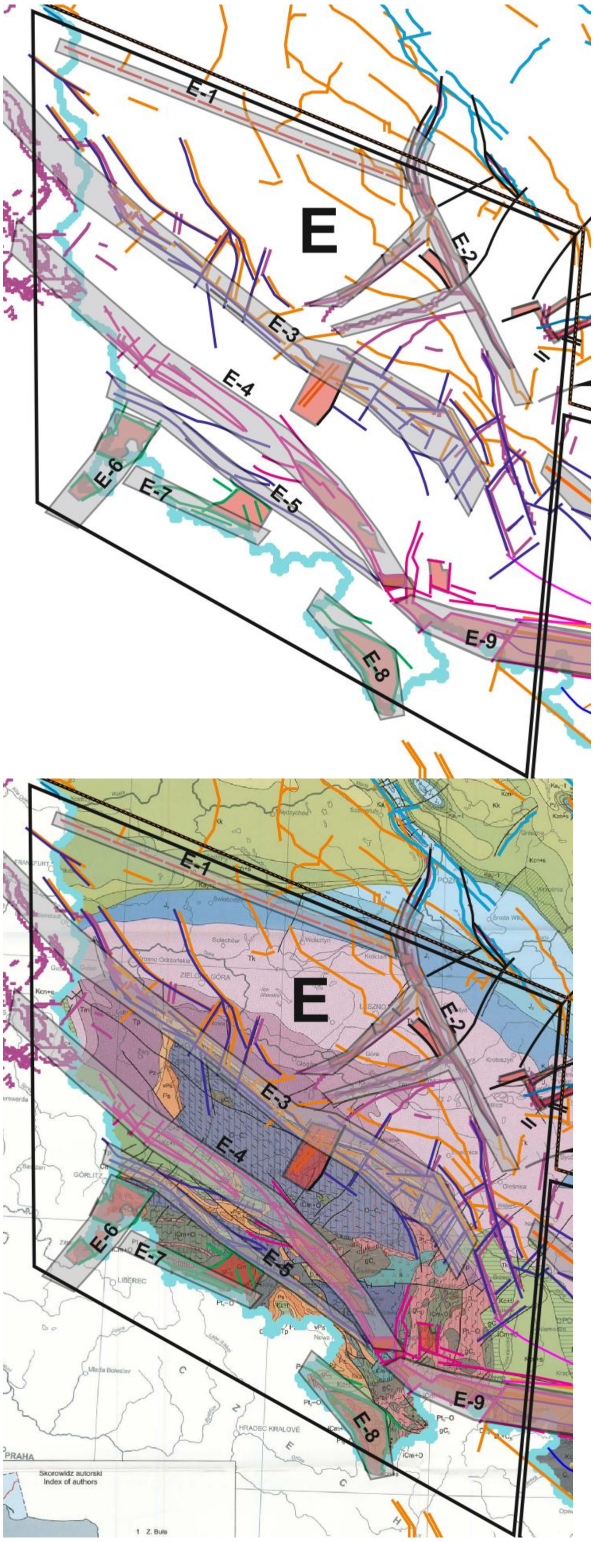


Fig. E.2. Fault zones (transparent grey) of the E area, including codes. Left sketch: no background, Right sketch: on the background of geological map without Cainozoic (after Dadlez et. al., 2000). The faults marked by orange, blue, purple and black are taken from different data sets. Transparent pink are Mesozoic-Cainozoic grabens.

15.7 F. Inner Carpathians

15.7.1 F.1. Tectonic evolution

The Carpathians are a fold-and-thrust belt formed during ALCAPA collision with European part of the Eurasian Plate (Fig. F.1). The main phase of collision took place in Miocene. At the surface, the suture between the ALCAPA and Europe is expressed by the Pieniny Klippen Belt (Fig. F.2) that separates the Inner Carpathians realm consisting of Alpean-provenance units and the Outer Carpathians consisting of complexes deposited at the margin of the European plate. The stack of nappes of the Outer Carpathians was formed mostly in Neogene. The gently dipping or subhorizontal thrusts extend tens of kilometres southward of their surface manifestation. The thrust geometry and complexity of tectonic deformations in the Outer Carpathians are beyond the scope of this Report, we thus focus on the three main, basement-rooted fault zones in the Inner Carpathians.

The Inner Carpathians (Fig. F.3) developed over the ALCAPA micro-plate basement, which was escaping from the Alps during the Oligocene up to the Miocene and was finally accreted to the European plate in the Miocene (Schmid et al., 2008). The northernmost part of ALCAPA is occupied by the Podhale Flysch Basin, which forms a syncline bounded from the S by the Tatra Mts. and from the N by the Pieniny Klippen Belt (Fig. F.2) (Jurewicz, 1997). The main Cretaceous phase of the Tatra Mts. folding led to the complex orogenic structure, which we are not considering in this Report. Therefore, in the Inner Carpathians we highlight the Pieniny Klippen Belt suture and two transversal fault zones: Białka and Biały Dunajec (Fig. F.3) which are all deeply rooted in the ALCAPA basement.

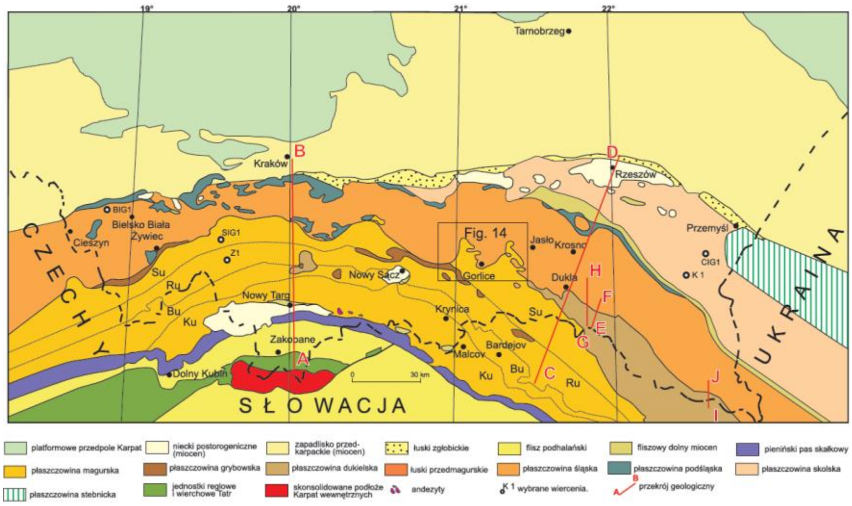


Fig. F.1. The tectonic sketch of the Western Carpathians (after Żelaźniewicz et al., 2011).

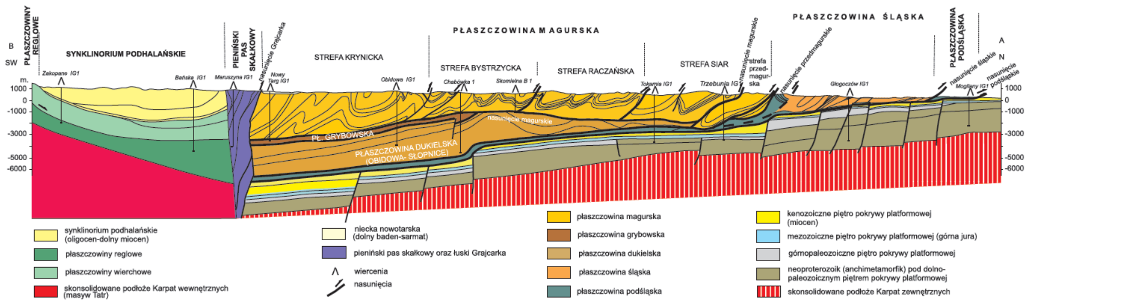


Fig. F.2. The schematic N–S trending cross-section through the Western Carpathians (after Żelaźniewicz et al., 2011). For location see Fig. F.1 – profile A–B.

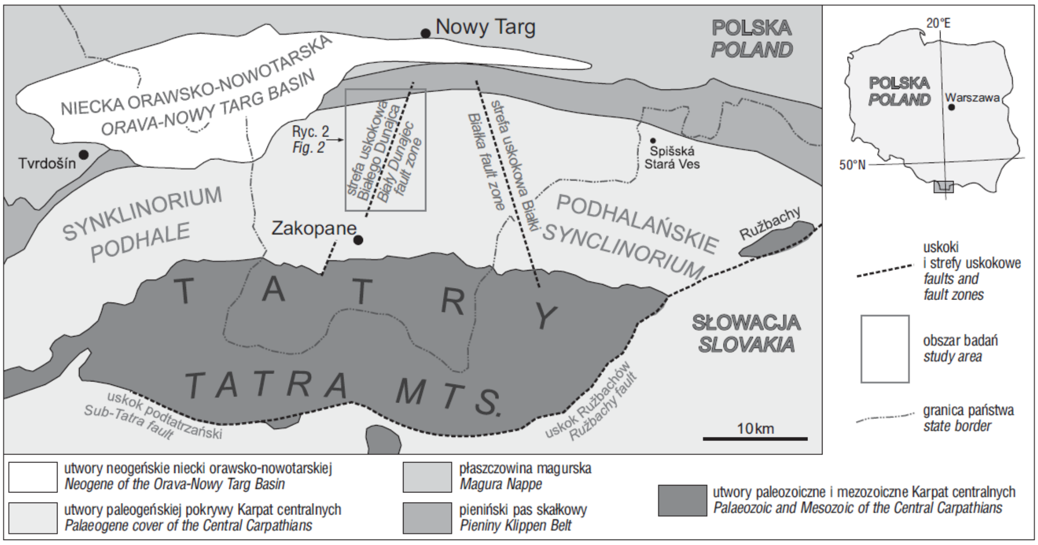


Fig. F.3. Tectonic sketch of the Inner Carpathians with indicated fault zones (after Mastella et al., 2012).

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16 LNEG - PORTUGAL

16.1 Introduction

The evolution of mainland Portugal has been strongly conditioned by its geographic position between the Atlantic Ocean and Mediterranean Sea, which is reflected in the geological domain as well as in its people and ways. This location, in relation with the evolution of the two water bodies, controlled the Iberian Peninsula (IP) geodynamic evolution along the Alpine Cycle.
The IP that was formed during the Variscan Cycle corresponds to the Hesperian Massif. It is constituted by an "ancient Iberian Terrane", build up from peri-Gondwanan terranes in the Cadomian Cycle, and by other terranes that are currently vestigial. The Mesozoic and Cenozoic basins developed over the Hesperian Massif. The extant tectonic structures contribute to the interpretation of this long geological history.

In general, the faults that can be recognised in Iberia can be differentiated in three distinct groups:
a) older structures with frequently controversial interpretation, only affecting Proterozoic and Paleozoic rocks. They correspond to shear zones that evolved from Cadomian sutures and Variscan transform faults and nappes, where the absence of stratigraphic markers difficults the evolutionary reconstitution and identification of reactivations;
b) late Variscan and neoformed Alpine faults affecting recent sediments, which frequently allows the determination of Mesozoic and Cenozoic kinematics, as well as tectonic inversions related to the Pyrenaic and Betic orogenies;
c) faults that do not crop out (hidden below alluvial deposits) or that have not had recent stratigraphic or geomorphological markers and therefore their activity in the last 5 or 3 Ma cannot be determined with security. This difficulty is increased by low activity rates during the Quaternary despite the evidence of high magnitude intraplate earthquakes in the historic and paleoseismological record.
In the hydrogeological perspective, Portugal's lithological, stratigraphic and tectonic-structural framework allows the presence of several aquifers in sedimentary and crystalline medium and, at the same time, the presence of several hydromineral and geothermal occurrences.

16.2 Cadomian and Variscan Cycles – an ancient history

The geological evolution of the Iberian Peninsula reflects the effects of two Wilson Cycles prior to the current one: the oldest is the Cadomian Cycle, followed by the Variscan Cycle. In fact, in a vast area of the western part of the IP, deformed rocks of Paleozoic and Proterozoic age, which constitute the Iberian basement, that is, the Hesperic or Iberian Massif, are representative of the westernmost segment of the European Variscan Chain (Ribeiro, 2013).
The Variscan Chain, which resulted from the Variscan orogeny at the end of the Paleozoic, shows a cross-sectional zonation of the structure (Ribeiro, 2013; Ballèvre et al., 2009; Simancas et al., 2009; Martínez-Catalán et al., 2009) with different meanings. The classic and often controversial zoning comprises the Cantabrian Zone (CZ), the Western Asturic-Leonese Zone (WALZ), both located only in Spanish territory, the Central Iberian Zone (CIZ), the Galicia Trás-os-Montes Zone (GTMZ), the Ossa Morena Zone (OMZ) and the South Portuguese Zone (SPZ) (Simancas, 2019), to which the Finisterra Terrain is added (Ribeiro et al., 2007; Ribeiro, 2013; Ribeiro et al., 2013; LNEG, 2016; Moreira et al, 2019).

In the Cadomian Cycle, whose orogeny ended in the Neoproterozoic with the agglutination of the Panotia supercontinent, the agglutination of the Gondwana continent is of particular interest to Iberia. In the Portuguese territory, testimonies of this process include Neoproterozoic rocks, possible inherited from previous orogenic cycles, which are unconformably covered by the Cambrian sediments. Also inherited from the Cadomian Cycle there are probably some shear zones which have suffered reactivation during the Variscan Cycle (Ribeiro, 2013).

The Variscan Cycle starts in the Cambrian period and ends with the formation of the Pangea supercontinent; it comprises several diachronic phases of variable duration. One of its most striking features is the presence of the Ibero-Armorican Arch, whose arching is continuous over time throughout the Variscan Cycle and is witnessed by the strong curving of the structures (Ribeiro, 2013; Dias et al, 2016). It is widely represented in the Iberian Massif.

From the geodynamic point of view, the most significant events recorded in the IP are related to global scale processes (Simancas, 2019):

• Gondwana amalgamation in the Neoproterozoic (Cadomian magmatic arc (Pereira et al., 2013) and Cadomian orogeny);
• Rifting in the Cambrian which led to the opening of the Rheic Ocean in the Lower Ordovician;
• Drift of Gondwana since the Lower Ordovician to the Devonian;
• Opening of the Galicia Trás-os-Montes Ocean (GTMO) (a Rheic arm) in the Lower Devonian;
• Subduction, with closing of the Rheic ocean and collision involving the Laurussian plate (Laurentia + Baltica) and Gondwana with the amalgamation of several peri- or northern Gondwanan domains, such as Avalonia and Armorica (Bàllevre et al., 2009), resulting in the formation of the Pangea supercontinent. The continental collision resulted in the construction of the Variscan Chain between the Middle Devonian and the lower Permian.

The study of these ancient orogenic cycles acting upon old, dismembered and reworked orogens, makes paleogeographic reconstitutions difficult, leading to non-consensual interpretive geodynamic models (Simancas, et al., 2009).

Much of the brittle and ductile tectonic structures that occur in the Portuguese territory are interpreted as inherited from the Variscan Cycle, or even the Cadomian Cycle.

Some of these larger ductile structures refer to sutures separating domains of the zoning of the Iberian Variscan basement mentioned above.

The approximately N-S trending Porto-Tomar-Ferreira do Alentejo Shear Zone is considered one of the most important structures of the Iberian Variscan basement, establishing the crustal limit of the Finisterra Terrain with the Iberian Terrain, to the east. It presents a polyphasic deformation and has been interpreted as a right-lateral transform shear zone at least since the Lower Devonian, possibly reactivating a Cadomian structure (Ribeiro et al., 2007; Ribeiro, 2013; Romão et al., 2006; LNEG, 2016; Moreira, et al., 2019), although this interpretation is not consensual.

The Tomar-Badajoz-Córdoba shear zone, with a general WNW-ESE trend, establishes the boundary between the OMZ and the CIZ. It has been interpreted by some authors as a crustal suture of Cadomian age reactivated as a left-lateral transpressive flower structure during the Variscan Cycle (Ribeiro el al., 2007, 2013; Romão et al., 2006), or as a Variscan suture representative of the closure of a narrow oceanic domain (Simancas et al, 2009).

The Ferreira-Ficalho thrust, with a general E-W trend and dipping towards N, is here referred because it is usually considered to underline the boundary between the OMZ and the SPZ. This boundary corresponds to a Variscan suture between the Iberian and Avalonia terrains and was first interpreted as corresponding to the Beja-Acebuches Ophiolitic Complex. Currently, it is considered that the evidences of the oceanic crust of the Rheic Ocean obducted on the southern

border of the OMZ (the Ophiolitic Complex) are incorporated in the Allochthonous Complex of Moura-Cubito (Araújo et al., 2013; Simancas et al., 2009; Simancas, 2019).
The thrusts of the Galician and Trás-os-Montes allochthonous massifs are interpreted as nappes of continental crust of Armorica and of GTMO obducted oceanic crust, thrusted over the Iberian Terrain, showing a displacement of over a hundred km accumulated between the Middle Devonian and the upper Carboniferous (Ribeiro et al ., 2007; Ribeiro, 2013).
At the end of the Variscan Cycle, crustal thickening is followed by isostatic readjustment of the crust, relaxation of orogenic stresses and the development of late brittle structures.
These structures generally correspond to newly created Late-Variscan (upper Carboniferous to Permian) faults, but also include reactivated faults which have been generated during the last phase of the Variscan deformation (upper Carboniferous) (Dias et al, 2013). Among these fault systems, the sets of sub-vertical faults trending close to N-S (NNE-SSW to NNW-SSE) and approximately E-W and ENE-WSW stand out for their length. Major examples of NNE-SSW oriented faults are the left-lateral Penacova-Régua-Verín and the Manteigas-Vilariça-Bragança strike slip faults, although this kinematics during the Late-Variscan period is not consensual (Ribeiro et al., 2007; Marques et al., 2002). The Seia-Lousã and Ponsul faults are examples of the ENE-WSW set, located in the CIZ, while the Vidigueira Fault, close to an E-W orientation and located in the OMZ, presents a more complex history, probably having been reactivated during the Late-Variscan phase. This fracture (later reactivated in the Alpine Cycle) is very expressive in the current morphology of the eroded and raised Iberian or Hesperian Massif.

16.3 The Alpine Cycle

The geodynamic evolution of Portugal during the Mesozoic is dominated by the opening of the Atlantic and Neotethys oceans. At the end of the Paleozoic era, the continental masses were gathered in the Pangea supercontinent, which suffered fragmentation during the new Wilson cycle, known as the Alpine Cycle.
The major tectono-stratigraphic units that were differentiated in the Portuguese mainland area are the Lusitanian basin, at the western part of the country, and the Algarve basin, at its southern part. These basins evolved in a regime of crustal stretching and subsidence with four major rift phases, from the late Triassic to the early Cretaceous (Ribeiro et al., 1979, 1990; Rasmussen et al., 1996; Kullberg, 2000). This new cycle gave rise to newly formed structures and reactivated inherited faults from the latter Variscan Cycle that were favourably orientated to the new stress field (A. Ribeiro, in Dias et al., 2013).
The most well accepted evolutional model for the Lusitanian basin consists of rifting phases showing: i) rooting in the variscan basement of the main faults of the basin (predominantly thick skinned style); ii) periods of symmetrical (horst and graben organization) and asymmetrical (half graben organization) geometrical evolution; iii) diachronous fracturing; iv) rotation of the main extensional direction (Kullberg, 2000).
In the Algarve, faults striking NE-SW and NW-SE acted as left and right-lateral shears, respectively. The Mesozoic section thickens radically southward across flexures subparallel to the coastline (E-W) that probably overlie synsedimentary growth faults at the basement (Ribeiro et al. 1990).
The complex structures of the Lusitanian basin are due in part to a geometrically complicated interaction between the Alpine stress field and pre-existing fractures, and also to the interplay of halokinesis (Ribeiro et al., 1990). This basin contains normal faults oriented N-S to NNE-SSW, some of them listric, and synsedimentary structures. During the Cretaceous, some late Variscan

faults striking NNE-SSW to NE-SW were probably reactivated with sinistral strike-slip motion (op. cit.). The passive margin regime dominated until the Cretaceous with only one inversion event occurring in Calovian (op. cit).
The Mesozoic is also marked by the existence of three magmatic cycles (early Jurassic, late Jurassic-early Cretaceous and late Cretaceous) in which the two first cycles were strongly controlled by pre-existing fractures (e.g. Kullberg et al., 2013 and references therein).
During the late Cretaceous there was a change in the dominant tectonic regime in Iberia, from the Atlantic distension to compression related to the Alpine orogeny, with N-S convergence between Nubia and Eurasia (Dewey et al., 1989; Rosenbaum et al., 2002a). At this initial stage, the microplate Iberia moved together with Nubia and its northern border was an active tectonic plate limit (Srivastava et al., 1990). This convergence led to the formation of the Cantabro-Pyrenean range in the Paleogene (e.g. De Vicente & Vegas, 2009). The compression reached its peak in the Eocene-Oligocene (Rosenbaum et al., 2002a). Intraplate deformation due to stress transmission from the active border was responsible for an important basement (Hisperic massif) structuration, with most of the Cenozoic basins being formed by lithospheric folding and movement along faults (e.g. Cloetingh et al., 2002; De Vicente & Vegas, 2009; De Vicente et al., 2011). By middle Oligocene, the Nubia-Eurasia convergence was already located at the southern border of Iberia (Vergés & Fernàndez, 2012). The subduction processes that took place in the western Mediterranean region, with the closure of the Tethys ocean and the collision of the Alboran terrane with Nubia and Eurasia margins, led to the formation of the Betic-Rif ranges in the Miocene, with a general NW-SE oriented SHmax (Rosenbaum et al., 2002b).
The alpine compressive deformation was mainly accommodated by reactivation of pre-existing faults, active during the Paleozoic and Mesozoic, with kinematics varying according to fault orientation relatively to the stress field (Ribeiro et al., 1990). The Lusitanian and Algarve basins suffered strong tectonic inversion, with Mesozoic normal faults subparallel to the SHmax having an important role in this process by reactivating, in part, as reverse faults (e.g. Ribeiro et al., 1990; Terrinha, 1998; Kullberg, 2000).
The present geodynamic setting is considered to have been established about 2 Ma ago, and is marked by the NW-SE to WNW-ESE oblique convergence between the Eurasian and Nubian plates, along the Azores-Gibraltar Fracture Zone. In the Gulf of Cadiz region, it consists in a diffuse tectonic boundary, with the deformation being accommodated along several families of fractures. This tectonic regime is traduced by paleoseismological evidence, mainly expressed by deformation affecting Quaternary sediments, as well as historical and instrumental seismic activity (Cabral, 1995, 2012; Dias, 2001; Zitellini et al., 2004; Rosas et al., 2009; Custódio et al., 2015; among others).

16.4 Overview of the hydromineral and geothermal sources distribution in the context of the tectonostratigraphic structures on mainland Portugal

On the mainland territory, there are about 200 legal water sources (springs and boreholes) distributed by 77 official concessions for natural mineral waters recognized by Portuguese Law, that includes 21 bottled waters according to the Directive 2009/54/EC (some concessions produce more than one brand of bottled water). There are also more than 120 water springs identified as potential hydromineral resources, either abandoned or publicly available (see figure 1).

Most of the natural mineral waters occur in the north and central regions of the country, in the Iberian Massif, emerging predominantly from granitic rocks, related with very deep fractured reservoirs and associated to major regional active faults (with overall NNE-SSW direction).
In this context, the following water types stand out:

- Sulphur waters – The most abundant type, characterized by the presence of reduced forms of the sulphur ion, high contents of silica and fluorine ions. Normally the pH values vary from 7.5 to 9.5, the water temperatures range from 20 to 69 °C and the total mineralization can reach 700 mg/L. These waters are used for thermalism.
- Natural CO2 water – Occurs in northern Portugal, only. The CO2 levels range between 500 and 2600 mg/L, the total mineralization goes up to 5700 mg/L, the pH values vary from 5.9 to 6.9 and water temperatures are typically below 20 °C; but in Caldas de Chaves they reach 77 °C. The majority of these waters is used for bottling, but in some cases are also used for thermalism and only in Chaves they are used for geothermal purpose.

In Iberian Massif (Central Iberian Zone), still deserving reference are the water type associated with quartzitic and granitic rocks:

- Silicate waters – The SiO2 content represents more than 30% of total mineralization. The hydrochemical facies are sodium chloride and sodium bicarbonate, for waters emerging from fractured quartzitic and granitic rocks, respectively. In generally, they are very low mineralized and acid waters (4.7 < pH < 6.3; geometric mean = 5.6), with temperatures reaching up to 29 °C. These waters are used for both bottling and thermalism.

In the Western and Southern Meso-Cenozoic sedimentary basins where sandstones and limestones are common lithologies, the natural mineral waters have the highest flows. The typical hydrochemical facies are sodium-chloride-bicarbonate and calcium-sulphate. The pH values are close to 7, the water temperatures range between 19 and 37 °C and the total mineralization varies from 180 to 6600 mg/L; but in Batalha mineralization (Salgada da Batalha borehole) reaches 32500 mg/L. These waters are usually related with active fault systems and their ionic composition is strongly influenced by the salt diapir structures or evaporites (halite and gypsum) levels in Lower Jurassic formations. These waters are used for thermalism and bottling.
In Portugal, groundwaters with a temperature of 20 °C or higher at the outlet are considered as resources with potential geothermal use. In mainland territory, the natural mineral water temperature varies between 9.5 and 77 °C and therefore natural mineral waters can simultaneously constitute geothermal resources. According to Portuguese database of WP 3.3 HOVER Project (GeoERA) there are 61 occurrences with temperature above 20 °C. Currently, there are 8 concessions in which water is used for both thermalism and geothermal heating.
To the purposes of the HIKE project, 121 springs/sources conditioned by tectonic structures were selected. However, some (22) of them are not associated with the fault segments present in the Portuguese 1: 1 000 000 scale Geological Map.

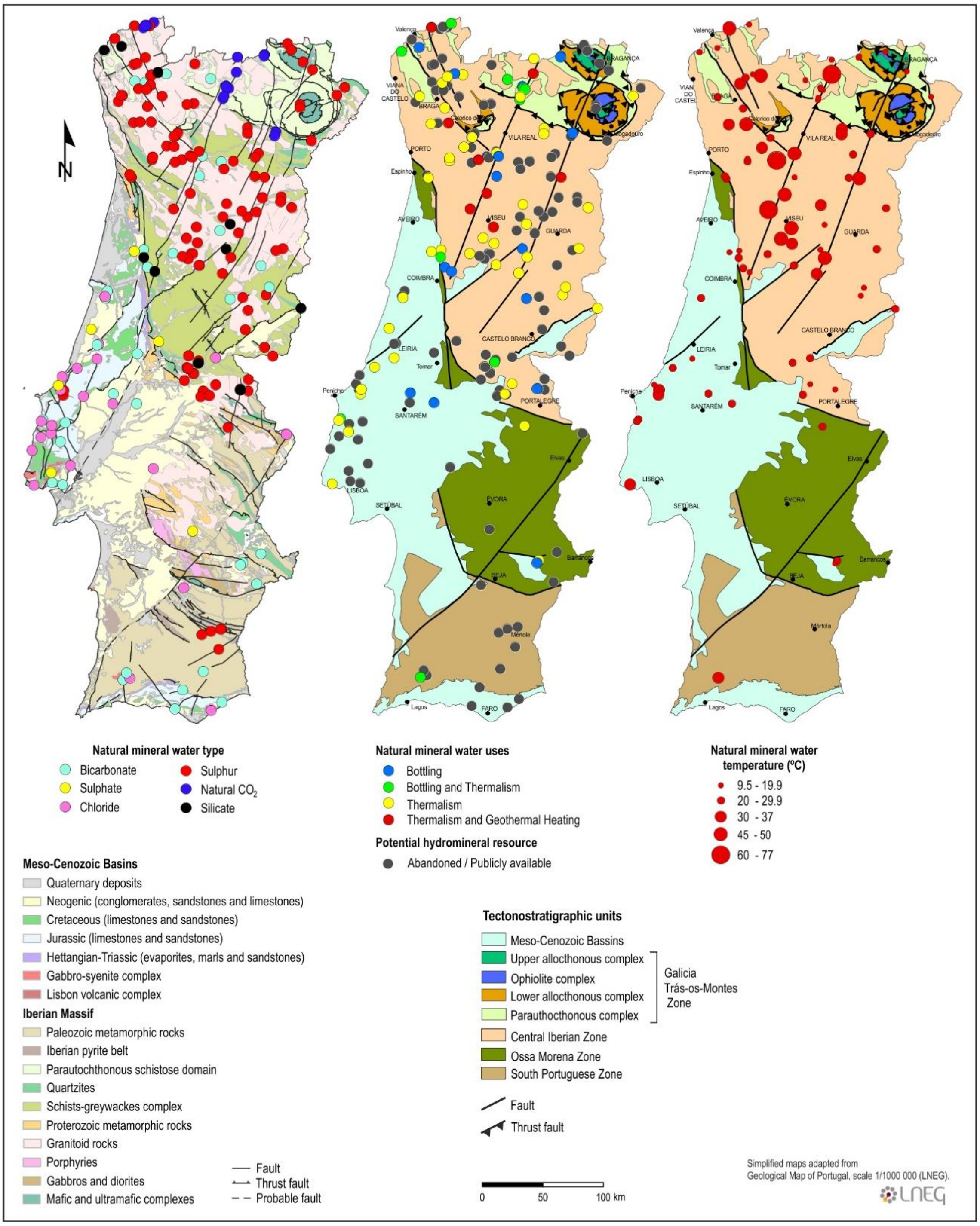

Figure 1: Overview distribution of type, uses and temperature of natural mineral waters in mainland Portugal (Almeida & Moura, 1970; Calado, 1992; DGGM, 1992; HIDROGENOMA Project; HOVER Project - GeoERA Groundwater; Lourenço & Cruz, 2010.

16.5 Methodology and data reliability

The faults located in Portugal mainland included in this database mainly correspond to those represented in the published geological map of Portugal at 1: 1 000 000 scale (LNEG, 2010), in terms of number and geometry. On the other hand, the geometry of the faults extant in the referred map was adapted from LNEG published and unpublished geological maps at different scales, based in outcrop characterization, geological mapping, lineaments analysis and scientific studies.

The information now made available is, however, product of recent evaluation and validation according to new advances in scientific knowledge (maps, papers, reports) and adapted to the defined format for this specific database. In this process, some geometries have undergone minor changes. Several issues arise in terms of reliability of the provided information. This is usually related to the scale of representation and mapping methods. For example: in the interpretation of faults/fault segments based on the existence of geomorphological lineaments or apparently anomalous limits between lithostratigraphic units, the interpreted fault's length has low reliability; usually at this scale, a single fault plane is a simplification of a much more complex deformation zone, probably consisting in several branches and sets of parallel faults; many fault segments are, at larger scales, represented as probable structures. However, at the 1: 1 000 000 scale, probable faults are not differentiated from confirmed faults.

Also, there are some mapped structures that have not been the subject of publications other than geological mapping. In these cases, there are difficulties in terms of attribute classification, having this been done based on maps interpretation and regional geologic studies, without field work validation. Most of the Portuguese faults have a long and complex tectonic history, usually throughout more than one tectonic cycle. However, in this database, the temporal activity of many of the represented structures is characterized according to the deformation that stands out in the geological mapping.

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17 GEOZS – SLOVENIA

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Geological Survey of Slovenia, Ljubljana, October 2020.

17.1 Introduction

The strongly varied topography, diverse lithological composition and extensive faulting with multiple structural overprints in Slovenia is the result of over 200 million years of near-continuous tectonic activity with successive rifting and orogenic phases. While northern, western and southern Slovenia are dominated by the Alpine and Dinaric mountain ranges buildup of Paleozoic, Mesozoic and Paleogene rocks, the northeastern and eastern Slovenia is a flat plain and hilly area, formed by crustal extension and deposition of a thick succession of Miocene-Quaternary marine and terrestrial sediments over the older bedrock (Figure 1).

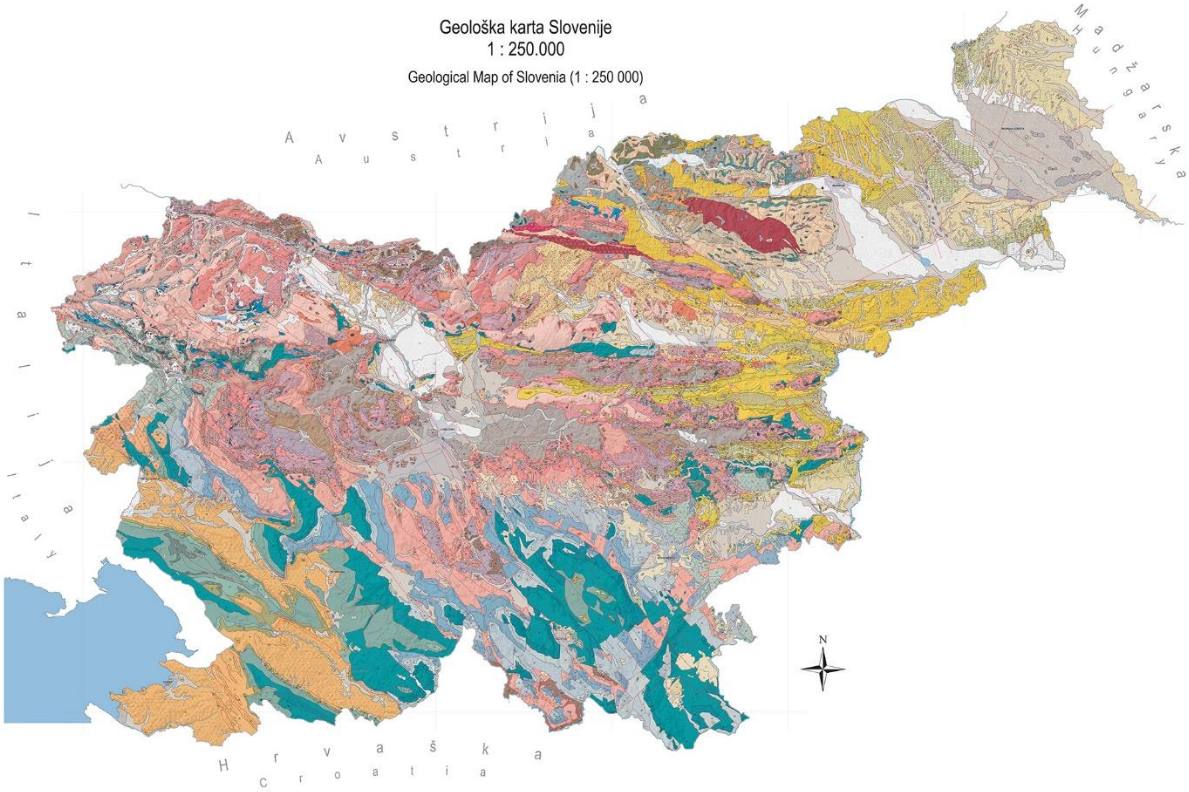

Figure 1: Geological map of Slovenia (Buser, 2009).

Lithological units, structural elements and faulting, originating in vastly different paleogeographic and depositional settings and tectonic phases overlap and interact, producing a complex network of structural and fault systems. While strata down to Devonian age are preserved and exposed on the surface (at the same time being the oldest known sedimentary rocks in Slovenia) and remnants of the Variscan tectonic/orogenic phase are evident in the Karavanke mountains of north Slovenia, it is the extensional faulting of the Early-Mesozoic (Triassic) rifting phase that produces the oldest well-preserved faulting (Mlakar and Čar, 2009).

All subsequent faulting and general structure was produced within the collisional setting of the European and African lithospheric plates, starting in Cretaceous and still ongoing.
Two distinct thrust and fold belts originated during the Cenozoic: the Paleogene Dinaric Thrust and Fold Belt and the Miocene South Alpine Thrust and Fold Belt (Castellarin and Cantelli, 2000; Poljak, 2007; Placer, 2008; Placer et al., 2010). Both produced distinct thrust fault systems that, while currently mostly inactive in the area of Slovenia, remain well-preserved and distinctly visible on the surface. The Dinaric Thrust and Fold Belt was produced by top-to-SW thrusting on shallow-dipping thrust planes, producing a nappe stack of thick successions of Mesozoic platform carbonates and Paleocene to Eocene flysch. Subsequently in early Miocene in northern Slovenia the Dinaric nappes underwent further top-to-S folding and thrusting during the formation of the South Alpine Thrust Belt (Placer, 2008) with subsequent formation of new thrusts. The South Alpine Thrust Belt comprises a number of nappes, preserved in the Julian Alps (NW Slovenia) and likely also in the Sava Folds in central Slovenia (Placer, 2008). The South Alpine Thrust and Fold Belt was deformed, offset and fragmented by the transpressive dextral strike-slip Periadriatic Fault System and Dinaric Fault System (Grad and Ferjančič, 1976; Buser, 1986; Placer, 2008). The Periadriatic Fault System formed during the extrusion of the ALCAPA crustal block/mega-unit, driven by slab rollback and thermal collapse in the Pannonian basin in the Miocene and is still active (Fodor et al., 1998; Vrabec and Fodor, 2006; Grenerczy et al., 2000). The Dinaric Fault System comprises subvertical strike-slip faults running in the Slovenian part of the Southern Alps and the Northern Dinarides (Poljak et al., 2000; Vrabec and Fodor, 2006; Moulin et al., 2016). The faults of this system cut older External Dinaric Thrust Belt and South Alpine Thrust and Fold Belt and have been dextrally active since the beginning of Pliocene. Currently, the active fault geometry, kinematics and activity is driven by the northward motion and counterclockwise rotation of the Adria microplate and the interaction between the eastward-moving ALCAPA and TISZA crustal blocks/mega-units (Brückl et al., 2010; Schmid et al., 2020). There are 6 active fault system with a number of long (>80 km) and active faults.

17.2 Structural elements

Structural elements and tectonic subdivision in Slovenia follow strong tectonic and paleoenvironmental boundaries. Paleozoic units outcrop mainly in the Karavanke Mountain Range (part of the Southern Alps) in north Slovenia and to a somewhat limited extent in parts of the External Dinarides.

While secondary tectonically-controlled or induced features exist in Paleozoic rocks, including lower Carboniferous flysch, little contemporary faulting is preserved (Buser, 1980). By late Permian to early Triassic a predominantly uniform Slovenian Carbonate Platform had formed (Buser et al., 2007). The first major structural elements formed during the Middle-Triassic (Ladinian) aborted rifting in the opening of Meliata-Meliac Ocean, NW part of the broader Neotethys embayment between the African and Eurasian plates, as extensional faulting lead up to the breakup of the Slovenian Carbonate Platform and the formation of the Julian Carbonate Platform and later the Julian High, the Slovenian Basin and the Dinaric Carbonate Platform (Buser et al., 2007; Ogorelec, 2011; Schmid et al., 2020).
Locally known as the Idrija tectonic phase, the normal faulting is preserved in western Slovenia, accompanied by evidence of intense Ladinian volcanism (Mlakar and Čar, 2009). Normal faults of the Idrija tectonic phase (Idrija Triassic Fault Set) are one of nine major structural elements in the Slovenian part of the HIKE database (Figure 2).

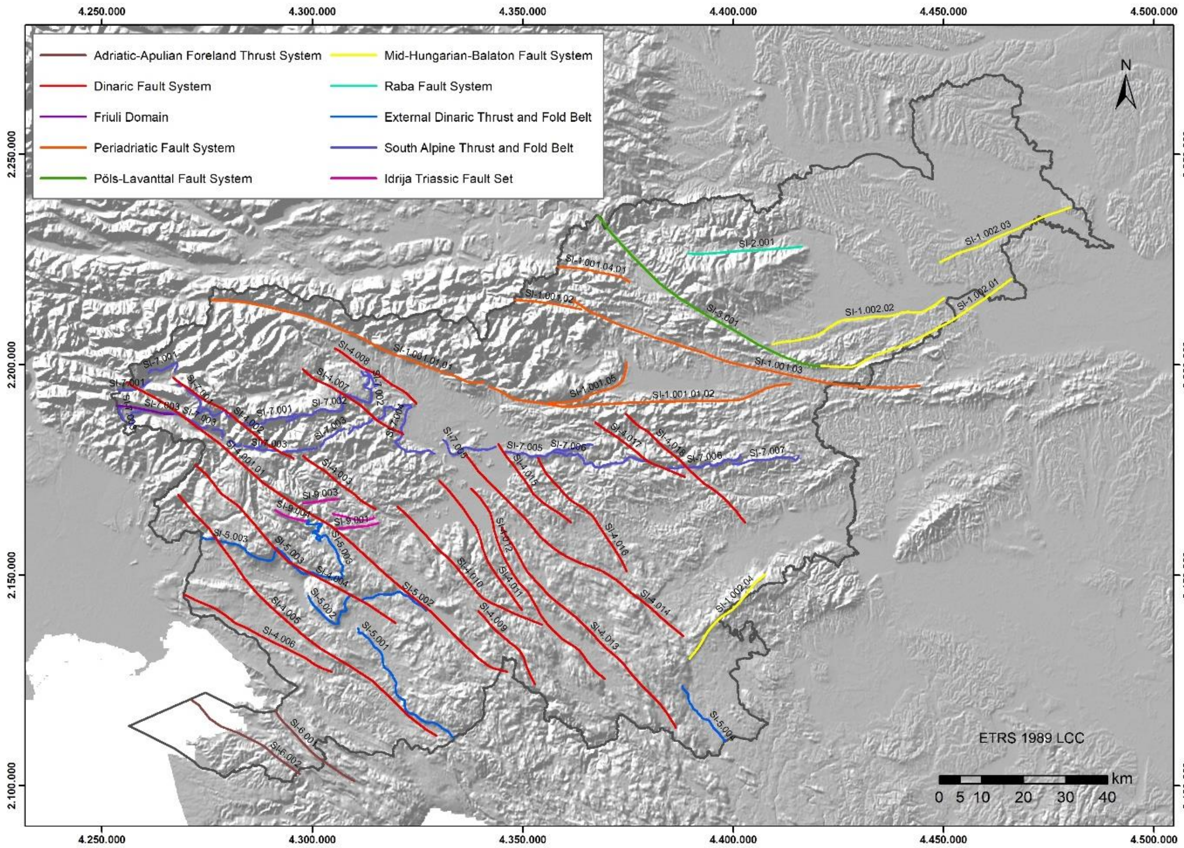

Figure 2. Faults in the Slovenian part of the HIKE database, color-coded by fault system attribution.

During the Late Mesozoic the regional geologic structure was controlled by the southward-progressing flysch basin produced by the subduction in the Neotethys/Alpine Tetyhs ocean further to the north, however, little faulting is evident. The next tectonic phase that produced widespread structural imprint is the Paleogene top-to-SW thrusting during the formation of the External Dinaride Thrust and Fold Belt. The External Dinarides formed during the Paleogene continuous convergence between the Adria Microplate and the European Plate, with thick carbonate successions of the Adriatic carbonate platform back-thrusting onto themselves and forming the External Dinaric Thrust and Fold Belt with associated peripheral foreland basin (Otoničar, 2007). The offsets along individual thrusts in W Slovenia are up to several tens of kilometers, producing a thick stack of overthrusting Dinaric carbonate platform-derived nappes (Placer, 1981, 2008), while in central, southern and eastern parts of Slovenia the structures are less distinct and offsets less well constrained.

The next distinct structural elements belong to the South Alpine Thrust and Fold Belt with corresponding nappes in the Julian Alps (SW Slovenia) and in the Sava Folds in central Slovenia. The thrust and fold belt structure is most distinct and still dominant in the Julian Alps, where the Southern Alpine Thrust Front is exposed (e.g. Placer, 2008). It becomes less distinct in central Slovenia, where it is partly covered with Cenozoic and Quaternary sediments and embedded within the younger (post-Sarmatian to post-Pannonian) Sava Folds further to the east (e.g. Placer, 2008).The South Alpine Thrust and Fold Belt is in Slovenia cut by younger structures, whereas in nearby Italy it is still active (e.g. Poli and Zanferrari, 2018). Part of the active Friuli Domain of the South Alpine Thrust and Fold Belt also extends to Slovenia as Kobarid Fault.

17.2.1 Idrija Triassic Fault Set

The oldest faults included in the Slovenian HIKE database segment originated during the Mesozoic (Triassic) rifting phase during the break-up of Pangea. Normal faulting of Ladinian origin during the aborted rifting phase in the opening of the Meliata ocean produced the oldest well-preserved and systematically mapped faulting in Slovenia. Locally designated as the Idrija tectonic phase, the faults have been mapped in detail within the scope of surface geologic mapping and the Idrija mercury mine works (Placer, 1982; Mlakar and Čar, 2010).

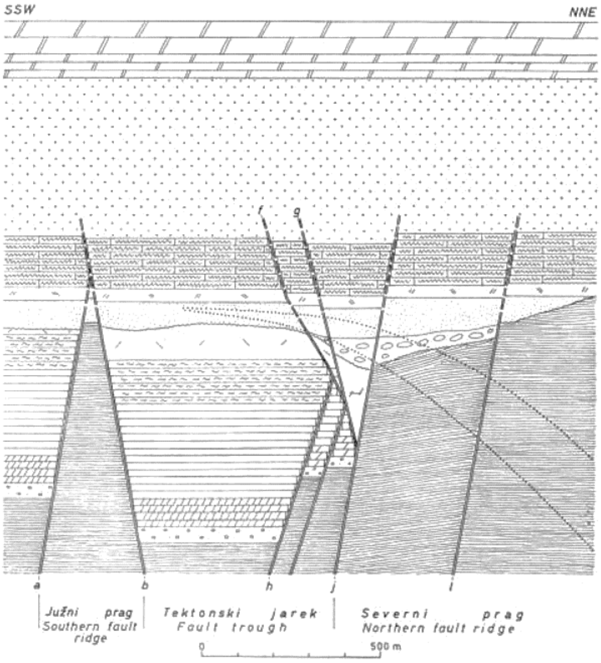

Figure 3. Middle-Triassic normal faulting in Idrija displacing the Ladinian and older strata and terminating in Lower-Carnian strata. Restored Paleogene folding and recent Dinaric strike-slip displacement (Placer, 1982). Faults of the Idrija Triassic Fault Set are cross-cut by younger External Dinaric Thrust and Fold Belt structure and recently active Dinaric Fault System dextral strike-slip faults.

Faults of the Idrija Triassic Fault Set displace Lower and Middle-Triassic (and older) strata up to the Ladinian and terminate in lower-Carnian strata (Figure 3). This termination is well observed in the field. They produce well distinguish graben and half-graben structures.

The Idrija tectonic phase normal faulting is steep-dipping, E-W striking and forms four distinct fault (sub)-sets (N to S) belonging to:

- Ravenovo Fault,
- Ledine Fault,
- Zavratec Fault,
- Rudišče Fault.

The Rudišče Fault is the site of the Idrija mercury deposit, the second largest mercury deposit in the world (Placer, 1982).

17.2.2 External Dinaric Thrust and Fold Belt

The next mapped [but not necessarily the immediate subsequent] tectonic phase includes the Paleogene top-to-SW thrusts of the Dinaric thrusting/orogenic phase (Poljak, 2007; Placer, 2008; Placer et al., 2010). The External Dinaric Thrust and Fold Belt comprises stacks of nappes derived from the large-scale upper Paleozoic to Mesozoic Adriatic Carbonate Platform, forming many kilometers thick stacks/carbonate successions. The formation of the External Dinaric Thrust and Fold Belt is associated with the convergent motion of the Adria microplate towards the Pannonian Domain, with thrust facing the Adriatic foreland.
In SW Slovenia the External Dinaric Thrusts produce major geomorphic expression, particularly along the southern and western slope of the Nanos plateau and the southern slope of the Trnovski Gozd plateau, with steep slopes and rock faces up to 1000 m high.
The External Dinaric Thrust and Fold Belt includes 4 thrusts:

- Snežnik Thrust,
- Hrušica Thrust,
- Trnovo Thrust,
- Bela Krajina W Thrust.

External Dinaric Thrusts are inactive.

1.1. South Alpine Thrust and Fold Belt

The South Alpine Thrust and Fold Belt comprises top-to-S thrusts, nappes and folds formed in the lower Neogene. The South Alpine Thrust and Fold Belt deforms and folds the External Dinarides Thrust Belt, producing a thick succession of Mesozoic platform carbonates and to a more limited extent deep-water pelagic carbonates and clastites as well as flysch. The thick carbonate succession is derived from the Triassic Slovenian Carbonate Platform (part of the broad Adriatic Carbonate Platform) and later from the Jurassic 'Julian high' and the Slovenian Basin to the south, ending with the southward progressing Cretaceous flysch.
The South Alpine Thrust and Fold Belt in Slovenia comprises mainly the Julian Alps, topographically the highest region of Slovenia, including the highest peak (Mt. Triglav, 2864 m). To the east, the South Alpine Thrust Front passes beneath the Quaternary sediments of the Ljubljana Basin and into the Sava Folds in central Slovenia. Seven major thrusts are recognized:

- Krn Thrust,
- Tolmin Thrust,
- Jelovica Thrust,
- Selca Thrust,
- Litija Thrust,
- Dole Thrust,
- Kum Thrust.

The South Alpine Thrust and Fold Belt continues to the west into Italy, where it is confirmed active and seismogenic as the Friuli Domain. There is some evidence of potential activity of South Alpine Thrusts in Slovenia (e.g. Rižnar et al., 2007; Milanič, 2010), however, the data is far from conclusive. The South Alpine Thrust and Fold Belt in Slovenia and the Friuli Domain in Italy are separated by the active dextral strike-slip faults of the Dinaric Fault System.
Friuli Domain comprises a number of active south-vergent thrusts and reverse faults with slip rates in the 0.2-0.6 mm/yr range. The domain is characterized by very significant seismic activity, with the latest major earthquakes including the 1976 M_w 6.5 (main shock), and three M_w>5.5 aftershocks (Grünthal et al., 2013). The generally E-W striking thrusts and reverse faults transition into the Dinaric Fault System towards the east in Slovenia, with the only Friuli Domain

fault extending into Slovenia being the Kobarid Fault. The Kobarid Fault in Slovenia is direct continuation of the Gemona Thrust in Italy.

17.2.3 Active faults

Active faults have been systematically compiled into the database and map of active, probably active and potentially active faults in Slovenia, where the activity during the Quaternary is taken as criterium (Atanackov et al., 2019). Five fault systems accommodate the broader-scale tectonic and geodynamic processes ongoing within the collision zone between the Europe and African lithospheric plates. The main drivers of fault activity are the northward motion and counterclockwise rotation of the Adria microplate about a pivot point in NW Italy (Weber et al., 2010) and the lateral eastward motion of the Pannonian domain, in which the TISZA and ALCAPA crustal blocks/mega-units move separately and at different velocities, producing additional smaller-scale dynamics. Active faults comprise the following fault systems:

- ***Adriatic-Apulian Foreland Thrust System****:* is the active outer edge of the External Dinarides Thrust and Fold Belt, an approximately 30 km wide zone of active low-angle thrusts to steeply-dipping reverse faults. The dominant faults in the system are the Črni Kal Thrust and Buzet Thrust. The Črni Kal Thrust continues to Italy as Palmanova Thrust. No significant historic seismicity is associated with this fault system.
- ***Dinaric Fault System****:* is a system of major NW-SE striking dextral strike-slip faults in western and central Slovenia. The dominant faults in the system are the Raša Fault, the Predjama-Avče Fault and the Idrija Fault, all confirmed active, with average estimated slip rates on the order 0.7-1.0 mm/yr (Moulin et al., 2016; Atanackov et al., 2019). The Idrija Fault is the likely source of the 1928 M_w 5.8 Cerknica earthquake and the 1511 M_w 6.9 Idrija earthquake. The Dinaric Fault System accommodates the CCW rotation of the Adria Microplate, with regional motion vectors of 2-4 mm/yr NNW-ward. The 1998 M_w 5.7 Bovec earthquake and the 2004 M_w 5.2 earthquakes were caused by the Ravne Fault, a comparatively smaller fault in the NW part of the Dinaric Fault System (Kastelic et al., 2004, 2008,; Grünthal et al., 2013). Other faults from the system are Čeplez, Divača, Dražgoše, Kranj, Planina-Podpreska, Rakitna, Mišja dolina, Želimlje-Ortnek, Dobrepolje, Žužemberk, Stična, Toplice, Zagorje, and Hrastnik Fault.
- ***Canavese-Tonale-Periadriatic-Mid-Hungarian Large-scale Fault System****:* in Slovenia consists of two major fault systems – the Periadriatic Fault System and the Mid-Hungarian-Balaton Fault System. The ***Periadriatic Fault System*** is a generally WNW-ESE striking dextral strike-slip fault system, delimiting the eastward-moving ALCAPA crustal block/mega-unit in the north from the Southern Alps in the south. It comprises a number of large active strike-slip faults, including: the Periadriatic Fault, the Sava Fault and the Šoštanj Fault, with average estimated slip rates on the order of 0.5-1.0 mm/yr (Atanackov et al., 2019). Other faults from this system are reverse Northern Karawanks Fault and Menina-Vransko Fault. Historic seismicity potentially (but not definitively) associated with the Periadriatic Fault System include: the 1348 M_w 7.0 Villach / Carinthia / Friuli earthquake and the 1690 Mw 6.6 Carinthia earthquake (Stucchi et al., 2012). The ***Mid-Hungarian-Balaton Fault System*** is the eastward continuation of the Periadriatic Fault System, however, it is defined by the interaction of the eastward-moving TISZA and ALCAPA crustal blocks/mega-units. The fault system is characterized by transpressional faulting, ranging from reverse

to strike slip. Slip rates are poorly constrained and estimated to likely be below 1 mm/yr across the entire zone (Serpelloni et al., 2016). There is very little historic seismicity in this zone in Slovenia: the 1838 M_w 4.5 Ormož Kog and 1839 M_w 4.8 Ormož Zavrč earthquakes may be tentatively attributed to it (Stucchi et al., 2012). The faults of this system comprise the Donat, Haloze, Ljutomer, and Orehovec Fault.

- ***Raba Fault System**:* only one sizeable potentially active fault, with little actual evidence of activity, is attributed to this fault system (the Lovrenc Fault). There is no significant historic seismicity in this zone.
- ***Pöls-Lavanttal Fault System:*** is composed of the dominant Labot Fault. The fault is over 150 km long and active, with 0.5-1 mm/yr slip rate based on GPS measurements (Pavlovčič Prešeren et al., 2005). The Labot Fault continues in Austria as Lavanttal Fault.

17.3 Data quality, origin and publication

Systematic geological mapping of Slovenian territory was last performed in 60s-70s through elaboration of Basic Geological Maps at 1:100.000 scale. Several updates were made on these maps, the latest one being the Geological map of Slovenia at 1:250.000 (Buser, 2009). The structure mapped at the Basic Geological Maps was summarized in Structural-tectonic map of Slovenia at 1:250.000 scale (Poljak, 2007). Later, larger scale geological maps were prepared in some areas: Kras Plateau at 1:100.000 (Jurkovšek, 2013 – compiled from two original maps at 1:25.000 and 1:50.000), Kozjansko at 1:50.000 (Aničič et al., 2004), Northeastern Slovenia at 1:100.000 (Jelen and Rifelj, 2011), Idrija-Cerkljansko Hills at 1:25.000 (Mlakar and Čar, 2009), Selca Valley at 1:25.000 (Demšar, 2016), Krško Basin at 1:25.000 (Poljak, 2017). In a meantime, various fundamental and applicative research projects resulted in production of detailed maps at specific location, that are reported and accessible in Geological Survey of Slovenia (GeoZS) archives, publicly or as confidential material. Unfortunately, no systematic geological mapping was carried out in Slovenia at the national level in the last decades.
GeoZS has a strong role in defining the geological input for seismic hazard assessments in Slovenia. Team of experts is working on identification of active faults employing various methods and data sources and characterizing seismic sources. In the last several years a compilation of all available data from maps, papers and reports was made to prepare a database of active faults in Slovenia and surrounding area (Atanackov et al., 2019). The database of active faults contains active, probably active and potentially active faults, where activity through the Quaternary is taken as representative. The faults are characterized and their attributes serve as a seismic hazard assessment inputs. Most of the data for fault characterization, however, comes from the surface observations (structural-geological mapping, geomorphological and paleoseismological data) and shallow geophysical observations (< ~100 m), whereas understanding of deeper structure is limited to a few areas where deeper geophysical data are available (e.g. in NE Slovenia, oil and gas investigations, geothermal energy; Krško Basin, investigations for nuclear infrastructure). Seismic sources are furthermore characterized with the use of seismological data (Atanackov et al., 2019).
At a national level, the most appropriate data sources for fault mapping are summarizing maps at 1:250.000 scale, which were derived from Basic Geological map at 100.000 scale (Poljak, 2007; Buser, 2009), and Database of active faults, which is limited to structures active through the Quaternary (Atanackov et al., 2019). Slovenian fault data for HIKE are thus compiled from these sources (Figure 4).

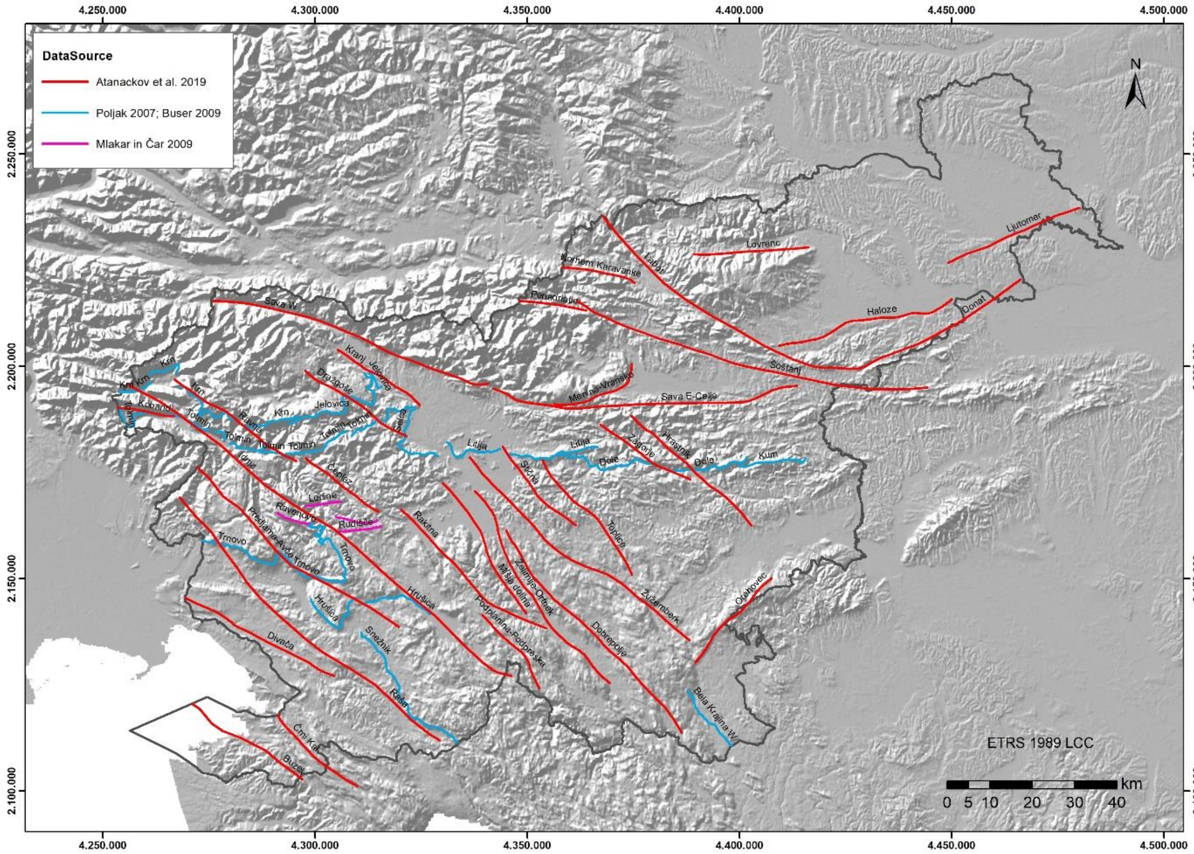

Figure 4: Slovenian fault data and their data source.

17.4 Local fault relevance and application

17.4.1 Seismic hazard

Slovenia is a region of moderate seismicity, with earthquakes of M~3 occurring on average every year, and a number of damaging and several destructive historic earthquakes. The historic record spans 1000 years and includes the following major events (note that historic events have large uncertainties in locations of epicenters, and some of these events possibly or even likely happened in the immediate cross-border area): the M_w 7.0 (I_{max}=IX-X) 1348 Villach earthquake, the M_w 6.9 (I_{max}=X) 1511 Idrija earthquake, the M_w 5.6 (I_{max}=VIII) 1689 Šentvid pri Stični earthquake, the M_w 6.6 (I_{max}=VIII-IX) 1690 Carinthia earthquake, the M_w 5.6 (I_{max}=VIII) 1699 Metlika earthquake, the M_w 5.9 (I_{max}=VIII-IX) 1895 Ljubljana earthquake, the M_w 6.2 (I_{max}=VIII) 1917 Brežice earthquake, M_w 5.8 (I_{max}=VII-VIII) 1926 Cerknica earthquake and the M_w 5.4 (I_{max}=VII-VIII) 1998 Bovec earthquake (Stucchi et al., 2012; Grünthal et al., 2013). Only the 1926 Cerknica and 1998 Bovec events have been attributed to causative faults, with the 1511 Idrija event also being tentatively linked with the Idrija fault, while all other events remain to be linked to a causative fault.

Active fault database supports the national and European efforts to assess the seismic hazard in this area. Majority of faults included in Slovenian fault database are considered or confirmed as active through the Quaternary (Figure 5).

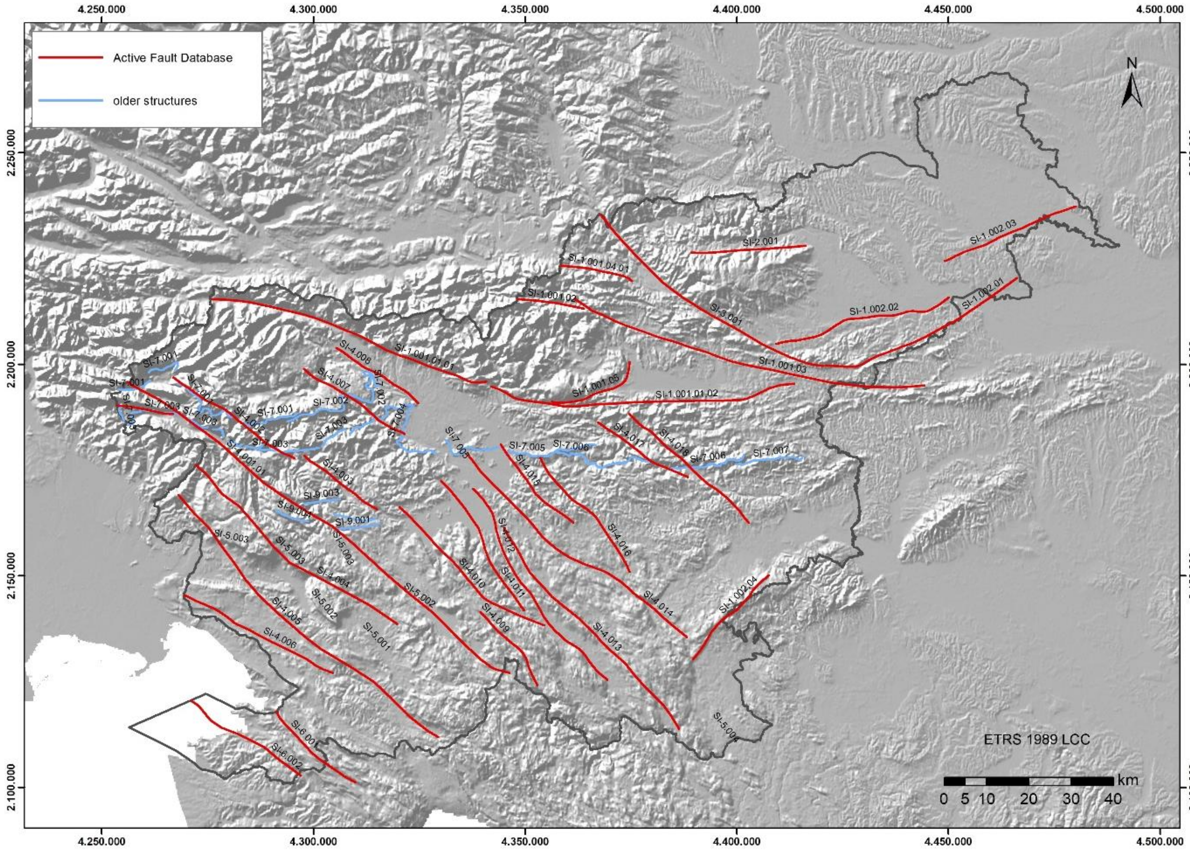

Figure 5: Faults included in HIKE database are mostly considered or confirmed as active through the Quaternary. Other important regional faults are older thrusts.

17.4.2 Induced seismicity

There have been no known cases of induced seismicity.

17.4.3 Geothermal potential

Major faults and fault systems are linked to zones of elevated temperature gradient and geothermal heat flux. Major thermal spa resorts are established over thermal springs on several regional faults, including: Dobrna and Topolšica spas on the Šoštanj fault and Rimske Toplice spa on the Žužemberk fault. Significant geothermal potential is being exploited for thermal spas, indoor heating and agricultural applications in NE Slovenia along the northern faults of the Mid-Hungarian zone.

17.4.4 Construction

Important power and transport infrastructure intersect significant active faults. The faults of the Adriatic-Apulian Foreland Thrust System intersect the A1 highway, including two tunnels (Kastelec and Dekani) and one major viaduct (Črni Kal), as well as the tunnels and bridges for the new Second Track of Divača-Koper line.

The complex geologic structure of the thrust system was a major factor in planning of the infrastructure. Faulting and resulting geologic structure in the Periadriatic Fault System was a major factor in the planning of the Karavanke tunnel, linking Slovenia and Austria, of which the second tube is currently under construction. Faulting was mapped in detail in the analysis of suitable locations for hydroelectric power plants in the middle part of the Sava River. Faulting was taken into account in seismic hazard assessment and fault displacement hazard assessment for nuclear power infrastructure in the Krško Basin.

17.5 Fault data included in HIKE fault database

Fault data from Database of active faults and the most important older structures from External Dinaric Thrust Belt and South Alpine Thrust and Fold Belt, as well as local data on Triassic normal faults near Idrija were included in Slovenian fault database. Database includes more than 70 faults, with 15 regional faults reaching more than 40 km length (Figure 6). The faults, fault systems and thrust and fold belts and fault sets are classified according to the semantic framework in HIKE. A correlation link with faults across the national borders are included, specifically in Italy and Austria. Fault attributes are provided, mainly general fault characteristics (observation and evaluation method, fault type), geometry attributes (length, strike, dip, rake), kinematic characteristics (sense of movement and offset determination) and references.

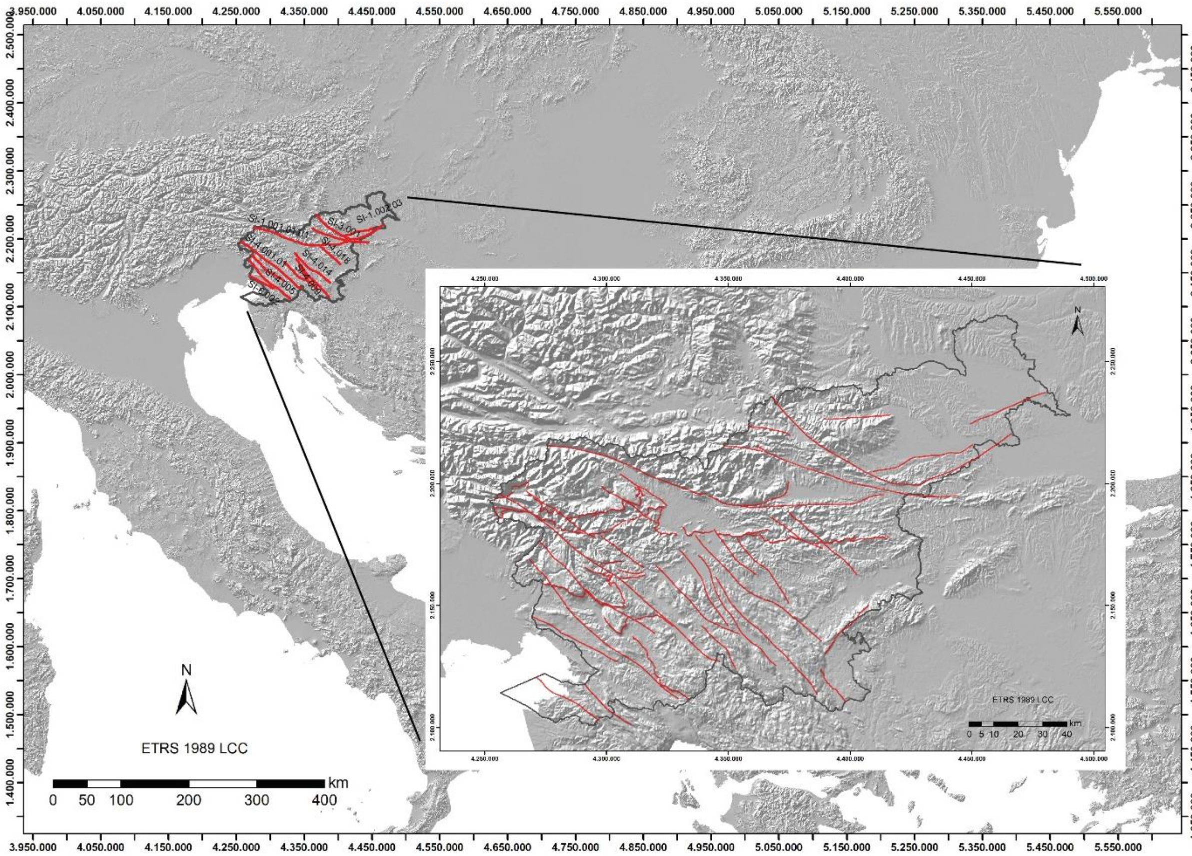

Figure 6: Slovenian faults included in HIKE database.

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18 GEOINFORM – UKRAINE

18.1 Explanatory note

In terms of geology, Ukraine is one of those countries that have virtually all the most important tectonic elements of the earth's crust. The marginal seas of the ancient continents, foothills and inland mountain slopes with their young folded belts - meganapnoria, ancient folded systems, age-old avlakogens, rifts and major depressions, an ancient platform with a huge foundation that overlooks the surface - here are just a few elements of the main structures territory of the country. The diversity of types of tectonic structures is due, on the one hand, to the long history of tectonic evolution of the earth's crust (over 3.8 billion years), on the other, to its territory belonging to the complex zone of articulation of the southwestern flank of the Eastern European platform, bordering hercinide (variscid) and further - with Alpine-Cimmerian mountain structures (Mediterranean mobile (folded) belt -MMB), where the processes of crust formation still continue in our time. These are seismically active meganapnoria of the Carpathians and the Mountain Crimea, which form the outer branch of the alpine folded structures of Europe.

In the platform areas there are two types of folded foundation for sedimentary covers: the first type is a crystalline foundation composed of intensively dislocated metamorphic, ultrametamorphic and intrusive complexes of archaea-paleoproterozoic (EPS structures, outer zone of the Pre-Dobrudzha depression); the second type - peneplenized epiorogenic zones, composed of dislocated metamorphosed and non-metamorphosed sedimentary-volcanic formations of the Riphean-Early Paleozoic (fragments of the Western European platform, hereinafter - WEP), Riphean-Jurassic, depression), Riphean-Permian (DDZ, southern side of the Pripyat depression) age.

The folded areas bordering the EPS structures were formed during several long epochs of tectogenesis. Folded varistids (hercinid) include: Donbass (the main phase of folding - Zaal) and the Prut ledge of Northern Dobruja, the formation of which underwent dislocation metamorphism in the Breton phase and secondary batch deformations of the superimposed (activation) late Cimmerian tecto. The Cimmerian-Alpine folded structures include the Mountain Crimea (the main phase is the Late Cimmerian). To the Alps - the Ukrainian Carpathians and the structures of the Kerch Peninsula, the main cover and sliding structures of which were formed in the Middle Miocene (Carpathian phase).

Very important feature of the epiorogenic zones bordering the platform in the west and southwest is also that they are not a single linear tectonic element pushed on an ancient craton, but a whole system of complexly deployed scaly bodies with the same vergence towards the platform and borders the latter in the form of "soldered" tapes, apparently around its perimeter. In this case (in any case within Ukraine), fouling begins with the formation of earlier geotectonic epochs and ends with alpine (Kruglov, 2007).

In accordance with the sequence of tectonic regimes, as the main factors in the formation of structural elements of the earth's crust, within the country are the Ukrainian Shield, Volyn-Azov Plate and Dnieper-Donetsk Basin (avlacogen), which is part of the Eastern European Platform; Rava-Ruska and Scythia epiorogenic zones and folded-covering structures - Donbass, Crimean and Carpathian meganapnoria. Large superimposed structures - Precarpathian, Preddobrudzky and Karkinitsky depressions are based on heterogeneous at the time of consolidation foundations, and Indolsky - superimposed on the foundation of the Scythian epiorogenic zone.

Within the Volyn-Azov Plate, the Dniester Pericraton, which turns into a South Ukrainian monocline in the south of the country, has been identified in the west. The latter is divided by

the Odessa fault into the Western (Moldavian Plate) and Eastern segments, which differ sharply in their Paleozoic history of development. The Dniester pericraton includes: the area of distribution of Volynskyi traps, Kovelskyi ledge, Volyno-Podolska monocline and Volyno-Polissya, Boyanetska and Lvivska depressions. The Dnieper-Donetsk basin (avlacogen) is divided into onboard and onboard zones and into the Central zone.
In the Crimean meganapnoria the tectonic covers of Yayla, Tavriyskyi, Vladislavivsky and Krasnopilsky are allocated. The Carpathian meganapnorium includes: the Pre-Carpathian advanced trough, within which the External or Bilche-Volytska autochthonous zone, the Central and Internal zones, or the Sambirskyi and Boryslav-Pokutskyi covers are distinguished; Flysch Carpathians are divided into External Flysch and Inernal Flysch covers; Marmarosk massif; zones of the Marmarosk and Peninsky rocks and the Transcarpathian inner depression with the superimposed Vygorlat-Gutynske volcanic zone, which is divided into four separate tectonic elements (Fig. 1).

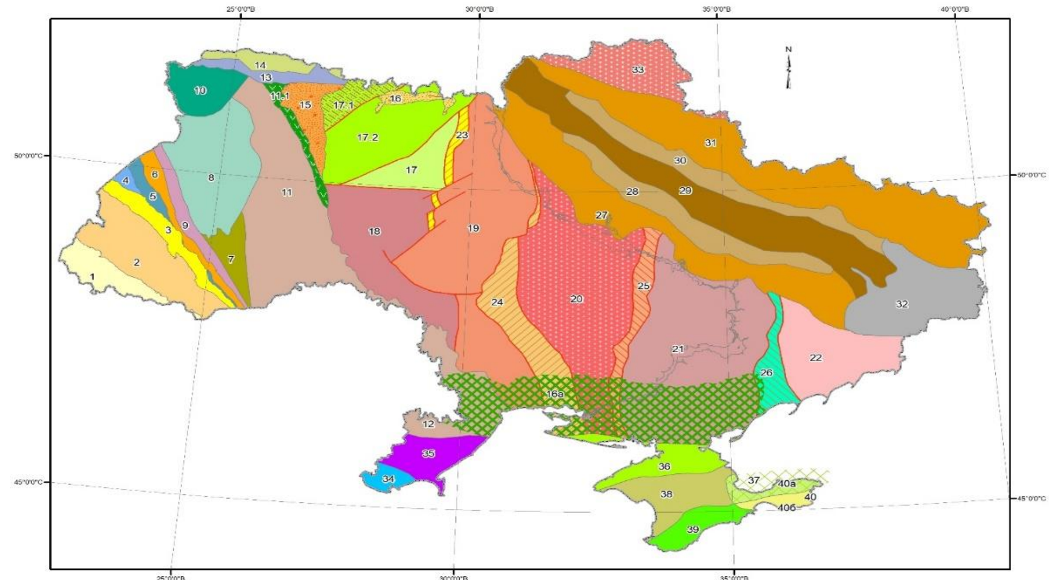

Fig.1 Scheme of tectonic zoning (according to S.S. Kruglov with clarifications and additions)

18.2 Legend

Carpatians Meganapnorium (1 - 3): 1 - Internal(Central Carpatians(Zacarpatska depression, Marmaroska zone, Marmarosk massif, Peninsky rocks zone); 2 - External (Flysch) Carpatians (tectonic flysch covers, Krosno zone Skybova cover); 3 - Pre-Carpathian depression (Boryslav-Pokutsky and Sambirsky covers); structures of the **Western European platform (4 –6):** 4 - Lezhaiska epiorogenic zone, 5 - Kokhanivska epiorogenic zone, 6 - Rava-Ruska epiorogenic zone; structures of the **Eastern European platform (7 - 33):** Volyno-Podilska plate (7 - 13), 7 - Boyanetsky depression; 8 - Lvivskyi Paleozoic trough; 9 - Roztotscka zone, 10 - Kovelskyi ledge; 11 - Volyno-Podilska monocline; 11.1 - the area of distribution of the Volynskyi traps, 12 - the Moldavska monoclinal, 13 - the North Ukrainian handful zone; 14 - Polissya saddle, 15 - Volyno-Poliska depression; 16 - Graben-syncline of the northern part of the USh, 16a - South Ukrainian monocline; Ukrainian Shield (17 - 26), megablocks: 17 - Volysky, 17.1 - Klesivska EFZ, 17.2 - Novograd-Volynska EFZ, 18 - Dniester-Buzky, 19 - Rosynsko-Tikytsky, 20 - Kirovohradsky (Ingulsky), 21 - Serednyodniprovsky, 22- Pryazovsky, suture (tectonic) zones: 23 - Vilensky, 24 - Golovanivsky, 25 - Kryvorighsko-Kremenchugsky, 26 - Orikhovo-Pavlogradsky, Pripyasko-Dnieprovska depression (27 - 32) as a part of the Dnieper-Donetsk depression (27 - 31): 27 - Southern side zone; 28 - Southern coastal zone; 29 - Dnieper-Donetsk graben (Central zone); 30 - Northern coastal zone; 31 - Northern side zone; Folded Donbass (32);Voronezh crystalline massif (33);
Skyfska epiorogenic zone (34 - 38): 34 - Nyzhnoprutskyi ledge; 35 - Preddobrudzky deflection; 36 - North Crimean (Karkinitsky) depression (N-Q); 37 - Indolsky deflection (P-N); 38 - Central Crimean uplift;
Crimean Meganapnorium (39 - 40): 39 - orogen of the Mountain Crimea (Tavriya and Yaylin tectonic covers) (T3-K1); 40 - Kerch folding-sliding structure; North Kerch - 40a (N-Q), South Kerch - 40b (N-Q).

Geological maps of Ukraine show a large number of rupture faults or fault systems, which are observed at different depths and are confined to certain tectonic taxa formed as a result of successive changes in geodynamic regimes. According to leading geologists, the following epochs of tectogenesis (from ancient to modern) can be traced in the geological chronicle of the subsoil of Ukraine - Azovo-Dnistrovska, Dnieprovska, Saksaganska, which is divided into early (Pobuzka) and late (Kryvorizhska), Klesivska, Ryphey- Kadomska(Baikalska), Caledonska, Varisthyiska, (Hercynska), Cimmeriyska, Alpiysko-Himalayska.

18.2.1 The Azovo-Dniestrovska epoch of tectogenesis

Corresponds to the time of the primary consolidation of the lithosphere, the formation of serogneis complexes of the protocor transitional (tonalite-enderbitic and tonalite-trondiemitite) type in time space, which is limited by the interval 3650÷3200 million years. Vertical metamorphic zonation (amphibolite / granulite facies of metamorphism) is characteristic of the complexes of the Early Archean protocor. But at the same time there is a lateral metamorphic zonation, which is due to the presence of dome structures, within which on the surface of the erosion section can be traced the oldest protocor complexes, metamorphosed in the granulite facies of metamorphism. MMB of azov-dnistride form the greenstone foundation of the southwestern edge of the EEP.

18.2.2 The Dnieper epoch of tectogenesis

Took place in the time interval of 3200-2800 million years, in the mesoarchaea. This is the epoch of the first inclusion of the plate tectonics mechanism and, as a consequence, the formation of green stone structures of theMiddle - Prydnieprovska USh and VKM (Pastukhov, Geodynamic map). If the Middle-Prydnieprovska structural-formation zone (hereinafter - MFZ) corresponds to the granite-greenstone region with microplate tectonics, the Ingulska and Priazovskaya MFZ - marginal zones of destruction of Paleoarchean protocontinental massifs or areas of collage of terrains on the border of continental tales.

Volcanic and volcanic-sedimentary strata of the Mesoarchaeum accumulated in conditions similar to the geodynamic conditions of enzymatic island-strong geostructures of the Phanerozoic. In the final stages of the Dnieprovska epoch of tectogenesis, the Midlle-Dnieprovska granite-greenstone region was cratonized with the successive formation of I- and S-granite complexes. In adjacent regions, this process was accompanied by tectonic-thermal processing of Paleoarchean protocor complexes.

IBCs of Dniprid are distributed within the Middle - Dnieprovskyi, Ingulo-Inguletskyi and Priazovsky MFZ USh and on VKM.

The Saksaganska epoch of tectogenesis took place in the time interval of 2800-2050 million years in the mobile zones of the Volyno-Podilsky and Priazovsky protocontinental massifs (microcontinents) and the Middle-Dnieprovskyi granite-greenstone region (Mesoarchean eocraton). This is the most complex and long epoch of tectogenesis, which the limit of 2500 million years divides into early and late.

The early Saksaganska or Pobuzgska epoch of tectogenesis, manifested itself in neo-Archaea and corresponds to the time interval of 2800-2500 million years. The accumulation of powerful volcanic-sedimentary strata occurred in conditions similar to those that exist in modern regional basins of the Okhotskyi type. The maximum manifestation of volcanic activity took place at the limit of ~2750 million years. The formation of a new crust of the transitional type (I-granites) ended at the boundary of ~2600 million years, and the collision complex I es of S-granites are manifested only in fragments (granite gneisses of the Pervomaiskyi and Alexandriyskyi types) and have an age of about 2500 million years. The most striking feature of this epoch is the formation in the neoarchae of thick strata of ferruginous quartzites of the Kryvorighskyi type.

The late Saksaganska or Kryvorizgsksa epoch of tectogenesis, was already manifested in the Paleoproterozoic in the time interval 2500-2050 million years. Boundary basins due to scattered subduction of the reversible type cease to exist and in their place, in pre-expensive conditions, residual flysch pools with a regressive cycle of sedimentation are formed, in the almost complete absence of volcanism. The growing collision at the end of the era led to the closure of flysch basins and the accumulation of the upper horizons of the earth's crust with the formation of orogenic belts at the turn of 2050 million years. Complexes - indicators of the final stages of orogeny are: first - molasoid complexes of marginal and intermountain depressions (2200-2100 million years); secondly, the Berdychivskyi, Zhytomyrskyi, Kirovohradskyi, and Anadolskyi S-granite complexes (2050 million years). The response of the late saxaganids is the processes of tectono-thermal processing of the Archean IBS, which are most pronounced at the boundary of the Riatsian and Orosyrian (according to MSS) periods of the Paleoproterozoic.

Volcanic activity at the early orogenic stage manifested itself only on the northwestern edge of the USh, within the Novograd-Volynsky vault-block uplift. As for the plutonic activity of the early orogenic stage, it manifested itself both within the Kirovohradskyi orogenic belt and within the adjacent relatively stable block structures of the archaea, with the exception of the Middle

Dnieper granite-greenstone region. We are talking about intrusions of monzodiorite magma of Bukinskyi, Novoukrainskyi, Khlibodarivskyi complexes.

18.2.3 The Klesiv epoch of tectogenesis

Covers the time interval 2050-1600 million years, and its structures, in relation to the structural surfaces of the early Precambrian, are superimposed. The time limit of ~1800 million years divides the class on the early and late.

18.2.4 Early klesiv

Is characterized by the gradual extinction of postorogenic processes that led to the formation of metasomatic complexes of this period within the active tectonic zones at the turn of 1900-1800 million years. The active tectonic regime continues only in the north-western part of the USh, where the Osnytsko-Mikashevytskyi volcanic-plutonic belt is formed in the time interval 2020-1970 million years.

18.2.5 Late klesiv

It is the time of the final cratonization of the crystalline basement of the southwestern edge of the EEP (including US), the time of completion of the continental crust, which is subject to the formation (1800 ÷1750 million years) of complex, multiphase plutons and plutonic complexes (Korostensky, Korsyn-Novomyrgorodsky, Pivdennokalchytsky, Oktyabrsky). All subsequent tectonic-metasomatic processes within the US took place only in the mode of short-term activation in local tectonic zones.

"Deep orogeny" led at the end of klesiv to the final division of the USh into megablocks bounded by suture zones. It is in Klesiv that three suture zones have been laid, along which vertical and subhorizontal displacements and collision collisions of megablocks took place (long-term manifestations): Orikhovo-Pavlogradska, Inguletsko-Kryvorizka and Golovanivska.

The emergence of faults and fault zones probably began in the Mesoarchaea with the "inclusion" of the plate tectonics mechanism. But at the late stage of formation of the continental crust of the USh, and EEP in general, there is the most intense process of brittle deformations, which led to the formation of faults of different depths, morphologies and directions. The crystalline basement of the US is dominated by faults and fault zones of the submeridional, northeastern, and latitudinal directions, for which there is repeated activation in subsequent tectonic periods. All elements of the lateral heterogeneity of the Ukrainian Shield are limited by fault systems, mostly deep. The Volyno-Polissya belt from the northwest adjoins the Volynskyi megablock along the Sushchano-Perzhansky fault, the Volynskyi megablock is separated from the Rosynsko-Tikytsky by the Brusylovsky fault, and from the Dniestrivsko-Buzky by the Andrushivsky fault; along the Pervomaisko-Traktemirovska fault system from the east to the Rosinsko-Tikitsky and Dniester-Bugskyi megablocks adjoins Kirovogradskyi which in turn on the east along the Kryvorizko-Kremenchugskyi fault borders on the Middle Dnieper megablock, the latter separated from the Orikhivo- Pavlogradskyi:

The Dniestrivsko-Buzky and Rosynsko-Tikitsky megablocks are bordered on the southeast and south by the Talnivsky and Buzky (Khmilnytsky) faults, and on the west by the Zvizdal-Zalisky and Nemyrivsky faults.

Phanerozoic epochs of tectogenesis differ from the Early Precambrian epochs both in duration and in the nature and scale of tectono-thermal processes.

18.2.6 Riphean-Kadom (Baikal) epoch of tectogenesis (Riphean Wend).

It is divided into early Baikal and late Baikal stages of IBS formation. Baikalide complexes are known along the western and southwestern slopes of the USh, within the graben-syncline structures in the north of the Volyno-Podilsky megablock. That is, it can be argued that the Baikal tectogenesis led to the separation of USh as a positive morphostructure due to the destruction of the southwestern flank of the EEP. Baikalids, in addition, were discovered within the Transcarpathian and Precarpathian Depression, the Scythian epiorogenic zone, where they form the Riphean foundation.
The initial stage of Baikalide is characterized by bimodal volcanism, and ends with the rooting of dikes and small intrusions of gabbro-dolerite, diorite, and occasionally granite.

18.2.7 Caledonian epoch of tectogenesis (Cambrian / Ordovician-Lower Devonian).

Caledonide complexes have been discovered along the western and southwestern slopes of the USh in the zone of its articulation with she VPP, as well as in the basement of the Carpathian orogen (Dilovetsky cover of the Transcarpathian Depression, Boryslav-Pokutsky cover of the Folded Carpathians), VPP caledonids begin with trap volcanism and from this time begins a sharp immersion of this plate against the background of positive movements of the USh.
The Varistian (Hercynian) epoch of tectogenesis is of the greatest importance for the formation of the general structural plan of the southern EEP. It began at the turn of 407 million years (on an international scale) and ended at the Permian / Triassic boundary (WFP, DDZ, Folded Donbass) and in the Early Triassic (the zone of articulation of the Scythian epiorogenic zone with the southern slope of the US).
It was this tectonic epoch that led to the separation of the USh as the main positive morphostructure of the southern flank of the EEP.The USh is surrounded by hercinids from the north and northeast (Pripyatska depression, Dnieper-Donetsk avlakogen, Folded Donbass), from the south (hercinids of the Steppe Crimea or the Scythian epiorogenic zone), from the west and southwest (hercinids of the Lvivska depression). Hercinidas also form the lower structural floor of the Pre-Dobruzha Depression, where they also border the submerged part of the crystalline basement of the southern part of the EEP. The epoch begins with an outbreak of volcanism within the Pripyatsko-Dnieprovska depression, which is most pronounced in the foundation of the Dnieper-Donetsk aulacogen. The Hercynian epoch of tectogenesis ends with the rooting of younger formations - intrusions of the South Donbas, Tatarbunary complexes and their analogues.

18.2.8 The Cimmerian epoch of tectogenesis

Begins with the Early Triassic (~ 245 million) and ends at the border of the Aptian and Albian Cretaceous tiers (~ 108 million). During this epoch, the active marginal geodynamic regime existed in the area traced from the folded structures of the Mountain Crimea and its submerged Kerch fragment through the Northern Dobrudzha to the Internal Carpathians (Marmaroskyi Massif cover, Rakhivskyi cover).
In the Northern Crimea, within the Prysyva Depression, a second branch of chimerids is observed, parallel to the first and probably formed above the zone of reverse subduction of the crystalline basement of the southern flank of the EEP under the Scythian epiorogenic zone. Apparently, the response of the collision of the USh with the Scythian plate is the manifestation of the superimposed Cimmerian fold in the northern coastal zone of the Folded Donbass.

18.2.9 The Alpine-Himalayan epoch of tectogenesis

Begins in the Early Cretaceous epoch (108 ÷ 110 million years) and is not completed at present. The main events of the epoch of alpine tectogenesis take place on the territory of the Crimea (Karkinitsky and Indolo-Kubanska depressions, cover-folding structures of the Kerch Peninsula) and the Carpathians.

In the Miocene there was a regime of island arcs, but only within the Transcarpathian Depression (Vygorlat-Gutyn volcanic ridge). In general, the alpine epoch of tectogenesis is characterized by orogenic geodynamic conditions, which led to the formation of the Carpathian and Crimean meganapnorii (single-branched orogens).

This is the nature of the Folded Carpathians. The Pre-Carpathian deflection occurs above the foreland of the immersion foundation of the EEP and the WEA and is gradually covered by the crust sharia plates of the Folded Carpathians. As for the Transcarpathian Depression, it is most likely a zone of collision (collage) of terrains, the crust of which is composed of oceanic, island-arc and microplate complexes.

For the Crimean meganapnoria, alpine orogeny may be superimposed. It is manifested to the south of the zone of reversible subduction (suture zone), which separates the meganapnorium from the Scythian plate. On the Kerch Peninsula, where modern alpine structures overlap the chimeras, there are widespread sliding movements, which lead to the gradual closure of the Indolskyi Depression.

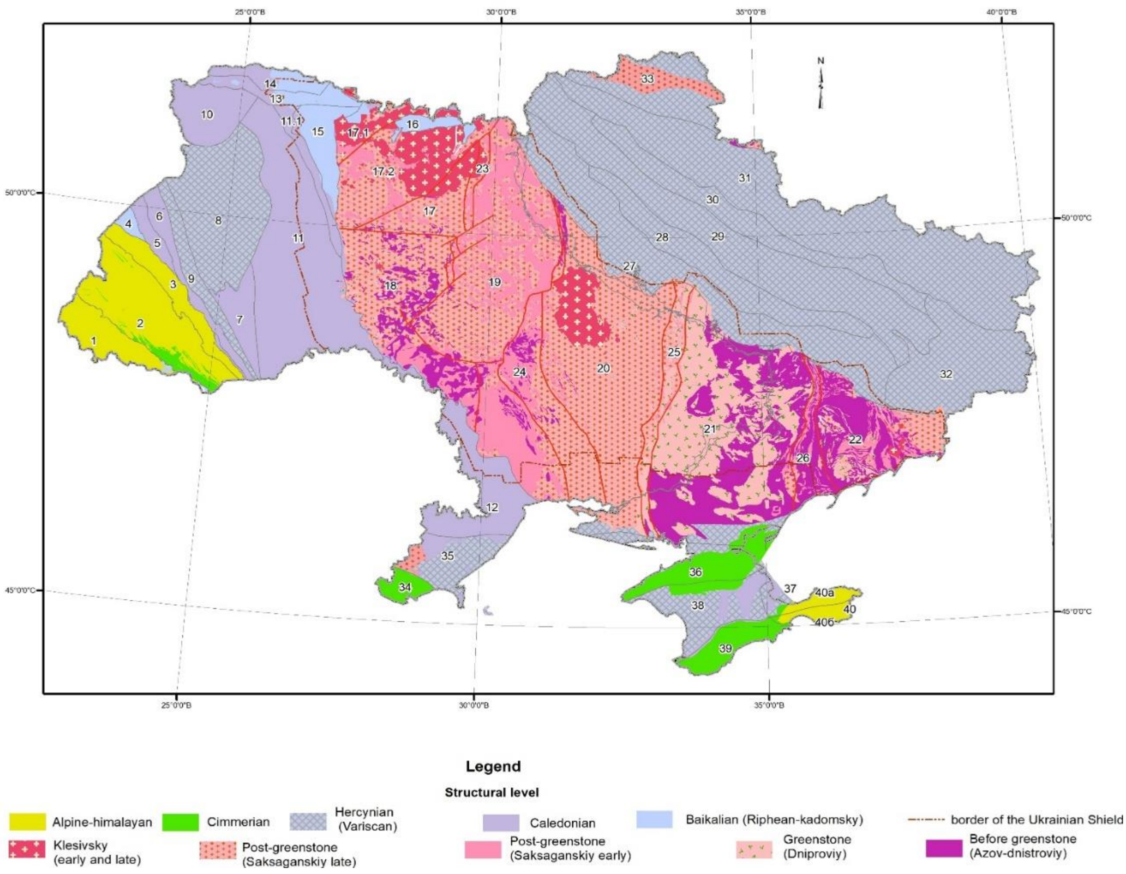

Fig.2 Scheme of distribution of SFK of different ages of tectogenesis (Klochkov, 2015)

Faults and fault systems distinguished by geological and geophysical features are directly related to tectonic elements of different ages (structural floors), which are composed of dislocated SFK and are covered by a sedimentary cover, where rupture faults are almost not manifested. Morphology, kinematics, orientation of faults are determined by the dominant directions of tectonic movements in one or another stage of tectogenesis. The depth of faults depends on their position in the structural hierarchy of tectonic units. Quite often there is an activation of existing fault systems of one or another extension in the periods of later phases of tectogenesis, which manifested itself in the adjacent territory. Almost all structural elements highlighted in the tectonic zoning scheme are limited by deep faults. According to their morphokinematic features, rupture disturbances are divided into discharges, throws, thrusts, left- and right-hand shifts, slides, faults of undefined morphology. For each structural element of the subsoil, the dominant directions and morphological types of faults are observed.

18.3 Structural elements of the EEP

18.3.1 The Volyno-Podilska Plate (VPP)

As an independent marginal structure of the Eastern European platform, is marked by a long multi-stage history of sedimentary basin development that existed within its boundaries and the predominance of stable immersions over ascending tectonic movements for most structures.Of all the geostructures surrounding the USh, the runway is the oldest. As a peripheral region of the pre-Baikal runway platform after the consolidation of its foundation developed under the direct influence of the Galician geosynclinal first in the mode of stretching, formation of paleorifts and deflections avlakogennogo type, accompanied by magmatismpericratonic lowering and alternating spatially connected or disconnected Paleozoic marginal platform depressions such as Boyanetsky, Lvivsky and Preddobrudzky. Tectonically, it is part of the Baltic-Transnistrian system of pericratonic subsidence. In the north, its border runs along the North Ratnivka deep fault, which limits the North Ukrainian (Lukivsko-Ratnivska) mountain zone from the north. In the north-west, the runway extends beyond the border, in the south-west it borders on the Rostock and Rava-Ruska epiorogenic zones, in the south-east it borders on the Moldavian Plate through the North-Moldavian ridge. In general, the actual boundaries of the plate are a trench-like structure known as the Teisseire-Thornquist line in the west and southwest and the USh in the east.
According to the generally accepted European scheme of tectonic periodization in Volyno-Podillya at the pre-Alpine stage, four structural-formation complexes are distinguished, which by age correspond to the structural floors of geosynclinal-folded regions: I. early Baikal (reef); II. Late Baikal (Wend Cambrian); III.Caledonian (Ordovician-Lower Devonian); IV Hercynian (Middle Devonian-Carboniferous). The involvement of the marginal part of the EEP in the pericratic deflection began with the trap volcanism of Volyn times. The trap and graben facies of the Volyn series of the Wends disagree with the continental deposits of the Volyno-Polissya depression and on the formations of the crystalline basement of the western and southwestern slopes of the USh. The eruption of basalt lavas was carried out along deep rift-forming faults, the marginal of which are Ratnivsky and Rivnendky. The spatial confinement of the deflection to the more mobile blocks of the Paleoproterozoic consolidation of the foundation (Volyno-Polissya volcanic-plutonic belt), sandwiched between more stable Archean blocks, can be traced.
The Late Baikal epoch marked the transition of Volyno-Podillya to a new (plate) stage of development. Its beginning (the end of the reef - early Vendian) is manifested in a sharp structural adjustment in connection with the establishment of the Galician geosynclinal system

along the southwestern edge of the EEP. Since then, the development of the region shows a clear longitudinal (northwestern) tectonic zonation and transgressive-regressive cyclicity of sedimentary rocks, represented by terrigenous Wendish deposits and changes in the Caledonian era by carbonate-terrigenous deposits of the Lower Paleozoic. The most common carbonate accumulation was in the Silurian. The section ends with variegated and red deposits of the Dniester series of the Lower Devonian, which are distributed within the linear Boyanetska depression. The latter was formed in the final phases of Caledonian tectogenesis along the marginal seam of the EEP.

Other structural elements of the runway are superimposed in relation to the Volyno-Podilsky monocline. First of all, it is the Lvivskyi Paleozoic depression, the Kovelskyi ledge, the North Ukrainian handful zone, the Polissya saddle. All these structures were formed as a result of Hercynian tectogenesis and usually have a tectonic nature of separation. Within the Lvivska Deflection, there are distributed deposits of the Middle-Late Devonian and Lower and Middle Carboniferous, which are complicated by tilts and thrusts of the north, north-western extension with a fall to the west-southwest. The dislocated deflection deposits lie on the sediments of the Volyno- Podilsky monocline inconsistently and probably form a batch-type structure. Volcanic and sedimentary formation complexes of the Kovelskyi ledge are typical for the entire Volyno-Podilsky monocline, but are much more complexly deployed, which is typical for compression zones. According to some researchers (Klochkov, 2015), the Kovelsky ledge can be considered as a deep shariah, which in its frontal part is limited by the lyrical Volodymyr-Volynsky throw-up. The amplitude of vertical displacements along this fault can reach 2.0 km. A characteristic feature of the Kovelsky deep layer is the presence of arcuate anticlinal structures associated with lystric thrusts, which complicate the Kovelsky deep layer.The North-Ukrainian handful zone is certainly an independent element of tectonic zoning, but it is superimposed on both the Kovelsky ledge and the Volyno- Polissya depression and the northern part of the USh. It consists of a system of sublatitudinal handfuls and grabens. The zone is composed of early Caledonian formations, among which the volcanics of the Volynsky series of the Lower Venda predominate. Under the structures of the Caledonian floor of the handful zone, deposits of the Polissya series of Baikalide and the crystalline basement can be traced. The amplitudes of vertical displacements along the Ratniv faults increase from 100 m on the eastern to 1000-1400 m on the western flank of the zone.

18.3.2 fault faults of Volyno-Podillya

The main regularities of the planned position of the **fault faults of Volyno-Podillya**, their role in the formation of large geostructures of the cover and tectonic zoning, the connection with the stages of tectonic evolution have been studied quite satisfactorily. In recent years, tectonophysical methods have been purposefully and systematically used to study them for the first time (O.B. Gitov, 1999-2001). The determination of morphokinematic characteristics of faults and their classification were based for Doryphaean formations on the analysis of gravimagnetic data in combination with GSZ data and direct geological data, and special studies were conducted for exposed Vendian and Phanerozoic deposits to determine the stages of deformation under the influence of deformations. Given the state of the study of fault tectonics of Volyno-Podillya and the results of research O.B.Gintov, it can be stated that at the level of the surface of the crystalline basement there is a picture of the fault-block structure is inherent in the USh.

Deep interblock and mantle-crust intrablock faults and fault zones continue without much change in geophysical characteristics and have close kinematics;

The vast majority of platform cover faults inherit systems of inter-block and intra-block fault zones in the foundation. The system of faults of the north-eastern direction is connected with the early Baikal tectonic stage. The Baikal stage of tectonic development is associated with the establishment of a system of sublatitudinal faults (Pivnichnoratnivsky and Pivdebnoratnivsky, Andrushivsky, Khmelnytsky). All of them were sedimentary and controlled the location of the centers of Polissya and Volyn magmatism or the area of Polissya and Early Volyn sedimentation. According to tectonophysical research O.B. Gintov they all were left-wing landslides. Late Baikal movements are associated with sliding deformations of the north-western extension, which played a crucial role in the establishment of the Dniester pericraton depression (Podilsky, Pridnestrovsky, as well as tending to the Galician folded belt Belz-Baluchinsky, Rava-Rusky, Peremyshlyansky.

Caledonian tectonic cycle according to O. B. Gintova was distinguished by the displacements of the north-eastern system of faults, the formation of discharges, flat folds and flexures of the north-western direction. The consequence of the Caledonian movements is the folding in the Rava-Ruska zone, the intensification of faults that limit the structures of the Epibaikal platform attached to the EES (Rohatynsky, Rava-Rusky, Horodotsky);

The Hercynian tectonic cycle was marked by the activation of almost all previously established systems. The system of sublatitudinal faults underwent the most contrasting movements. Gintov, there were left shifts and which controlled the formation of the North-Ukrainian handful zone. The northeastern faults of Vyzhivskyi, Stokhodskyi, Lokachynskyi, Lutsky, Horynskyi, and Sushchano-Perzhanskyi were also mobile, and they became more active. These movements are connected with the formation of the Lvivsky Paleozoic trough, the Volynsky Paleozoic uplift, its internal complications (Ovadnenska and Lyubomlska antiforms, the Turyisky shaft, etc.), the Volodymyr-Volynsky high-amplitude discharge.

In the Cimmerian and Alpine stages, the faults of all systems became more active. Deformations were especially active in the Carpathian part of the region, where the north-eastern wing of the Stryjsky depression was formed, as well as the Lvivsky Cretaceous depression (displacements and discharges in the zones of Rava-Rusky, Horodotsky and other faults). Contrasting alpine activation of faults of the north-western and meridional extension and within the outer zone of the Lvivska and Boyanetska Paleozoic depressions, Volyno-Podilsky monocline. These are mostly slides, throws with raised hanging wings (Podilsky, Krasylivsky faults), sometimes torn flexures (Ustechko-Pelchansky). These deformations correspond to the Austrian phase, the younger phases of the alpine cycle are weakly recorded, except for the Carpathian (middle Miocene), which is associated with the formation of the Precarpathian depression. The responses of these movements are manifested in low-amplitude movements of the mosaic of small blocks within the entire Volyno-Podillya. Linear long violations of the Carpathian direction according to O.B.Gintova acted as spreads and right-hand landslides, submeridional - as left shifts, sublatitudinal - as right.

Summarizing the above, we can, based on the conclusions of tectonophysical research O.B.Gint and other data, conclude: the system of sublatitudinal faults manifested itself most actively in the Riphean, Early Wendish, Middle Paleozoic (Breton phase), submeridional system - in the Breton phase of the Hercynian and Austrian phase of the Alpine cycles. The system of faults of the northeastern extension was most active in the Riphean and Middle Paleozoic and the system of the northwestern direction in the Late Wendish, Middle Paleozoic, Late Cretaceous, and Miocene.

18.3.3 The Pripyatsko-Dnieperivska depression

Along with the Donetsk folded structure (DSS), is part of the western segment of the Sarmatsko-Turansky lineament [Tectonics of Ukraine, 1988]. The Loyivsko-Brahynsky ledge is divided into two depressions - Pripyatska and Dnieprovsko-Donetska.

The Pripyatska depression is located mainly outside the state border. In the south, it is limited by the system of edge discharges of the North-Ukrainian hand zone. The amplitude of the main discharges here reaches several hundred meters and they are stepped.

Structural and formational characteristics of the studied part of the section of the sedimentary cover of DDZ is the main source of information about the dynamics of the conditions of its formation. Based only on this part of the section, a number of geologists date the foundation of the depression to the Middle Devonian epoch, ie the age of the oldest deposits discovered by wells. Other experts link the emergence of DDZ with significant geodynamic events that occurred at the boundary of the Proto-Neogene.

The sequence of fairly fully documented stages of DDZ development in the Phanerozoic begins in the Middle Devonian and ends in the Pliocene-Quaternary (actutectonic stage). It includes (according to Kruglov, 2007): Middle Devonian dorift, Late Devonian rift, Tournai-Early Viseu epirift, coal myogeosynclinal, Early Permian Revival-rift-syneclis, Mesozoic Einepine synecline. Each of these stages corresponds to a tectonic-sedimentation complex, which includes a number of formations associated with a certain unity of lithogeodynamic parameters, and at the same time, quite clearly separated by different types of interformation formations. Within the Central zone (graben), the rifting nature of which is no longer in doubt, the most powerful incision of the hercinid remains. Baikalides within the DDZ are not disclosed. However, according to geophysical studies, a graben was recorded in its south-eastern part, the deposits of which have physical properties that differ significantly from the parameters and sedimentary strata lying above the section and the rocks of the crystalline basement. The vast majority of researchers attribute these sections to the reef. Manifestations of Cimmerian and Alpine tectogenesis within the DDZ certainly take place, but they are in relation to the Hercynian structural floor are superimposed structures of activation of the syneclise stage of the DDZ development.

DDZ, according to most researchers, has both longitudinal and transverse zonation. In the north-eastern section there are: South onboard, South onboard, Central, North onboard, North onboard zone. The southern side zone corresponds to the north-eastern slope of the USh. The crystalline basement within its boundaries is immersed to the northeast at angles from 1-2degrees to 5-6degrees and is complicated by a system of discharges.The northern side zone is essentially the slope of the VKM, which has a greater slope relative to the slope of the USh. In its lower part it is complicated by thrusts with a southwestern direction of tectonic flow. Both sides of the DDZ are complicated by numerous local protrusions and depressive immersions of the surface of the crystalline basement.

The northern and southern riparian zones have a stepped structure and are characterized by a sharp immersion of the crystalline basement by a system of stepped discharges. The total amplitude of the discharges can reach 7.5 km, and the angles of incidence 70-85degrees (Tectonics of Ukraine, 1988). These tectonic elements are delimited from the Central Zone, which is the most submerged part of the DDZ and better known as the Dnieper-Donetsk Graben, the so-called marginal faults. In most cases, they are essentially systems of narrow stepped blocks, which due to high-amplitude discharges are quickly immersed towards the axial part of the depression. The possibility of the presence of Laramian and, less likely, Zaalian fold folds from among them is not excluded.

The central zone has a complex structure. According to drilling and seismic sounding, there are a number of protrusions and depressions significantly complicated by rupture dislocations, sometimes of significant amplitude. According to Yu.V.Arsiriya within the graben is observed and transverse zonation in the form of segments of the earth's crust of the Central zone. In the direction from northwest to southeast, five transverse subzones are separated [Kruglov,2007; Tectonics of Ukraine,1988]: north-western, complex dislocations, large shafts and depressions, pre-Mesozoic salt diapirs, south-eastern.

The northwestern subzone has a predominant distribution of Devonian formations, much of the section of which is of volcanic origin. The Chernihiv maximum of gravity is timed to it. Halokinesis is almost absent.

The subzone of complex dislocations differs in the presence within it of the Ichnia group of salt-dome structures bordering the Guzhivaka depression. In terms of deep structure, this subzone does not differ from the coastal zones.

The subzone of large shafts and depressions is composed mainly of shaft-like uplifts In size, these are structures of the third order, complicated by saddles between them. There is only a limited number of local isometric uplifts.

The subzone of pre-Mesozoic salt diapirs, first, corresponds to its name. Secondly, the shaft-like elevations of the subzone are narrow, their axes undulate along the extension and form a number of structures of the IV order. These are salt diapirs with a pre-Mesozoic level of salt mass rise, which are clearly fixed in the structure of the Mesozoic in the form of domes. Between them are the so-called "interdome" uplifts buried under the same Mesozoic sediments. French salt in the domes interacts with the salts of the Kramatorsk world of the lower Permian and forms with them mushroom-shaped morphological forms.

The south-eastern subzone of the Central Zone is the most submerged and within its boundaries all the structural elements of the DSS can be traced at a considerable depth.

Within the crystal bed of the DDZ, the main tectonic elements of the higher-order US (deep interblock suture zones and megablocks) extend to the slopes of the Voronezhsky crystalline massif in the north. For the most part, these are submeridional direction structures bounded by deep faults, which were laid in the early stages of EEP formation. Two intermittently shifted fault zones of the north-western extension are mapped in the depression itself. These zones roughly coincide with the modern boundaries of the graben, although their constituent parts in many places outline a narrower band. Another pair of the same intermittent violations and the same orientation was also identified. They are even closer to each other, but lower in rank. All elements of the north-western extension are younger than the submeridional ones and are most likely related to the late Proterozoic rifting of the Sarmatian Paleo-shield. Submeridional Archean-Lower Proterozoic zones of deep faults do not have a direct clear reflection in the morphology of the bed, hence in the sedimentary cover of DDZ.The dominant position is occupied by high-amplitude disturbances of the north-western extension. However, a fragmentary detailed study of this surface reveals the existence of an extensive system of multidirectional discharges of smaller amplitudes. All disjunctives generally create a complex system of blocks, especially in the northwestern half of the region. Here, inside the graben, they form numerous protrusions of various sizes. Some of them are grouped into two strands that extend along the graben.

Further to the southeast, these strands are leveled. Penetration of disturbances in a sedimentary cover is unequal. Their existence is limited to the floors of discrepancies, primarily confined to the boundaries of geological bodies formed in the Paleozoic. Most of them cease to exist, and some are renewed during the revolutionary periods of development of the depression, but with decreasing amplitude. A very small number of discharges reaches pre-Paleogene mismatch (laramian folded phase). In summary, it should be emphasized that the tectonics of DDZ and its tectonic elements of different orders were formed due to the action of both vertical and horizontal movements, among which the leading place should be given to the first. The most obvious effects of horizontal shifts are recorded in the south-eastern part of the region. These are the change of the dominant north-western extension of structures of all orders to the sublatitudinal in the subzone of pre-Mesozoic salt diapirs, the presence in the north-south-eastern centrocline of strands of north-eastern orientation (as in the zone of small fold DSS) and some other features.

18.3.4 The folded Donbass

Is a constituent structural element of a single chain of Hercynian epiorogenic structures of the southwestern and southern frames of the EEP. We are talking about the north-western dead-end branch of the Scythian-Turan epiorogenic zone. This is the north-western end of the positive sweet structure known as the "Karpinsky Wall", which does not border the EEP, like other epiorogenic structures, but can be traced within the actual platform. Therefore, on the Tectonic Map of Ukraine [132] the Folded Donbass is considered as a part of EEP.

In the south, the Folded Donbass is separated from the USh by a complex system of discharges of the South Donbass block tectonic zone. In the north, the border of the Folded Donbass, which separates it from the Starobilsko-Millerovskaya monocline of the VKM, is the North Donetsk discharge zone and the Mariinsky thrust, which has a north-western extension. The western border of the Folded Donbass passes in the zone of its articulation with the structures of the DDZ and is quite conditional, because its structures are immersed under the structures of the DDZ/ It coincides with the south-eastern flanks of the Kalmius-Toretskaya and Bakhmutska basins, the section of which ends with deposits of the evaporite formation of the Permian age.

The central axial structure of Donbass is a zone of large (extended) linear folds, covering the main area of the open basin, represented by sublatitudinal Main and Southern syncline folds, which can be traced along the entire basin and separated by the Main anticline with steep angles of 60 degrees wings. The western part of the vault of the Main Anticline is complicated by a longitudinal Axial thrust; other parts - slides and small forms of dislocations. In the eastern part - Sulino-Konstantinovsky thrust. The main anticline and both synclines are divided by the Rovenkivsky transverse deep fault zone into western and eastern parts. Axial rupture faults of the Main Anticline control magma-hydrothermal processes that form polymetallic mineralizations of the Nagolny ridge and Mykytivka.

To the north and south of the Central zone of large linear folds are zones of small (small) folds. There is a clear difference in the folds of the north with the predominance of plicative dislocations with a large variety of folds in shape and size and the south, where the rupture forms (discharges) of submeridional and sublatitudinal extension and scattering folds predominate. The latter can be called a zone of folded-block (block) dislocations with active fluid-dynamic changes.

Summing up, we note that the discovery and expansion of the paleorift (DDZ together with the Folded Donbass) took place during the Late Devonian in the directions from the inner corner of the platform from southeast to northwest and from the axial part to the sides with successive occurrence on the crystalline Precambrian basement. Devonian, and at the stage of deflection - Carboniferous, which formed a successive transgressive series of terrigenous, carbonate, volcanic and hemogenic strata.

Each of the stages of development, as well as each of the selected tectonic elements in the DDZ, have their own specific development and are separated by paired deep faults. The most significant among them is probably the Dnieprovskyi deep fault (fault zone), which separates the EEP from the DDZ and the Folded Donbass. It is traced by tectonic-magmatic and relief-forming events from the reef to the anthropogenic. The regressive stage in the Hercynian structural-stratigraphic complex of the Greater Donbass, which began to form from the end of the Carboniferous and was formed in the conditions of mainly continental regime during the Permian and Triassic as a red stratum, is located within the Devonian graben.

18.3.5 The South Ukrainian monoclinal

As a constituent structural element of the EEP covers the area of distribution of sedimentary strata that cover the foundation of the platform. Its northern boundary corresponds to the boundary of the Neogene sediments that cover the southern slope of the Ukrainian Crystal Shield. The southern boundary of the monocline in the northern part of the region is carried out by regional disturbance (Main Azovskyi fault), which is also the northern boundary of the Scythian epiorogenic zone, further west along the northern edge of the Karkinitsky Depression, and in the Western Black Sea coast on the northern edge of the Pre-Dobruja fault. According to the stratigraphic completeness and thickness of the sections within the monocline, there are two parts: western and eastern. In the western part, west of the meridian of Odessa, the section of the sedimentary cover includes sediments from the Vendian to the anthropogenic, while in the eastern part it is practically only from the Cretaceous to the anthropogenic.
The structural plan of both the western and eastern parts of the monocline is generally simple and is characterized by a gentle fall of sedimentary strata in the southwestern and southern directions. Isopachites of the cover can withstand mainly sublatitudinal extension with some complications in the form of half-protrusions, low-amplitude uplifts and local depressions.

18.4 Epiorogenic zones

The main structural elements traced in the foundation of the "young Hercynian platforms" are **epiorogenic zones**. In relation to EEP, they are part of the ancient orogenic belts, which should limit the platforms in the classical version. If the plates, or the most submerged segments of the south-eastern flank of the EEP are the peripheral zones of this platform, then the epiorogenic zones are external to the platform. The epiorogenic zones include: the WEP structures that form its folded foundation, the Scythian epiorogenic zone and the folded Donbass (description is given above).
According to the adopted scheme of tectonic zoning (Fig. 1) called **Rava-Ruska epiorogenic zone**, the map shows the block of the foundation of the Western European Plate (WEP), bordering on the Roztotskyi block Baikalide, which extends the Volyno-Podolsky edge of the EEP. However, there is no direct geological data on the existence of this block of Baikalids and its structure is reconstructed only by geophysical methods.
In the structure of the foundation of the WEP Rava-Ruska zone stands out as a small fragment of a long zone of Caledonian folds, most of which, like the rest of the young platform, in the modern structure is covered by a folded-orogenic complex of the Precarpathian advanced trough. Its north-eastern boundary is defined by the front of the Rava-Rusky thrust, along which the Caledonian folded complexes partially cover the Lvivskyi Paleozoic trough. From the south-west, the Kokhanivska zone of the Salair fold is pushed into the Rava-Ruska zone along the Gorodotsky fault, which is confirmed by the drilling of parametric wells. The Kokhanivska zone, in turn, along the Krakovets fault is complicated by a thrust from the Lezhaisky massif of the

Baikal fold [Tectonic map..., 1986], and according to S.S. Kruglov - Caledonian (Geodynamics, 1999,) (12), p. 72).

The Rava-Ruska zone within the territory of Ukraine is the regional structure of the EEP on its north-eastern flank. The capacity of the Late Caledonide zone exceeds 1.0 km. They are composed of intensively deployed strata of dark gray argillites (graptolite shales) with single layers of limestone (Silurian-Lower Devonian). Argillites are crushed into overturned folds with angles of incidence of the wings from 50 to 85 degrees. The degree of dislocation thickness decreases markedly in extension - in the south-easterly direction. The lower structural tier of the zone is composed of flysch IBC Cambrian-Ordovician.

The closure of the Rava-Rusky myogeosynclinal path is connected with the Caledonian folding epoch. According to GDP-200, the folded foundation of the zone occupies the most elevated position and is characterized by depths from 0.5 to 1.5 km; has a clear syncline shape, complicated by brachial folds. In the neighboring Kokhanivska zone, the depth of the foundation exceeds 4 km.

IBCs of the Kokhanivska zone are composed of dislocated and usually diagenetically altered flysch deposits of the Vendian and Cambrian. As well as within the Rava-Ruska zone, these formations belong to the sandy-clay flysch formation near relatively deep sea basins, divided by cordilleras. The width of the Kokhanivska zone with the Salair age of consolidation does not exceed 20.0 km.

The Lezhaiska zone, better known as the massif, is composed of IBS of the Baikal folded complex - strongly dislocated and episonally-metamorphosed formations of the quartz-phyllite formation of the terrigenous flysch of the Riphean age. According to the results of GDP-200 Lezhaisk zone traced to the southeast to the border with Moldova. And then the baikalid distribution zone of the Lezaj zone is traced to Central Dobruja (Romania). The conditions of occurrence of rocks and the internal structure of the IBS zone are practically not studied. The depth of the Baikalide is ~ 4.0 km, and in the part of the zone submerged under the Outer Carpathians it exceeds 7.0 km. The width of the zone in the north-western part of Precarpathia reaches 40.0 and more km.

After the Caledonian folding phase, the Rava-Ruska zone, together with the Lezhaiska and Kokhaniva zones of older consolidation epochs as part of the future (epigertsin) Western European platform, acted as a relatively rigid block, which, like "buffer" structures, extinguished the resonant geosynclines. At the final stage of Hercynian tectogenesis, the zones of the Late Proterozoic-Early Paleozoic consolidation underwent intense folding-sliding dislocations facing the ancient EEP, after which they acquired the features of the outer edge of the heterogeneous foundation of the Epigerian or Western European platform.

The Scythian epiorogenic zone extends in the sublatitudinal direction along the southern edge of the EEP and is mostly hidden under the waters of the Black and Azov Seas. On land, it covers the southern part of the Western Black Sea coast and the Plain Crimea.

The northern boundary of the Scythian epiorogenic zone is the thrusts that trace from the Western Black Sea coast through the northwestern shelf of the Black Sea (north of the Kiliyske and Golitsynske uplifts), the central part of the Plain Crimea and the Sea of Azov (north of the Azov Shaft). Along these faults, with a vertical amplitude of 1.5–2.0 km and a horizontal component of the order of the first kilometers of the green-shale basement rock with a Paleozoic and Mesozoic-Cenozoic (up to Eocene inclusive) rocks covering them, they are pushed to the southern part of the South Ukrainian region.

In the south, the Scythian epiorogenic zone borders the Crimean-Kerch Alps, or the Western Black Sea deep-water basin.

The foundation of the Scythian epiorogenic zone is composed of a greenish-shale complex of Proterozoic and for the most part is covered by sedimentary strata of the cover of different ages.

The internal structure of the zone is complicated by the northern vergence thrusts formed at the alpine stage of evolution, at the Eocene – Oligocene boundary. On the territory of Ukraine, the zone is divided into two segments - Western (Prydobrudzky) and Central (Crimean-Azovskyi). Eastern segment - Pre-Caucasian is located outside Ukraine. The conditional boundary between the Western and Central segments of the zone is drawn by most researchers along the Odeska tectonic zone.

The Lower Prut ledge (Western segment) of Northern Dobrudzha is composed of deployed IBCs of the Caledonian, Hercynian, and Cimmerian stages of tectogenesis. The most ancient formations within the ledge are the rocks of the complex of "green shales", opened by a number of wells. In the northern part of the ledge, the section of green shales increases stratigraphically upwards siltstone-argillite-limestone strata of the Silurian-Lower Devonian and carbonate formations of the Middle-Upper Devonian. Permo-Triassic red terrigenous deposits are inconsistently deposited on these deposits.

The internal structure of the ledge is complex and in general the ledge is pushed on the adjacent formations of the Preddobrudzky depression from the north.

Northern Dobrogea is divided into two zones - Mechin and Tulcea. The Mechyn zone is located outside Ukraine and is the south-western part of Northern Dobrudzha, which is separated from Central Dobrudzha (a segment of the Moesian Plate) by the deep Pechenyaga-Kamyana fault (throw with a left-hand landslide component). According to the morphology and features of the geological structure of the adjacent blocks of the earth's crust, it does not differ from the known Rava-Ruskyi fault. The Mechyn zone is composed mainly of Paleozoic sediments, while the Moesian plate has an Epibaikal basement. This makes it possible to consider Northern Dobrudzha as an analogue of the EEP structures discovered in the foundation of the Precarpathian Depression and to consider the Pechenyaga-Kamyana deep fault zone as the boundary between the EEP and the WEP.

The IBCs of the Hercynian stage of tectogenesis of the Tulcea zone are overlain by the Early Cimmerian Triassic IBCs, with which they are crushed into conformal folds, thrown to the northeast. In general, the Tulcea zone can be considered as a sharia with a scaly-folded structure having a northern and northeastern direction of tectonic flow (vergence). In the north, the Tulcea sharia is limited by the Novosilskyi and Izmailkskyi thrusts.

In the Cimmerian era of tectogenesis Lower Prut ledge is complicated by thrusts along the submeridional arc faults. Formed Rhine (Valley) dome structure (bounded on the east by the Cahul-Yalpugskyi thrust), in the center of which is mapped an array of alkaline and subalkaline rocks of the valley complex.

The Pre-Dobrudzha depression is located between Dobrudzha and the Eastern European platform, which determines the complex nature of its foundation and long history of development. In the south, the depression sinks under the thrusts of the Novosilsko-Izmailska tectonic zone, and in the north its structures are limited by the Belgorod-Dniester thrust zone, which separates it from the Chisinau syncline of the Moldavian plate. But the northern flank of the depression is almost unexplored. It is possible that the deep boundary of the deflection runs along the shear thrusts of the Chadyr-Lung and Artsyz tectonic zones of northern vergence. The foundation of the deflection morphologically sinks within local depressions to depths of 7–9 km, while on their periphery it rises to the level of 2.8–4.0. The platform cover complexes are composed mainly of Middle and Upper Jurassic argillites and are overlain by terrigenous deposits of the Paleogene and Quaternary systems.

Within the Pre-Dobrudzha Depression, a kind of IBS was formed - derivatives of several tectonic epochs. The crystalline base of the deflection is increased by the IBC of the cover of the Caledonian epoch of tectogenesis. Complexes - indicators of early caledonids are terrigenoustuffogenic formations of wends, terrigenous deposits of the Cambrian. Their thickness reaches 1500 m. Then the incision increases IBS of late Caledonids, composed of carbonate-terrigenous deposits of the Silurian-Lower Devonian, the thickness of which does not exceed 200 m. The presence of these complexes indicates that during the Caledonian tectonic era the territory of Predobrudzky belongs to to the only Baltic-Transnistrian pericraton depression of the marginal part of the EEP.

The most common within the deflection of IBS Hercynian era of tectogenesis, which played a crucial role in the formation of the Pre-Dobrudzha depression as a foothill. Early hercinides are represented by quasi-platform deposits of dolomite-limestone, terrigenous and evaparite-limestone formations. But the most powerful (up to 4,000 m) are the foothill molasses complexes [Tectonics of Ukraine, 1988]. Molasses complexes are moderately deployed. Crumpled in sloping folds with angles of incidence of the wings 20-45 degrees.

Magmatic formations of the Carboniferous- Lower Triassic probably belong to a single volcanic-plutonic complex of the active continental margin of the Andean type [Tectonics of Ukraine, 1988]. The spatial position of the centers of volcanism is controlled by a system of arc and radial faults.

18.4.1 Central Crimean uplift (steppe Crimean structures), the Karkinitsky and Indolsky depressions

The Crimean-Azov (Central) segment includes the **Central Crimean uplift** (steppe Crimean structures), **the Karkinitsky and Indolsky depressions**. The boundaries of the Scythian epiorogenic zone within the Crimean peninsula and the adjacent shelf are significantly specified according to the results of GDP-200. It is established that it is limited by fault systems - South and North, which act as suture zones. The northern seam zone is buried under the Karkinitsky alpine depression. Within the peninsula, it can be allocated under the name Krasnoperekopska and has a thickness of about 4-5 km.

From the south it is limited by the North Tarkhankutskyi deep throw-push. The southern (Crimean) seam zone has a thickness of 10-12 km and is traced along the line of m.m. Balaklava-Simferopol-Belogorsk. IBS epiorogenic zone of the Central segment is heterogeneous and belong to several tectonic epochs, the formation of which were maximally deployed in the Hercynian and Cimmerianperiods.

Hercynids of the Steppe Crimea go under the surface of the platform cover within the Central Crimean uplift, which covers the central and southwestern part of the Plain Crimea. The foundation here is characterized by a relatively shallow deposit and is covered by a low-strength cover of Cretaceous Eocene deposits, sometimes eroded in the pre-Maikop period and inconsistently covered by the Maikop or Nadmaikop deposits.

The internal structure of the Scythian epiorogenic zone is complicated by the northern vergence thrusts formed at the alpine stage of evolution at the Eocene – Oligocene boundary. The platform cover of the Central segment of the Scythian epiorogenic zone was formed during the Alpine epoch of tectogenesis. It occurs with sharp angular and stratigraphic discrepancies on the Cimmerian and older IBS.

18.4.2 The Karkinitska depression

Is a sublatitudinal depression filled with a thick layer of Lower Cretaceous terigenic-clayey, Upper Cretaceous – Eocene clayey-carbonate, Oligocene – Miocene clayey-terrigenous, and Miocene – Pliocene-Carboniferous. The deflection is localized in the joint zone of the Eastern

European platform and the Scythian epiorogenic zone, which is the reason for its structural and tectonic asymmetry.
The northern side of the depression, located on the Eastern European platform, is, in fact, a gentle monoclinal with the rocks falling to the south. The south side, located on the Scythian epiorogenic zone, is complicated by thrusts, along which local uplifts are formed, mostly brachyform, asymmetric, with more steep northern wings. In the central part of the apta-alba sediments, a graben is clearly manifested, which is limited by longitudinal and diagonal faults both from the south and from the north. The amplitude of displacements along faults in pre-Cretaceous strata is 1-1.5 km. This system of faults, at the beginning of the alpine stage of tectogenesis, is associated with the localization of outbreaks of andesitic volcanism of the central and fractured type. From the Upper Cretaceous and onwards, the deflection loses the features of a graben-like structure and acquires the features of an intraplatform depression.

18.4.3 Indolskyi deflection.

In the land part there is only its centricline closure, while most of the depression is hidden under the waters of the Sea of Azov. The depression is filled with Cretaceous and Paleogene formations, which are covered by very strong deposits of the Maikop series and the Nadmaikop complex. The northern boundary of the depression coincides with the southern boundary of the Azov shaft, while the southern boundary runs along the front line of the Vladislavovske cover. In the southern part of the depression in the structure of Maikop and Nadmaikop deposits a significant role belongs to clay cryptodiapirs and diapirs complicated by depressed synclines.
In general, for the central part of the Scythian epiorogenic zone, the dominant directions of the structural elements are sublatitudinal (west-east). Among the faults are dominated by throws, thrusts. The orthogonal system of faults is mainly shear.

18.4.4 Orogenic zones of Alpine-Cimmerian folded structures (meganapnoria)

On the territory of Ukraine there is a fairly clear zonation of the main geostructural units that border the EEP: EEP epiorogenic zones-folded structures. The latter are marginal members of this triad. In the southwest it is the Carpathian Meganapnorium, which belongs to the northern branch of the Alpine belt of Eurasia, in the south - the Cimmerians of the Mountain Crimea and the Alpids of the Kerch Peninsula and the Indol Depression. The geodynamic regime of their formation differs: from the conditions of island arcs (Carpathian Meganapnorium) to the active continental margins (Crimean Meganapnorium).

18.4.5 The Carpathian folded structure (meganapnorium)

Within the country is the Ukrainian Carpathians, which is part of the huge Carpathian Arc, which stretches from the Vienna Basin in the northwest to the Balkans and southeast. Separating from the Northern Alps only by the superimposed, mostly Neogene depression of the Vienna Basin, steeply curved first to the north, then to the east and finally to the south, the Carpathian Arc with its outer edge discordantly attached to the essentially different in history of the Center of geostructural elements.
On its outer periphery, it creeps far, first into the Czech Crystal Massif, the Eastern Sudetenland and the Upper Silesian Coal Basin, then into the system of linear caledonid and Baikalide dislocations. In the east, within the Ukrainian segment of the arc, it completely overlaps these folded borders, which are soldered to the ancient platform and far "splashes" on the pericratondorifeal Eastern European platform. (Kruglov, 2004). The rear part of the arc is

occupied by the largest depression in Europe of Miocene, Pliocene and Quaternary sediments, which is separated by the Romanian Apuseni massif into two tectonic depressions: the larger Pannonian and the smaller Transylvanian. According to sharp structural-formation and historical-geological differences, the whole arc is divided into the Inner or Central and Outer or Flysch Carpathians. The Inner Carpathians are an area of manifestation, in addition to Miocene, also of Domiocene folds. At the same time, some of their areas have been folded repeatedly only in the Alpine era. The Outer Carpathians are an area of only Miocene folding with some migration in time from the innermost units to the platform framing. The boundary between them is the area of the Penin rocks, which before the Paleogene developed in the type of the Inner Carpathians, and then - the Outer. The scheme of tectonic zoning of the Carpathian meganapnorium is shown in Fig.3.

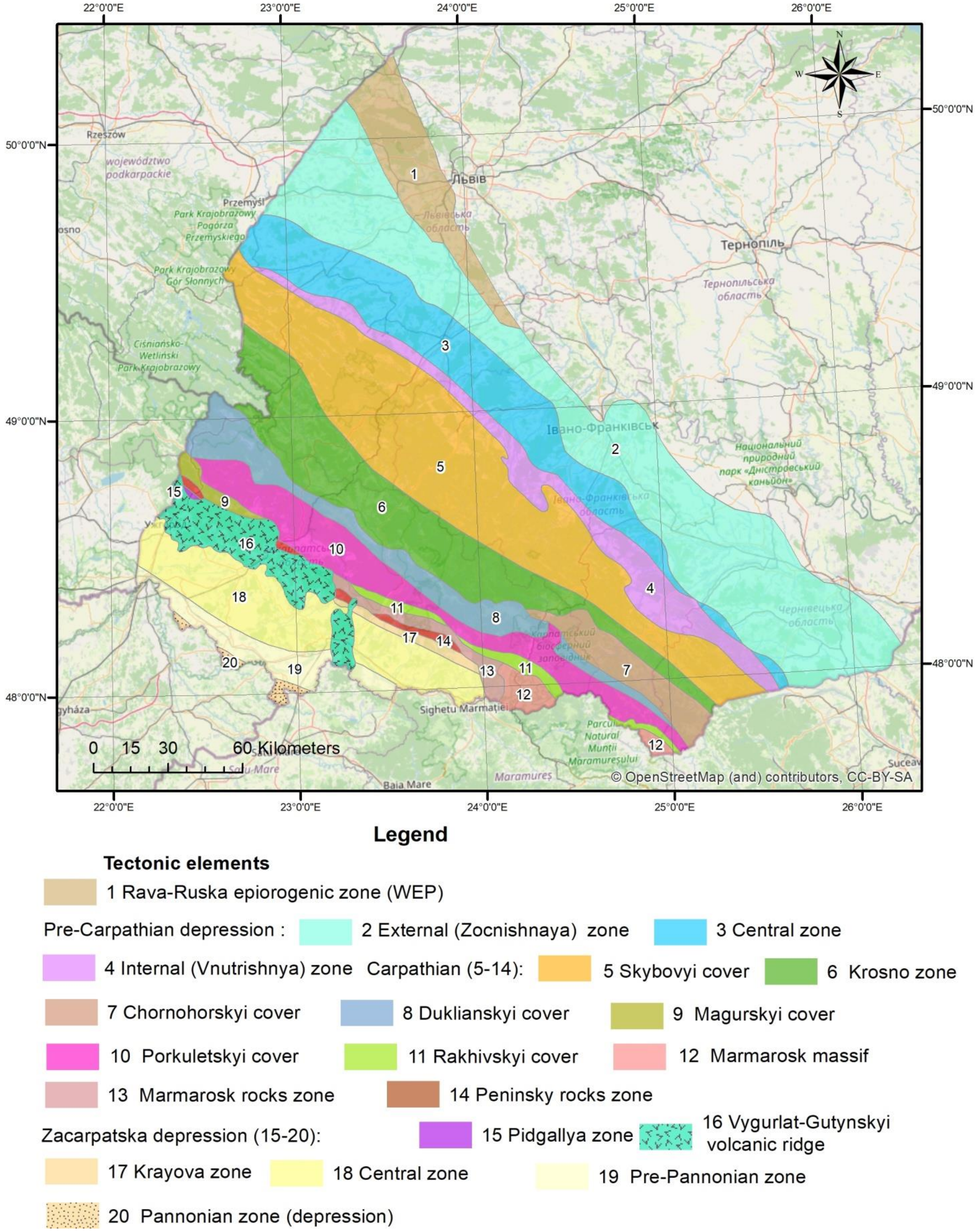

Fig. 3. Scheme of tectonic zoning of the Carpathian meganapnorium (according to Kruglov S., 1988)

In addition to differences in the time of manifestation and the number of folding phases, these areas differ sharply in their formational performance. The Outer Carpathians are an area of distribution of exclusively high-power flysch formation (Cretaceous - Lower Miocene) and are almost amagmatic everywhere. The Inner Carpathians are marked by a set of different formations. A special position is occupied by the Marmaros crystalline massif and the area of Marmaros rocks, located on its north-western extension. These tectonic units are wedged between the Outer Carpathians and the area of the Penin Rocks. Before the Paleogene, the history of their geological development was very close to the Inner Carpathians, and in the Paleogene, part of them is extended to the flysch mode of development.
The allocation of only five structural and formation zones in the Carpathians is based on these principles of tectonic zoning: Inner Carpathians, with Miocene-Pliocene depressions superimposed on them, which play the role of inner (rear) molasses deflections, Peninskyskel zone, Marlikarpa Karst advanced or marginal deflection.
The allocation of smaller tectonic elements within the Flysch Carpathians (which occupy more than half of the entire area of the arc) is based on structural-facial (usually structural-lithological) features and the main unit of zoning here is already the structural-facial zone. Almost all these zones in the Miocene are transformed into independent tectonic covers, which are articulated with each other behind the scenes. According to modern ideas (Kruglov S., 1988, Kruglov S., 2004), independent structural-facial zones of the Carpathians are characterized, to some extent, by the autonomy of their development in the Cretaceous and Paleogene times (and, in part, in the Early Miocene) and . In the pre-expensive stage, they were torn from their base along the frontier faults with complete overlap of the surface or underwater cordilleras that separated them. All the coverings of the Outer Carpathians are characterized by their scaly (tiled) pressure on each other with a vergence towards the platform frame, and on the maps they are depicted by alternating linear bands with a rock-like tectonic joint.

18.4.6 Pre-Carpathian regional depression

Within the **Pre-Carpathian regional depression**, according to the peculiarities of the structure and formation, three separate structural-formation zones are distinguished: Inner or Boryslav-Pokutska, Central or Sambirska and Outer or Bilche-Volytska. The first two are tectonic covers in the modern structure which are limited by lyrical throw-ups, and the third is composed of autochthonous formations.
The Bilche-Volytska (or External) zone is based on an ancient platform base and its epipaleozoic folded environment. It has a multi-storey structure, a general monoclinic immersion under the Carpathians, stepped blocks of its domiocene base are immersed in the same direction. It is composed of a Neogene complex of upper molasses, which have a typically platform brachyform fold.S.S. Kruglov is considered the Samborskyi cover as an allochthonous, completely detached from its autochthonous tectonic plate, composed of dislocated saline terrigenous-clay molasses and pushed on the outer part of the depression at a distance of at least 18 km [Tectonics of Ukraine, 1988]. The time of formation of this cover is estimated as post-Sarmatian, but Miocene. The cover is complicated by elongated thrusts of the second rank. Lower-Middle Miocene deposits are crushed into rather steep but simple folds. Sloping troughs composed of Pliocene sediments are occasionally observed. Boryslav-Pokutsky cover is represented by complexly deployed rocks of flysch and molasses formations. The internal structure is folded-scaly. This is a system of narrow slices, within which antiform, overturned and lying folds of northeastern vergence are widespread, which are also complicated by sliding disruptions [Tectonics of Ukraine, 1988].

Some thrusts separating scales, chips, and folded tiers in the near-surface part of the cover are very steep, almost thrown back to the Outer Carpathians, but with depth their steepness decreases to 40-50degrees at a depth of 3-4 km, and deeper than 6 km, for drilling data does not exceed a few degrees.
This is the structure typical of cartoons in their front part. Within the cover, structural traps containing oil and gas deposits and manifestations are common. The lower horizons of the slices are composed of flysch deposits of the Lower Cretaceous - Paleocene, and the upper - molasses of the Early Miocene.

18.4.7 The External or Flysch Carpathians

The External or Flysch Carpathians are closed between the advanced depression in the northwest and the Marmara belt and the area of the Penin rocks in the southwest. According to the peculiarities of the Cretaceous and Paleogene flysch deposits developed here and, to a lesser extent, by the style of their internal structure, a series of structural-facial zones are distinguished, which in the orogenic stage almost all of them were transformed into tectonic covers. From the outer part of the Carpathians to the inner part the following main structural-facial units are distinguished: Skibova, Krosnenska, Chernogirska, Duklyanska, Porkuletska, Rakhivska and Magurska. All of them, with the exception of Krosnenskaya, were transformed in the Miocene into tectonic covers. They consist of Cretaceous, Paleogene, and the lowest horizons of the Miocene strata, which have a flysch appearance and only insignificant in thickness and distribution of Miocene deposits of olistostromic origin, which are probably molasses. Their total capacity reaches 10 km. The lithological uniformity of the flysch section and the proximity of the mechanical properties of the rocks caused similar features of the morphology of the folded and discontinuous dislocations developed here — the folded-scaly style of the internal structure with clearly defined monovergence toward the platform frame.(pic.4)

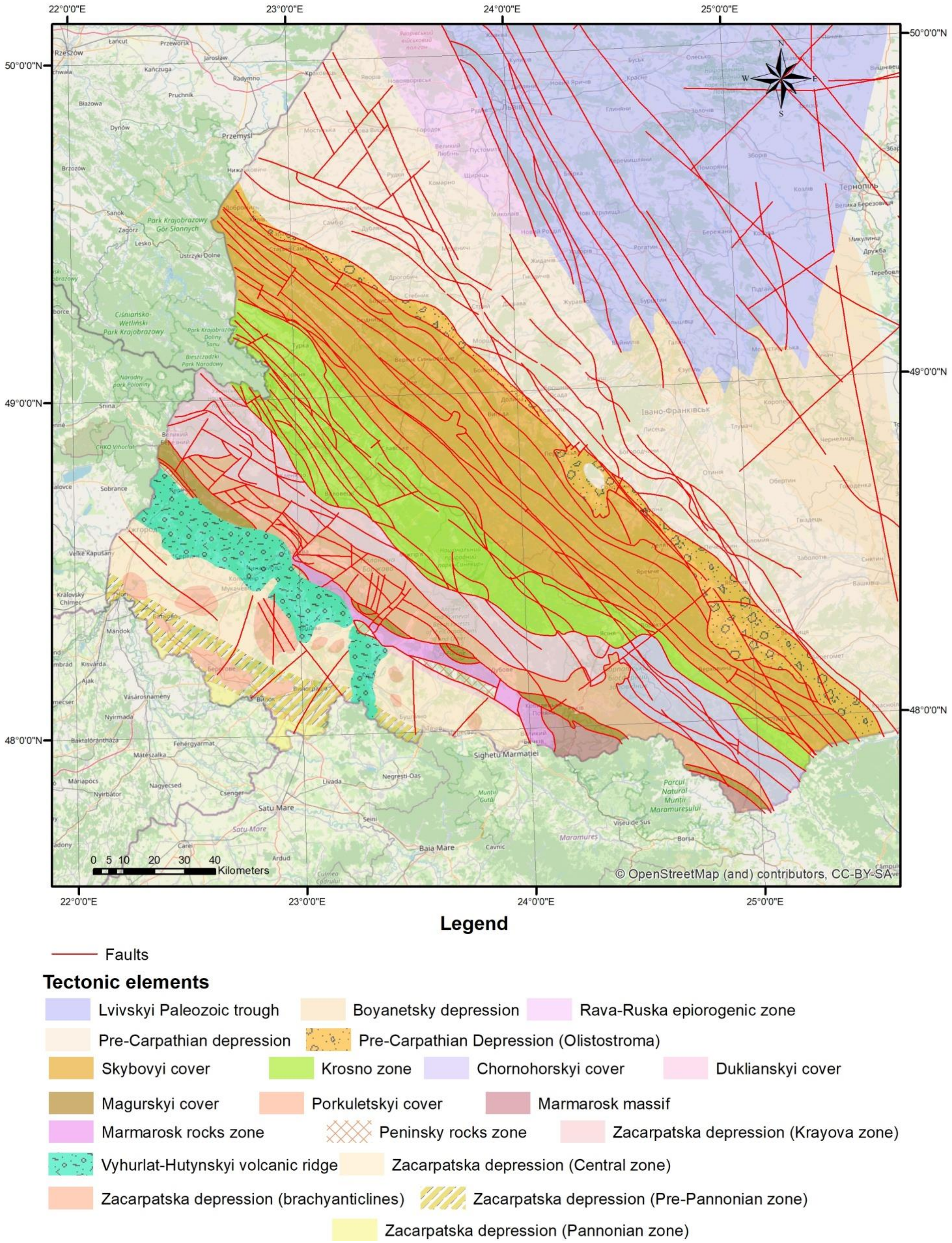

Fig.4 Distribution of faults (tilts, thrusts) within the Flische (External) Carpathians.

18.4.8 Transcarpathian internal deflection

Is divided into 4 zones: National or Monoclinal, Central or Zone of salt-diapiric and brachianticlinal folds, Prypanonian and Pannonian. Deflection is a Neogene depression, which is imposed on a complex dislocated heterogeneous foundation, which occupies the area of the rock-like joint of the Inner Carpathians and the Marmara belt. More than 3 kilometers of orogenic complex of terrigenous molasses is located in shallow folds complicated by salt rods. Overlain on the deflection is a Neogene multiphase ridge of volcanic formations, mostly of main composition, obviously fractured and central, which traces in the west along the Peninsky rocks zone and in the east along the Pannonian zone.

18.4.9 The Crimean meganapnorium

Borders the Central segment of the Scythian epiorogenic zone from the south. Tectonic regime - active marginal, associated with a gradual-discrete slip under the Scythian plate of the Black Sea plate, which is characterized by a mixed type of crust - suboceanic, in deep depressions and subcontinental within the Central Black Sea (according to V.V. Yudin) handful.

Active marginal geodynamic regime of the Crimean meganapnorium has its own peculiarities. First of all, this is a manifestation of: cover-sliding tectonics with significant amplitudes of horizontal displacements and the formation of injection folds, mainly of southern vergence; zones of melange and gravitational olistostrom; significant seismicity in the presence of a long-lasting seismofocal zone; endogenous and mud volcanism. Mud volcanism is widespread within the Indolo-Kubanska rear depression

According to the peculiarities of the geological structure and, first of all, the deep structure, the Crimean meganapnorium is divided into two megastructures: the Cimmerian orogen of the Mountain Crimea and the Kerch folding-sliding structure of the Alpine epoch of tectogenesis.

18.4.10 Orogen Mountain Crimea

Is a cover-folded structure that emerged in the final stages of the Cimmerian era of tectogenesis and remains active throughout the Alpine. According to the authors of the Tectonic Map of Ukraine [2004], two coverings take part in its construction - Yayly and Tavriysky, which have a near-latitudinal extent. A significant role in the structure of the Crimean Mountain fold structure is played by transverse faults, the most significant of which are Alushta-Salgir and Feodosia.

Alushta-Salgir fault divides the orogen of the Mountain Crimea into two parts, differing in deep geological structure, and Theodosius fault separates the Cimmerian-Alpine orogen from the alpine folded-covering structure of the Kerch Peninsula.

Both covers of the Mountain Crimea are formed on the border of alba and senoman. The covers form an allochthonous complex pushed on the autochthonous, the youngest element of which is the Lower Cretaceous deposits of aptu-alba. The covers are covered with a post-cover cover, the oldest element of which is Cenomanian formations, which with angular mismatch overlap the allochthonous and stratigraphically increase upwards with an almost continuous section of Turon-Maastricht, Paleocene-Eocene deposits.

18.4.11 Taurian cover

Hypsometrically lower position is occupied by the **Taurian cover**, which is composed of intensively deployed flysch of the Taurian series. Locally it contains coarse-grained strata with the age of exotic blocks from coal to early Cretaceous. This makes it possible to consider individual horizons of the cover as zones of melange.

Under the Taurian cover lies an autochthonous complex, the upper element of which is the Lower Cretaceous (pre-Apt) terrigenous deposits, and the lower - neocom deposits [Tectonics of Ukraine, 1988].

18.4.12 Yayla cover

Hypsometrically and structurally the highest position in the allochthonous composition is occupied by the **Yayla cover**, composed mainly of Upper Jurassic and Neocomian carbonate deposits. The cover on the modern topographic section is significantly eroded and preserved in the form of individual fragments of the original single cover.
The integumentary complex is significantly eroded and exfoliated in the form of fragments. It is represented by Lower Cretaceous flysch-like deposits of valange-barem, which are stratigraphically upwards with the thickness of aptu-albu clays. The post-cover complex begins with Cenomanian deposits and increases stratigraphically upwards with younger Upper Cretaceous, Paleocene-Eocene deposits.

18.4.13 The Kerch alpine folding-sliding structure

Is unique in its structural structure and most of it, and possibly the whole, is a component of the Indolo-Kubanskyi (Indolskyi) rear (according to V.V. Yudin) depression. The area of articulation of the Kerch folded structure with the system of the Mountain Crimea is very complex and still little studied. The main role in the structure of the Kerch Peninsula (according to Kruglov, 1988) is played by two coverings of northern vergence, namely - Krasnopilskyi and Vladislavivskyi. Lower Cretaceous (Apt? –Albian?) Terrigenous, Upper Cretaceous carbonate and Paleocene – Eocene terrigenous-carbonate deposits take part in the construction of these coverings. The covers are formed at the Eocene – Oligocene boundary and are complicated at the Miocene – Pliocene boundary. The role of deep faults in the structure of the earth's crust is so significant that geologists around the world are now interested in it.

First of all, attention is paid to the connection with the zones of deep faults of mineral deposits. Fractured tectonic faults played a major role in shaping the structure of the foundation of the Ukrainian Shield. Deep faults caused block-block movements of the earth's crust, the origin and development of large geostructures, increased metamorphic and magmatic activity, the influx of juvenile matter in the form of magmatic and hydrothermal products. In the conditions of linear fault zones there were local geological systems and the most favorable conditions for deep sedimentation, metamorphic and magmatic differentiation of matter. The structural elements of the Precambrian foundation of the Ukrainian Shield are Archean cratons and Paleoproterozoic mobile belts, divided by suture zones and deep-sequential fault faults, mostly submeridional and northeastern. A significant number of tectonic zones of the USh were activated in the subplatform and platform periods of development. A feature of the Neoproterozoic and Paleozoic stages of development of the southwestern part of the EES is the formation of superimposed depressions and ancient pericratonic depressions that arose during the stages of destruction and fragmentation during the Baikal stage of tectogenesis.

In the Riphean there was a radical restructuring of the tectonic plan - earlier submeridional directions changed to north-western, north-eastern and sometimes latitudinal. The Volyno-Polissya rift is established and the formation of the Dnieper-Donetsk paleorift begins.

Undoubtedly, a significant role in these processes belongs to the deep faults of the crystalline basement of the corresponding direction. In the Caledonian era, rupture faults were localized in the formations of the Carpathian orogen foundation, the Pre-Dobruzh depression, and the Scythian epiorogenic zone of the Steppe Crimea.

Further development of disruptive disturbances of these structural taxa were in subsequent epochs of tectonic evolution, the most effective of which was the Hercynian period.
From the beginning of the Varian (Hercynian) stage, a number of depressions are laid on the southern edge of the EEP. From the Middle and especially the Late Devonian-Early Carboniferous begins the powerful development and spread to the northwest of the Dnieper-Donetsk Paleorift, which was due to the stretching and reduction of the thickness of the continental type crust. Riftogenesis was accompanied by the formation of fault faults of the north-western direction. Orogenesis in the Donbass led to the formation of plicative deformations of IBS, which are complicated by rupture disorders of the throwing-sliding morphokinematics.

The Cimmerian stage was most pronounced in the Northern Black Sea coast, where most of the Varian structural complex was covered by Cimmerian movements with the formation of geosynclinal depressions on the border of the EEP and the Scythian epiorogenic zone (plate).
The latitudinal direction of the structural elements became dominant, and the rupture disturbances at the time of the closure of the sedimentation basins due to orogenic processes, turned into throws and thrusts with northern vergence. At the late Commerce stage formed the Mountain Crimean folded structure. As a result of alpine tectogenesis, the Cimmerian SFKs of the Crimea were torn from the autochthonous and formed tectonic covers.

With the alpine period of tectogenesis associated throws-thrusts of the north-western direction of the Carpathian meganapnorium and sublatitudinal thrusts of the Mountain Crimea and the Kerch folded structure. The probability of faults is directed towards the ancient platform (EES). Subordinate faults of folded structures of the Carpathians and the Crimea are intersected by transverse disjunctive faults, usually of the landslide type. In addition, in the Alpine era there is activation of faults of earlier structural units.

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