Hazard and Impact Knowledge for Europe

Deliverable D4.1

HIKE project synthesis

Summary of findings and recommendations

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1 INTRODUCTION

Our society is strongly dependent on secure access to subsurface energy, mineral resources and groundwater. Both from environmental and societal perspective it is important that subsurface resources and storage capacities are exploited in a safe and responsible manner. The HIKE project compiles data and knowledge developed by national and regional geological surveys which can be used to support identification, prevention and mitigation of induced hazard and impacts.

Hazard and risk management is key to achieving Sustainable Development Goals

Access to clean and secure energy, mineral resources and groundwater is an intrinsic aspect of the United Nations Sustainable Development Goals and society's needs in general. These commodities are inevitably connected with subsurface activities, yet these activities may also pose a risk to the environment and human health. Through the drilling of wells or the extraction and injection of substances, the state of the subsurface will be altered. This includes the thermochemical and geomechanical characteristics, in-situ stress state and the composition of formations and fluids which can ultimately lead to impacts at surface (e.g. ground motions, surface deformation) and to other vulnerable resources (e.g. pollution of ground- and surface waters). In order to abide to the SDG's and national regulations on safe and responsible exploitation these hazards and impacts must be minimized. HIKE supports this challenge with demonstration of methodologies and transparent information and knowledge developed by Geological Survey Organizations.

Towards a European service supporting subsurface hazard and impact research

HIKE has contributed three main results to support research and investigation of hazards and impacts: i) a novel information system for faults and other tectonic features, ii) four real case studies in which advanced assessment methodologies are demonstrated, and iii) a knowledge share point for reports, tools and datasets on induced subsurface hazards and impacts. The results are a stepping stone towards integrating, harmonizing and implementing knowledge and information for responsible subsurface exploitation throughout Europe.

This report provides a synthesis of the main results of the HIKE project and recommendations for future improvements and implementation.

2 MAIN RESULTS AND ACHIEVEMENTS

2.1 European Fault Database

Faults are omnipresent in the subsurface and represent planar features along which movements take place (e.g. earthquakes) or fluids may migrate to groundwater formations or surface environment. Although some databases exist for seismogenic faults (i.e. faults that generate natural earthquakes), there are far more other faults that could pose hazards induced by nearby subsurface activities. For this reason HIKE has developed a novel European Fault Database in which the spatial distribution and attributes of these faults are stored and made publicly available for various studies and applications.

2.1.1 Introduction

Faults are common geological features in the subsurface which define the characteristics and distribution of rock formations as well as the geo-mechanical response of the subsurface to natural and anthropogenic influences. Young and active (seismogenic) faults are often associated with the occurrence of natural earthquakes. Such faults are typically present in regions where the earth crust is moving due to plate-tectonic processes and stresses build up. Due to the risk posed on society, many of these faults are registered and monitored in databases such as the European SHARE database[1] and various national registers.

The vast majority of faults in the subsurface however is inactive. These tectonic structures are either visible in surface outcrops or they appear as distinct linear/planar features and discontinuities in subsurface horizons and intervals. Many are hidden under a thick overburden. Until now there was no European online platform with a comprehensive and harmonized overview of passive and buried faults. Few online national databases exist (e.g. Italy[2] and Austria[3]), yet most information is dispersed and presented in varying and heterogeneous formats. In many countries the geological programmes have only limited focus on the development of a consistent national and regional overview of faults and many aspects and attributes are still underexplored. Some exceptions exist such as the GeoMOL project[4] which focused on the 3D modelling and representation of faults in subregions of Southern Germany, Austria and Northern Italy. Detailed fault assessments are typically conducted in location-specific studies yet often these results are company-confidential or hidden in project archives. With the lack of a general fault classification framework, it is generally difficult to place these results in a regional context.

With the development of the European Fault Database, the HIKE project has taken a major step in the assessment, publication and application of national and European fault data. The project outcomes are not limited to the collection and publication of data and information only. HIKE has also resulted in a new incentive and approach to establish and improve fault information at national and transnational level according to common pan-European workflows and standards. The development and implementation of semantic principles assists geological surveys and other knowledge institutes with the interpretation, analysis, classification and cross-border

1 http://diss.rm.ingv.it/share-edsf/SHARE_WP3.2_Database.html
2 http://sgi2.isprambiente.it/ithacaweb/#1
3 https://www.geologie.ac.at/en/services/web-applications/multi-thematic-geological-map
4 https://www.geomol.eu

correlation of faults consistent with regional and pan-European tectonic boundary concepts. These concepts also enabling the linkage of national fault data with scientific publications and other online published datasets. Cross-border correlations can be established without the need to make these faults also geometrically consistent, thus providing a solution for the fact that datasets and status of mapping and modelling can strongly differ between regions and countries. With the integration in the European Geological Data and Information platform (HIKE D2.5[5], see Figure 2-1), the HIKE Fault Database is intended to provide a sustainable foundation for future fault modelling, characterization and dissemination at the European Geological Surveys.

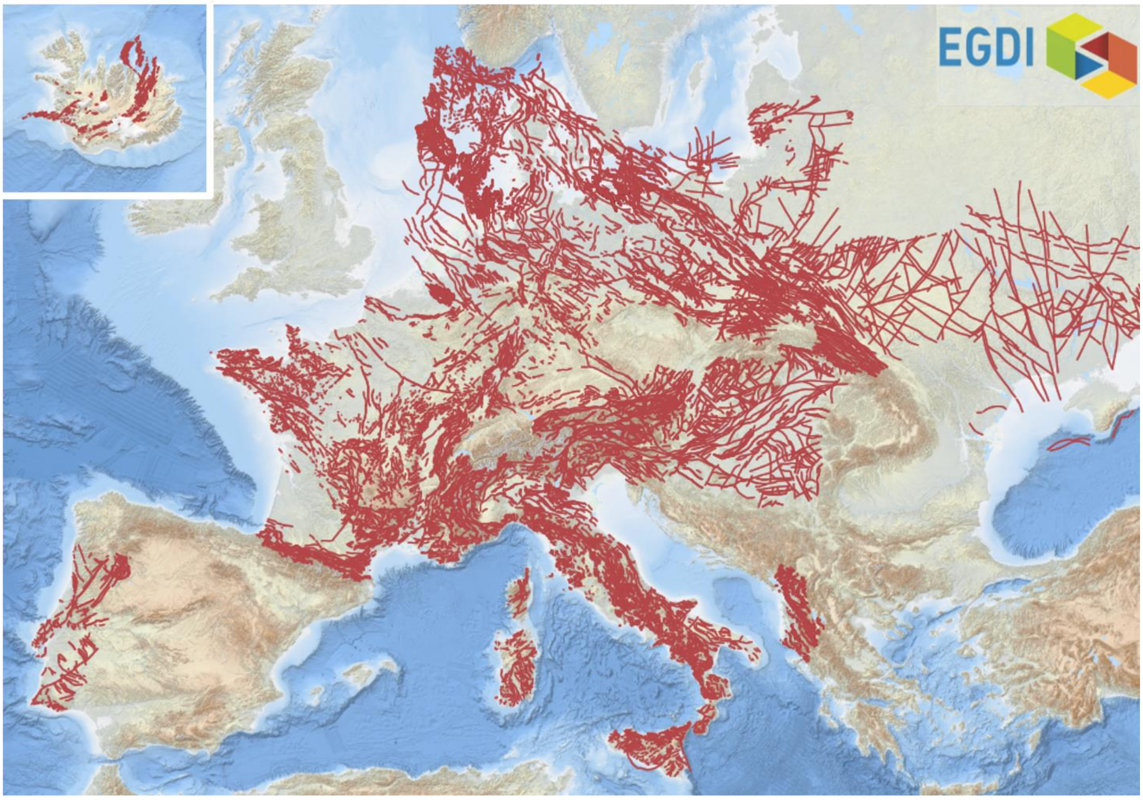


Figure 2-1: The HIKE Fault Database in EGDI

2.1.2 Fault Database concept and specifications

The HIKE Fault Database is a first-of-its-kind database for all types of geological faults covering most of the participating countries in the project as well as additional non-participating countries that are liaised with other projects (e.g. Pannonian Basin). One of the key challenges for the Fault Database is that it needs to incorporate a huge variety of local and national datasets. Only few countries have established detailed 3D fault models and here different representation formats and software tools are used. In most cases, faults are represented just as lines on 2D maps. These can be surface expressions or intersections with subsurface horizons or specific depth levels. Fault characteristics are sparsely available and often only for specific case study areas. The type of evaluated parameters strongly depends on the local setting (e.g. seismicity-related parameters in regions with natural earthquakes). Last but not least, the scale

5 HIKE European Fault Database – GeoERA

of fault mapping varies greatly from region to region, making it hard to establish cross-border correlations. An example is the representation of a complex fault zone as a single trace vs its break-up into smaller individual sub-faults.

In order to resolve the above challenges, the Fault Database concept has been divided into four main categories: Geometry, Attributes, Semantics and Meta-data. Each of these categories follows a set of conventions and specifications to ease the compilation of existing national data into a pan European repository and to provide the flexibility for future expansions and updates. Detailed specifications are described in the HIKE D2.1: Fault Data Catalogue[6]. A brief outline of the database elements is given below (see Figure 2-2):

- Geometry: The core of the HIKE database is defined by the geometrical definitions delineating the shape and location of faults at the surface and/or at intersections with one or more stratigraphic horizons at varying depths. Faults can include multiple representations at different scales, depth intersections, structural levels and formats (2D/3D), each of which is tied to a unique fault identifier.
- Attributes: Fault attributes are a placeholder for describing the characteristics of a fault. The HIKE Fault Database supports a wide variety of characteristics that are commonly used in mapping and structural analysis: these include local identifiers (e.g. name, country, geological age), static spatial characteristics (e.g. fault length, strike, dip angle), kinematic characteristics (e.g. displacement, timing of first/last movement) and geomechanical aspects (e.g. tendency to generate earthquakes). The attributes definitions are made consistent with international standards and code lists. The specifications may be updated with new attributes.
- National fault vocabularies based on semantic principles. HIKE has implemented a common and hierarchical tectonic boundary classification framework. Each country has labelled its faults and fault systems in this framework using nationally and regionally defined concepts (names and definitions of faults including narrower and broader relationships to regional/local faults and fault systems). The concepts are used for regional correlations, linking faults to external information sources and citations and providing a consistent structural framework for new interpretations and modelling updates.
- A hierarchical metadata definition describing the origins and quality-related aspects of the fault data origins. HIKE implements a common metadata definition including separate underlying definitions for individual datasets delivered at country, region and project level.

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

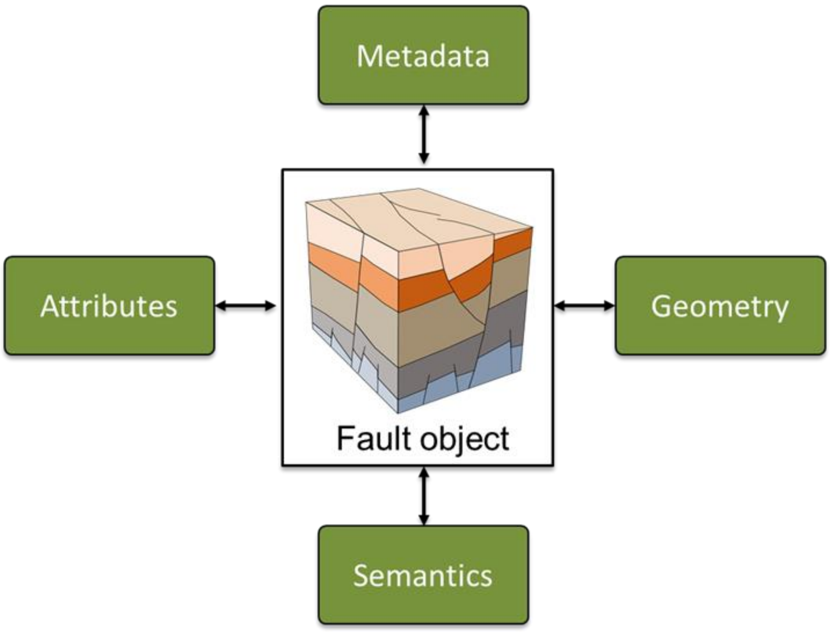


Figure 2-2: Schematic outline of the general Fault Database concept. Each fault or group of faults is represented as an individual object in the database and specified in terms of geometry, attributes, semantics and meta-data.

2.1.3 Fault data collection and country reports

At the start of the HIKE project, the status of fault mapping and analysis was still strongly heterogeneous across Europe. In most countries fault data was still very incomplete and lacking attributes and consistent classifications. Italy, as an exception, already possessed an online database with comprehensive fault information at different scales as well as quantified kinematic attributes. Much of this information was established in national mapping programmes in order to get a better understanding of natural seismic hazards. Austria developed its national Fault Database in 2016/2017 based on a comprehensive tectonic boundary classification framework. Both country databases were pivotal for the development and definition of the HIKE European FDB. Most other countries developed some fault maps at various levels of detail and completeness. These sources were either not accessible online or published in a format that is suitable for web GIS. Fault geometries and attributed followed different conventions and classification were lacking.

The HIKE project represents a milestone in the compilation, harmonization and dissemination of national-scale fault data in Europe. The current FDB includes the available data from all 19 partner institutes as well as various data sources resulting from other GeoERA projects. A total of 269.349 single fault features sorted to 28.078 fault IDs have been uploaded in the current database. Collaboration with the GeoConnect³d project[7] has resulted in a significant extension of the current fault maps in the countries linked to the Pannonian Basin Area. In the 3DGEO-EU project[8], new information has been provided from cross-border mapping activities at the

7 https://geoera.eu/projects/geoconnect3d6/
8 https://geoera.eu/projects/3dgeo-eu/

German-Dutch border. The project HOTLIME[9] has provided new data and insights in the Southern German region. Specific efforts have been made here to establish correlations with the neighbouring Austrian region. The collaboration with the Ruhr-to-Rhine area in GeoConnect[3]d has resulted in a joint development of the structural (tectonic-boundary) framework and a correlation between Belgian, Dutch and German fault in this region.

Each country has provided the faults according to the agreed specifications and standards. All datasets are accompanied by a country data report describing the general background of tectonic development and faults and the status and typical applications for fault information (HIKE D2.2[10]). A common workflow for data delivery and uploading ensures an efficient integration in EGDI including various quality control procedures (HIKE D5.2[11]). Single datasets can be replaced or extended when new updates become available. The main challenge will be to establish a common maintenance procedure with associated funding in order to process these updates after the end of the HIKE project and the GeoERA programme..

Although the HIKE project has greatly improved the compilation, coverage, consistency, accessibility of fault data across Europe, there are still many opportunities to improve and extend fault data in the future. Some countries only have information on the surface location of faults which could be extended with definitions at different depth and stratigraphic levels. Few countries have full 3D representations of faults (e.g. Netherlands, parts of Germany, Poland). This may be implemented in other countries as well. The same goes for the fault attributes and properties. These possibilities strongly depend on the availability of exploratory source data such as seismic surveys, well data and geophysical reconnaissance data. Report HIKE D2.3[12] provides an overview of the benefits and limitations of various types of data sources, observation techniques and modelling methods used and their implications for HIKE.

2.1.4 Implementation of the tectonic boundary classification

Naming of faults and fault systems leads often to misunderstandings if local names are used across borders. For the European FDB, it is essential that fault datasets from different origins and of different scales become compatible, even without the use of standardized fault name lists. Alternatively, such regional or historical fault names can be processed as cross-linked related concepts to get the context that specifies the meaning of these descriptive labels. Using Linked Data principles and SKOS references, a mapping to a global context on the Semantic Web can be defined. Therefore, the European FDB will be accompanied by the generation of SKOS vocabularies in accordance with the LinkedData principles.

The project vocabulary supports the ranking of faults into hierarchical (tectonic) framework in order to accommodate different scales and/or different levels of information. It is subdivided into two parts (called "schemes"): the first one describes the general terms or structural framework concepts used in the HIKE project for fault classification and ranking. Figure 2-3 shows the different concepts currently included (extended from the Austrian classification scheme). The second scheme defines the national/regional fault inventory and has been

9 https://geoera.eu/projects/hotlime6/
10 http://geoera.eu/wp-content/uploads/2021/10/D2.2b_Annex_HIKE_Country_Reports.pdf
11 http://geoera.eu/wp-content/uploads/2021/10/D5.2b_HIKE_User_Manual.pdf
12 http://geoera.eu/wp-content/uploads/2021/10/D2.3_HIKE_Fault_Characterization_Data_Report.pdf

delivered by each geological survey together with the fault data. The full definitions and descriptions of the general framework and the individual national and regional classifications can be accessed via the GeoERA vocabulary schemes[13]. An example is shown in Figure 2-3.

The implementation of the semantic concepts provides many major benefits to the HIKE Fault Database which have significantly increased its applicability for:

- Linking faults to key publications
- Possibility to correlate faults and fault systems across Europe
- Multi-scale representations of individual faults and fault systems
- Linking individual faults and fault systems to information in external databases
- Providing a structural classification framework for future mapping and modelling

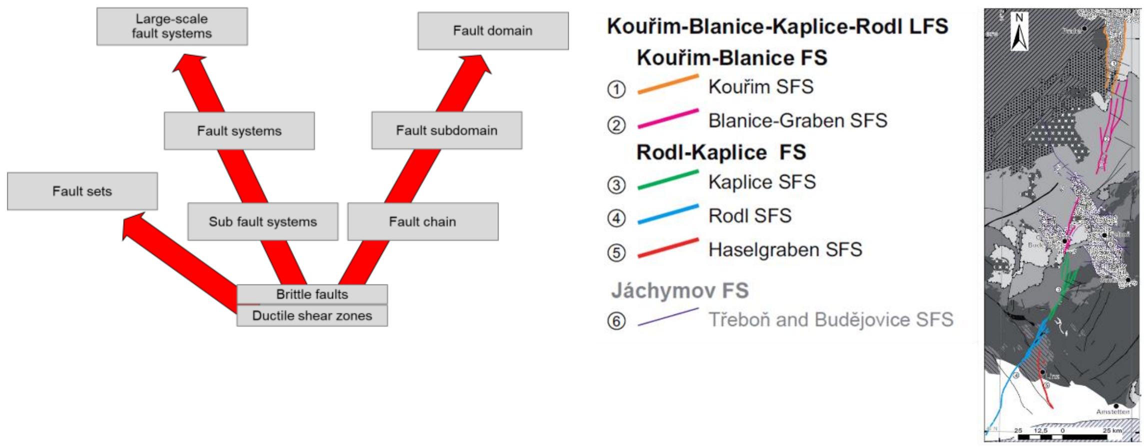


Figure 2-3 Left: Definition of the general hierarchical tectonic boundary classification terms used in the HIKE Fault Database. Right: Example of local classification of one of the large-scale fault systems in Austria (after Hintersberger et al., 2017)

2.1.5 Fault Database applications

Faults are not only important to study natural earthquakes. They are also pivotal for studying the structure and properties of the subsurface and the exploration of potential sites for energy production and storage reservoirs. In HIKE report D2.4[14] we describe various use cases. A brief summary is given below:

- Faults are important for a consistent mapping and modelling of subsurface formations. These projects on their turn deliver fault information that can be included in the FDB. The vocabularies linked to the FDB as well as the Structural Framework from GeoConnect[3]d, assist the visualization, interpretation and correlation of faults within the broader structural-geological context. The 3DGEO-EU project and national mapping studies provide examples and guidelines for regional interpretation of faults in cross-border areas.

13 https://geoera.eu/projects/hike10/semanticnetwork/
14 http://geoera.eu/wp-content/uploads/2021/10/D2.4_HIKE_Fault_DB_Evaluation.pdf

- Many hydrocarbon occurrences are contained in structural traps bounded by faults. While detailed mapping (beyond the target scale of HIKE) is key to identifying individual prospects for oil and gas, the regional mapping of faults supports the understanding of burial and uplift over geological time. The GARAH project illustrates how this information is used to assess the generation of hydrocarbons and the migration pathways from source rocks into the reservoir.

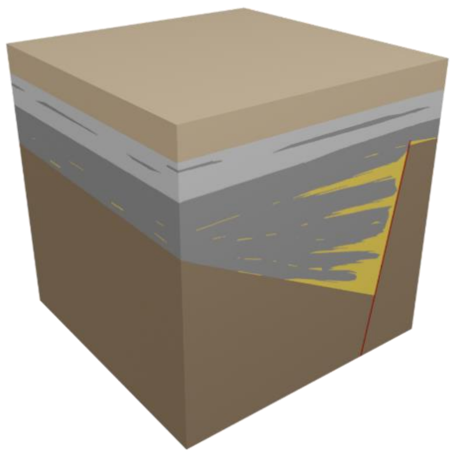
- The development of geothermal resources from deep carbonate or tight clastic reservoirs largely depends on the presence of faults and fracture networks as potential fluid pathways and zones of enhanced flow. In some cases these faults also represent zones of positive temperature anomalies in situations where they act as a conduit for deeper (hotter) formation water. With open-loop hydro-geothermal systems, the faults may be used as targets for re-injection. In this case the possibility of induced or triggered seismicity should be considered. In the HOTLIME project and GeoMOL project, the role of faults in deep carbonate geothermal systems has been assessed.

- Like with hydrocarbons, the presence of storage prospects may depend on trapping structures bounded by faults. The HIKE case studies present a workflow to assess the safe long-term containment of fluids and gases like CO_2 and hydrogen by analysing the sealing capacity of the faults within and adjacent to the reservoir.

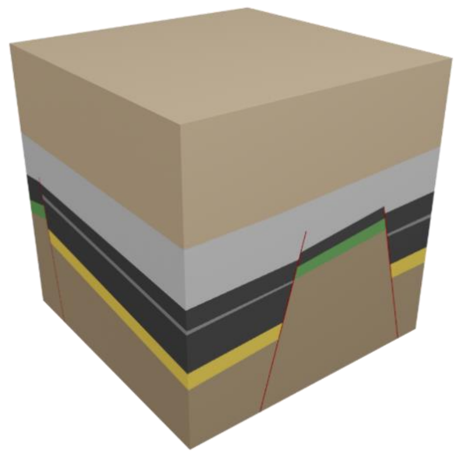
- Earthquakes occur as a result of sudden slip motions along fault planes. Changes to stresses in the subsurface or the friction of fault planes may cause these motions and can be triggered by natural processes and/or human activities (e.g. pressure changes in the reservoir, differential compaction, invasion of fluids into the fault plane). The HIKE case studies have investigated improved methods and models to assess the localization of earthquakes in the subsurface which is crucial for determining causal relations. Other cases and studies present approaches to assess and prevent potential seismic hazards resulting from extraction and injection projects

- 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). 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

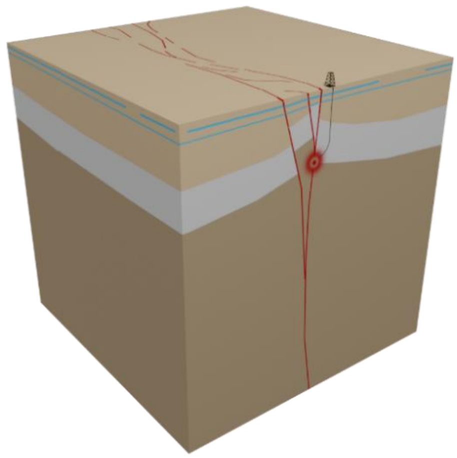
- The construction of tunnels or bridges for both, cars and trains along European trunk sections is a major transnational challenge, especially in the presence of faults. Due to the complex geological situation at most of the construction sites, intensive geological investigations are part of these large projects, normally starting about 10 years before construction starts. In all cases, detailed understanding of the local fault inventory is of utmost importance.
- The construction of reservoir dams was and is necessary for a self-sustaining energy management. Therefore planning and construction is in a close connect to the local tectonic situation including faults



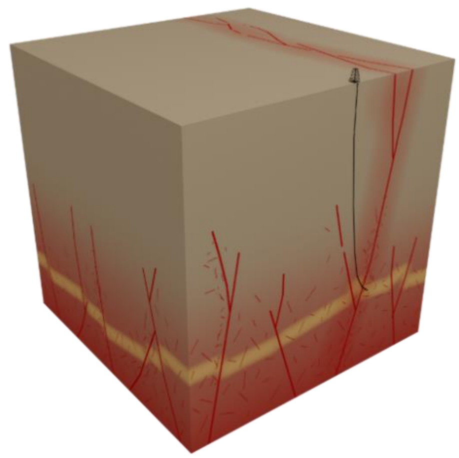
Sedimentation and erosion are typically controlled by uplift and subsidence which takes place along faults. Such patterns are important for understanding the distribution of rock formations and resources within.



Faults often define structural highs and side-seals for reservoirs in which oil and gas can be trapped. These reservoirs may also be developed for storage uses (CO_2, gases).



Faults can generate earthquakes. Seismogenic faults are naturally active. Passive faults can cause induced earthquakes due to nearby injection and production activities. Open faults may act as conduits for migration of injected fluids to groundwater layers.



Faults and associated fracture networks are often important factors defining the required flow rates in geothermal production. If open, the faults can also form conduits for deep thermal waters to the surface. Sometimes specific groups of minerals have formed near fault zones.

Figure 2-4: Examples of aspects for which fault information is needed

2.2 Methods and Case Studies

The assessment of risks mostly takes place in the context of local projects. As a consequence there is a great diversity in methods and practices applied while data sets are often heterogeneous and maintained in different repositories. The level of knowledge varies greatly among the different European institutions and strongly depends on the maturity of subsurface *activities and the locally existing regulatory frameworks for risk management. Within the HIKE project we take a first important step towards overcoming these differences and facilitating a level playing field for hazard assessment. We have done this among others by demonstrating and bringing together state-of-the-art methodologies and information sources in real subsurface hazard case studies*.

2.2.1 Introduction

HIKE WP3 has developed and tested novel methodologies building on top of results from previous projects and research. The work has advanced current state-of-the-art knowledge across different energy exploitation scenarios and various geological settings. The ultimate goal is to improve hazard and impact assessments and provide the basis for better standardization of these evaluations across Europe. With the joint development of methods, workflows and datasets an intensified research collaboration and improved transfer of knowledge has been established.

Different types of energy exploitation of the subsurface give rise to different challenges. These include, but are not limited to: induced seismicity, induced subsidence, as well as reservoir sealing and leakage. The processes are to a varying degree relevant for both energy extraction and subsurface storage. A common theme for these hazards is the importance of faults. Faults can guide subsurface motion as well as provide pathways for leakage. Furthermore, faults can be activated due to changes in external conditions such as pressure changes and lubrication by liquids.

Based on the participating partners' expertise four case studies have been formulated to cover as broad range of methodologies as possible. In all case studies the relevance of the Fault Database being established in WP2 has been explored. Furthermore, cross-cutting relations between individual case studies has been identified. The outcome of the case studies are made publicly available through the share point in WP4, publications and conference presentations and proceedings.

The following sections summarize the key results from the HIKE methodology and case studies

2.2.2 Advanced localization of seismic events (Denmark, Netherlands and Iceland)

Rationale

Knowing the precise location of earthquakes is important for multiple reasons:

- The registration of anthropogenic (induced) earthquakes can be a first warning sign of problems in energy exploitation and subsurface storage
- Careful monitoring of microseismicity in combination with precise locations can in some cases reveal sleeping or unknown faults waking up before major triggered events occur
- In many cases it is important to discern causal relationships between registered earthquakes and natural or anthropogenic events in order to take appropriate preventive or mitigative safety measures.

Earthquakes carry important information on the current state of stress in the subsurface as well as information about the location of weaknesses. On all of the above occasions the precise localization is needed to link earthquakes to specific faults. Precise hypocenter determination can be of great value in concert with other methods such as surface deformation and stress field modelling.

Using small magnitude earthquakes as a first warning system in energy exploitation is quite common, especially in a form of the so-called Traffic Light System (TLS). The reliability depends on the quality of the earthquake monitoring system especially as small earthquakes can be elusive and hard to locate precisely. Low signal-to-noise levels, insufficient number of seismograph stations as well as over-simplified methods and subsurface models pose challenges that need to be overcome to increase reliability.

Ultimately improved localization of earthquakes will contribute to improving the basis for hazard and impact assessments for subsurface energy exploitation and storage projects and thus, to a better scientific basis for standardization of these assessments across Europe. Reduced uncertainty on locations can also lead to more efficient mitigation during subsurface activities.

Approach

Report D3.2 (HIKE_Improved_Seismic_Events_Localization) presents three case studies focusing on advanced localization of seismic events. The case studies cover three different aspects of subsurface utilization: a geothermal field in Iceland, a decommissioned gas field in the Netherlands and active HC producing fields in Denmark.

The case study area in Iceland is on land and equipped with a denser network of seismometers than the offshore case study areas in the Netherlands and Denmark. The selected site contains the Hverahlid Field used for geothermal energy production at the Hellesheidi power plant. For The Netherlands, we have chosen two decommissioned gas fields as case studies where seismicity occurred after the end of production: the Roswinkel and Castricum gas fields. With new initiatives to re-use old, decommissioned gas fields to energy or CO_2 storage together with the fact that seismicity is still occurring at one of the decommissioned gas fields, the exact location and spatial uncertainty of the seismic events is of high importance. Similarly, in Denmark structures in the North Sea are under consideration as future storage sites for CO_2. This includes both the Nini West depleted reservoir as well as the Hanstholm formation, which is unrelated to hydrocarbon production. Nini West is located far off-shore posing a challenge for land-based earthquake detection. The Hanstholm formation is close to the cost of Jutland, but also close to a known active seismic zone. Improving the quality of hypocentre solutions will add significant value to the process of maturing these reservoirs for future storage. Due to the sparsity of the seismic network and the relatively small number of earthquakes, all of Denmark is included in the analysis, not only the oil and gas producing fields in the North Sea. To make up for the scarcity of seismographs, the use of Ocean Bottom Seismometers (OBS) has been explored.

Main findings

Incorporating data from Ocean Bottom Seismometers (OBS) when locating offshore earthquakes has the potential to significantly improve hypocenter precision. Data from the seabed have appeared 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 potential for improved hypocenter determination when real-time solutions are not required.

Locating an earthquake recorded on a network of seismographs involves solving the wave equation for P- and S-waves propagating through the subsurface. The subsurface 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.

The least successful part of the investigation was the testing of the non-linear Monte Carlo based analysis software NonLinLoc. 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 (Figure 2-5). Further work is needed to explore and master the full potential of this method. A strength of the method is that it provides a much better understanding of the location errors than classical inversion methods.

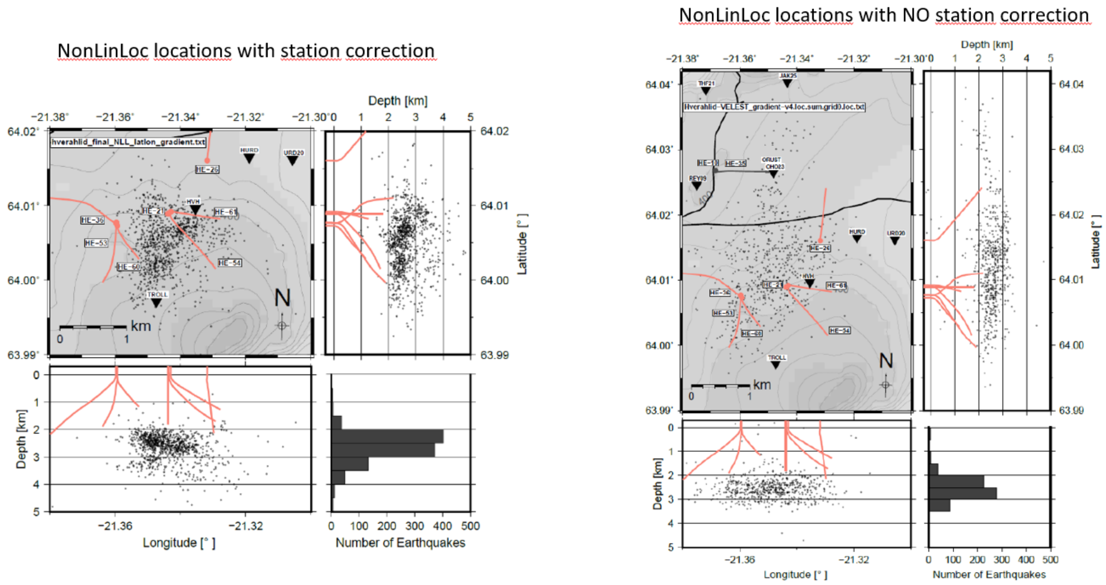


Figure 2-5: Difference between earthquake locations with and without stations corrections in Iceland

2.2.3 Evaluation of methodologies for the assessment of surface displacements (Po Basin in Italy)

Rationale

In the last years, the advanced synthetic aperture radar (SAR) interferometry (InSAR) has proven its effectiveness in the assessment of ground motion with millimetric accuracy. Its integrated use with traditional (in-situ) topographic height determination techniques, such as geometric leveling and Global Navigation Satellite System (GNSS), is consolidated in underground fluids extraction areas for detecting and monitoring land subsidence. Nevertheless, the lack of a specific standardized methodology does not allow for evaluating different results obtained from different types of analysis.

Moreover, PS-InSAR (Permanent Scatterers Interferometric Synthetic Aperture Radar) interferometry data has been used in order to analyze the present crustal mobility with the aim to shed lights on the relation between fault systems and seismic activity at regional scale.

Approach

Report D3.3 (HIKE_Subsidence_Assessment_Techniques) presents two case studies: Po Plain 1, localized in Emilia-Romagna region, and Po Plain 2 in Piemonte region. The first case study show methodologies relevant for the assessment of induced hazards and impacts that are related to the exploitation of subsurface resources. Case study 2 is focused on the analysis of the relation between crustal mobility and fault systems.

The objectives of the first case study "Po plain 1" are twofold:

1. Highlight the uncertainties in the assessment of ground motion, despite the existence of the "Guidelines for monitoring seismicity, ground deformation and pore pressure in subsurface industrial activities" (issued by the Italian Ministry of Economic Development), investigating a case of controversial evaluation of land subsidence (Comerci & Vittori, 2019) in a territory located a few kilometers south of the current Po river delta (Emilia-Romagna region). Nevertheless, the Ground Motion services in progress at European (European Ground Motion Service) and national (Mirror Copernicus) levels will necessarily reduce the uncertainties in the calibration of InSAR data with GNSS data.
2. Show the importance of having a high-detail 3D geological model (i.e. chronostratigraphy and lithology of Pleistocene-Holocene sedimentary bodies and faults) aimed at defining the long-term natural component of subsidence, considering the role of compaction and tectonic activity. For this case a model in the central Po plain (Lombardia region) was used.

A second case study (Po Plain 2) evaluated induced surface displacements by applying the PS-InSAR technique over Piemonte region (western Po Plain).
The objectives of the second case study "Po plain 2" are:

1. Define a tool to assess the present-day crustal mobility that could correlate with the active faults distribution.

2. to improve seismotectonic models by detection of unknown tectonic structures,

   In order to analyze the present crustal mobility and neotectonics of NW Italy (so-called "Alps-Apennines interference zone"), spatial statistics (Hot Spot and geostatistical analysis) of PS-InSAR data has been done.

Main findings

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, the study results of "Po Plain 1" point 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. Furthermore, 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.

The analysis in "Po Plain 2" 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. 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 shows a differential uplift and crustal mobility between the inner Cottian Alps and the Western Po Plain that included three major tectonic structures (e.g., the Col del Lis-Trana and the Cavour tectonic lineaments, western N-verging Padane Thrust Front). Based on the geometrical, geological, seismological, geophysical and morphological correspondence observed between IKB and tectonic structures it seems that the southern segment of the IKB highlights a different crustal mobility due to a current tectonic extensional regime while northern segment of the IKB can be interpreted as a "statistically-defined" boundary that separates areas with the different tectonic regime: compressive or transpressive to the west and extensive to east.
Furthermore, in the eastern part of Po Plain 2, the geological correspondence observed between IKB and the Scrivia tectonic lineaments could highlight a present day tectonic deformation driven by a N-S steep tectonic feature associated to the Scrivia valley lineament; while the correspondence observed between IKB and the eastern N-verging Padane Thrust Front could highlight a present day growth of a fold related to a blind thrust.

The ground motion tendency suggested by IKM seems to be in overall agreement with the different geological and geophysical datasets. This correspondence suggests that a current tectonic mobility and the differential uplift of the sectors analyzed are 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.

2.2.4 Development and application of novel methods for reservoir sealing assessment (Poland)

Rationale

Together with growing industrial development and the need to halt climate change, there is an increasing interest in the potential of subsurface storage. Recently, the main focus of the underground space capacity analysis is associated with the possibility of carbon dioxide sequestration. However, the geological structures may also be used for storage of natural gas, hydrogen, or final disposal of acid gases. Bearing in mind that the stored substances are potentially dangerous for the environment, the underground rock structures have to be wellsealed to prevent any leakage from the target formation. To this end geological storage options are assessed in depleted oil and gas reservoirs, deep saline aquifers, deep-seated coal beds, salt caverns, and mines. The most important factor controlling the potential storage level is a tight caprock surrounding the confined reservoir structure. The best lithologies constituting a sealing level are evaporates and shales with high clay content. Laterally, the confinement of the storage is often created by a convex structure such as an anticline or by a fault plane with sealing properties.

Approach

Within the presented study in D3.4 HIKE Improved Reservoir Seals Assessment, a storage option for liquids such as methane or CO_2 in the Wysoka Kamieńska Graben (WKG) located in the north-western Poland is considered. The potential storage formation ought to be thick sandstones or other reservoir rocks with a sealing complex on the top. Within the area of Polish Lowlands, there are two major units capable of fulfilling these conditions: (1) the Zechstein series built from the dolomitic reservoir rocks (the Main Dolomite of the 2nd cyclothem) and thick sealing layers of rock salts and anhydrites and (2) the Lower and Middle Jurassic aquifers and seals, which are sandstones and shale respectively. Within the Main Dolomite, the hydrocarbons accumulation was found and exploited within the past decades. However, recently the field is considered depleted, and the remaining pore space is filled with brine, potentially reducing the volume of storage options. Thus, only the storage option within the Jurassic layers was investigated. The additional reason for choosing this level was a depth interval between 800 - 1000 meters below the surface, which is preferable for CO_2 sequestration due to appropriate physical conditions (temperature and pressure) to achieve its supercritical state.

Within the geological context of the study, the fundamental question was the sealing capacity of graben bounding faults to check the existence of potential pathways for fluid migration. Studies presented in the literature indicated the fault planes might act as the seal or as the conduit units, depending on geological condition. The evaluation of the fault sealing potential requires considering numerous factors: possible diagenesis, a level of compaction coupled with the overpressure, tectonic load, or recent tectonic stress field. All of these factors may significantly influence the potential risk of safe sequestration or exploitation increasing the possibility of leakage through the fault plane. Therefore, evaluation of fault sealing potential should be integrated within the basin modelling studies.

Main findings

The access to the 3D seismic survey and borehole data enabled to perform a tectonic development of the Wysoka Kamieńska Graben (WKG) and evaluate the sealing potential of its bounding faults within the Lower and Middle Jurassic. The sealing potential has been evaluated based on the so-called shale gouge ratio (SGR) - the parameter dependent on shale volume (Vsh) in rocks. The received, qualitative results indicate good and moderate confinement of the Hettangian reservoir, poor to moderate seal of the Pliensbachian reservoir, and lack of seal of the Bajocian reservoir. The Hettangian reservoir having prospect for confinement within the WKG and characterized by large thickness, low clay content and regional extent can be considered as a potential storage formation.

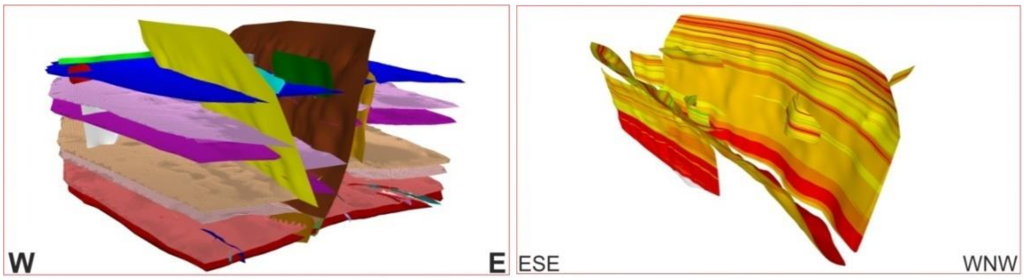


Figure 2-6: Digital model of the Wysoka Kamieńska Graben and a 3D model of SGR parameter comprising a gouge component of fault seal for WKG margin faults.

Considering the potential integration with the HIKE European Fault Database, modelling of sealing potential for all remaining seismic-scale faults has also been performed. The smaller faults, though less significant from the point of view of the potential CO2 storage, provide important information about the tectonic development of the area, thus they should not be neglected within this study.

2.2.5 Assessment of seismicity and safety in storage, case studies in Lacq Rousse, France

Rationale

The use of underground space, and even more, its reuse always pose questions of safety of the activities. Proper assessment of structures' behaviour during and after any human activity is crucial both for safety of further activities development as well as for social approval/licence to operate. The Lacq-Rousse (Southwestern France) area is a depleted gas field, which commercial exploitations ended in 2013. A CO_2 injection and storage experiment was carried out in 2010-2013 (51 kton in total) (Thibault et al., 2014). Although the CO_2 injection did not induce any significant earthquakes in the area, a few felt earthquakes of magnitude up to 4.5 has been observed since 2014 (Aochi & Burnol, 2018). It is an important task to distinguish if the earthquakes are induced, triggered or cause by natural processes. And, if not natural, which activity in fact is responsible for them.

Approach

The case study D3.5 HIKE Subsurface Injection Safety Seismicity focuses on the seismicity related to underground storage in Lacq-Rousse. The seismicity in the area is monitored by public observational networks. The publicly accessible catalogue is provided by Bureau Central Sismologique Français (BCSF) and Réseau National de Surveillance Sismique (Rénass)[15]. A few earthquakes of magnitude 3.5-4.0 are known in the area. We observe that the seismicity is detected down to magnitude 1.5 in the area. Although the precise mapping of the seismicity (many earthquakes) generally allows identifying the activated fault structures, errors in the order of kilometres remain due to the sparse station distributions and the fact that the earthquakes occurred isolated with no obvious aftershocks. 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. The objectives of the case study were (1) archiving the available catalogues and (2) performing the moment tensor inversions of moderate earthquakes to complete our knowledge in the area.

[15] http://www.franceseisme.fr/sismicite.html, last accessed as of the 31st may 2021

Main findings

The Lacq-Rousse gas field is significantly relaxed within the reservoirs regardless of the CO_2 injection experiments as of 2013. Felt earthquakes occurred in the upper crust above the reservoirs in 2013, 2016 and 2017. These are considered to have released the residual stress of the crust due to the compaction of the reservoirs. The obtained mechanisms are qualitatively consistent with the known fractures systems, briefly NWW-SEE running faults and the estimated Coulomb stress change due to the compaction of the reservoir. However, it is difficult to identify a particular fault to each earthquake, because of the limit of location precision, the embedded structure for moderate earthquakes (Mw3.25, Mw3.9 and Mw3.21, respectively) and the isolated occurrence with no aftershocks. On the other hand, the recent 2020/06/20 Mw3.5 earthquake is a strike-slip faulting mechanism at a depth deeper than the reservoir. This is considered instead as a natural earthquake, but no particular fault is identified. Our study provides an increment in the understanding of the current status of the reservoir and the surrounding seismicity.

2.3 Knowledge Share Point

The Knowledge Share Point represents a central repository and online access point for data sources, state-of-art method reports and case study outcomes relevant to an improved hazard and impact assessment. The share point has been be developed on the basis of meta-databases that incorporate links to locally hosted information sources. Thereby it provides end-user oriented search and download functionalities. The definition of a semantic framework (keywords) and implementation in a LinkedData concept, assists in linking the various contents within the share point.

The Knowledge Share Point is intended to further evolve and grow as new information is added after the project lifetime.

3 CONTRIBUTIONS TO GEOERA SPECIFIC RESEARCH TOPICS

The HIKE project was submitted under the Specific Research Topic (SRT) GE4: "Induced Impacts and Hazards". This topic is related to the challenge to support a responsible use of subsurface space and resources, and to help minimising and mitigating unintended impacts, such as induced seismicity, subsidence or impact on groundwater. This challenge requires an improved geological knowledge base for predicting and preventing adverse consequences of exploitation. In the following sections we evaluate the relation between HIKE's main deliverables and the SRT objectives.

3.1 SRT scope and objectives

The SRT has the following scope description:

GE4-1: Inventory and evaluation of recommended, state of art practices, methods and information sources used in impact and induced hazards assessment

GE4-2: Collation of these practices into a shared European knowledge base and research area, categorised by different subsurface uses and geological settings

GE4-3: Identification and demonstration of improvements that advance the state of art for impact and induced hazards assessments in different parts of Europe, e.g. by advancing novel 3D/4D modelling approaches enabling a more reliable earthquake localisation, or a better assessment of faults prone to induce/trigger seismic events. These improvements are preferably demonstrated in realistic case studies and key problem areas

GE4-4: Filling-in of critical knowledge and information gaps that hamper an adequate assessment of impacts and induced hazards in Europe, among others, by generating, processing and integrating existing and new data into a robust and updatable European Information Platform

GE4-5: Establishment of high standard information services that support policy making and facilitate societal awareness to minimize and mitigate impact an hazards.

3.2 European Fault Database

3.2.1 Contribution to National and European challenges

The HIKE Fault Database has resulted in a first-of-its-kind platform providing access to information on geological faults covering the majority of European countries including additional non-participating countries liaised with other GeoERA projects (e.g. the Pannonian Basin Area in the GeoConnect³d project). The data has been gathered from national and regional mapping programmes, repositories and new interpretations using standardized and common agreed methods and specifications (**GE4-1**). These methods and specifications provide a foundation for future extensions and information improvements. The implemented Tectonic Boundary Classification is intended and expected to become a major driver for better harmonized models based on similar concepts supporting stratigraphic interpretations and correlations (**GE4-2**).

The database provides a large extension of the current European information on seismogenic faults. With the inclusion of passive and buried faults the HIKE database provides a source for other types of fault-related research domains in a wider variety of geological settings and underground uses. So far this information was difficult to access as it only existed in local and non-harmonized archives. Both nationally and at European level this effort has resolved a major gap that became more and more apparent due to the diversification of subsurface uses, the increased attention for environmental and societal impacts and the ongoing digitalization in geosciences (**GE4-4**). Through the implementation of HIKE Fault Database in the EGDI, the information remains available after the end of the project and the GeoERA programme while providing the opportunity to continue its development in future collaborative research activities and policy support (**GE4-5**).

The collaboration among partner geological surveys and the developed practices in HIKE have significantly increased the knowledge base which has stimulated many countries to improve their fault models and information (**GE4-2**). Leading surveys with advanced fault data platforms have had an important contribution to this development. The development and implementation of the Linked Data principles and Tectonic Boundary Classification for faults is perhaps the most prominent example. This development went parallel with many other GeoERA projects which also used these principles. For this reason it has been relatively easy to exchange information and to jointly work on mutual applications (**GE4-1 and GE4-5**). In this context the type of information and knowledge in the database has been used as a basis for the Hazard and Impact Case Studies (**GE4-3**). Other foreseen applications are:

- Investigation of natural seismic hazards (including possibilities to embed links with existing national and European information platforms)
- Assessment of induced seismic hazards
- Assessment of the impact of faults on potential future subsurface uses and resources (e.g.: geothermal energy, underground storage, minerals exploration, hydrocarbons and methane emissions)
- Reconstruction of the historical geological development at large

3.2.2 Remaining challenges and recommendations

With the development of the European Fault Database, various challenges and topics for improvement were encountered that are beyond the scope of the HIKE project. These challenges are briefly explained below including recommendations to address them in following national and European research programmes:

- The status and quality of fault mapping and modelling still greatly differs between the geological surveys of Europe. While some countries have highly advanced datasets and models, other regions of Europe are marked by sparse and sometimes outdated fault information. These differences are notably expressed by the spatial coverage of fault maps, the resolution and detail of fault geometries, the depth ranges covered, the availability of full 3D fault representations and maybe most of all, the coverage of spatial and kinematic fault attributes. Gaps may be a consequence of lacking (public) data or low priority in the national geological research programmes. Resolving these gaps requires substantial national or European funding including public release of essential subsurface datasets such as seismic surveys and well logs. The HIKE project results can facilitate the modelling, harmonization and embedding of new information.

- The HIKE database provides a partial coverage of Europe. Although additional (non-partner) countries were involved in the collection of fault data, there is still no data included from the Norway, Sweden, Finland, the UK, Spain, and large parts of south-eastern Europe. HIKE provides the guidelines, templates and procedures to facilitate the incorporation of new datasets at a basic level with minimal efforts. Data owners may optionally choose to take additional efforts for more advanced data processing (e.g. level of detail for the Tectonic Boundary Classification, coverage of fault attributes, inclusion of links with external datasets, etc.)

- The implementation of the Tectonic Boundary Classification is an early endeavour. For most countries the definition is still a first version with limited level of detail. Like stratigraphic classification frameworks, there is a need for further formalization, possible supported and governed by a competent scientific authority. It will likely take a long time before there is a mature implementation. HIKE considers this a crucial development for fault-related resource and hazard assessments, just like the stratigraphic framework is essential for geological research.

- The majority of data in the HIKE database is defined at regional to national scales. With the limited coverage of attribute data, there possibilities for application is detailed hazard assessments are limited. Such details will have to be established and provided by local studies. The HIKE Fault Database can support this integration through the linked data principles and common standards.

3.3 Methods and case studies

All case studies conducted within the HIKE project contribute to the Strategic Research Topics **GE4-1**, **GE4-2, GE4-3** focusing on improvements and add-ons to the broad range of methodologies employed both in reservoirs characterisation for subsurface use planning as well as direct geo-hazard assessment and cross-cutting evaluation for more precise and reliable results. They have concentrated on seismic hazards and leakage related to human underground activities but directly connected with tectonics and faults network, being able to contribute to the FDB input on one hand and presenting opportunities how to use the data gathered in it in the future on the other. They also indicate directions of future work for further filling-in critical knowledge and information gaps in the area of geo-hazard identification, prediction and mitigation (**GE4-4**).

3.3.1 Contribution to National and European challenges

Evaluation and prediction of hazards and impacts on natural environment in Europe caused by (or derived from) geo-energy application is of a paramount importance both for energy security in general and for ensuring fair and even distribution of costs and benefits under the wide term of energy justice. High-quality hazard assessments in concert with state-of-the-art monitoring methods are also critical for public acceptance of future energy exploitation and climate solutions. Case studies conducted within the HIKE project show that there is a vast catalogue of methods of such assessment, implementing wide range of technologies starting from geophysical logs interpretations, on-land permanent signals monitoring and satellite measurements of various parameters combined with advanced 3D and 4D modelling. However, credibility of their results might be questioned, especially in cases of not sufficient availability or resolution of data, a lack of good reference values and a lack of possibility of cross-checking with other existing results in some way related to problems in question. In big scale activities it might be not enough to estimate an uncertainty of performed assessment, as they might appear not sufficient for proper subsurface use planning and management. An instant development and international cooperation in the field of natural and induced hazards assessment and mitigation is a clue for further safe and efficient progress of geo-energy contribution to climate neutral Europe.

The in-depth work on hazard related methodologies in relation to geo-energy has highlighted the need to assess the long-term stability and behaviour of the subsurface with higher precision than ever before. In addition to the demand for greater precision, also quantitative knowledge of the related uncertainties is required to link individual hazards to distinct locations. The determination of geo-hazards is site specific, but the methodologies involved as well as the need for common standards is an overarching matter for all of Europe.

Hazard assessments for natural seismicity are typically not linked to the seismicity of a specific fault. Instead, the analysis is carried out for a broader area. While the classical seismic hazard methodology based on a long timeline of natural seismicity is still a necessary component, it is far from sufficient for mitigation purposes. Changing the stresses on a fault by injecting or extracting fluids for e.g. harvesting geothermal energy or storing CO_2 can lead to unintended seismic activity. Being able to track the micro-seismicity more precisely - ideally linking it to specific faults or zones in the subsurface - can serve as a first warning of fault reactivation, allowing for action to protect public safety and infrastructure. Furthermore, precise tracking of micro-seismicity may allow for quick intervention if there is increased risk of CO_2 or other gas escape from a deep reservoir.

Improving the methodology for locating earthquakes contains several components, all of which have been explored in the HIKE project:

a) more precise hypocentres which can be achieved through denser data collection, better subsurface velocity models and more advanced analysis methods
b) a deeper understanding of the uncertainties on the hypocentres which can be achieved through various statistical methods and stochastically analysis. This aids to discern if an earthquake is related to a specific fault or not
c) full waveform inversion to obtain the earthquake source mechanism can reveal if the earthquake is related to the natural seismicity in the area or to induced stresses

The long term seismological monitoring of an already utilised reservoir (e.g. for HC production) is important to assure the security in general and for potential future usage. In case of depleted HC reservoirs it is inferred that the residual stress due to the compaction can play an important role for the continued seismicity for many years after the end of exploitation. It is crucial to estimate how long it takes to relax the residual stress for the regional seismic hazard assessment. It is also important to follow up on the seismicity and reservoir state, not only for the current security but also for the potential (re)use of the reservoir such as underground gas storage or CO_2 storage as required by the EU Storage Directive (2009).

Ground motion observations can vastly contribute to geo-hazards assessment not only in case of surficial landslides but also in deep subsurface applications security assessment. In general, ground motion is correlated to several natural and anthropogenic phenomena such as tectonic activity, subsidence, underground fluid exploitation or storage. All these phenomena and activities have significant implications from an economic, environmental, and social point of view. Topographical variations can have negative impacts on the hydrodynamic setting, the hydraulic and road infrastructure, the coastline setting, the biological ecosystems, and the salinization of aquifers. Therefore, an efficient monitoring of ground movements and the best possible understanding of the causes that determine them are more than ever necessary for the relevant, countless and of various kinds implications that they have on our society.

Satellite based methodologies are explored and improved to study the present-day crustal mobility and the differential uplift mostly driven by the activity of major faults. In particular, the relative ground movements suggested by the Iso Kinematic Maps constructed from satellite measurements could give new perspectives for interpretation of present day kinematic trends.

InSAR satellite-based methodology combined with geological and seismology knowledge can be useful to provide constraints on modelling earthquake source mechanisms to guide the land use and subsurface use planning, industrial layouts, urban and major infrastructure development as well as public health hazard assessment.

Many challenges are related to analysing subsidence in a region naturally affected by land subsidence because of its geographical and geological features to which the effects of anthropogenic activities are added. Distinguishing the natural subsidence from the anthropogenic component requires careful analysis and measurements over extensive areas as well as detailed ground (in-situ) observations in order to validate and calibrate satellite-based data.

A sufficient sealing of subsurface reservoirs is very important with regard to resources protection (e.g. preservation of hydrocarbons plays) as well as for safety of storage utilities. Since a fault may act as a barrier for fluid flow or a migration path, appropriate recognition of its properties is extremely important for prospection of hydrocarbons and proper development planning. Sealing faults may constitute a trap forming a hydrocarbon reservoir or transform large reservoirs into smaller compartments with different reservoir pressure and fluid characteristics, hindering efficient exploitation. On the other hand, open and permeable faults may cause a loss of mud circulation leading to serious technical problems during the drilling operation (Cerveny et al., 2004; Knott, 1993) as well as environmental hazards.

The fault sealing analysis is also crucial in terms of underground storage planning. To assess if a reservoir is appropriate for storage, an evaluation of its long-term confinement stability is a key point. Thus, the sealing or non-sealing properties of faults need to be evaluated considering the significant increase of fluid pressure during the CO_2 or other substances injection.

Proper evaluation of faults sealing potential based on shale gouge ratio is highly dependent on spatial data which allow for proper identification of fault geometry as well as geochemical data providing reliable quantitative information on clay minerals occurrence in fault-hosting rocks. Detailed information of this kind is not very common and even if exists, not easily accessible. Gathering step by step this information from existing records and further research to acquire new results especially in areas with high underground use potential or prone to seismic hazards to store them in standardised and public data base would certainly help in broader use of presented fault sealing assessment method as well as further improvement in fighting of shortages in this kind of assessment.

Each methodology tested within the HIKE project has been studied by local experts within their own country, while having regular cross-country cross-disciplinary meetings to improve the common perception of geo-hazards. The meetings have also served as a way to communicate the capabilities as well as the limitations of the individual approaches. While progress has been made within all of the fields of study, HIKE is just one important step towards better hazard assessments. Further research is needed within each methodology, and more work is needed to ensure the impact beyond the partner institutions.

The findings will be communicated through the Knowledge Share Point, but a more aggressive approach could ensure a faster and even more effective distribution not just among partner institutions but across all of Europe.

3.3.2 Remaining challenges and recommendations

Within case studies various challenges and topics for improvement were encountered that are beyond the scope of the HIKE project. These challenges are briefly explained below including recommendations to address them in following national and European research programmes:

1. The EU Storage Directive (2009)[16] requires careful monitoring and hazard assessment for maturing reservoirs for CCS, during injection, and for an extended period after the termination of activities. To solve this at a pan-European scale it is important to have similar standards and methodologies across the countries for subsidence, fault sealing and seismicity. As storage sites can be located in border regions, a common understanding of methodologies and standards for estimating geo-hazards will assure a mutual understanding of the safety of a project. This is equally important for geothermal plants that carry the risk of inducing seismicity.

2. The development of improved monitoring and hazard assessment methodologies needs to be accelerated in order to aid Europe reach the 2050 CO_2 reduction goals. The HIKE project has explored and improved methodologies to assess the three main potential hazards related to geo-energy and subsurface storage:
    a) induced and triggered seismicity
    b) subsidence
    c) fault sealing and leakage

3) Satellite techniques prove to be capable tools supporting geo-hazards identification and quantitative evaluation. The European Commission, in the framework of the Copernicus Programme, in 2018 started financing the implementation of the European Ground Motion Service (EGMS), aimed at providing reliable and timely information regarding natural and anthropogenic ground motion phenomena in Europe. The objective is to detect ground displacements (including land subsidence) with millimetric accuracy, by applying the SAR technology taking advantage of the images continuously acquired by the ESA Sentinel-1 satellites. The European Environmental Agency (EEA), which is entrusted with the realization of the service, is exploring the availability of in-situ networks exploitable for the validation and the calibration of the ground motion data. The first release of EGMS is expected in 2022

16 Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006

and will have an annual update. There are great expectations for improvement of subsidence study once the better reference net is available.

4) All hazard assessment methodologies require reliable input of data. In many cases this data acquisition is very expensive and sometimes not possible if not performed in line with industrial activities. Thus solving the issue of data disclosure and data access is an urgent challenge to improve European hazard and risk assessment. Even data availability regulations across all Member States will allow for creating common standards for risk evaluation. The sooner such standards in geo-energy projects are implemented, the bigger chance for social and administrative acceptance of subsurface projects and thus for benefits in achieving set climate and environmental goals with use of them.

4 FUTURE OUTLOOK FOR GEOLOGICAL SERVICES OF EUROPE

The GeoERA participants are now preparing for a follow-up in the Coordination and Support Action "Geological Services for Europe" (CSA-GSE). Below we give provide recommendations on the embedding of HIKE results in this research programme.

- The HIKE Fault Database is a pivotal component for the development of a European Structural Framework. This framework is intended to be used to link resource inventories to geological units.
- The mapping and characteristics of faults are a key input for assessing deep geothermal resources in tight carbonate rocks (see HotLime) and the viability of secure storage sites (containment).
- The Semantics and LinkedData principles defined in HIKE are expected to become a crucial element of the Geological Services in order to establish relations between data and information sources.
- The principles of the Knowledge Share Point can generically be used to exchange relevant reports, guidelines, tools and (external) data sources.

The assessment of (local/regional) hazards is not included in the scope of the CSA-GSE call. It is recommended however to continue collaboration between geological survey organizations to inform stakeholders on the potential hazards and risks associated with exploitation of resources and capacities assessed in CSA-GSE. These aspects and linked research challenges may be addressed in the yearly updates of the Strategic Research and Innovation Agenda in CSA-GSE.

5 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

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