Hazard and Impact Knowledge for Europe

Deliverable D2.3

Geological Characterization of Faults

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GENERAL INTRODUCTION

Report on characterization results/methods, the quality of derived fault information, comparability of fault information originating from various locations/vintages/measurements, and future recommendations for advanced determination of fault parameters based on potential field and seismic reflection data

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1 INTRODUCTION

1.1 Document background and scope

This report presents an overview and background to the modelling and characterization of faults in the European Fault Database (FDB). It provides a general description and overview of the different types of faults and their descriptive elements, followed by an evaluation of different methods and approaches used to model fault geometry and define geological attributes and kinematic behaviour. Many details and applied modelling and characterization approaches and case studies are described among others in the HIKE Deliverables D2.2b, D2.4 and various reports from the 3DGEO-EU, HOTLIME and 3DGeoConnect[3]d projects

This report is a complementary part of the entire suite of deliverables from workpackage 2 (Fault Database Development). It serves as a reference for the following documents:

- The specifications in HIKE deliverable D2.1b[1] (in particular the fault descriptive elements and observation techniques).
- The country reports in HIKE deliverable D2.2b[2] (in particular the applied fault observation methods and modelling techniques)
- The fault database application and evaluation report in D2.4[3] (in particular the consequences of applied observation and modelling techniques for the general applicability in various studies and analyses)
- The report incorporates links and references to the research studies performed in work package 3 (Hazard and Impact case studies and methods).

1.2 Document structure

Chapter 2	provides a general description to the HIKE European Fault Database (FDB) and introduces the purpose and context of fault characterization
Chapter 3	Contains an overview and brief definition of the various descriptive elements of faults, fault types and fault-related phenomena in rock formations.
Chapter 4	comprises an overview of various fault observation methods and their strengths and weaknesses with regards to fault modelling and characterization
Chapter 5	similarly discusses the different methods and techniques to model fault geometries and analyse fault various attributes and characteristics. Again, in looks at strengths and weaknesses.
Chapter 6	discusses how faults can be classified and the applicability of the Tectonic Boundary Classification used in the HIKE FDB.
Chapter 7	presents several new fault characterization case studies that have been performed within the context of the HIKE project.

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

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

[3] http://geoera.eu/wp-content/uploads/2021/10/D2.4_HIKE_Fault_DB_Evaluation.pdf

1.3 Abbreviations

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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 BRIEF INTRODUCTION TO THE EUROPEAN FAULT DATABASE

General description

The HIKE project has established a comprehensive database of faults in Europe (hereafter FDB) which standardizes and collates information and knowledge from different national and regional mapping programmes. Existing other European fault databases are mainly restricted to information on seismogenic faults[4] or major faults appearing at surface only[5]. The HIKE FDB has been developed in order to take into account any type of fault represented at arbitrary depth levels.

While seismogenic faults are crucial for investigation of tectonic earthquakes, the locations of passive and capable faults are essential to understand induced hazards potential related to subsurface activities. A comprehensive overview of all faults in the subsurface (both shallow and deep) is needed to understand and reconstruct the geological development of the subsurface and the distribution of important resources like geo-energy, groundwater and minerals.

The HIKE FDB not only provides the actual data for identified faults in the subsurface. It also delivers essential knowledge associated to these faults, e.g. via key citations and documents which are linked to the fault objects using a generic vocabulary system and tectonic boundary classification framework based on semantic (LinkedData) principles[6].

2.1 Heterogeneous data sources

The current version of the HIKE FDB contains a large amount of fault data which, in many cases, has not been published online before. The data are often heterogeneous due to various reasons, e.g.:

- Europe comprises a large variety of local and regional geological settings which determine the type, appearance and behaviour of faults and other tectonic features.
- The level of (prior) exploration and production of economic resources determine to a great extent the availability of data and information from subsurface acquisition and geological reconnaissance programmes. Focal areas for oil and gas exploration for example, are typically densely covered by deep seismic data, wells and other geophysical measurements. In other areas subsurface information may be sparse except for some shallow boreholes and surface outcrops. In many cases the information from industry is considered confidential. Consequently, there is a huge variation with regards to the density, depth-range and quality exploration data. This largely determines to what extent faults can be observed and at what scale and detail.

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[4] SHARE database: http://diss.rm.ingv.it/share-edsf/SHARE_WP3.2_Database.html

[5] OneGeology Europe: https://www.eurogeosurveys.org/projects/onegeology-europe/ (now included at: http://www.europe-geology.eu)

[6] Hintersberger et al. (2017): The new database "Tectonic Boundaries" at the Geological Survey of Austria, Jb. Geol. B.-A., vol. 157, p. 195-207

- The importance and relevance of faults to societal aspects may differ per region and country. For this reason, faults may have been investigated at different levels of detail with focus on different aspects. Italy is a good example in this respect. Due to the occurrence and impacts of natural earthquakes, there is a strong focus on kinematic fault attributes needed to better predict potential (natural) hazards. As a result, the Italian database is not only very detailed in scale, but it also incorporates a more comprehensive suite of different fault attributes than most other countries. In some other areas the fault information is limited to some large-scale geometric data only.
- The maturity and state-of-art of mapping programmes varies significantly across Europe. Few countries have a full 3D national model which greatly helps to analyse and visualise faults. In other areas, detailed geological information is mostly limited to the surface level and shallow formations. The differences in data and mapping programmes is notably seen in border regions where the maps show sharp contrasts between neighbouring countries. Often, there are significant discrepancies in the mapping of faults across borders.

The HIKE partners and experts from other GeoERA projects have defined a robust platform which is capable to store, maintain and disseminate heterogeneous fault from different sources. Rather than harmonizing the fault data itself, the HIKE project provides standards which enable the integration and correlation of heterogeneous sources.

2.2 HIKE European Fault Database

In the following sections we provide a summary of the different components of the HIKE FDB. Specific details are provided in HIKE Deliverable D2.1b

2.2.1 Fault geometry

Faults are 3D planar structures which intersect and offset geological layers and formations and can be represented in many different ways (Figure 2-1). They are rarely singular and isolated features. Often faults are part of a complex fracture network or larger fault system with micro- to macroscale features.

The HIKE FDB stores and represents faults as so-called fault traces that can ben imaged in a 2D map view. These traces are the linear or polygonal intersections of faults with subsurface formations or the surface level. While a fault typically intersects with multiple formations at different depth levels, the FDB may also store multiple fault traces for one fault. In combination, these traces provide an insight in the 3D geometry of the fault. The default representation is the surface trace of the fault or the shallowest intersection of a buried fault.

The current FDB primarily focuses on fault geometries at national to European scale. Faults can be stored and represented at different scale levels, however. A fault zone consisting of many individual faults may, for example, be stored as a single feature at large scales and multiple fault elements at smaller scales. In the database these different representations are all associated with the same fault system id via the vocabulary.

Specific geometrical features or 3D data are typically provided via repositories at the national level. These repositories may be provided as a link in the associated vocabulary or meta-database.

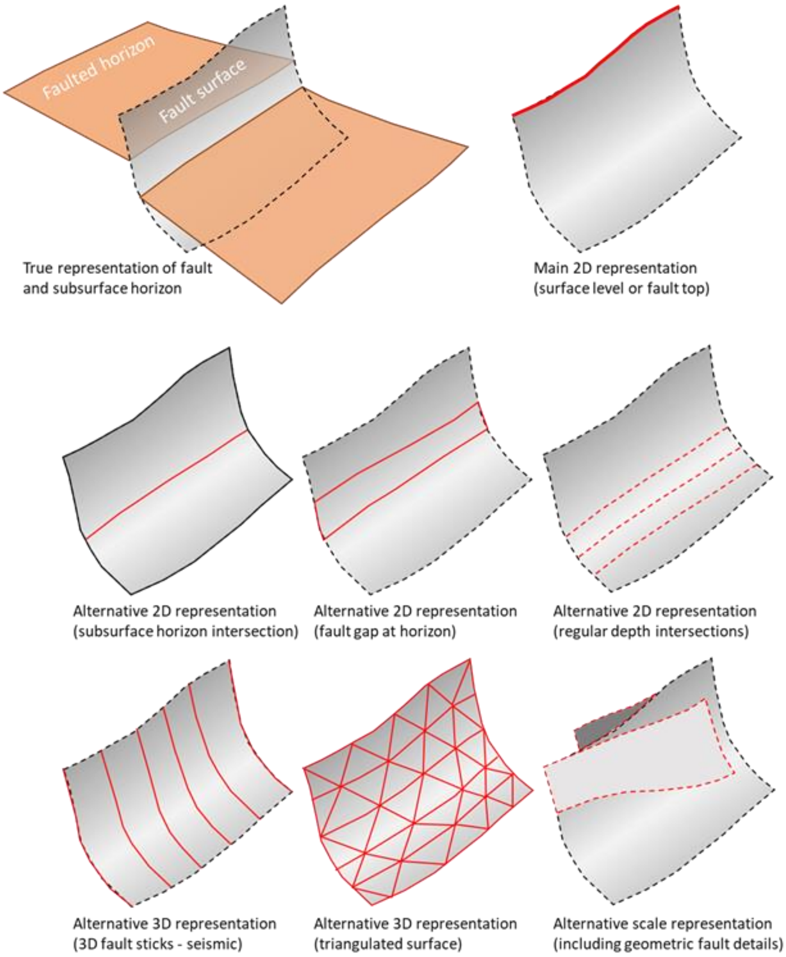

Figure 2-1: Overview of different geometrical definitions of faults

2.2.2 Fault attributes

In order to reflect the various levels of knowledge and data availability for each single fault, the attributes of the HIKE FDB are defined at four levels:

• Fault geometry level: These attributes describe the geometrical representation of the fault. As there can be more than one representation per fault these attributes are linked to a specific geometrical representation.

• Fault object level as part of the fault attribute database. These attributes describe the fault object in the geoscientific context. These attributes are independent from the geometrical representation of the fault and support a wide variety of characteristics that are commonly used in mapping and structural analysis:

- Basic identifiers such as the fault name, country
    - Static spatial characteristics such as fault length, strike, dip angle,
    - Kinematic characteristics such as displacement, timing of movement
    - Behaviour aspects such as seismic activity, open/sealed to flow
    - Evaluation aspects such as interpretation and observation methods

- On the semantic concept level as part of the vocabulary. The vocabulary allows to include information that concerns the database entries. In addition, the vocabulary provides the possibility to link to already existing fault databases such as, for example, SHARE.

- On the fault dataset level. On this level attributes describe the dataset as a whole and not the individual faults.

2.2.3 Vocabulary and Tectonic Boundary Classification Framework

Naming of faults and fault systems often leads to misunderstandings if local names are used across borders (e.g., Karawanken Fault System (German) vs. Karavanke Fault System (Slovenian) vs. Karavanks Fault System (English)). For the FDB, it is essential that fault datasets from different origins and of different scales become comparable, even without the use of standardized fault name lists. For the FDB, such regional or historical fault names are processed as one vocabulary entry with several alternative (local) names to keep the local descriptive labels. Each fault object in the FDB is linked with one vocabulary entry.

Using LinkedData principles and SKOS references, a mapping to a global context on the Semantic Web is defined. Therefore, the FDB is accompanied by the generation of SKOS vocabularies in accordance with the LinkedData principles. In addition, the newly generated vocabulary provides the possibility to link to already existing databases, such as the SHARE database or national fault databases, such as the ITHACA database of active faults[7]. Moreover, it creates context by linking to other sources of information, i.e., publications regarding the specific fault (system) or Wikipedia articles.

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

[7] http://sgi2.isprambiente.it/ithacaweb

2.2.4 *Metadata*

Metadata of the FDB is stored in the EGDI Metadata Catalogue[8]. There is a metadata record for the entire FDB, but because the faults are provided as a national (or regional) data set of multiple faults, each data set has its own metadata record, named e.g. “Tectonic boundaries in Austria” or “Tectonic boundaries in Bavaria”. These national/regional metadata records are used to reference the source and the specifications of each individual dataset. They are linked to the overall FDB record via the build-in parent/children functionality of the EGDI Metadata Catalogue.

The next chapters evaluate the various approaches for mapping and characterizing faults. The specific implications of specific geological settings, levels of exploration and used methods for fault observation and modelling are presented in the HIKE D2.2 Fault data country reports[9].

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

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

3 FAULT TERMINOLOGY AND DEFINITIONS

This chapter provides a brief description of common terminologies and definitions used to describe fault types, fault elements, fault appearances, fault-fault relations and typical fault-related features in the surrounding rock formations. In this chapter, we mostly follow the terminology of Peacock et al., 2016.

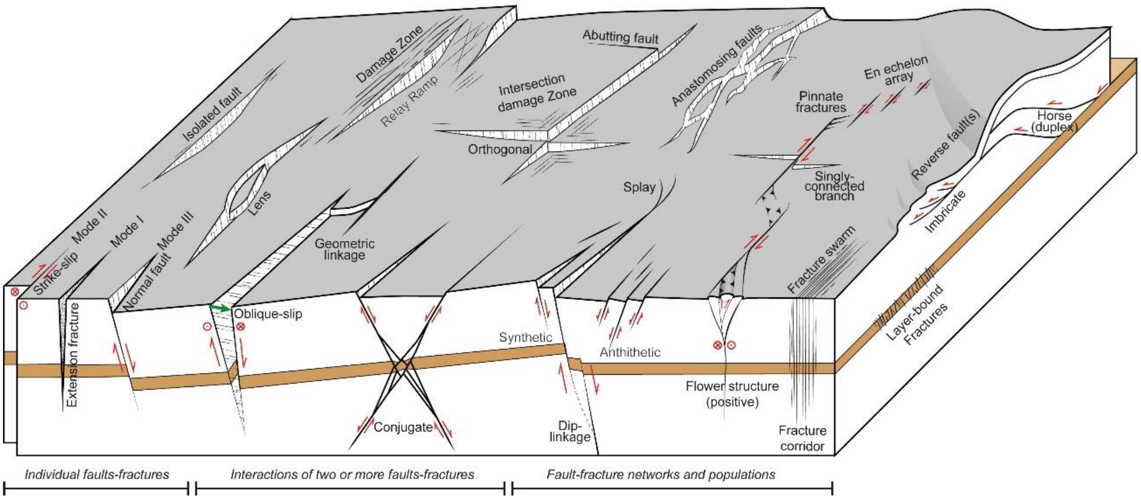

Figure 3-1: Schematic overview of fault types and fault relationships (after Peacock et al., 2016)

3.1 Fault descriptive elements

3.1.1 Fault plane

The fault plane represents the fractured surface along which rock formations have been displaced. This surface can have many shapes and orientations depending on the type of fault and/or structural domain. Fault planes can appear either as very sharp interfaces or as wider fault gouge zones. Smaller individual faults may represent segments in larger-scale fault systems. On large-scale overview maps such fault systems may be represented as one single fault plane though.

3.1.2 Fault trace

The fault trace typically represents the line of intersection with the surface level (i.e. the fault outcrop). There are also horizontal or lateral intersections in the subsurface, for example:

- A **stratigraphic fault trace** representing the intersection with a certain layer or horizon.
- An **iso-depth fault trace** representing the intersection with a specific depth level
- A **top or bottom fault trace** representing the top or bottom margin of the fault plane (e.g. in case of a buried fault or a restricted fault)

3.1.3 Fault cross section

The fault cross section is the vertical profile of the fault plane. It typically shows how the fault extends below the surface and is needed to define aspects like fault offset, timing of fault movement, etc. The cross section is typically defined in a plane that is perpendicular to the fault strike. For determination of the fault displacement, the cross section should be parallel to the lineation (i.e., striae or slickenlines).

3.1.4 Fault strike

The fault strike defines the orientation of the fault trace and is defined as the compass direction (relative to the north) of the fault trace. Following this definition, the fault strike can have two values and is therefore often given as wind direction, e.g. NNW-SSE. Sometimes, the right-hand-rule can be applied that defines the strike as the orientation counter-clockwise (in the direction of “the thumb”) of the faults dip direction (in the direction of “the fingers”). In larger and more complex faults the strike may vary laterally. In this case the strike may either be represented as a single average strike for the entire fault length or a range of strike values measured for the fault plane.

3.1.5 Fault dip

The fault dip defines the angle between the fault plane and a horizontal plane as measured in the vertical plane perpendicular to the fault strike (i.e. the fault cross-section). The dip can vary laterally and with depth. Typically, the dip of the fault decreases with increasing depth until it meets a low angle fault detachment. In thrust faults, the dip is usually near horizontal except for the ramps where rock formations are pushed on top of other formations (see Duplex and Thrust fault).

3.1.6 Fault offset and displacement

Faults form where rock formations are broken and where broken are displaced relative to each other. The fault displacement represents the actual distance in the direction of movement between two originally adjacent points on the surface of a fault. The displacement can be curved, so need not be a straight line between the two originally adjacent points. The fault offset measures the apparent displacement of a marker (either in vertical cross-section for normal and reversed faults or along-strike in strike-slip faults). Over geological time, displacements can become very large (up to 10’s or 100’s of kilometres for some large-scale fault systems). Note that fault movements may change direction and sense over time and can even become reverse, so obscuring earlier displacements. This may be a huge complicating factor in reconstructing the history of fault development.

3.1.7 Fault length

This is the length of the fault trace between the two extremities (fault tips), measured in a horizontal plane (i.e. up to where fault displacements are determined). The length can be either measured as the true length when it is measured along the curving fault trace or as the linear distance between the two lateral extremities of the fault plane.

3.1.8 *Fault height*

The fault height is the true vertical distance between the upper and lower boundary of the fault plane. Often the height is hard to determine as the fault detachment planes may be located deeply within the earth and beyond the detection range of most observation techniques. Sometimes, however, detachment planes are located at shallow depths, for example when a fault meets a ductile rock salt interval or in the case of thrust faults.

3.1.9 *Fault gap*

With normal, extensional faults, rock formations are displaced relative to each other. When the fault plane is non-vertical, the top- and bottom interfaces of the rock formations appear to move away from each other on map view. This way widening gaps for both interfaces may develop. Depending on the scale of mapping these gaps can be represented as a polygonal fault intersection, yet in most national scale geological maps, these gaps are neglected and simplified into a centre-line fault trace.

3.1.10 *Fault heave*

Heave is defined as the horizontal component of the dip-separation of a normal or reverse fault measured in vertical cross- section perpendicular to the fault strike (Hills, 1940, Billings, 1942). Heave is defined in terms of the separation, hence it applies to the dip of a fault and to the displacement. Only for a pure dip-slip fault (no oblique-slip component) is the heave equivalent to the horizontal component of the displacement (Peacock et al., 2000).

3.2 Fault types

3.2.1 *Normal fault*

Normal fault planes are dipping at moderate to high angles. The hanging wall block has moved downwards relative to the footwall block. Normal faults are typically associated with a horizontally extensional and/or vertically compressional (gravitational) structural setting.

3.2.2 *Reverse fault*

Like normal faults, reversed fault planes are dipping at moderate to high angles. The hanging wall block has moved upwards relative to the footwall block at an angle almost perpendicular to the fault strike. Reversed faults are typically associated with a horizontally compressional structural setting.

3.2.3 *Strike-slip fault or wrench fault*

With strike-slip faults, the rock formations at both sides of the fault have moved laterally with respect to each other (i.e. parallel to the fault strike). The sense of motion can be dextral (right-lateral) or sinistral (left-lateral). The lateral movement is typically associated with a compressional structural setting and creates a sort of torque motion. That’s why these faults are also called wrench fault. Strike-slip fault planes are typically vertical to sub-vertical. Therefore, it is not possible to make a clear distinction between a hanging wall and a footwall block. The Pyrenean mountain ranges and the San Andreas fault are typical examples for strike-slip faulting.

3.2.4 Oblique-slip faults

Oblique-slip faults can be seen as a hybrid type of fault as they show both lateral and vertical displacement. The sense of motion can be dextral or sinistral and the vertical component can be either normal or reversed. Typically, these faults form when tensional or compressional stresses are applied at an angle on pre-existing faults, resulting in transtensional or transpressional local stress conditions.

3.2.5 Thrust fault

Thrust faults define a sliding plane where sections of the earth crust have moved over other parts of the crust. The plane is typically sub-horizontal with higher-angle ramps where the crust has broken and started moving on top of the crust in front. Sometimes multiple sections have slid on top of each other, thereby creating a so-called duplex. Thrust faults are purely compressional and responsible for the formation of many mountain ranges (e.g. the Alps). They often form where continental plates are colliding frontally.

3.2.6 Detachment fault/plane/zone or master fault

A detachment plane is defined as a fault forming a basal surface along which overlying strata are detached (Pierce, 1963). The term detachment is now commonly used for a regionally extensive, gently dipping normal fault. Faults may run deep into the earth, yet eventually they will terminate in a detachment plane or zone. This zone may represent a more ductile interval where the fault planes transform into a zone of plastic deformation or folding. Another possibility is that faults meet a common plane of displacement which often has a near horizontal orientation parallel to the orientation of the bedding plane. In particular in an extensional (normal faulting) regime, the individual faults may have a decreasing dip angle meeting with a low-angle or sometimes even a sub-horizontal detachment fault. The detachment fault and the connected individual faults are typically grouped together in a (larger) fault system.

3.2.7 Detached fault

A detached fault or layer-bound fault is vertically terminated by a subsurface boundary or stratigraphic interval. Typically, this happens where the fault crosses a more ductile layer like rock salt. If thick enough, this layer may accommodate the fault displacement through plastic deformation, thereby preventing the progression of faulting to deeper layers.

3.2.8 Listric fault

A listric fault is a curved normal fault typically linked to a detachment plane (and thus represents a type of detached fault) with a near horizontal orientation at the base and a steep (high angle) orientation near the top (concave geometry). Sometimes, listric faults appear in a succession with intervening tilted fault blocks above a commonly shared detachment. They typically represent extensional tectonic settings.

3.3 Fault activity

3.3.1 Active fault or seismogenic fault

An active (or seismogenic) fault is moving or has very recently moved. In general, these faults are still likely to react upon build-up stresses on the fault plane. At some critical point the fault moves thereby releases the stresses. This process repeats itself over geological time until plate-tectonic reorganizations result in a change of the regional stress field and the faults are no longer critically stressed. The activity of faults is directly observed from often frequent and sometimes high magnitude earthquakes. Active faults typically occur at the surface where they may lead to active deformation. Blind faults are an exception to this. The time interval for faults to be considered active varies between geological settings, but normally the last several 10.000 up to several 100.000 years are taken into account.

3.3.2 Passive fault

Passive faults have been active a very long time ago. In the current situation there is no build-up of tectonic stresses that would be capable of generating movements and earthquakes. In basins, passive faults are typically hidden below an undisturbed sediment overburden. Therefore, specific subsurface observation techniques (e.g. seismic, geomagnetic or gravitational surveys) are required to detect and map these faults. Passive faults may become critically stressed due to anthropogenic activities (e.g. production or injection of fluids). As they are likely to represent weaker zones in the subsurface, these stresses may lead to induced earthquakes.

3.3.3 Capable fault

A capable fault is defined as a fault with a significant potential for displacement at or near the Earth's surface (International Atomic Energy Agency, 2010[10]). Capable faults are not necessarily associated with observed movements and earthquakes. Yet from circumstantial geological evidence, it is expected that these faults may eventually become active as increasing natural stresses are acting on the fault plane. Subsurface activities may trigger the fault movement before that time. Typically, this may happen when injected fluids enter the fault and thereby reduce the friction below a critical level, or when injection or extraction of fluids leads to increasing (differential) stresses acting on the fault.

3.3.4 Blind or buried fault

A buried fault is simply a fault which is hidden under a non-faulted overburden. In most cases such faults need to be detected by ground-penetrating observation techniques such as seismic surveying. The presence of the fault can however be inferred from indirect surface observations, for example elevations in the landscape and presence of thermal springs. Although (deeply) buried faults are often passive, this is not guaranteed (see blind fault)

[10] IAEA SSG-9 (2010): https://www-pub.iaea.org/MTCD/publications/PDF/Pub1448_web.pdf

A blind fault exists in the subsurface only as it has not (yet) reached the surface. Typically, blind faults are associated with the ramp part of a thrust fault where the rock layers at the top edge are folded instead of faulted. Blind faults can be active. In general, the displacement along a fault plane is not uniform and represents an ellipsoidal displacement profile (Allan diagram) with maximum values at the faults centre that diminish to zero at the fault tips. With such a displacement profile it is expected that active faults are partly blind, but potentially come to surface as the fault grows in length due to continuing displacement.

3.3.5 Inferred fault

An inferred fault is a fault for which insufficient data exists to prove its presence and determine the exact location from direct observations. This may happen when the fault is partly or completely covered by younger sediments and only dispersed and widely spaced observation points are available. In this case the presence and location of the fault trace and/or fault plane can only be obtained after interpolation. Otherwise, the presence of a fault may be suspected based on morphological features (e.g. elevation differences, river avulsions,), seismic activity that can be linked to a specific location or the presence of thermal springs at which deep water has migrated along a buried fault. Many deep faults in the HIKE FDB are inferred and therefore associated with a certain degree of uncertainty.

3.4 Fault relationships

3.4.1 Isolated faults

An isolated fault is a single fault with no connections to other faults. Its lateral extent is restricted, and the fault is not a part of a larger (segmented) fault or fault system. Sometimes multiple scattered and isolated faults which share similar characteristics (e.g. orientation, age, type) are grouped into a fault zone.

3.4.2 Horizontally segmented faults

Large faults may consist of a series of multiple smaller faults which are aligned in a stepwise fashion and together define the larger fault trace or fault plane. In between horizontally segmented faults there may be a folded or faulted (breached) relay ramp.

3.4.3 Vertically segmented faults

Faults can also be vertically segmented into multiple smaller faults that dip in the same direction (dip-linkage). Generally, this can happen at the interface of a more ductile layer which acts as an intermediate detachment plane for the fault which continues downward below this layer with a small lateral offset.

3.4.4 En-echelon faults / step faults

En-echelon faults are a specific type of segmented faults which consist of small, closely spaced, parallel or subparallel, stepwise overlapping faults. The orientation of the minor faults is typically oblique to the overall structural trend.

3.4.5 Anastomosing faults

Anastomosing fault patterns are characterized by a group of wavy, subparallel faults that merge and diverge, similar to braided river patterns

3.4.6 Approaching faults

Approaching faults are simply two or more faults that are dipping in different directions, but do not intersect.

3.4.7 Intersecting faults

Faults may terminate against another fault, thereby creating a T- shaped configuration. The fault that terminates against the other fault is called the abutting fault. Both faults may have developed simultaneously or during different stages of the structural evolution. In the latter case the abutting fault is most likely the older fault. Fault splays are similar but differ by the fact that they show a Y-shaped configuration. Orthogonal faults represent a situation where faults cross without showing clear lateral offsets. Cutting faults intersect each other either orthogonally or at a smaller angle. Here one of the faults does generate an offset of the other fault, thereby creating a Y-shaped fork or split. Both faults may have developed simultaneously or during different stages of the structural evolution. In the latter case the fault with the offset is the older one. Conjugate relationship between two intersecting sets of faults formed under the same stress field.

3.4.8 Synthetic faults

A type of minor fault whose sense of displacement is similar to its associated major fault. Antithetic-synthetic fault sets are typical in areas of normal faulting.

3.4.9 Antithetic faults

A minor, secondary fault, usually one of a set, whose sense of displacement is opposite to its associated major and synthetic faults. Antithetic-synthetic fault sets are typical in areas of normal faulting

3.5 Fault timing

3.5.1 Synchronous faults

Multiple faults that have been active within the same geological time period.

3.5.2 Asynchronous faults

Multiple faults that have been active during different geological time periods.

3.5.3 Reactivated fault

A single fault that has been active (or evolved) during different geological periods. Typically there has been a period of inactivity between these time intervals. Due to changes in the structural setting, these faults may become re-activated. Typically, reactivated faults are recognized in geology because they have multiple signatures. For example, a fault may have initially developed as a normal fault in an extensional setting (seen from the offset and thickening of the rock formations in the hanging wall block). At a later stage the fault may become a reversed fault in a compressional setting. In this case the hanging wall has moved upward again (seen again in the offset of layers and presence of erosional hiatuses). It is quite normal that existing faults are reactivated as they already present a weakened zone in the subsurface.

3.6 Faulted formations

3.6.1 Footwall and hanging wall blocks

With a non-vertical fault, the intersected rock formation can be subdivided into the part that is positioned below the fault plane and a part that is resting on top. These are respectively called the footwall block and the hanging wall block, non-respective of the type of movement along the fault plane.

3.6.2 Pop-up structure

A pop-up structure appears where a (small) part of the subsurface has been locally uplifted in between two closely space reverse faults. Like its name says, it seems as if a part of a subsurface formation has popped-out of the surrounding interval.

3.6.3 Positive flower structure

Positive flower structures form in convergent wrench zones, i.e., strike-slip faults under transpression or at restraining bends within strike-slip zones. The structure resembles a shallow anticlinal structure bounded and transected by upward spreading reverse-component faults that converge at depth.

3.6.4 Negative flower structure

Negative flower structures form in divergent wrench zones, i.e., strike-slip faults under transtension or at releasing bends within strike-slip zones. The structure resembles a shallow synclinal structure bounded and transected by upward spreading normal-component faults that converge at depth.

3.6.5 Duplex or imbricate fan

Occasionally a series of thrust faults may occur in a sequence. The formation blocks in between have deformed into fault-bend folds that are stacked on top of each other. Such a stacking of thrust sheets is called a duplex or imbricate fan.

3.6.6 Roll-over anticline

When a listric fault with a low-angle or sub-horizontal base develops in an extensional setting, the strata in the hanging wall are gradually rotating to accommodate the decreasing dip-angle at larger depth. This results in a gentle bending (or folding) of the layers in an anticlinal fashion. The bended formations are called a roll-over anticline.

3.6.7 Graben and half-graben

In extensional settings, extensive subsidence may take place where the subsurface formations are displaced in downward direction along normal faults. This way a basin may develop which is bounded by a fault at one side (half graben) or at both sides (graben). The higher fault-bounded regions in between grabens are called horsts.

3.6.8 Pull-apart basin

Pull-apart basins are a specific type of transtensional graben associated with releasing bends in divergent wrench zones. Negative flower structures exist laterally of -or may evolve in- pull-apart basins.

3.6.9 Fault core and fault gouge

When observed from a distance, faults are typically seen as sharp planar interfaces where formations have been displaced relative to each other. Closer inspection, however, will often reveal that the fault plane itself has a more complex structure. It may define a brittle fracture zone, called the fault core, in which the rock formations are crushed and milled into a fine powder called fault gouge. In some cases, clayey and shaly intervals may be smeared into the fault plane, resulting in a seal blocking fluid flow. Often this zone is neglected in fault maps, yet for larger faults it may be relevant to parameterize this zone as it will determine the degree in which fluids are able to migrate though the faulted zone.

3.6.10 Fault damage zone

The damage zone defines an area around the fault core (central plane) that consists of a variety of scattered fault-related structures such as smaller slip planes, fractures and other types of deformation structures. These smaller structures together with the main fault are responsible for the total fault displacement. The width of the fault damage zone can vary between cm’s up to 100’s of meters depending on parameters such as lithology and associated diagenesis, depth of faulting, displacement, structural setting and fault mechanism.

4 FAULT DETECTION AND MODELLING

This chapter evaluates some of the typical methods to detect and model faults using field observations, geophysical measurements and geological reconstructions.

4.1 Outcrops and surface expressions

General description

Outcrops provide the unique opportunity to observe geological phenomena in a highly detailed and in-situ environment. Typically, outcrops are present in areas where (ancient) terrains are elevated and erosional processes (e.g. incising rivers, glacial scours) have eroded the cover, thus creating rock intersections. Outcrops can also be created by human activities such as open pit mining, road constructions and subsurface engineering (see example in *Figure 4-1*).

a

Figure 4-1: Examples of faults observed in a vertical, man-made, outcrop. The scale of these faults is smaller than the typical national and regional mapping scale, yet it is possible to precisely determine the shape, offset and characteristics (source: www.zmescience.com).

A special type of outcrop information is provided by satellite images and airborne photos. With these types of observations, it is often possible to map faults over large distances. With the birds-eye view it is often possible to see the bigger structural picture, which is not directly obvious from field observations. This is also nicely illustrated in *Figure 4-2:* Without the airborne and satellite images it would be much more difficult to determine the fault offset (a) or relate the surface morphological features to the fault (b).

- 

a

- 
b

Figure 4-2: Two examples of satellite and airborne observations. a) The upper photo shows the large kilometre-scale Piqiang fault in the Taklamakan desert (China) as observed from satellite images. This is an old passive fault that is revealed after erosion of the top sediment cover. Due to the lack of vegetation the sharp offset of the geological formations in this strike-slip fault are clearly visible (source: Nasa Earth Observatory). b) The lower image shows an airborne photo of the active San Andreas major fault system in California. Here the offset and details are less clearly observable, yet the image illustrates nicely that the actual fault consists of many associated smaller fault features which also have a clear surface expression (source: https://www.britannica.com/place/San-Andreas-Fault. Accessed 28 September 2021).

The quality and usefulness of outcrops for fault observation depends on several factors, including:

- The lithification of the exposed sediments (soft sediment outcrops tend to quickly degrade and lose details on the fault characteristics)
- The degree of overgrowth and anthropogenic activities (i.e. hiding of parts of the exposed rock formations)
- The degree of weathering of an outcrop which may have resulted in an altering or poor recognition of geological features

- The size and orientation of the outcrop in relation to the local geological setting and scale of features.

For faults, the information from outcrops can vary from mm scales up to kilometre scales. In most cases, small fault and fractures can be observed by offsets of strata and the crystallization or rock gouge features at fault planes. Large outcrops can show large-scale faults in the order of tens of meters and allow to determine the amount and sense of movement along the fault plane, the architecture and characteristics of the faulted zone and possibly also the timing. When the width of the fault zone and/or the amount of offset exceeds the scale of the outcrop, it becomes more difficult to assess these aspects from direct observations. In these cases, other observation techniques may be more appropriate to make concrete observations. This is typically the case for the deeper (buried) parts of large (growth) faults and fault systems where the outcrops reveal a juxtaposition of rock formations that is not representative for the true (maximum) displacement.

Strengths

- With good quality outcrop data it is often possible to obtain a direct and precise determination of the fault location, geometry, offset, and sense of movement. Outcrops can provide information on the dip and direction of the fault plane but also the characteristics such influence on surrounding rock formations, transmissivity to groundwater, associated minerals, etc. Depending on the size and quality of the outcrop, the fault can be traced over larger distances.
- In certain instances, the circumstantial observations may give an indication of (recent) fault activity such as development of topographical features (ridges, elevations), formation of springs and deflected river courses.
- The information from outcrops is generally public and open for anyone, unless it concerns a restricted area. This is a clear benefit with respect to subsurface observations from boreholes and seismic surveys which are often confidential to the companies that acquired the data.
- Outcrops are easy to integrate with air photos and satellite images, resulting in an often-detailed overview for larger regions.

Limitations

- Only the top part of the fault is visible. The deeper (buried) sections of faults need to be inferred from other data or structural analysis and interpretation.
- The same is true for buried faults which cannot be detected from direct observation. In some instances, buried faults may be inferred from circumstantial outcrop observations.
- Often, the orientation, size and/or quality of the outcrop make it impossible to obtain a complete picture of a (large-scale) fault.

Implications for the HIKE European Fault Database

Outcrop data provide an important source of information for the identification of faults. This is typically the case for mountainous areas (e.g. Alps, Pyrenees) and regions where subsurface observations are very sparse. Often, the consequence is that these regions provide no, or very limited information on the deeper parts of the fault or the 3D geometry. If in mountainous areas the surface trace of the fault can be mapped, structural mapping and -contouring techniques can help to reconstruct the 3D geometry. Although observations can contain a lot of (high resolution) details, the faults have been generalized for applications at national scale. Details are either archived in geological survey archives or scientific publications and reports (often mentioned in the HIKE FDB vocabulary, citations and country data reports). Satellite images and aerial photos may present an opportunity to extend the mapping of faults with surface expressions across Europe. It would be interesting to assess the possibilities to include satellite images in EGDI to support such development.

4.2 Seismic surveys

General description

Seismic reflection surveys (Figure 4-3) are ideal for observing the location and geometry of faults at depths up to several kilometres, depending on the specifications and set-up of survey acquisition. A seismic dataset can either be acquired in 2D (cross-section) or 3D (cube). Typically, a source generates seismic waves which are sent into the subsurface. While the waves propagate with depth, they reflect on rock interfaces characterized by a density contrast (e.g. two layers with different compositions or fluid contents). The reflected waves generated at multiple source locations are recorded by receivers and then processed into a continuous seismic image of the subsurface. While the signal reflects subsurface interfaces with a density contrast, faults will typically show up as an offset of recorded seismic reflectors. In vertical cross-section these offsets should generally be larger than the seismic resolution which is typically in the order of several meters for P-waves, but can be of a few tens of centimetres for S-wave surveys. With detailed and good quality 3D data and specific processing techniques it may be possible to also detect faults with small offsets below the seismic resolution.

Typically, 3D seismic data provides a continuous image of the subsurface which supports the definition of the entire fault architecture. In combination with vertical intersections, the possibility to display the 3D data in horizontal intersections (“time slices”) provides ample means way to determine the true fault geometry (Figure 4-4. 2D seismic data only portrays a cross-section of the fault at one specific location. Sometimes 2D lines are acquired in closely spaced grids which allows for a semi-continuous subsurface image.

Although seismic surveys have significant benefits over most other observation techniques, there are several challenges to consider:

- The depth is recorded in terms of the (travel) time between the generation of the wave at the source and the return of the reflected wave at the receiver. The real depth can only be obtained when the seismic velocity of the rock intervals is known. This velocity depends on many factors (lithology, fluid content, compaction, etc.) and may vary significantly per layer and generally increases with depth. As velocity measurements are often sparse, the true depth is generally one of the biggest sources of uncertainty in seismic interpretation.

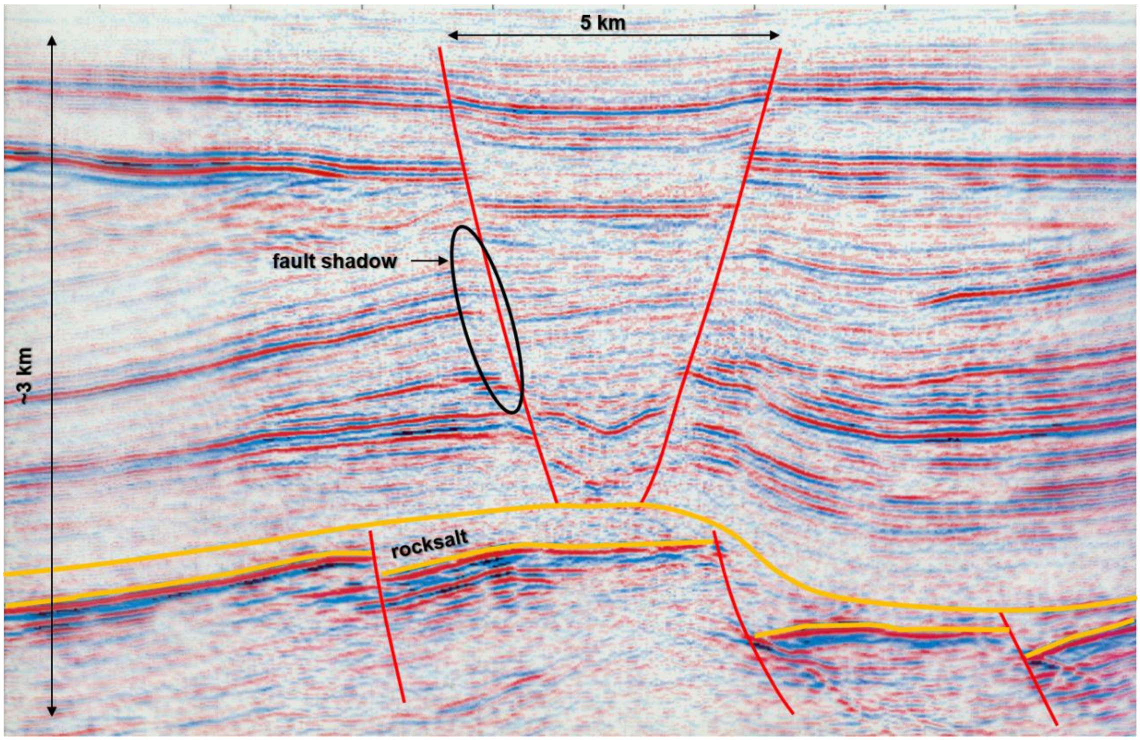

Figure 4-3: Vertical 2D seismic section with interpreted faults (red). The upper faults are blind faults that do not reach the surface. At depth, these faults terminate in a ductile salt layer and can therefore also be classified as detached faults. The faults below the salt layers do not penetrate the salt layer and are classified as buried faults. All faults would be missed in surface outcrops.

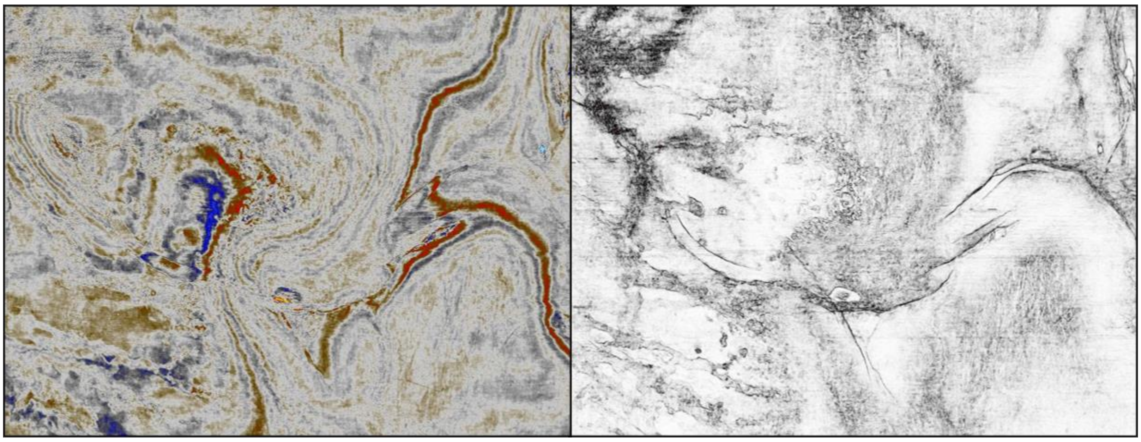

Figure 4-4: Left: horizontal (time-slice) intersection of a seismic 3D amplitude cube. Right: same time slice but now shown with edge-detection attribute that highlights the faults.

- Seismic data is well equipped for (near) horizontal layers. Specific processing and migration techniques are required to correctly represent non-horizontal and discontinuous features. The processing of seismic data involves a great deal of analysis and interpretation and may incorporate additional uncertainties.

- The resolution and quality of the raw seismic image, which primarily depends on the set-up used for acquisition, the seismic source and possible disturbances during measurements. The resolution generally becomes poorer with increasing depth as the high-frequency signatures become lost and the seismic wave energy is progressively absorbed and reflected by overlying strata. Some set-ups are specifically designed for shallow observations (tens of meters), while others are made for deep observations (hence the shallow part is often poorly imaged).

  Sometimes the fault itself influences and distorts the reflected seismic wave signals and may produce so-called shadow zones with poor imaging below the fault (Figure 4-3). In this case additional processing may be needed to improve the image.
- 2D surveys should be oriented more or less perpendicular (90 degrees) to the fault plane. At smaller angles the representation of the fault will be unreliable or even impossible.

- Seismic surveys are ideal for mapping faults in areas without surface outcrops (e.g. offshore and low-lying areas)

Strengths

- Representation at large depths is possible
- Applicable to multiple geological environments and not affected by water table depth, like ground penetrating radar
- Continuous data supporting a comprehensive view on the complete fault architecture over larger distances
- Typically, 2D and 3D surveys are widely available in oil and gas exploration areas. It should be noted however that the data is often owned by private companies and not available for public use.

Limitations

- No details on small features or actual lithologies
- Possibly large uncertainties related to seismic data processing and lack of information of seismic velocities in rocks
- Degrading quality with increasing depths, very heterogeneous surface conditions or anomalies with high density contrast
- Quality highly sensitive to relative orientation of seismic transect to fault orientation
- A dense grid of 2D lines is needed to capture the full 3D architecture of the fault

Implications for the HIKE European Fault Database

In several regions, faults have been mapped from seismic survey data. Typically, these areas have high quality fault definitions based on 3D models. The areas are often recognizable by a higher fault density and -resolution for which it is possible to define fault intersections at different depth/stratigraphic intervals.

4.3 Gravitational and magnetic surveys

General description

Gravity is measured by a gravimeter that measures the gravitational acceleration at a location enforced by the total mass present below that location plus the acceleration related to the rotational movement of the gravimeter due to the rotation of the Earth. If a body of relatively higher or lower density than the standard global density model is present below the subsurface, a gravity anomaly will be observed. The distribution of rock densities in the subsurface determine the shape and intensity of the gravity anomaly.

Rocks can be magnetized due to the Earth's magnetic field. For instance, when volcanic deposits cool down, the magnetic minerals align their orientation to the imposed magnetic field. Another example are marine sediment deposits, such as clays, where the particles rotate during sedimentation parallel to the Earth's magnetic field. The amount of magnetisation, the magnetic susceptibility, is a rock property.

Structural juxtaposition of rocks of different densities and/or susceptibilities results in sharp contrasts between highs and lows of gravity, respectively, magnetic anomalies. Where these contrasts are approximately linear and of considerable length, a 2D fault line can be interpreted. Asymmetries in the anomalies might indicate to the dipping direction of the fault. However, as gravity and magnetic anomaly are also referred to as potential field data and are affected by non-uniqueness (this means that multiple distinct geological models can satisfy the observed field), the depth can often not be resolved. Therefore, if it cannot be related to known lithologies, the depth position of the 2D fault line remains speculative.

Terrestrial measurements of the Earth's gravity field are practically available worldwide, but with different resolutions varying between wide-mashed national surveys and local surveys with closer measurements. The use of gravity and magnetic anomaly data is common practice in early stages of hydrocarbon, mineral and geothermal exploration. Especially when airborne data is acquired, these operations can be cost saving compared to seismic surveying. Grav-mag data interpretation can sufficiently delineate larger structural domains and sedimentary basins (Figure 4-5).

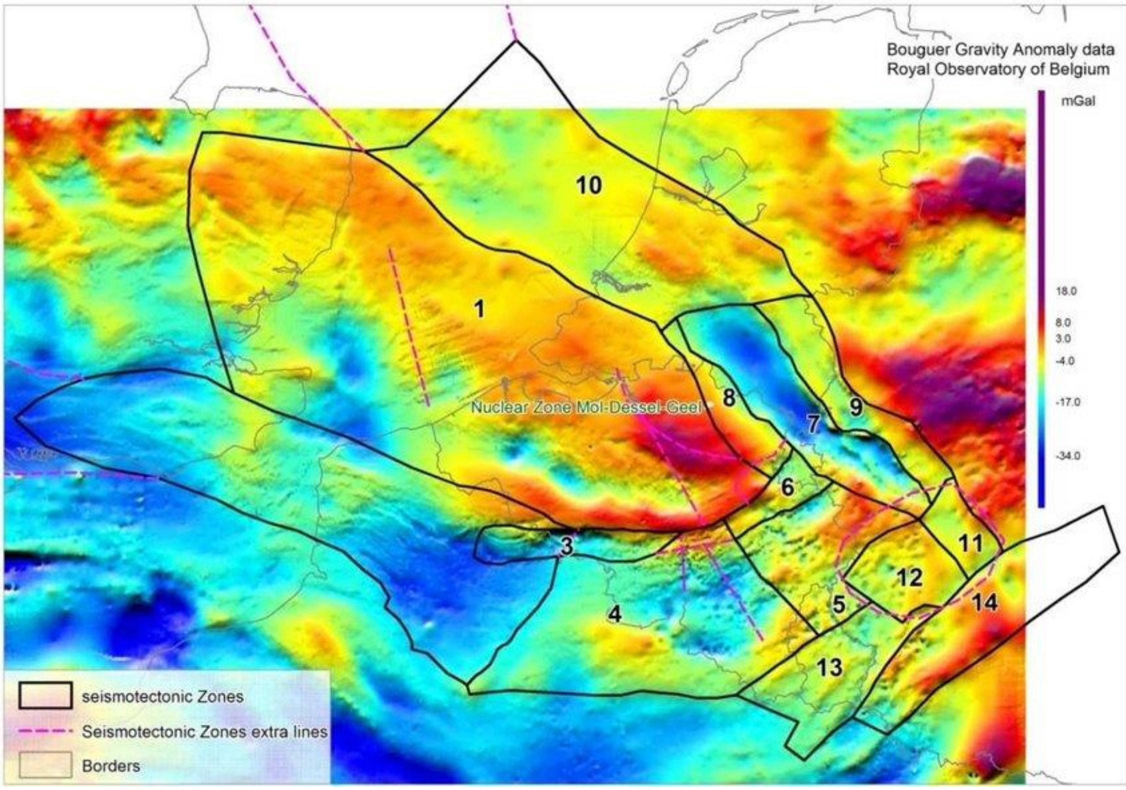

Figure 4-5: Bouguer gravity anomaly data from northern France, Belgium and the southern part of the Netherlands illustrating the delineation of the main seismotectonic zones. Data compiled by Royal Observatory of Belgium. Figure modified after Verbeeck et al., 2009.

Strengths

- Interpretation of deep structures (including faults) is possible
- Local, high resolution gravity/magnetic surveying allow for a detailed fault interpretation.
- Relatively cost efficient compared to other surveying techniques

Limitations

- No details on small features or actual lithologies
- Usually data density is low, especially in the case of regional surveys.
- Faults are only visible if related with density/magnetisation contrasts. Therefore, faults with small offsets in sedimentary basins may be not be identified in potential data.
- Possibly large uncertainties related to exact position of faults as interpretation is often based on interpolated data grids. Linear contrast may be artefacts of the interpolation applied. This comes apparent when low- and high-density datasets are compared.
- Magnetic anomaly contrasts are not uniquely related to faults and can be produced by other geological features (dykes, intrusions, etc.)

Implications for the HIKE European Fault Database

In several regions, faults have been mapped from gravitational and/or magnetic survey data. These regions are typified by low fault density and -resolution. Generally, there is high uncertainty concerning the exact position of the faults unless verified by other observation techniques. Sometimes the interpreted faults permit confident visual correlation with interpretations of regional fault systems based on seismic lines.

4.4 Well cores and logging techniques

General description

Well cores and well logs obtained from boreholes are commonly used to assess local information and characteristics of buried (deep-seated) faults and fractures. Borehole information is ideal to study the more detailed aspects of (smaller scale) faults and fractures but less well suited for mapping and characterizing larger faults as the spatial extent and complexity of the fault plane cannot be captured by a one-point intersection.

In well cores, faults are typically represented by an anomaly in the stratigraphic sequence, this can either be stratigraphic hiatus or a -doubling in the rock sequence. The fault plane may appear in the well core as a clean sharp contact, a distorted and fractured interval or even a loss zone where no core material could be recovered due to severe break-up of the rock formation. In gamma-ray logs, density logs and resistivity logs, faults may appear as anomalous spikes in the recording as the porosity or mineral composition of the fault zone itself can differ from the underlying and overlying intervals. Also, here it may be apparent that the fault offset has resulted in an anomalous stratigraphic sequence. It should be noted however that a hiatus or anomalous sequence could also result from an erosional hiatus or a fold. In calliper logs (measuring the borehole geometry), fault zones may be represented as intervals where the borehole diameter suddenly increases. This can be due to the washing out of unconsolidated (fractured) parts of the rock formation during drilling. Finally, operators often use so-called FMI logs (Full-bore Formation Micro Imager) to establish a 360 degrees image of the borehole interior. These logs are very useful to observe small faults and fractures and measuring their precise orientation.

For the mapping of large-scale fault extents, many wells are needed. In combination with seismic data, this may result in a detailed image of the fault. Through the interpolation of stratigraphic horizons or surfaces one may observe sudden breaks in the expected trend and orientation of stratigraphic horizons. This can be a sharp vertical displacement, a sudden increase or decrease in thickness, or a different orientation of the stratigraphic interval. If there is a very dense network of boreholes, the fault may be accurately mapped, yet in general the localization is characterized by large uncertainties as the fault may be projected anywhere between widely spaced boreholes. Ideally, the borehole information can be combined with seismic survey data to better pinpoint the fault location.

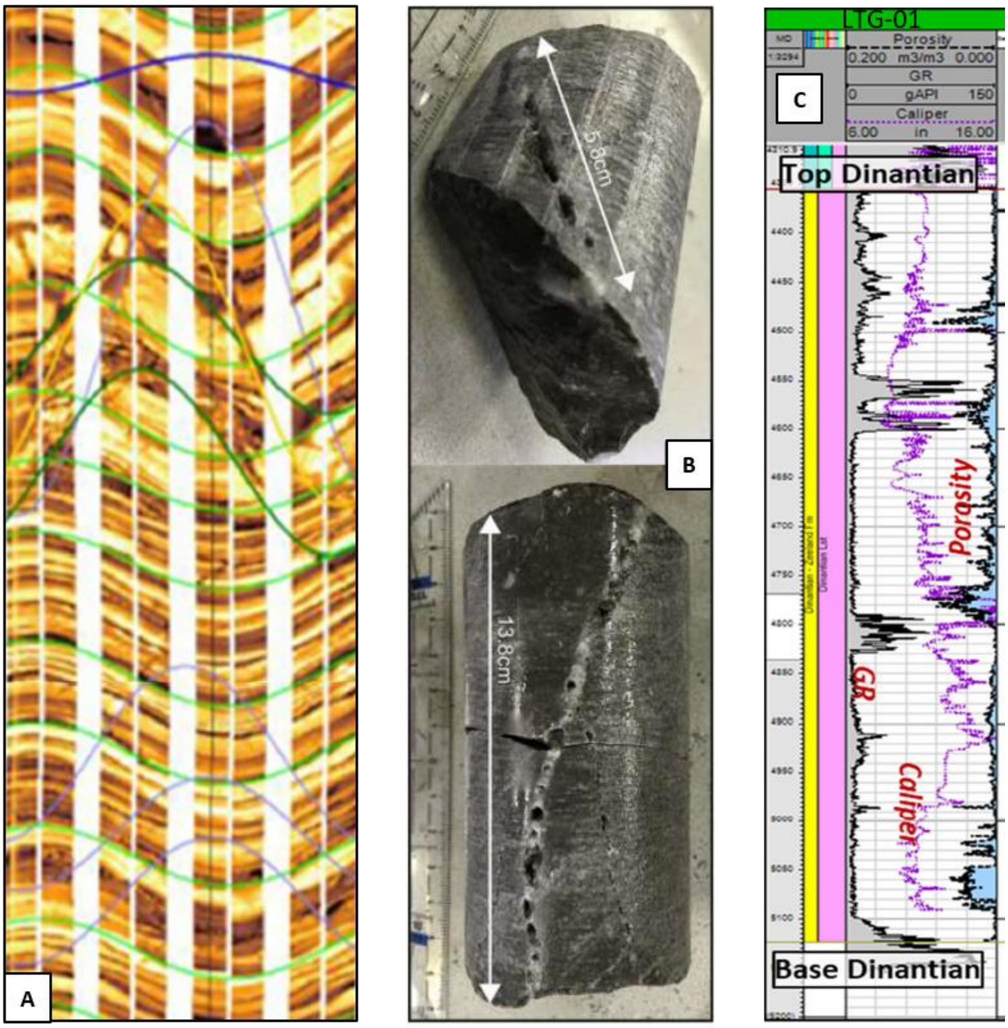

Figure 4-6: A) FMI log of well CAL-GT-01 (the Netherlands; modified after Van Leverink & Geel, 2019) showing examples of natural conductive fractures (1 m core length). Dark colors indicate high conductivity and lighter colors high resistivity. The sinuses are interpretations of different features like bedding planes (light green), conductive fractures (dark green), partially conductive fractures (orange), faint trace fractures (purple). B) Fractures in Dinantian carbonates from borehole Heibaart DZH1 in Belgium (Van der Voet et al, 2020). C) Example of fracture expression in well logs of well LTG-01 (the Netherlands; modified after Van Leverink & Geel, 2019). Here the caliper log (purple) lines up with (fracture) porosity (in light blue) and serves as a proxy for fracture density. Note that also the Gamma-Ray (GR) log shows spikes that correspond with high fracture porosity, plausibly related to differences in mineral composition.

Strengths

- Detailed local characteristics which are otherwise invisible on seismic, magnetic and gravitational surveys
- FMI may deliver a detailed insight in fracture orientations
- Well cores and logs provide true-depth information

Limitations

- No or very limited information of the fault plane presence, orientation, shape and extent unless intersected by a dense network of intersecting boreholes.
- In the well core or log it may be difficult to differentiate the fault from e.g. erosion surfaces or folds. Sometimes the fault is represented by a loss zone (no recovery of core material)

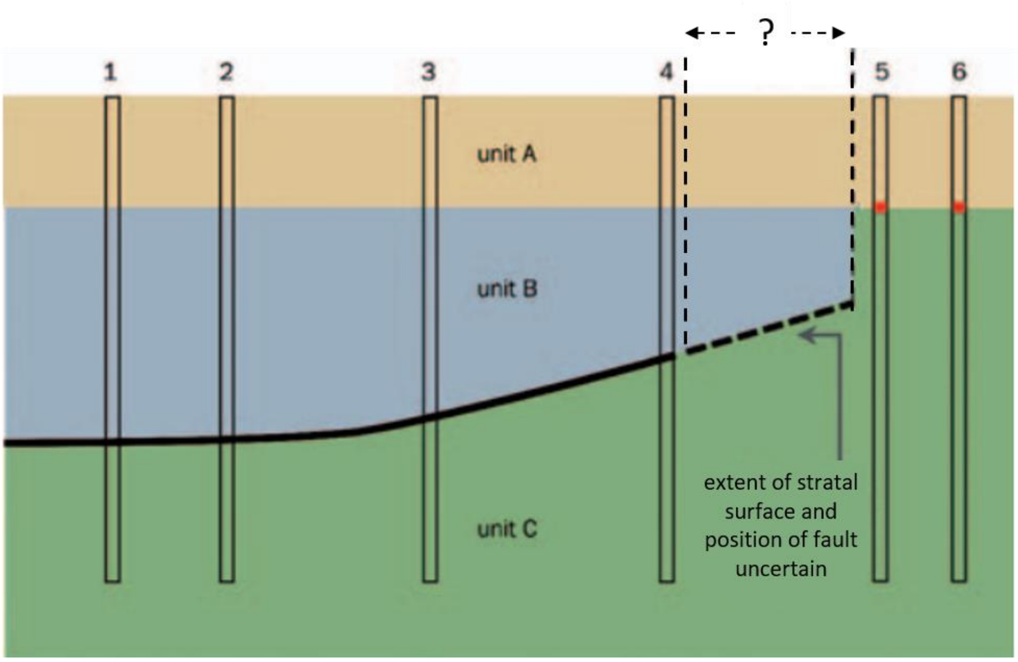

Figure 4-7: Sketch explaining how interpolation of borehole data introduces uncertainties with the proper positioning of faults. Note that an interpretation with pinch-out of unit B (in between wells 4 and 5) is an alternative option that cannot be excluded based on just the borehole data (modified after Gunnink et al., 2013).

4.5 Inferred fault detection

General description:

In some cases, the fault can only be detected from indirect observations. Some examples are given below:

- A fault may result in sudden elevation differences in the surface topography which can be traces over the length of the fault. HIKE deliverable D3.3[11] provides an example in the Northern Italian region including methodologies to determine the fault location.
- Open (permeable) faults can become conduits for deep geothermal waters moving towards the surface. The occurrence of thermal wells can be an indication for a nearby fault.

[11] http://geoera.eu/wp-content/uploads/2021/10/D3.3_HIKE_Subsidence_Assessment_Techniques.pdf

- With a dense network of seismometers, the depth and location of earthquakes may be determined. These locations are typically form an indication that an active fault is present. HIKE deliverable D3.2[12] described in further detail how fault locations can be detected this way.
- Sudden change of geological or geographical characteristics along a linear contact zone.

Strengths:

- The inferred data can contribute and improve fault determination from other data sources. For example:
    - The observation of thermal wells at the surface may confirm that a fault observed in seismic survey data is indeed open for fluid flow
    - The presence of seepage and iron mineralisations at the surface (Figure 4-8) confirms the presence of the locally sealing Dutch Peel Boundary Fault. The fault can be readily observed in seismic data but does not always have an evident expression at surface.
    - Registered and localized earthquakes provide information on the kinematic behaviour of a mapped fault.

Limitations:

- Inferred observations typically provide very inaccurate data on fault depth, location and shape. These observations are by themselves unsuitable for fault mapping and modelling.

[12] http://geoera.eu/wp-content/uploads/2021/10/D3.2_HIKE_Improved_Seismic_Events_Localization.pdf

Figure 4-8: Seepage and iron mineralisations ("wijstgronden") on the footwall block of the Peel Boundary Fault. (source: https://www.naturetoday.com/intl/nl/nature-reports/message/?msg=26288. Accessed 6 October 2021).

5 FAULT MODELLING AND CHARACTERIZATION

In this chapter the benefits and limitations of various fault observation and characterization methods are evaluated for different fault modelling aspects. The following abbreviations are used in the tables

Ranges and accuracy scales:

cm	=	range and resolution of several centimeters
dm	=	range and resolution of several 10's of centimeters
m	=	range and resolution of several meters
dam	=	range and resolution of several 10's of meters
hm	=	range and resolution of several 100's of meters
km	=	range and resolution of several kilometers

AOP	=	At Observation Points (direct)
BOP	=	Between Observation Points (interpolated)
INF	=	Inferred (indirect)

5.1 Fault presence and expression at/near surface level

Table 5-1 summarizes the suitability of observation methods to detect and determine fault expressions near or at surface level. Outcrop data as well as satellite and airborne images are preferred in this case, yet these methods rely on exposed surfaces (no overgrowth or sediment cover) or a clear expression of a fault in the surface topography. In low-lying areas with young sediment covers, the applicability of outcrop and satellite/airborne data may be limited.

While outcrop data generally provides an unambiguous and very detailed proof of a fault's presence, these observations may have a limited geographical extent (e.g. road sections, excavation sites or rocks exposed in cliffs and eroded surfaces). Satellite and airborne data, however, may expose the trace of a fault over very long distance, provided that the fault is present at surface and not overgrown or covered by sediments. Outcrop data can be used to validate fault observations and increase accuracy in satellite and airborne data.

Borehole data can be used in combination with either outcrop or satellite data to provide information on the continuation of a fault with depth. As boreholes represent point data, their sole use often has limited value for the determination of a fault's extent unless there is a dense pattern of boreholes across and along the fault.

The upper (near-surface) parts of seismic survey data often have limitations for interpretating horizons and faults due to a high noise-to-signal ratio. In some cases, specific processing techniques can be applied to detect sharp and contrasting transitions and anomalies in shallow 3D seismic survey data which may indicate the presence of faults. Boreholes can be used to validate this. The combination of shallow seismic data and boreholes is particularly useful in low-lying areas with a young sediment cover.

Gravitational, magnetic and geo-electric surveys may be used to detect linear features which can be indicative for the presence of near-surface faults. In this case, it is important that the rock sections at both sides of the fault or the fault zone itself, have distinct and contrasting gravitational, magnetic or electric resistivity properties.

a) Fault presence and expression at/near surface	**Outcrop data**	**Satellite or Airborne images**	**Sparse borehole dataset**	**Dense borehole dataset**
Applicability	very good	Good	moderate	moderate
benefit	direct and umambiguous detection	possibly traceble over long distances	direct and often umambiguous detection in cored sections	direct and often umambiguous detection in cored sections
limitation	limited horizontal and vertical extent	Depending on good exposure of rock formations and lithological variations	Only at point of borehole intersection. Inferred between boreholes	Only at point of borehole intersection. Inferred between boreholes
Accuracy / resolution	cm - m (AOP)	m - dam (AOP)	cm (AOP) hm - km (BOP)	cm (AOP) dam - hm (BOP)

b) Fault presence and expression at/near surface	**Sparse 2D Seismic**	**Dense 2D Seismic**	**3D Seismic**	**Geophysical field data**
Applicability	moderate	moderate	moderate	moderate
benefit		possibly traceble over long distances	3D provides full extent, detailed topology	May validate presence of (suspected) subsurface fault
limitation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	Low accuracy, indirect evidence
Accuracy / resolution	m - dam (AOP) hm - km (BOP)	m - dam (AOP) dam - hm (BOP)	m - dam (AOP)	dam - hm (INF)

Table 5-1: Evaluation of observation techniques for detecting fault presence and (near) surface expression. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)

5.2 Fault presence and expression at depth (buried faults)

Table 5-2 summarizes the suitability of observation methods to detect and determine presence and expression of deeply buried faults. Seismic and geophysical (potential) field data are preferred in this case, yet these methods are expensive and not always accessible to the public as they are owned by private companies. In general, outcrop data has very limited value for tracing faults at depth. If the fault is not present at surface or overgrown or covered by sediments satellite and airborne data are less suitable to trace a fault over very long distance,

Whereas outcrop data are unsuitable for tracing faults at depth, seismic data generally provide a clear proof of the fault's presence at depths to several kilometres. Depending on the size of the seismic survey, these observations have a large geographical extent. Most seismic data are not able to image the deeper parts of faults, i.e., for seismogenic faults it is not possible to connect surface rupture with the seismic source. For areas with sparse 2D seismic coverage the interpolation of individual fault interpretations (fault sticks), often render inaccurate representations of the fault geometry. Especially in 2D seismic data, flawed processing (mainly migration) makes that observed features might be laterally displaced such that the exact location of the fault is difficult to assess. In densely populated areas or protected nature areas, the acquisition of seismic data may be limited, and interpolation uncertainties are generally large.

Gravitational, magnetic and geo-electric surveys may be used as indirect evidence for faults at depth that juxtapose rocks with different densities, magnetic and electric resistivity properties. Data density is strongly dependent on the type of acquisition (field, air-born, offshore, or satellite) and impinges on the ability and accuracy of fault positioning. Geophysical field data however can be used in conjunction with sparse 2D seismic data to resolve the trace of a fault over very long distances.

Borehole data can be used in combination with either seismic or geophysical data to provide information on the continuation of a fault with depth. As boreholes represent point data, their sole use often has limited value for the determination of a fault's extent unless there is a dense pattern of boreholes across and along the fault. Few boreholes penetrate faults, but where they do well logs and cores may hint at fractures and/or mineralization associated with a nearby fault. The exact position within a fault zone is hard to establish. Mismatched borehole data can be interpreted as fault related but should preferably be confirmed by seismic data.

a) Fault presence and expression (buried, at depth)	**Outcrop data**	**Satellite or Airborne images**	**Sparse borehole dataset**	**Dense borehole dataset**
Applicability	not suitable	poor	poor	moderate
benefit		possibly traceble over long distances	direct and often umambiguous detection in cored sections	direct and often umambiguous detection in cored sections
limitation		Depending on surface expression (deformation) Low accuracy	Only at point of borehole intersection. Inferred between boreholes	Only at point of borehole intersection. Inferred between boreholes
Accuracy / resolution		hm - km (INF)	cm (AOP) hm - km (BOP)	cm (AOP) dam - hm (BOP)
Depth range		dam - hm	m - km	m - km

b) Fault presence and expression (buried, at depth)		Sparse 2D Seismic	Dense 2D Seismic	3D Seismic	Geophysical field data
	Applicability	moderate	Good	Very good	poor
	benefit		possibly traceble over long distances	3D provides full extent, detailed topology	May validate presence of (suspected) subsurface fault
	limitation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	Often poor imaging at shallow depth, need to extrapolate from deeper observation	very low accuracy, indirect evidence
	Accuracy / resolution	m - dam (AOP) hm - km (BOP)	m - dam (AOP) dam - hm (BOP)	m - dam (AOP)	hm - km (INF)
	Depth range	dam - km	dam - km	dam - km	dam - hm

Table 5-2: Evaluation of observation techniques for detecting fault presence and expression at larger depths. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)

5.3 3D fault geometry

Table 5-3 summarizes the suitability of observation methods to determine the 3D geometry of faults. To establish the 3D geometry of faults with high accuracy, outcrop or seismic data are preferred. The observation methods apply to different resolutions and depth ranges, though. Borehole data are in general unsuitable, unless densely spaced with multiple boreholes that intersect the fault plane providing point clouds that define the 3D geometry.

a) Fault 3D geometry		Outcrop data	Satellite or Airborne images	Sparse borehole dataset	Dense borehole dataset
	Applicability	moderate	not suitable	poor	moderate
	benefit	high accuracy		High accuracy where borehole intersects fault plane	High accuracy where borehole intersects fault plane
	limitation	limited horizontal and vertical extent		Very low accuracy (inferred from interpolated stratigraphic layers)	Possibly low accuracy (inferred from interpolation of layers), no details on fault plane topology
	Accuracy / resolution	cm - m (AOP) hm - km (BOP)		cm (AOP) hm - km (BOP)	cm (AOP) dam - hm (BOP)
	Depth range	m - dam (AOP)		m - km	m - km

b) Fault 3D geometry		Sparse 2D Seismic	Dense 2D Seismic	3D Seismic	Geophysical field data
	Applicability	moderate	Good	Very good	poor
	benefit	Detailed and large depth range along lines	Provides full 3D extent of fault (horizontal/vertical), good overview of topology	3D provides full extent, detailed topology	
	limitation	Low accuracy (interpolation between lines). Limited details on fault plane topology	Possibly reduced accuracy due to artifacts in 2D seismic imaging	Accuracy may decrease with deth	very low accuracy, indirect evidence
	Accuracy / resolution	m - dam (AOP) hm - km (BOP)	m - dam (AOP) dam - hm (BOP)	m - dam (AOP)	hm - km (INF)
	Depth range	dam - km	dam - km	dam - km	dam - hm

Table 5-3: *Evaluation of observation techniques for determining the 3D geometry of faults. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)*

The geometry of fault planes can be accurately interpreted in 3D seismic data. Several software packages contain automated fault detection or even AI functionality to “trace” faults. Nowadays, the success of these methods largely depends on the quality (resolution) of the seismic data. With sparse 2D seismic data large parts of the fault geometry are too simple planar representations of the true geometry. With increasing line density, the degree of oversimplification diminishes.

In general, earth observation data do not provide information on the 3D geometry of faults as they only provide fault lines based on indirect evidence.

5.4 Fault displacement

Table 5-4 summarizes the suitability of observation methods to determine the displacement of faults. Very accurate observations on fault displacement may be made in outcrops, however the observations are of limited extent and are only detectable if the displacement is smaller than the outcrop. Along its strike, faults typically have variable displacement that amounts to zero at the fault tips and is maximum near the faults centre. Therefore, the observed displacement in outcrop may not be representative for the entire fault plane. Usually, vertical components of the fault displacement can be readily identified in seismic data, whereas horizontal displacements can only be inferred from typical deformation styles (e.g. flower structures). One of the merits of 3D seismic data or dense 2D seismic data is that variable fault displacement along a fault plane can be determined. In sparse 2D seismic data (especially long-offset regional lines) vertical displacement can be observed at even greater depths than in 3D seismics. Earth observations, in general, are unsuitable for the detection of vertical fault displacements, but distinct later displacements may be detected on air photos and satellite imagery. Even on a regional scale, the lateral offset of rock bodies can be inferred from gravity or magnetic data. Unless supported by well- or seismic data, geophysical field data cannot be used to assess vertical fault displacement.

Fault displacement may be inferred from mismatches between wells. In fact, the inferred displacement is very often the reason to postulate a fault. Where borehole data is sparse there is ample room for different interpretations. Also, for borehole data applies that the denser the data the more certainty is associated with estimating fault displacement.

a) Fault displacement		**Outcrop data**	**Satellite or Airborne images**	**Sparse borehole dataset**	**Dense borehole dataset**
	Applicability	moderate	moderate	poor	moderate
	benefit	Very accurate determination	possibly large offsets in horizontal direction can be observed		
	limitation	Limited vertical section, limited suitability for large displacements (horizontal and vertical)	No vertical displacement, only for surface faults	No direct observation, depends on interpolation, possibly highly inaccurate	No direct observation, depends on interpolation, possibly inaccurate
	Accuracy / resolution	cm - m (AOP) hm - km (BOP)	m - dam (AOP)	cm (AOP) hm - km (BOP)	cm (AOP) dam - hm (BOP)
	Depth range	m - dam (AOP)		m - km	m - km

b) Fault displacement		**Sparse 2D Seismic**	**Dense 2D Seismic**	**3D Seismic**	**Geophysical field data**
	Applicability	Good	Good	Very good	poor
	benefit	Good sense of vertical displacements over large depth range	Good sense of vertical displacements over large depth range	Good sense of vertical displacements over large depth range. Possibly also horizontal displacements	
	limitation	Often impossible to determine horizontal displacements. Possibly significant uncertainty between lines	Difficult to determine horizontal displacements.		Very inaccurate or even impossible to determine displacement
	Accuracy / resolution	m - dam (AOP) hm - km (BOP)	m - dam (AOP) dam - hm (BOP)	m - dam (AOP)	hm - km (INF)
	Depth range	dam - km	dam - km	dam - km	dam - hm

Table 5-4: Evaluation of observation techniques for determining fault displacements. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)

5.5 Fault relationships and timing

Table 5-5 summarizes the suitability of observation methods to determine fault relationships and timing of fault activity. Outcrops, especially those with multiple faces (3D outcrops) are suitable to study fault relationships and relative timing of fault activity. Satellite- and airborne images only are of value for study relationships at surface but can be of utmost importance in understanding complex fault patterns at depth. Boreholes and/or core data can only be used to assess the relationship and relative timing of fracture groups. When the mismatch between boreholes is used to infer the presence of faults, the borehole stratigraphy can be used to determine the timing of faulting.

Seismic data is very suitable to study fault relationship in the vertical dimension and fault timing can easily be determined from the (seismo)stratigraphy. In using 2D seismic data, fault plane geometries (and thus the relationship between faults) importantly depend on the ability to construct the fault plane if data coverage is low. Geologically unrealistic fault geometries will produce similarly unrealistic relationships and utmost care is needed in such instances. In order to study fault relationship in 3D, the use of 3D seismic data is required, as this is the only data that allow for both vertical and horizontal fault observations. The use of edge-detection seismic attributes is very useful for the detection of fault patterns and – relationships in time slices. Usually, the applicability of these attributes reduces with depth as the seismic signal to noise ratio increases.

a) Fault relationships and timing	**Outcrop data**	**Satellite or Airborne images**	**Sparse borehole dataset**	**Dense borehole dataset**
Applicability	moderate	poor	not suitable	poor
benefit	Different fault timings and phases can be determined in high detail	large geographical extend		
limitation	Not suitable for deeper setions of the fault	Only useful for relationships in horizontal section		No direct determinantion (inferred using modelling and interpolation)

b) Fault relationships and timing	**Sparse 2D Seismic**	**Dense 2D Seismic**	**3D Seismic**	**Geophysical field data**
Applicability	moderate	Good	Very good	not suitable
benefit	Relationships and timing can be determined in detail along lines	Relationships and timing can be determined in detail along lines and interpolated between lines	Relationships and timing can be determined in full 3D and detail	
limitation	Difficult to determine relationships and timing in 3D (only along lines)	Interpolation between lines may introduce uncertainties	at large depths, decreasing quality of seismic image complicate detailed analysis	

Table 5-5: Evaluation of observation techniques for determining relationships and timing of fault activity. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)

5.6 Fault conductivity and sealing

Table 5-6 summarizes the suitability of observation methods to determine the conductivity (transmissivity) and/or sealing capacity of faults. Direct observations or measurement allow for the best possible assessment of these fault properties. Therefore, outcrop and borehole data provide detailed insight in fault and fracture permeability. Indirectly, seismic interpretation in combination with well data may the basis for a subsurface lithology model that can be used to determine juxtaposition relationship across a seismically interpreted fault. The relationship in combination with the amount of displacement are used to calculate shale-gouge ratio's, i.e., to determine where the fault is sealing or conductive. The type of analysis is most suited for 3D seismic data.

a) Fault (zone) conductivity and/or sealing		**Outcrop data**	**Satellite or Airborne images**	**Sparse borehole dataset**	**Dense borehole dataset**
	Applicability	moderate	not suitable	Good	Good
	benefit	Can be determined accurately at surface observation point		Borehole data (cores) may provide detailed insight in fault and fracture permeability	Borehole data (cores) may provide detailed insight in fault and fracture permeability
	limitation	Cannot be determined for deeper sections, except based on indirect observations (e.g. outflow of deep thermal formation water)		Uncertain between boreholes	

b) Fault (zone) conductivity and/or sealing		**Sparse 2D Seismic**	**Dense 2D Seismic**	**3D Seismic**	**Geophysical field data**
	Applicability	conditional	conditional	conditional	not suitable
	benefit				
	limitation	Only in combination with well data (e.g. fault gouge analysis)	Only in combination with well data (e.g. fault gouge analysis)	Only in combination with well data (e.g. fault gouge analysis)	

Table 5-6: Evaluation of observation techniques for determining conductivity and sealing capacity of faults. a) outcrop and borehole data; b) geophysical data. AOP = at observation points. BOP = between observation points (interpolation). INF = inferred (indirect)

CONCLUDING REMARKS

- The information in the HIKE FDB is based on data from a wide variety of sources and mapping studies from different vintages. The geometrical representation and characterization of faults is to a great extent determined by the type, coverage and quality of exploratory data (seismic, wells, outcrops, etc.), but also by the applied modelling techniques.

- National mapping studies primarily focus on the geometrical representation of faults within 2D and 3D geological models and maps. Areas with decent seismic coverage (2D and 3D) have the best potential to model the entire geometry in 3 dimensions with low to moderate uncertainty ranges. Regions with mainly outcrop data have the potential to map the surface location of faults in great detail yet the deeper (buried) sections are characterized by large uncertainty ranges. In areas with mainly buried faults and only sparse well and 2D seismic data, the modelling and localization of faults is subject to large uncertainty ranges. Through interpolation and use of gravitational and magnetic survey data it may still be possible to obtain a good impression of the major structural elements.

- The determination of specific fault attributes is mostly performed with a specific goal in local studies. Examples are the modelling of fault sealing capacities at potential storage sites or kinematic properties which determine the tendency of a fault to generate earthquakes. For this reason, it is mostly impossible to provide a comprehensive coverage of such attributes at national and European scales (except perhaps properties derived from the fault geometry)

- In many regions mapping and modelling of faults is still in an early stage and there is a significant scope for improving and extending fault information and increasing accuracy, details and confidence levels. HIKE and other GeoERA projects (e.g. 3DGEO-EU, HOTLIME, GeoConnect³d) present various strategies and methodologies to establish cross-border 3D fault models and to assess specific attributes.

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