Hazard and Impact Knowledge for Europe

Deliverable D2.4

Fault Database Evaluation and Applications

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GENERAL INTRODUCTION

This report summarizes various project activities under GeoERA and national research programmes which have a relation to fault data and knowledge. For each case the relevance and applicability of the HIKE Fault Database has been reviewed.

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1 INTRODUCTION

1.1 Document background and scope

The HIKE project has resulted in a novel database and information system for faults in Europe's subsurface. These faults are relevant for developing the (3D) geological framework, assessing resource potentials and understanding the kinematic behavior of the subsurface and associated hazards and risks.

With this report we assess the potential uses and limitations of the HIKE Fault Database for different types of applications and research domains.

1.2 Document structure

1.3 Abbreviations

CSA	Coordination and Supply Action
FDB	Fault Database
GSO	Geological Survey Organisation
SF	Structural Framework

1.4 HIKE partners

#	Participant Legal Name	Institution	Country
1	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO	TNO (coordinator)	Netherlands
2	Albanian Geological Survey	AGS	Albania
3	Geologische Bundesanstalt	GBA	Austria
4	Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium	RBINS-GSB	Belgium
5	Geological Survey of Denmark and Greenland	GEUS	Denmark
6	Bureau de Recherches Géologiques et Minières	BRGM	France
7	Bundesanstalt für Geowissenschaften und Rohstoffe	BGR	Germany
8	Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg	LBGR	Germany
9	Landesamt für Geologie und Bergwesen Sachsen-Anhalt	LAGB	Germany
10	Bayerisches Landesamt für Umwelt	LfU	Germany
11	Islenskar orkurannsoknir - Iceland GeoSurvey	ISOR	Iceland
12	Istituto Superiore per la Protezione e la Ricerca Ambientale	ISPRA	Italy
13	Servizio Geologico, Sismico e dei Suoli della Regione Emilia-Romagna	SGSS	Italy
14	Agenzia Regionale per la Protezione Ambientale del Piemonte	ARPAP	Italy
15	Lietuvos Geologijos Tarnyba prie Aplinkos Ministerijos	LGT	Lithuania
16	Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy	PIG-PIB	Poland
17	Laboratório Nacional de Energia e Geologia	LNEG	Portugal
18	Geološki zavod Slovenije	GeoZS	Slovenia
19	State Research and Development Enterprise State Information Geological Fund of Ukraine	GEOINFORM	Ukraine

2 FAULT DATA APPLICATIONS

2.1 Introduction

Faults play a crucial role in driving natural geological processes as well as the exploration and use of subsurface resources and capacities. As major structural features, faults have shaped the subsurface by outlining subsiding basin areas in which sediments have deposited as well as mountain ranges and orogens where the earth crust has been uplifted and eroded. In tectonically active regions, fault movements can generate earthquakes. But also deeply buried and passive faults may generate earthquakes when triggered by anthropogenic activities such as for example production and injection of fluids and gases. With the construction of tunnels and bridges, faults can be a challenge for engineering as they can represent less stable sections in the subsurface or a cause for intrusion of water. Last but not least, faults are critical in the exploration of suitable areas for resource exploration and storage of gases and fluids (e.g. CO_2, energy carriers) as they outline structures and confined reservoirs and define the seal.

2.2 Application areas involving fault information and knowledge

The sections below provide a brief overview of potential research and development areas in which faults play an important role.

2.2.1 Geological modelling and Structural Framework

Geological maps and models are a main source for fault data in the FDB. The location of faults may of course be deduced from direct observations, yet the resulting information may have a very limited value for further applications. Only through detailed interpretation, mapping and 3D modelling, it is possible to obtain a comprehensive insight in the full geometry, characteristics and kinematic properties of faults as well as their relation to other faults and adjacent rock formations. Besides HIKE, several other GeoERA projects have produced and provided fault geometries and characteristics to the FDB, including 3DGEO-EU, HotLime and GeoConnect³d. Examples are given in Paragraph 3.2.

Faults control the distribution of geological layers in two ways. First of all, faults may influence the depositional processes as they typically delineate subsiding areas where sediments accumulate (basins) and areas of uplift where erosion takes place. Secondly, faults may fracture, displace and deform formations after their deposition and burial. This not only affects the spatial configuration of layers, it also determines the main properties of rock formations such as the permeability, conductivity and geomechanical strength. Especially in orogenic mountain belts tectonic movements during different stages in geological time have resulted in a complex configuration of faults and thrust planes.

Fault interpretation is often one of the first steps in a geological mapping and modelling workflow preceding the interpretation and modelling of geological formations. At national to regional scales, major faults and fault systems typically define the tectonic boundaries of structural elements which define areas where the deposition and deformation of rock units have been subject to a more-or-less similar geological development. The geological country reports in HIKE deliverable 2.2b[1] provide an overview of the location and geological development of structural elements identified in the participating countries. The major tectonic boundaries and smaller faults within structural elements are essential input for a geologically sound interpretation of layers (e.g. determining consistent orientation, extent, offset and juxtaposition of geological layers). Sometimes, such information is established through a kinematic (palinspastic) reconstruction of the subsurface in which case the movements of geological layers along faults are reversed to obtain insight in the original situation at times of deposition and to analyze whether determined fault movements are geologically consistent (e.g. preservation of volumes and thicknesses).

Paragraphs 3.2.3 to 3.2.5 present advanced methods to observe and model faults in areas lacking 2D and 3D seismic survey data or other means to detect faults. Paragraph 3.7.1 includes an example of how the relation between surface deformation and faults can be established from InSAR data.

2.2.2 Hydrocarbon exploration

Fault data and knowledge is essential for hydrocarbons exploration at both local and regional scales.

At regional level, fault models are needed to establish basin modelling and petroleum systems studies. These studies reconstruct the different stages of geological development over time taking in account i) basin subsidence and uplift events, ii) timing of deposition of source, reservoir and sealing layers, iii) temperature development and iv) generation, migration and trapping of hydrocarbons. The faults not only delineate subsided and uplifted areas but also de evolution of seals and traps. GARAH presents an example of this application which is described in Paragraph 3.3.1.

At the local level operators assess individual prospective structures, among others to estimate the volume of hydrocarbons in the reservoir as well as to determine possible strategies for hydrocarbon extraction. Highly detailed fault data are used in the first place to evaluate the geometry and spill points of the structure and reservoir. Within the reservoirs detailed measurements and assessments are needed to determine whether internal faults are stimulating or hampering the flow of hydrocarbons. This is typically evaluated using 3D seismic attribute analysis and well production tests. In general, the data in the HIKE FDB lacks the level of detail to be useful for evaluation of individual hydrocarbon structures.

2.2.3 Geothermal Exploration and development

In geothermal exploration and development the presence of faults may be a prospectivity indicator or a reason for concern.

Especially for deep geothermal projects, open fault and fracture networks are considered a prerequisite for flow in the otherwise low-permeable rock formations. Reservoir stimulation

[1] http://geoera.eu/wp-content/uploads/2021/10/D2.2b_Annex_HIKE_Country_Reports.pdf

techniques such as fracking are used to improve and extend the fracture networks. Knowledge regarding the 3D geometry and characteristics of faults is essential for planning drilling and reservoir stimulation campaigns. Regional fault maps can be used as a proxy for identifying prospective areas and developing strategies for effective geothermal deployment. Paragraph 3.4.1 presents how the HotLime project has implemented fault models in the characterization of regional geothermal potentials.

Another concern is the possibility that drilling fluids and deep formation waters enter vulnerable groundwater layers via open and connecting faults (see Paragraph 3.8)

2.2.4 Geological storage

Like hydrocarbon exploration, subsurface storage depends on the presence of sealed traps. Often the capacity to permanently contain fluids and gases in reservoirs depends on the sealing capacity of the faults delineating the structure. In the case of hydrocarbon fields, the sealing capacity at geological time scales has been proven by the presence of the same hydrocarbons. In unexplored aquifers the sealing capacity needs to be proven. Paragraph 3.5.1 presents an example from HIKE Work Package 3 showing how the sealing capacity of local and regional faults can be modelled using 3D geological data.

2.2.5 Natural and induced seismicity

The presence of both active (seismogenic) and passive faults can be a major reason for concern for nearby subsurface activities such as natural gas production, geothermal production and geological storage. Geothermal projects based on doublet configurations (i.e. with a cold water re-injection well) may trigger earthquakes in active or capable (stressed) faults as the injected water invades into the fault plane and lowers the fault friction to a critical level. In hydrocarbon production projects as well as underground storage projects, differential stresses may develop across faults due to pressure differences and/or uneven compaction and de-compaction. In this case, even long-time passive faults may become re-activated. Paragraph 3.6.2 provides an example how regional fault information can be used to support the Seismic Hazard Assessment of geothermal projects in order to manage and reduce risks before actual development and production takes place (e.g. by adjusting project designs, production strategies and operational set-ups). Paragraph 3.6.1 presents a study to better localize earthquakes for a better understanding of causal relations with natural and anthropogenic processes. An example on storage and seismicity from HIKE Task 3.4 is presented in Paragraph 3.5.2.

2.2.6 Groundwater

Faults are important in groundwater systems because of local changes in hydraulic conductivity, discontinuity of aquitards and aquifers and possible connection of multiple aquifers. The core zone of a fault often has a lower hydraulic conductivity creating a hydraulic barrier to groundwater flow (e.g. '*wijstgronden*' in the Netherlands – Bense et al., 2003; Laperre et al., 2019). Damage zones along faults may reduce hydraulic resistance of aquitards to vertical flow resulting in preferential flow paths (e.g. salinization of groundwater abstraction near the fault due to brackish water in deeper aquifers). Faults are the primary natural geological pathway for effects of energy related activities in the deep subsurface on groundwater resources (see Paragraph 3.8.1).

2.2.7 Engineering

The localization and analysis of faults may be important for engineering projects. One example is the detection of capable or even active faults near sensitive infrastructures such as dykes and nuclear plants. In these cases, detailed studies are needed to determine and manage eventual risks. Another example is tunnel and bridge construction where faults may represent conduits for invading groundwater in the tunnel sections or a potential risk zone for tunnel stability.

3 CASES AND EXAMPLES

3.1 Introduction

In this chapter we present various use case examples from HIKE, other GeoERA projects and some national studies where faults are an important part of the scope. This may either relate to the generation of fault information or to the application of such data. With each example we will summarize the use case and address how this relates to the HIKE FDB or how the FDB may be used in future work.

3.2 Geological modelling and Structural framework

3.2.1 Project 3DGEO-EU: cross-border 3D modelling of faults

Summary

The 3DGEO-EU project focuses on the consistent modelling and cross-border harmonization of geological and structural models in several key regions of Europe (see *Figure 3-1*). In this context, faults and fault networks form the essential framework to build the 3D layer models (i.e. horizon modelling). In the 3DGEO-EU Deliverable 5.1 report "Methods, bottlenecks, best practices and accompanying descriptions to faults in 3D models", each of the study areas addresses the following workflow elements to establish harmonized fault models:

- Observation methods for faults
- 3D modelling of faults
- Fault harmonization
- Fault classification and attributation

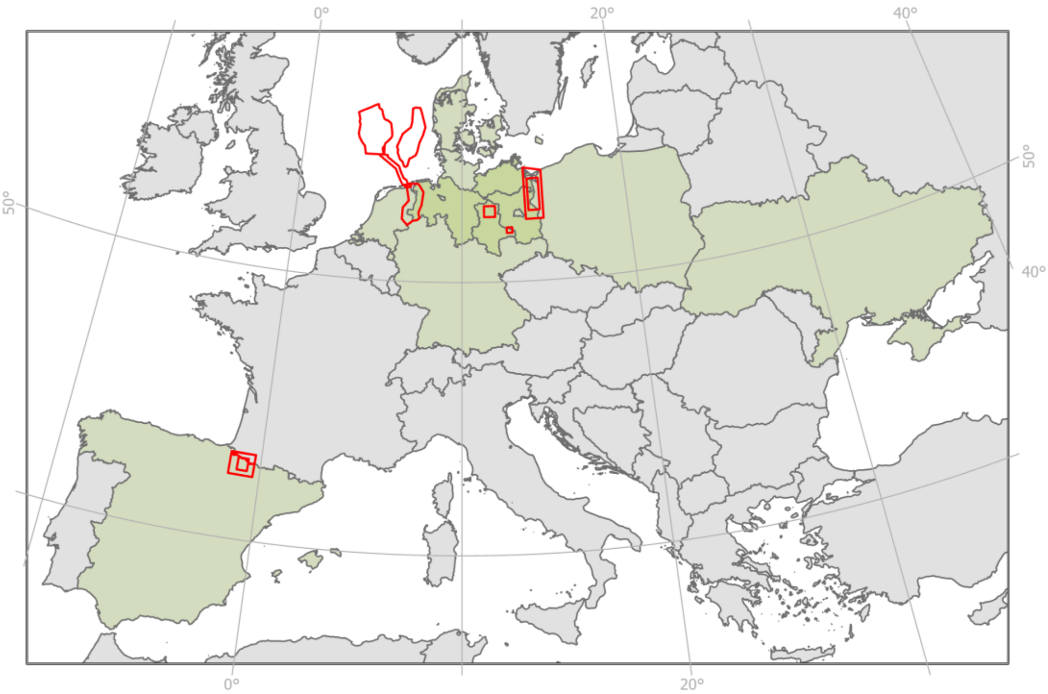


Figure 3-1 Overview map of participating countries, case study and pilot areas of the work package "Faults" in the 3DGEO-EU project

The report presents different challenges which emerge when harmonizing models across country borders. The modelling seldomly starts from an empty sheet as most areas in Europe have a long history of prior investigations and mapping activities with different purposes, observation methods and modelling techniques. Heterogeneous data sets, independent exploration concepts, technical limitations and legal restrictions often exclude the existence of a uniform data base. Consequently, inconsistent data, variable processing techniques as well as interpretational and regional geological concepts hamper the cross-border fault harmonization. Each of the study areas illustrates the impacts of several of these challenges including solutions to make models consistent.

From the study area experiences the reports recommends to address the following questions for clarification:

- Are there any legal restrictions or technical discrepancies between the project partners?
- Which situation and state of knowledge exist in each project partner's research at the beginning of the harmonization process?
- Which kind of raw data is available on both sides of the border?
- Are there any discrepancies between interpretational and regional geologic concepts across borders?

Applicability for the HIKE Fault Database

The 3DGEO-EU experiences and solutions in the study areas provide essential guidelines for the future improvement and harmonization of fault models in Europe. Both HIKE and 3DGEO-EU have a similar range of target scales and scope of fault modelling aspects. The presented solutions are also directly applicable to the development of state-of-art national fault models.

The fault modelling activities at the Federal state boundaries of Saxony Anhalt and Brandenburg have resulted in an update of national and regional models at both sides. The improved fault information is included in the HIKE FDB. Other areas of 3DGEO-EU are not yet uploaded.

3.2.2 Project GeoConnect³d: Implementation of Structural Framework

Summary

The project GeoConnect³d has established the Structural Framework (SF) which provides a new methodological approach to prepare and disclose geological information for policy support and subsurface management. The SF is composed of limits and units, which are also referred to as structural framework elements (Figure 3-2). In summary, these elements can be defined as below:

- Limits are surfaces such as faults and unconformities.
- Units are bodies such as orogens and grabens

As an expansion to traditional structural frameworks, in the GeoConnect³d SF not only structural geology elements are added, but also other important surfaces (planes) such as contacts and unconformities. The SF focuses on these surfaces (SF limits) as a starting point of the model. Because the location of limits is less prone to interpretation mistakes than that of geological units, this results in a more robust model that can provide a stable backbone for external data. By focusing on limits, the SF also results in a more explicit representation of the state-of-the-art geological knowledge, including unknowns - represented as open ends in units (e.g. Figure 3-2).

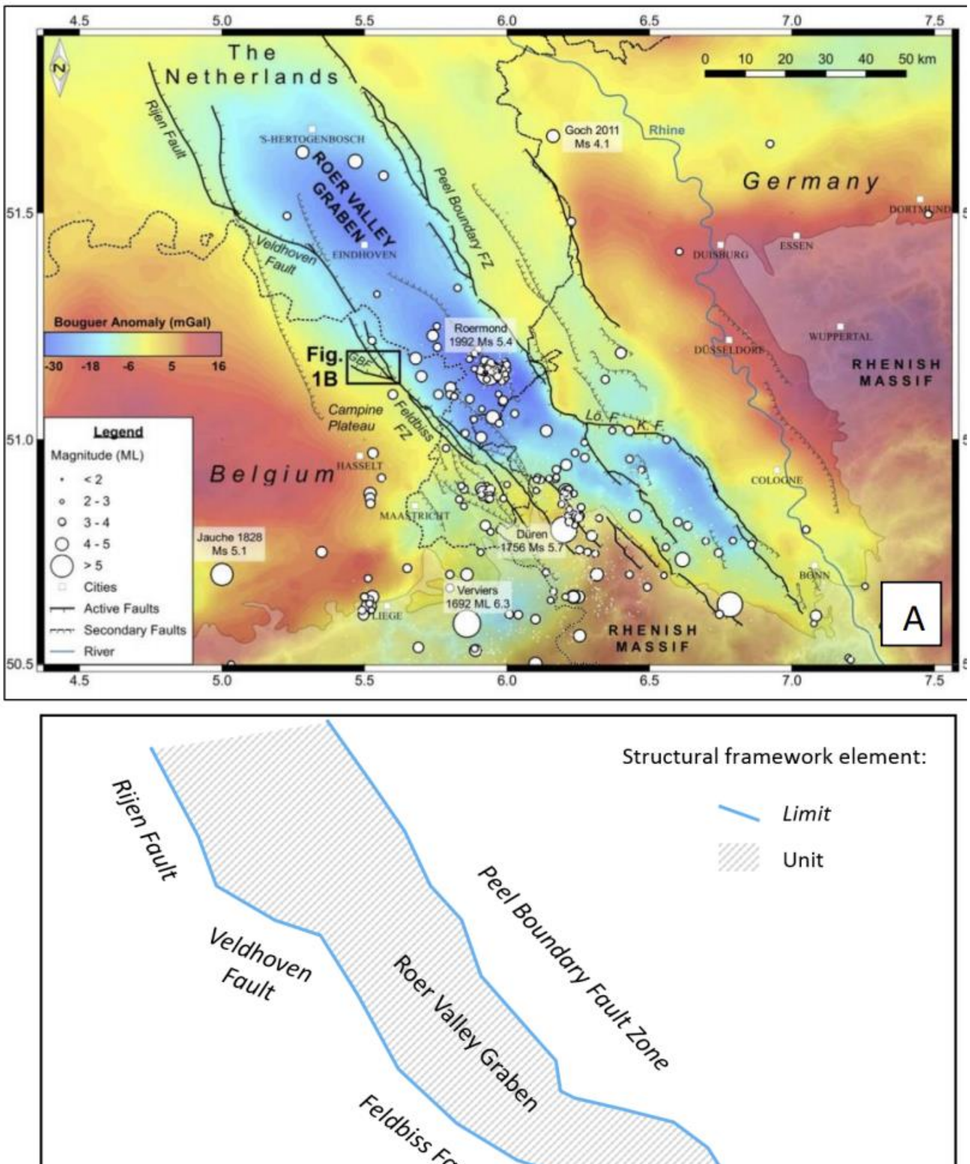


Figure 3-2: Example of structural framework elements (simplified) in the Roer Valley Graben (RVG) at broad scale (1:2,000,000 or broader). A) Border fault configuration and Bouguer anomaly map of the RVG (from Deckers et al., 2018). B) Simplified view of the RVG in the context of the structural framework, with faults as limits to the graben unit. Note open ends in the NW and SE parts of the graben.

From the very start of GeoERA, the HIKE project and GeoConnect³d project have worked closely together in defining and linking the SF and FDB concepts. This collaboration consisted of the following main activities:

- **Definition of the Structural Framework concept in relation to the HIKE FDB**: Faults and fault systems are key features defining the limits of the Structural Framework. HIKE and GeoConnect³d have developed a joint specification for faults to ensure that the FDB data can be used in the SF. This included the implementation of tectonic boundary classifications (vocabularies) and multi-scale definitions of faults
- **Integrated modelling in study areas.** The Roer-to-Rhine area has been a focal area to jointly develop the concepts and models in GeoConnect³d and HIKE. Both projects share the same database, although the SF vocabulary introduces custom properties that slightly differs from that of the FDB. Shared expertise between projects was helpful to handle cross-border issues and resulted in a robust, harmonized model (Figure 3-3).
- **Transfer of fault information:** The HIKE FDB has been extended across the entire Pannonian Basin including the incorporation of fault data from 8 countries consistent with the HIKE FDB specifications (Figure 3-4). Most of the Pannonian Basin area was not covered by the HIKE partners. This successfully demonstrated the transferability of information between the SF and the FDB.

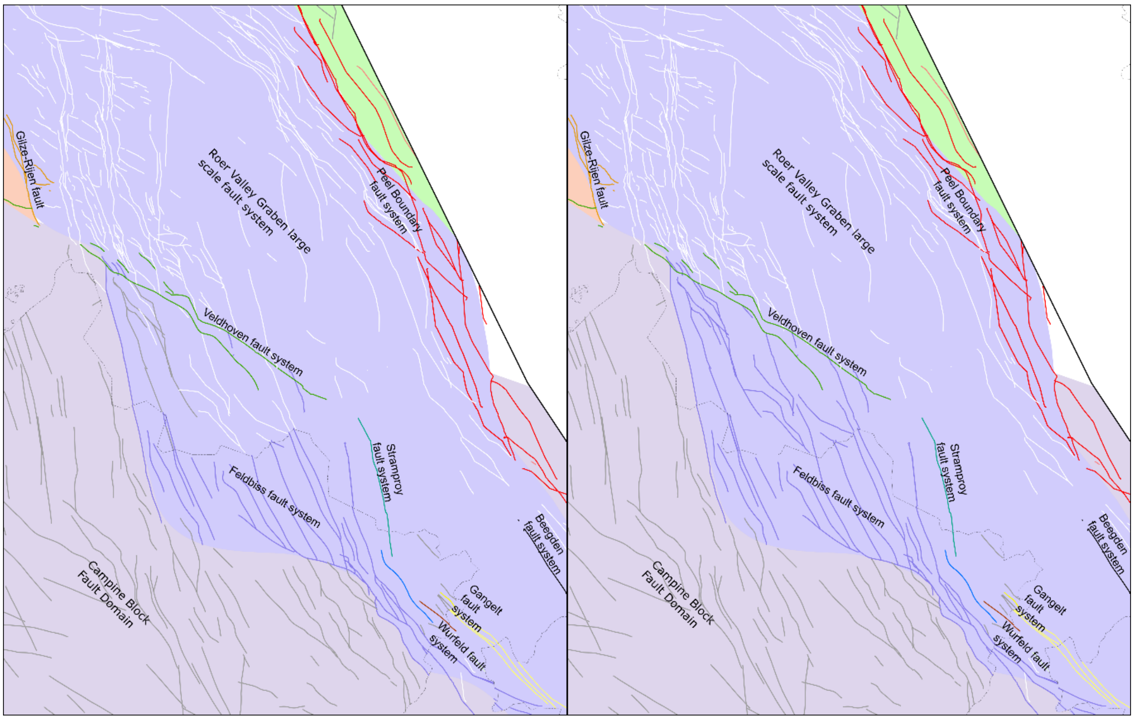


Figure 3-3: The SF before (left) and after (right) cross-border harmonization. Note that in the left figure, on the border of Belgium and the Netherlands (grey dashed line), the same faults change from color from white (Roer Valley Graben Large Scale Fault System) to blue (Feldbiss Fault System), due the fact that in the Netherlands these faults were assigned to a higher-level concept when compared to the Flemish input. Also, in the left figure, some faults that are situated within the area covered by the Roer Valley Graben unit (blue) were associated with the Campine Block Fault Domain (grey). In the right figure, both cases were corrected, creating a harmonized map.

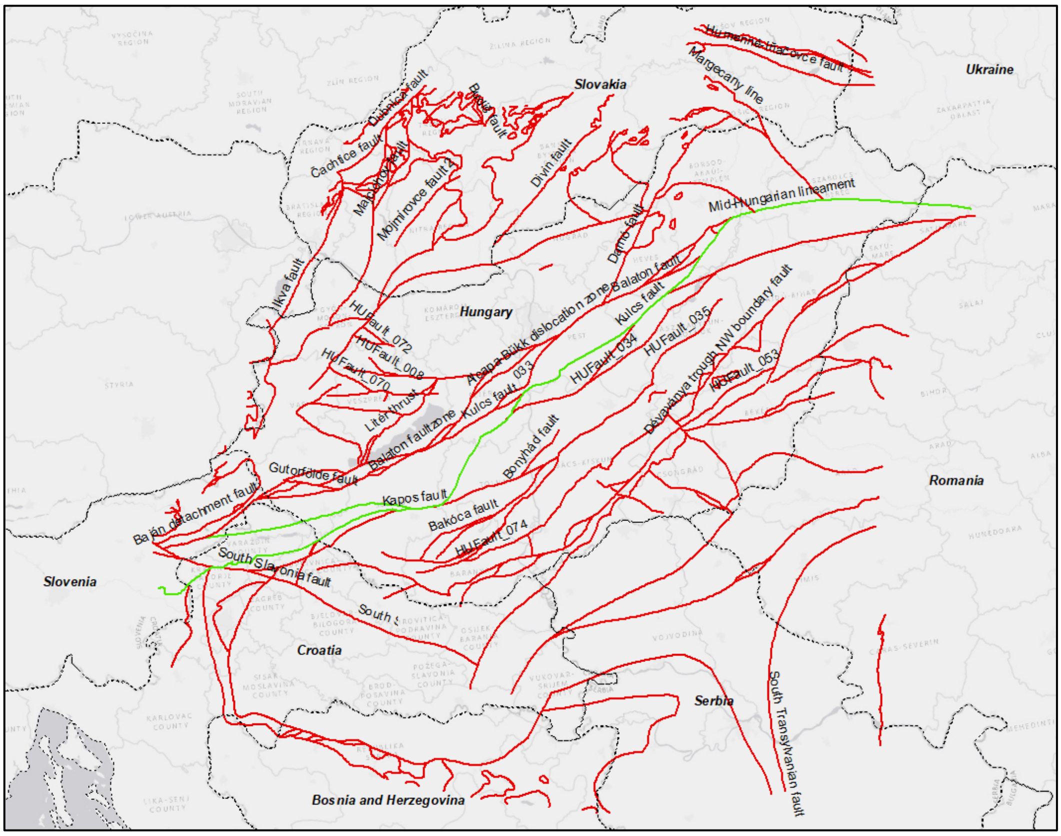


Figure 3-4: Fault map of the Pannonian Basin derived from the SF and incorporated into the FDB. Red = faults, green = lineaments.

Applicability for the HIKE Fault Database

The future development and deployment of the SF and the HIKE FDB are closely intertwined. As new fault modelling results become available, there will be a stronger base to extend and improve the SF. The upcoming CSA "Geological Services for Europe"[2] is planning to continue the implementation and development of the SF as a central framework for European geological information. In order to maximize the benefits, following recommendations are made:

- As GSO's continue to improve national/regional fault models and information, there should be a continued support to incorporate these data in the SF/FDB. It is recommended that all GSO's in Europe participate to sustain and extend the coverage of harmonized fault data.
- Tectonic boundary vocabularies need to be kept up to date and aligned with the SF in order to ensure the integration with the FDB. This also involves the definition of relationships with geological units.
- With more fault data becoming available at different scales, the SF will be able to expand the possibilities for multi-scale exploration and exploitation of geological information.

[2] Link to csa call

3.2.3 2D geoelectric survey at Vilshofen (Bavaria, Germany)

Summary

Geoscientists from Bavaria (LfU, University Erlangen) and Austria (GBA) collaborated in a geophysical field campaign with the scope of validating an inferred cross border blind fault system SE of Vilshofen. In this area, Mesozoic formations and Tertiary sediment units from the alpine foreland basin (Molasse Basin) onlap on intensely faulted crystalline Moldanubian basement rocks. Information from maps and drillings (< 150 m depth) suggest a propagation of basement faults into the covering sediment units and thus into shallow regions of the subsurface at 100-500 m depth. In an integrated approach, results and fault interpretations from a legacy airborne helicopter electromagnetics dataset (HEM, Siemon et al. 2007) were re-evaluated in a digital 3D map project (see Figure 3-5) and afterwards validated by electrical resistivity tomography (ERT, 2 km long profiles) field measurements.

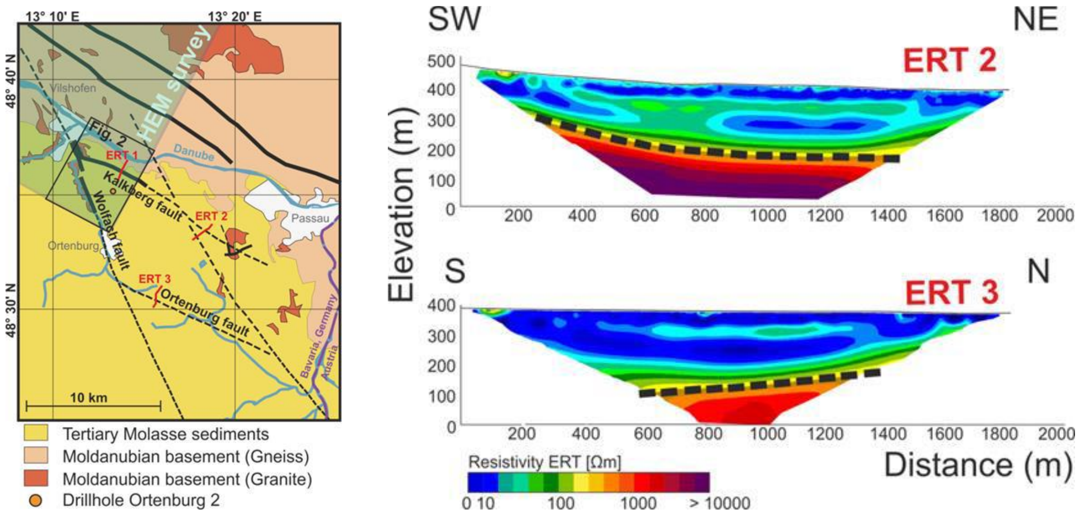


Figure 3-5: Left: Schematic geological map with observed (bold) and inferred (dashed) faults and blind faults. The HEM survey polygon only covers faults N and NW of the area of interest. Electrical resistivity tomography (ERT) survey lines were set up at locations where the blind fault system had already been discussed by various authors (e.g. Unger & Schwarzmeier, 1982). Right: Results of ERT profiles 2 and 3 show undisrupted inclined contact (dashed line) of the carbonate/basement rocks and the overlying, predominantly Tertiary sedimentary sequence.

In the study area, significant lateral variations of airborne electrical resistivity and ERT field measurements suggest a sharp geological contact between low resistive sedimentary units and high resistive basement rocks at depth, which is interpreted as the geometry of the Kalkberg fault (Figure 3-6). Interpretations of other ERT profiles (ERT2 and ERT3) that were measured to validate the anticipated propagation of strike of the Kalkberg fault and the location of a parallel fault. Against anticipations from literature, results of ERT profiles 2 and 3 disprove the existence of blind faults at the measured locations. Also they suggest an undisrupted inclined contact (dashed line) of the carbonate/basement rocks and the overlying, predominantly Tertiary sedimentary sequence (Figure 3-5, right).

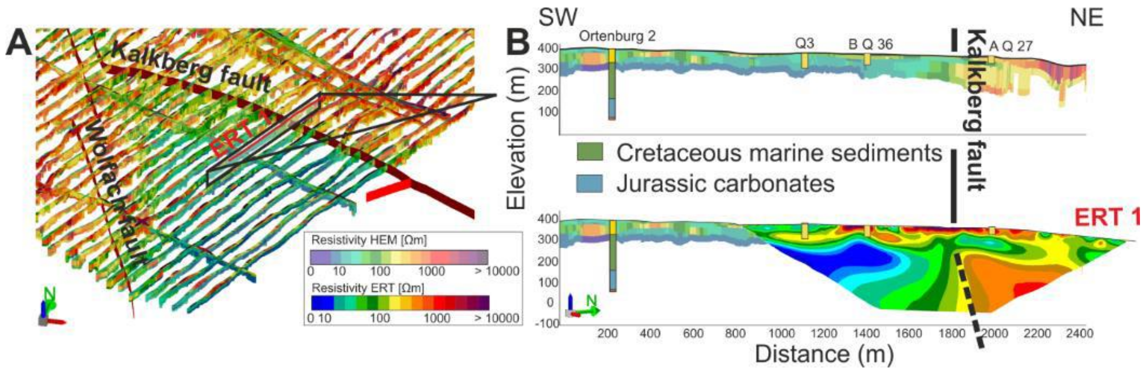


Figure 3-6: *(A) 3D visualization of HEM sections with faults that displace electrically low resistive (10-100 Ωm) Tertiary and Cretaceous sediment units from the Molasse Basin and high resistive (> 500 Ωm) Moldanubian basement rocks to the E (Kalkberg fault) and NW (Wolfach fault). (B) In comparison to HEM resistivity sections (top), results from ERT measurements (bottom) can help validate the fault location at depth and suggest to narrow assumptions towards the fault dip.*

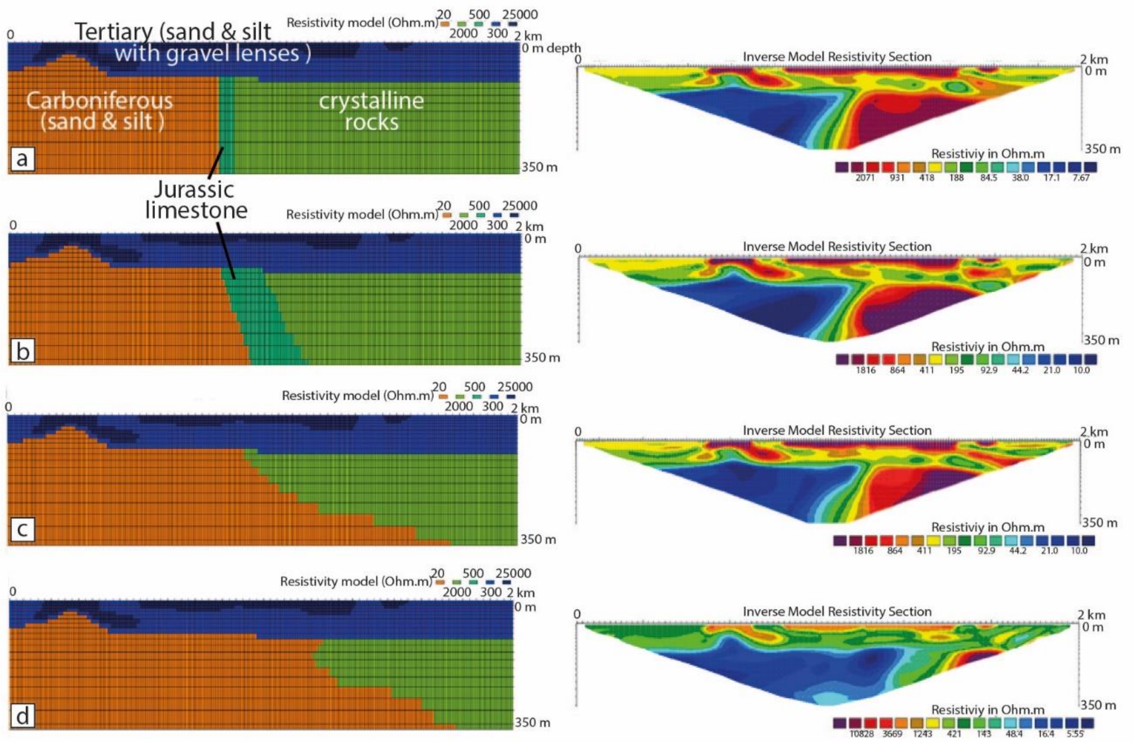


Figure 3-7: *Left: Resistivity models to test the sensitivity of the ERT profiles to fault parameters of the Kalkberg fault via forward modelling: (a) geologically most realistic model with a vertical fault zone characterised by Jurassic limestone, (b) steeply NE-dipping fault with Jurassic limestone, (c) shallowly NE-dipping fault without limestone, (d) fault position shifted towards NE. Right: respective forward modelling results shown as resistivity section (comparison with original measurements: see Figure 3-6 bottom right)*

Using various starting models with different fault dip directions and varying density contrasts, we wanted to explore the constraints on the fault parameter given by the ERT1 profile (see Figure 3-7). Model (a) is the geologically most realistic model, based on geological mapping and borehole information (Unger & Schwarzmeier, 1982), whereas model (b) represents a fault steeply dipping to the NE (while the geological assumption would be a vertical or SW-dipping fault) associated with Jurassic limestone within the fault zone. Model (c) does not take into account the Jurassic limestone fault and represents a fault shallowly NE-dipping fault. Model (d) repeats model (c), but the contact between the crystalline and the Carboniferous sediments is shifted towards the NE. The forward modelling results do not show significant differences between models (a)-(c), indicating that the 2k m long ERT profile does not show any sensitivity for the width of a fault zone nor the dip direction. However, the location of the fault can be determined with good accuracy.

Applicability for the HIKE Fault Database

The aim of this case study was the evaluation of the suitability of geoelectrical profiling campaigns to provide fault parameters, such as location, dip and dip direction.

In this case study, the very long ERT profiles provide good results regarding the existence of assumed faults and their location. Due to their larger EINDRINGTIEFE compared to shorter ERT profiles of standard extend up to 400 m, they proved to show better constraints on fault locations. However, more specific fault parameters such as dip and dip direction seem not be resolvable. Thus, usage of long ERT profiles is a practical and fast method to prove the existence and location of assumed buried faults in regions without other available constraints.

3.2.4 Reprocessing of vintage aerogeophysical data with focus on fault interpretation (Austria)

Summary

In Austria, a large area is covered by airborne geophysical data, mostly acquired during the 1980s and 1990s by the Geological Survey of Austria (GBA). The acquiring method was expensive and therefore terminated after 2012, but processing tools have improved during the last twenty years. Therefore, we explored the re-use of this existing data set in regards to its potential to identify and locate geological features, especially faults. In addition, the usage of such vintage data can be challenging, not only because of, e.g. the lack of the original unprocessed data or inconsistent elevation measurement during different campaigns, but also because of the lack of suitable modelling software. The application of GIS technologies opens up an opportunity, for rapid processing of geophysical datasets independently of their quality and precession, and provides the possibility of combining multiple geospatial datasets. Nevertheless, the question remains how reliable the results of such non-modelling approaches are and if they are applicable to the study of tectonic problems.

The study region covers about forty square kilometres in the north of Austria, where a set of airborne geophysical data was acquired between 1983 and 1997. At that time, the individual sets were processed, interpreted and compiled into reports, which, at that time, reflected state-of-the-art knowledge (Seiberl & Heinz, 1986, Seiberl & Roetzel 1996, Supper, 1999). In the study area, we selected four prominent and partly well mapped tectonic structures in order to test different geological settings for the applicability of the tested GIS tools. We applied the GIS–

based tools on the vintage airborne geophysical data together with gravity data provided by the Austrian Federal Office of Metrology and Surveying (BEV).

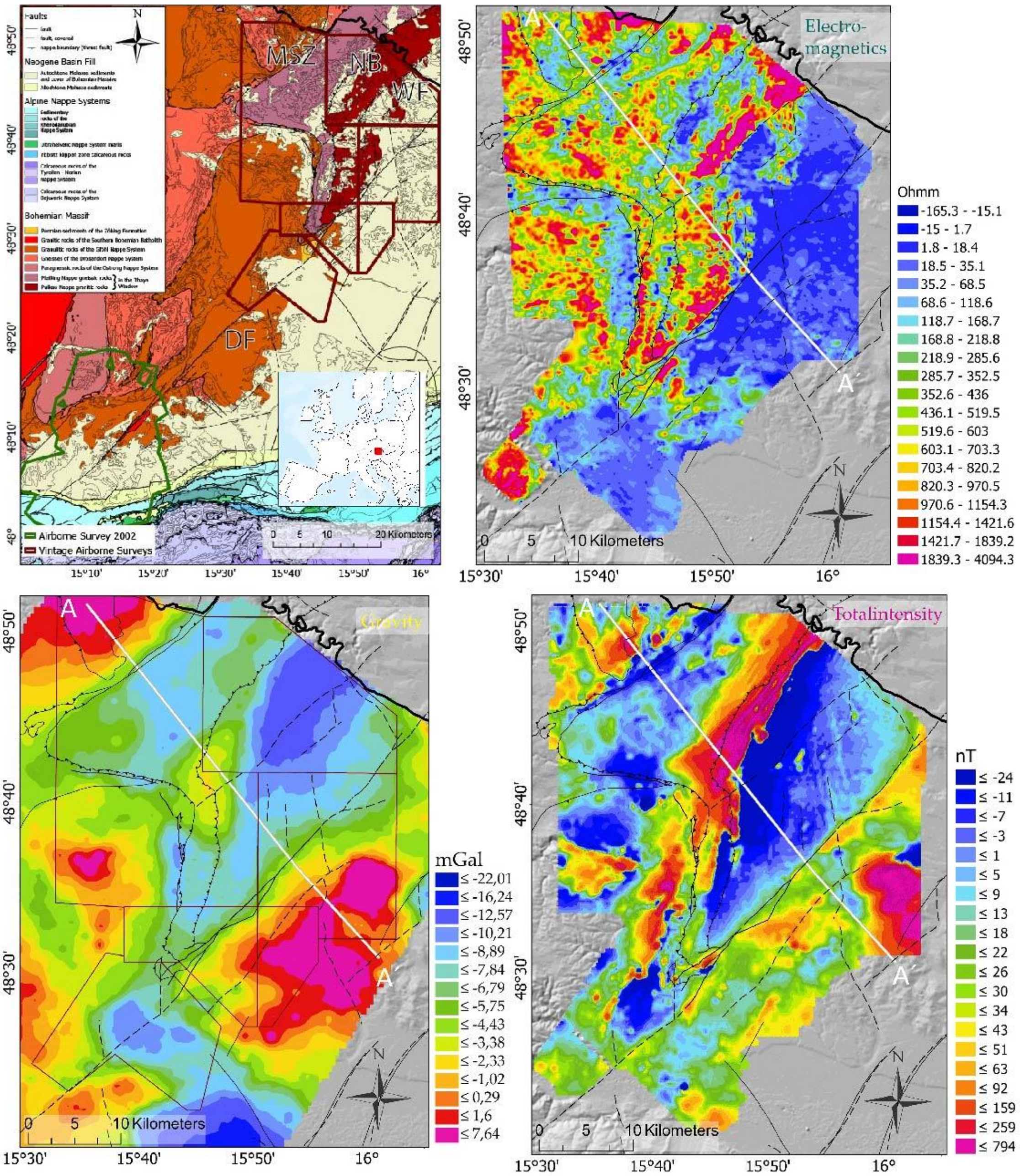


Figure 3-8: Top left: Geological map of the study area, indicating the locations of the considered faults. DF: Diendorf Fault, MSZ: Moldanubian Shear Zone, NB: Nappe boundary between Pleißing and Pulkau nappes, WF: Waizendorf Fault. Red boxes indicate area covered by aerogeophysical data. Top right: Airborne electromagnetic measurements. Bottom left: gravity data, obtained from BEV. Bottom right: Airborne magnetic total intensity data. Tectonic structures and profile A are shown as references.

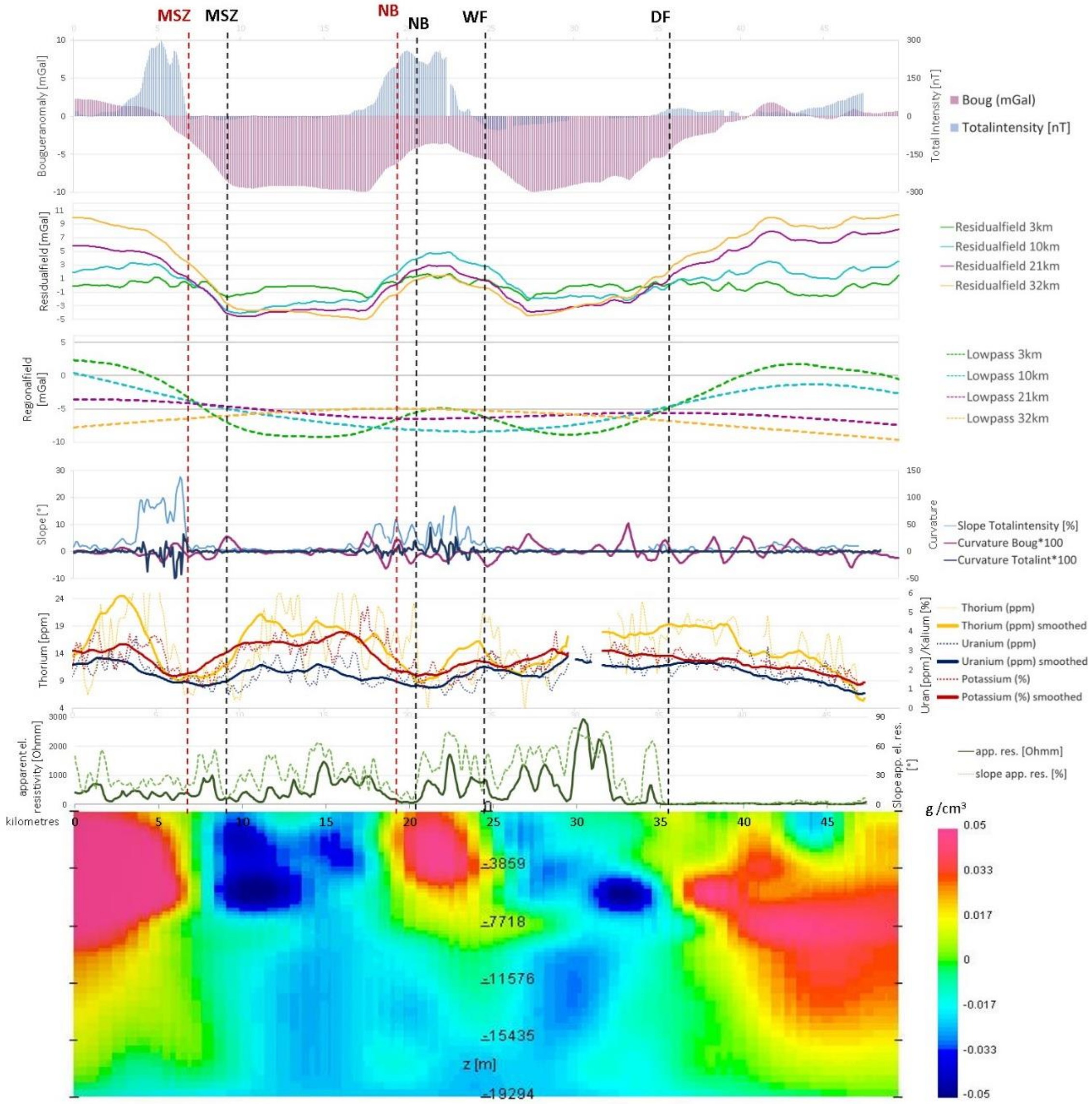


Figure 3-9: Comparison of different geophysical datasets and the respective transformations with the 3D-modelled density contrast (containing all wavelengths) along profile A and locations of the faults visible in the geological map (MSZ= Moldanubian Shearzone, NB = nappe boundary between two geological nappes, WF = Waitzendorf Fault, DF = Diendorf Fault. At the surface, MSZ and NB show a moderate dip towards the west, which might cause the shift between modelled location and geological map position

The following faults were selected as major structures (see Figure 3-8): The Diendorf Fault (DF) and the Waizendorf Fault (WF), two (N)NE-(S)SW striking left-lateral faults limiting as they limit the crystalline rocks in the NW from the Neogene sediments of the Molasse basin in the SE (Roetzel et al., 2002). However, geomorphology or surface geological mapping does not easily recognize the northern part of the DF, where it runs parallel to the WF, as it is supposed to continue mostly under Quaternary loess cover within the Molasse basin. Both, the DF and the WF limit the tectonic Thaya Window towards the east, where the Moravian Superunit is exposed (Figure 3-8). Towards the west, the Thaya Window is limited by the SW-dipping Moldanubian

Shearzone (MSZ), separating it from the Moldanubian Superunit. Within the Thaya Window, one major SSW-dipping, roughly N-S striking regional thrust separates the Pleißing and the Pulkau nappes, consisting both of orthogneisses of different compositions (Linner et al., 2019).This nappe boundary is indicated as NB.

view	method	field under consideration	tectonic structure				applied key GIS-tool
			MSZ	NB	WF	DF	
Graph along profile A	Gravity	Bougueranomaly	not visible	not visible	not visible	not visible	IDW
		Boug - Profile Curvature	visible with limitations	not visible	visible with limitations	not visible	Profile Curvature
		Regionalfield A (LP=3km)	visible with limitations	visible with limitations	visible	visible with limitations	Focal Statistics
		Regionalfield B (LP=10km)	not visible	not visible	not visible	not visible	Focal Statistics
		Regionalfield C (LP=21km)	visible with limitations	visible with limitations	visible	visible with limitations	Focal Statistics
		Regionalfield D (LP=32km)	not visible	not visible	not visible	not visible	Focal Statistics
	Magnetics	Total intensity	visible	not visible	visible with limitations	visible	IDW
		Total int. - slope	visible	not visible	visible	not visible	Slope
		Total int. - curvature	visible	not visible	visible	not visible	Profile Curvature
	AEM	Apparent Resistivity	not visible	not visible	not visible	visible	IDW
	Radiometrics	Uranium	visible with limitations	not visible	visible with limitations	not visible	IDW
		Potassium	visible with limitations	visible with limitations	visible with limitations	not visible	IDW
		Thorium	visible with limitations	visible with limitations	visible with limitations	not visible	IDW
Surface	Gravity	Bougueranomaly	visible with limitations	not visible	not visible	visible with limitations	IDW
		Boug - Profile Curvature	visible with limitations	not visible	not visible	visible with limitations	Profile Curvature
		Boug - Aspect Slope	visible with limitations	visible with limitations	not visible	visible with limitations	Aspect Slope
	Magnetics	Totalintensity	visible with limitations	not visible	not visible	visible	IDW
		Totalint. TIN / low z - tol.	visible	not visible	not visible	visible	Raster to TIN
		Totalint. TIN / high z - tol.	visible with limitations	not visible	visible	not visible	Raster to TIN
		Totalint. - slope	visible	not visible	not visible	visible	Raster to TIN / Slope
		Totalint. - aspect slope	visible	not visible	not visible	visible	Aspect Slope
	AEM	Apparent Resistivity	visible with limitations	not visible	visible	visible with limitations	IDW
	Radiometrics	Potassium	visible with limitations	visible with limitations	not visible	not visible	IDW
		Uranium	visible with limitations	not visible	visible	not visible	IDW
		Thorium	visible with limitations	not visible	visible	not visible	IDW
3D	Gravity	Density contrast	visible	visible	not visible	visible	-

LP= Lowpass
TIN=triangulated network
z - tol. = z -Tolerance
IDW = Inverse distance weighted interpolation

Legend: visible / visible with limitations / not visible

Table 3-10: Overview of the used GIS tools to explore vintage aero-geophysical data and their suitability to detect the respective fault positions.

The detection of geological faults in geophysical data sets relies on the circumstance that geophysical properties on both sides of the fault are different, mostly with an abrupt change. The capabilities of GIS tools in analyzing digital elevation models can be also used to explore and visualize geophysical data, which are helpful in gaining insight into the nature of data before modelling, or in case where no modelling software is available (Lobatskaya & Strelchenko, 2016; Luiso et al., 2016). We applied several edge-approximating GIS tools with varying starting conditions to the data sets. In addition, for the determination of four different gravity regional fields, the tool *focal statistics* is used. We then look for linear features in each of the datasets individually and finally compare the positions of the obtained lineaments with mapped faults in the respective area. Based on this comparison, we qualitatively evaluate the usefulness of each data set separately and the combined data sets in respect to detect geological faults and their characteristics (see Table 3-10). In addition, all data available at the location of all four faults are visualized by plotting them along profile A, aiming again to investigate their correlation with one another (Figure 3-9). The study will be submitted soon to Geosciences[3], providing detailed description on data processing and the applied GIS tools, and more in-depth interpretation.

Applicability for the HIKE Fault Database
The reuse of vintage datasets can pose challenges for modern geophysical modelling, due to missing detailed preprocessing information or significant uncertainties or lack of precise tracking, etc. Nevertheless, they are often the only available datasets in a target region and can contain valuable information concerning fault detection. We explore here the potential of such vintage airborne geophysical datasets (magnetics, AEM, radiometrics) to detect the location and dip direction of geological faults, using a non-modelling interpretation approach based on multiple edge-approximation GIS tools. We applied our approach in a geologically well-known region where four different types of faults are mapped. The applicability of the tools used in this study depend on the geological setting of each fault and is evaluated based on the comparison with geological data (see Table 3-10). In general, edge-approximation tools, especially used on a combination of datasets shows reliable results concerning the location and strike of faults, and even seems to be able to predict reliably the dip direction of a fault.

3.2.5 Fault detection based on shear wave seismic reflection data in Portugal

Summary
In Portugal mainland, while old geological faults can be mapped in outcrop, active fault slip-rates are low (< 1 mm/yr) and surface ruptures are easily erased by erosion and/or covered by sediments during the long recurrence rates, opening the way to the use of geophysical methods to locate and characterise active faults beneath the Quaternary cover. Co-seismic vertical displacements are usually below 2 m in Quaternary sediments. Among the several geophysical methods, seismic and ground penetrating radar (GPR) offer the best resolution. GPR is often problematic in areas where clays are present and the water-table is shallow. The shear-wave seismic method offers resolutions of the order of a few tens of centimetres and has been applied, in combination with the P-wave method, to locate and characterise several active faults in the Lower Tagus Valley region beneath the Holocene cover.

This is the case of the Azambuja faults (Carvalho et al., 2013), Porto Alto (Carvalho et al., 2012) and Vila Franca de Xira (Carvalho et al., 2016; 2020), for example. The studies performed by LNEG allowed to confirm that these faults have had activity in the last 14 K years, provided rough estimates of slip-rates, and contributed to increase the known fault length, therefore increasing the magnitude of the maximum expected earthquake.

Figure 3-11 shows the stacked section of one of the shear-wave profiles acquired over the Porto Alto Fault. The fault had previously been identified in oil-industry P-wave seismic reflection data which acquisition parameters were not adequate to image the shallowest 100 m of the

[3] https://www.mdpi.com/journal/geosciences

subsurface. An approximately 1 km-long P-wave profile was then acquired to locate an area where the fault was closer to the surface. Here, the shear-wave profile shown in *Figure 3-11* was acquired, using a seismic source that can reach an investigation depth of 70-80 m, and a receiver and source spacing of 1m.

The data was carefully interpreted analysing not only the stacked sections but also looking for evidences of faulting in shot gathers, common-depth-point gathers, the velocity field and the presence of diffractions (Ghose et al., 2013). The seismic section indicates the presence of several fault segments (some confirmed by a spatially coincident GPR profile acquired by the University of Évora), which confirmed that the fault had activity in the last 14 K years. Borehole data from nearby boreholes allowed to establish the depth of the Holocene alluvial cover and sedimentation rate. This information will make possible to estimate the maximum age of the last event that occurred in this fault segment.

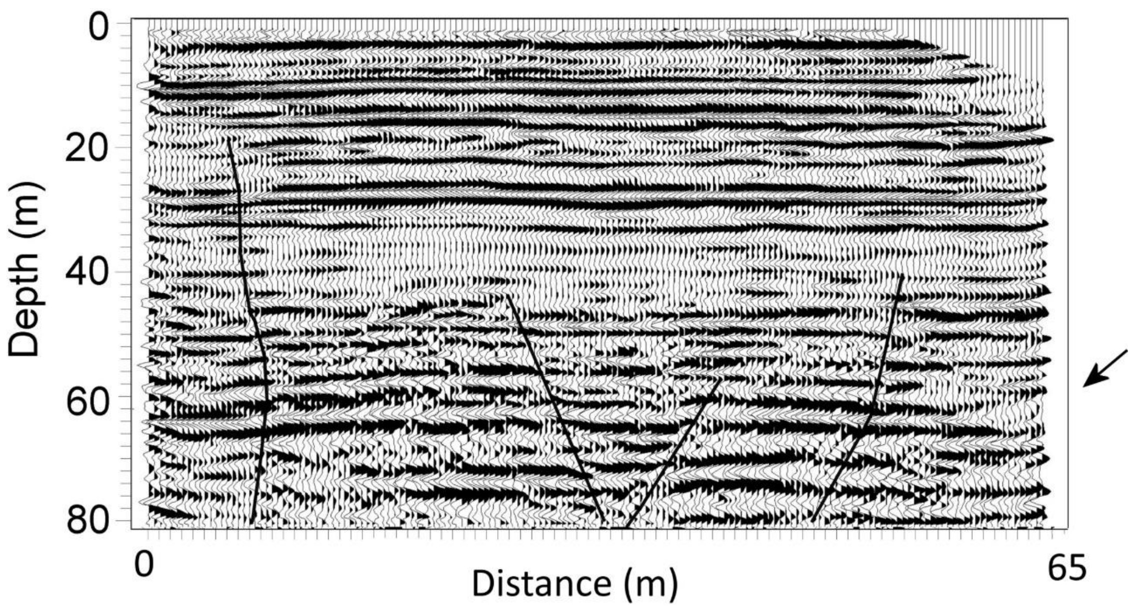


Figure 3-11: Porto Alto stacked shear-wave seismic section with fault interpretation overlaid. Black lines indicate interpreted faults (adapted from Carvalho et al., 2012). Arrow shows probable base of Holocene alluvium according to nearby borehole data.

The Vila Franca de Xira Fault, which is thought to be the source of the 1531 Lisbon earthquake that caused over 1,000 fatalities, was also revisited and geoelectrical, P-wave and shear-wave data were acquired, using the same approach as in Porto Alto: first acquire P-wave and geoelectrical data followed by surgically sited shear-wave data. The fault was observed to affect Upper Miocene formations and post-deformation was suggested but never before evidences of Holocene deformation were found. After the shallowest fault segments were identified in geoelectrical and P-wave data, shear-wave seismic profiles were acquired at two sites, Vila Franca de Xira (VFX) and Castanheira do Ribatejo (CDR), to investigate the fault under the Holocene alluvial cover (*Figure 3-12*a). The same interpretation flow of Ghose et al. (2013) was followed.

*Figure 3-12*b) and c) show the stacked sections acquired at VFX and CDR, respectively, with the location of interpreted fault segments indicated by arrows. Also available were borehole data including geophysical logs, at CDR, and cone penetration test (CPT) data and nearby boreholes at VFX. These data allowed, together with a stratigraphic framework of the region, to identify the major seismic reflectors observed in the stacked sections (Refl.i) and therefore estimate part of the fault's history (Carvalho et al., 2020). For this purpose and to confirm the interpretation carried out, 2D elastic and visco-elastic modelling were performed. The fault activity in the Holocene was confirmed and a vertical displacement of 3 m was estimated for a 14 K year aged geological horizon, while deformation was visible to affect another shallower geological interface with an age of 4 K years (Carvalho et al., 2020).

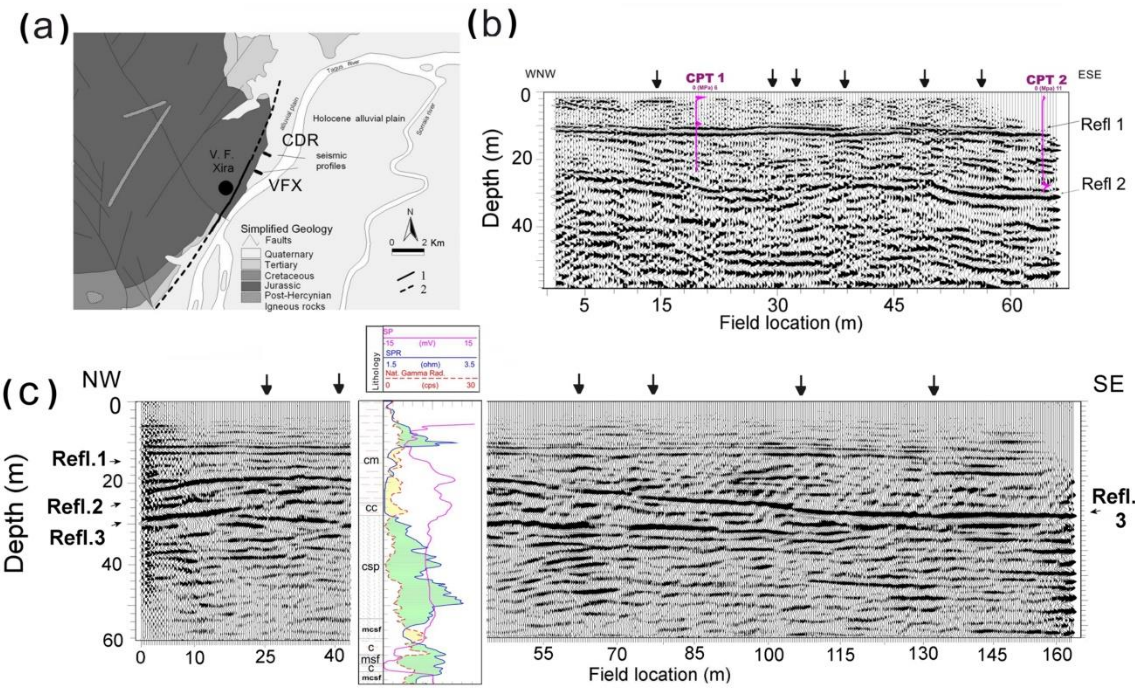


Figure 3-12: a) Location of shear-wave seismic data acquired at the holocene alluvial plain at Vila Franca de Xira (VFX) and Castanheira do Ribatejo (CDR), over the Vila Franca de Xira Fault (adapted from Carvalho et al., 2016; 2020). b) shear-wave stacked seismic section acquired at Vila Franca de Xira. CPT- location of cone penetration test. c) stacked section acquired at Castanheira do Ribatejo, showing also location of a borehole drilled over the profile and respective logs. Black arrows indicate location of interpreted faults. Refl.i indicate reflectors that according to nearby boreholes and the River Tagus stratigraphic framework correspond to intra-Holocene horizons.

Applicability for the HIKE Fault Database

Several active faults parameters, which are part of the HIKE Fault Database, have had their parameters estimated/updated based on geophysical data, namely shear-wave seismic reflection data. These are the case of the examples shown/mentioned above and of several other faults in the Algarve region, such as the Carcavai or S. Marcos-Quarteira faults, for example. The most striking example is possibly the Porto Alto fault. This blind fault was only identified and its parameters estimated using P-wave and shear-wave seismic reflection data. Data interpretation was corroborated by 2D visco-elastic modeling, nearby boreholes, GPR and two shear-wave cone penetration tests (SCPT).

3.3 Hydrocarbon exploration

3.3.1 Project GARAH: WP2 - hydrocarbon assessment, perspectivity and hazards (North Sea)

The aim of WP2 of the GeoERA - GARAH project is to produce a harmonized view on the energy resources in the North Sea Basin with specific focus on the conventional and unconventional hydrocarbon resources. In the context of this study, several GIS maps and geological data were collected that are of relevance for the assessment of hydrocarbon plays and prospects. The main task was to harmonize and evaluate these maps and to make them available for the general public and stakeholders. Another focus of this work package was the creation of two 3D basin models to give an example of the added value of detailed petroleum system modelling for the assessment of hydrocarbons (study areas see Figure 3-13). A third point of attention within the GARAH project was the compilation of a list of hazards related to hydrocarbon production as well as alternative/multiple-use of the subsurface.

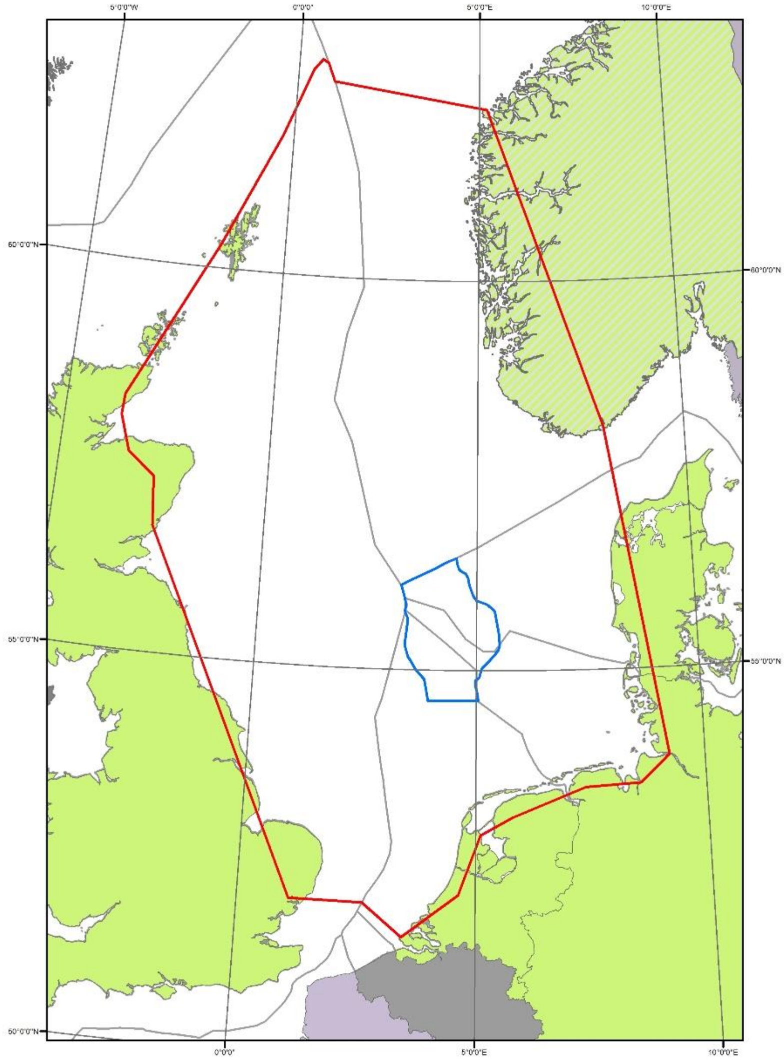


Figure 3-13: Map showing the study areas

Applicability for the HIKE Fault Database

The different work packages of the GARAH project have direct applicability for the Fault Database produced in the HIKE project. One of the main controlling factors for hydrocarbon generation, migration and trapping is the structural evolution of the area. The HIKE Fault Database provides a detailed overview of the age, location, direction and throw of the larger faults, allowing for better mapping of the play elements as well as providing an overview of possible migration routes. This information is relevant for the large scale HC play and prospect assessment but even more so for the 3D petroleum system modelling.

The 3D petroleum system modelling uses the burial and thermal history of a study area to calculate hydrocarbon generation, migration and accumulation volumes. For this purpose, the age and lithological properties (e.g., porosity, permeability, compaction, thermal conductivity) of the layers are used to construct a discretized numerical model. The model uses a deterministic forward modelling approach starting at the time of deposition of each layer until present day and reconstructing the burial and thermal history and related processes such as sedimentation, erosion, compaction, temperature, pressure. The theoretical and numerical background is described in detail in Hantschel and Kauerauf (2009). The information provided by the 3DGEO-EU project and the mapped faults in the HIKE Fault Database allow for a more detailed assessment of the burial and erosion history as the faults delineate specific boundaries of subsiding and uplifting areas as well as the timing of fault movement. Provided that the fault attributes also hold information of the actual offsets, such information can further enhance the 4D geological framework for basin analysis leading to a more accurate assessment of the hydrocarbon generation (Figure 3-14). It also gives additional information to help model possible HC migration routes from the source to the reservoir along open or across faults as well as model fault bounded reservoirs or possible leakage through faulted seals.

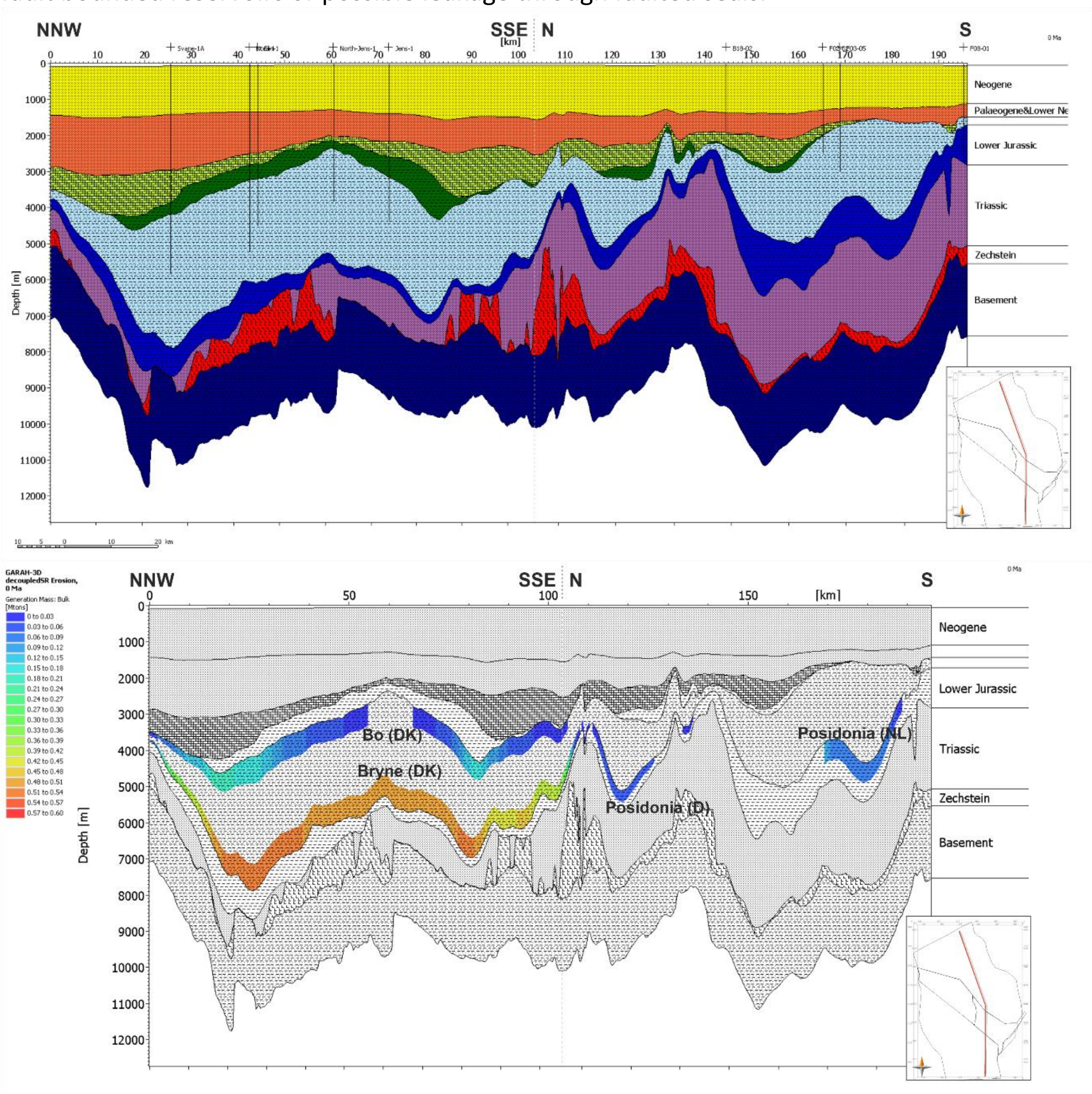


Figure 3-14: Example of a 2D transect through the current 3D model showing the current definition of (a) the main formations and (b) the hydrocarbon generation mass from the main source rocks included in the model. The red line on the inset shows the position of the transect.

The HIKE Fault Database is also of added value to the hazard and multiple use assessment of the North Sea basin area. Faults along or in producing reservoirs or in aquifers used for water or CO2 injection can have a risk of reactivation due to changing stress and therefore cause induced seismicity. By integrating the Fault Database with the location of known producing fields or aquifers used for CO2 storage or geothermal energy these risks can be visualized. Furthermore, faults can act as migration pathways and therefore can indicate areas with a higher risk of leakage of e.g., CO2 from subsurface storage locations.

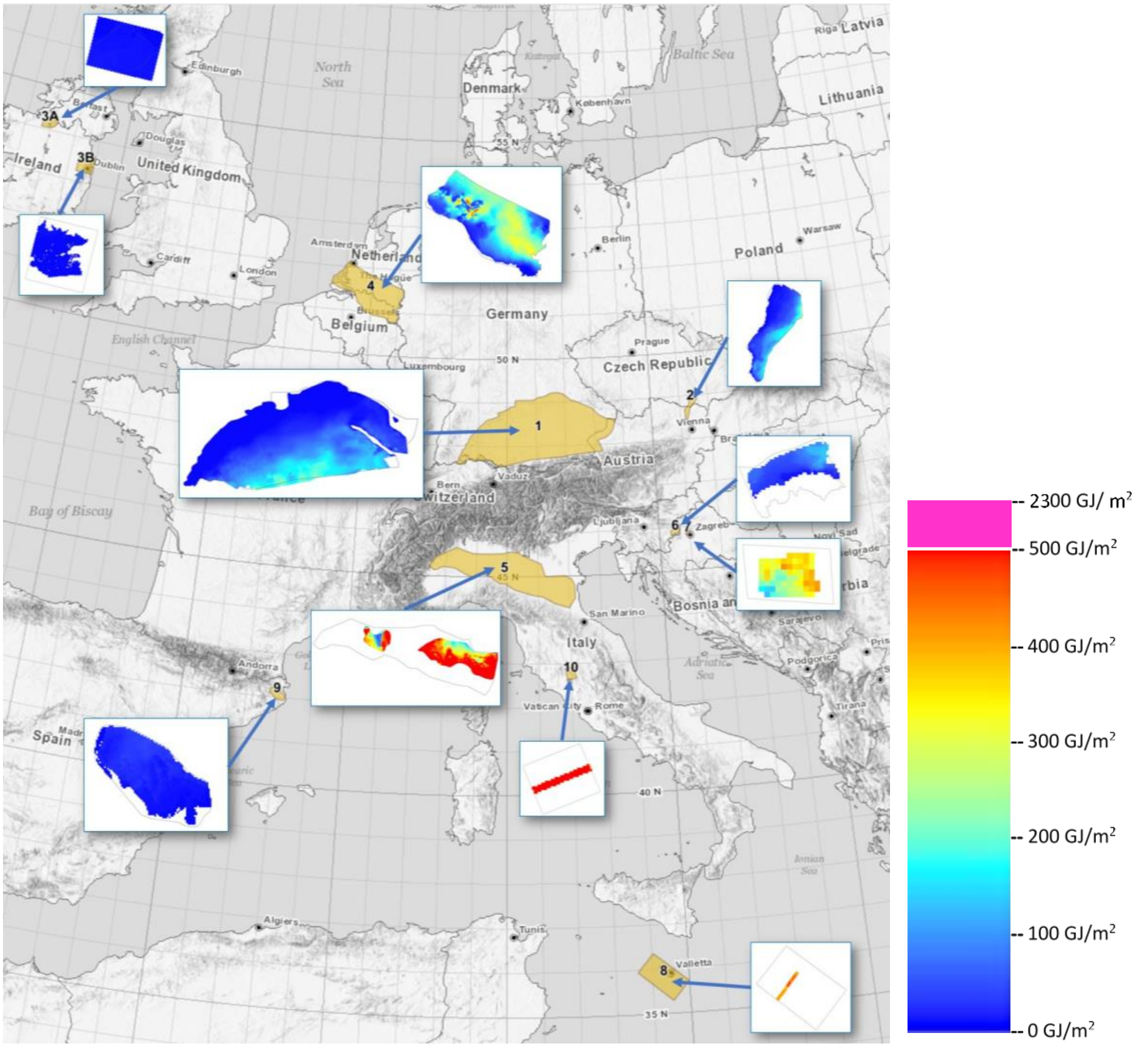
3.4 Geothermal Exploration

3.4.1 Project HotLime: Geothermal characterization and fault modelling

Summary

The HotLime project focuses on the mapping, characterization, estimation, comparison and prospect ranking of hydrothermal plays in deep carbonate rocks. Despite the significant geothermal potential in carbonate rocks world-wide, the exploitation faces many challenges deep drilling is required to encounter suitable temperatures. Moreover, deep carbonate formations are typically very tight and only able to generate sufficient flow in the presence of fractures/faults and karsts. Exploration and exploitation is consequently characterized by high drilling costs and large geological uncertainties.

Faults and fractures are considered crucial indicators for producible geothermal prospects in deep carbonate rocks. Dense fracture networks are typically found in the core and damage zones along faults. Fracture density and faults are observable in seismic data and therefore phenomena which can be mapped without the need to carry out highly expensive drilling campaigns.



1: Upper Jurassic carbonates in the central part of the North Alpine Molasse Basin (DE/AT)
2: Upper Jurassic carbonates in the Molasse Basin-Carpathian Foredeep transition zone (AT/CZ)
3: Carboniferous carbonates in (a) Lough Allen Basin and (b) Dublin Basin (IE)
4: Dinantian carbonates at the flanks of the London-Brabant Massif (NL/BE)
5: Upper Triassic to Middle Eocene carbonates of the Po Basin (IT)
6: Triassic carbonates of the Krško-Brežice sub-basin (SI)
7: Miocene and Triassic carbonates of Zagreb hydrothermal field (HR)
8: Triassic carbonates of the Pantelleria-Linosa-Malta rift complex (MT)
9: Eocene carbonates of the Empordà Basin (ES)
10: Triassic carbonates of Tuscan, Umbria and Marche nappes in the Umbria Trough (IT)

Figure 3-15 Location of HotLime's case study areas showing the stored heat (Heat-in-Place) of the carbonate reservoirs as depicted and elucidated in the HotLime Geothermal Atlas (Diepolder & HotLime Team 2021).

Figure 3-15 shows the 11 study areas which have been evaluated in HotLime, following a common workflow for mapping and geothermal base assessment and a concerted depiction for comparison. This workflow for estimating the Heat-in-Place (Muffler & Cataldi 1978) minimally requires of the following parameters for geothermal base assessment:

- Depth and geometry (volume) of the reservoir
- Fault distribution pattern (also as areas of secondarily enhanced permeability and so higher production favorability leading to a reduced exploitation risk)
- Temperature of the reservoir (broad-brush average or depth serialized)

Depending on the local data situation, additional assessment steps could be implemented such as fully 3D reconstructions and integration of reservoir models and faults in depth domain. For now, the inventory of the fault traces at the top of the reservoir is an overlay to all maps indicating primary conduits for hydrothermal fluids and zones of possibly higher, but not quantifiable Heat-in-Place (see the HotLime Geothermal Atlas and Factsheet Faults).

Applicability for the HIKE Fault Database

HotLime's case studies have resulted in a variety of multidimensional spatial information sets for the determination of deep geothermal potential in carbonate rocks. These datasets include among others fault maps and models. HotLime has closely collaborated with the HIKE project to establish a common approach to map, characterize, store and disseminate fault information. Above all, both projects use the same Simple Knowledge Organization System (SKOS) within the Linked Open Data Semantic Web which underpins the fault and tectonic boundary vocabularies. One of HotLime's main areas in the southern parts of Germany (#1 in Figure 3-15) has been selected to demonstrate the cross-border correlation of faults.
The assessment of deep geothermal potential in carbonate formations as presented by the HotLime project, is one of the potential key applications for the HIKE Fault Database. This combination is considered essential for GeoERA's follow-up programme "CSA Geological Services for Europe" which is expected to start in 2022. This programme focuses among others on the development of a pan-European atlas for geothermal resources. The combination of HotLime's workflows and the information in HIKE are an import basis for the evaluation of this potential

3.4.2 HIKE Task 3.1: Iceland, geothermal

Summary

The HIKE project includes Iceland´s fault and structural elements database that is primarily based on the Geological Map of Iceland - Bedrock data compilation project at a scale of 1:600.000 by *Hjartarson and Sæmundsson (2014)* and represents the regional structural data coverage (Figure 3-16). The database includes the results of half a century of surface fault mapping across Iceland (e.g., Einarsson *and Sæmundsson, 1987; Erlendsson and Einarsson, 1996; Einarsson et al., 2002; Clifton and Kattenhorn, 2007; Einarsson, 2008; Hopper et al., 2014; Hjartardóttir et al., 2015; Magnúsdóttir et al., 2015*) that were routinely conducted during geothermal field exploration, as well as academic projects within the volcanic zones and around central volcanic systems across Iceland. Assessing the primary fault system of a potential geothermal system is used as a first step of delineating such field area. Detailed smaller scale field mapping campaigns are added to the fault and structural elements catalogues, as exploration of a geothermal system progresses into a field production and development stage.

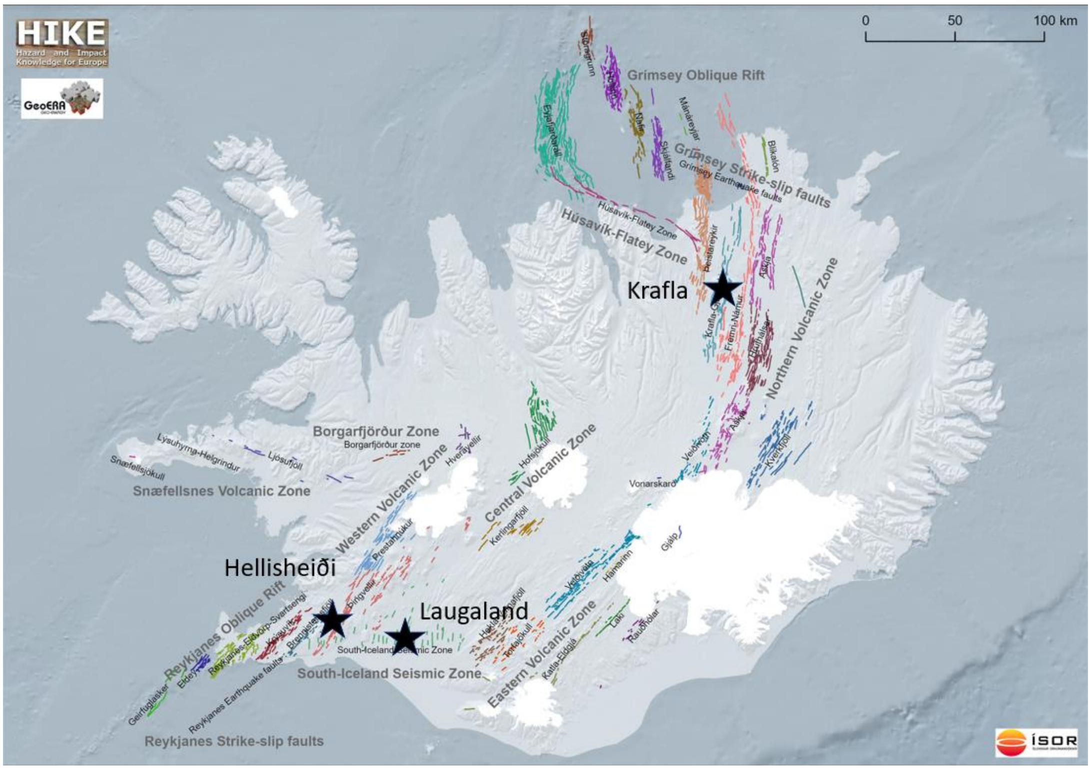


Figure 3-16 Map of Iceland showing the Icelandic faults available in the HIKE Fault Database. Locations described in the text are as shown as black stars.

A sound understanding of the subsurface structural framework in geothermal systems is implemented in conceptual or steady-state geological models. Such frameworks are crucial for geothermal exploration or development projects by providing an essential data input for comprehensive visualization of structure and flow-path geometries in any high- or low enthalpy system under investigation (*Guðni Axelsson, 2013*). Information from structural surface mapping are primary input data for these structural framework models besides the recording of reservoir typical parameters, such as temperature, pressure, permeability, or fluid chemistry. A structural framework model describes and highlights the main permeable productive zones (feed-zones) in a geothermal reservoir. Most feed-zones encountered in Icelandic geothermal fields are connected to fault or fracture systems that are closely linked to intrusive dyke or sill segments of fissure systems. Geological stratigraphy and layer boundary associated permeability is observed to a lesser degree. Furthermore, good subsurface fault mapping is of importance, as fault systems can act as barriers to fluid flow or reservoir temperature as well (*Khodayar et al., 2015*).

An example of a low-enthalpy system is Laugaland í Holtum in the south of Iceland (*Olsen, 2014; Sæmundsson and Hafstað, 2015*). It is one of numerous low to medium temperature geothermal areas located within the South Iceland Seismic Zone (SISZ), a transform fault between the Western Volcanic zone, Reykjanes Oblique Rift, and the Eastern Volcanic Zone (Fig. 1) (Flóvenz et al., 2015). The 97°C – 104°C hot water from the Laugaland field has been used for spatial heating since 1982 (*Flóvenz et al., 2015*). The operation in Laugaland targets roughly N-S striking strike-slip faults that are characteristic of the SISZ and are included in the HIKE Fault Database.

In 2000 injection into the field started as a way to mitigate pressure draw down in the system. Shortly after a M 6.4 earthquake occurred with epicenter ~6 km away from the production wells in Laugaland. There have been speculations that the pressure increase following the onset of injection triggered the large magnitude event (Flóvenz et al., 2015). The documenting and mapping of all faults in the SISZ is therefore very important for accurate hazard assessment.

Traditionally in Icelandic high-enthalpy geothermal systems, production wells have been placed in the centre and most active part of a rift graben, and closest to active fault-fissure systems, such as within the Hellisheiði high-enthalpy geothermal field (e.g. *Sæmundsson, 1967; Franzson et al., 2005*). Injection wells on the other hand, have been placed along the outer rift graben border fault systems and along the edges of temperature anomalies that are well distanced to the production wells and fault-fracture conduits, as to avoid direct cold-fluid incursions into the reservoir that presented a major problem for the Hellisheiði high-enthalpy geothermal field (e.g. *Gunnarsson et al., 2010; Gunnarsson, 2011*). Linked to the Hellisheiði field is the Húsmúli injection zone that is located along the NW boundary fault system of the Hellisheiði field area. Here, the geothermal field production is supported by 5 injection wells that were drilled in between 2007 and 2011. Prominent NE-SW striking normal faults that are featured in the HIKE Fault Database, are the main targets of the wells, as the injected fluids travel along the fault systems back into the ground, and thereby recharge the geothermal system and mitigate pressure draw down (Figure 3-17). This has been done successfully in most high-enthalpy fields in Iceland. Induced seismicity is observed and must be managed, but large seismicity events (> M1.5 events) are rare (e.g., Gunnarsson, 2011; Flóvenz et al., 2015). Figure 3-18 shows a three-dimensional model of the faults of the Husmuli area, their subsurface projection, and comparison to the main encountered injection zones of injection well HN-09. The well was drilled and logged in 2007 to 2008, which enabled near vertical sub-surface fault zone projections. These projections were based on surface fault zone observations and temperature and lithology log analysis for the primary injection- and feed-zones

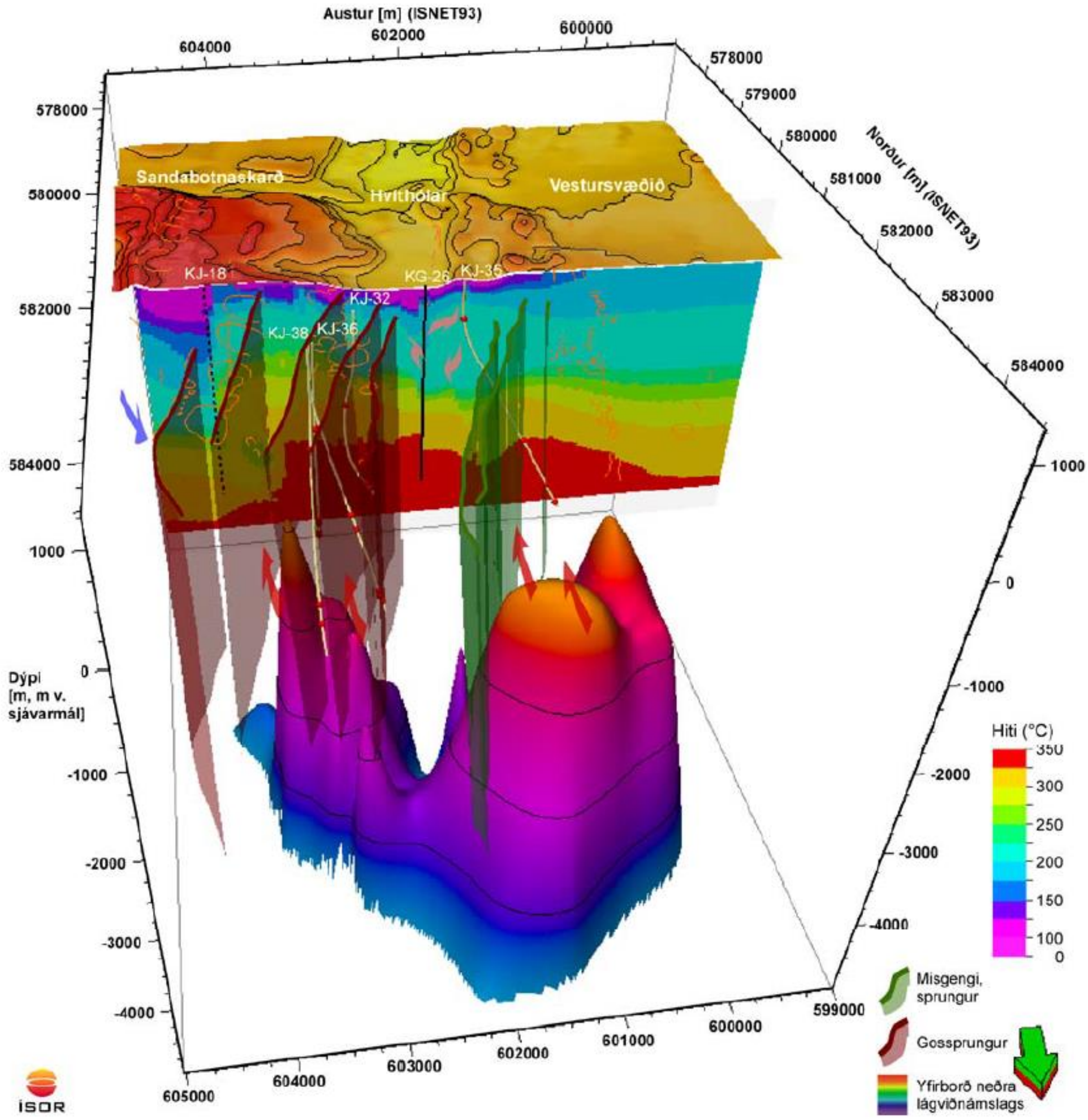


Figure 3-17. North view onto the 3D conceptual model of the Krafla high-temperature geothermal system. Faults are outlined by green planes and fissures by red planes that are vertically projected downwards from their surface expressions (Sæmundsson, 2008; Jóhannesson & Sæmundsson, 2009). The rainbow-colored surface shows the top of the lower low resistivity layer based on a 3D MT-TEM model. Red arrows show the location of upwelling and blue arrows the location of cold inflow. The cross section in the back shows the logged and modelled in-situ temperature distribution (Mortensen et al., 2009).

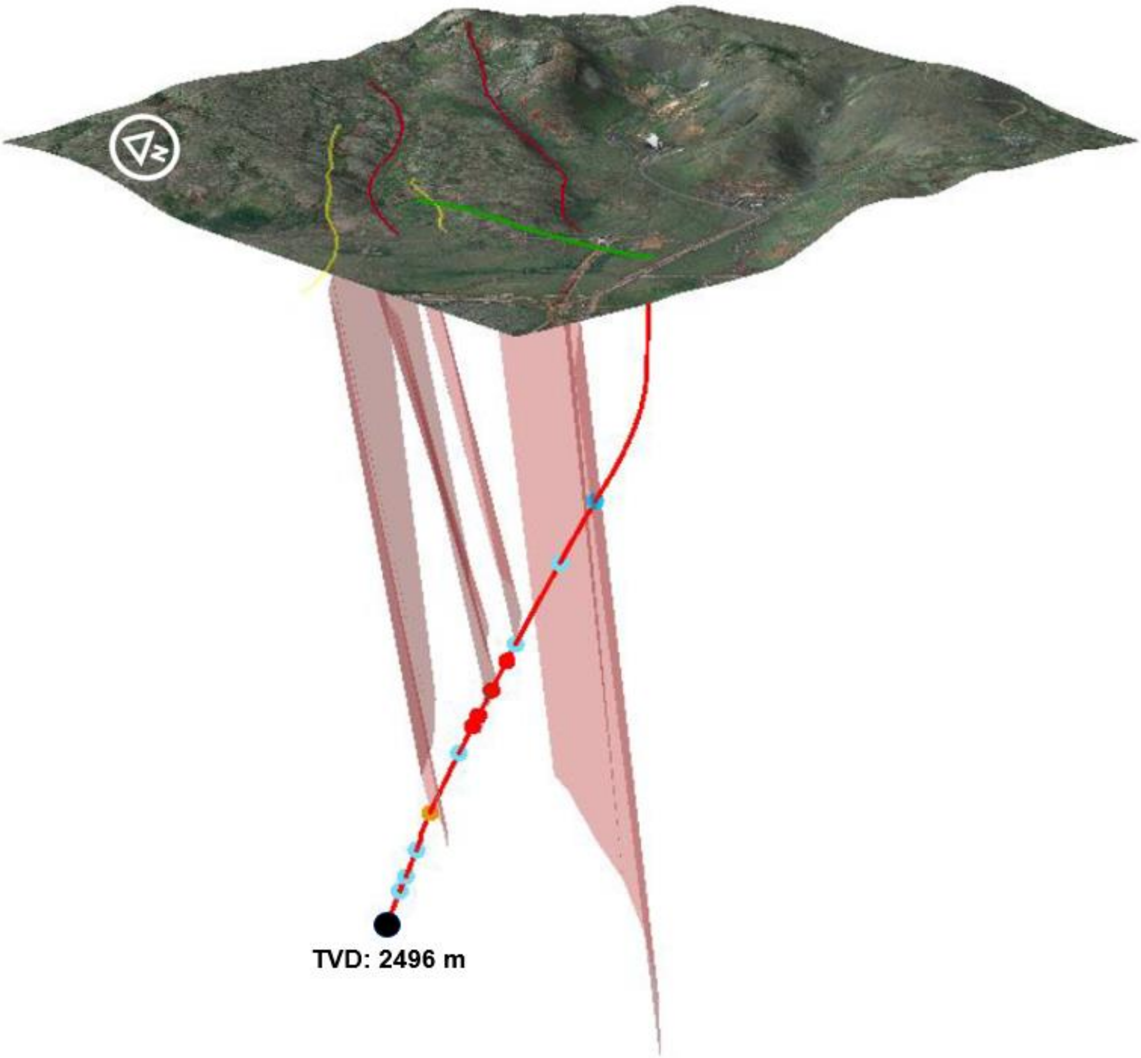


Figure 3-18. A southwest view of the 3D visualization model of the near vertical (6-7° due SE dipping) Húsmúli fault zone that is located close to the north-western edge of the Hellisheiði geothermal system. The fault system intersects borehole HN-09 and is shown in red with its main feed-zones displayed as red and blue circles. Modified from Harðarson et al., 2008.

A new method for the sequestration of CO_2 has been developed in Iceland within the Carbfix project (Snæbjörnsdóttir et al., 2018, www.carbfix.com). The highly successful method pumps CO_2 into the subsurface, where it is turned into calcite, $CaCO_3$. CO_2 enriched water is injected into prominent normal faults, which allow for injection under low pressure conditions. The pressure, temperature, and fluid pH conditions must be just right for calcite to form (Snæbjörnsdóttir et al., 2014; Snæbjörnsdóttir et al., 2017; Snæbjörnsdóttir et al., 2018, Clark et al., 2020). The first injections in the Carbfix project took place in the Gráhnúkar area south-east of the Hellisheiði geothermal power plant, but in 2014, CO_2 sequestration started in the Húsmúli injection field just north east of the power plant. The condition Húsmúli appear to be perfectly suited for sequestration.

Applicability for the HIKE Fault Database
The fault and structural elements compiled within the HIKE Fault Database give valuable data input for future exploration of high to low-enthalpy geothermal systems in Iceland. Although presently the demand for electricity is sufficiently covered for the country, new geothermal fields will have to be developed in the future, as the demand for hot water for e.g., space heating is rising, and electricity supplies need to be maintained. Furthermore, will it be necessary to drill infill production boreholes into existing geothermal fields, which are in active utilization, as well as infill injection boreholes to identify suitable areas for continued injection of wastewater. Here, surface fault mapping plays a crucial role in combination with subsurface micro-seismicity recordings and borehole fault projections. Future borehole planning will continue to aim at identifying interception points of new wellbores into surface to sub-surface projected fault structures, which have proven to be great pathways for geothermal fluids.

3.5 Geological storage

3.5.1 Project HIKE Task 3.3: Reservoir sealing assessment

Summary
Task 3.3 of the HIKE project covered modeling of fault sealing potential within the Wysoka Kamieńska graben, located in the NW part of Poland. The investigated structure comprises a currently depleted oil field, from which 0.42 mln tons of crude oil has been exploited since 1972. Previous interest in the investigated area by the Polish Oil and Gas Company allowed for the gathering of the geological and geophysical data, reused for analysis of the structure and evolution of the graben. Performed analysis and fault sealing potential assessment was used in the project of hypothetical underground storage, located within the Jurassic formations (Bobek et al. 2021).

The input model provided by the data owner comprised an interpretation of the 3D seismic survey covering an area of 40 km^2. The acquired dataset included nine main seismic horizons and segments of 42 faults of various sizes and throws (Figure 3-19). The input model has been supplemented by the geophysical logging data from five boreholes located within the investigated graben. The dataset from borehole logs allowed to reconstruct the lithostratigraphic units, separately for the interior and exterior of the graben. The main seismic horizons, horizons for lithostratigraphic units and fault segments have later been transferred from the Petrel to the T7 software, where have been combined into 3D gridded surfaces. Polygon lines created at the contact of fault surfaces with the hanging wall and footwall horizon surfaces enabled calculation of the fault throw, juxtaposition plots, and shale gouge ratio used for the fault sealing potential assessment.

The assessment of the fault sealing potential is based on the assumption that this parameter is governed by two components: (1) the sealing properties of the strata juxtaposed on both sides of the fault (juxtaposition component of seal) and (2) the sealing properties of the fault zone itself (fault gouge component of seal) (Yielding et al. 1997, 2010). The juxtaposition component enables an indication of the possible communication pathways between the reservoir blocks on the opposite sites of the fault plane. Respectively, the gouge component is dependent on the lithology of the host rock and the throw of fault. Modeled juxtaposition plots in the graben boundary faults indicated, that the Triassic sequence is generally well-sealed while the major part of Jurassic formations seems to be poorly sealed. The gouge component has been evaluated on the ground of the so-called Shale Gouge Ratio (SGR). The accepted thresholds for SGR (SGR of <20% is characteristic of non-sealing disaggregation-zones, while values growing in a range of 20%<SGR <50% indicate successively growing fault sealing potential and SGR of >50% points to a perfect seal) implies a generally good seal within Triassic layers, while the sealing potential of Jurassic formations decreases upwards.

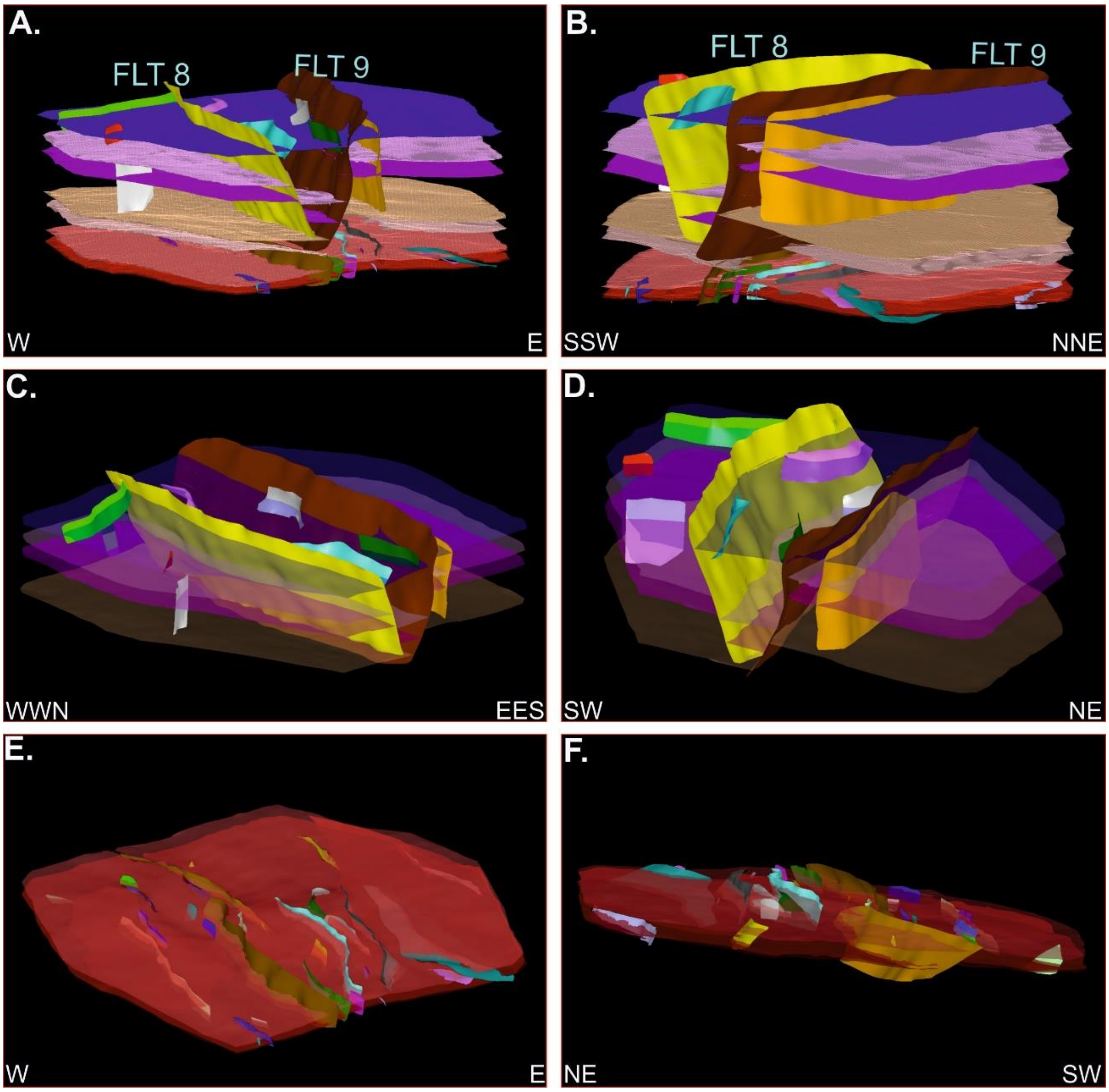


Figure 3-19: A set of faults and horizons recognized as a result of seismic interpretation (A and B). The biggest faults were detected within the Mesozoic formations (dark blue horizon - Lower Jurassic, light brown - the top of Zechstein), where two main faults create a striking NNW - SSE graben (C and D). More faults were detected within the Zechstein layers (red horizons), but their throws are generally smaller (E and F).

Applicability for the HIKE Fault Database

Recognition of faults and their attributes is a crucial part of fault sealing analysis. Within the used T7 software, interpreted seismic-scale faults are stored in the form of sticks (also called "fault segments") or/and gridded surfaces (Figure 3-19) at specific coordinates in the 3D space. Created 3D models of faults (Figure 3-20) can be exported to the shapefile and stored in the Fault Database. However, since we do not have performed the interpretation of the seismic survey ourselves (lack of seismic image in a depth domain), faults in form of segments are not available for the Wysoka Kamieńska graben.

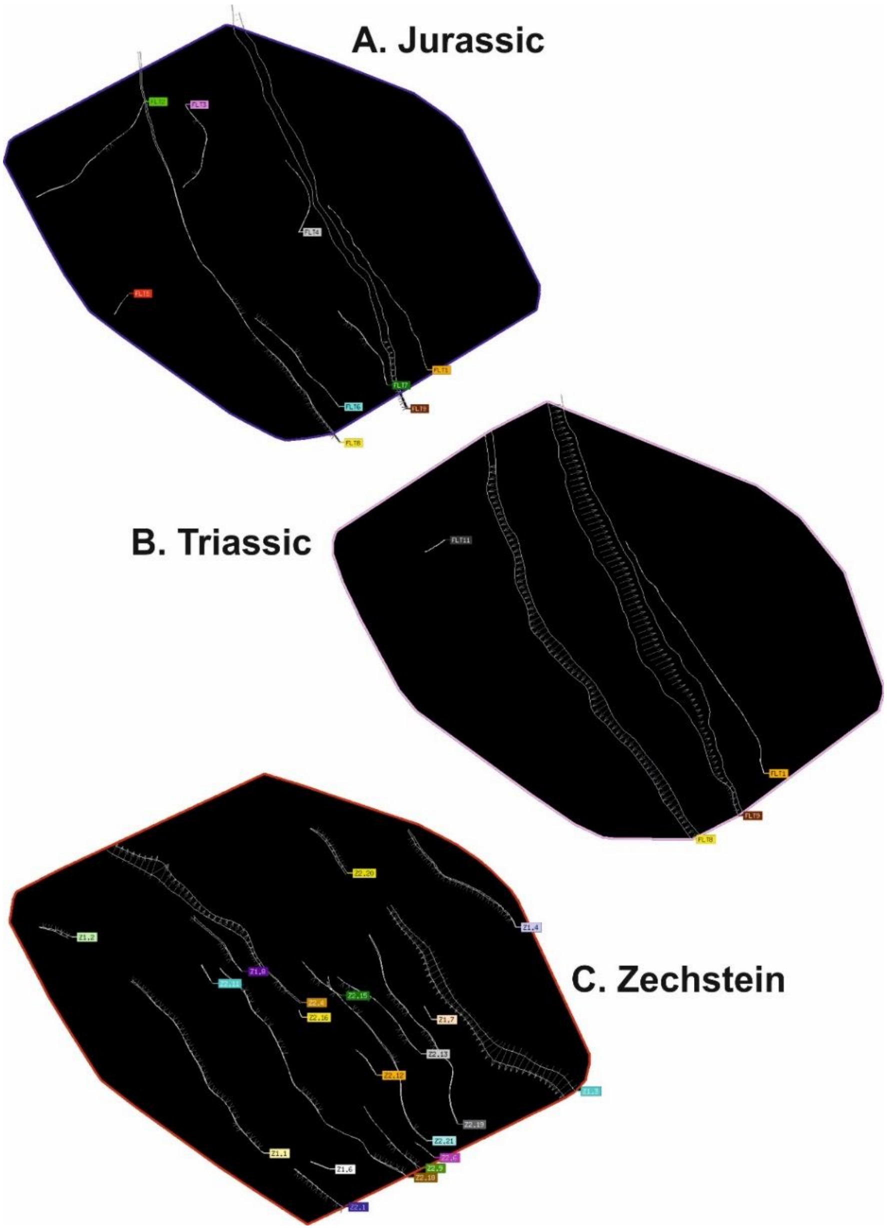


Figure 3-20: Example of polygon maps generated in T7 software for the selected seismic horizons. Every fault polygon may be converted into a shape file and stored in the Fault Database.

Aside from the 3D representation, faults within the T7 software can also be stored in the form of 2D polygon maps. The term "polygon map" means one closed or two open lines created at the points of contact between the footwall and hanging wall of a particular horizon and a fault surface. In T7 software fault polygons are created for all horizons interpreted from the seismic survey and isochores derived from boreholes data within the coordinates constrained by the created project. Every fault polygon may be exported to the shape file and stored in the database.

Modeling of fault sealing potential in the T7 software includes also a calculation of faults' attributes. 3D faults representation acquired from seismic interpretation allows calculating attributes such as strike azimuth, dip direction and angle, throw, surface coordinates (x, y, z), and length of every detected fault. All calculated attributes can be exported as numerical values into an Excel spreadsheet and complement the Fault Database.

On the other hand, the information stored in the Fault Database may also be used for fault sealing analysis if additional data from boreholes are available. Assuming, the Fault Database contains the shape files of 3D fault representation (sticks or surfaces) from the investigated area, the available set of faults may be imported to the software and proper modeling can be performed. In the case of the potential interest of the area covered by the data in the Fault Database in terms of hydrocarbon exploitation, CO_2 sequestration, etc., the fault sealing analysis may be performed even, if the raw seismic survey is not available. Thus, using a Fault Database in such a study may save the time required for seismic data interpretation.

3.5.2 HIKE Task 3.4: Seismicity and Storage (France)

Summary

The Lacq-Rousse area (Southwestern France) encompasses a depleted gas field whose commercial exploitation ended in 2013. The field was used for a CO2-injection and storage experiment in 2010-2013 (51 kton total injected CO2). Although no induced earthquakes ware registered during the CO2 injection phase, several earthquakes occurred since 2014 with a magnitude up to 4.5. It is an important task to distinguish if the earthquakes were induced, triggered or caused by natural processes.

With a precise mapping of many seismic events, it is generally possible to identify which fault structures have been activated. However, due to the sparse station distributions and the isolated occurrence of earthquakes with no obvious aftershocks in the Lacq-Rousse area, error ranges can be as high as a few kilometers. Then again, a single earthquake can provide useful information with moment tensor solutions to verify the coherency of the mechanism with the known fault structure and tectonic settings. Throughout the HIKE project, BRGM has archived the available catalogs and performed the moment tensor inversions of moderate earthquakes using full waveforms to complete the knowledge in the area (Figure 3-21). The results provide the following insights for the area, consistent with the known orientations of the faults and tectonic stress:

- There are no moderate earthquakes in the reservoir.
- Shallower earthquakes (around 4 km) infer the relaxation of the upper crust above the reservoir. (e.g. the normal faulting of the 2016/04/25 earthquake)

- A deeper earthquake is likely to relate the naturally active fault systems. (e.g. strike-slip faulting of the 2020/06/03 earthquake).

Applicability for the HIKE Fault Database

The obtained focal mechanism of earthquakes is necessary to interpret the known faullt system. The earthquakes of interest occur at greater depth and as a result it is still difficult to identify which fault of the map is ruptured. However, the comparison (Figure 3-21) allows to assess the consistency of the earthquake in the known stress field. Without the fault maps, one cannot carry out such important task as to identify wheteher the earthquake is induced (directly related to the reservoir operation), triggerred (outside of the reesrvoir, indirectly related to the reservoir state) or caused by natural processes (no obvoius link to activities in the reservoir). The challenge stil remains in the fact that most faults are embedded at depth around the reservoir. The expected fault mechanisms can be different for various depth ranges. For further investigations it will be necessary to map not only the major fault traces but also secondary, embeded faults surrounding the reservoir. It will be useful to accompish the stress field analysis in and around the reservoir, according to the systematic analysis of the focal mechanism as well as surface deformation if detectable.

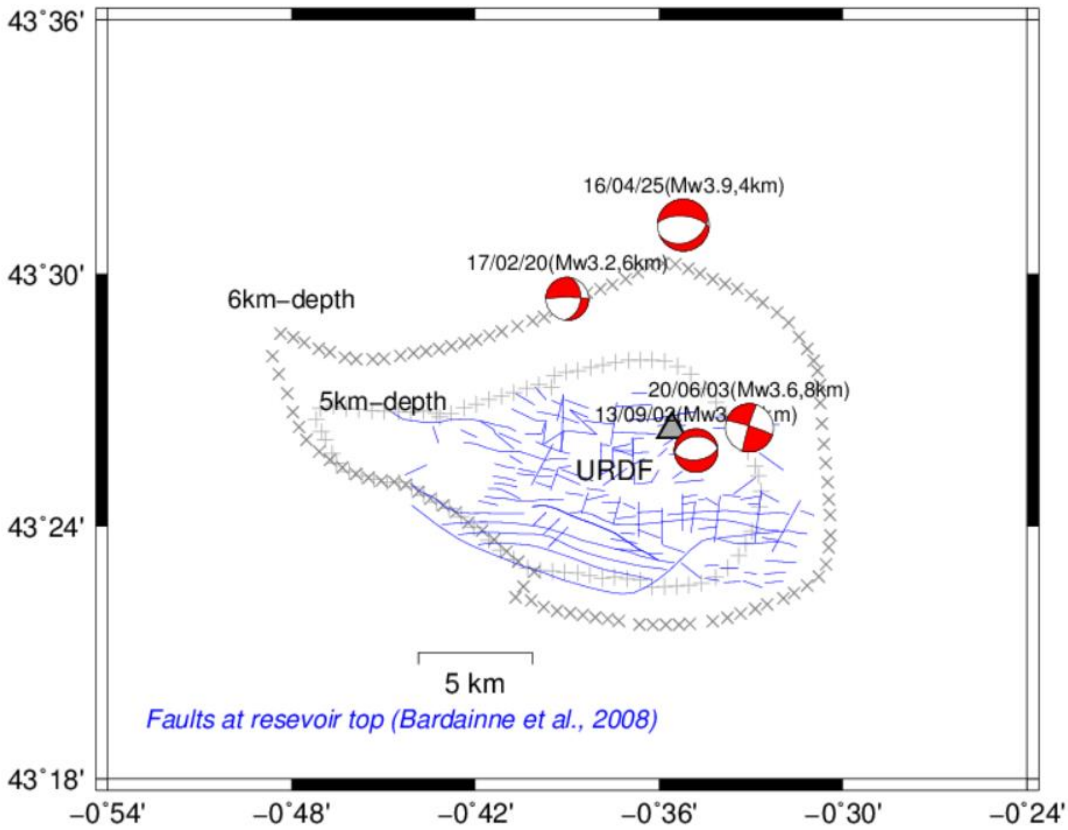


Figure 3-21: Location map Lacq-Rousse with faults at top reservoir

3.6 Natural and induced seismicity

3.6.1 Project HIKE Task 3.1: Localization of seismicity, NL/DK

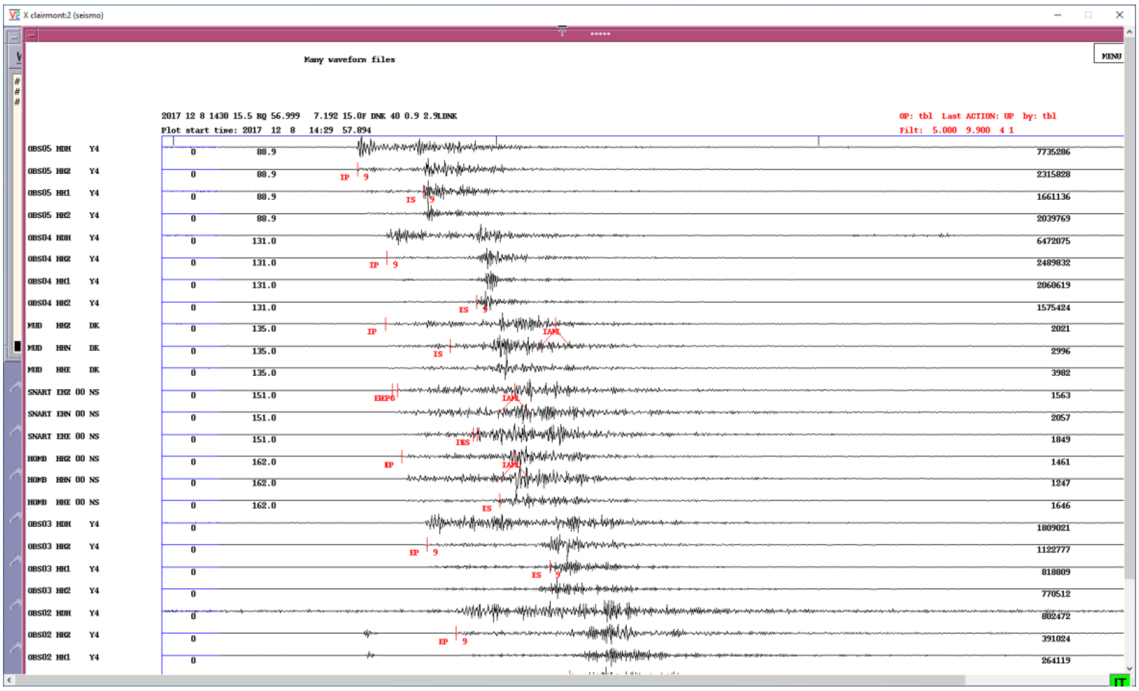
Summary

Earthquakes carry important information on the current state of stress in the subsurface as well as information about the location of weaknesses. Energy exploitation activities and energy storage are inherently connected to changes in pressure in the subsurface. Different pressure changes are applied depending on the level of activity. Especially rapid changes in pressure are known to lead to induced and triggered earthquakes (Ellsworth, 2013; Bommer et al, 2015) and in some cases lead to reactivation of otherwise stable and unknown faults (Horton, 2012). Even smaller felt earthquakes can generate considerable interest and concern in the general public and in some cases, increased small magnitude seismicity is an indication of larger events to follow.

Small earthquakes can be elusive and hard to locate precisely due to low signal-to-noise levels, insufficient number of seismograph stations as well as over simplified methods and subsurface models. These challenges need to be overcome to be able to more accurately relate micro-seismicity to anthropogenic activities, and to be able to relate earthquakes to individual faults – both known faults and faults previously unknown.

Improved determination of hypocenter solutions can be achieved in several different ways: a) improved recording of the events, b) improved velocity models, and c) improved analytical methods. Aspects of all three approaches have been explored.

Incorporating data from Ocean Bottom Seismometers (OBS) when locating offshore earthquakes has the potential to improve hypocenter precision. Data from the seabed have been shown to be of a high quality with high signal-to-noise ratio, and the data has successfully been combined with data from land-based seismographs. However, there are several challenges related to OBS data: the instruments do not have connection to satellites during deployment, and the time stamps on the data are dependent on the internal clock of the instruments. The internal clock is drifting and the absolute times of P- and S-wave arrivals cannot be used. Instead the differential P-S time is used in the analysis. The lack of real-time data from an OBS makes it unsuitable as a component in a mitigation system but shows great promise for improved hypocenter determination when real-time solutions are not required.



Seismograms from OBS'es and onshore seismographs from an earthquake in the North Sea on 2017-12-08. The earthquake magnitude was 2.9ML

Locating an earthquake recorded on a network of seismographs involves solving the wave equation for P- and S-waves propagating through the subsurface. The velocity model is a critical a priori parameter, and the solution is highly dependent on the quality of the model. Applying station corrections to a 1D velocity model has been demonstrated to improve the hypocenter solutions, placing them closer to known faults with less scatter in the locations, both horizontally and vertically. Likewise, an improved velocity model based on local data can reduce the scatter.

Finally, the non-linear Monte Carlo based analysis software NonLinLoc was tested on data from Iceland, the Netherlands and Denmark. The software turned out to be very difficult to get to work properly, in particular the choice of grids for the velocity model as well as the search grid for the solution were non-trivial. However, good results were obtained in Iceland. Further work is needed to explore and master the full potential of this method.

Applicability for the HIKE Fault Database

Faults are an important factor when assessing subsurface stability. Large fault systems as well as smaller individual faults constitute zones of weakness where sudden release of energy in the form of earthquakes may occur.

Using standard earthquake analysis tools and the commonly available data often results in hypocenters with uncertainties too large to connect a specific earthquake to a specific fault. The seismicity mapped in this manner is useful for determining the general seismic hazard in the area, but it is insufficient to discern if a given fault is active or not.

Reducing the uncertainty on the hypocenters can lead to better distinction between active and passive faults. In connection with subsurface projects such as CCS it is critical to know if a fault inside or close to a reservoir is active or not.

A high quality fault database as well as precise hypocenter determination is crucial for detecting the first signs of instability as expressed in small induced earthquakes. A detailed Fault Database playing in concert precise hypocenter determination is a critical pillar in safe storage and exploitation. Together this can form the basis for efficient mitigation such as the Traffic Light System (TLS).

3.6.2 Seismic Hazard Assessment for Geothermal projects and licenses (Netherlands)

Summary

For any subsurface activity whether it is oil or gas extraction, subsurface storage of energy carriers or residues, coal mining, salt production or geothermal heat production, subsurface conditions are influenced in the form of a pressure and/or temperature perturbation. This pressure and temperature perturbation does change the subsurface stress condition to a certain extend and consequently may result in subsidence and seismicity. Seismicity may occur when the critical shear failure threshold of an existing fault is overstepped and fault reactivation is induced. Induced seismicity may pose a risk, either a nuisance, damage or safety risk, when it exceeds a certain magnitude.

It is mandatory for geothermal operators to submit a production plan which includes a seismicity hazard and risk assessment (SHRA) next to elements such as a prognosis of the amount of heat production, operational settings and interference with other subsurface activities. At present there is a guideline how to address the SHRA in the production plan document submission (Q-con GmbH & IF Technology B.V., 2016). However, based on the lessons learned in the first years of production plan evaluations it was concluded by the Ministry of Economic Affairs and Climate (MEA) that this guideline is an adequate first version of an SHRA methodology, but that an update is necessary to align with changing production strategies and new insights in the seismicity issue and prevent ambiguity in the interpretation of the key elements to address. Therefore, a project was initiated to define an improved version of the SHRA for geothermal systems. This project is currently still in progress, but the framework has already been defined. The assessment starts with a screening of the seismicity hazard. One of the key questions in this screening procedure that needs to be answered is whether the geothermal project is situated in an area which is naturally sensitive to seismicity. In the Netherlands, the Larger Ruhr Valley Graben Area is such a seismicity sensitive area. Additionally, it is thought that large fault zones bounding the main structural elements (e.g. Kombrink et al., 2012) are such seismicity sensitive areas. These so called ‘major relevant fault zones’ comprise multiple amalgamated faults which, to a large extend, show an offset of Late Cenozoic strata, can be linked to past tectonic earthquakes and are to some extend situated in areas where induced seismicity is prominent.
For a simple and unambiguous execution of this key-element analysis the idea is to compile and release a reference map with the defined ‘major relevant fault zones’. The purpose of this map is to serve as the reference map on which the area of influence of a geothermal system is plotted. When the geothermal area of influence overlaps with a major relevant fault zone or has a certain proximity to two or more faults within the fault zone, then the seismicity hazard for this specific key-element is regarded as “not negligible” and a more detailed hazard and possibly risk

assessment is foreseen. For the compilation of this ‘major relevant fault zone’ reference map the HIKE Fault Database is used.

Applicability for the HIKE Fault Database

In the HIKE Fault Database of The Netherlands, the faults are classified in three categories, namely:

- Level 1: individual faults from the regional interpretation by the TNO geomodelling department,
- Level 2: individual faults observable on seismic data which bound structural elements (e.g. as defined by Kombrink et al., 2012) and extend up to the Upper North Sea Group or even up to the surface, and
- Level 3: statistical center of defined level 2 faults.

The database proved to be well geared in the fault typing or annotation to be used directly for the compilation of the reference map. All faults annotated with the label “level 2” were selected as they largely fit with the above mentioned definition of a ‘major relevant fault zone’. Referring to an existing fault database which is maintained “evergreen” when new interpretations are made or new data is becoming available, such as the SCAN 2D seismic lines (EBN, 2021), makes the actualization of the reference map feasible with minimum effort. It provides the unique possibility to reproduce the workflow used for the compilation of the first version of the ‘major relevant fault zone’ map to compile an updated version in a time efficient manner on a proper public dataset.

For the specific purpose of the handling of this key-element it needs to be noted that the faults in the HIKE Fault Database stem from regional mapping projects where exact location of faults is not the prime target. Additionally, they are mapped on either 3D seismic surveys, dense 2D-coverage or very sparce 2D-seismic coverage. Consequently, there is a location uncertainty of the fault traces and it does vary per location. Evaluation revealed that based on the type of seismic coverage the fault position could be shifted with different shifts in meters. To take this uncertainty into account in the reference map the fault trajectories at specific stratigraphic horizons (the regional mapping horizons closest to the geothermal reservoir formations), are buffered with a buffer width of 250, 500 and 750 m respectively.

Figure 3-22 presents the resulting ‘major relevant fault zone’ map displaying the buffered level 2 fault traces from the HIKE Fault Database at 4 stratigraphic levels. It needs to be noted that the map also shows the natural and induced earthquakes from the KNMI database as well as events reported from historic documents by (Houtgast, 1991) from before the official registration start. The latter were annotated with a certainty qualifier: when ML >= 0.5 then the event reported is likely an earthquake, when labelled ML < 0.5 another cause is most likely. As with the location uncertainty of the faults the location of the epicentre of the earthquake has an uncertainty as well, which may be several kilometers.

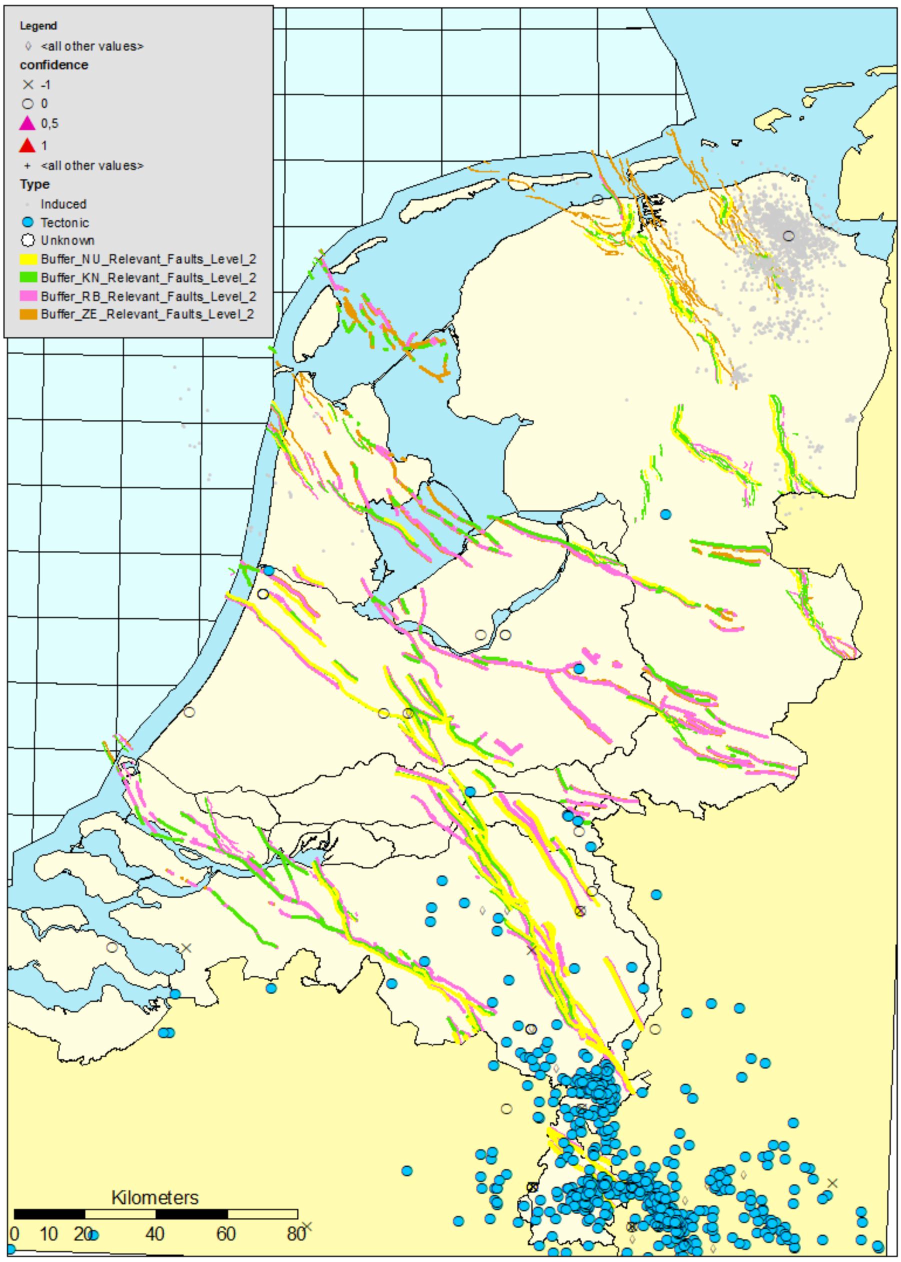


Figure 3-22: Overview of "major relevant fault zones" selected from the HIKE Fault Database, presented as polylines at different stratigraphical levels. Also measured seismic events are shown.

3.7 Subsidence

3.7.1 HIKE Task 3.2: Fault-based surface deformation using InSAR method (Italy)

Summary

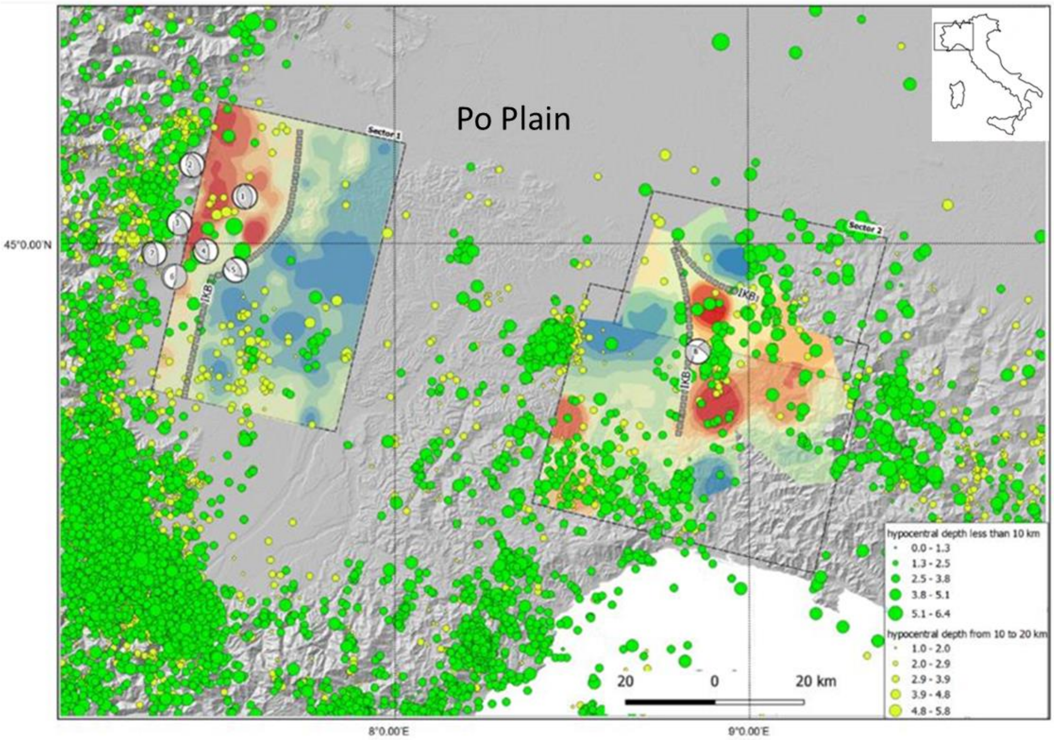
Two case studies in Italy have been presented, focused on the ground motion analysis and monitoring using InSAR method.

The first case study analysed a portion of territory naturally affected by land subsidence, because of its geographical and geological features, to which the effects of anthropogenic activities are added. The Adriatic coastal area located just south of the Po river delta is particularly sensitive to topographical variations for the possible negative impacts on the hydrodynamic setting of the Comacchio Valleys, the hydraulic and road infrastructures, the coastline setting, the biological ecosystems, and the salinization of aquifers.

The integrated use of the InSAR method with the traditional (in-situ) topographic height determination techniques, such as geometric levelling and Global Navigation Satellite System (GNSS), is consolidated for detecting and monitoring land subsidence in areas where underground fluids are extracted. Nevertheless, the lack of a specific standardized methodology does not allow for evaluating different results obtained from different types of analysis. Starting from the description of two independent estimations of land subsidence in the Agosta (Comacchio, Italy) area, where an environmental impact assessment procedure was carried out following a request for gas exploitation, this report points out the need for a standardized methodology, focused on the in-situ calibration of InSAR data. This last purpose requires an adequately dense and homogeneous reference GNSS network. The in-progress initiatives, at the European and national level, aiming at providing a Copernicus Ground Motion service could offer the opportunity to structure a reliable and dedicated GNSS network, starting from the large number of stations run by different institutions already existing in Italy.

A methodology for the assessment of the tectonic contribution to subsidence is also provided, showing the need for well constrained chronostratigraphic information to be added to the tectonic data. Therefore, the complementation of 3D faults included in the Fault Database with detailed chronostratigraphic data would allow further and wider application of the up to now stored information.

In the second case study, in order to analyse the present crustal mobility and neotectonics of NW Italy, namely the so-called “Alps-Apennines interference zone”, spatial statistics (Hot Spot and geostatistical analysis) of PS-InSAR (Permanent Scatterers Interferometric Synthetic Aperture Radar) data has been done, with the aim to shed lights on the relation between fault systems and seismic activity of the region.



N.	Yr	Mo	Dy	Hr	Mn	Sec	Long	Lat	Depth	Ml	Az1	Dip1	Rake1	Az2	Dip2	Rake2	AzP	DipP	AzT	DipT	Ref.
1	1992	9	13	5	0	37.4	7.610	45.105	4.26	3.4	350	50	90	170	40	90	80	5	260	85	S
2	1981	2	8	4	30	10.5	7.439	45.152	5.00	4.4	335	40	60	192	56	113	266	9	153	69	E
3	1980	1	5	14	31	19.9	7.419	45.034	4.00	4.8	215	55	140	331	58	42	92	2	185	51	E
4	1990	2	11	7	7	47.8	7.476	44.987	24.00	2.7	0	65	120	126	38	43	69	15	313	59	E
5	1990	2	11	7	0	37.8	7.547	44.965	16.00	4.2	120	55	60	345	45	126	231	6	333	65	E
6	1969	10	9	3	31	36	7.400	44.950	33.00	4.2	174	11	-118	22	80	-85	299	54	108	35	P
7	1983	9	6	22	43	18.4	7.390	44.970	5.00	3.8	0	72	75	221	23	129	102	26	248	60	N
8	2003	11	04	09	26	57	8.87	44.76	8	4.7	300	71	-172	207	83	-19	162	18	255	8	U

Figure 3-23: Map of instrumental and historical seismicity that includes the westernmost Po Valley, the internal border of the western Italian Alps (Cozie) and the northern Apennines and the Ligurian Alps from the database of the seismic network of the North-Western Italy (RSNI). Green circles represent shallow seismicity (hypocentral depth less than 10 km) and deeper seismicity (hypocentral depth between 20 and 10 km) light green circles respectively. Focal mechanisms. Numbering corresponds to that of table 1. Iso-kinematic map and Iso-Kinematic Boundaries (IKBs) of the sector 1 and sector 2. Table: Locations and parameters of the focal mechanisms in Fig. 2. Yr.: year; Mo: month; Dy: day; Hr: hours; Mn: minutes; sec: seconds; Long.: longitude; Lat.: latitude; ML: local magnitude; Az1(2), Dip1(2), Rake1(2): azimuth, dip, rake of fault plane 1 (2), in degrees; AzP(T), DipP(T): azimuth and dip of P(T) axes, in degrees.

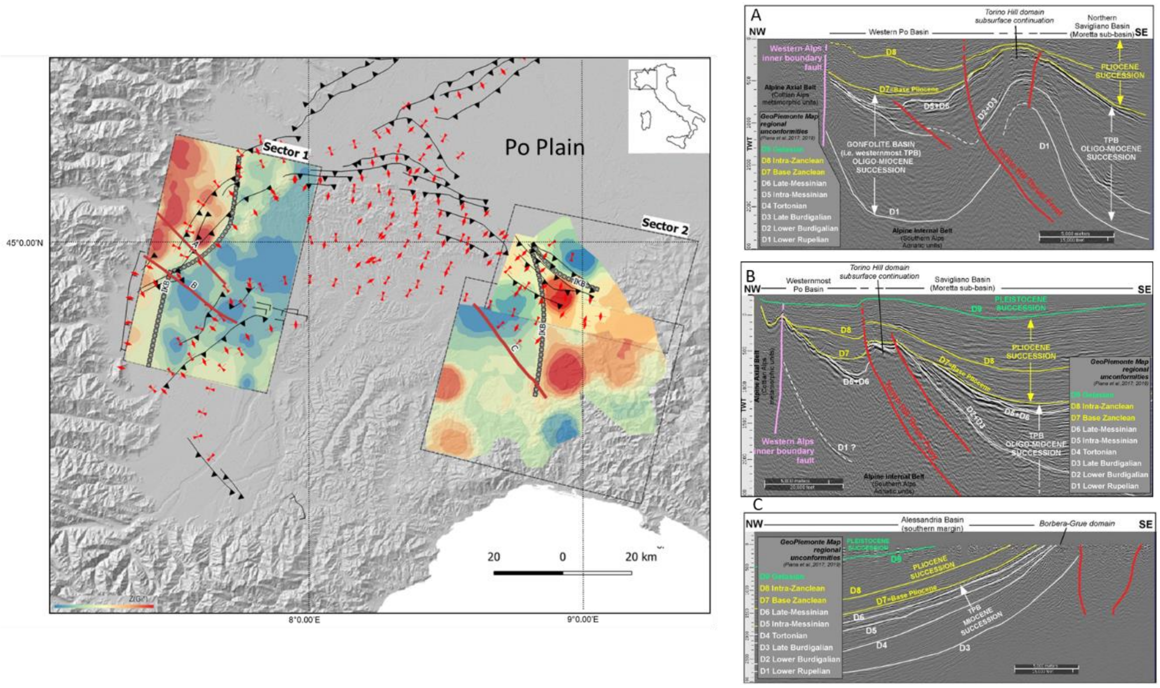


Figure 3-24: Iso-kinematic map and Iso-Kinematic Boundaries (IKBs) of the sector 1 and sector 2 with tectonic framework of the main faults and thrust-fold-belt (black lines indicate the blind thrust and in red lines indicate asymmetric anticline-syncline folds pair) of Western Po Plain masked at surface by Quaternary deposits. Padane Thrust Front (PTF); Scrivia Fault (SF), Savigliano Thrust (ST). A, B, C traces of the seismic cross section.

A. Line drawing of seismic line A in the sector 1. Traces of the seismic lines are shown in map (left figure), the unconformity codes have been recognized between easternmost part of the Cottian Alps and the subsurface western termination of the TH domain and on the back of the TH domain and correspond to those proposed in the Geo Piemonte Map (Piana et al., 2017; 2019) Traces of the N-verging Padane Thrust Front systems and tectonic lineaments consistent with interpretation of the "Cavour structure" on surface.

B. Line drawing of seismic line B in the sector 1. Traces of the seismic lines are shown in map (left figure), the unconformity codes have been recognized between easternmost part of the Cottian Alps and the subsurface western termination of the TH domain and on the back of the TH domain and correspond to those proposed in the Geo Piemonte Map (Piana et al., 2017; 2019). Traces of the N-verging Padane Thrust Front systems and tectonic lineaments consistent with interpretation of the "Cavour structure" on surface.

C. Line drawing of seismic line C in the sector 2. Trace of the seismic lines are shown in map (left figure), the unconformity codes have been recognized in the Alessandria Basins and correspond to those proposed in the Geo Piemonte Map (Piana et al., 2017a ;2017b). Traces of the tectonic lineaments consistent with interpretation of the faults Scrivia and Lemme trends on surface.

This analysis allowed to define a number of kinematically homogenous areas, represented in some Iso-Kinematic maps (IKM), where the homogenous areas are inferred to represent sectors characterized by relative ground movements (uplift or sinking) and maybe different tectonic regime. These movements should occur mainly along the boundaries (IKB) of the IKM areas

(Figure 3-23). The distribution of the IKB, which may thus correspond to regional faults or tectonic contacts, have been compared with the surface data of the Piemonte Geological Map at 1:250,000 scale, with subsurface stratigraphic and tectonic data (interpreted on seismic lines provided by ENI SpA in the frame of the "HotLime GeoERA" project, funded by the European Union, Horizon 2020) and with the available seismological and GPS data.
The IKM seem to indicate differential uplifting ratios between the inner Cottian Alps and the Western Po Plain, separated by some N-S major faults: (e.g., the Col del Lis-Trana and the Cavour tectonic lineaments), as well as between the western termination of the N-verging Padane Thrust Front (Monferrato Front) and the Padane plain. Furthermore, the Villalvernia-Varzi Line and Scrivia fault seem to constrain the distribution of the IKM and IKB, while further investigations are required for the interpretation of the SW Alps internal boundary and the adjoining Langhe sedimentary domain.
The ground motion tendency suggested by IKM seems to be in overall agreement with the different geological and geophysical datasets (Figure 3-23 and Figure 3-24). This correspondence suggests a current tectonic mobility and the differential uplift of the sectors analysed mostly driven by the activity of above major faults. Therefore, on the basis of these good agreements, this methodology could also be used to associate a "weight" about the tectonic activity of faults as future expansions of the HIKE Fault Database.

Applicability for the HIKE Fault Database

In the procedures for the assessment of land subsidence or the definition of areas with homogeneous kinematics, object of this report, the knowledge of the tectonic component assumes primary importance. It is known that part of the regional subsidence measured in the Emilia-Romagna region has a tectonic origin (e.g. Carminati et al., 1999 and 2003b). Moreover, the geology is characterized by thrust faults and fault propagation folds related to the Apennine chain front. Therefore, the mapping and 3D modelling of faults as well as the definition of their kinematics are certainly useful for the estimation and interpretation of subsiding phenomena. The methodology, described in the case study 1, takes into consideration the tectonic component of ground deformations related to the activity of blind faults. In particular, the workflow consists of successive steps of restoration of the modelled stratigraphic surfaces, through unfolding, decompaction and unload, and removal of regional tilting and measure of the residual vertical separation along with antiformal structures, controlled by blind fault. But, to obtain an affordable estimation of the natural component of the subsidence this approach needs i) a well-constrained 3D geological model with high detail geometry of the Pleistocene-Holocene sedimentary boundaries to obtain the thickness of the units, ii) high detail 3D geometry of the thrusts, ii) the sand/shale percentage for each unit, iv) well-defined chronological constraints unit ages. This means that the only information stored in the Fault Database is necessary but not enough for the purpose. In fact, the information contained in the Fault Database should be accompanied by detailed stratigraphic information, in particular on Pleistocene-Holocene deposits. Enriching as much as possible the database with information on the 3D geometry of faulted and/or deformed stratigraphic horizons could be a possible development of the project that would allow further and wider application of the stored information.

A further target of the second case studies was to define continuous velocity surface maps (Iso-Kinematic Maps: IKM) to identify regional areas characterised by homogeneous kinematics behaviour and their boundaries (Iso-Kinematic Boundaries: IKB), without focusing on PS absolute velocity values. IKB are viewed as tools to more easily verify if the PS-InSAR data on present-day crustal mobility could fit with the distribution of real tectonic structures or other geological features on the field. When IKBs correspond with a set of known geological and seismological features (faults, morpho-structural alignments, hydrographic elements, hypocentral alignments, etc.) they could be used directly to constrain a seismotectonic or regional kinematic model. In this way, the relative ground movements suggested by the IKM, concentrated mainly along the IKB, can support the interpretation of the present-day kinematic trends. Furthermore, the IKM could lead to the detection of very recent tectonic lineaments that are probably still growing at present, or also to suggest different current tectonic mobility between adjacent regions. The ground motion tendency suggested by IKM seems to be in overall agreement with the different geological and geophysical datasets. This correspondence suggests a current tectonic mobility and the differential uplift of the sectors analysed mostly driven by the activity of above major faults. Therefore, on the basis of these good agreements, this methodology could also be used to associate a “weight” about the tectonic activity of faults as future expansions of the HIKE Fault Database.

3.8 Groundwater

3.8.1 Project VoGERA: Groundwater vulnerability for deep activities

Summary
The overall aim of the VoGERA project is to provide data for the development of conceptual models of shallow groundwater vulnerability to deep sub-surface energy activities using existing data, information and experience of GeoERA partners and from previous projects. The models are validated at a number of pilot study sites.

Understanding and managing hazards and risks associated with potentially harmful activities in order to meet the environmental objectives of the EU Water Framework Directive (2000/60/EC) and Groundwater Directive (2006/118/EC) is a prerequisite for protecting groundwater for future generations. Groundwater protection has traditionally focused on safeguarding water resources from hazards at (or near) the surface. As a result, the risks from near-surface activities are relatively well understood and managed. The controversy surrounding the shale gas industry development in Europe has highlighted the lack of information and systematic practices across the EU for managing a range of hazards to groundwater from energy-related activities in the deep sub-surface.

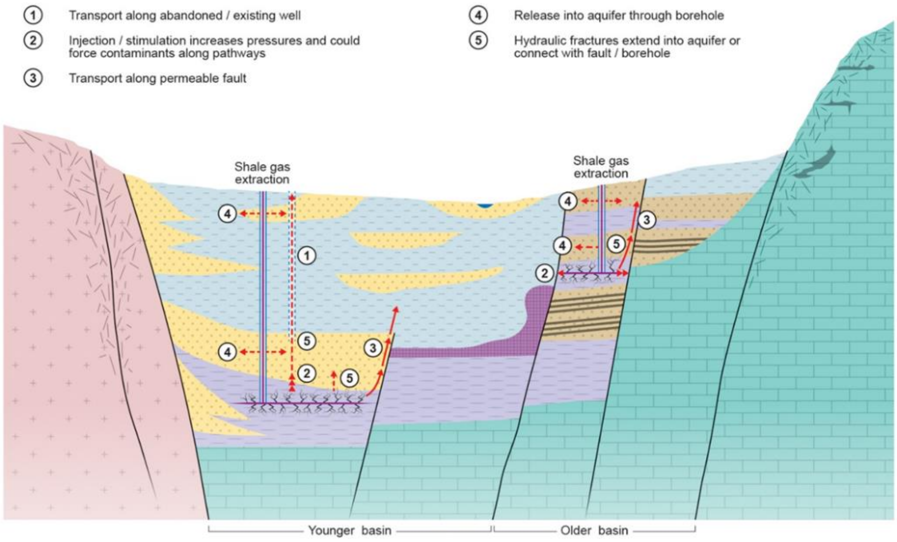


Figure 3-25 conceptual model for contamination pathways for shale gas and oil.

A literature review (Zaadnoordijk et al., 2019) revealed that the main pathways for negative effects of deep sub-surface activities on groundwater resources are anthropogenic: leaching of contaminants from the surface at the construction site and flow through boreholes that have not been sealed properly or wells that have lost their integrity. Of the natural geological pathways, faults have the highest risk, followed by fractures, and finally porous flow. A tool for preliminary risk assessment has been set up using these findings (Bianchi et al., 2021). The tool has been tested for four pilot areas where the geological pathways have been investigated (Zaadnoordijk et al., 2021).

Applicability for the HIKE Fault Database

The HIKE Fault Database provides important information for the assessment of risks for groundwater resources from underground activities, because of its prominent role among natural pathways. The faults at the Belgium and Dutch pilots have been studied specifically in the VoGERA project, while previous work at the British pilot provided important information on the fault at the Vale of Pickering.

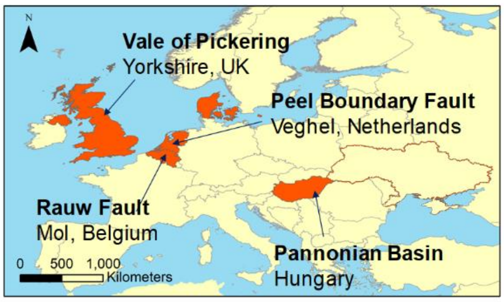


Figure 3-26 Pilots in the VoGERA project.

4 CONCLUSIONS AND RECOMMENDATIONS

The HIKE Fault Database (FDB) is an important new component in the broad range of geoscience information products which links many research disciplines and application areas. Togehter with other GeoERA projects, the development of the database in HIKE has strongly enhanced and improved the accessibility to fault information. This is considered as a first and major step towards future applications in resource assessments, safe and sustainable use of the subsurface and understanding risks on environment and society. The unlocking of that potential however depends on whether the Geological Survey Organizations decide to continue improving both the data and the platform functionalities.

The current experiences lead to the following key findings and conclusions

1. The FDB has unlocked many fault data sources which were not accessible to the public domain before. In many cases, the fault data was stored in in-house repositories and formats that are unsuitable for online dissemination. In some countries, the HIKE project and associated GeoRA projects have stimulated new fault mapping and modeling activities leading to a significant extension of information coverage and, in some cases, better harmonized and consistent fault datasets.

2. The collaboration between HIKE and other GeoERA projects which have generate fault data (3DEGO-EU, HotLime, GeoConnect^{3}d) has resulted in the development of standards for fault mapping and characterization. These standards have helped and stimulated the application of fault data in new geoscience products such as the Structural Framework, Tectonic Boundary classifications (vocabularies) and geothermal potential maps in deep carbonate formations.

3. The unlocking and public dissemination of fault information in the first place generates awareness on the presence of faults. On the one hand, the awareness can be an important trigger to evaluate the potential impacts of faults in more detailed (e.g. local assessments). On the other, the maps may indicate where additional fault information is required to develop a comprehensive overview and whether there is a scope to generate new data. In many partner countries, the activities in HIKE have already initiated such developments.

4. The current contents of the FDB are typically suitable for national to regional scale studies. This includes the development of regional models, the identification of prospective areas for deep geothermal energy production (fractured formations) and the indication of areas which are prone to generating natural or induced earthquakes. For many applications and studies in the European and National context the HIKE FDB provides a good basis and starting point. It must be noted however that the level and quality of fault mapping and characterization is still very heterogeneous across Europe. This should be considered when appliying the information

5. From the presented case studies, it can be concluded that the existing data in the FDB requires additional and more detailed modelling steps in order to support location-specific studies and assessments (e.g, fault sealing, linking seismic events to faults,

determine induced hazards resulting from drilling, injection and production, etc.). Typically attributes and geometrical representations must be tailored for the required analyses.

6. The current FDB holds two important solutions to overcome some of the above limitations. The first solution is the possibility in the FDB to represent faults at different scales and resolutions. Only a few countries make use of that option now and for most other countries the state of mapping is still too immature. The second option is to include links to external data sources which hold the required information. The implemented vocabulary system enables such links at a fault-by-fault level. This approach has major benefits compared to providing only a generic link to the entire data source. The current FDB already includes these links for data sources on natural seismicity (e.g. SHARE and ITHACA seismogenic fault databases).

Recommendations

1. The first and most important recommendation is to continue implementing the HIKE FDB in geological survey mapping programmes. The FDB provides a robust framework which can help surveys to improve their fault data. The current information is still very heterogeneous which may hamper applications at pan-Eueropean scale. While new data is added, the coverage and quality will increase which leads to an increased value and a broader scope for applications. If the the FDB and the data are not regularly updated, then the value for applications will soon decline.

2. The upcoming research programme CSA-GSE (European Geological Services for Europe[4]) provides a unique opportunity to extent the information and functionality of the FDB and to apply it for national to European scale resource assessments. In particular projects like HotLime, 3DGEO-EU and GeoConnect[3]d describe typical use cases which have a strong link with the CSA-GSE programme.

3. The FDB should include more information regarding the geological uncertainties and confidence ranges of the data included. This is crucial for many of the applications. Likewise, information could be included at fault and national dataset level on which applications are considered viable and which not.

4. The applicability can be further enhanced by
    a. More detailed, 3D and multi-scale fault representations
    b. Better coverage of fault atributes (including new attibutes)
    c. Information on dynamic fault properties and time-dependent attributes
    d. Expanding the links to external data sources.

[4] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d3-02-14

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