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GEO-ENERGY
Hazard and Impact Knowledge for Europe

Deliverable D2.2b

Final fault data collection report and database

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1 INTRODUCTION

This is the final fault data collection report describing the contents of the populated European fault database (FDB) with standardized and processed fault data embedded in the European Geological Data Infrastructure Platform (EGDI). This report also includes a country data evaluation and a European geological/statistical analysis and evaluation of the database contents (quality, extent, scale, applicability for research).

One of the ambitions of the GeoERA-HIKE project was to develop a European FDB that can broadly support geological research on tectonic boundaries and deformation zones in Europe. In particular, the FDB is linked to research and assessments of induced hazards and impacts that are related to the exploitation of subsurface resources and capacities[1]. The FDB describes and defines faults and deformation zones as 2D spatial objects with associated static and dynamic geological, mechanical, petrophysical, chemical and thermal properties that support further assessments.

The development of the FDB is motivated by the fact that, except for seismogenic faults[2], a centralized and uniform administration and standardisation of geological fault data is currently lacking in Europe. Through the FDB, the HIKE project strives to improve, integrate and disclose relevant faults and fault zones and their characteristics in various national and transnational geological settings. The extent of the FDB covers entire Europe (both on- and off-shore), including all depth ranges and all geological settings covered by exploration and exploitation activities. This database was developed, populated and tested over a period of ~2 years. The partners in the project consortium are the primary contributors of fault data. In addition, the FDB benefited from cooperation with other GeoERA projects and national geological programmes in order to collect supplementary fault data, in particular from modelling and characterization projects under GE2 (HotLime), GE5 (3DGEO-EU) and GE6 (GeoConnect3D). This collaboration helped to increase the spatial coverage of the FDB and was facilitated by joint technical workshops.

[1] http://geoera.eu/wp-content/uploads/2021/10/D3.2_HIKE_Improved_Seismic_Events_Localization.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.3_HIKE_Subsidence_Assessment_Techniques.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.4_HIKE_Improved_Reservoir_Seals_Assessment.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.5_HIKE_Subsurface_Injection_Safety_Seismicity.pdf

[2] Woessner, J., Laurentiu, D., Giardini, D. et al. The 2013 European Seismic Hazard Model: key components and results. Bull Earthquake Eng 13, 3553–3596 (2015). https://doi.org/10.1007/s10518-015-9795-1

2 FAULT DATA COLLECTION PROCEDURE

This chapter briefly summarizes the followed procedures for collecting, harmonizing, processing and compiling the country fault data provided by the HIKE and other GeoERA partners.

2.1 General Fault database structure and concept

In 2018 and early 2019 the HIKE partners established the overall outline and concept of the FDB architecture. This structure consists of four main components, i.e.: 1) fault geometries, 2) fault attributes, 3) fault vocabularies and 4) meta-data. A first overview of typical geometry descriptions and attributes was made. The concepts were discussed with HIKE partners, liaised GeoERA projects and the GIP-project in several workshops[3].

Faults in the FDB are shown as 2D geometries (vector line data), which are the geometrical representations of 3D fault planes intersecting at a certain stratigraphic level or surface. The faults are classified according to a semantic tectonic boundary classification framework (fault vocabulary). The Austrian Fault Database[4] formed the basis for the initial specification of this classification vocabulary, but has been extended to cover the needs for partners. The final classification is published in Chapter 5.2 of deliverable D2.1b[5] and is included in the project vocabulary[6] using Linked Data principles and SKOS references, thereby providing a mapping to a global context on the Semantic Web.

The vocabulary also provides the possibility to sort faults into hierarchical rankings, in order to accommodate different scale levels and/or different levels of information. Fault objects can be described as individual objects, but faults are almost always related to other faults either in a regional or kinematic sense. Individual faults can be either hierarchically grouped into kinematically linked fault systems, which then again can be linked transregionally into large-scale fault systems. On the other hand, faults can be also grouped into fault sets of parallel trending faults with similar kinematic characteristics. Different fault sets can be then grouped into fault domains in order to highlight their kinematic linkage.

In addition, the vocabularies provide the possibility to link to already existing databases, such as the SHARE database or national fault databases, such as the ITHACA database of active faults, and create context by linking to other sources of information, i.e., publications regarding the specific fault (system) or Wikipedia articles.

Metadata of the FDB are stored in the EGDI Metadata Catalogue[7]. There is a metadata record for the entire FDB, but because the faults are provided as a national (or regional) data set of multiple faults, each data set has its own metadata record, named e.g. “Tectonic boundaries in Austria” or “Tectonic boundaries in Bavaria”. These national/regional metadata records are used to reference the source and the specifications of each individual dataset. They are linked to the overall FDB record via the build-in parent/children functionality of the EGDI Metadata Catalogue.

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[3] HIKE workshop in Augsburg on 4-5 Feb 2019 and HIKE-workshop in Vienna on 11-13 Mar 2019.

[4] Hintersberger, E., Iglseder, C., Schuster, R. & Huet, B. (2017). The new database “Tectonic Boundaries” at the Geological Survey of Austria. Jahrbuch der Geologischen Bundesanstalt. 157. 195-207.

[5] http://geoera.eu/wp-content/uploads/2021/10/D2.1b_HIKE_Fault_Data_Characterization_Catalogue.pdf

[6] https://data.geoscience.earth/ncl/geoera/hike/category/7856&lang=en

[7] https://egdi.geology.cz/record/basic/5edf7bd4-9270-4188-b69d-7ddd0a010833

Although the FDB incorporates an extensive set of fault attributes, most of the available data are still limited mainly 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.).

2.2 Initial fault data inventory and concept specifications

In order to establish an overview of the expected coverage and characteristics of national fault datasets, all HIKE partners have provided an inventory of available fault GIS and attribute data at national and regional scales. This initial inventory was made in 2019. The map in Figure 2-1 shows the initial sources that were potentially available.

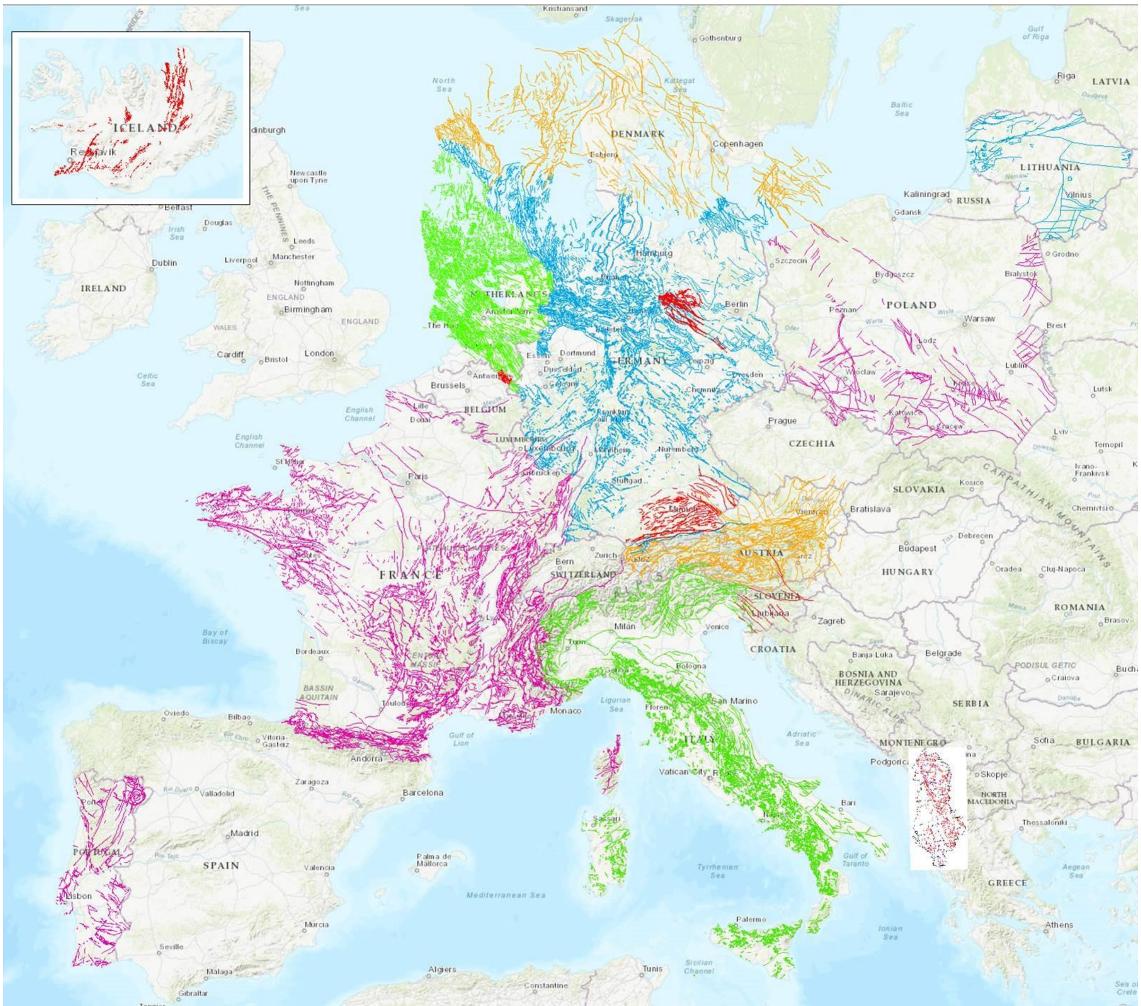

Figure 2-1: Overview of the 2019 inventory of available fault GIS and attribute data at national and regional scales.

Based on the overview a concept specification for the FDB architecture was established. These specifications were reviewed by the partners and reported in two reports:

- HIKE report D5.1a[8] is an internal report and provides a detailed technical description and specification of the FDB framework including all data types and attributes. This report formed the basis for the initial platform architecture development by the GIP-project. The data type specifications and vocabulary elements have been clarified in several other documents and inventories by the GIP-project.
- HIKE report D2.1b[9] is a publicly available fault data specification and characterization catalogue for the FDB. It is a catalogue for data providers and end users explaining in detail the exact formats and parameters for the FDB.

2.3 Fault data collection and definition of vocabularies

Beginning of 2020, the HIKE partners started an extensive campaign to prepare, collect and process all national fault datasets. Additionally each partner established a geological country fault data report in order to provide a scientific geological background to the information delivered. To this end a guideline was established explaining how to prepare the fault data (GIS, attributes), how to set-up the national tectonic boundary classifications and associated vocabularies and how to deliver the data in Geopackage format. The following tools and templates where provided:

- Example datasets
- An excel template for the fault attribute definition
- An excel template for the specification of the national fault vocabularies (prepared by GIP-project).

The templates and guidelines are included in HIKE report D5.1b[10]

As the entire data collection process was carried out amidst the COVID-19 outbreak there was no opportunity to organize the planned live technical workshop intended to support the fault data collection process. Instead it was decided to set up a two to four weekly schedule of online bilateral meetings with all HIKE partners. These meetings were used to support and monitor the data collection process of individual partners, clarify all procedures, have regular Q&A sessions, and monitor the preparation of the geological country data reports. The majority of partners had to work from home and often lacked the appropriate IT support to prepare and process the fault data. Due to these unexpected challenges, the data collection process took much longer than expected and finally ended in the second quarter of 2021
Each partner ultimately provided the following requested inputs:

- A GeoPackage file containing a GIS dataset of all mapped and evaluated faults as well as the associated fault attributes
- An excel file containing the complete national fault vocabulary definition
- A country report providing a geological background on the provided fault data (see Annex 1)
- A country fact sheet containing a general and uniform description and clarification of the data provided (see Chapter 3)
- A metadata description of the provided dataset

[8] HIKE D5.1a: Technical IP requirements of the Fault Database (internal document).
[9] https://geoera.eu/wp-content/uploads/2021/10/D2.1b_HIKE_Fault_Data_Characterization_Catalogue.pdf
[10] HIKE D5.1b: Technical IP requirements of the Knowledge Share Point (internal document).

2.4 Data processing, compilation, testing and QC

The FDB coordination teams of work package 2 (Fault Database) and work package 5 (GIP interface) worked closely together with the GIP project team members to compile and prepare all the data for the European FDB platform. The majority of this phase took place in 2020 and lasted until the end of the project in October and involved the following activities:

- All data sets have undergone an extensive quality control to check for deviations in agreed standards and specifications (GIS data, attribute data, vocabulary information and metadata). Identified issues were communicated with the data providers who made corrections and requested updates.
- The FDB coordination teams (work package 2 and 5) established the links between the provided GIS fault data, the fault vocabularies and the metadata. Each link was inspected to identify any inconsistencies which were resolved by the project partners. The GIP-P team assisted in enabling the functionalities in the EGDI platform.
- In Germany the data was delivered by multiple organizations with overlapping areas. BGR provided the data at a national (lower detail) level, while some Federal States provided more detailed information for their regions. A harmonization between the national and regional fault data did not take place as part of the HIKE project.
- With the compiled and processed dataset, the FDB coordination team and partners assessed possibilities to improve and extend the functionalities. The overview below provides some major improvements that have been implemented:
  - Where possible and relevant, the provided fault data has been linked with external fault databases and information systems such as the SHARE and ITHACA databases. It is now possible to directly access additional information from these sources.
  - In some countries the partners have made a specification and implementation of multi-scale fault definitions. This allows to choose between various levels of detail for the visualization and analysis of the fault data. The functionality has been embedded in the online FDB platform.
  - In some countries, additional efforts have been made to improve the cross-border correlation of fault data. This was either done through the revision of 2D and 3D fault models (e.g. in collaboration with the HOTLIME, 3DGEO-EU and GeoConnect³d projects), or by establishing cross-border links between the national fault vocabulary definitions (e.g. by defining semantic relations).
  - It is now possible to directly shift between vocabulary information and fault GIS data.
- Finally the entire populated online FDB platform was tested. Any remaining issues were resolved with the EGDI / GIP-project teams.

3 FAULT DATA COLLECTED FOR THE FDB

Collection and harmonization of fault data is hampered by the fact that the contributing countries may have experienced different tectonic histories and show huge differences in their (sub)surface structuration. In this respect the HIKE project implemented state of art and novel methodologies and workflows in order to improve fault characterization in various geological settings. Specific attention was paid to resolving critical issues that hamper the integration of fault data from different sources and vintages. Although there are agreed upon standards for data delivery to the FDB (see section 2), full cross-border harmonization was not a main objective of the HIKE project. In other words, data is provided as is and cross-border inconsistencies do exist, except for several countries (among others the Netherlands, Belgium, Austria, Bavaria, and the Pannonian Basin and Roer-to-Rhine partners from GeoConnect^{3}d) who have made improvements in this direction (see Paragraph 2.4). As such, the data base can serve as good stimulant for future harmonization efforts that are directed towards practical and specific applications.

3.1 Summary of delivered data

In total 28.078 unique fault vocabulary definitions (with unique ID's) are delivered to the HIKE-FDB that are represented by 269.348 fault geometries. The total length of all fault geometries is 1.594.110.504 m. All institutes, either representing countries or federal regions were asked to accompany their delivery to the FDB with a country report that describes quality and origin of the data delivered, the geological evolution that produced structural elements and their bounding and transecting faults, the fault pattern, fault characteristics and the local relevance of having fault data. Table 3-1 presents a summary of the delivered fault information. Next to the country reports, a brief synthesis of the information is captured in country fact sheets that are provided in 3.2. For the full country reports and proper references to supporting data or literature the reader is referred to Annex 1.

Table 3-1: *Metadata summary of collected fault data*

	region	2D seismic	3D seismic	Grav/ mag	Wells	Surface mapping	2D maps	3D models	map scale smallest	mapping scale largest	#	stratigraphic coverage	Natural seismicity	Induced seismicity	Landslides	Resource exploration	Ground water	Geo/hydr othermal energy	Infra structure	Storage	onshore	offshore
TNO	Netherlands								-	1:250.000	6700	Carb-Quat										
AGS	Albania								1:5.000	1:200.000	274	preC-Eoc										
AT	Austria								-	1:1.000.000	784	preCarb-Quat										
BE	Belgium								-	1:250.000	518	preVar, Perm-Ceno										
BGR	Germany								1:500.000	1:2500.000	915	preVar- Ceno										
DK	Denmark								-	1:750.000	16	top pre ZE										
FR	Pyrenees								1:50.000	1:1.000.000	-	-										
IS	Iceland									1:600.00	2254	Miocene-Quat										
ISPRA	Italy								1:50.000	1:1.000.000	5134	preCarb-Quat										
LAGB	Saxony-Anhalt								-	1:50.000	2988	base ZE & top Meso										
LBGR	Brandenburg								-	1:500.000	-	Paleoz-Quat										
LfU	Bavaria								1:50.000	1:100.000	-	Paleoz-Quat										
LNEG	Portugal								-	1:1.000.000	149	preC- Cenozoic										
LT	Luthuania								-	1:500.000	308	preC-Carb										
PL	Poland								-	1:1.000.000	147	preC-Quat										
SLO	Slovenia									1:250.000	70	Trias-Ceno										
UKR	Ukraine									1:1.000.000	371	preCarb-Quat										

not applicable or mentioned
partly/regionally or potentially applicable
generally applicable

3.2 Country factsheets

3.2.1 The Netherlands - TNO

Organization: Date: Author(s)/contact person:	Geological Survey of The Netherlands (TNO) 2021-04-01 Serge van Gessel, Johan ten Veen, Hans Doornenbal, Maryke den Dulk

3.2.1.1 Introduction

TNO is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.1.2 General data metrics and sources

Mapping scale:	National (1:250.000)
Number of faults:	6319 faults in vocabulary; 100187 features in database
Geographical coverage:	Nation-wide including land and sea area. Regional variations in data density and detail related to exploration areas for oil and gas (3D vs 2D seismic data)
Stratigraphic coverage:	Faults are defined across ca. 10 stratigraphic levels from the Carboniferous up to the Holocene and surface level. The depth ranges up to 6 kilometres.
Format:	The faults for the deep and shallow subsurface are delivered as 2D intersection lines for each dissected stratigraphic horizon. There are references to 3D fault surfaces defining the basis for 2D fault geometries. 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 neighbouring countries (in particular Germany and Belgium). 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.)

3.2.1.3 Fault data acquisition and mapping

2D/3D seismic:	Predominantly 3D and some areas 2D surveys (outside key hydrocarbon exploration areas). For gas exploration many detailed fault models have been developed at reservoir levels.
Gravitational and magnetic surveys:	Not used for fault mapping
Wells:	Well data are mainly used to predict the location of shallow (Neogene) faults
Surface mapping and outcrops:	Holocene and Pleistocene faults are sometimes recognizable in the surface topography (e.g. height differences, river terraces).
Mapping/Modelling:	All faults are defined in 3D geological models covering the entire country. These models include uncertainty information.

3.2.1.4 Structural elements

Most of the structural elements recognized today have developed during the Mesozoic (Figure 3-1), often as a result of reactivation of NW-SE Paleozoic fault systems. The first order classification of structural elements includes highs, platforms and basins. A high is defined as an area with significant non-deposition and erosion down to Carboniferous or Permian strata (Rotliegend and Zechstein). A platform is characterized by the absence of Lower and Upper Jurassic strata due to Late Jurassic erosion down to the Triassic. The term graben (or basin) is used for a fault-bounded basin where, in general, Jurassic sediments are preserved. For both platforms and basins, a further subdivision has been made. Platforms may either represent 1) areas where Cretaceous rocks overlie Triassic rocks or 2) areas where Cretaceous rocks lie directly on top of Permian sediments. Since most Jurassic basins in the Netherlands were subject to inversion during Late Cretaceous and Paleogene times, a subdivision is made between basins that experienced strong inversion (absence of Upper Cretaceous and older rocks) or mild inversion (presence of Lower and Upper Cretaceous rocks). The objective of a structural elements map is to distinguish between areas that experienced markedly different burial and erosion history. Structural elements are often bounded by fault zones/ systems. Therefore the main fault systems have been included in the structural elements map and new boundaries have been drawn along faults as much as possible. The following four maps provide further insight in the geological development of the structural elements during the Paleozoic, Mesozoic and Cenozoic.
Annex 1 provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.1.5 Fault characterization and definition

For the Netherlands, all fault data from the deep and shallow national geological mapping programs are included (Figure 3-2). The faults for the deep subsurface are delivered as 2D intersection lines with the main stratigraphic horizons and as 3D surface models (optional downloads). 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 fault patterns and fault styles in the Dutch subsurface originate from repeated extensional and compressional phases, leading to several reactivation and inversion stages, especially withing the major Mesozoic basins. The Zechstein halite-bearing formation generally acts as a fault detachment interval, separating Paleozoic faults from the younger Mesozoic and Neogene faults. As shown in the fault maps, 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. Repeated (oblique) reactivation of basement faults has led to a high degree of fault parallelism. This dominant NW-SE fault trend is inherited from the mid-Paleozoic when Avalonia, including the London-Brabant Massif, collided with Baltica to form Laurussia. Examples of this mid-Paleozoic fault trend are the major Hantum and Mid Netherlands fault zones which show evidence of repeated reactivation. The Early Permian NE-SW to ENE-WSW orientation is the second most common fault trend.

Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.1.6 Local fault relevance and application

Natural Seismicity	The south eastern 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.
Induced seismicity	Especially in the north-eastern 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. 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.
Geothermal:	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. A Seismic Hazard Assessment guideline is being developed for new geothermal projects.
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
Infrastruture/ construction:	Especially in the southern part of the Netherlands, where faults associated with the Roer Valley Graben come at or near the surface.
Hydrocarbon-EP:	If the baffling function of a fault is sufficient, a fault may play a role in the formation of hydrocarbon traps ("fault traps"). Faults act as important conduits for hydrocarbon migration as well.
Mining:	For coal mining activities (now ceased) faults were of important for coal seam continuity and operational issues (instability groundwater flow). Modern sinkholes occur that are associated with (intentionally) shallow collapsed mine shafts where the collapse generated faults in the overburden

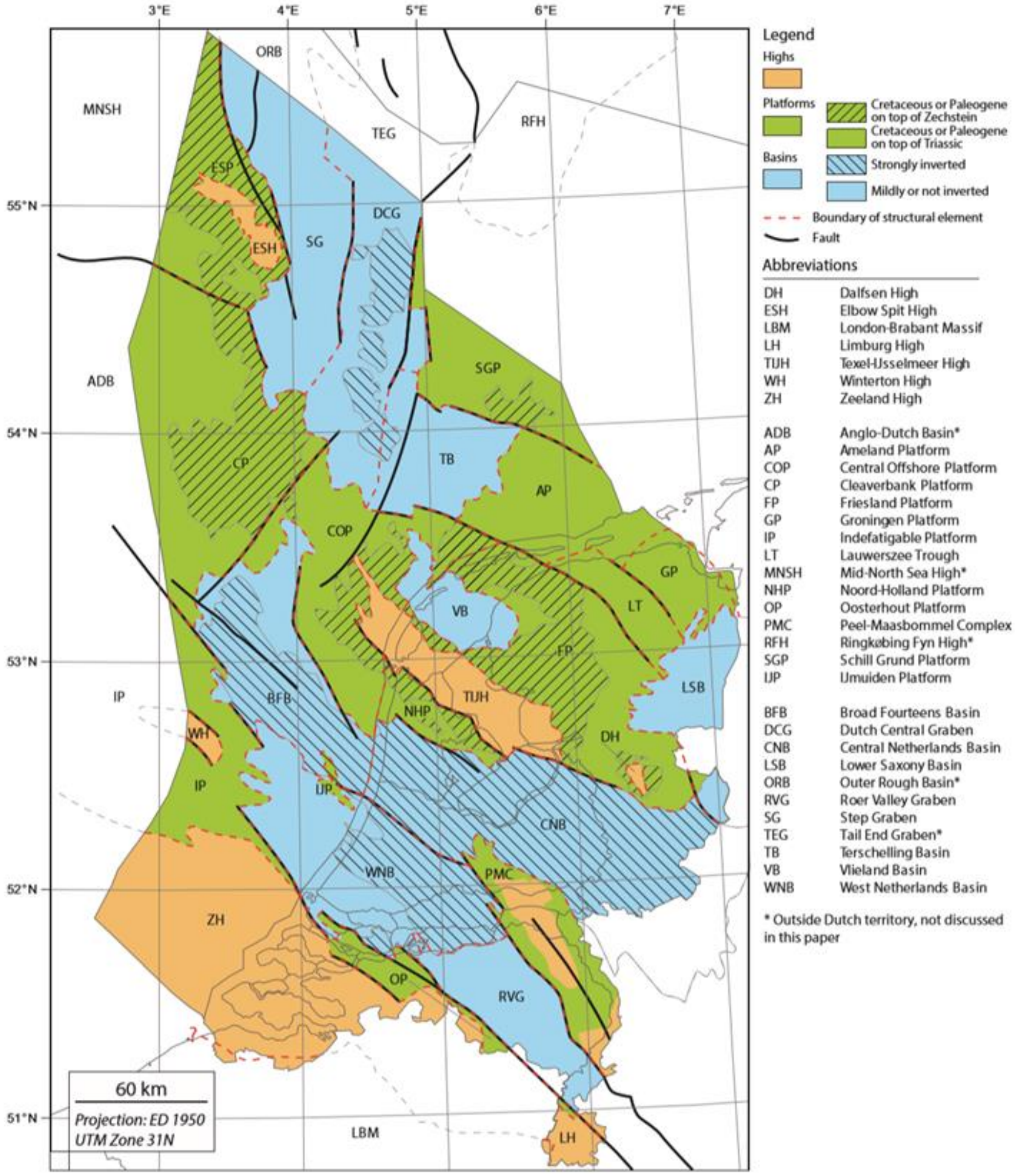

Figure 3-1: Late Jurassic - Early Cretaceous structural elements and main faultzones of the Netherlands.

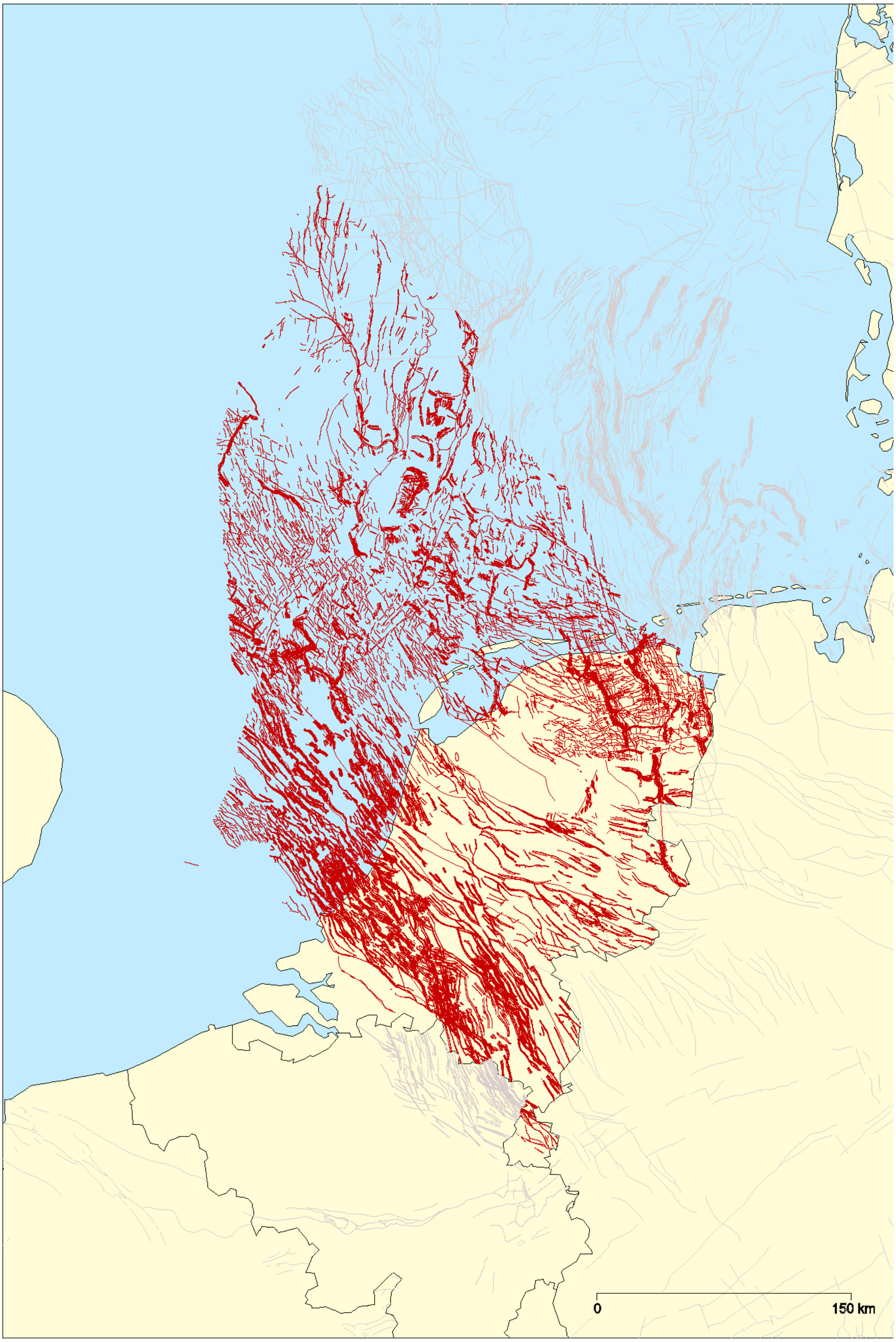

Figure 3-2: Location of mapped national faults and fault systems in the Netherlands contributed to the HIKE-FDB, reference depth Upper Permian, base Zechstein Group.

3.2.2 Albania - AGS

Organization: Date: Author(s)/contact person:	Albanian Geological Survey (AGS) 2021-03-15 Siri Hamiti, Ndoc Vukzaj, Rushan Çako, Elisa Prendi, Maga Ceroni, Alfred Mara

3.2.2.1 Introduction

AGS is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.2.2 General data metrics and sources

Mapping scale:	National (1:200.000) regional (1:5.000, 1:10.000 and 1:25.000)
Number of faults:	272 faults in vocabulary; 4715 features in database
Geographical coverage:	Nation-wide with strong regional variations in data density and detail. More detailed information on fault characteristics is given for one area because in this area we can find almost all the fault types found in Albania (normal faults, thrust, overthrust). In this area we find ophiolitic rocks also sediments of ages from Triassic to Eocene. In this sector we have the presence of basin and platform sediments.
Stratigraphic coverage:	Predominantly subdivided in deep crystalline basement faults (Precambrium) and faults cross-cutting the younger (Paleozoic – Cenozoic) sediment cover.
Format:	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. The major tectonic domains, main fault systems and faults are classified according to the semantic framework defined in HIKE. The fault attributes for which we completed are: LOCAL_NAME; EVAL_METH; OBSERV_METH; FAULT_TYPE; YOUNG_UNIT; OLD_UNIT; DIP_ANGLE; DIP_DIRECT; STRIKE; MOVE_SENSE; REFERENCE; ACTIVE; CAPABLE; and ACTIVITY.

3.2.2.3 Fault data acquisition and mapping

2D/3D seismic:	2D
Gravitational and magnetic surveys:	In our country were carried out: Gravitational surveys in the following tectonic zones: Jonike, Kruja; Magnetic surveys in the following tectonic zones: Mirdita, Alpe, Gashi.
Wells:	Some areas with wells down to 1000 m
Surface mapping and outcrops:	Cartographic works at a scale of 1: 25 000 for sedimentary formations. 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.
Mapping/Modelling:	We don’t have 3D models

3.2.2.4 Structural elements

Structural elements of Albania are based on their position in the Dinarid-Helenic arc, which is the southern branch of the Mediterranean Alpine thrust belt, The transition between the Dinarides and Helenides is formed by the Albanides. The external (western) Alabanides are separated from the internal (eastern) Albanides by a major SW vergent thrustzone that is associated with the subduction of the Apulian plate.

3.2.2.5 Fault characterization and definition

Both platforms and basins are affected by tectonics, normal faults, 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 N-S but there are many other cases where the extension of the axis of faults goes from east to west, northeast-southwest, etc.

Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.2.6 Local fault relevance and application

Natural seismicity	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
Landslides	Protection of the territory from possible landslides
Resource exploration	Accurate data are obtained on the possible exploration of useful minerals such as Chromium, Oil, Gas, etc.
Groundwater	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
Geothermal energy	Hydrothermal energy is found in the areas with ring faults (Peshkopi diapir), and near the transverse fault Tepelene-Permet (Benja thermal waters).

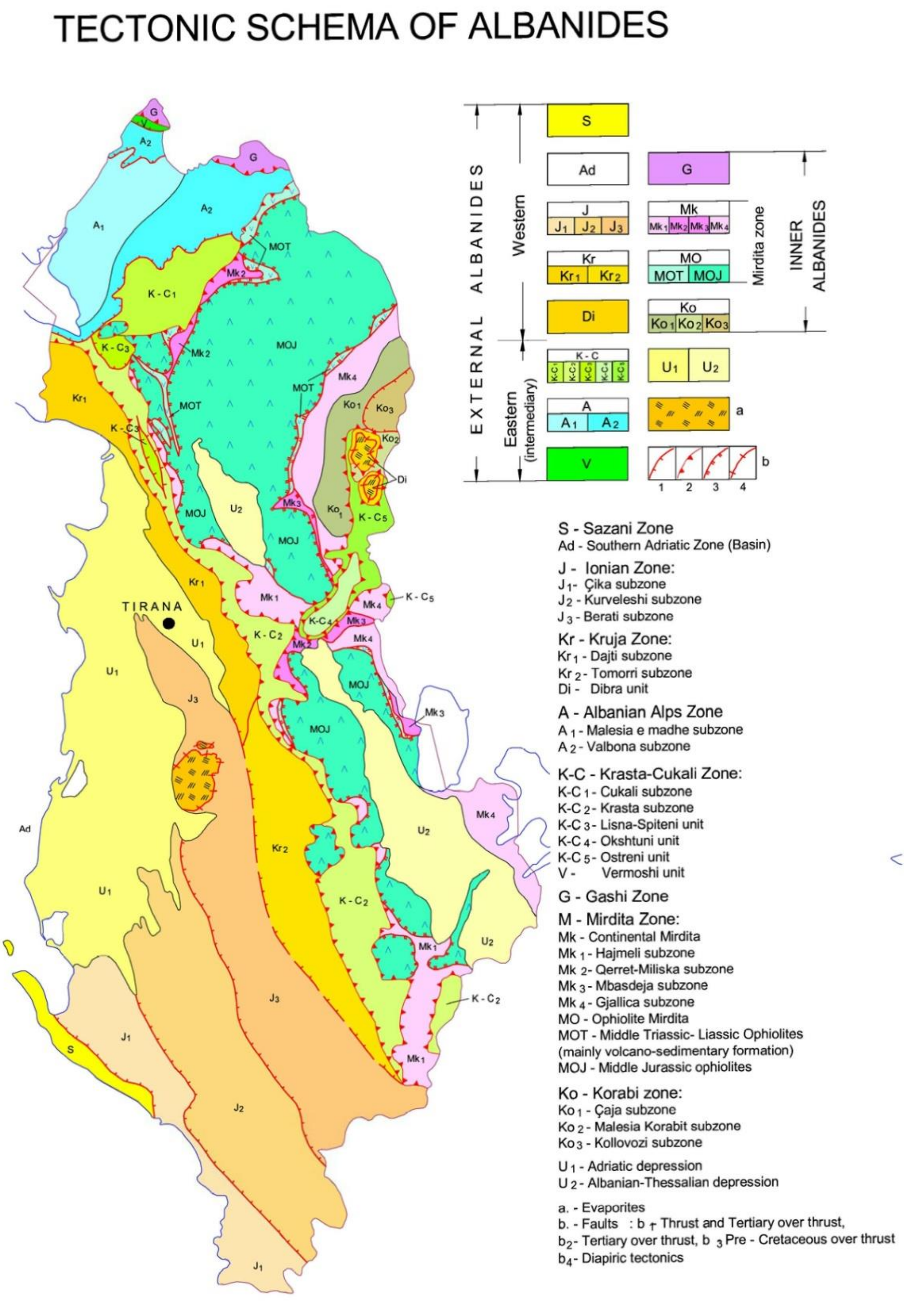

Figure 3-3: Scheme of the distribution of faults and main structural elements of Albania.

Figure 3-4: Location of mapped national faults and fault systems in Albania contributed to the HIKE-FDB. Faults are represented at surface level.

3.2.3 Austria - GBA

Organization: Date: Author(s)/contact person:	Geological Survey of Austria (GBA) 2021-05-05 Esther Hintersberger

3.2.3.1 Introduction

GBA is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.3.2 General data metrics and sources

Mapping scale:	National (1:1.000.000)
Number of faults:	238 faults in vocabulary; 1160 features in database
Geographical coverage:	Nation-wide with strong regional variations in data density and detail. 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
Stratigraphic coverage:	Precambrian to Quaternary. The oldest rocks (Dobra Gneiss) is 1.38 Ga old. Deformation events range from Ordovician (Caledonian), Variscan, Alpine and more recent extrusion tectonics.
Format:	Mostly mapped 2D fault traces at the surface, except for faults in the Neogene basins, which are mapped at the base of the respective Neogene basin. The main faults, fault systems and fault zones are classified according to the generic semantic framework in HIKE. This includes correlation links with the faults in neighbouring countries (in particular Germany, Slovenia and Italy). Fault attributes are mainly limited to geometric aspects (length, strike, dip, surface area), fault type (normal, reversed, etc.), timing of fault activity and observation/evaluation method (seismic interpretation, inferred modelling, etc.).

3.2.3.3 Fault data acquisition and mapping

2D/3D seismic:	Especially the Vienna and Molasse basins have been investigated by industrial 2D and 3D industry seismic exploration campaigns
Gravitational and magnetic surveys:	Not generally applied.
Wells:	Well interpretation for fault mapping is used to support 2D/3D seismic data interpretation and 3D fault modelling.
Surface mapping and outcrops:	Predominant method of fault mapping, as the majority of the tectonic boundaries cropping out at the surface. The ongoing national mapping program providing geological maps at the scale of 1:50k (and since 2019 at the scale of 1:25k) is not completed on national level.
Mapping/Modelling:	Local 3D modelling exists for faults in the Vienna and Molasse basins

3.2.3.4 Structural elements

The topography and also the deformation history in Austria is dominated by the Alpine orogeny. Austria can be subdivided into three major paleogeographic areas with distinct fault patterns.

1) The **Bohemian Massif**, mostly north of the Danube at the border to the Czech republic and Bavaria, is situated on the European tectonic plate and is dominated by Variscan deformation and contains the oldest rocks of Austria. The major structures have been reactivated during the Alpine orogeny.

2) The **Alpine orogen,** with the Eastern Alps represents the most dominant geological super unit in Austria. Here, the fault pattern is dominated by 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.

3) A group of **Neogene Basins** consisting of the North Alpine foreland molasse basin, the Vienna Basin, and the Styrian Basin, which is tectonically linked to the larger Pannonian Basin further east. 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.

3.2.3.5 Fault characterization and definition

Next to a geographic zonation (or structural elements), historically, tectonic structures in Austria are differentiated into two major groups (Figure 3-5): 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.

The **Bohemian Massif** is dominated by conjugate sets of steeply dipping NE-SW striking, left-lateral and NW-SE striking right-lateral faults that originated as ductile to ductile-brittle shear zones during the Variscan orogeny (~290 Ma) and were reactivated during the Late Cretaceous and the Miocene. Minor Quaternary reactivation occurred and sparse seismicity has been observed. In addition, NNE-SSW trending, gently to the E dipping thrust faults were active during the Variscan orogeny in the Carboniferous (340-325Ma).

The **Eastern Alps,** the most prominent geological super unit in Austria, are subdivided into three groups showing distinct fault patterns:

Bounded towards the north by the Alpine Thrust, the **Penninic Units** (including the Rhenodanubian flysch) **and Helvetic Units** consist of EW-trending, S-dipping faults with N-directed kinematics along nappe boundaries which were active during Paleogene to Neogene times. They are closely spaced, steeply dipping thrust faults, mostly indicating out-of-sequence thrusting. They are displaced by younger NE-SW left-lateral strike-slip faults active during upper Oligocene to recent times. Partly Quaternary reactivation and sparse seismicity is observed.

The **Northern Calcareous Alps** are dominated by large south-vergent, mostly E-W-trending nappe boundaries that were active during the Cretaceous to Paleogene Eo- and Neo-Alpine Events. They are post-dated 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 (fault sets #19-#21 in Figure 1).

The main structures of the **Austroalpine Units south of the SEMP Fault System** (#29 in Figure 3-5) are (N)E-(S)W-trending basement nappe boundaries that represent top-to-the-W thrusting during the Cretaceous Eoalpine Event and show a later overprint by top-to-the-SE normal faulting. These earlier structure are reactivated and crosscut by Neo-Alpine strike-slip faults with mainly right-lateral kinematics. During the Neo-Alpine event, the most dominant fault pattern are NW-SE to NNW-SSE trending right- lateral faults active during late Oligocene to Miocene times. 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 3-5) 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 sub fault 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. Ongoing moderate seismicity suggest Quaternary movement along the mentioned structures.

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 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 3-5) 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. The **Styrian Basin** comprises mostly N-S striking normal faults.

3.2.3.6 Local fault relevance and application

Infrastructure	Austrian mountainous landscape demands the construction of several tunnels for both, cars and trains. Due to the complex geological situation at most of the construction sites, intensive geological investigations are part of these large projects. In all cases, detailed understanding of the local fault inventory is of utmost importance
Natural seismicity:	Austria is characterized by moderate seismicity with moment magnitudes (Mw) up to 6.0 documented since the 13^{th} century. Even though a statistical overview of earthquake occurrence in Austria is available, the linkage to the origin of earthquakes, i.e. active faults, is not yet well established.
Induced seismicity:	Induced seismicity has not been observed or systematically documented. Future reactivation of the faults might have an effect on the preservation of the oil and gas fields as well on related infrastructure
Hydrocarbons:	Ongoing oil and gas production since the 1960's in the Vienna Basin and the Molasse basin in Upper Austria has provided detailed information on the geometry of faults within these basins.
Hydrothermal:	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.
Geothermal:	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 favourable for the usage of geothermal energy exploration, even though the potential is far greater than the actual exploitation.

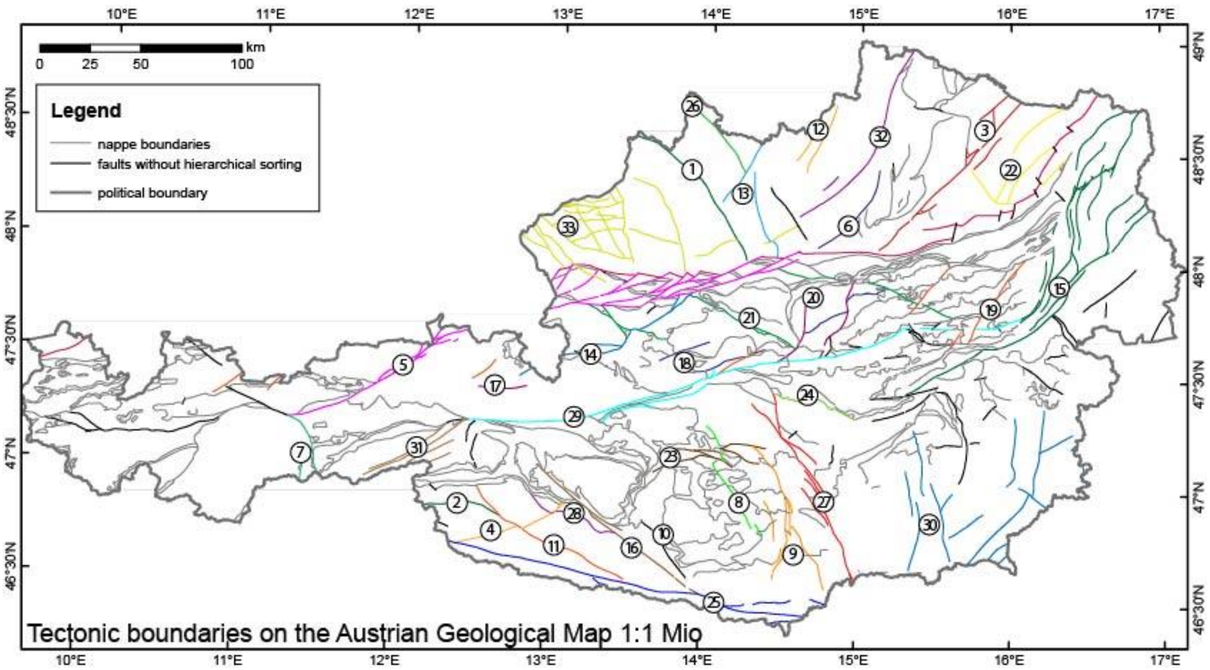

Figure 3-5: Tectonic boundaries in Austria at the scale 1:1.000.000, differentiated between steeply dipping strike-slip and normal faults (black and colours) and mostly gently dipping nappe boundaries (grey) showing large thrusting. The numbers indicate the respective (large-scale) fault systems and 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-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.

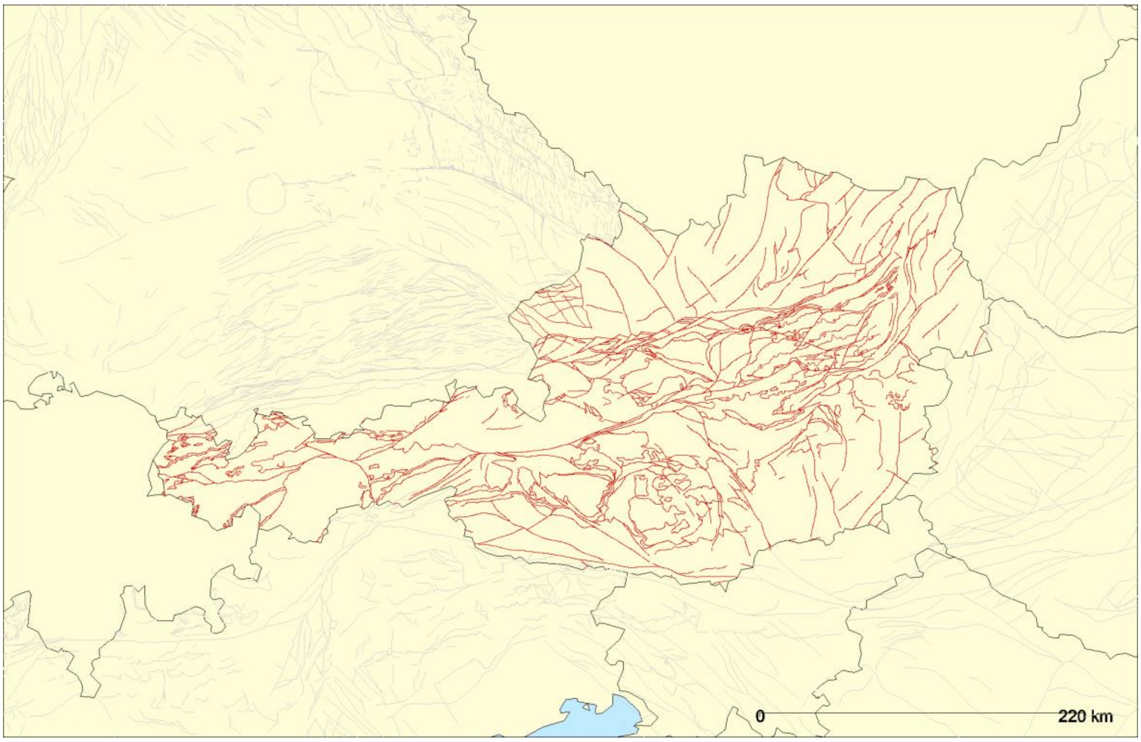

Figure 3-6: Location of mapped national faults and fault systems in Austria contributed to the HIKE-FDB. Faults are represented at surface level except for faults in the Neogene basins, which are mapped at the base of the respective Neogene basin.

3.2.4 Belgium - GSB

Organization: Date: Author(s)/contact person:	Geological Survey of Belgium (GSB) 2021-04-12 Renata Barros & Alejandra Tovar

3.2.4.1 Introduction

GSB is a small partner in HIKE for the methodology development. It is contributing to the HIKE Fault Database with national-scale fault information collected in the scope of the GeoConnect³d project with a focus on the Roer-to-Rhine area. Fault data that cover the north eastern part of the country (Flanders) are originating from VITO. Faults form the southern part (Wallonia) are originating from GSB. The Belgian fault report (Annex 1) provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.4.2 General data metrics and sources

Mapping scale:	Regional (1:250.000)
Number of faults:	171 faults (VITO) and 30 (GSB)in vocabulary; 1188 VITO) and 30 (GSB) features in database
Geographical coverage:	Derived from the GeoConnect³d structural framework model with focus on the Roer-to-Rhine area of interest, with strong regional variations in data density and detail. 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. No data for the north western part (outside area of interest).
Stratigraphic coverage:	Predominantly subdivided in basement faults (pre-and syn-Variscan) and faults cross-cutting the younger (Permian to Cenozoic) sediment cover.
Format:	Faults are delivered as 2D intersection lines reference surfaces. These are the surface (in the southern part of Belgium), and the bases of Quaternary, Neogene, Paleogene, Cretaceous, Jurassic and Permian-Triassic, as well as the top of the Dinantian (north eastern part of the country). The fault systems are classified according to the generic semantic framework in HIKE. This includes a correlation link with the faults in neighbouring countries (in particular the Netherlands). Fault attributes cover basic information on geometric and timing aspects, as well as reference surface for the trace, fault type, and observation/evaluation method.

3.2.4.3 Fault data acquisition and mapping

2D/3D seismic:	2D surveys, focused mainly in the north eastern part of Belgium.
Gravitational and magnetic surveys:	Residual Bouguer gravity anomaly map of Belgium.
Wells:	Flemish wells.

Surface mapping and outcrops:	Predominantly regional geological maps of scale 1:25,000 (Walloon Region) and national geological maps of scale 1:40,000; structural maps when available (scale 1:75,000), Topographical maps (DHMv2 for Flanders).
Mapping/Modelling:	Coal layer depth maps of Flemish mines. H3O-projects in the NE part of the country.

3.2.4.4 Structural elements

The structural framework of Belgium (**Fig. 1**) developed as part of the GeoConnect³d project summarizes the main geologic and tectonic elements in the country. In the structural framework model, faults and other (largely) planar features (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.
- The Condroz inlier, limited by the contact between its more competent rocks and surrounding Upper Devonian shales.
- The Ardenne inliers Stavelot and Rocroi Massifs, limited by angular unconformities between the inliers and Pridoli-Lochkovian.

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
- 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.
The Belgian fault report (Annex 1) provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.4.5 Fault characterization and definition

The main fault styles can be broadly divided into two different domains in the south and in the north. 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 (**Fig. 2**). The northern domain is composed of basement rocks belonging to the Lower Paleozoic Brabant Massif (WNW-ESE striking faults) – not covered in the data delivered for Belgium since it falls out of the Roer-to-Rhine area of interest of GeoConnect³d, as well as

sedimentary cover from the Devonian to Quaternary associated with subsidence stages and syn-sedimentary tectonics (NW-SE to NNW-SSE striking faults – **Fig. 2**). The Belgian fault report (Annex 1) and the HIKE fault database provide a detailed description of the fault patterns and characteristics.

3.2.4.6 Local fault relevance and application

Nuclear waste storage:	Surface disposal site for low-level radioactive waste in the Mol-Dessel area, interface between Campine Basin and Roer Valley Graben. Test facility for high-level radioactive waste on the same site.
Underground energy storage potential:	Underground pumped storage hydropower potential being investigated in various abandoned coal and slate mines in the Variscan realm (Ardenne Allochton).
Natural seismicity:	Moderate seismic activity in the Roer Valley Graben, extending northwards to the southern North Sea.
Induced seismicity:	Restricted events related to geothermal exploitation at the Balmatt geothermal power plant in Mol, interface between Campine Basin and Roer Valley Graben. Events in the Mons Basin (Ardenne Allochton) probably related to past mine activity.

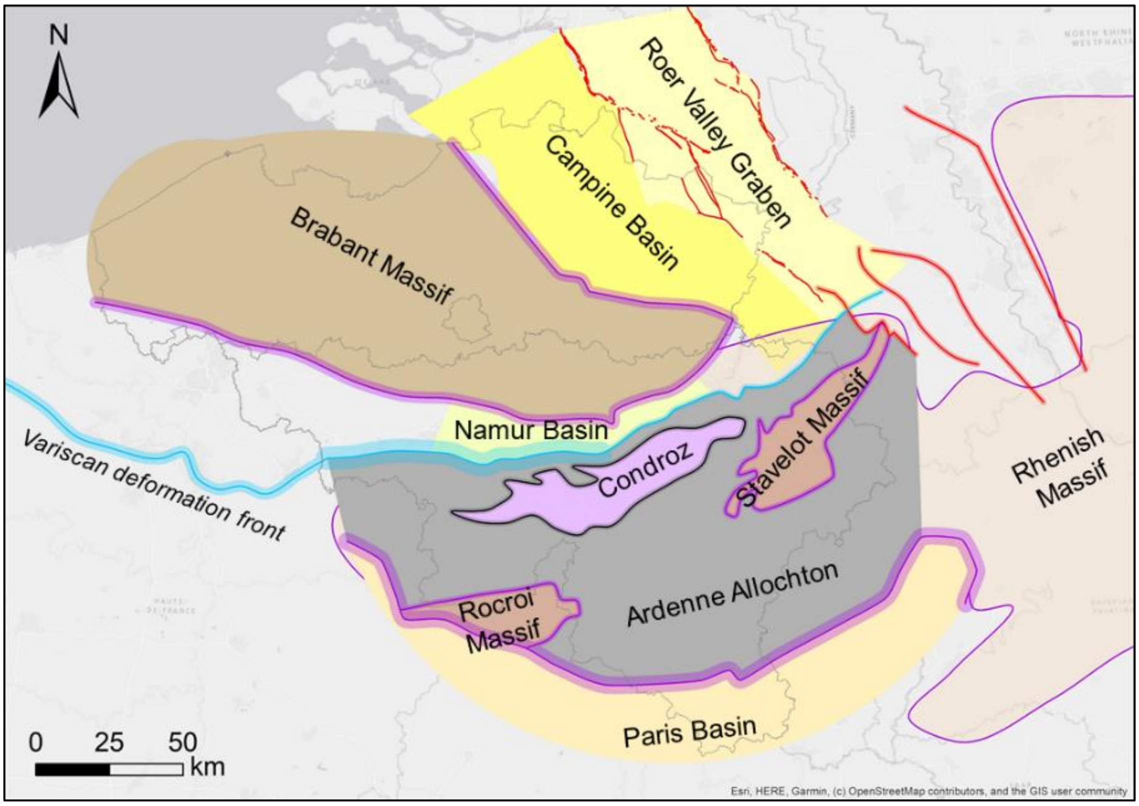

Figure 3-7: GeoConnect³d structural framework highlighting main limits and units in Belgium. Geological limits represented: unconformities in purple, contact in black, deformation front in light blue, and faults in red.

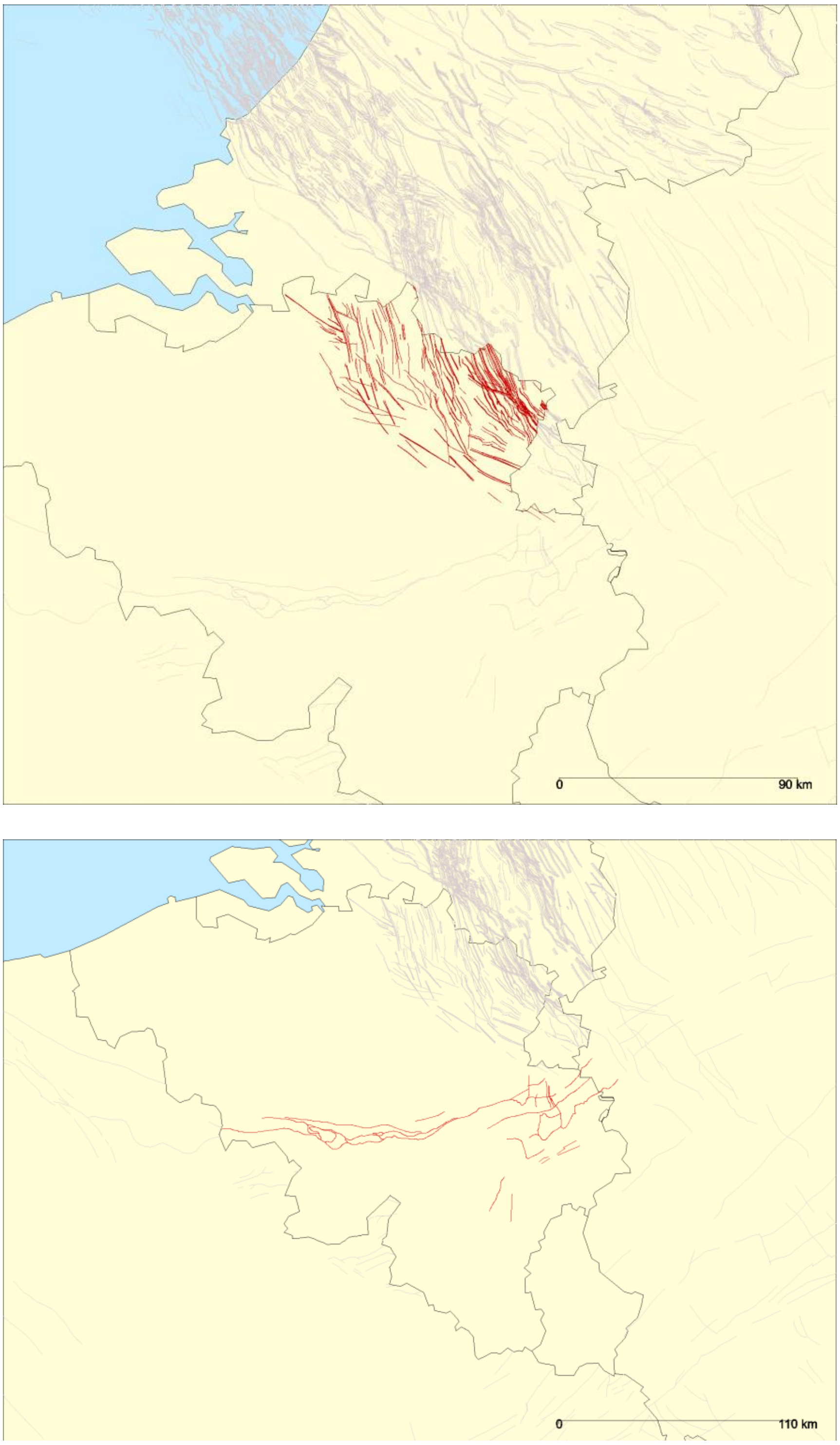

Figure 3-8: Fault traces from the GeoConnect³d structural framework of the Roer-to-Rhine area of interest (inside dashed line) contributed to the HIKE-FDB. Upper: data from VITO represented at multiple reference surfaces. Lower: data from GSB represented at surface level.

3.2.5 Denmark - GEUS

Organization: Date: Author(s)/contact person:	Geological Survey of Denmark (GEUS) 2021-03-11 Peter Britze, Finn Jakobsen

3.2.5.1 Introduction

GEUS is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.5.2 General data metrics and sources

Mapping scale:	National (1:750.000)
Number of faults:	16 faults in vocabulary; 1686 features in database
Geographical coverage:	The fault data extends beyond the borders of the Danish area and includes bordering Norwegian, Swedish, German and Polish (regional) fault data.
Stratigraphic coverage:	The 'Top pre-Zechstein' either represents the top of the youngest - Palaeozoic deposits or the top of the Precambrian rocks where Palaeozoic deposits are absent. It is the deepest regional surface that 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 on this surface. Fault zones have not been mapped in areas where no data are available or where the reference surface is absent
Format:	The fault zones at the top pre Zechstein surface are represented as 2D lines.

3.2.5.3 Fault data acquisition and mapping

2D/3D seismic:	Fault zone mapping used all 1993 public domain 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.
Gravitational and magnetic surveys:	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.
Wells:	Fault zone mapping used all public domain well data in the Danish area
Surface mapping and outcrops:	-
Mapping/Modelling:	The fault zones presented in the Danish territory are published with the 1994 Geological map of Denmark, 1:750.

3.2.5.4 Structural elements

The major structural elements within the Danish area are delineated by fault zones as represented in the Europe Web GIS (Fig. 1). These major structural elements are, from

northeast to southwest: the Skagerak-Kattegat, the Sorgenfrei-Tornquist, the Norwegian - Danish Basin, the Ringkøbing-Fyn High and the North German Basin. The Central Graben delimits the Ringkøbing-Fyn High to the west. Annex 1 contains a listing of all major and minor elements and fault zones affecting the mapped surface and also includes literature references.

3.2.5.5 Fault characterization and definition

No specific information on the fault zone characteristics is provided. The HIKE fault database stores strike and length attribute data. From the 16 identified fault objects only 15 are individually defined, all others are grouped as “No Name” faults

3.2.5.6 Local fault relevance and application

Underground energy storage potential:	Numerous structural closures off-shore as well as on-shore are under consideration.
Natural seismicity:	Denmark has a relatively low level of natural seismicity with the most active regions off the NW coast of Jutland and in Kattegat. As methods and data for calculating earthquake hypocentres advance, the ability to tie seismicity to specific faults improves as well. This is particularly important for identifying suitable formations for CO2 storage.
Induced seismicity:	Not mentioned
Hydrocarbons EP	All oil and gas production is found in the westernmost part of the Danish North Sea, almost exclusively in the Central Graben area
Other?	Not mentioned

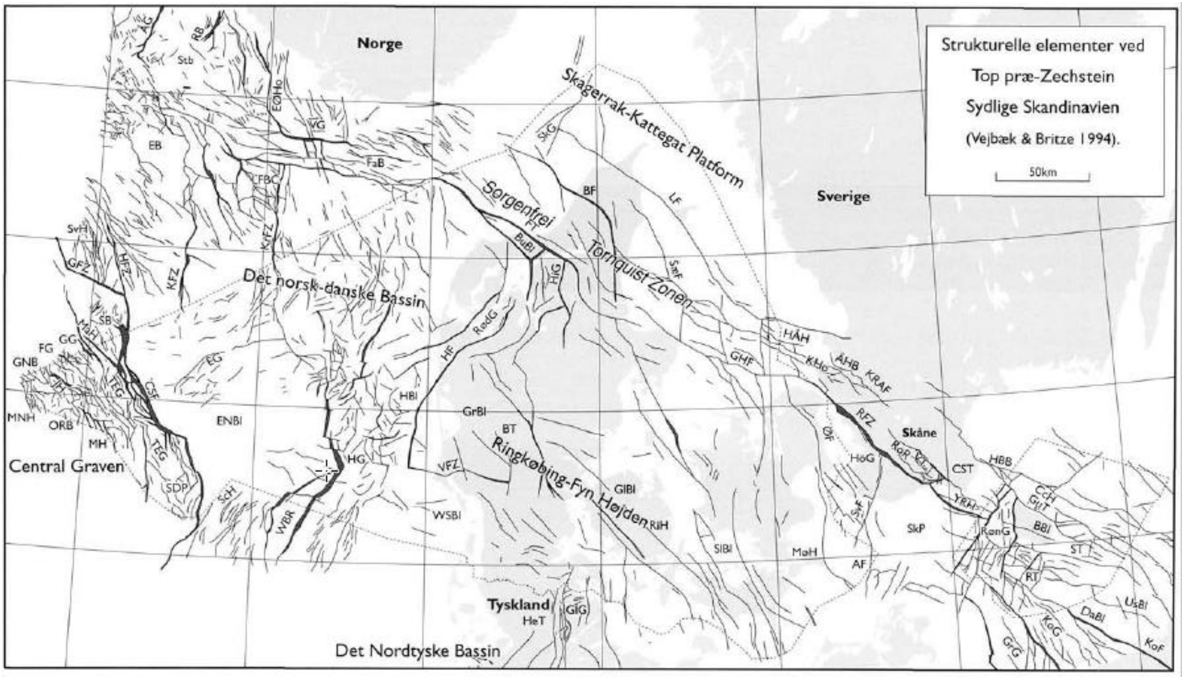

Figure 3-9: Scheme of the distribution of major faultzones (at top pre-Zechstein level) and structural elements in the Danish sector and bordering regions

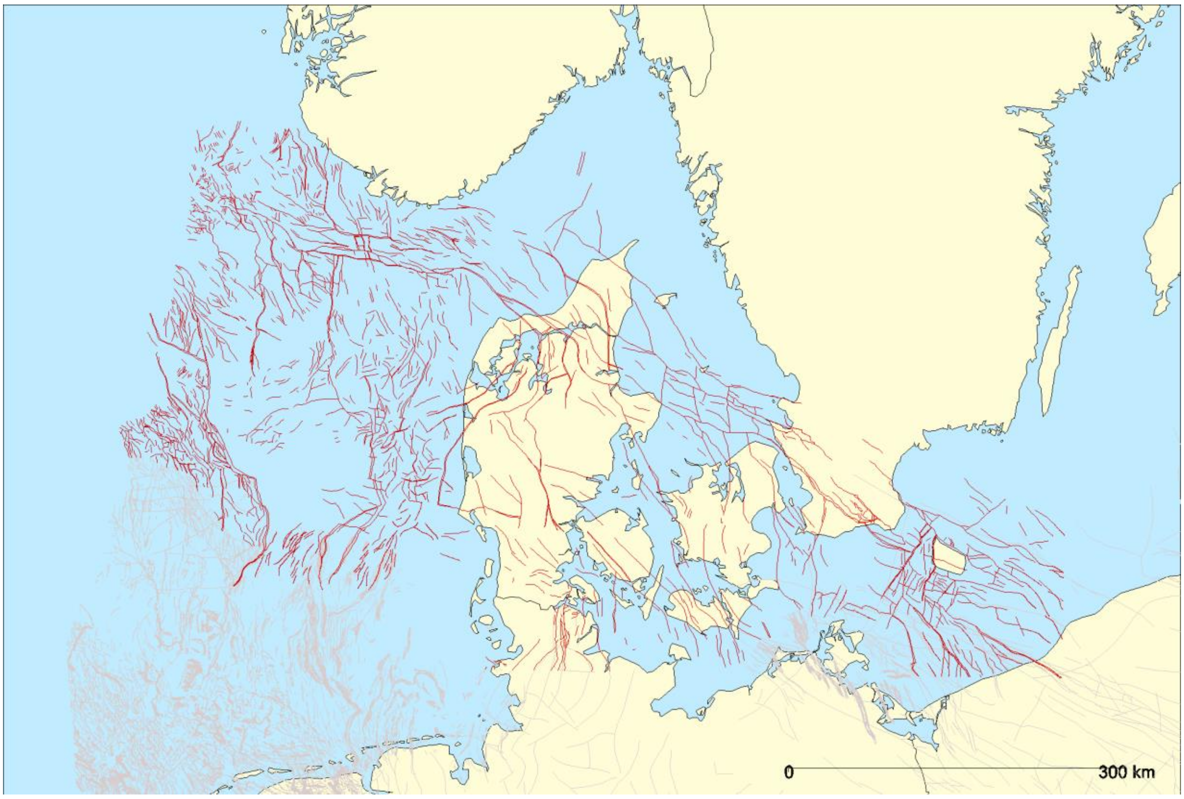

Figure 3-10: Location of mapped national faults and fault systems in Denmark contributed to the HIKE-FDB. Faults are represented at pre-Zechstein level.

3.2.6 France - BRGM

Organization: Date: Author(s)/contact person:	French Geological Survey (BRGM) 2021-03-11 Thierry Baudin

3.2.6.1 Introduction

BRGM is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.6.2 General data metrics and sources

Mapping scale:	National (1:1.000.000) regional (1:50.000)
Number of faults:	7893 faults in vocabulary; 7893 features in database
Geographical coverage:	- National - only the Pyrenees domain
Stratigraphic coverage:	-The sixth edition of the Geological Map of France at 1:1,000,000 scale, compiled in 1993 and published in 1996, was revised in 2002 before publication of a new edition in 2003. New data include those from the national 1:50,000-scale geological mapping survey (currently under completion) undertaken as part of scientific and technical programmes, and those from recent compilation documents of bordering countries and the submarine shelf. The design and making of this map were the responsibility of the French Geological Survey, with the collaboration of many research workers from French and foreign universities and other scientific organizations, and Geological Surveys in neighbouring European countries. The map was drawn out to highlight the structural character and maximize readability, although data at this scale are inevitably schematic compared to the detail found in the original larger-scale source documents. - All faults in the Pyrenean domain were created during convergence of the Iberian microplate and the European Plate, i.e. from Late Santonian (84 Ma) - Early Miocene (20 Ma). Most of them are inherited from the Albian rifting and then inverted during the collision phase.
Format:	2D lines

3.2.6.3 Fault data acquisition and mapping (only for Pyrenees)

2D/3D seismic:	Only in the western most part of the North Pyrenean domain and 2 Ecors profiles respectively in the central and western Pyrenees
Gravitational and magnetic surveys:	From National gravity and magnetic maps
Wells:	Only in the northernmost part of the Pyrenees

Surface mapping and outcrops:	Not mentioned
Mapping/Modelling:	Sheets of the Geological Mapping Program 1:50,000 were consulted next to papers and thematic scientific publications. Entire 3D model and some local 3D model provided by the RGF program.

3.2.6.4 Structural elements

National level

The structural data, mainly derived from the Structural Map of France at 1:1,000,000 scale (1980), have been greatly improved compared to former editions. Structural features, particularly deformation trends and major faults, are schematically displayed according to two criteria:

1) the relative degree of displacement, indicated by the thickness of the line: major, large and minor faults;
2) the sense of movement, indicated by various symbols: normal and detachment faults, reverse faults and thrusts, and strike-slip faults.

The general polyphase nature of the faults, which causes complications for the aforementioned criteria, renders impossible the distinction of timing of movement or whether deformation was brittle or ductile. Finally, certain surface and subsurface data of major structural importance are highlighted using specific symbols: significant isobaths within basins, salt diapirs within trenches, Messinian canyons throughout the Mediterranean region.

A profile through the Pyrenees (fig. 1) shows a fan-like, flower-like arrangement. The structure is strongly asymmetric with a steeper and narrower French northern side and a much wider and more gently inclined Spanish southern side. The double-sided orogen can be divided into several tectonic zones, from north to south, that are bounded by east–west-trending major faults. Three of these major faults limit the main current tectonic zones of the North (French) Pyrenean Thrust Belt. These are from South to North : the North Pyrenean Fault (NPF), The North Pyrenean Frontal Thrust (NPFT) and Sub-Pyrenean Thrust (SPT).

3.2.6.5 Fault characterization and definition (only for Pyrenees)

All the faults belonging to the Pyrenean domain were created during convergence between the Iberian microplate and the European Plate. The northernmost SPT thrust fault is a blind thrust and constitutes the limit between the Pyrenean domain and the Aquitaine basin. The North Pyrenean Frontal Thrust (NPFT) corresponds to the northward inversion of the North Pyrenean rift basins. In the eastern part the NPFT joins the Corbières 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. To the South of the latter's, the Axial Zone (ZA) corresponds to the south margin of the Cretaceous rift-basins.

Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.6.6 Local fault relevance and application (only for Pyrenees)

Underground energy storage potential:	Western part of the North Pyrenean foothill basin

Natural seismicity:	The North Pyrenean Fault is seismically active with some transfer Faults in the north Pyrenean Zone
Induced seismicity:	induced seismicity following gas extraction, since 1950's, in the Lacq basin (North Pyrenean Zone)
Hydrocarbons EP:	In the Lacq basin (North Pyrenean Zone)
Other?	Whyte Hydrogen production (along the North Pyrenean frontal Thrust)

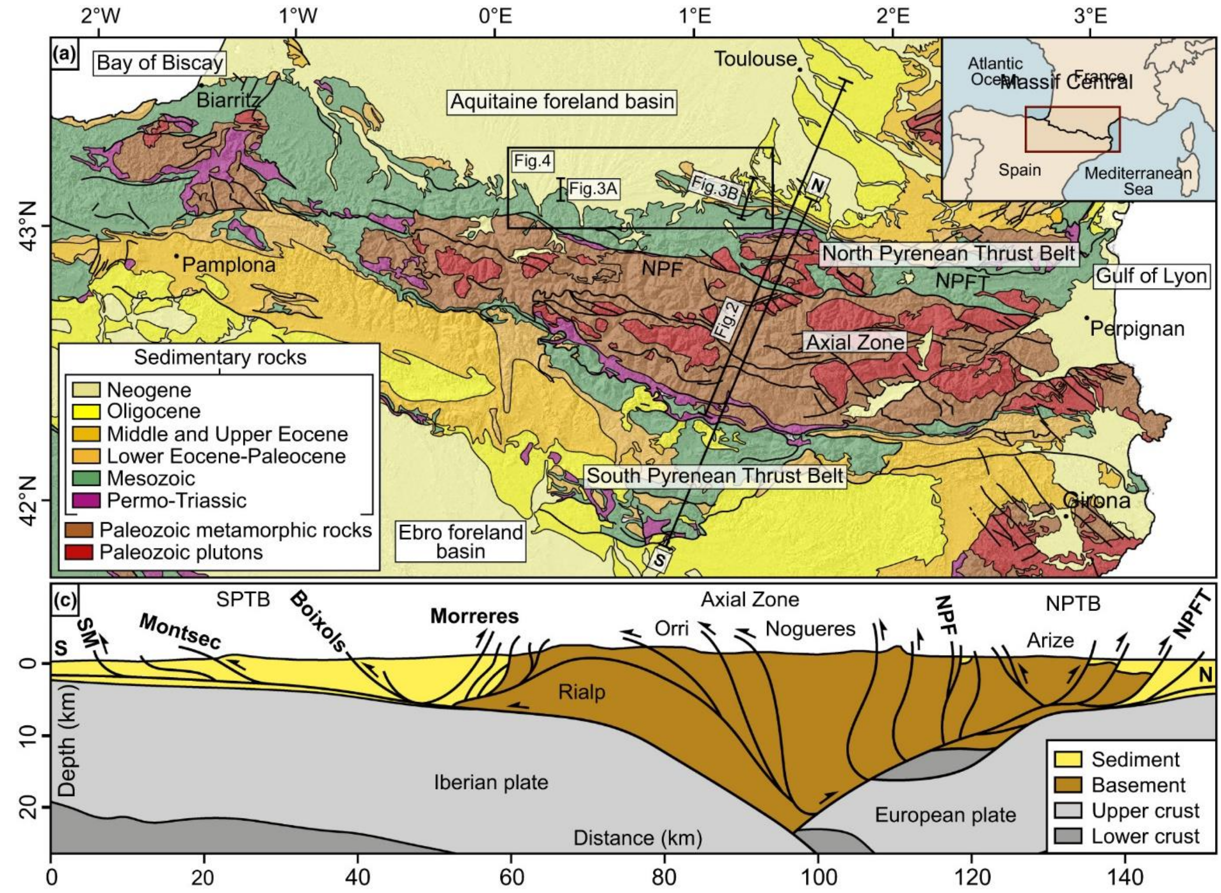

Fig. 1 Geology of the Pyrenean system. (a) Geological map of the Pyrenees from the 1:1,000,000 BRGM geological map of France (modified after Bernard et al., 2020); (c) Simplified geological cross sections of the central Pyrenees modified after Muñoz (1992)

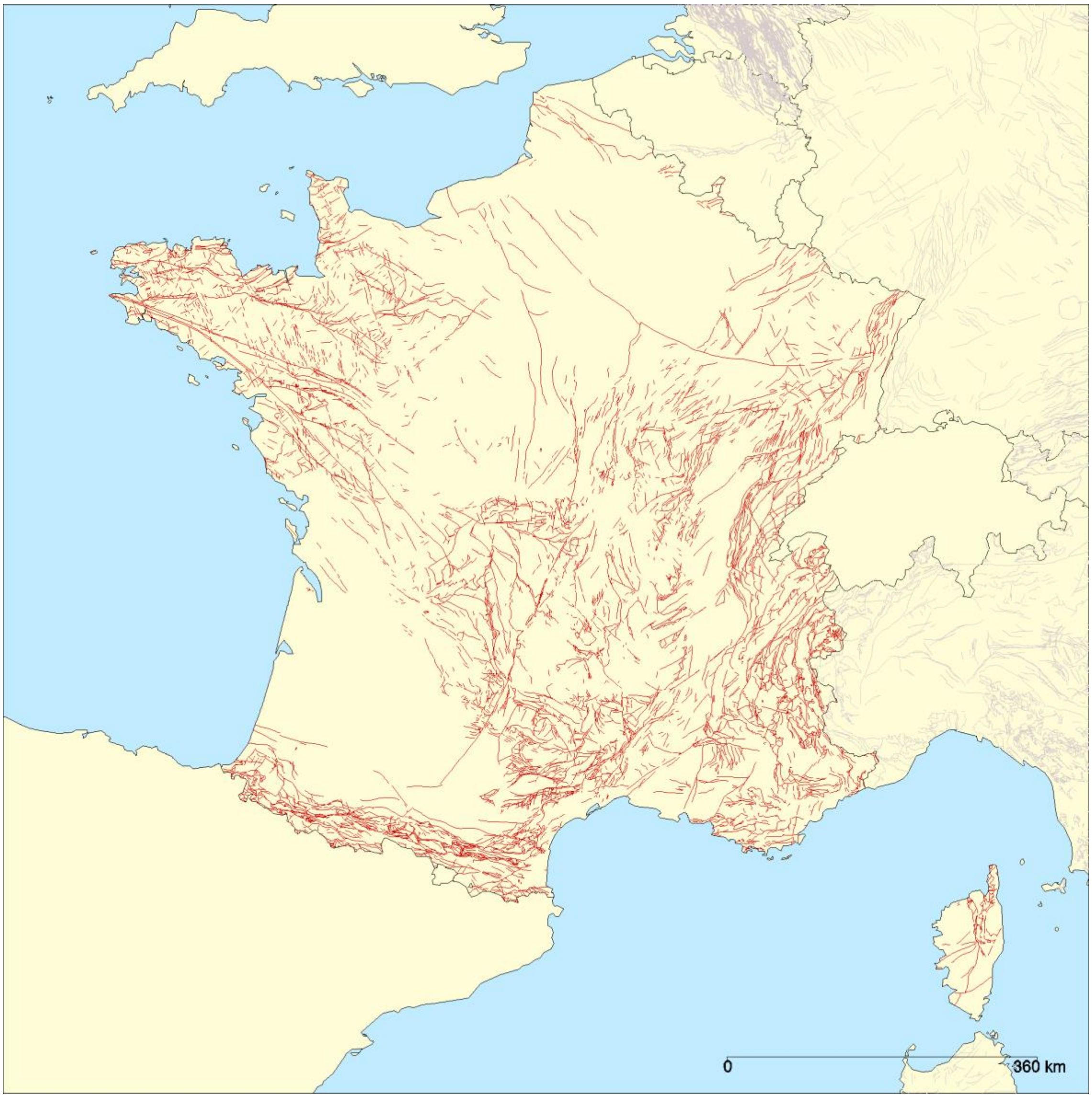

Figure 3-11: Location of mapped national faults and fault systems in France contributed to the HIKE-FDB. Faults are represented at surface level.

3.2.7 Germany - BGR

Organization: Date: Author(s)/contact person:	Federal Institute for Geosciences and Natural Resources (BGR) 2021-03-10 Heidrun Louise Stück, Fabian Jähne-Klingberg

3.2.7.1 Introduction

BGR has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. The concepts of principal and overarching tectonic boundaries presented for entire Germany by the BGR are in an overview scale. For some German Federal States, more detailed concepts are available. The fault data considered contributed by the BGR 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: 500000), 2.) Baltic Sea (1:1000000 - 1:250000), 3.) Central German North Sea (1:1000000 - 1:100000), 4.) Entenschnabel region - The northwestern German North Sea sector (1:1000000 - 1:50000). Chapter 8 of Annex 1 (Country report, BGR) provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics of the origins and geological relevance of fault information.

3.2.7.2 General data metrics and sources

Mapping scale:	National (1:500.000 to 1:2.500.000)
Number of faults:	onshore: 915, offshore: 112 Baltic Sea, 1780 North Sea. In total 2711 faults in vocabulary; 29085 features in database.
Geographical coverage:	Nation-wide, on- and offshore with strong regional variations in data density and detail. Sparse sub-surface fault information in the central part due to lack of seismic and well data (mainly defined by outcrop data).
Stratigraphic coverage:	Subdivided in pre-Rotliegend basement and younger basins especially within the extent of Central European Basin system. In Mid-Germany surface outcrops of Variscan to Pre-Variscan basement also define the structural pattern. In southern and western Germany Cenozoic Rifts and basins as well as thrust-belts of the Alps highlight the latest major events of structural evolution in Germany. (Fig. 1)
Format:	Predominantly generalized 2D polylines, detailed 3D interpretation data for selected regions.

3.2.7.3 Fault data acquisition and mapping

2D/3D seismic:	2D and some 3D surveys are mainly concentrated in three areas, the North German Basin as well as the North Sea and Baltic Sea offshore, the South German Molasse basin and the Upper Rhine graben as these are the focal areas for exploration of oil and gas, salt mining and geothermal exploration.
Gravitational and magnetic surveys:	Covering entire country in an overview scale, used to show the bedrock geology as well as deep fault structures.

Wells:	Mostly in the northern (including offshore) and southernmost parts of the country, i.e., in areas with hydrocarbon exploration and production licenses.
Surface mapping and outcrops:	Especially for regions with a Mesozoic surface geology or with basement outcrops. No clear information from surface mapping in regions with Quaternary and Neogene cover in Northern Germany and Mid-Germany. Due to strong activity during Neogene to Quaternary within the Lower Rhine Bight, the Upper Rhine Graben, the Molasse basin and the Alps, fault information can be derived from surface mapping data.
Mapping/Modelling:	The used fault datasets were compiled from former mapping projects. These were used for a complete exploration and structural interpretation of the subsurface of Germany and as a basis for the evaluation of different potentials of the subsurface. No site explorations were represented in these data, or they were only roughly generalized. • Fault data for the onshore area of Germany originate on the data compiled within the "Geothermal Atlas" (Schulz et al. 2013). These data are made up of an integration and merging from different map series, such as e.g. the Geological surface map of Germany (Toloczyki et al., 2006; GK1000), the Geotectonic Atlas of North West Germany and the German North Sea Sector (Baldschuhn et al. 2001), the Southern Permian Basin Atlas (Doornenbal & Stevenson 2010) and several more, which then were collected and generalized within the frame of the Geothermal Atlas (Schulz et al. 2013). The presented spatial data of faults consist exclusively of generalized, horizon independent lineaments from overview structure maps or of generalizations from surface maps. • For the Central German North Sea offshore area contributed fault data consist of fault intersections with 13 Mesozoic to Cenozoic horizons + the Late Paleozoic Base Zechstein (Baldschuhn et al., 2001). For the northwestern part of the German North Sea, the Entenschabel, faults originate on interpretations 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.

	• At this point it should be noted that the generalization accomplished in the frame of the "Geothermal Atlas" originally not includes a comparison of data available at the geological state authorities. The necessary generalization and harmonization of faults in an overview scale may therefore differ in details from detailed data hosted by geological state authorities of Germany. This is particularly evident on Bavarian or Saxony-Anhalt territory, where the faults depicted at the finer, more detailed scale can differ locally quite significantly in their extent, location and naming than in the small-scale overview of 1: 500 000 to 1: 2,500 000.

3.2.7.4 Structural elements

The 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. Therefore, most basement outcrops in Mid- and Southern Germany show Palaeozoic but also pre-Cambrian rocks with a predominantly Variscan overprint. In parts, evidence of Cadomian orogeny is also preserved in Mid-German basement outcrops. The Pre-Carboniferous basement of the northern North German Basin and of the German North Sea basin is characterised by a Caledonian overprint.
Since the Rotliegend, the Central and Western European development was characterized by intraplate tectonics and associated processes such as the formation of several sedimentary basins and graben structures. Based on the dominant fault pattern, the predominant direction and the structural style of important fault zones as well as facial trends, several main structural regions are distinguished. These include the North German Basin and its sub basins (such as the Glückstadt Graben, Horn Graben, Hessian Depression, Lower Saxony Basin), the Münsterland Basin, the Upper Rhine Graben, the Lower Rhine Bight/Graben, the Molasse Basin, the domains of the Alps, the Rheinisches Schiefergebirge and other Pre-Permian basement outcrops of Mid- and Southern Germany as well as the Permo-Carboniferous Saar-Nahe Basin. 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 clearly separate individual structural regions.

Chapter 8 of Annex 1 (Country report, BGR) provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.7.5 Fault characterization and definition

Sedimentary basins and grabens respectively of Germany (Fig.1) have a varied appearance due to their different structural histories and can be broken down regionally into the following 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 as well 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 related faulting in the Mesozoic and Cenozoic overburden above the Zechstein and Upper Rotliegend salt layers.
3. Narrow, complexly structured normal to oblique fault zones in Central Germany, "young" rifts are witnesses of the European, Cenozoic rift system (Upper Rhine Rift, Eger Rift)
4. Fold and thrust belts are characteristic for the Northern Alpine and parts of the Molasse basin in the northern foreland.
5. 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
6. Several German Low mountain ranges, such as the Harz or the Thüringer Wald are partially bordered by reactivated Late Variscan to Rotliegend faults or newly formed steep basement reverse faults during the Late Cretaceous
7. Narrow complex graben-systems mapped 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).

This general information on structural styles and trends was used to define within the frame of GeoEra-HIKE a new interpretation of the structural framework (Fig. 3.-13), for enabling in an abstracted manner a systematic classification and distinction of generalized fault data in Germany (Fig.3-15). The structural map presented here was compiled from different regional tectonic maps, several publications or geological surface maps and finally consists of 222 defined structural regions. Due to the inevitable simplification, the following aspects should be taken into account when considering the data presented here:

- Although the delivered fault data illustrated in the structural map within a defined structural region may vary with respect to e.g. their fault pattern. Nevertheless, they have undergone the same structural-geological development by being assigned to a structural region.
- Even if the transitions between individual structural elements as a GIS dataset always show sharp transitions, some transitions between the structural elements are only imprecisely defined. Other borders of structural elements are clearly defined by faults.
- Due to a different degree of generalization and different data basis, the structural elements newly created for this study deviate from the generalized compiled fault lineaments of the Geothermal Atlas (Schulz et al., 2013).

Chapter 8 of Annex 1 (Country report, BGR) and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.7.6 Local fault relevance and application

Underground energy storage potential:	Not mentioned
Natural seismicity:	Figure 3-14 show the distribution of events with magnitude > 2

Induced seismicity:	Figure 3-14 show the distribution of suspected events with magnitude > 2
Hydrocarbons EP	Oil and Gas exploration and production predominantly in the western parts of the North German Basin or the Rhine Graben and Molasse Basin

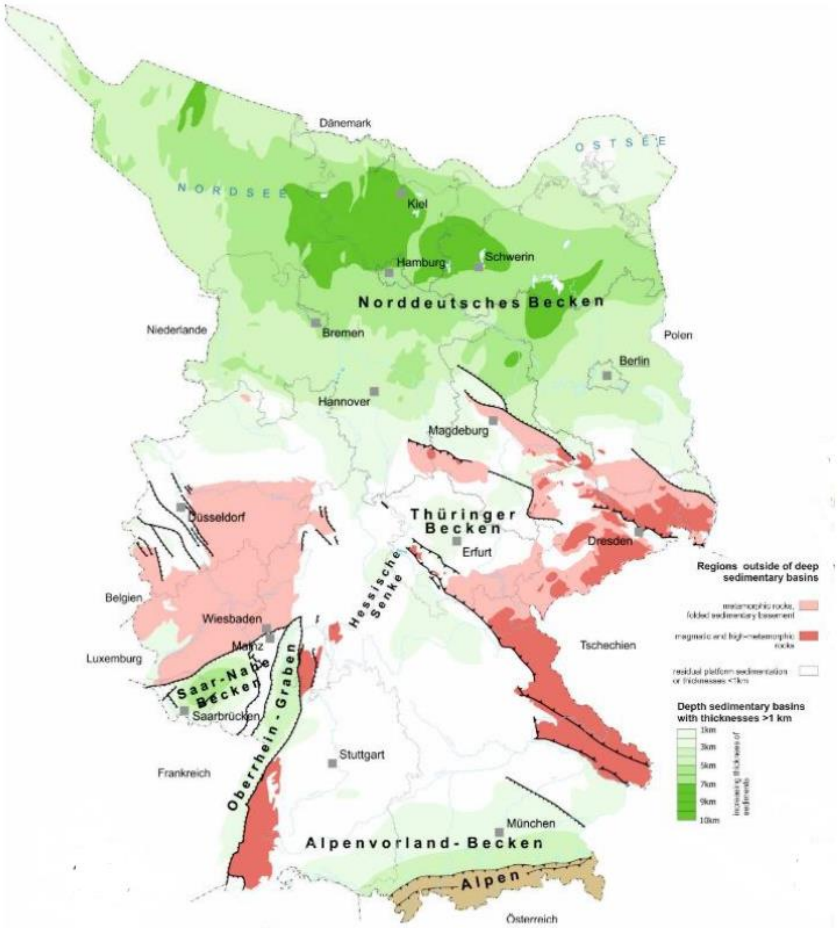

Figure 3-12: Scheme of the distribution of the main structural elements of Germany (after Ref). Red and pink colors represent outcropping magmatic and metamorphic rocks, respectively. Green colors represent sedimentary basins with thickness (0-10km) in green scale. White areas represent platform domains with a sedimentary cover < 1km.

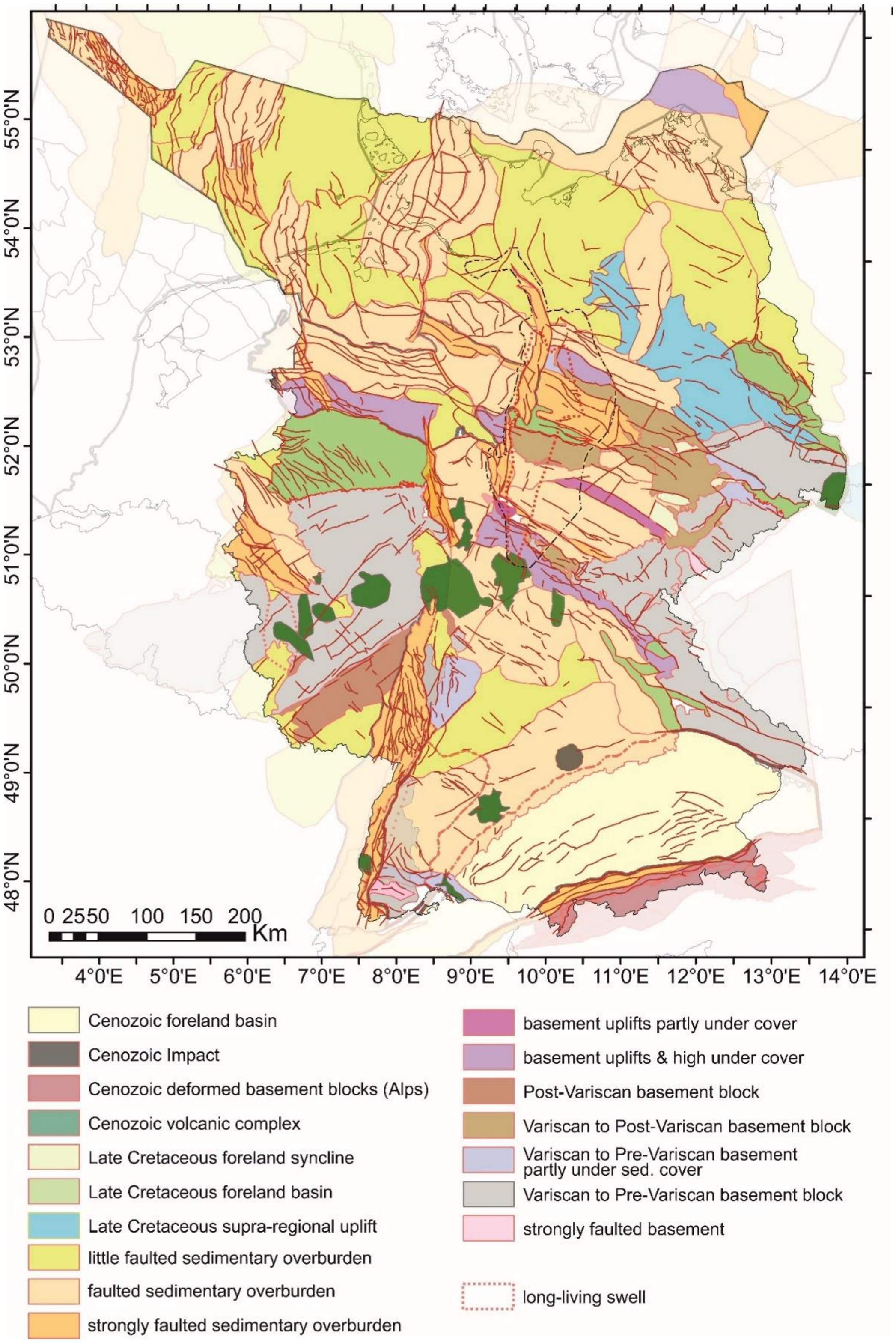

Figure 3-13: Tectonic scheme of Germany at the scale 1:500.000 overlain by compiled faults from the Geothermal Atlas.

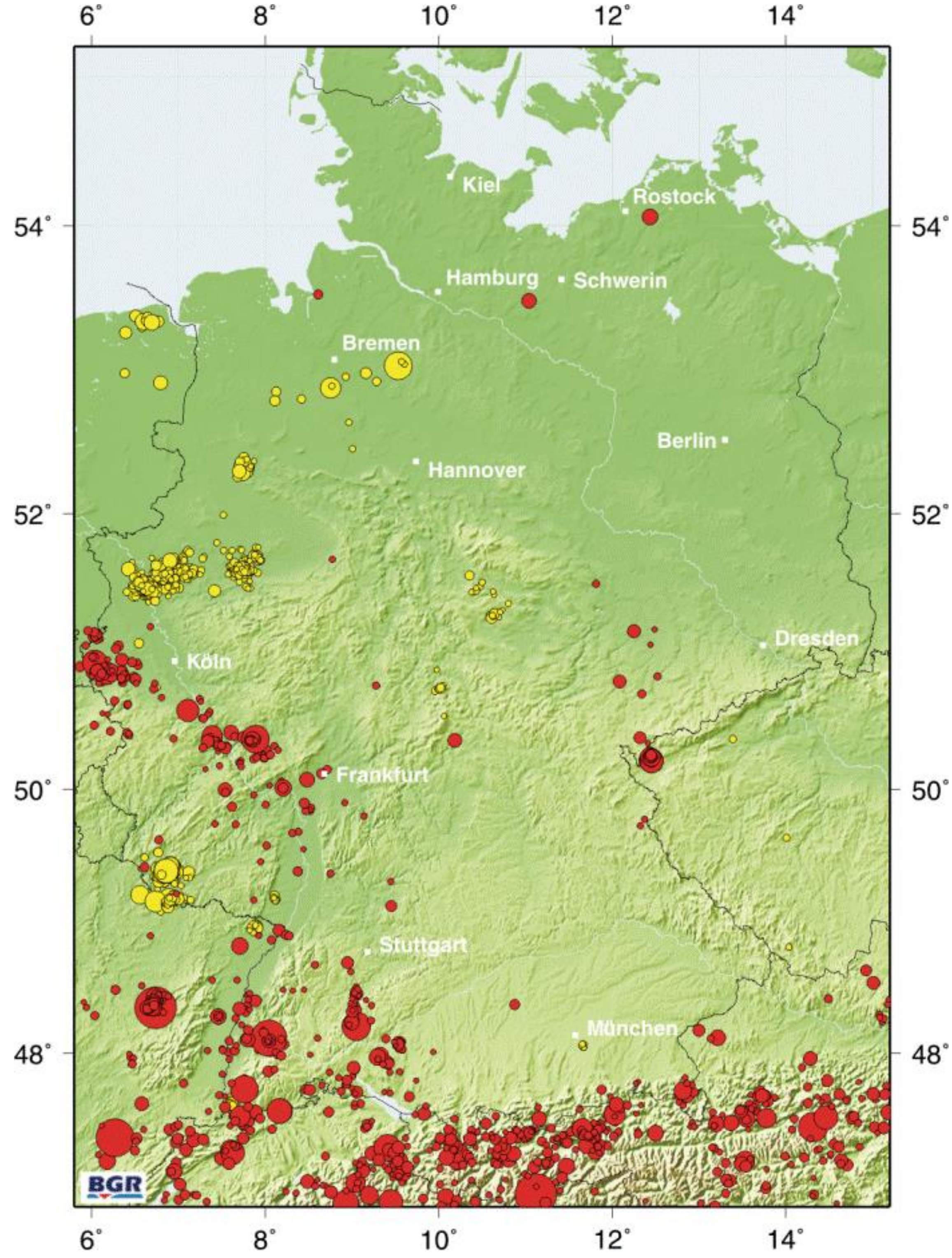

Figure 3-14: Seismicity in and around Germany: events 2000 - 2011 with magnitude > 2; red: tectonic earthquakes, yellow: probably induced earthquakes; Source: BGR

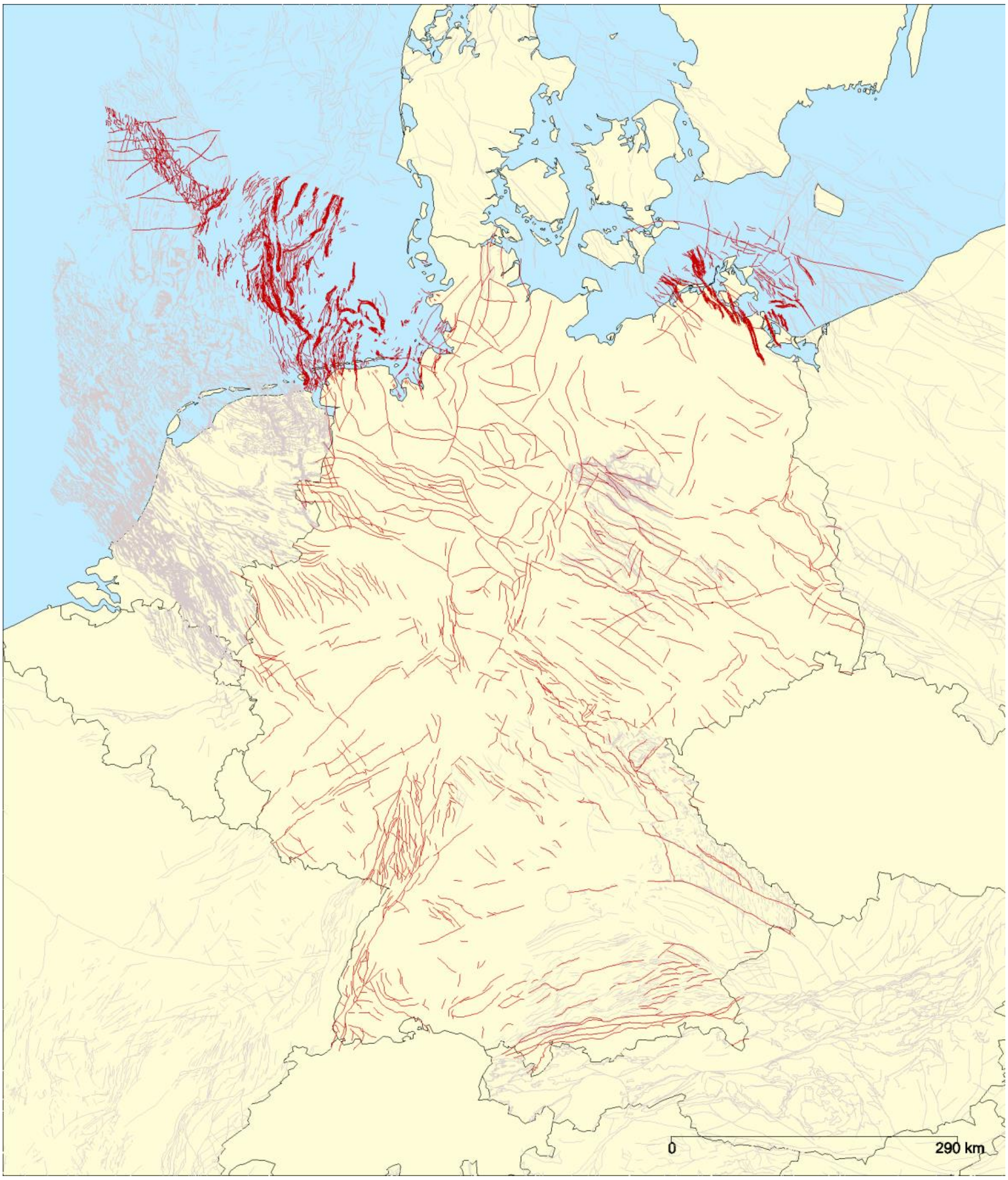

Figure 3-13: Location of mapped national faults and fault systems in Germany contributed to the HIKE-FDB. Based on compiled faults from the Geothermal Atlas for the onshore and generalized faults of offshore Germany from 3DGEO-EU WP5. For the onshore faults are represented at multiple surface levels. Most of faults in Mid- and Southern Germany, with exception of the Rhine-Graben and Molasse basin, are defined by outcrop (surface)

3.2.8 Brandenburg (GER) - LBGR

Organization: Date: Author(s)/contact person:	Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg (LBGR) 2021-03-31 Christoph Jahnke, Thomas Höding

3.2.8.1 Introduction

LBGR is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.8.2 General data metrics and sources

Mapping scale:	National (1:500.000)
Number of faults:	59 faults in vocabulary; 59 features in database
Geographical coverage:	Nation-wide with strong regional variations in data density and detail.
Stratigraphic coverage:	Precambrian/Paleozoic (pre-Permian) to Cenozoic.
Format:	The faults included in the database are delivered as 2D lines representing the generalized position of the faults (without a defined depth). They are derived from direct observation in wells and seismics (Permian to Cenozoic) or are inferred (most basement faults). The described fault attributes are mainly limited to the geometric characteristics, t.m. length, strike or dip direction.

3.2.8.3 Fault data acquisition and mapping

2D/3D seismic:	The faults were interpreted and mapped/modelled in accordance to 2D seismic depth sections.
Gravitational and magnetic surveys:	Basement faults were postulated in accordance to potential field data (gravimetry and magnetic).
Wells:	In addition to the geophysical indicators several faults are locally detected in deep drillings (Permian to Cenozoic strata).
Surface mapping and outcrops:	All faults are covered by Cenozoic and Quaternary cover. There were some Geological Maps used as like as the Geophysical Atlas of the GDR (Reflection Seismics), 1:100.000, Leipzig, 1975-1990, Geological Map of the GDR 1:500.000 (Geology at the base of Cenozoic, Tectonical map) Berlin 1989, the Atlas of the Geology of Brandenburg State 1:1.000.000, Cottbus 2010 and some thematic scientific publications.
Mapping/Modelling:	The provided fault traces are a generalization of 3D-models (“Brandenburg 3D”, “TUNB”) and the maps mentioned above.

3.2.8.4 Structural elements

The area of Brandenburg is situated in the South Eastern part of the North German Basin (a part of the Central European Basin System). The North Eastern part of Brandenburg is in close

contact to the border zone of the NGB and the Polish Trough. In the southern part Variscian Blocks were uplifted during the inversion phase of the North German basin (Upper Cretaceous to Paleogen). The present structural inventory of Brandenburg can be roughly subdivided 3 major structural domains, defined according to the position in the North German Basin (South Eastern margin including the structural subdomain of the Variscian Lusatian Block, the central basin and the North Eastern border). These domains show typical fault pattern (fault type, striking, timing, stratigraphic coverage).

3.2.8.5 Fault characterization and definition

Only faults at a national/transnational scale of ca. 1:500.000 are provided (length >10km). The major structural elements in the southern part of Brandenburg are the NW-SE striking Central German Main Escarpments and related parallel structures (post-variscian dextral strike-slip faults of a crustal wrench-system, inversion in Late Cretaceous/Early Cenozoic). A second fault set is cross-directional orientated (NE-SW). Partially old Variscian structures were reactivated in the varying stress regimes from Permian to Cenozoic. In the Central Basin the fault orientation differs: a) basement faults with influences up to the Mesozoic striking NNE-SSW, b) ENE-WSW striking faults in Permocarboniferous and c) complex fault zones striking ± E-W reaching from the basement to the Mesozoic. In the Northeast of Brandenburg NNW-SSE striking faults can be found (belonging to the Western-Pommerania fault system at the Northeastern border of the North German basin). The regional faults transect the post-variscian sequence of the Brandenburg-part of the North German Basin and divide it into several blocks. So a block structure ("Schollenbau") can be observed especially in the pre-Permian subsurface of Brandenburg (as well as in the whole northern Germany). The intense halokinesis of the Permian salt starting in Late Triassic led to a partial decoupling of the tectonics of the Pre-Zechstein strata and the Mesozoic/Cenozoic succession. Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.8.6 Local fault relevance and application

Infrastructure	Nearly no relevance to infrastructure
Nuclear waste storage:	Planning and prospecting strategies for the disposal of radioactive waste in wide areas. Tectonic faults as described here are an exclusion criterion in the search for a nuclear waste deposit. This search is currently taking place throughout Germany, including Brandenburg
Underground energy storage potential:	Storage of gas and oil took and takes place at several locations in Mesozoic pore storages (Bunter Sandstones, Keuper sandstones) and in salt caverns in the Zechstein. One test-site for CO2-storage was situated in Keuper sandstone. The locations lie outside of regional fault zones. Local faults (e.g. crestal grabens at the top of salt anticlines) have to be taken in account in the planning.
Natural seismicity:	Brandenburg is a state with very low seismic activity. Seismicity induced by tectonic faults is not documented in recent times
Induced seismicity:	Brandenburg is a state with very low seismic activity. Seismicity induced by tectonic faults is not documented in recent times
Hydrocarbon	Especially in the southeast of the country, faults can form and influence geological trap structures (Permian Staßfurt Series). Hydrocarbons have

	been detected in the vicinity of such faults and have also been produced in recent decades
Groundwater	Groundwater extraction take place from shallow Quaternary and Tertiary aquifers. In some regions shallow aquifers are connected to deep saline aquifers along fault zones reaching the Cenozoic (especially influencing the Rupelian Clay, the major seal between fresh and saline ground water in Brandenburg).

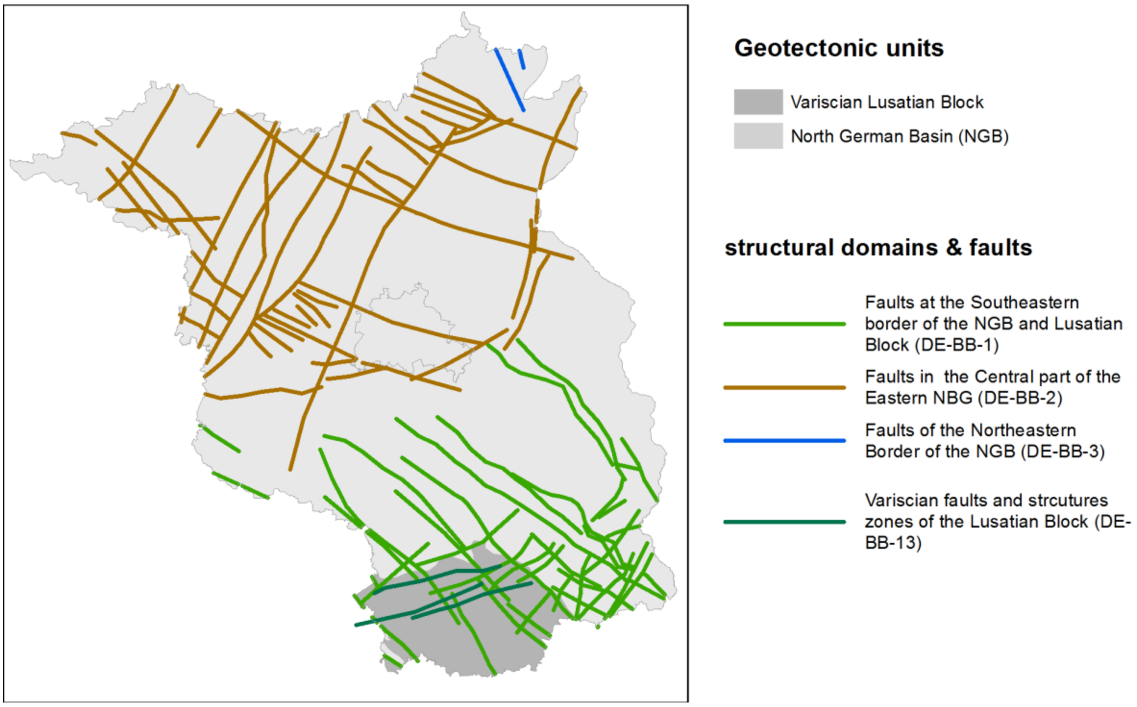

Figure 3-14: Geotectonic units, structural domains and related faults in Brandenburg.

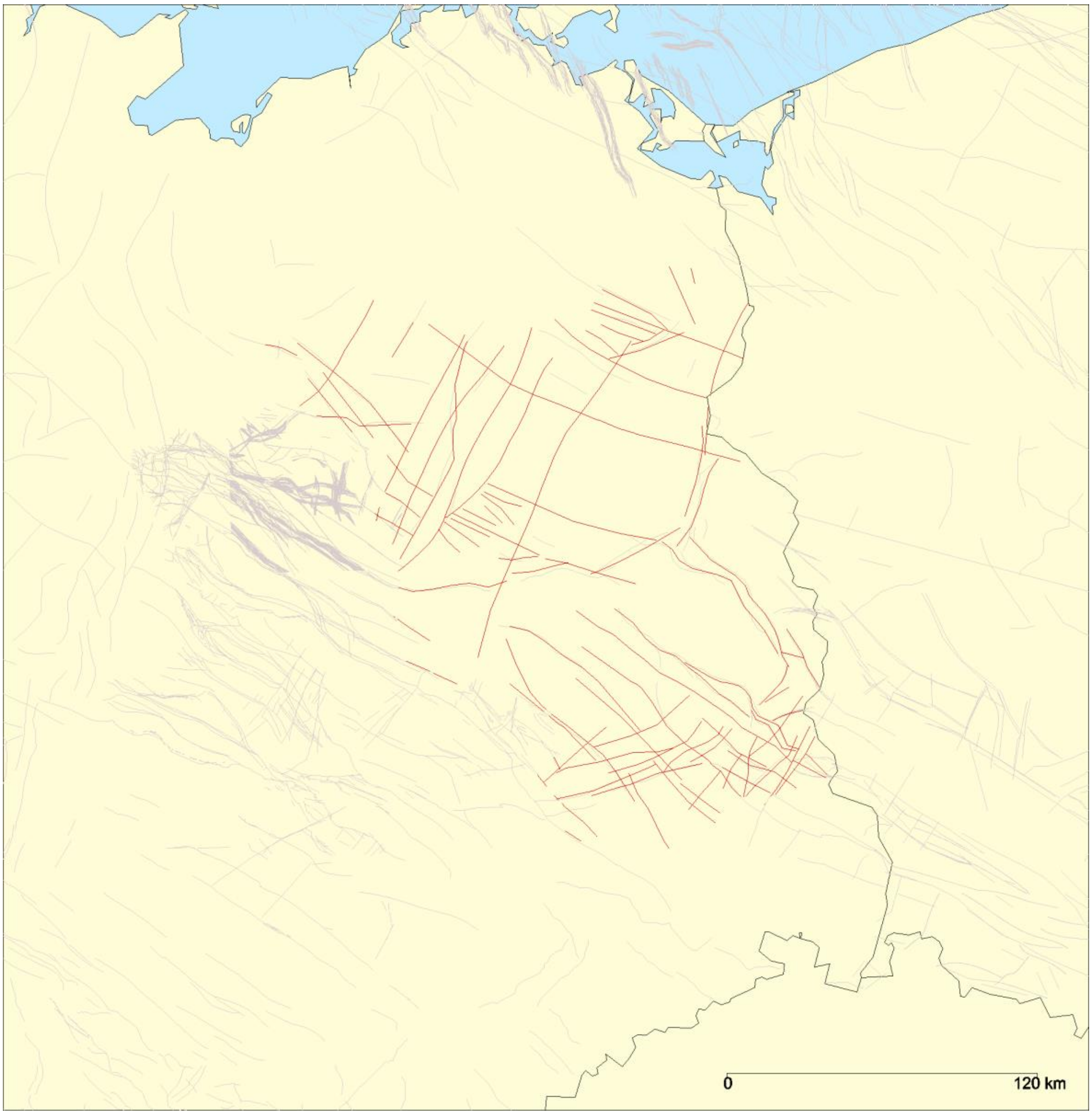

Figure 3-15: Location of mapped faults and fault systems in the federal state of Brandenburg (Germany) contributed to the HIKE-FDB. Faults are represented as generalized fault traces at depth.

3.2.9 *Saxony-Anhalt (GER) - LAGB*

Organization: Date: Author(s)/contact person:	Geological Survey of Saxony-Anhalt (LAGB) 2021-03-25 Alexander Malz

3.2.9.1 Introduction

LAGB is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.9.2 General data metrics and sources

Mapping scale:	Fault data will be available for the HIKE fault database in scales of up to 1:50’000.
Number of faults:	829 faults in vocabulary; 109529 features in database
Geographical coverage:	State-wide with strong regional variations in data density, detail and type. Sparse fault information in central and eastern parts due to lack of seismic data and well data.
Stratigraphic coverage:	Both shallow- and deep subsurface faults. Generalized fault lines (Level-1) from large-scale 3D models 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. Exemplarily, faults referred to main lithostratigraphic units extracted from detailed 3D models (Level-2). Shallow faults taken from geological maps and faults of intermediate depths taken from regional to local maps of the Cenozoic (Level-3).
Format:	For areas were yet no 3D model exist, Level-1 data were completed with existing fault traces from local and yet unpublished investigation reports. A generalization has been made to make local data suitable for HIKE. Intersecting lines of faults with regional geologically and economically relevant stratigraphic horizons (footwall and hanging wall cut-off lines) of the Mesozoic was derived from detailed models (Level-2). These fault data will be available for the HIKE fault database in scales of up to 1:50’000. All yet available fault data from the deep and shallow subsurface will be included in the HIKE fault database. The dataset was complemented with additional surface expressions of faults (Level-3). Detailed faults for the deep subsurface are classified according to a generic semantic framework.

3.2.9.3 Fault data acquisition and mapping

2D/3D seismic:	>700 depth-converted reflection seismic sections were interpreted. These data predominantly cover the northern

	(Altmark) and western (Subhercynian Basin) parts of the state (Level-1 and Level-2 faults).
Gravitational and magnetic surveys:	Covering entire country, used for mapping major fault lineaments along uplifted blocks of pre-Mesozoic basement (Harz block and Flechtingen High)
Wells:	Well data was used for 3D modelling. Dense data available in the north western part of Saxony-Anhalt. Sparse information available in the eastern and southern parts of the state (Level-1 and Level-2 faults).
Surface mapping and outcrops:	Sparsely available. Faults mostly covered by Cenozoic and Quaternary cover. Extracted from geological maps in scale of 1:25’000 adjacent to main basement uplifts (Level-3).
Mapping/Modelling:	Compilation of existing regional to local maps, geophysical data, seismic data. 3D modelling performed in ~50% of the area. 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. All fault sticks were transferred into three-dimensional fault surfaces. During 3D modelling and parameterization efforts fault traces will become systematically collected for map sheets in the scale of 1:50’000. 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 (Level-2). These fault data will be available from the HIKE fault database in scales of up to 1:50’000.

3.2.9.4 Structural elements

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. 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. 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.

Annex 1 provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.9.5 Fault characterization and definition

Only structural elements and fault zones of regional importance subdividing the realm of Saxony-Anhalt are described. The Altmark area comprises 6 major tectonic blocks that trend either NNE-SSW or NW-SE. The Flechtingen High to the south forms an approx. 100 km long and 20 km wide, NW-SE trending surface outcrop of Palaeozoic rocks in central Saxony-Anhalt. The internal structure of the Subhercynian Depression, located between the Flechtingen High and the Harz Mountains, is characterized by NW-SE-trending fault zones salt

structures, thin-skinned anticlines and long-wavelength fault-related folds and deep synclines. 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. NW-SE- and subordinated NNE-SSW-striking fault zones, long-wavelength folds and local Cenozoic depressions characterize the Thuringian Syncline in 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'. Faults and structures of Mesozoic age dominantly strike NW-SE and subdivide the northeastern Thuringian Syncline Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.9.6 Local fault relevance and application

Nuclear waste storage:	Planning and prospecting strategies for the disposal of radioactive waste in wide areas.
Underground energy storage potential:	Storage of gas takes place in salt structures in the Altmark area and parts of the Subhercynian Basin.
Natural seismicity:	Natural seismicity is documented in the southern part of Saxony-Anhalt. Earth quakes with magnitudes < 3 occur are distributed along the N-S-trending Leipzig-Regensburg Zone.
Induced seismicity:	Not mentioned
Hydrocarbon	Gas production predominantly in the northwestern (Altmark) region of the state.
Groundwater	Groundwater extraction from deep aquifers occurs in the southern part of Saxony-Anhalt. In parts shallow aquifers are connected to deep saline aquifers along fault zones.
Other	

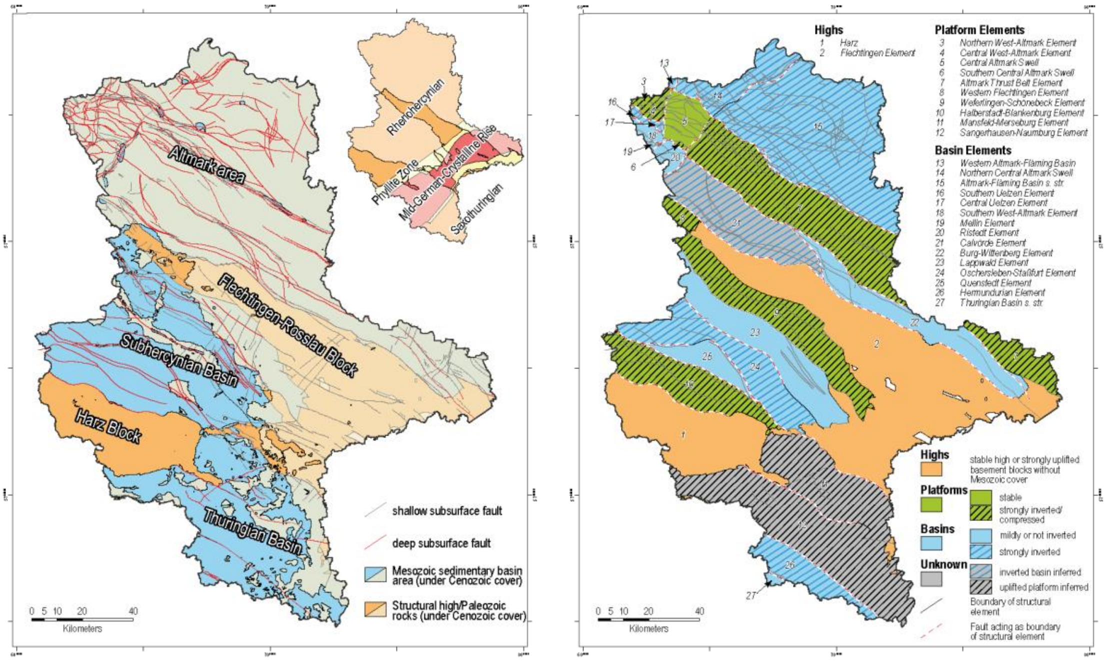

Figure 3-16: Left) Structural overview of Saxony-Anhalt (without Quaternary cover) with major regional geologic units as well as major deep and shallow subsurface faults (regional faults in the fault database). Inset map on the upper right corner shows the Palaeozoic segmentation of the basement. Right) Regional and local structural elements of Saxony-Anhalt as defined in the fault database.

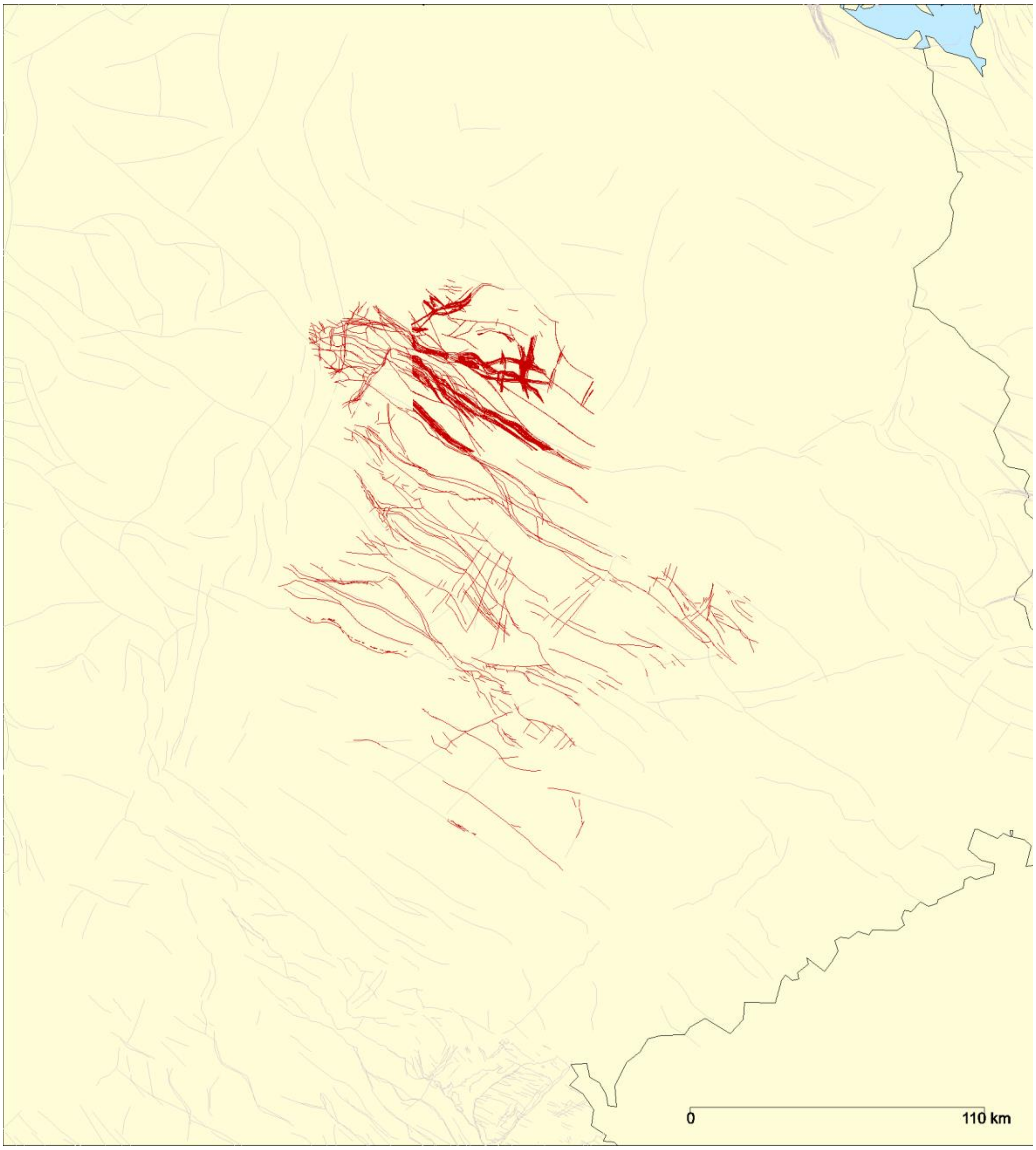

Figure 3-17: Location of mapped national faults and fault systems in the German federal state of Saxony-Anhalt contributed to the HIKE-FDB. Fault are represented at various reference levels.

3.2.10 Bavaria (GER) - LfU

Organization: Date: Author(s)/contact person:	Bavarian Environment Agency (LfU), Geological Survey 2021-03-16 Gerold W. Diepolder, Timo Spörlein

3.2.10.1 Introduction

LfU is a partner in HIKE and has contributed various scale fault information to the HIKE Fault Database for the entire extent of the state, w/o the Alpine Domain. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.10.2 General data metrics and sources

Mapping scale:	Various scales: National (1:500,000) for the northwest of Bavaria (Scarpland) as presently under revision and update, regional (1:100,000) for the Molasse Basin, sub-regional (1:100,000 to 1:50,000) for the Franconian Alb and Bohemian Massif.
Number of faults:	272 faults in vocabulary; 4715 features in database
Geographical coverage:	Data focused on the federal state of Bavaria, but with embedding in the regional setting
Stratigraphic coverage:	Paleozoic – Quaternary
Format:	The faults for the deep subsurface are delivered as 2D intersection lines either at surface or, for the blind faults of the Molasse Basin, at the top Jurassic level (HotLime 2020). 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 FDB. 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.

3.2.10.3 Fault data acquisition and mapping

2D/3D seismic:	2D and some 3D surveys are used in the deeper parts of the Molasse Basin domain.
Gravitational and magnetic surveys:	Used in the Lower Bavaria – Upper Austria Molasse Basin shallow parts where no seismic data is available, for accentuating the basement structures.
Wells:	Drillings > 100 m depth from the BIS-BY database have been used wherever available.
Surface mapping and outcrops:	In the Bohemian Massif domain and Cuesta Region (in the latter generalized as presently under revision and update)
Mapping/Modelling:	A 3D models was constructed (layers and faults) for the Molasse Basin and northern adjoining Franconian Alb (Diepolder & HotLime Team 2020, HotLime 2020), by revision, extension and refinement of pre-existing 3D geological models from GeoMol and a variety of smaller, detailed 3D geological models also considered in mapping the fault network of the Scarpland domain.

3.2.10.4 Structural elements

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 3-20). Four structural domains can be distinguished:

1) The Alps as part of the Alpine-Carpathian orogen that formed during Cretaceous – Cenozoic collision of the Adriatic and European plates. This domain comprises elements of both plates.
2) The Molasse Basin represents a foreland basin along the forefront of the emerging orogenic belt that formed due to the large-scale down warping of the European Plate and which was progressively infilled with 'Molasse' sediments eroded off the northward thrusting Alps during Cenozoic times. Jurassic sedimentary sequences make up the footwall of the, up to 5 km deep, Molasse Basin.
3) The Scarpland (Cuesta Region) is situated north of the Molasse Basin and is characterized cuesta topography with progressively older (Triassic-Jurassic) strata towards the northwest. The lowermost cuesta forming sequence is the Triassic Buntsandstein, which rests upon non-metamorphic Permian sediments in post-Variscan troughs that directly overlie older low-grade to high-grade metamorphic rocks associated with plutonic rocks; both formed during Variscan orogenesis.
4) The Variscan basement, which is made up of three stratigraphic-lithologic-tectonic zones, the Mid-German Crystalline Rise, exposed in a small inlier only, the Anterior Spessart in Bavaria's very northwest, and the Saxothuringian and Moldanubian Zones, exposed in the Bohemian Massif along the Czech border in Bavaria's east (Figure 3-20)).
5) The 14.6 Myr old Ries asteroid impact crater is situated in western Bavaria in the southernmost Cuesta unit, the Swabian-Franconian Alb.

3.2.10.5 Fault characterization and definition

Fault information is given for each domain, except for the Alps:

1) Alps: no fault data provided as currently under revision and update.
2) Molasse Basin: All faults of the Central Molasse Basin are blind and the fault geometries and concepts refer to the fault traces on the top of Upper Jurassic carbonate sequence. The central part of the South German Molasse Basin, is characterized by syn- and anti-thetic normal faults related to flexure-like strain of the foreland basin. Faults predominantly trend subparallel to the basin's centreline and the Alpine Thrust Front. The Lower Bavaria - Upper Austria Molasse Basin fault domain, overlapping the Austrian-German border is dominated by roughly NW-SE trending (Variscan strike) reactivated Permo-Carboniferous faults that subdivide the basin into sub-basins and troughs (Figure 3-21).
   The northern boundary of the Molasse Basin is formed by the Swabian-Franconian Alb fault domain, a SW-NE trending ridge (cuesta) formed by SE dipping Jurassic platform carbonates. The Molasse Basin's southern margin is formed by the Alpine thrust front. 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.
3) Bohemian Massif: 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. 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. 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. 4) 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 3-21) and show indications of multiple extensional and compressional events (graben and horst).

3.2.10.6 Local fault relevance and application

Infrastructure	Radwaste repository see “other”
Geothermal Energy:	Karstified carbonate rocks of the Upper Jurassic at great depth (underneath the Molasse Basin) host central Europe’s most prolific hydrothermal aquifer. Here, synthetic normal faults are the prime target for geothermal E&P (> 25 in operation, 3 presently under development).
Underground energy storage potential:	Several exploited hydrocarbon deposits bound to structural traps of antithetic faults in the Molasse Basin are utilized for underground gas storage to cover the seasonal swing.
Natural seismicity:	Minor and limited to a small area in NE-Bavaria aligned with Eger Graben on Czech territory, whose northern boundary cross-over with Mariánské Lázně Fault Zone (Figure 3-20) forms the hypocentre of Nový Kostel recurrent earthquake swarms. No specific fault (system) in Bavaria can be aligned with this seismicity.
Induced seismicity:	Rare and minor (M_L < 2.5); only a few instances in the Grater Munich Area over the last decade which are under suspicion to be related to deep geothermal reinjection wells.
Hydrocarbon	Antithetic normal faults of the Molasse Basin form structural traps of hydrocarbon deposits exploited in the 1960’s to 1990’s, at present considered mature with only few residuals left. Respective oil and gas fields are mentioned in the vocabulary concepts.
Groundwater	Ubiquitous, all groundwater E&P in bedrock and basement rocks is geared towards intersecting/tapping faults.
Other	Deep-seated faults are a prime criterion for exclusion in the present stage of radwaste repository location search in Germany.

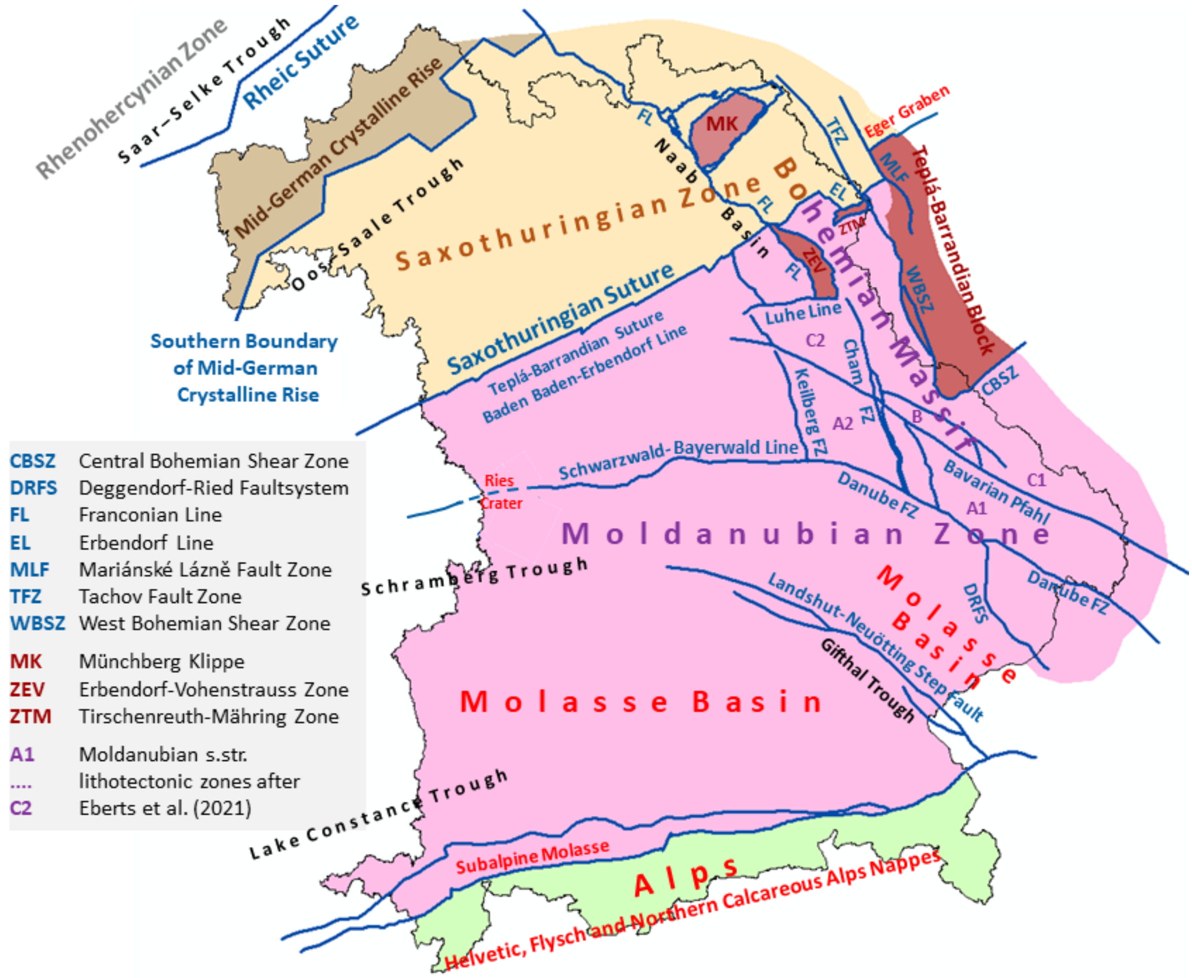

Figure 3-18: Basement units and their limits in Bavaria and eastern adjoining areas (the adjoining areas are shown to elucidate the contextual relation only and are not considered in the FDB or vocabulary). Next to the basement units the map shows limits and principal fault systems as well as Permo-Carboniferous troughs (Variscan molasse), labelled in black, and post-Variscan structures deforming the basement, labelled in red. Most of the Variscan structures have been reactivated in Late Cretaceous and Cenozoic (Saxonian deformation) due to the Alpine orogeny and its distant effects.

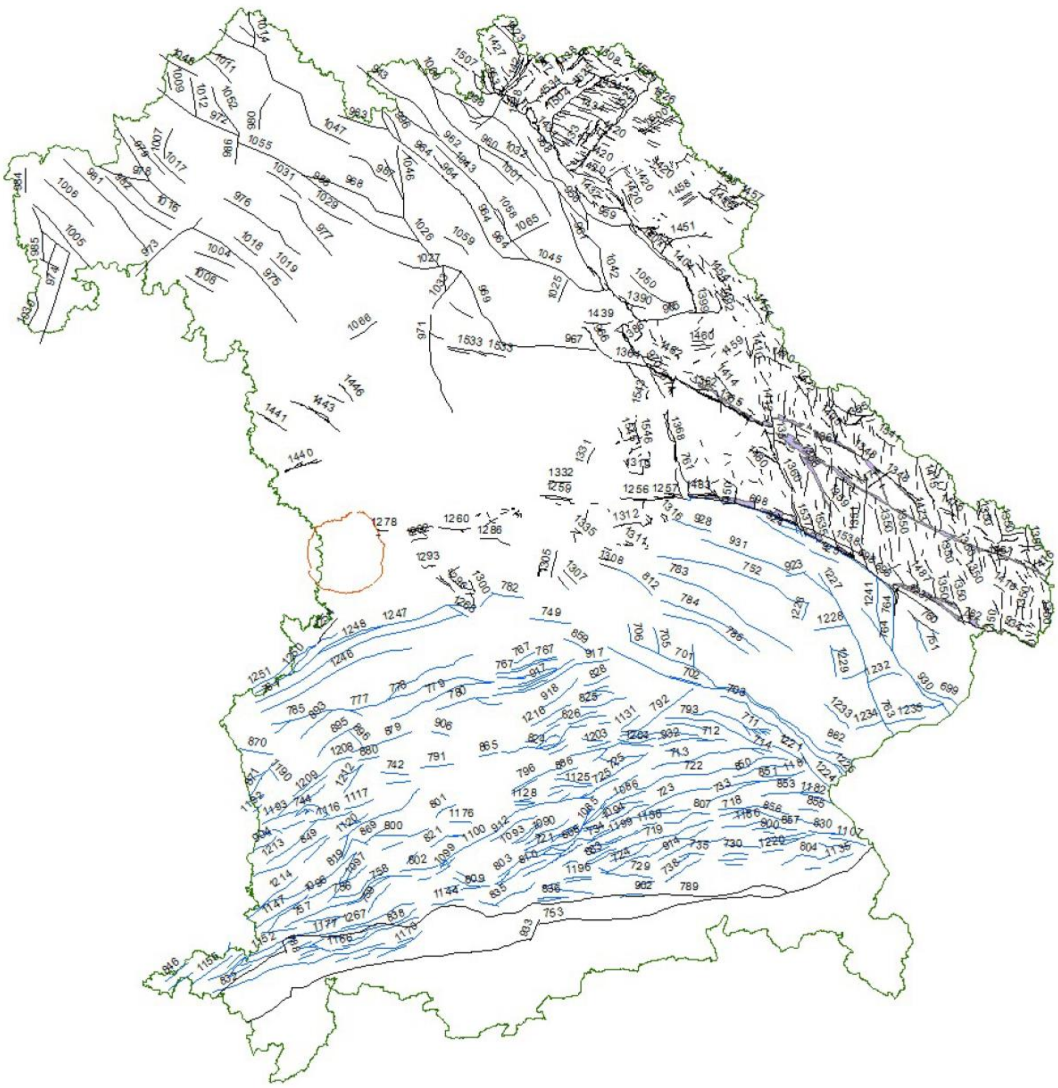

Figure 3-19: Synopsis of the faults and shear zone as stored in and retrievable from the European FDB, and described in the connected vocabulary https://data.geoscience.earth/ncl/geoera/hike/faults/7378. Black: surficial faults, blue: traces of blind faults at the top of Upper Jurassic Molasse Basin footwall, orange: Ries Impact crater rim.

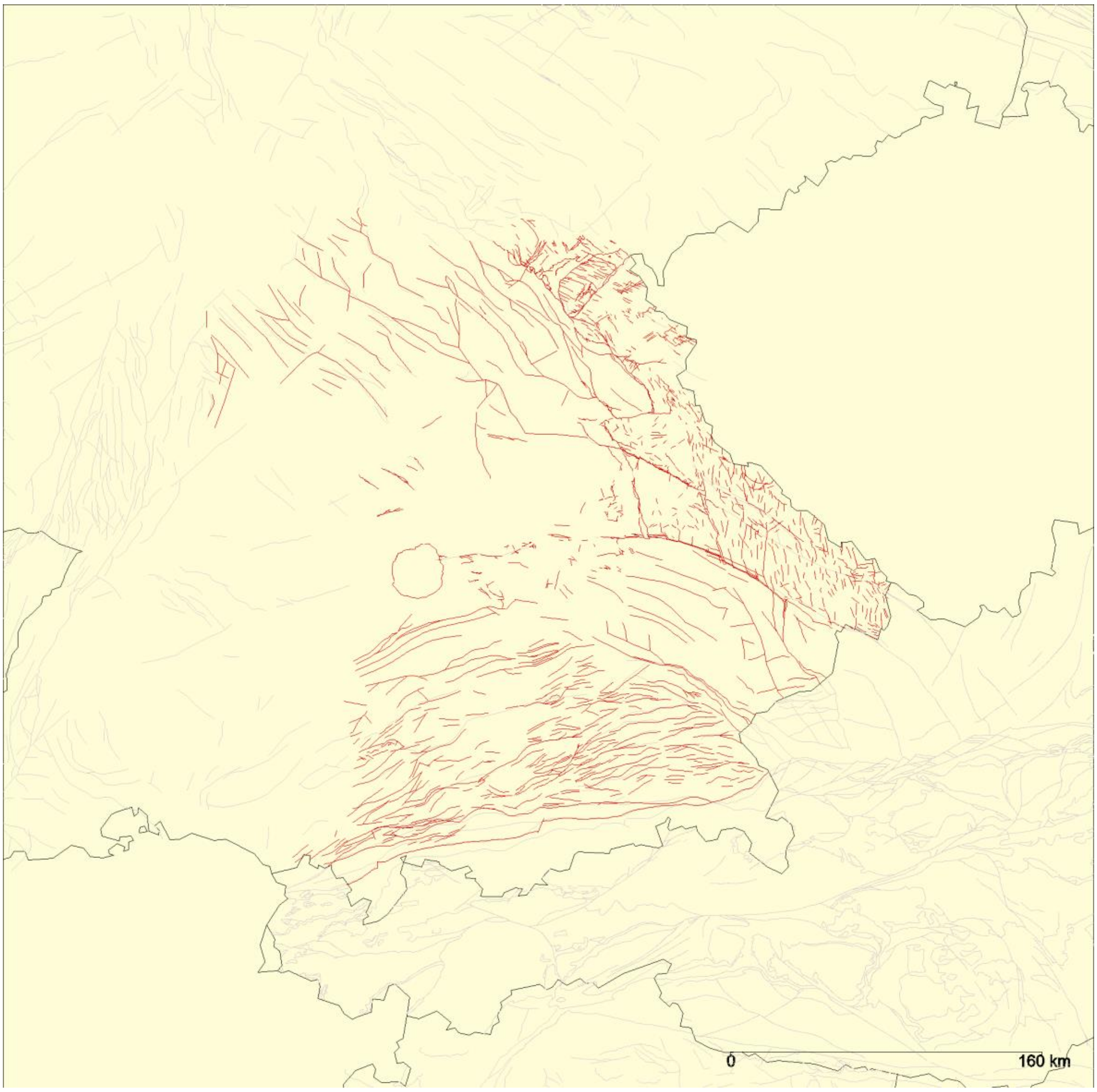

Figure 3-20: Location of mapped national faults and fault systems in the German federal state of Bavaria (red) contributed to the HIKE-FDB. Reference level of the faults is described in Figure 3-19.

3.2.11 Iceland - ISOR

Organization: Date: Author(s)/contact person:	Iceland Geosurvey (ISOR) 2021-03-11 Sigríður Kristjánsdóttir, Albert Þorbergsson

3.2.11.1 Introduction

ISOR is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.11.2 General data metrics and sources

Mapping scale:	National (1:600.000)
Number of faults:	59 faults in vocabulary; 2678 features in database
Geographical coverage:	The dataset covers the active plate boundaries and adjacent areas crossing the island as well as the plate boundary in the southern and northern offshore
Stratigraphic coverage:	Iceland's rock formations predominantly consist of basalt. Most observed fault affect basalts of Quaternary age. The age of the basalt increases away from the active rift axis and can reach up to Miocene (16-17 Ma) in age.
Format:	The faults are represented as 2D lines.

3.2.11.3 Fault data acquisition and mapping

2D/3D seismic:	-
Gravitational and magnetic surveys:	-
Wells:	-
Surface mapping and outcrops:	Faults have been mapped either in the field or by examining aerial photographs. Most faults submitted by ISOR are located close to the plate boundaries. Areas outside the boundaries have not been mapped as extensively and surface features have been eroded by glaciers and weathering. Additionally, the offshore has been mapped within the EMODnet project using primarily seafloor bathymetry.
Mapping/Modelling:	The faults are from the institutes 1:600,000 catalogue.

3.2.11.4 Structural elements

Iceland is a volcanic island located in the North Atlantic. It is forged by the interaction of excessive volcanic activity and plate spreading. Three main types of plate boundaries cross the country, i.e., volcanic rift-zones, transform faults and oblique rifts. Volcanic rift-zones are the surface expression of the North American-Eurasian divergent plate boundary and consist of several large central volcanos that area associated with faults and fissures that are frequently arranged in en-echelon pattern along the axis of the hosting volcanic rift-zone. Transform fault zones are (close to) parallel to the direction of plate spreading and accommodate the offset of the plate boundary that crosses Iceland by faulting oriented

transverse to the zone. Strike-slip faulting is dominant and volcanism insignificant. The oblique rifts are aligned oblique to the direction of spreading resulting in a combination of typical transform tectonics and rifting with volcanism. Both processes show episodic activity but with very different periods.

3.2.11.5 Fault characterization and definition

The main type of structures 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.

3.2.11.6 Local fault relevance and application

Natural seismicity	Natural 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 may occur on pre-existing faults which are re-activated when the built-up stress exceeds the strength of the rock.
Induced seismicity	Induced seismicity is common and exclusively related to the exploitation of geothermal systems.
CO_2 sequestration	A new method for the sequestration of CO_2 has been developed in Iceland within the Carbfix project (www.carbfix.com). A reliable fault database is crucial both for finding suitable faults to pump the fluid into and to estimate hazards due to the injection.
Infrastructure	Fault mapping is used in Iceland to assess hazard for infrastructure such as roads, buildings, electrical lines, and pipelines for hot and cold water. However, the data in the 1:600,000 catalogue from ÍSOR is not detailed enough for this type of assessments.
Geothermal Energy:	Geothermal systems in Iceland are fracture dominated but these fractures are on a much finer scale than what ÍSOR has provided to the HIKE database. There have been some cases where major faults mapped on the surface have served as the target for production or injection of geothermal fluid and some of those are included in the 1:600,000 catalogue from ÍSOR.
Underground energy storage potential:	Not applicable
Hydrocarbon	Not applicable
Groundwater	The faults in the 1:600,000 database provided by ÍSOR have not been used to map groundwater flow.
Other	Not mentioned

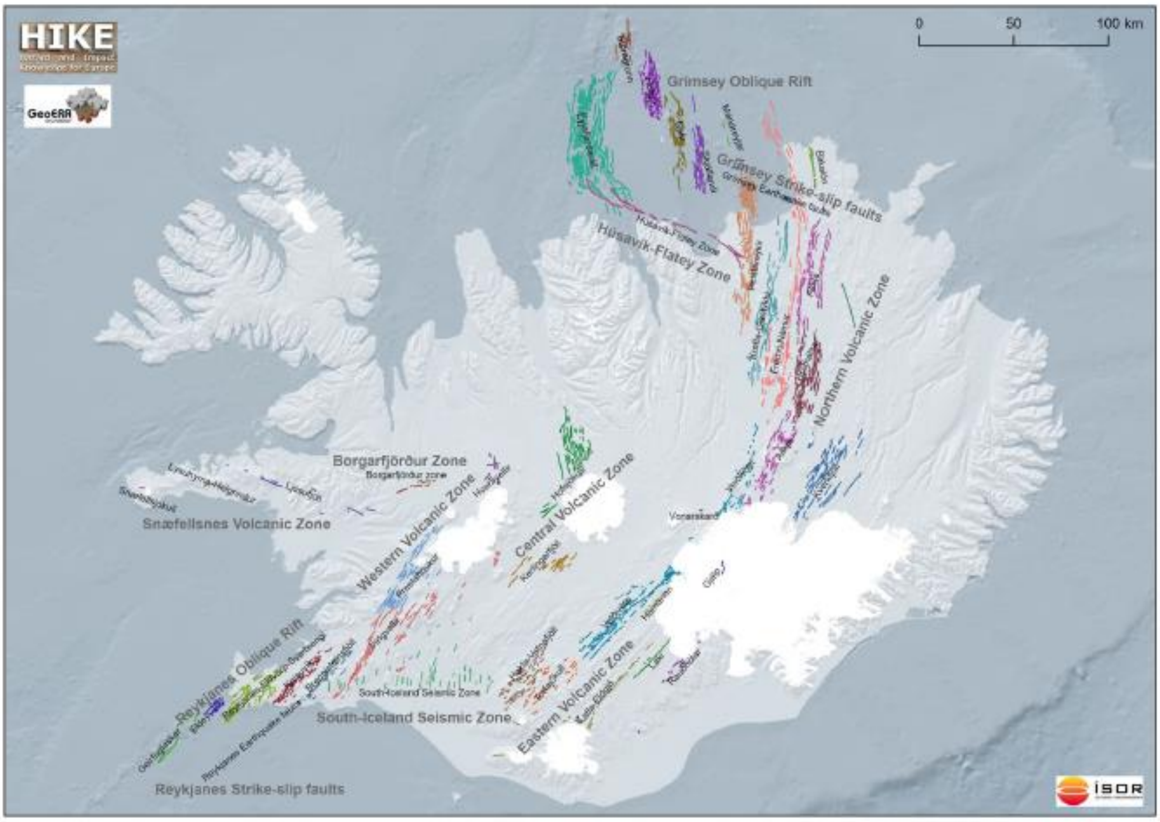

Figure 3-21: Map of the faults and fissures submitted to the HIKE database by ÍSOR including the names of the defined structural elements. Fault and fissure sets which belong to a distinct volcanic systems have the same color

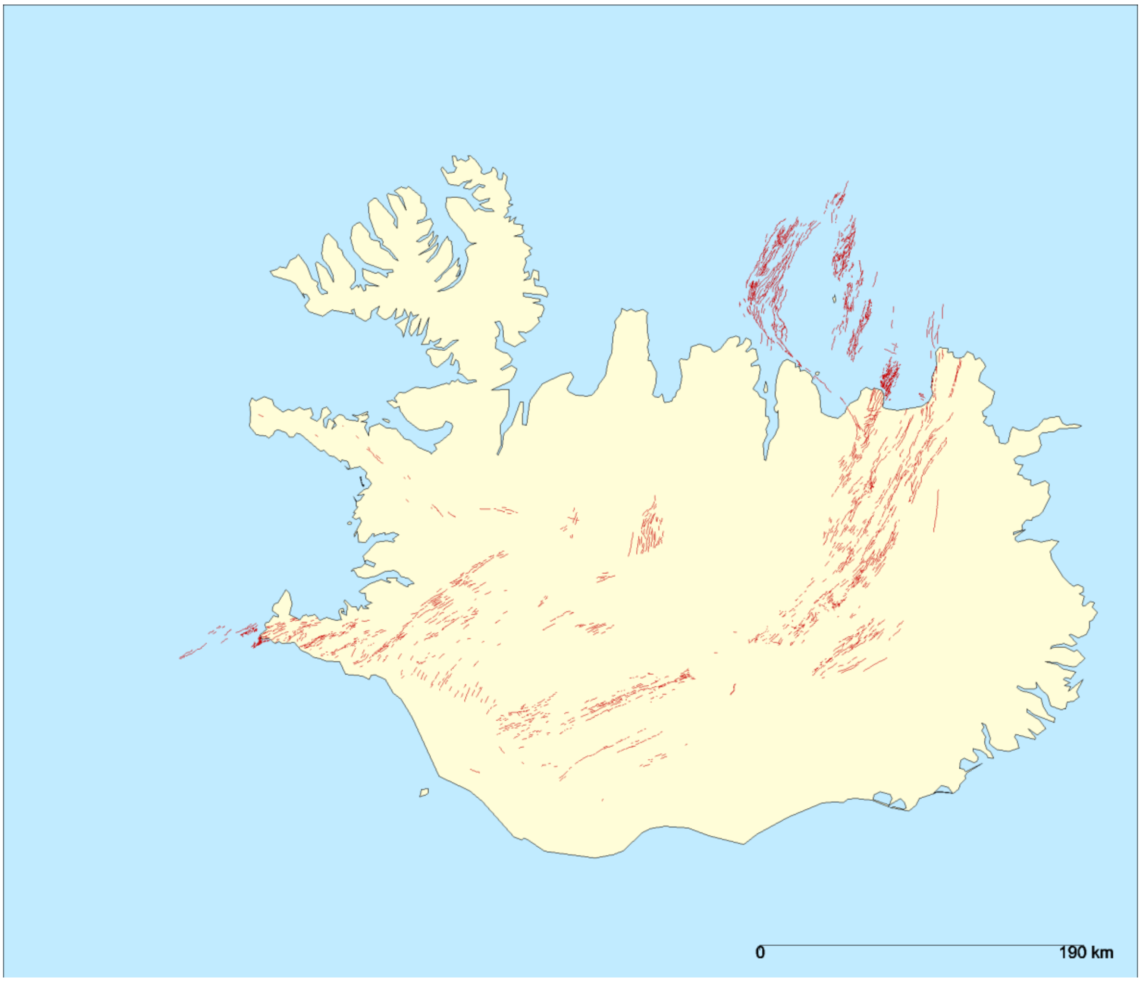

Figure 3-22: Location of mapped national faults and fault systems in Iceland contributed to the HIKE-FDB. All faults are represented at surface level.

3.2.12 Italy - ISPRA

Organization: Date: Author(s)/contact person:	Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) 2021-03-31 Pio Di Manna, Chiara D'Ambrog,; Maria Pia Congi.

3.2.12.1 Introduction

ISPRA is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.12.2 General data metrics and sources

Mapping scale:	National (1:1.000.000) regional (1:50.000)
Number of faults:	272 faults in vocabulary; 4715 features in database
Geographical coverage:	The Italian contribution to the HIKE fault database includes onshore faults only. An extensive overview 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”..
Stratigraphic coverage:	Precambrian to Quaternary
Format:	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 (on request). The major tectonic domains, main fault systems and faults 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 for some faults.

3.2.12.3 Fault data acquisition and mapping

2D/3D seismic:	Predominantly 2D surveys in the Po Plain area
Gravitational and magnetic surveys:	Gravity measurements and derived gravity anomaly maps in the Po Plain
Wells:	Predominantly in the Po Plain
Surface mapping and outcrops:	Especially outside the Po Plain, Sheets of the Geological Mapping Program 1:50,000 were consulted next to papers and thematic scientific publications
Mapping/Modelling:	3D geological models, with particular attention to the Po Plain area.

3.2.12.4 Structural elements

From Precambrian to Recent, numerous plate tectonic events drove and controlled the overall tectonic framework of Italy. On this basis, the Italian territory can be subdivided into the seven tectonic regions that share a common history characterized by multiple tectonic events. From north to south these include: the Alps, the Po Plain, the Apennines, the Apulia and Hyblean foreland, the Calabrian-Peloritan arc, and 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. In the other parts of Italy, the Variscan orogeny has been overprinted by the Alpine orogeny. The Alps 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. 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 African Plate (Adria promontory or Adria microplate). 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. 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.

3.2.12.5 Fault characterization and definition

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. 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 neighbouring countries (in particular Slovenia). 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.) Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.12.6 Local fault relevance and application

Infrastructure	Urban planning and critical facilities siting (dams; regasification power plant; nuclear waste repository, etc.)
Geothermal energy	Geothermal plants in the Po Plain and along the Tyrrhenian coast and in the main volcanic areas
Underground energy storage potential:	Storage of gas and oil takes place in the Po Plain
Natural seismicity:	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. 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
Induced seismicity:	Evaluation of the potential interaction between faults traces and the location of anthropogenic seismic-relevant activities.
Hydrocarbons EP	Oil and Gas exploration and production predominantly in the Po Plain, in the Southern Apennines and Sicily
Groundwater	Faults are key elements in the geological modelling supporting the groundwater exploration since they can represent a barrier or an easy to flow way for water, acting for the groundwater compartmentalisation.
Other?	Faults can play a relevant role in the diffusion of pollutants in the environment from natural or artificial reservoirs. In addition, active offshore faults and /or inland faults not far from the coast could represent a source of tsunami.

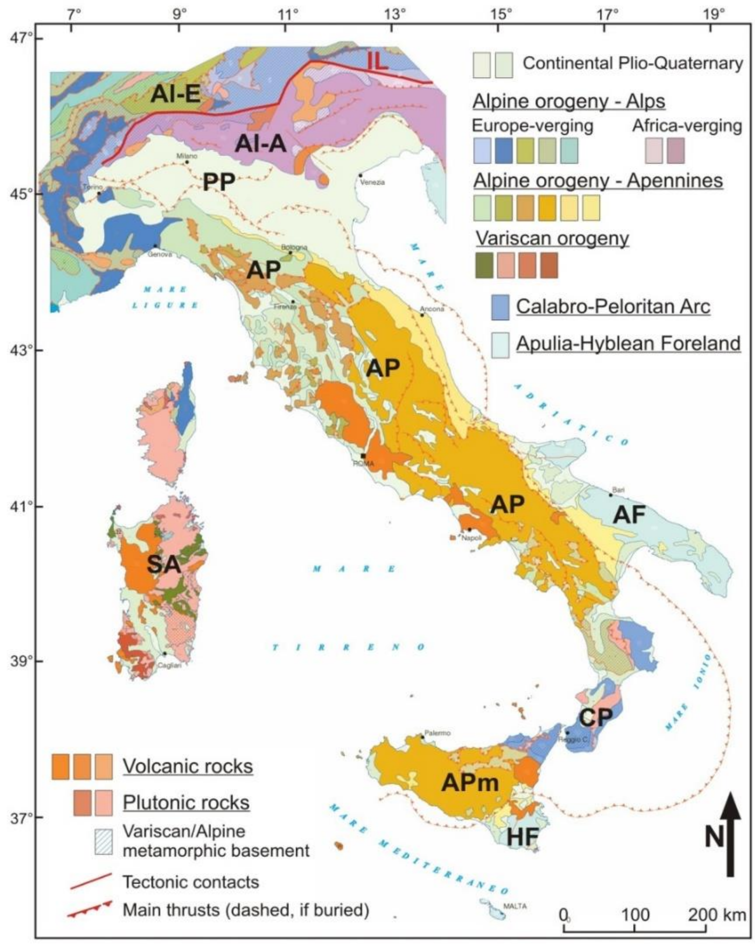

Figure 3-23: Tectonic regions of Italy (modified after ISPRA, 2011). AI = Alpine orogeny (AI-E = Europe vergent domain, AI-A = Africa vergent domain); PP = Po Plain; AP = Apennines; AF = Apulia Foreland; HF = Hyblean Foreland; APm = Apennines - Maghrebides; CP = Calabride-Peloritan arc Domain; SA = Sardinia".

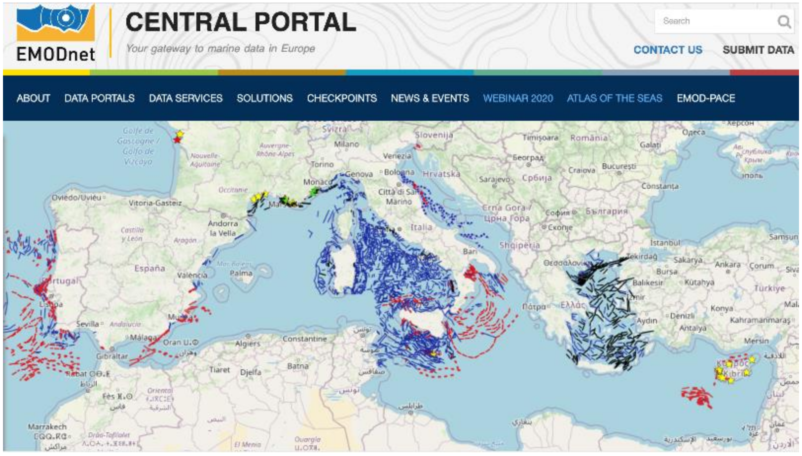

Figure 3-24: Screen shot of the EMODnet web portal showing the Tectonics lines mapped in the Mediterranean Sea

Figure 3-25: Location of mapped national faults and fault systems in Italy contributed to the HIKE-FDB. Faults are represented at surface level.

3.2.13 *Lithuania - LGT*

Organization: Date: Author(s)/contact person:	Geological Survey of Lithuania (LGT) 2021-03-04 Jurga Lazauskienė, Gintarė Andriuškevičienė, Artūras Baliukevičius

3.2.13.1 Introduction

LGT is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.13.2 General data metrics and sources

Mapping scale:	National (1:500.000)
Number of faults:	22 faults in vocabulary; 102 features in database
Geographical coverage:	Nation-wide with strong regional variations in data density and detail. Sparse fault information in central and eastern parts due to lack of seismic data and well data.
Stratigraphic coverage:	Predominantly subdivided in deep crystalline basement faults (Precambrian) and faults cross-cutting the younger (Paleozoic – up till Carboniferous) sediment cover.
Format:	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 neighbouring 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.)

3.2.13.3 Fault data acquisition and mapping

2D/3D seismic:	Predominantly 2D and some 3D surveys in western part of Lithuania within hydrocarbon (HC) exploration and production licenses (area where sediment cover is thickest)
Gravitational and magnetic surveys:	Covering entire country, used for mapping major fault lineaments in crystalline basement
Wells:	Southern (iron ore exploration/mapping) and western margins of Lithuania (HC exploration). In the central parts of Lithuania deep well data is rather sparse
Surface mapping and outcrops:	Not mentioned. Faults mostly covered by undisturbed Mesozoic, Cenozoic and Quaternary cover
Mapping/Modelling:	All available not confidential fault data from the deep wells, national geological mapping programs, industrial reports, scientific publications and the other investigation projects

3.2.13.4 Structural elements

The territory of Lithuania is located in the central part of the Baltic Basin – a Phanerozoic sedimentary basin situated along the western edge of the East European Craton. 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 (Figure 3-28). 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. Annex 1 provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.13.5 Fault characterization and definition

The crystalline basement is strongly dissected by tectonic faulting, with two major types of faults prevailing: i) the oldest Precambrian faults in the crystalline basement which do not dissect the sedimentary cover and ii) faults juxtaposed by younger Phanerozoic features which 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. Within the HIKE fault database (Figure 3-29) 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, the West Lithuanian Fault Domain, the Middle Lithuanian Shear Zone and the East Lithuanian Fault Domain. These major fault domains are hierarchically subdivided into smaller subdomains, fault systems, fault sets, fault chains and individual faults, and subfaults. Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.13.6 Local fault relevance and application

Nuclear waste storage:	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 project 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 and neotectonic activity 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.
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 analysed for their suitability suitable to be considered as prospective.
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.
Induced seismicity:	Tests being conducted to investigate potential effects and intensity from induced seismicity
Infrastructure	Not mentioned
Geothermal energy	The heat flow in Lithuania ranges from 30 mW/m^2 in the East to nearly 100 mW/m^2 in the West Lithuanian geothermal anomaly. Some convective heat transfer in the sedimentary cover and crystalline basement seems to disturb heat flow along some faulted path ways. The largest Middle Proterozioc cratonic Žemaičių Naumiestis intrusion represents prospective HDR geothermal potential; some parts of the intrusion are intensely tectonised. The most prospective parts of the intrusions show subhorizontal foliation with associating subhorizontal fracturing (Šliaupa et al. 2010).
Hydrocarbons EP	Conventional oil exploration and production is predominantly carried out in Western Lithuania. The structural evolution of the area have had a significant impact on formation of the petroleum play. The main oil prospects are related to the late Caledonian NNE-SSW and W-E oriented fault zones associating local uplifts. Most producing oil fields are tectonically screened due to the culmination of late Caledonian time faulting.
Groundwater	The tectonic faults are key factor for Injection type mineral water resources formation in Southern Lithuania. Such type of mineral water is used in resort towns Druskininkai and Birštonas, where detailed geological-hydrogeological investigations were conducted over one hundred years of their exploitation. The faulted zones in the crystalline basement are often indicated by the hydrogeochemical anomalies, pointing to intense vertical migration of the groundwater along the faulted pathways in the southern Lithuania. Druskininkai mineral water springs are related to migration of mineralised water from crystalline basement at the intersection of 3 tectonic zones: Druskininkai zone, the Middle Lithuanian Suture zone and some lower-order NW–SE and NE–SW faults.
Other	Not mentioned

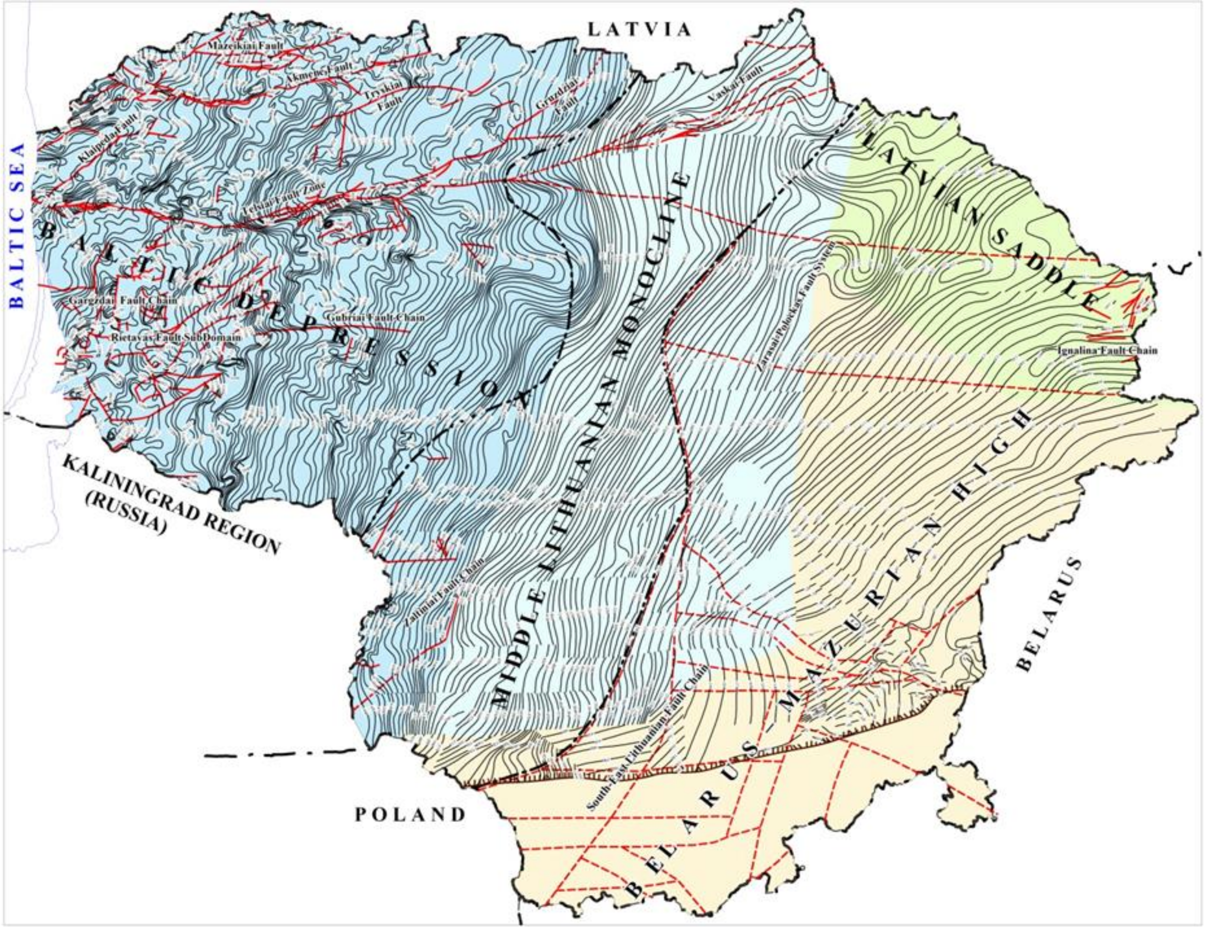

Figure 3-26: Scheme of the distribution of faults and main structural elements of. Red solid and dashed lines indicate the distribution of faults; black lines – isohypses of the base of the Silurian.

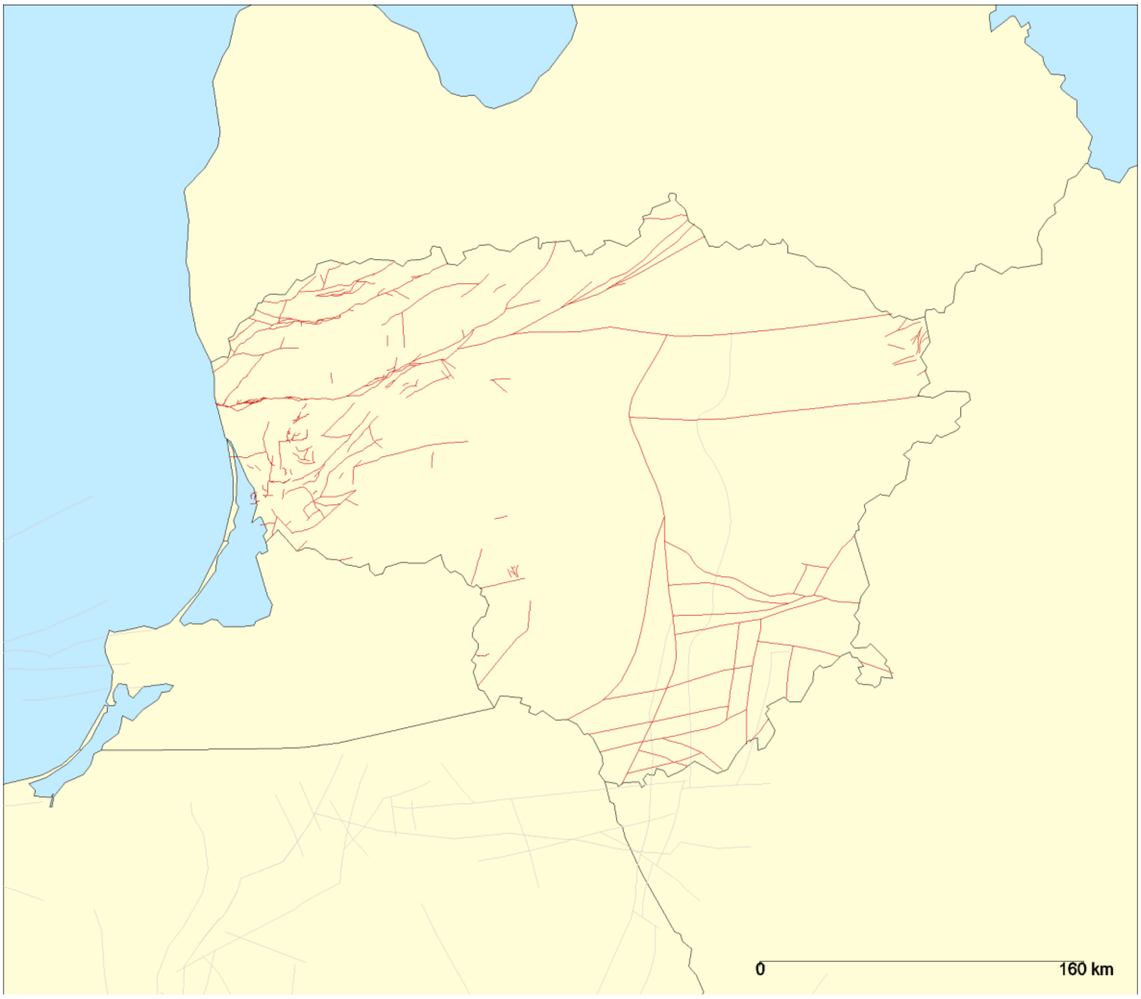

Figure 3-27: Location of mapped national faults and fault systems in Lithuania contributed to the HIKE-FDB. Faults are represented at youngest intersected surface level. The faults for the deep subsurface are delivered as 2D intersection lines and inferred modelling with the oldest (Precambrian) and youngest (Tournaisian) dissected stratigraphic horizons indicated.

3.2.14 Poland – PIG-PIB

Organization: Date: Author(s)/contact person:	Polish Geological Survey (PIG-PIB) 2021-04-01 Marek Jarosiński, Tomasz Gogołek, Urszula Stępień, Ewa Krzemińska, Sylwester Salwa, Ryszard Habryn, Paweł Aleksandrowski, Ewa Szynkaruk, Monika Konieczyńska

3.2.14.1 Introduction

PIG-PIB is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.14.2 General data metrics and sources

Mapping scale:	National (1:1.000.000)
Number of faults:	2711 features in database
Geographical coverage:	Entire territory of Poland
Stratigraphic coverage:	Precambrian to Quaternary
Format:	Geopackage, 2D fault lines at 18 stratigraphic levels (defined in attribute table) from Proterozoic to Cenozoic.

3.2.14.3 Fault data acquisition and mapping

2D/3D seismic:	2D Seismic refraction and deep seismic reflection profiles used for deep crystalline basement. 2D and 3D seismics were used in various mapping projects that were then compiled and generalized for the final HIKE database.
Gravitational and magnetic surveys:	Used for detecting location of faults and deformation zones, primarily in the crystalline basement but also in other areas.
Wells:	Used to assist (match) the interpretation of seismic survey data and as data points in mapping projects.
Surface mapping and outcrops:	Holocene and Pleistocene faults are sometimes recognizable in the surface topography (e.g. height differences, river terraces). Bedrock faults are usually mapped on surface during various serial (e.g. 1:50 000) and non-serial mapping campaigns, where bedrock outcrops.
Mapping/Modelling:	Consistent 3D model of entire country is in preparation. Currently, many faults including those cutting subcropping bedrock, have been identified in various mapping campaigns (both surface and subcrop mapping) at various scales. Some of those are included in the database.

3.2.14.4 Structural elements

One of the most important crustal boundaries of Europe – the Teisseyre-Tornquist zone (TTZ) [or Trans-European Suture Zone (TESZ)], extending from the Baltic Sea in the NW to the Black Sea in the NE, runs diagonally across Poland separating the thick crust of the Precambrian East European Craton to the NE from the thinner crust of the Palaeozoic Platform to the SW. At more detailed scales the lower, consistently discernible level of the present-day tectonic structure of Poland is the post-Variscan domain, where the differentiation of crustal blocks is

best visible. 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. Such decoupling also makes the pattern of fault zones quite different at the Palaeozoic and Mesozoic levels.
Figure 3-30 shows the main tectonic units of Poland which are subdivided in 6 key areas: (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. The thin-skinned structure of the thrust-and-fold belt of the Outer Carpathians is not further discussed in the report..

Annex 1 provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.14.5 Fault characterization and definition

Although nation-wide fault maps are available for entire Poland, only a limited set could be included in the HIKE fault database (north-eastern part, see Figure 3-2). This area is defined as area A in Figure 3-1 and is completely covered by Phanerozoic sedimentary rocks only 0.3–1 km thick in the region of the Mazury–Belarusian antecline (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, magnetotelluric measurements, 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 or CELEBRATION. 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. The fault (or lineament) locations are visible on the maps of the depth to the crystalline basement and the top Neoproterozoic (Fig. 15.2 in Annex 1)

For the EEC area including Mazury region, an integrated gravity and magnetic data modelling was performed along the refraction/wide-angle seismic reflection profile P4 (Fig. 15.3 in Annex 1). 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.

Areas B and C are covered by dense 2D seismic profiles and several 3D seismic surveys, obtained from oil & gas exploration and partially exposed at the surface in the Holy Cross Mts. These data were basis of many geological mapping campaigns that in turn permitted compilation of country-scale fault network presented in detail in Annex 1. In the broadest

sense these two areas comprise faults formed in several tectonic stages along the SW margin of the stable crust of the EEC, that included series of Palaeozoic accretion events (the latest of which was Variscan origeny), followed by the formation of the Permian basin and the Mesozoic Mid-Polish Trough (later inverted to form the Mid-Polish Swell). Faults in areas D and E are either inferred from oils and gas exploration data (seismics and wells), mining data or surface/subsurface mapping. In these parts of Poland Palaeozoic sedimentary rocks and Precambrian crystalline basement partly outcrop at or near surface. Fault patterns are very complex, showing cross-cutting relationships and frequent reactivations as they comprise these older trends overprinted by Mesozoic and Cainozoic events, including Alpine orogeny influence that built the Inner (Area F) and Outer (not discussed here) Carpathian orogenic belt. Annex 1 and the HIKE fault vocabulary provide a detailed description of the faults and tectonic boundary classification.

3.2.14.6 Local fault relevance and application

Infrastructure - construction	not mentioned
Natural Seismicity	Poland is not considered as a seismic country and natural hazards are rather related to surface mass movements like landslides not with natural activation of faults
Induced seismicity	not documented except for mining hazards mentioned below
Geothermal:	not documented
Storage/CCS:	not documented
Injection:	not documented
Groundwater	Occurrences of CO2 gas seeps in groundwater springs due to gas migration along i.a. local faults especially in sub-Carpatians and radon in some parts of Sudety mountains.
Hydrocarbon-E&P	not documented
Mining	Mining hazards related mainly with deep coal mines and coal production influencing natural stress fields. The presence of faults seems to be less important, at least there are no common evidence on increase hazards due to faults occurrences.

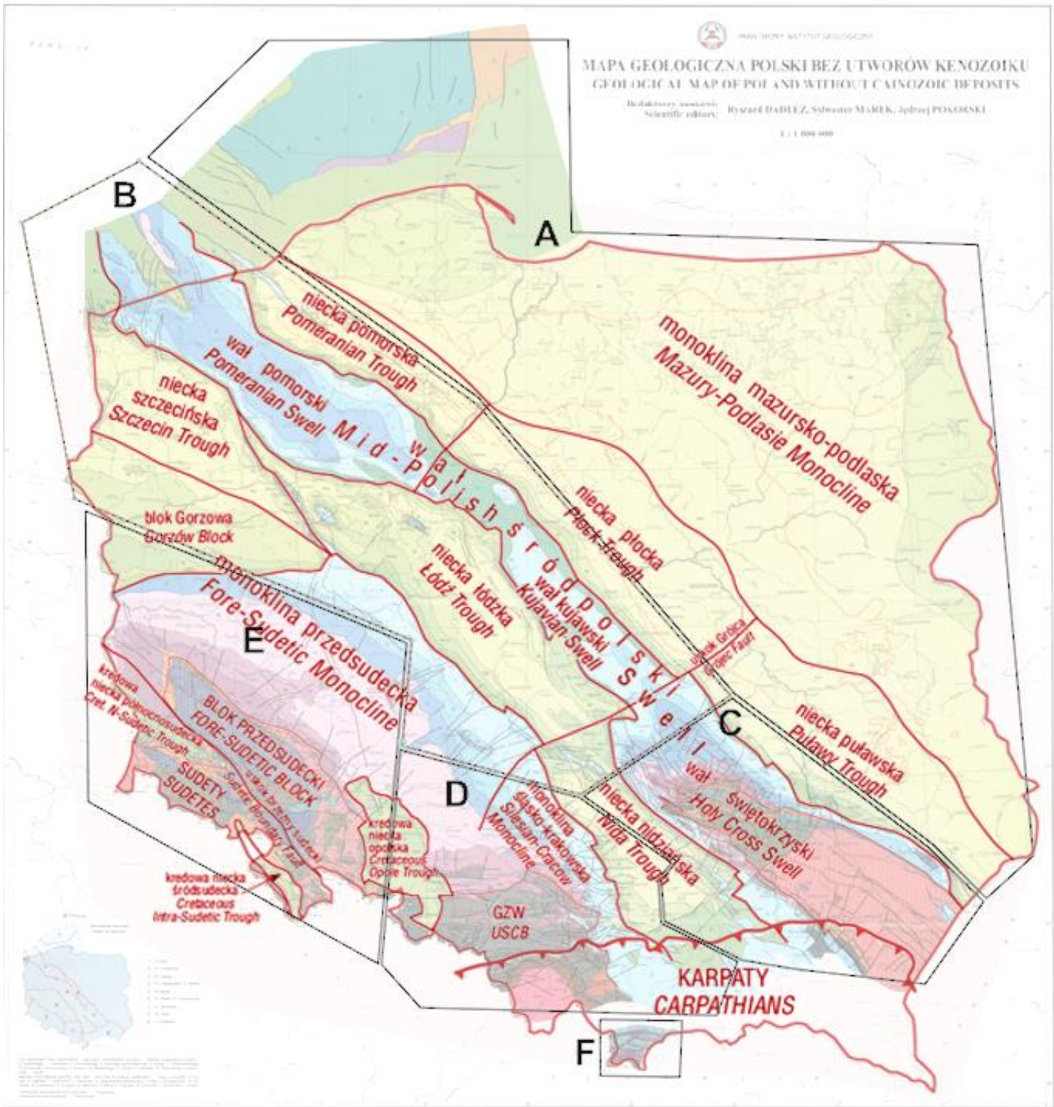

Figure 3-28: The areas (A-F) described within the country report of Poland (Annex 1) displayed on top of the geological map of the sub-Cenozoic complex. In red the conventional structural units designated at the pre-Cenozoic surface, created in the course of the Late Cretaceous inversion of the Polish.

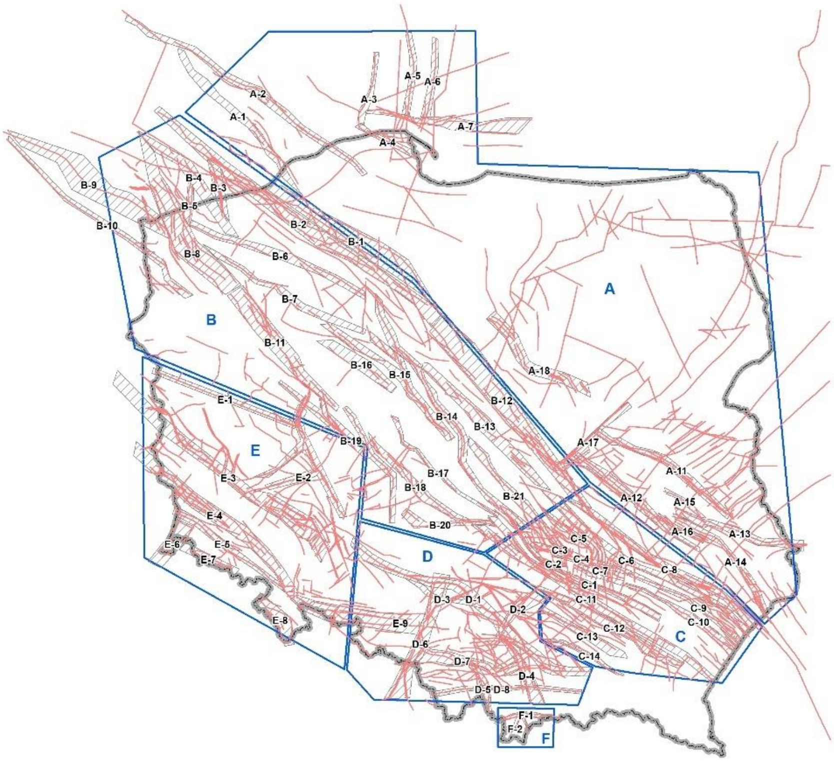

Figure 3-29: Composite map of faults compiled for the HIKE database and presented in the country report. Grey, dashed areas: Major fault zones. Blue areas: territorial subdivision as discussed in country report of Poland (Annex 1).

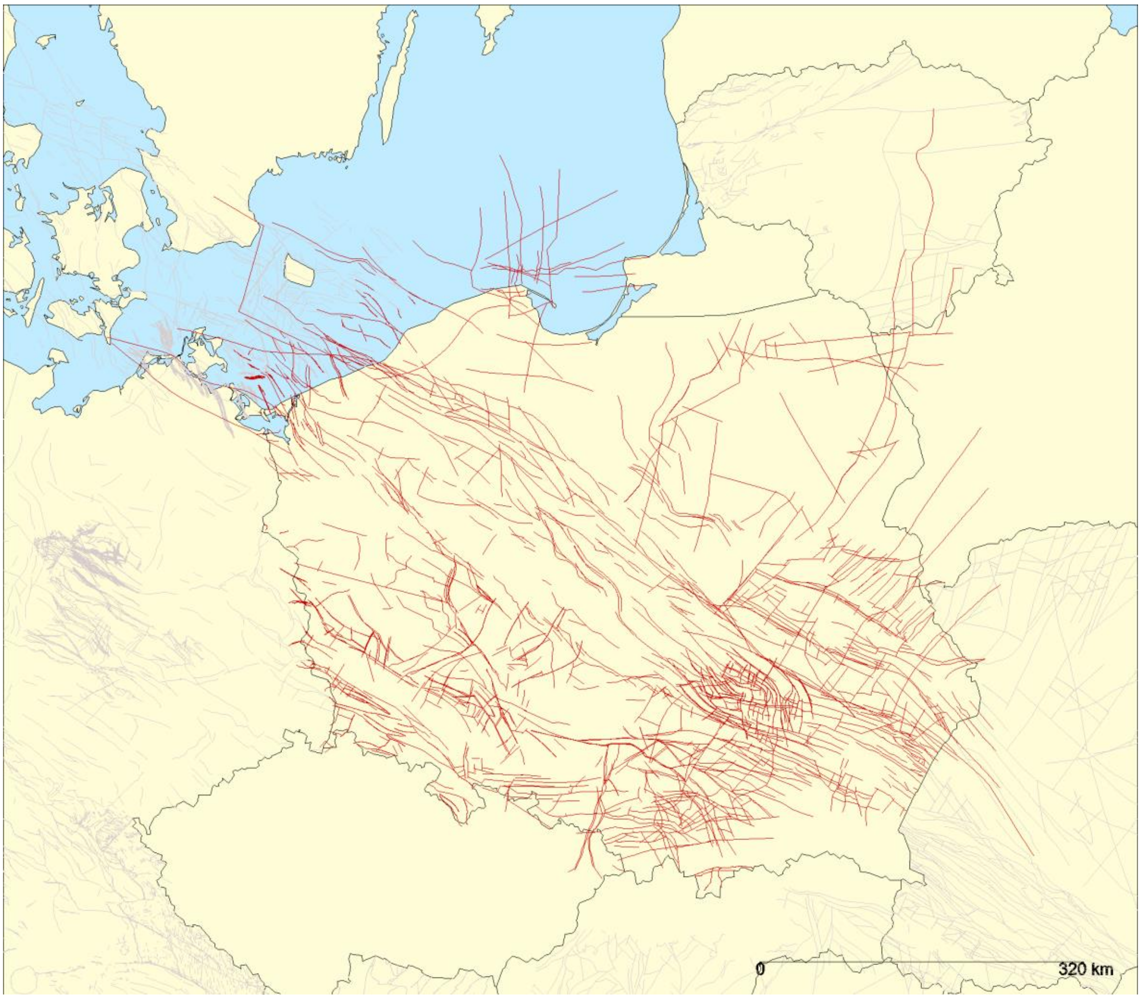

Figure 3-30: Location of national faults and fault systems of Poland as included in the HIKE fault database.

3.2.15 Portugal - LNEG

Organization: Date: Author(s)/contact person:	Laboratório Nacional de Energia e Geologia (LNEG) 2021-03-31 Ricardo Ressurreição, Susana Machado, Catarina Moniz, José Sampaio, Ruben Dias, João Carvalho, Judite Fernandes, Elsa Ramalho e Augusto Filipe

3.2.15.1 Introduction

LNEG is a partner in HIKE and has with contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.15.2 General data metrics and sources

Mapping scale:	National (Portuguese 1: 1 000 000 scale Geological Map), some LNEG published and unpublished geological maps at different scales were consulted
Number of faults:	156 faults in vocabulary; 358 features in database
Geographical coverage:	Nationwide
Stratigraphic coverage:	Precambrium - Cenozoic
Format:	The information made available is the product of recent evaluation and validation according to new advances in scientific knowledge (maps, papers, reports) and adapted to the defined format for the European FDB.

3.2.15.3 Fault data acquisition and mapping

2D/3D seismic:	2D seismic in the Lower Tagus, Alvalade and Algarve basins
Gravitational and magnetic surveys:	Alvalade basin
Wells:	Predominantly in the Meso-Cenozoic basins
Surface mapping and outcrops:	Sheets of the Geological Mapping Program 1: 200.000 and 1: 50.000, were consulted next to papers and thematic scientific publications
Mapping/Modelling:	not used

3.2.15.4 Structural elements

Portugal is situated on the Iberian Peninsula (IP), which was formed during three plate tectonic cycles: the oldest is the Cadomian Cycle, followed by the Variscan Cycle and finally the Alpine cycle. In a vast area of the western part of the IP, deformed rocks of Paleozoic and Proterozoic age constitute the Iberian basement (Hesperic or Iberian Massif) and are representative of the westernmost segment of the European Variscan Chain (Ribeiro, 2013). Many of the brittle and ductile tectonic structures that occur in the Portuguese territory are interpreted as inherited from the Variscan and Cadomian Cycles. Some of the larger ductile structures observed today refer to sutures in the Iberian Variscan basement.

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 possibly inherited from the Cadomian Cycle are some shear zones with reactivation during the Variscan Cycle (Ribeiro, 2013). The Variscan Cycle starts in the Cambrian and ends with the formation of the Pangea supercontinent; it comprises several diachronic phases of variable duration. One of the most striking features is the presence of the Ibero-Armorican Arch, whose arching is continuous over time throughout the Variscan Cycle and witnessed by the strong curving of the structures (Ribeiro, 2013; Dias et al, 2016). It is widely represented in the Iberian Massif. The geodynamic evolution of Portugal during the Mesozoic is dominated by the opening of the Atlantic and Neotethys oceans (Alpine cycle) that led to the fragmentation of Pangea. The major tectono-stratigraphic units that were differentiated in Portugal 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. This new cycle gave rise to newly formed structures and reactivated inherited faults from the Variscan Cycle that were favourably orientated to the new stress field. 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. During the Cenozoic, compression related with the Alpine orogeny promoted tectonic inversion of the major Mesozoic basins.

3.2.15.5 Fault characterization and definition

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 Pyrenean 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 certainty. 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. 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. Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification

3.2.15.6 Local fault relevance and application

Water resources	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. 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.
Geothermal resources	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 act as 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 thermal and geothermal heating.
Infrastructure/ construction	Largest density of population/infrastructure occur in the Lisbon and Oporto areas, with approximately 5 Mi inhabitants. The Lisbon area is close to several active mapped faults, such as Lower Tagus fault zone that includes the Vila Franca de Xira, Azambuja and Pinhal Novo faults.
Natural seismicity:	Portugal mainland has a moderate to low seismicity, typical of a passive margin. However, it is located near the boundary between the Eurasian and African plates. The slow lithospheric deformation that characterizes this geodynamic environment was responsible for some of the largest earthquakes in Europe, generated in intraplate and interplate context. The relation between the seismicity and individual faults is often difficult to establish, and it has been typically classified as a diffuse seismicity. Recent studies identified well-defined seismic clusters and lineations that can be correlated with major fault zones. Neotectonic studies identified several active faults during the Plio-Quaternary, however, with slow slip rates are and long recurrence intervals, such as several mapped faults in the Algarve and Lusitanian basins as well as in the pre-Mesozoic basement.
Induced seismicity:	Unknown
Underground energy storage potential:	Salt layers in the Lusitanian and Algarve Basins are under study
Hydrocarbons EP	Oil Exploration exists in the Algarve Basin offshore and Lusitanian basin onshore and offshore
Other?	CO_2 storage potential in Lusitanian Basin and Sines regions

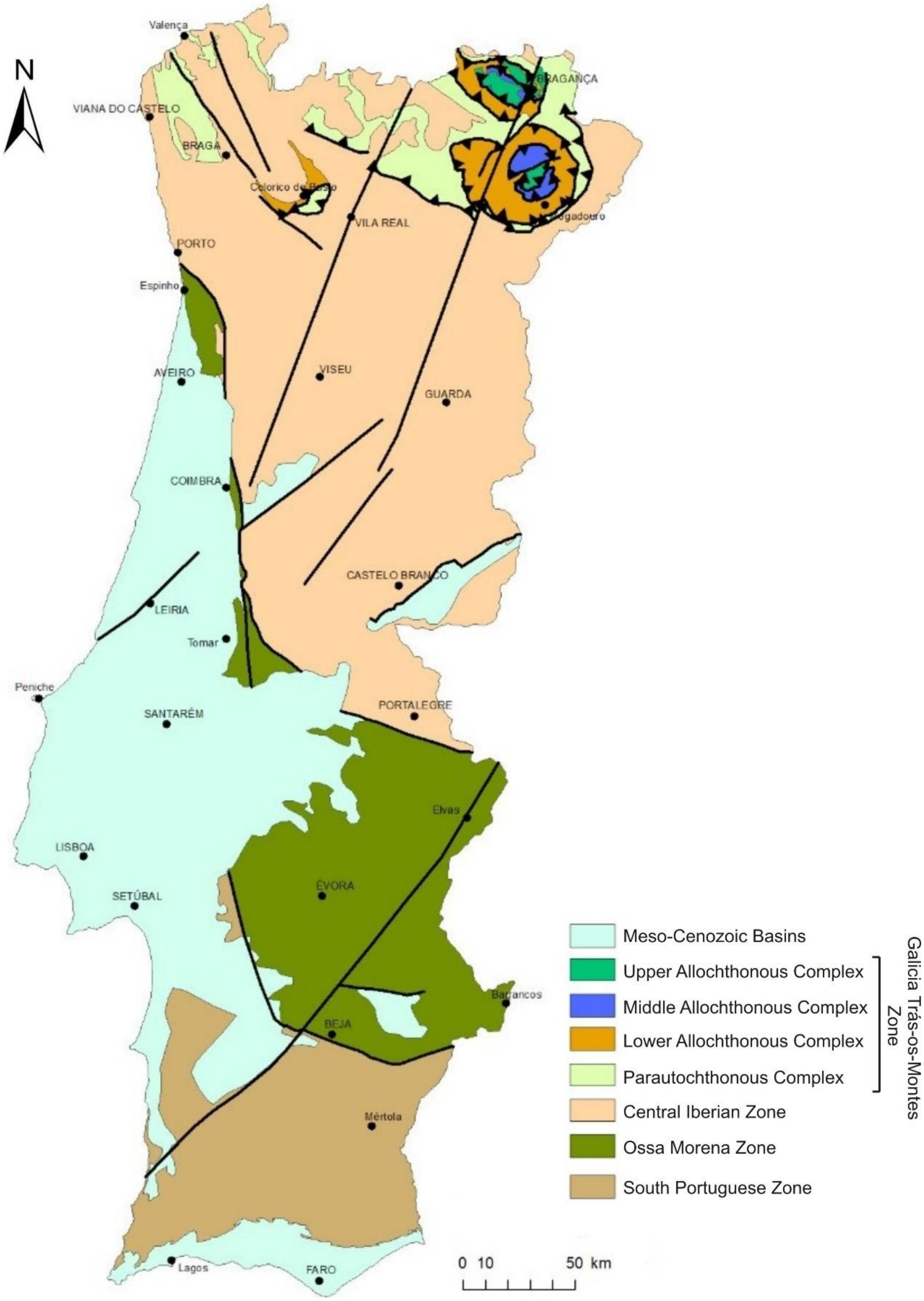

Figure 3-31: Major tectono-stratigraphic domains of Portugal mainland

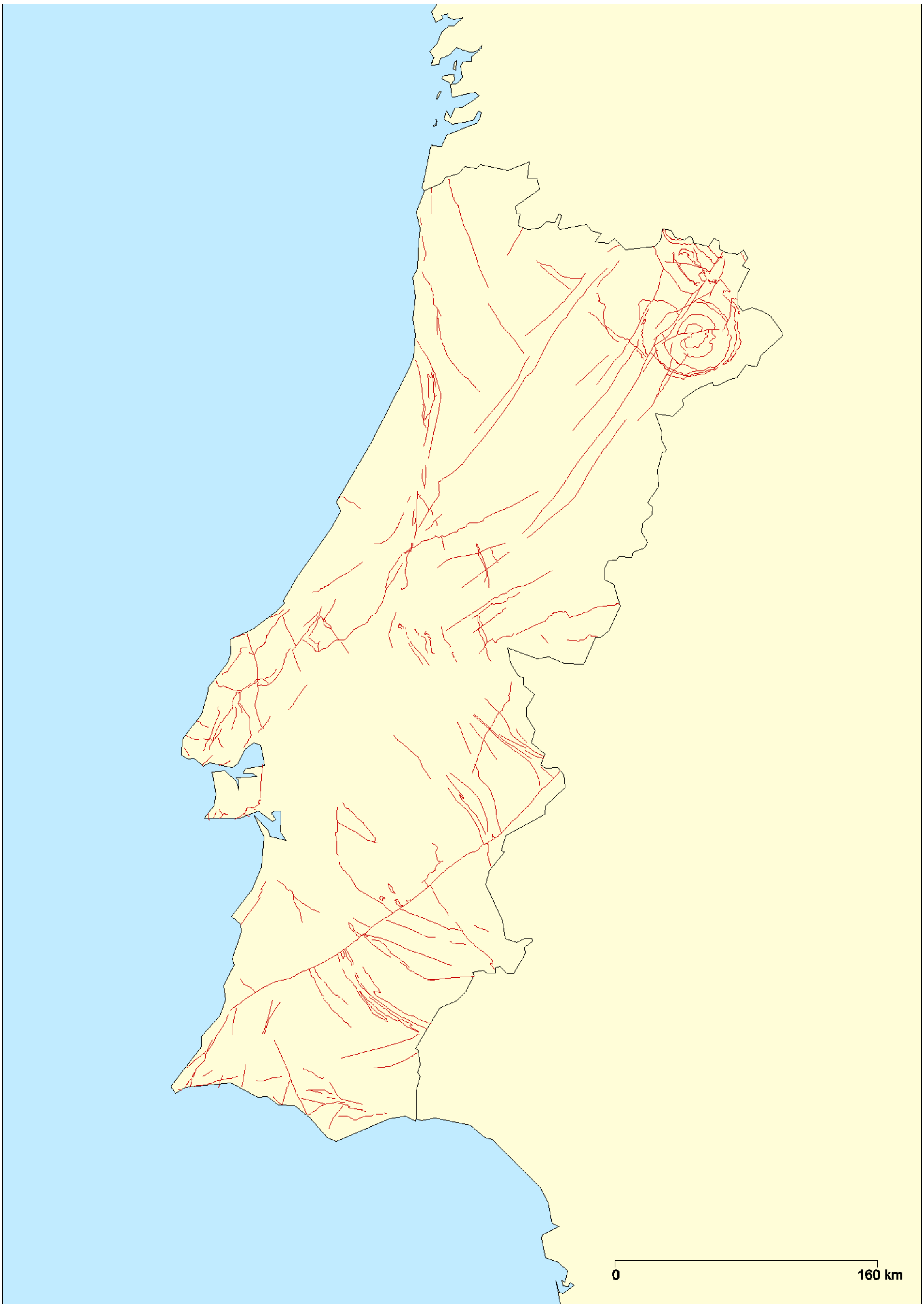

Figure 3-32: Faults in mainland Portugal contributed to the HIKE-FDB. Faults represented at surface level

3.2.16 Slovenia - GeoZS

Organization: Date: Author(s)/contact person:	Geological Survey of Slovenia (GeoZS) Geološki zavod Slovenije 2021-03-23 Bogomir Celarc, Jure Atanackov, Petra Jamšek Rupnik

3.2.16.1 Introduction

GeoZS is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.16.2 General data metrics and sources

Mapping scale:	National (1:250.000)
Number of faults:	48 faults in vocabulary; 84 features in database
Geographical coverage:	Nation-wide with strong regional variations in data density and detail. Sparse fault information in central and eastern parts due to lack of seismic data and well data.
Stratigraphic coverage:	The oldest faults included in the Slovenian HIKE database originate from Triassic rifting phase. Further two distinct thrust and fold belts are formed during Cenozoic: the Paleogene Dinaric Thrust and Fold Belt and the Miocene South Alpine Thrust and Fold Belt, which are cut and displaced by Dinaric Fault system of strike-slip faults.
Format:	The faults are delivered as 2D lines mapped at the surface and/or in the subsurface during mining activities and partially with wells. The faults, fault systems, thrust and fold belts and fault sets are classified according to the generic 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.

3.2.16.3 Fault data acquisition and mapping

2D/3D seismic:	Deep 2D surveys in northeastern part of Slovenia within hydrocarbon exploration and production licenses.
Gravitational and magnetic surveys:	Gravity data are available for the Krško Basin and the Ljubljana Basin.
Wells:	Most of the wells are located in northeastern part of Slovenia (HC exploration). In other parts of Slovenia well data is very sparse. Some wells were used for fault mapping, either directly or indirectly.
Surface mapping and outcrops:	Systematic geological mapping was executed in 60s-70s and some detailed mapping with published maps in certain areas. 250.000 scale map (Figure 3-35), is derived from basic Geological map at 100.000 scale.

Mapping/Modelling:	Database of faults, which were active in Quaternary: a compilation of all available data from maps, papers and reports. Older faults are summarized from structural-geological maps.

3.2.16.4 Structural elements

Structural elements and tectonic subdivision in Slovenia follow strong tectonic and paleoenvironmental boundaries. While secondary tectonically-controlled or induced features exist in Paleozoic rocks, including lower Carboniferous flysch, little contemporary faulting is preserved (Figure 3-35). The first major structural elements formed during the Middle-Triassic (Ladinian) as extensional faulting, locally known as the Idrija tectonic phase, the normal faulting (Idrija Triassic Fault Set) is preserved in western Slovenia.

The next tectonic phase that produced a widespread structural imprint is the Paleogene top-to-SW thrusting during the 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 active Adriatic-Apulian Foreland Thrust System at its outer edge.

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. It becomes less distinct in central Slovenia, where it is partly covered with Cenozoic and Quaternary sediments. Part of the active Friuli Domain of the South Alpine Thrust and Fold Belt also extends to Slovenia. The South Alpine and External Dinaric Thrust and Fold Belt is in Slovenia cut and displaced by Dinaric Fault System, represented by NW-SE striking dextral strike-slip faults.

Periadriatic Fault System and the Mid-Hungarian-Balaton Fault System are in Slovenia part of the Canavese-Tonale-Periadriatic-Mid-Hungarian Large-scale Fault System. In the eastern Slovenia, there are two other important fault systems: Raba Fault System and Pöls-Lavanttal Fault System.

Annex 1 provides a detailed description of the structural element characteristics and tectonic evolution.

3.2.16.5 Fault characterization and definition

Within the HIKE fault database (Figure 3-36) ten major features have been distinguished in the territory of Slovenia: one Triassic fault set, four main Cenozoic thrust and fold belts and five active strike-slip or transpressive fault systems.

<u>Idrija Triassic Fault Set</u>: The oldest well-preserved and systematically mapped faults in Slovenia are formed during the Mesozoic (Triassic) rifting phase with the break-up of Pangea. The Idrija tectonic phase consists of steep-dipping normal faults, E-W striking and forms four distinct fault (sub)-sets.

<u>External Dinaric Thrust and Fold Belt:</u> The formation of this thrust and fold belt is associated with the convergent motion of the Adria microplate towards the Pannonian Domain, with thrust facing the Adriatic foreland. The External Dinaric Thrust and Fold Belt includes 4 thrusts.

The <u>South Alpine Thrust and Fold Belt</u> comprises top-to-S thrusts, nappes and folds formed in the early Neogene. It deforms and folds the External Dinarides Thrust Belt. Seven major thrusts are recognized. It continues to the west into Italy, where it is confirmed active and seismogenic as the <u>Friuli Domain</u>, that comprises a number of active south-vergent thrusts and reverse faults.

<u>Adriatic-Apulian Foreland Thrust System</u> 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.

Dinaric Fault System consists of numerous NW-SE striking dextral strike-slip faults in western and central Slovenia. Several dominant faults of this system were confirmed active. 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 and several reverse faults. 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. Raba Fault System is also partially represented in Slovenia. One potentially active fault, with little actual evidence of activity, is attributed to this fault system. Pöls-Lavanttal Fault System is in Slovenia represented by the dominant and active Labot Fault which continues in Austria as Lavanttal Fault. Annex 1 and the HIKE fault database provide a detailed description of the faults and tectonic boundary classification.

3.2.16.6 Local fault relevance and application

Nuclear waste storage:	Investigations for nuclear infrastructure (low- and intermediate-level nuclear waste repository) have been executed within the Krško Basin.
Underground energy storage potential:	No activity
Natural seismicity:	Slovenia is a region of moderate seismicity, with earthquakes of M~2-3 occurring on average every year, and a number of damaging and several destructive historic earthquakes. The historic record spans approximately 1000 years and includes several major events (magnitudes up to Mw ~7.0). Active fault database supports the national and European seismic hazard assessment efforts. Majority of faults included in Slovenian fault database (except for the Idrija Triassic Fault Set, the External Dinaric Thrust and Fold Belt and most of the South Alpine Thrust and Fold Belt) are considered or confirmed as active through the Quaternary and potential earthquake sources.
Induced seismicity:	No known cases.
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 (of the Dinaric Fault System, the Periadriatic Fault System and the Mid-Hungarian Fault System). 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.
Construction:	Important power and transport infrastructure intersect significant active faults. The faults of the Adriatic-Apulian Foreland Thrust System intersect the A1 highway, one major viaduct as well as the tunnels and bridges for the new Second Track of Divača-Koper line. The A1 highway is also intersected by all large regional faults of the Dinaric Fault System.

	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.
Mining:	Faulting related to the Idrija fault has been mapped within the Idrija mercury mine. Structural control of the mercury deposit by the Idrija fault was critical in the development of the mine and planning of exploitation. The lignite coal seam in the Velenje coal mine is structurally modified (offset, faulted) by the regional Šoštanj fault and the entire local transtensional sedimentary basin that contains the coal seam is controlled by the Šoštanj fault. The brown coal seam of the Hrastnik coal mine is displaced by the Hrastnik fault.
Hydrocarbon EP	Ljutomer Fault and associated folds, part of the Mid-Hungarian-Balaton Fault System represent potential structural traps for hydrocarbons.
Groundwater	Some faults, particularly thrust faults are important in the aspect of ground water reservoir potential and determination of the ground water flow direction.

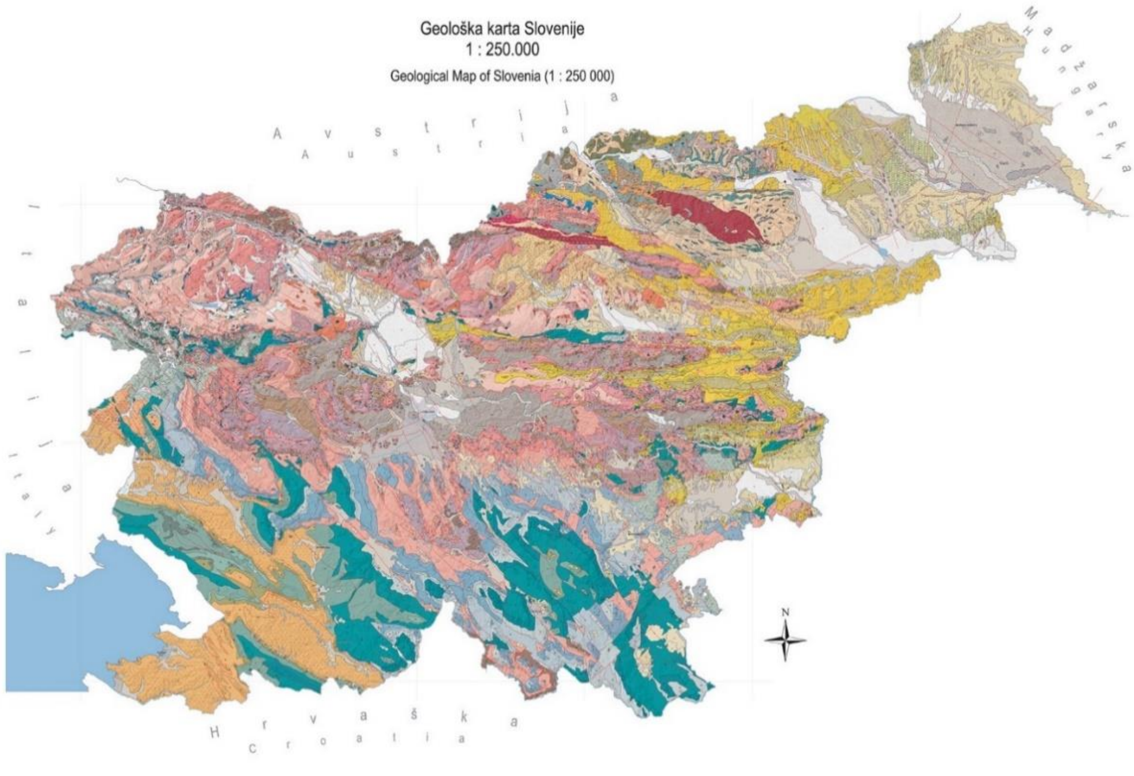

Figure 3-33: Geological map of Slovenia.

Figure 3-34: Slovenian faults included in HIKE database. Faults are represented either at surface or subsurface level.

3.2.17 Ukraine - GeoInform

Organization: Date: Author(s)/contact person:	GEOINFORM (GBA) 2021-03-23 Alexandr Shevchenko, Igor Melnyk, Alisa Lapshyna

3.2.17.1 Introduction

GEOINFORM is a partner in HIKE and has contributed national-scale fault information to the HIKE Fault Database for the entire extent of the country. Annex 1 provides further geological background related to the fault data. This country fact sheet summarizes the key characteristics on the origins and geological relevance of fault information.

3.2.17.2 General data metrics and sources

Mapping scale:	National (1:1.000.000)
Number of faults:	272 faults in vocabulary; 4715 features in database
Geographical coverage:	Ukraine's contribution to the HIKE fault database includes only those faults shown on a 1: 1,000,000 scale tectonic map of Ukraine issued by UkrDGRI in 2007 (editor-in-chief S. Kruglov). Faults regional and buried (DDZ, foundation of Carpathian folded structure, Scythian plate, north-western shelf of the Black Sea, etc.) were not included in the HIKE project database.
Stratigraphic coverage:	The formation of faults and fault zones in different regions of Ukraine covers the age of Precambrium to Quaternary
Format:	Faults included in the database are represented in the form of two-dimensional lines that show the reliable position of faults on the surface (by direct observations) or (mostly) probable (by interpretation of geophysical data) in areas covered by sedimentary rocks. The main tectonic taxa, dominant fault zones and faults have a classification that corresponds to the semantic structure of the HIKE project. Fault attributes are limited mainly by geometric parameters (length, direction of extension), kinematics, method of observation and assessment of significance.

3.2.17.3 Fault data acquisition and mapping

2D/3D seismic:	Faults in the structures covered by the sedimentary cover were detected by seismic surveys (mainly in the areas of hydrocarbon accumulation - DDZ, Carpathian region, Black Sea shelf). Due to scientific research of the earth's crust by the system of geophysical seismic profiles (common depth point (CDP) method), deep faults were studied, which play a leading role in the selection of tectonic regions of Ukraine.
Gravitational and magnetic surveys:	According to gravitational and magnetic observations, the vast majority of faults within the shallow occurrence of the crystalline basement (USh and its slopes, Voronezh crystalline massif) have been identified.

Wells:	Data on wells were used to map faults in different tectonic regions of Ukraine, primarily in sedimentary cover.
Surface mapping and outcrops:	Sheets of the state geological map of scale 1: 200.000 were used, which became the basis for compiling the Tectonic map of Ukraine.
Mapping/Modelling:	Modelling wasn’t used

3.2.17.4 Structural elements

The long history of tectonic evolution of the Earth's crust (over 3.8 billion years) and the zone of articulation of the southwestern flank of the Eastern European Platform (SEP) with bordered structures Hercinid (Variscid) and further - with Alpine-Cimmerian seismically active mountain structures of the Carpathians processes of formation of the earth's crust are still going on in our time, caused a complex tectonic structure of the territory of Ukraine. Figure 3-37 shows a simplified scheme of tectonic zoning of Ukraine, where from west to east stand out: Carpathian folded structure (1-3), structures of the Western European platform (4), Volyn-Podilska plate (5), Ukrainian shield (6), Dnieper-Donetsk depression (7), Voronezh crystalline massif (8), in the south - Folded Donbass (9), South Ukrainian monoclinal (10), Scythian plate (11) and Folded structure of the Mountain Crimea (12). There are two types of folded foundation for sedimentary covers in the platform areas: the first type is a crystalline foundation composed of intensively dislocated metamorphic, ultrametamorphic and intrusive complexes of archaean-paleoproterozoic (EPS structures, western segment of the Scythian plate); 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), Riphean-Jurassic (Scythian plate), Riphean-Upper Triassic.

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

3.2.17.5 Fault characterization and definition

Database faults are grouped according to the hierarchy proposed by the HIKE project concept. The main criterion for the distribution of faults is that they are confined to the relevant tectonic region with a clearly defined geological history and tectonic evolution, the special nature of the fault pattern and their spatial distribution. All faults in the database are divided into 8 groups that belong to a certain structural element. The main faults and fault zones are classified according to the general semantic structure of HIKE.

Unfortunately, the issue of harmonization of the faults of the database presented by Ukraine with the faults of neighbouring countries (first of all, Poland, Hungary, Romania) has not been resolved yet. Attribute tables of faults are still limited by geometric aspects (length, direction of extension), type of fault (main, secondary), its morphology (normal, reset, tilt, thrust, etc.) and the method of observation / evaluation (interpretation of seismic, gravel-magnetic data and etc.)

The № # application and the HIKE fault database contain a more detailed description of the faults and a description of the tectonic regions. (Annex № # refers to our explanatory note).

3.2.17.6 Local fault relevance and application

Infrastructure	Not mentioned
Natural seismicity:	Seismically active regions of Ukraine (Carpathian and Crimean regions) are associated with the geodynamic evolution of the Mediterranean mobile belt. The study of faults in these areas in combination with other data (geomorphological observations, points and foci of earthquakes, earthquake intensity, etc.) is relevant in terms of detecting active and passive tectonic faults and preventing the dangers associated with these natural phenomena.
Induced seismicity	Not mentioned
Hydrocarbons	Local faults play a leading role in the formation of structural traps for hydrocarbon deposits in the DDZ, the Carpathian region, etc.
Hydrothermal	Hydrothermal waters are concentrated in Ukraine mainly in the Transcarpathian region, where they are associated with Miocene-Pliocene volcanism, as well as in the south of Ukraine, mainly in the Khersonska region. Local faults play a role in the spread and localization of thermal spring deposits.
Geothermal	Not mentioned
Groundwater	Within the US, the vast majority of drinking groundwater is concentrated in aquifers of fractured crystalline rocks, which are controlled by local faults.

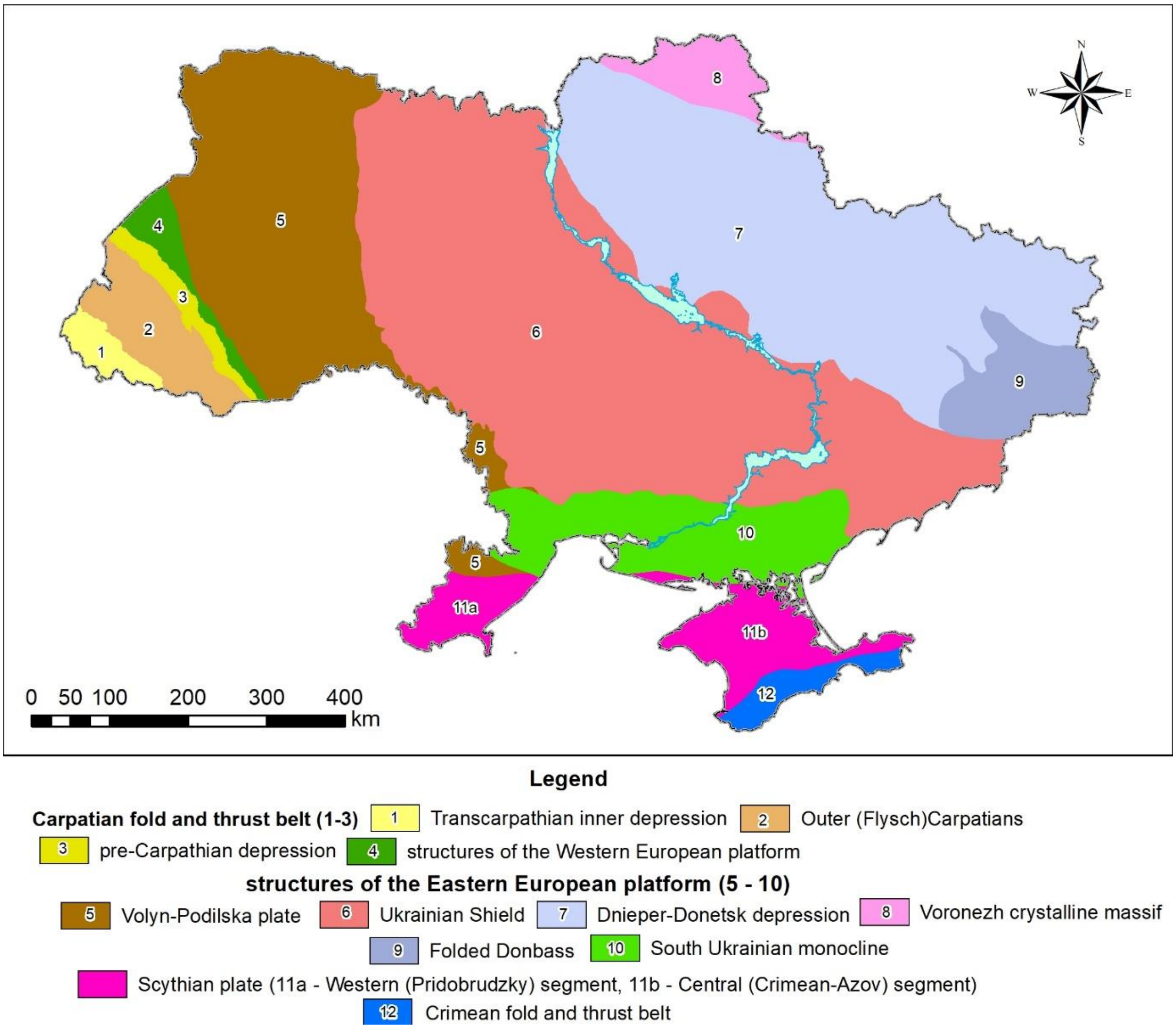

Figure 3-35: A simplified scheme of tectonic zones of Ukraine

Figure 3-36: Location of mapped national faults and fault systems in Ukraine contributed to the HIKE-FDB. Faults are represented either at surface or subsurface level.

3.2.18 Other fault data entries

Next to the fault data delivered by individual countries or federal states, other GeoERA projects produced harmonized fault datasets in cross-border- or multinational regions.

3.2.18.1 R2R area

This area is one of the two Structural Framework areas of GeoConnect3d in which faults were harmonised between Belgium (Flanders), Germany and the Netherlands. The fault geometries delivered to the HIKE-FDB are identical to those of the GeoConnect^{3}d R2R area mentioned in the R2R “limit” vocabulary in which a link with the HIKE fault data is implemented.

3.2.18.2 Pannonian Basin area

This area is one of the two Structural Framework areas of GeoConnect3d in which faults were harmonised[11] between Romania, Slovakia, Hungary, Bosnia-Herzegovina, Croatia, Slovenia, and Ukraine. By including the Pannonian Basin fault in the HIKE-FDB, faults from individual countries that were no HIKE partner were incorporated. Factsheets, however, are not available for these countries (with the exception of Slovenia and Ukraine).

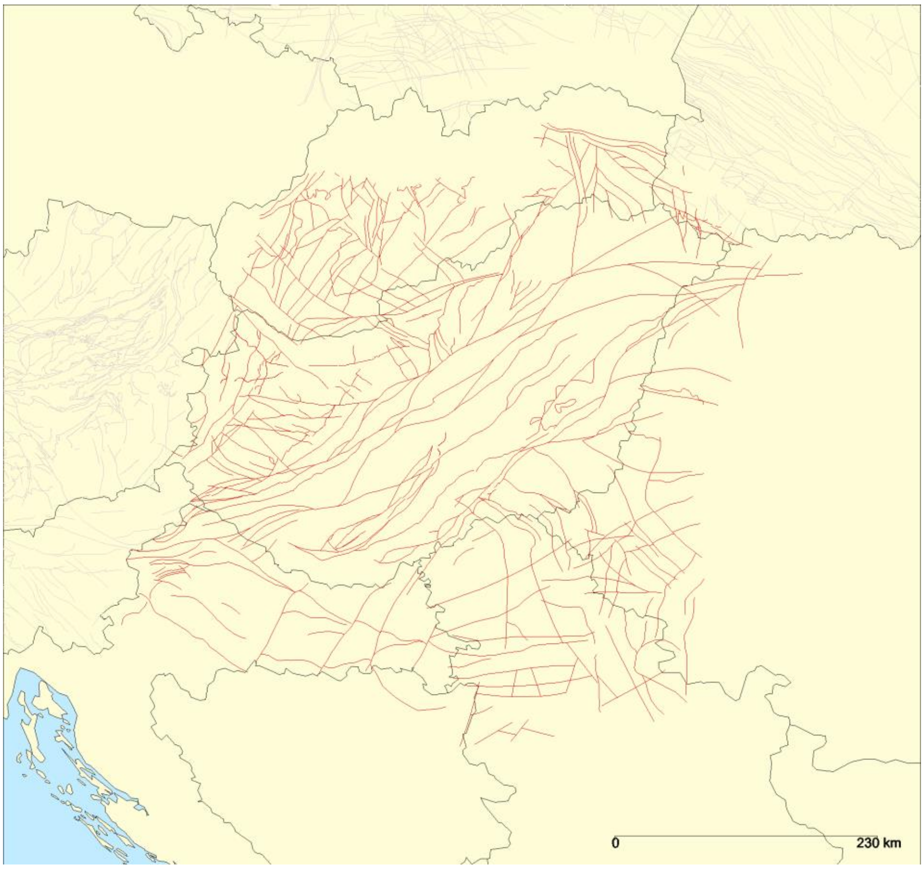

Figure 3-37: Location of mapped national faults and fault systems in the Pannonian Basin Structural Framework are, which are contributed to the HIKE-FDB as well. Faults are represented either at surface or subsurface level.

[11] Include reference to Pannonian Basin report

4 MAIN OBSERVATIONS AND RECOMMENDATIONS

Based on the provided fault data and the country reports (as summarized in 3.6) the following general conclusions can be drawn.

4.1 Summary of fault data coverage

4.1.1 Regional fault data coverage and scale

- In general, the type, density and quality of source information is very heterogeneous across Europe (see 4.1.8). As a consequences the mapping scale, coverage and quality of faults varies strongly per region (also within countries).
- Many fault maps are based on vintage data. The progress of fault mapping updates varies per country. Only a few countries have a programme for regular updating of faults.
- The mapping scales range between 1:50.000 (e.g. some Federal State regions in Germany) up to 1:.000.000 for countries where fault data have been extracted from vintage national and European maps. In recent and more modern 2D and 3D national mapping and modelling programmes, the mapping scales typically vary between 1:200.000 – 1:500.000.
- Most countries provided nation-wide, onshore fault data, whereas only few offshore dataset are included. The latter exclusively concerns the southern North Sea Basin. Italy includes a link to EMODnet web portal for reference to offshore faults.
- Typically, where the data is provided by national geological institutes, the fault data has nation-wide coverage. For some countries there are exceptions:
    - Although Poland does have fault maps covering the entire country, these data are owned and maintained by different institutions who are not a partner in HIKE. Within the frame of HIKE and GeoERA it was not possible to acquire and process this information to the required quality levels. For this reason fault information is lacking in parts of Poland
    - In France the general dataset from the OneGeology[12] platform was used to provide a nation-wide GIS coverage. This data has not been processed to the standards of HIKE and lacks information on attributes and vocabularies. A detailed specification and comprehensive dataset was delivered for the French Pyrenees only (data and country report).

      In Germany, each federal state has its own institute and the provided fault data is limited to the state only. Next to these data, a nation-wide fault data set (on- and offshore) is provided by the national institute BGR. This issue is solved, however in the HIKE FDB viewer where the country-wide data from BGR is displayed at scales larger than 1:500.000. When zoomed in past that level, the more detailed data from the participating federal states is shown within the territories of those states, whereas the BGR data is shown for the rest of Germany.
- Faults extending past country borders that were causing overlap with the same faults on the other side were trimmed by the partners in order to tidy up the border areas.

[12] Include reference to OneGeology Europe

4.1.2 Stratigraphic coverage and depth ranges

- With some exceptions the provided faults cover multiple stratigraphic intervals from Holocene to pre-Carboniferous age. In most cases the faults are represented by a single trace (often the intersection at surface level or the upper-most stratigraphic level in case of a buried fault), which is considered valid for a limited depth range assuming (near-) vertical orientation of the fault plane.
- Some countries have defined multiple intersections per fault at different depth or stratigraphic levels. In these cases the vertical intervals cover several hundreds to thousands of meters. This typically applies for countries who have derived their fault information from 3D model data.

4.1.3 Source data

- The most common data types used for mapping and modelling of faults are surface maps, 2D seismic surveys and gravitational/magnetic surveys. 3D seismic data and deep well data are mostly limited to areas of interest for oil and gas exploration. Even if 3D seismic surveys are conducted, the public accessibility can be limited as these data are often not owned by geological survey organizations. In many countries faults have been mapped
- HIKE report 2.3[13] evaluates the convenience and suitability of different types of source data for mapping and characterization of faults and the general consequences for quality and reliability of mapping. 2D and 3D seismic data are most convenient for detailed mapping of faults at greater depths (up to several kilometres, depending on the nature and quality of the survey). Gravitational and magnetic data also reveal faults at depth, yet the precision and accuracy is typically very low.
- Wells are less well suited for 2D and 3D fault mapping based on direct observations, yet these data assist the mapping and modelling of stratigraphic levels which are displaced by the faults. Also, the wells may provide direct information on certain fault characteristics.

4.1.4 Fault attributes

- So far, the available information on fault attributes is limited. Countries have provided the mandatory attribute information. Other attributes are mostly related to stratigraphic information and geometry aspects. Often these data depend on detailed studies. To date, information that relates to fault kinematics are not provided. Table 4-1 gives an overview of the percentage to of fault attributes are filled.
- Some countries (e.g. Italy) have highly mature fault datasets with extensive coverage of fault attribute information. These data are also captured in online national databases and which are accessible via the fault vocabulary system.
- In the future, more attribute data will be needed to improve the applicability of the FDB for specific studies and assessments (e.g. seismicity, leakage). Work package 3 provides several examples from the conducted case studies (see HIKE deliverables D3.2 to D3.5 and the synthesis report in D4.1[14]).

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[13] http://geoera.eu/wp-content/uploads/2021/10/D2.3_HIKE_Fault_Characterization_Data_Report.pdf

[14] http://geoera.eu/wp-content/uploads/2021/10/D3.2_HIKE_Improved_Seismic_Events_Localization.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.3_HIKE_Subsidence_Assessment_Techniques.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.4_HIKE_Improved_Reservoir_Seals_Assessment.pdf
http://geoera.eu/wp-content/uploads/2021/10/D3.5_HIKE_Subsurface_Injection_Safety_Seismicity.pdf
http://geoera.eu/wp-content/uploads/2021/10/D4.1_HIKE_Synthesis_Report.pdf

Table 4-1: Overview of percentage of attributes filled

Attribute	% filled	Attribute	% filled
SCALE_TO	100	OBSERV_METH	58
SCALE_FROM	100	REF_SURF	53
METADATA	100	YOUNG_UNIT	41
ID	100	DIP_DIRECT	41
GEOM_3D	100	TIMING	41
FAULT_TYPE	100	DIP_ANGLE	40
COUNTRY_CD	100	OLD_UNIT	38
CAPABLE	100	DEPTH	37
ACTIVE	100	MOVE_SENSE	4
REFERENCE	99	ACTIVITY	1
REF_TYPE	99	VER_THROW	0
FAULT_TYPE_URI	99	TIME	0
LOCAL_NAME	97	STRIKESLIP	0
EVAL_METH_URI	97	RAKE	0
EVAL_METH	97	PITCH	0
STRIKE	96	OFFSET_DET	0
LENGTH	92	NET_SLIP	0
CONCEPT_URI	87	HOR_THROW	0
CONCEPT_ID	87	DISPLACE_M	0
OBSERV_METH_URI	59	DIP_SLIP	0

4.1.5 Cross border correlation

The entire dataset is harmonized through the use of one data model and corresponding code lists, but also through the use of Project Vocabularies that were developed during the HIKE project. This has led to a Europe-wide database that describes faults from all partners in a harmonized way; Values from different partners mean the same thing. Several partners have also worked with their neighbours to make sure that geometries and naming of their faults are consistent cross-border. Examples where correlations have been improved include:

- R2R are: This area is one of the two Structural Framework areas of GeoConnect3d in which faults were harmonised between Belgium (Flanders), Germany and the Netherlands.
- Pannonian Basin area: This area is one of the two Structural Framework areas of GeoConnect^{3}d in which faults were harmonised between Romania, Slovakia, Hungary, Bosnia-Herzegovina, Croatia, Slovenia, and Ukraine
- The Alpine Molasse basin between Bavaria (Germany) and Austria

4.1.6 Multi-scale information

Originally, ten levels of scale dependency were foreseen. After delivery of the first datasets, it became clear that a map with so many scale dependent features lacked consistency when zooming in and out, with features appearing and disappearing everywhere. Therefore, it was decided to only implement scale-dependency where this removed clutter on the map in areas where the density of delivered faults was very high. Examples where multi-scale data have been implemented include:

- The Netherlands
- Germany (Federal States vs BGR)
- Belgium (Flanders)

4.1.7 Vocabulary definitions

Occasionally, vocabularies are used to link to external data sets, such as links from Italian faults to the ITHACA database and links of Project Vocabulary values to INSPIRE code lists.
Apart from cross-border harmonisation of fault objects, vocabularies are used for cross-border correlation as well. For example in the border areas between Austria and Germany, Slovenia and Italy.

4.1.8 Data homogeneity

Given the fact that different observation methods are used, the provided data set is not homogeneous. This concerns:

- Scale
- The degree to which the fault objects are generalizations of the true geometry, involving:
    - The linearity of the faults
    - The continuation of the faults (or the number of segments}
- Number of intersection levels next to the surface intersection (the normal geological map representation)
- Type of faults

These inhomogeneities are striking when data sets overlap, as is the case for Germany, for which the fault data was not harmonized on a national level.

4.2 Recommendations for data improvement

- The HIKE FDB development has been a major stimulation for many countries to compile, upgrade and disseminate information on national faults. The platform and vocabulary system have had a large impact on the overall state-of art of fault knowledge and accessibility of data.
- The procedures have resulted in standards that can be used for a more homogeneous mapping of faults in the future
- FDB can be even more useful if it includes also other (tectonic) features that can support policy making. For instance, volcanoes, etc.
- The HIKE project recommends the following improvements for the coming years
    - Continuation of fault mapping in national programmes to improve and resolve observed data gaps and inconsistencies. The national programmes should follow the standards and guidelines established in HIKE and to upgrade the current information in the FDB
    - The fault vocabularies provide an essential framework for fault interpretations and correlations (like a stratigraphic framework for mapping of horizons and layers). They also help to understand the hierarchy and interdependencies of larger fault systems and networks as well as the major structuration of Europe. We recommend that the countries keep updating and extending the vocabularies and to formalize definitions in publications and scientific papers. A more mature and complete framework will support the application of fault data

as well as the harmonization and correlation across border. A consistent framework will greatly improve the understanding of the tectonic development of Europe and the implications for better understanding of safety and hazards.

- The extension of attribute information will be challenging as this typically depends on detailed and location-specific studies. Italy, however, is a good example of what could be realized on the longer term. For a regional analysis, further coverage of geometry, stratigraphic and kinematic attributes is preferred.
- Most data are still defines at one vertical level. Consistent modelling of faults across different depth and stratigraphic intervals will help to better understand the 3D architecture of fault networks