Hazard and Impact Knowledge for Europe

Deliverable 2.1b

Fault Data Characterization Catalogue

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1 INTRODUCTION

1.1 Document Background and Scope

This document presents the scientific justification for the technical Fault Database Specifications as described in GeoERA-HIKE Deliverable 5.1a (European Fault Database Technical Specifications). It serves as a catalogue explaining the various attributes, concepts and datasets included in the HIKE European Fault Database. Besides this report, the contents will also be available in an interactive format integrated in the online platform (Fault Database in EGDI[1]).

1.2 Document Structure

Chapter 2	provides the general purpose of this deliverable in the context with other WP2 deliverables;
Chapter 3	summarizes the general structure of the HIKE European Fault Database Framework and identifies the aspects that are part of the fault data catalogue;
Chapter 4	explains all the attributes of faults within the European Fault Database and provides a scientific background, where needed;
Chapter 5	provides a the description of the semantic concepts used to hierarchically structure the fault data and link to other databases;
Chapter 6	provides recommendations and guidelines regarding the maintenance of the fault data catalogue contents.

1.3 Abbreviations

DMP	= Data Management Plan
DOI	= Digital Object Identifier
EGDI	= European Geo Data Information Platform
EGS	= EuroGeoSurveys organization
EPOS	= Project ”European Plate Observing System”
FDB	= HIKE European Fault Database
GEOSCIML	= data model and data transfer standard for geological data
GIP	= Project ”Geo-Information Platform”
GSO	= Geological Survey Organization
HIDB	= Hazard and Impacts database
HIKE	= Project ”Hazards and Impacts Knowledge Europe”
IAEA	= International Atomic Energy Agency
INSPIRE	= Infrastructure for Spatial Information in Europe
ISO	= International Organization for Standardization
ISO19115	= Geographic information — Metadata
LOD	= Linked Open Data
MICA	= Project ”Mineral Intelligence Capacity Analysis”
RDF	= Resource Description Framework
SHARE	= Project ”Seismic Hazards Research Europe”
SI	= International System of Units
SKOS	= Simple Knowledge Organization System
URI	= Uniform Resource Identifier

[1] https://geoera.eu/projects/hike10/faultdatabase/

WFS = Web Feature Service
WMS = Web Map Service

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 BACKGROUND

2.1 Introduction

The HIKE European Fault Database holds collected and integrated fault information from national and regional mapping and modelling projects and repositories, maintained by project partners and several other geological survey organizations from associated GeoERA projects. The fault information has been established over a period of tens of years using many different standards, methods and formats. Consequently it was not possible to just compile the data into one comprehensive dataset. At the start of the project the partners have therefore been involved in the specification of common standards and methods needed to classify, parameterize and display fault information. These standards are partly compliant with existing INSPIRE standards and extended with new specifications where needed. HIKE Work Package 5 has embedded the standards and definitions into an internal specifications and guidelines document for the purpose of

1. Developing the common data architecture of the HIKE European Fault Database
2. Supporting the uniform mapping and collection of fault data by project partners

This report summarizes the established standards and specifications into a public document. First of all, this document provides end-users with a catalogue which helps to access and evaluate the information in the HIKE database. Secondly, the specifications can be used by GSOs and other institutes to establish and upload additional faults datasets. Finally this document will form the basis for possible future updates and extensions of the specifications, e.g. introducing new data types and parameter sets.

2.2 Relation to other documents

This document is part of a group of documents associated to the HIKE European Fault Database. These documents are accessible via the HIKE website[2] and are introduced below:

D2.2: The Data Collection report which summarizes per country and partner what data has been collected including a technical and geological background on how the data was established and how it related to the regional and national geological setting.

D2.3: Fault Characterization report which summarized a generic scientific background on fault definitions and characterization methods.

D2.4: Fault Database Application report: a bundled case study report which describes the implementation approach, effectiveness of the FDB and recommendations for improvement and broader implementation.

D5.2b Fault Database Guidelines report which provides the practical guidelines for developing and uploading new datasets as well as using the HIKE database platform and GIS functionalities.

[2] https://geoera.eu/projects/hike10/documents/

3 HIKE FAULT DATABASE FRAMEWORK

3.1 Introduction

The HIKE project has resulted in the development of a European Fault Database that aims to collate and harmonize relevant information and knowledge on all geological faults. Prior European fault databases are mainly restricted to showing information on seismogenic faults or major faults appearing at surface only. The HIKE European Fault Database (hereafter FDB) is developed in order to take into account any type of fault represented at arbitrary depth levels.

While seismogenic faults are crucial for investigation of naturally occurring earthquakes, the location of passive and capable faults is essential to understand possible induced hazards related to subsurface activities. The 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 FDB not only provides the actual data for identified faults in the subsurface and at the surface. It also delivers essential knowledge on 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 principles. In addition, vocabulary entries provide also a link to existing fault database entries.

In the following sections we provide a summary of the different elements which together define a fault object in the FDB.

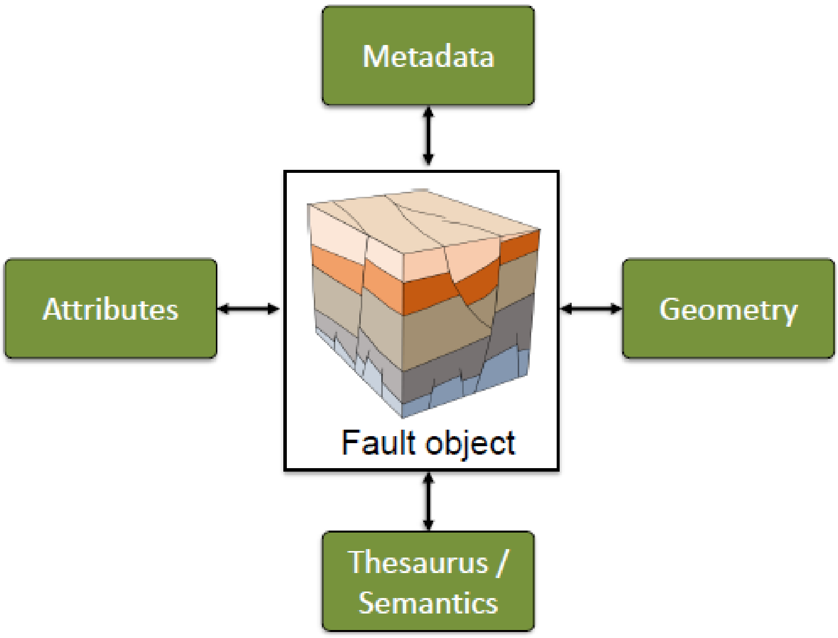

Figure 3.1: Definition of a fault object in the HIKE project. See detailed description of all four levels in section 3.2.

3.2 The fault object

Figure 3.1 shows the general framework which defines a fault object in a schematic overview. The individual fault data elements and their mutual relationship are described in the following sections. The next sections give a detailed overview of the specifications for each element.

3.2.1 Fault geometry, spatial definition and coordinate system

In the FDB, faults are represented and viewed as 2D geometries on map view in the preferred coordinate system ETRS89 / LCC Europe (EPSG:3034). As the 2D geometries are the geometrical representation of 3D fault planes, one fault might be represented by more than one fault trace, e.g. on different depth levels or at different stratigraphic levels (see Figure 3.2). The default representation is the surface trace of the fault or, in the case of buried faults, the top or bottom of the fault plane. The respective details are stored in the attribute set of each geometric line (see section 4.9).

In addition, faults can be also represented with different geometries at different scale levels, e.g. a detailed network of faults at a large local scale might be represented by a generalised pattern at national scale. In the now existing FDB, two scale ranges have been applied: a pan-European overview ranging between the scales of 1:15.000.000 and 1:1.000.000 and a detailed view between the scales of 1:1.000.000 and 1:25.000. The scale dependency is mostly adopted in Germany, where overview geometry is provided by the national GSO BGR, while more detailed geometry is provided by the regional GSOs LAGB (Saxony-Anhalt), LBGR (Brandenburg), and LfU (Bavaria). Also, the Netherlands provide scale-dependent geometries, whereas most countries do not. For future development, a more detailed, fault-by-fault, scale-dependency is stored in the attributes (see section 4.9), but is not applied in the current EGDI portal.

3.2.2 Fault attributes

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

- On 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 used to identify these geometries uniquely.
- On the 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 goes over the database entries. In addition, the vocabulary provides the possibility to link to already existing fault databases, e.g., SHARE or national fault databases.

• As metadata on the fault dataset level. On this level attributes describe the dataset as a whole and not the individual fault

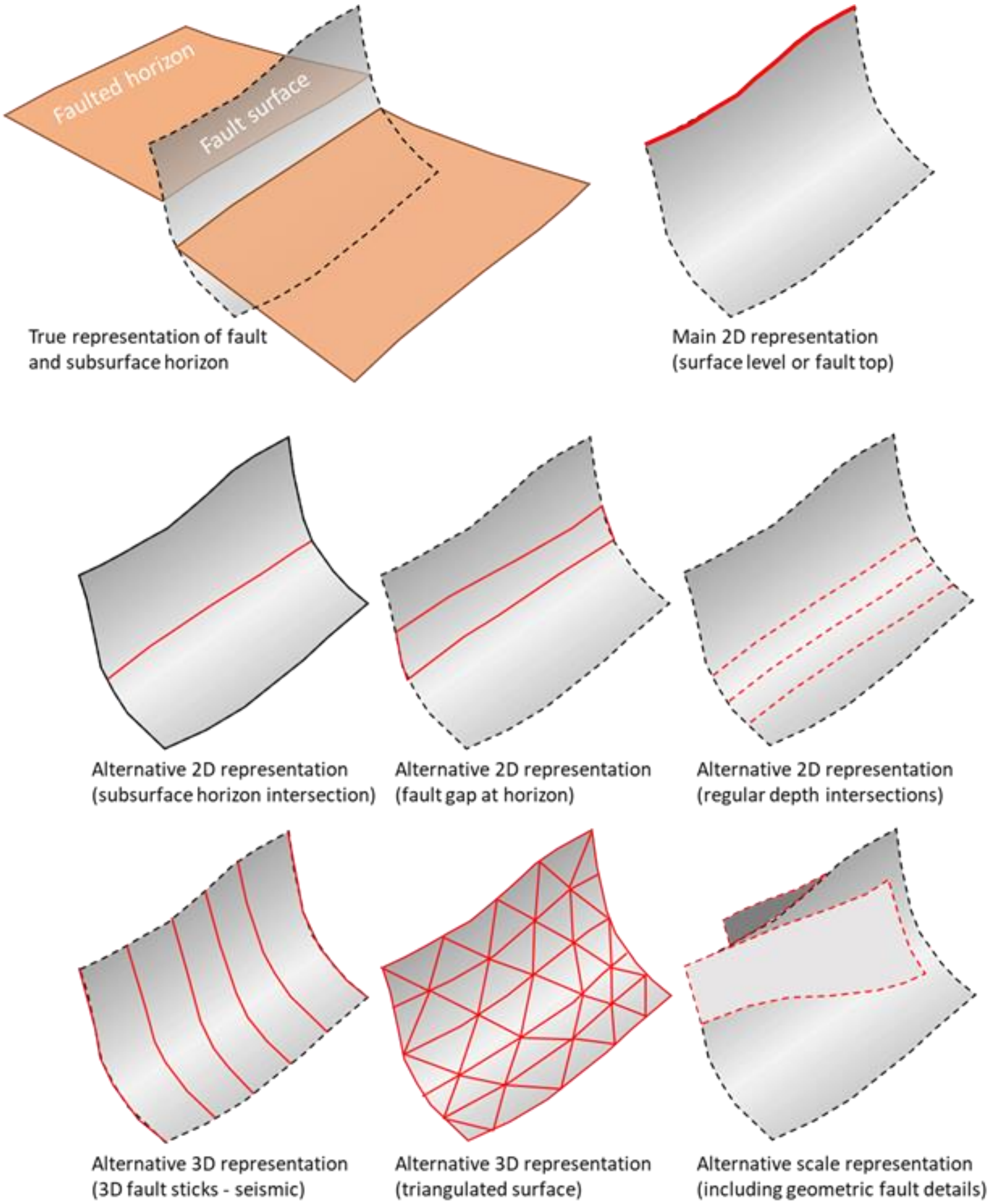

Figure 3.2: Overview of different geometrical definitions of faults

3.2.3 Fault semantic definition and hierarchy

Fault objects are described as individual objects, but faults are almost always related to other faults in regional or kinematic sense. The relation between faults can be *hierarchical* from the level of an individual fault up to large-scale fault systems. Faults can also be related to each other on a more equal level like *similar to*. How faults can be related is described in Chapter 5 on semantic framework specifications.

3.2.4 Metadata

Metadata of the FDB is stored in the EGDI Metadata Catalogue[3]. There is one 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 and are referenced from the metadata attribute on the features in the database.

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

4 FAULT CHARACTERISTICS STORED IN THE ATTRIBUTE TABLE

4.1 Introduction

This chapter focuses on the scientific description of the attributes of a fault object in the HIKE FDB as they appear on the EGDI platform. Most attributes are available both as readable attribute and as link to either the GeoERA HIKE vocabulary or to INSPIRE code lists if in use. These attributes describe the fault object in the geoscientific context. Noticed that some attributes can be defined time-dependent. In this case, there will be one row for each geochronological era (see sections 4.2, 4.4.3, 4.4.4, and 4.6.2). Thus, there could be more than one attribute set (row) per fault ID (see section 5.2.3).

4.2 Geochronological terminology

This section details the usage of chronostratigraphic and geochronological terminology within the HIKE FDB.

In classic geological terminology, there is a clear separation between chronostratigraphic (rock) units, divided into lower, (middle), and upper units, and geochronological (time) units, divided into early, (middle), and late units (e.g., Haile, 1987[4]). As the differentiation is only visible if the divisions lower/upper or early/late are in use, they were merged into one INSPIRE code list “GeochronologicEra”, e.g., as in “Early/Lower Cretaceous”. Subsequently, in the now existing version the geochronological expressions were skipped, so that now the INSPIRE code list “GeochronologicEra” consists of chronostratigraphic terms such as “Lower Cretaceous”. We are aware of the contradiction to the classic geological usage, but as we try to use as many INSPIRE code lists as possible, we applied the INSPIRE code list for both, geochronological and chronostratigraphic use. For the majority of the terms, the difference is not noticeable.

The INSPIRE code list “GeochronologicEra” is based on the 2012 version of the International Chronostratigraphic Chart[5] used for several chronostratigraphic and geochronological attributes within the HIKE FDB:

Faults are not always stable objects once initiated. They might change their type of faulting (see section 4.4.4), their sense of movement (see section 4.6.2), or they might be reactivated during a later time after an inactive phase. Therefore, the mentioned fault attributes can be defined time-dependently. If attributes of a fault are time-dependent, the respective geochronologic eras, periods, series/epochs or stages/ages need to be defined in the Timing attribute (see section 4.4.3). In this case, there will be one row for each geological era (see details in the respective section). Thus, there could be more than one row per fault ID (see section 4.3.2)

In addition, generation of faults and their activity afterwards can be defined as events in time, recorded in the stratigraphic layering of the geological units where the faults are

[4] Haile, N.S. (1987) Time and age in geology: The use of upper/lower, late/early in stratigraphic nomenclature. Marine and Petroleum Geology, 4/3, 255-257
[5] https://stratigraphy.org/ICSchart/ChronostratChart2012.pdf

cutting through. Especially activities of faults in basins are recorded in the stratigraphic layering of the respective basin fill. Therefore, the activity of a fault can be described by the oldest and youngest sediments that have been recorded to be disturbed by the fault. If available, the chronostratigraphic information is stored in the attributes "young_unit" and "old_unit" (see sections 4.4.5 / 4.4.6).

Finally, the mapping of (buried) faults within basins is often carried out along a certain chronostratigraphically defined horizon. If this is the case, the related chronostratigraphic unit is listed in the attribute "REF_SURF" (see section 4.9.2).

4.3 Basic information on the fault object

This section provides basic information for the identification of fault objects in their national and international context.

4.3.1 Country Code

Name: COUNTRY_CD
Required: true
Type: varchar
As the HIKE FDB consists of national and regional datasets provided by the respective GSO partner, the country code provides a fast overview of the origin of each fault attribute entry. The country code is provided according to ISO 3166-1 alpha-2. If there are multiple data providers per country, an additional subdivision code is added according to ISO 3166-2 separated by hyphen.
Example: NL (TNO, Netherlands) or DE-BY (LfU, Bavaria, Germany)

4.3.2 Fault ID

Name: ID
Required: true
Type: varchar
To be able to uniquely identify faults that are collected in the HIKE FDB, each fault object is given a systematic unique identifier, an ID. This ID is the key to the fault object, connecting the fault attribute table entries with the fault geometry and also with the project vocabulary. Several sets of attributes can exist for one fault object, see TIMING further down. This ID is connected to the GSO partner that delivers the fault data. The ID is constructed of the country code of the data provider, hyphen and a sequence number. The country code used is according to ISO 3166-1 alpha-2. If there are multiple data providers per country, then an additional subdivision code is added according to ISO 3166-2 separated by hyphen.
Example: NL-0001 (TNO, Netherlands) or DE-BY-0001 (LfU, Bavaria, Germany)

4.3.3 Fault Local Name

Name: LOCAL_NAME
Required: false
Type: varchar
The name as which the fault is locally known. A fault has been given names since the time of geological mapping has started. But the usage of local names provided in the local languages has sometimes created confusion, especially if faults cross international borders, so that the same fault might have different local names (e.g. Lavanttal (AT) /

Labot (SI) fault). English translation of local names is to be avoided where the local name has no commonly used English translation. E.g. “Lavanttal Fault” is preferred to “Lavant Valley Fault”, whereas “Vienna Basin Fault System” is preferred to “Wiener Becken Fault System“, because “Vienna Basin” is a commonly used English translation, even outside of the geoscientific literature context.

4.3.4 Link to HIKE vocabulary

Name: CONCEPT_URI
Required: false
Type: link
This is the link with the vocabulary of named tectonic boundaries of the HIKE FDB, where additional non-structured information for each fault are provided. The connection with other faults across international borders is also shown here. Additional sources of information, e.g. other fault databases, e.g. the European Database of Seismogenic Faults (EDSF/SHARE) or national fault databases can be linked via the vocabulary entry. When a fault is uploaded in the HIKE project vocabulary a resource-URI for the fault is generated. If single faults do not have their own project vocabulary entry, they are linked to the next higher hierarchical level. For a more detailed description, see Chapter 5 about the GeoERA HIKE vocabulary.

4.4 General fault characteristics

In this section, general fault characteristics regarding the time and type of activity of a specific fault as well as an indication how the fault characteristics have been obtained are described here. As all the following attributes are based on code lists, the attribute is given both, as readable attribute in the first column and as link to the respective code list or vocabulary URI in the second column, marked by the additional “_URI”.

4.4.1 Evaluation method

Name: EVAL_METH(_URI)
Required: true
Type: varchar (link)
The information given for the “evaluation method” is used as a rough quality measure for the following fault attribute set. It should give a qualitative statement how reliable the observations and the derived fault attributes are. The definition of the attribute parameters is partly related to the GeoSciML classifier code list MappedFeatureObservationMethod[6], but do not exactly match the description and does not include all options.

4.4.1.1 Direct observation

This evaluation method describes the highest evaluation quality, which related to a "direct visual observation", e.g. at an outcrop at the surface.

4.4.1.2 Observed at depth

The option “observed at depth” refers to the fact that the respective fault information has been observed at depth and the fault is generally assumed to be buried.

[6] http://resource.geosciml.org/classifierscheme/cgi/2016.01/mappedfeatureobservationmethod

4.4.1.3 Inferred
The evaluation method “inferred” describes that the fault is neither directly observed at the surface nor observed at depth by reliable methods, but its location and specification are based on inference from available evidence.

4.4.2 Observation method

Name: OBSERV_METH(_URI)
Required: true
Type: varchar (link)
This attribute gives an overview of the most important method how the location and the characteristics of a fault objects were obtained. The list of possible methods is based on the INSPIRE code list SurveyTypeValue[7] and includes some definitions of the GeoSciML classifier code list MappedFeatureObservationMethod[8], but do not exactly match the description nor its purpose in the INSPIRE or GeoSciML data model.

4.4.2.1 1D resistivity survey
The fault and its characteristics have been observed during a campaign of vertical electric sounding measurements, which provides information regarding the change in apparent resistivity of the subsurface with depth.

4.4.2.2 2D resistivity survey
The fault and its characteristics have been observed during a campaign of 2D multi-electrode direct current measurements, in which current is applied to the ground using electrodes and the earth response (voltage or potential difference) is recorded and presented as a 2D geoelectric section showing apparent resistivity distribution.

4.4.2.3 3D resistivity survey
The fault and its characteristics have been observed during a campaign of 3D multi-electrode direct current measurements, in which current is applied to the ground using electrodes and the earth response (voltage or potential difference) is recorded and presented as a 3D block showing apparent resistivity distribution.

4.4.2.4 2D seismic survey
The fault and its characteristics have been observed during a campaign of 2D seismic measurements, where the behavior of artificially-generated seismic waves in the subsurface is recorded. A seismic wave or pulse is generated at the surface by an active seismic source which can be a vibration, mechanical impact, or near-surface explosion.

4.4.2.5 3D seismic survey
The fault and its characteristics have been observed during a campaign of 3D seismic measurements, where the behavior of artificially-generated seismic waves in the subsurface is recorded. A seismic wave or pulse is generated at the surface by an active seismic source which can be a vibration, mechanical impact, or near-surface explosion.

[7] http://inspire.ec.europa.eu/codelist/SurveyTypeValue
[8] http://resource.geosciml.org/classifierscheme/cgi/2016.01/mappedfeatureobservationmethod

4.4.2.6 Airborne geophysical survey
The fault and its characteristics have been observed during a campaign of airborne geophysical measurements, where the geophysical data is obtained by an apparatus fixed to a helicopter, fixed wing, or ultra-light aircraft, depending on location and topographic relief.

4.4.2.7 Ground magnetic survey
The fault and its characteristics have been observed during a campaign of surface magnetic measurements, recorded at an observation point on the earth's surface.

4.4.2.8 Ground gravity survey
The fault and its characteristics have been observed during a campaign of surface gravity measurements, recorded at an observation point on the earth's surface.

4.4.2.9 Borehole logging survey
The fault and its characteristics have been observed during a campaign of borehole logging, where physical, chemical, and structural properties of penetrated geological formations are measured using tools that are lowered into a borehole on a wireline cables.

4.4.2.10 CPT survey
The fault and its characteristics have been observed during a campaign of cone penetration test (CPT) sounding measurements, where the geotechnical engineering properties of soils are determined by pushing an instrumented cone into the ground at a controlled rate.

4.4.2.11 Frequency domain EM survey
The fault and its characteristics have been observed during a campaign of frequency-domain electromagnetic (EM) measurements, where the electrical conductivity of the subsurface through electromagnetic induction is mapped by using continuous wave field methods.

4.4.2.12 Georadar survey
The fault and its characteristics have been observed during a campaign of ground penetrating radar (GPR) or georadar, where high-frequency electromagnetic waves are used to map below-ground lithology or buried objects.

4.4.2.13 Magnetotelluric survey
The fault and its characteristics have been observed during a campaign of magnetotelluric measurements where the electrical resistivity structure of the subsurface is measured through the measurement of electrical and magnetic fields at the earth's surface.

4.4.2.14 Seismological survey
The fault and its characteristics have been observed during a campaign of seismological measurements, where vibrations from natural earthquakes or rupture processes (due to hydraulic stimulation) are used as a source for structural imaging of the subsurface.

4.4.2.15 Sonar survey
The fault and its characteristics have been observed during a campaign of sonar (sound navigation and ranging) measurements, where underwater sound propagation is used, among other applications, for bathymetric mapping, sub-bottom profiling, and gas leak detection.

4.4.2.16 Time-domain EM survey
The fault and its characteristics have been observed during a campaign of time-domain electromagnetic (EM) surveys, where active-source soundings are used to provide information about the electrical structure of the shallow subsurface.

4.4.2.17 VSP survey
The fault and its characteristics have been observed during a campaign of Vertical Seismic Profiling (VSP), where the detectors for seismic measurements are in a borehole.

4.4.2.18 Observed borehole material
The fault and its characteristics have been directly observed in material obtained from a borehole (e.g., borehole core). If the observation method is “observed borehole material”, the evaluation method (see section 4.4.1.1) should be given as “direct observation”.

4.4.2.19 Observed outcrop
The fault and its characteristics have been observed and located directly in outcrop(s), where geologist(s) occupied location of phenomenon, and traced it explicitly over mapped extent. If the observation method is “observed at outcrop”, the evaluation method (see section 4.4.1.1) should be given as “direct observation”.

4.4.2.20 Inferred projection between observed locations
The determination of the location of the fault, its existence or/and its characteristics is based on inferred continuity with observed locations, and assumption of continuity of the feature. If “inferred projection between observed locations” is given, the evaluation method (see section 4.4.1.1) should be set as “inferred”.

4.4.3 Timing of time-dependent attributes

Name: TIMING(_URI)
Required: false
Type: varchar (link)
If the kinematic characteristics of a fault are time-dependent, e.g., a fault has a varying fault type (see section 4.4.4) during different geochronological periods/epochs/ages, the respective geochronological time needs to be defined in the “TIMING” attribute. A record (row) is added for each period/epoch/age for which information is available. For example: a fault is a reverse fault during Cretaceous and a normal fault during Miocene:
first row: TIMING=Cretaceous FAULT_TYPE=reverse fault
second row: TIMING=Miocene FAULT_TYPE=normal fault
Chronostratigraphic periods/epochs/ages are in reference to the INSPIRE code list “GeochronologicEra” based on the International Chronostratigraphic Chart v2012. For more details on this topic see section 4.2.

4.4.4 Fault type

Name: FAULT_TYPE(_URI)
Required: true
Type: varchar (link)
Faults can described as one of the three basic fault types (normal, reverse or strike slip fault). All other fault types give the possibility for providing more detail and could be defined as a combination of these types with specific angles or movements. For the FDB, the INSPIRE code list FaultTypeValue[9] is filtered from variations purely on dip angle or movement direction as the can be defined with properties elsewhere in the FDB (see sections 4.6.2). The additional fault types “ring fault” and “fissure” that do not appear in the INSPIRE code list are defined in the GeoERA HIKE vocabulary (see sections 5.2.1.6 and 5.2.3.1, respectively). If a fault type is not known or cannot be specified, it is set to “unknown” and it is linked to the generic INSPIRE code list FaultTypeValue entry “fault”. The report of HIKE Deliverable 2.3 “Geological Characterization of Faults” provides a more detailed description and background for each type of fault.

Possible value	INSPIRE-ID
normal fault	<FaultTypeValue>/normalFault
reverse fault	<FaultTypeValue>/reverseFault
strike slip fault	<FaultTypeValue>/strikeSlipFault
thrust fault	<FaultTypeValue>/thrustFault
detachment fault	<FaultTypeValue>/detachmentFault
horizontal fault	<FaultTypeValue>/horizontalFault
extraction fault	<FaultTypeValue>/extractionFault
pure extraction fault	<FaultTypeValue>/pureExtractionFault
mixed extraction fault	<FaultTypeValue>/mixedExtractionFault
oblique slip fault	<FaultTypeValue>/obliqueSlipFault
scissor fault	<FaultTypeValue>/scissorFault
wrench fault	<FaultTypeValue>/wrenchFault
unknown	<FaultTypeValue>//fault
fissure	https://data.geoscience.earth/ncl/geoera/hike/category/7868
ring fault	https://data.geoscience.earth/ncl/geoera/hike/category/7868

< FaultTypeValue>=http://inspire.ec.europa.eu/codelist/FaultTypeValue

4.4.5 Geochronological age of youngest faulted unit

Name: YOUNG_UNIT(_URI)
Required: false
Type: varchar (link)
This attribute refers to the geochronological age of the youngest geological unit which was affected by movement along the fault. This attribute is mostly relevant in sedimentary basin environments with a well-defined chronostratigraphy, where this

[9] http://inspire.ec.europa.eu/codelist/FaultTypeValue

attribute should refer to the youngest unit where the fault is detected. This is normally the youngest unit whose base shows a throw.
The age of the youngest faulted unit is in reference to the INSPIRE code list GeochronologicEra based on the International Chronostratigraphic Chart v2012. For more details on this topic see section 4.2.

4.4.6 Chronostratigraphic age of fault detachment surface

Name: OLD_UNIT(_URI)
Required: false
Type: varchar (link)
This attribute refers to the geochronological age of the oldest geological unit which was affected by movement along the fault. This attribute is mostly relevant in sedimentary basin environments with a well-defined chronostratigraphy, where this attribute should refer to the oldest unit where the fault is detected.
The age of the oldest faulted unit is in reference to the INSPIRE code list GeochronologicEra based on the International Chronostratigraphic Chart v2012. For more details on this topic see section 4.2.

4.5 Attributes related to the spatial orientation of faults

Faults in the FDB have geographically referenced geometries. Thereby these faults can be displayed on a map and localized. This section details the spatial definitions and attributes of faults.

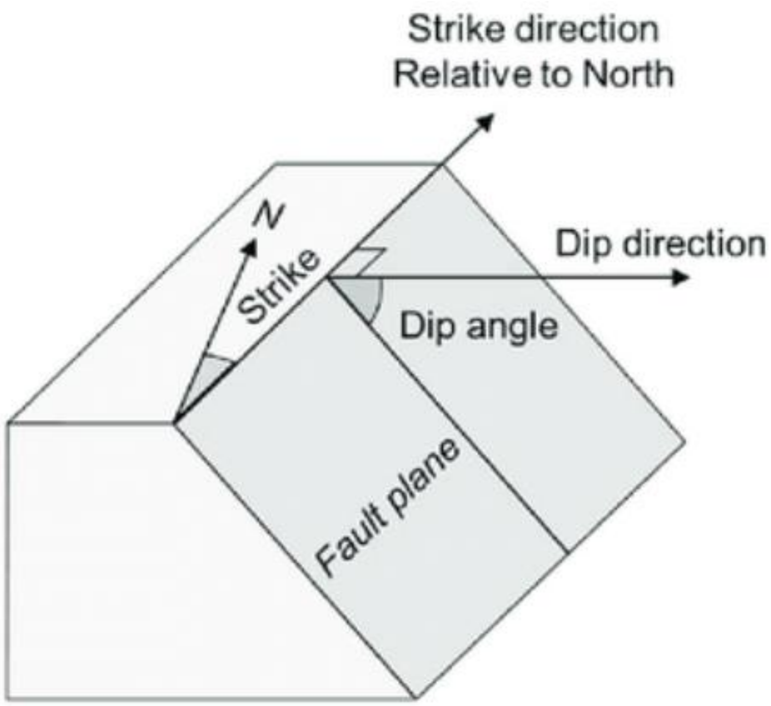

Figure 4.1: Schematic diagram illustrating the fault strike direction and dipping angle, taken from Markou & Papanastasiou (2018)[10]

[10] Markou & Papanastasiou (2018) Petroleum geomechanics modelling in the Eastern mediterranean basin: analysis and application of fault stress mechanics. Oil Gas Science Technologies – Rev. IFP Energies nouvelles, 73, doi: https://doi.org/10.2516/ogst/2018034

4.5.1 Length of the fault

Name: LENGTH
Required: false
Type: integer
The length of the fault is the distance between the tips of a fault, usually measured along a fault trace and in the horizontal plane (Peacock et al., 2000)[11]. This horizontal plane can be taken as the map view of the fault. Where the map may be a surface, depth or horizon map. In case of (large-scale) fault systems the length is more a calculated figure of the conceptual collection of individual faults whereas the length of individual faults is actually measured or observed. The length of the fault is defined in meters along the fault line in map view.

4.5.2 Dip angle

Name: DIP_ANGLE(_URI)
Required: false
Type: varchar (link)
The dip angle reports the angle that the (generalized) fault plane makes with the horizontal plane measured perpendicular to the strike of the structure and in the vertical plane as a numeric value or term. The dip angle is the angle between the dip vector on the fault plane and a horizontal plane. Dip angles range between 0° (horizontal) and 90° (vertical). For the purpose of the FDB, the faults are sorted into five dip angle categories (see list below).

Possible value	Dip angle range
vertical	90° >=dip angle >= 85°
steep	85° > dip angle >= 60°
intermediate	60° > dip angle >= 30°
gentle	30° > dip angle >= 5°
horizontal	5° > dip angle >= 0°

4.5.3 Dip direction

Name: DIP_DIRECT
Required: false
Type: varchar(3)
Dip direction is the azimuth perpendicular to the strike of the structure. For the purpose of the FDB, the faults are sorted into dip direction categories. Directions are classified in 16 classes of each 22.5 degrees (see list below)

[11] Peacock, D. et al (2000) Glossary of normal faults. Journal of Structural Geology, 22, 291-305

Possible value	Description	Dip direction range
N	North	348.75° < dip dir <360°; 0<= dip dir <= 11.25°
NNE	North-Northeast	11.25° < dip dir <= 33.75°
NE	Northeast	33.75° < dip dir <= 56.25°
ENE	East-Northeast	56.25° < dip dir <= 78.75°
E	East	78.75° < dip dir <= 101.25°
ESE	East-Southeast	101.25° < dip dir <= 123.75°
SE	Southeast	123.75° < dip dir <= 146.25°
SSE	South-Southeast	146.25° < dip dir <= 168.75°
S	South	168.75° < dip dir <= 191.25°
SSW	South-Southwest	191.25° < dip dir <= 213.75°
SW	Southwest	213.75° < dip dir <= 236.25°
WSW	West-Southwest	236.25° < dip dir <= 258.75°
W	West	258.75° < dip dir <= 281.25°
WNW	West-Northwest	281.25° < dip dir <= 303.75°
NW	Northwest	303.75° < dip dir <= 326.25°
NNW	North-Northwest	326.25° < dip dir <= 348.75°

4.5.4 Strike

Name: STRIKE
Required: true
Type: varchar(7)
The strike of a fault (or fault trend) is defined as the compass direction, relative to north, of the line formed by the intersection of a rock layer or other planar feature with an imaginary horizontal plane. The intersection of two flat planes is a straight line, and in this instance, the line is geologic strike (see fig. 4.1). The definition of strike for the FDB is interpreted bidirectional, without inferring to a certain dip direction. Strike is defined in classification of eight classes of each 22.5 degrees (see list below).

Possible value	Description	Strike range
N-S	North to South	0° <= strike <= 11.25°; 168.75° < strike <= 180°
NNE-SSW	North-Northeast to South-Southwest	11.25° < strike <= 33.75°
NE-SW	Northeast to Southwest	33.75° < strike <= 56.25°
ENE-WSW	East-Northeast to West-Southwest	56.25° < strike <= 78.75°
E-W	East to West	78.75° < strike <= 101.25°
ESE-WNW	East-Southeast to West-Northwest	101.25° < strike <= 123.25°
SE-NW	Southeast to Northwest	123.25° < strike <= 146.25°
SSE-NNW	South-Southeast to North-Northwest	146.25° < strike <= 168.25°

4.6 Attributes related to kinematic fault characteristics

Kinematic fault characteristics describe attributes related to the relative movement of two opposite fault blocks. All kinematic fault characteristics can be defined time-dependent (see sections 4.2 and 4.4.3).Where the attributes are based on code lists, the attribute is given both, as readable attribute in the first column and as link to the respective code list or vocabulary URI in the second column, marked by the additional "_URI".

4.6.1 Maximum displacement

Name: DISPLACE_M
Required: false
Type: integer
Displacement in meters as measurement in map view. If the dip-slip component is dominant over the strike-slip component then maximum displacement is measured perpendicular to the fault line/trace. If the strike-slip component is dominant over the dip-slip, the displacement is measured parallel to the fault trace. Ideally, if this attribute is provided, the offset determination attribute (see section 4.6.3) should be also filled.

4.6.2 Sense of movement

Name: MOVE_SENSE(_URI)
Required: false
Type: varchar (link)
Movement sense describes the relative direction of movement of bodies of rock across a fault surface, as defined by the IUGS Commission for Geoscience Information (CGI) Geoscience Terminology Working Group. A subset of the respective GeoSciML classifier code list FaultMovementSense[12] is used here, mainly excluding French translations.

Possible value	GEOSCIML-ID
detachment	<faultmovementsense>/detachment
dextral	<faultmovementsense>/dextral
generic_decollement	<faultmovementsense>/generic_decollement
no_movement_sense	<faultmovementsense>/no_movement_sense
normal	<faultmovementsense>/normal
normal_dextral	<faultmovementsense>/normal_dextral
normal_sinistral	<faultmovementsense>/normal_sinistral
reverse	<faultmovementsense>/reverse
reverse_dextral	<faultmovementsense>/reverse_dextral
reverse_sinistral	<faultmovementsense>/reverse_sinistral
sinistral	<faultmovementsense>/sinistral
thrust	<faultmovementsense>/thrust
thrust_decollement	<faultmovementsense>/thrust_decollement

<faultmovementsense>=http://resource.geosciml.org/classifier/cgi/faultmovementsense

[12] http://resource.geosciml.org/classifier/cgi/faultmovementsense

4.6.3 Fault offset determination

Name: OFFSET_DET(_URI)
Required: false
Type: varchar (link)
Method how the displacement across a fault has been determined. Offset determination methods can be provided for either a measured displacement or in a more general sense for the sense of movement.

4.6.3.1 Palaeogeography

This term describes the usage of paleogeographic reconstructions for the determination of the amount of displacement across a fault.

4.6.3.2 Crosscutting relationships

This term refers to the principle of cross-cutting relationships for the determination of displacement across a fault. Cross-cutting relationships is a principle of geology that states that the geologic feature which cuts another is the younger of the two features. It is a relative dating technique in geology.

4.6.3.3 Well/seismic interpretation

This term refers to the determination of displacement across a (mostly buried) fault based on interpretation of well and/or seismic information.

4.6.3.4 Paleoseismicity study

This term describes the usage of paleoseismicity studies for the determination of the amount of displacement across the fault. Paleoseismicity refers to geologically recorded earthquakes, most of them unknown from human descriptions or seismograms. Geologic records of past earthquakes can include faulted layers of sediment and rock, injections of liquefied sand, landslides, abruptly raised or lowered shorelines, and tsunami deposits.

4.6.3.5 Displacement on maps

This term refers to the determination of displacement across a fault based on information shown on geological maps.

4.6.3.6 Seismicity

This term refers to the determination of displacement across a fault based on seismological information shown on geological maps.

4.6.3.7 Sediment structures

This term refers to the determination of displacement across a fault based on sediment structures.

4.6.3.8 Paleostress measurements

This term refers to the determination of displacement across a fault based on paleostress analyses.

4.6.3.9 Field observation

This term refers to the determination of displacement across a fault based on geological field observations such as shear sense indicators or offset observed at outcrop scale.

4.6.3.10 Microfabrics

This term refers to the usage of microfabric analysis to determine the characteristics of displacement across a fault. The microstructural characterization of a crystalline material includes the determination of grain number and size distribution, chemical composition, spatial distribution of phases, crystallographic and structural relationships between grains as well as intragranular misorientation.

4.7 Reference

Name: REFERENCE
Required: false
Type: varchar
The bibliographic reference provides the most important reference for this fault and its geometry. This can be either a scientific publication (article or report) or a geological map. It is given in the style of Author(s), Year, and may include also the link to the source. Further information and references can be found at the respective GeoERA HIKE vocabulary entry (see section 4.3.4 and Chapter 5).

4.8 Expert knowledge about faults

For some faults, detailed information regarding a specific fault offset are determined, e.g., for faults observed in seismic surveys, a certain type of offset is normally determined. Other faults have been determined to be seismogenically active or capable. With the additional expert attributes, data providers have the opportunity to provide such special information.

4.8.1 Active fault

Name: ACTIVE
Required: false
Type: boolean
Boolean value stating whether fault is considered seismogenically active or not. An active fault has moved in the recent geologic past and that is expected to move within a future time span of concern for the safety of a specific building. Depending on the general earthquake recurrence rate, the time to consider ranges between tens of thousands of years for high seismicity regions (e.g. Upper Pleistocene to present) or longer for intraplate regions of low seismicity rates (e.g. Pliocene – Quaternary to present).[13]

4.8.2 Capable fault

Name: CAPABLE
Required: false
Type: Boolean
Boolean value stating whether fault is considered as capable. A capable fault is an active fault that has a significant potential for displacement at or near the ground surface[14].

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[13] IAEA, The Contribution of Palaeoseismology to Seismic Hazard Assessment in Site Evaluation for Nuclear Installations, IAEA-TECDOC-1767, IAEA, Vienna (2015)

[14] IAEA, Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-9, IAEA, Vienna (2010).

4.8.3 3D geometry availability

Name: GEOM_3D
Required: false
Type: boolean
Boolean value stating whether 3D geometry is available through the HIKE partner that delivered the fault data. Contact information of the respective partners is part of the dataset metadata (see section 4.10). Specific geometrical representations and datasets (e.g. 3D representation, exclusive analytical data) may be included for download depending on availability and public accessibility.

4.8.4 Related subsurface activity

Name: ACTIVITY(_URI)
Required: false
Type: varchar (link)
Known human subsurface activities in relation to the fault. The definition of the attribute parameters is related to the INSPIRE code list BoreholePurposeValue[15], but do not exactly match the description nor its purpose in the INSPIRE data model.

4.8.4.1 Exploration of minerals

Activity for examination of the subsurface with regard to the locating and/or extracting mineral resources from the subsurface.

4.8.4.2 Exploration of oil & gas

Activity for examination of the subsurface with regard to the availability of fossil energy resources and planning the extraction thereof.

4.8.4.3 Exploration of geothermal energy

Activity for examination of the subsurface with regard to the utilization of geothermal energy resources and design of geothermal heat pumps.

4.8.4.4 Exploration of groundwater

Activity for examination of the subsurface with regard to the extraction of groundwater from an aquifer for various purposes (domestic, industrial, water supply intake and other).

4.8.5 Net slip

Name: NET_SLIP
Required: false
Type: floating-point number
The net slip describes the total slip on the fault in meters (see red arrow parallel to the slickenlines/striae in the fault plane in Figure 4.2)

[15] https://inspire.ec.europa.eu/codelist/BoreholePurposeValue/

4.8.6 Horizontal throw

Name: HOR_THROW
Required: false
Type: floating-point number
The horizontal throw describes the horizontal component of the net-slip on the fault in meters (see horizontal plane (blue) in Figure 4.2)

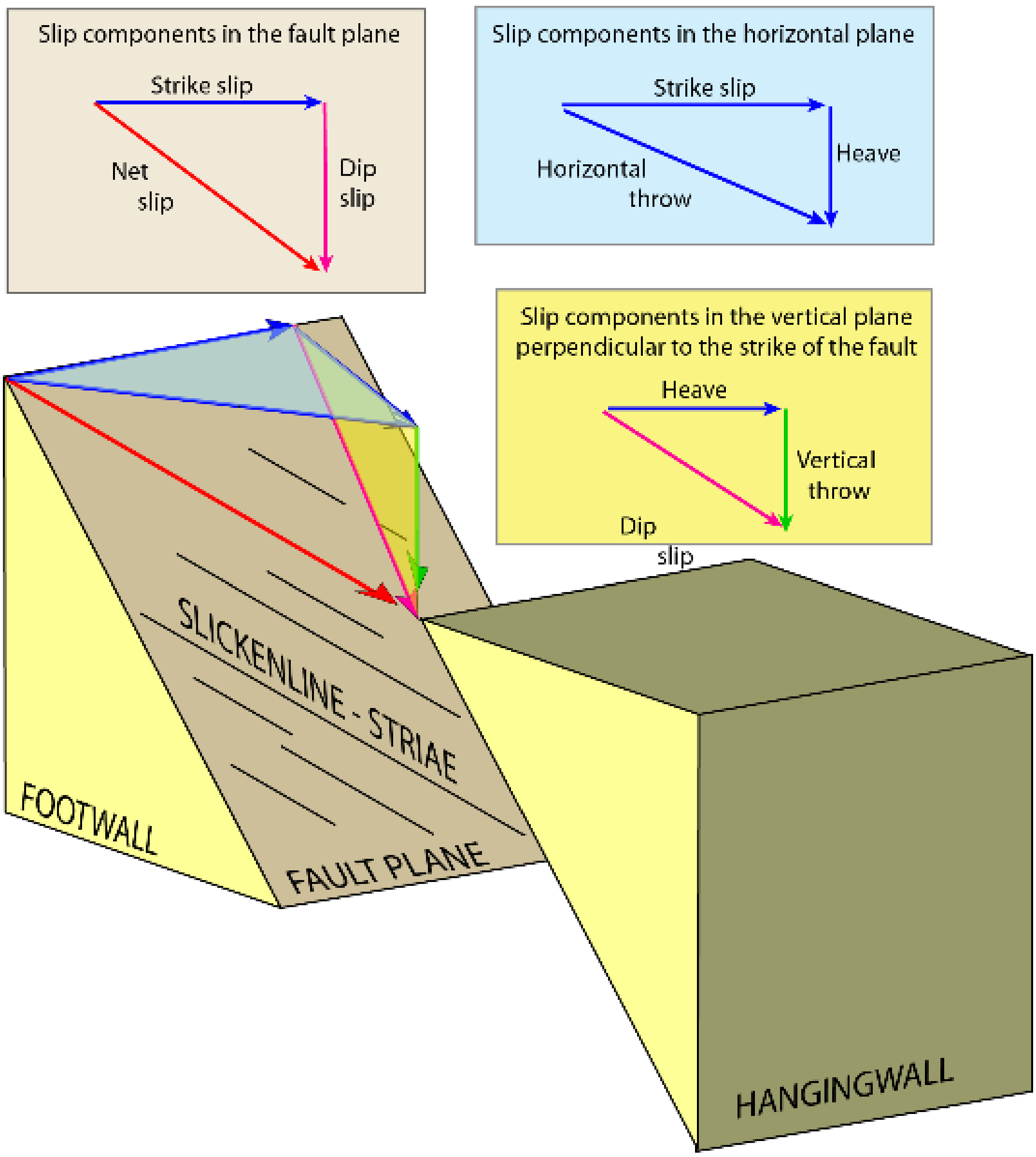

Figure 4.2 overview of the different types how offset can be determined along a fault plane (illustration from P. Rey's course on Structural Geology)[16]

[16] http://www.geosci.usyd.edu.au/users/prey/Teaching/Geos-2123/Faults/Sld11.html

4.8.7 Vertical throw

Name: VER_THROW
Required: false
Type: floating-point number
The vertical throw describes the vertical component of the net-slip on the fault in meters (see green arrow in the vertical plane (yellow) in Figure 4.2).

4.8.8 Strike-slip

Name: STRIKESLIP
Required: false
Type: floating-point number
The strike-slip describes the strike-parallel slip component of the net-slip on the fault in meters (see blue arrow parallel to the strike of the fault in the box model in Figure 4.2).

4.8.9 Dip slip

Name: DIP_SLIP
Required: false
Type: floating-point number
The dip-slip describes the dip-parallel slip component of the net-slip on the fault in meters (see red arrow parallel to the dip of the fault in the box model and in the vertical plane (yellow) in Figure 4.2).

4.8.10 Rake

Name: RAKE
Required: false
Type: floating-point number
Rake is the direction a hanging wall block moves during rupture, as measured in degrees on the plane of the fault. It is measured relative to fault strike, ±180°. For an observer standing on a fault and looking in the strike direction, a rake of 0° means the hanging wall, or the right side of a vertical fault, moved away from the observer in the strike direction (left lateral motion). A rake of ±180° means the hanging wall moved toward the observer (right lateral motion). For any rake>0, the hanging wall moved up, indicating thrust or reverse motion on the fault; for any rake<0° the hanging wall moved down, indicating normal motion on the fault.[17]

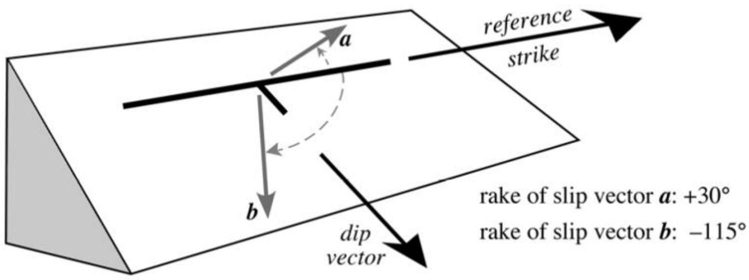

Figure 4.3: Definition of the rake of slip vector Source: A Primer on Focal Mechanism Solutions for Geologists (Vince Cronin, 2010)[18]

[17] Definition from OPENSHA (http://www.opensha.org/glossary-strikeDipRake)
[18] https://croninprojects.org/Vince/Course/IntroStructGeol/Focal_mechanism_primer_v4.pdf

4.9 Attributes related to 2D fault geometries

This section details the geometrical and spatial specifications of the faults within the FDB. 2D (map view) geometrical representations are obligatory and used to visualize, select and analyse faults in the EGDI platform. These attributes describe the geometrical representation of the fault. As there can be more than one representation per fault, these attributes are used to identify these geometries uniquely.

2D -map view- geometries are representations of the 3D fault plane. There are different types of map view geometries (numbers refer to Figure 4.4)

- (1) Surface trace. Fault as observed at surface level.
- (2) Top or base. Top or base of the fault plane.
- (3 left) Base or top of fault unit. Intersection of the fault plane with the specified stratigraphic unit.
- (3 right) Iso-depth line. Iso-depth line of the fault plane.

Figure 4.4 shows a schematic overview of different types of spatial representations as part of the fault object specification.

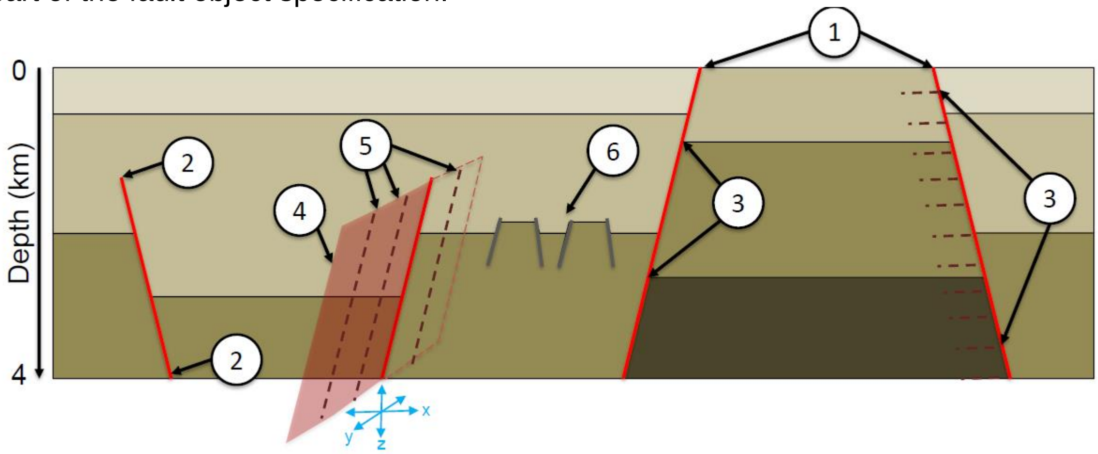

Figure 4.4: Overview of the fault spatial definitions. Numbers are explained in the paragraph above and in the following sections.

4.9.1 Type of Reference

Name: REF_TYPE
Required: true
Type: varchar
This attribute defines the type of representation of the 2D line.

4.9.1.1 Surface

Fault trace at Earth's surface level (see number 1 in Figure 4.4).

4.9.1.2 Top of the fault

Topline of the fault plane, the fault is not extending above this line (see number 2 in Figure 4.4).

4.9.1.3 Base of the fault
Baseline of the fault plane, the fault is not extending downwards below this line (see number 2 in Figure 4.4).

4.9.1.4 Top of faulted unit
Intersection of the fault plane with the top of the faulted stratigraphic unit (see left number 3 in Figure 4.4). If this type is specified as “Type of Reference”, specification of “REF_SURF” (see section 4.9.2) is required.

4.9.1.5 Base of faulted unit
Intersection of the fault plane with the base of the faulted stratigraphic unit (see left number 3 in Figure 4.4). If this type is specified as “Type of Reference”, specification of “REF_SURF” (see section 4.9.2) is required.

4.9.1.6 Specified depth
Iso-depth line on the fault plane (see right number 3 in Figure 4.4). If this type is specified as “Type of Reference”, specification of “DEPTH” (see section 4.9.3) is required.

4.9.1.7 Specific Time
Specific time slice where the fault trace has been observed in case that the data wherein the fault trace has been observed is still in the original time domain (e.g., two way travel time for seismic data). If this type is specified as “Type of Reference”, specification of “TIME” (see section 4.9.4) is required.

4.9.1.8 No Reference
The geometry does not reference a specific part of the fault (as the option above do). This option is used in case of generalized version of the fault (usually at small scale level).

4.9.2 Referenced surface

Name: REF_SURF(_URI)
Required: false
Type: varchar (link)
If “Type of Reference” is specified as “top of faulted unit” or “base of faulted unit”, then “Referenced Surface” must be specified as well (see section 4.9.1). Here, the geochronological age of the stratigraphic unit on whose surface the 2D fault geometry is mapped on, must be provided in form of chronostratigraphic periods/epochs/ages in reference to the INSPIRE code list “GeochronologicEra” based on the International Chronostratigraphic Chart v2012. For more details on this topic see section 4.2.

4.9.3 Depth

Name: DEPTH
Required: false
Type: varchar
If “Type of Reference” is specified as “specified depth”, then “DEPTH” must be specified as well (see section 4.9.1.6). Depth refers to the vertical depth below the Earth’s surface in m.

4.9.4 Time

Name: TIME
Required: false
Type: varchar
If "Type of Reference" is specified as "specified time", then "TIME" must be specified as well (see section 4.9.1.7). Time is given in seconds and refers to two-way travel time.

4.9.5 ScaleFrom

Name: SCALE_FROM
Required: false
Type: integer (1)
Least detailed scale (smallest scale) from which the given 2D fault geometry is valid. This scale is defined as number referencing to the following Table 1.

1 (pan European)	1:15,000,000
2	1:10,000,000
3	1:5,000,000
4	1:2,000,000
5	1:1,000,000
6	1:500,000
7	1:250,000
8	1:100,000
9	1:50,000
10 (detail)	1:25,000

Table 1: Scale ranges as defined by the FDB (but not in use at the EGDI portal so far)

4.9.6 ScaleTo

Name: SCALE_TO
Required: false
Type: integer (1)
Most detailed scale (largest scale) from which the given 2D fault geometry is valid. This scale is defined as number referencing to Table 1.

4.10 Metadata information

Name: METADATA
Required: true
Type: link
Metadata provides the link to the national/regional metadata records of the FDB stored in the EGDI Metadata Catalogue. 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, which is referenced here. The overall FDB record is linked via the build-in parent/children functionality of the EGDI Metadata Catalogue to the national/regional metadata records.

4.11 Concept ID

Name: Concept_ID
Required: true
Type: integer
Automatically generated link to allow the harvesting of the FDB via the GeoERA HIKE vocabulary. It contains the number of the concept within the vocabulary (= part of the URI).

5 SEMANTIC DEFINITIONS USED IN THE GEOERA HIKE VOCABULARY

5.1 Introduction

Naming of faults and fault systems leads often to misunderstandings if local names are used across borders. For the 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 (Simple Knowledge Organisation System)[19] references, a mapping to a global context on the Semantic Web can be defined. Therefore, the FDB is accompanied by a SKOS vocabulary in accordance with the LinkedData principles.

This project vocabulary provide the possibility to sort faults into hierarchical rankings, in order to accommodate different scale levels and/or different levels of information. The project vocabulary is subdivided into two parts: the first one describes the general terms used in the HIKE project for fault classification and ranking. The second scheme defines the national/regional fault inventory and will be delivered by each GSO partner together with the fault data.

5.2 Fault classification terms

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/7856

In this section of the GeoERA HIKE vocabulary, the terms (concepts) for ranking and classifying faults are defined. The classification scheme of the Austrian Fault Database has been used as starting point, but additional terms have been determined in order to satisfy regional differences in Europe. The different ranking concepts are interchangeable, e.g. a fault domain can be subdivided into fault sets or fault systems, depending on the regional/local circumstances.

5.2.1 Description terms for single features

5.2.1.1 Tectonic boundary

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/856

A Tectonic Boundary is a shear displacement structure separating tectonic units and includes all brittle to ductile style structures along which displacement has occurred, from a simple, single 'planar' brittle or ductile surface to a fault system comprised of tens of strands of both brittle and ductile nature (after GeoSciML Modeling Team, 2017[20]). In general, the terms “tectonic boundary” and “fault” are interchangeable.

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[19] https://www.w3.org/TR/skos-reference

[20] http://www.onegeology.org/docs/technical/GeoSciML_Cookbook_1.2.pdf

5.2.1.2 Fault

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/863
The term fault is used here in the sense of a discrete deforming interface separating two rock masses along which one mass has slid past the other (Neuendorf et al., 2005)[21]. Deformation in faults is dominated by brittle deformation mechanisms (Schultz & Fossen, 2008)[22]. In general, the terms "tectonic boundary" and "fault" are interchangeable.

5.2.1.3 Subfault

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/864
A subfault is a subordinated discrete interface separating two rock masses along which one mass has slid past the other, belonging to an ordinated fault (Neuendorf et al., 2005, Hintersberger et al., 2017[23]).

5.2.1.4 Shear zone

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/865
A broad planar zone of relatively intense localised deformation (shearing) in which progressive deformation is non-coaxial (Passchier & Trouw, 1996[24]; Hintersberger et al., 2017). Shear zones may contain either brittle or ductile fault rocks. Here, deformation in shear zones is dominated by ductile deformation mechanisms (Schultz & Fossen, 2008, and references therein) involving dynamic recrystallization, diffusive mass transfer, dislocation creep and/or grain-boundary sliding. It also includes the term "Mylonite Zone" describing relatively thick zones of intensive ductile shearing (Mawer, 1986)[25].

5.2.1.5 Nappe Boundary

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/858
The mostly in Austria used term describes a discrete, brittle or ductile, shearing horizon between tectonic units (e.g. nappes, nappe systems). In this definition, „discrete" refers to map scale, since in the field a nappe boundary can correspond to a diffuse tectonic mélange zone with elements of both units that it separates (Hintersberger et al. 2017).

5.2.1.6 Ring fault

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/7868
A ring fault, also known as caldera fault, is a fault that occur within a collapsed volcanic caldera and the site of bolide strikes, such as an impact crater. Ring faults are result of a series of overlapping normal faults, forming a circular outline. The only ring fault in Europe is the Ries Crater Rim of the Noerdlinger Ries in Bavaria.

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[21] Neuendorf, K. et al. (2005) Glossary of geology, 5th ed.: Alexandria, Virginia, American Geological Institute, 779 p
[22] Schultz, R.A. & Fossen, H. (2008) Terminology for structural discontinuities. AAPG Bulletin, 92/7, 853–867, Tulsa, Oklahoma.
[23] Hintersberger, E. et al. (2017) The new database "Tectonic Boundaries" at the Geological Survey of Austria. Jahrbuch der GBA, 157/1-4, 195-207
[24] Passchier, C.W. & Trouw, R.A. (1996) Microtectonics. 289 p., Berlin (Springer)
[25] Mawer, C.K. (1986) What is a Mylonite? Geoscience Canada, 13/1, 33–34

5.2.2 Hierarchical ranking classification terms:

Single geometries with common kinematic connection and similar deformation history can be grouped into one of the following classification terms. The fault hierarchy is stored in the vocabulary and can be explored there in. In such a case, unnamed faults or tectonic boundaries are linked to the hierarchically higher term and the information provided there.

5.2.2.1 Fault System

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/862
A Fault System corresponds to an alignment of connected and kinematically related faults and/or shear zones active during at least one or potentially several geological events and that may contain different deformation styles (modified after Neuendorf et al., 2005). The faults within a fault system must be related spatially and kinematically at least during one main deformation event (Hintersberger et al., 2017).
A Fault System can be either subdivided into several Subfault Systems and/or Fault Sets or it can be grouped with other fault systems and fault sets into a Large-scale Fault System or a Fault Domain.

5.2.2.2 Fault Set:

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/857
A Fault Set describes an alignment of parallel trending faults that are kinematically and temporally linked, but where the spacing between the single fault zones exceeds the displacement observed along the fault. It does not correspond to the term "fault zone" (Hintersberger et al., 2017).

5.2.2.3 Step fault

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/860
This is a fault system consisting of a number of faults with parallel fault planes, the separated blocks slipping in the same direction along parallel planes giving a step-like feature. This fault is also called a fault terrace.

5.2.2.4 Fault Chain:

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/869
A string (linear array) of faults (including minor subfaults) inferred to represent one single supraregional fault. Faults of the same type and formed during the same deformation episode.

5.2.2.5 Fault Swarm

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/859
A fault swarm is an array of discrete faults with small offsets of same type and formed during the same deformation episode, most probably resulting from distortion caused by movment of blocks along faults with curved profiles (Laubach et al., 1995[26]). A Fault Swarm is not necessarily linearly arranged, whereas the fault chain describes a linear array of faults.

[26] Laubach, S. E. et al (1995) Fault and joint swarms in a normal fault zone. Mechanics of jointed and faulted rock, Rotterdam, Balkema, 305-309.

5.2.2.6 Subfault System

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/866
A Subfault System is a part of a fault system defined by spatial, temporal or kinematic characteristics that are different from the overall deformation of the related fault system during at least one main deformation event (Hintersberger et al., 2017). Shear displacement structures containing at least a ductile and a brittle part are hierarchically considered as a Subfault System. For example, the Brenner SFS consists of the ductile low-angle Brenner Shear Zone and the steeper brittle Brenner Fault.

5.2.2.7 Large-scale Fault System:

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/861
A Large-scale Fault System (LFS) corresponds to the highest level of the Tectonic Boundaries Classification Scheme and describes an alignment of connected and kinematically related fault systems that extend transregionally, typically over hundreds of kilometers. (Hintersberger et al. 2017). In the hierarchical ranking, fault systems are merged into a Large-scale Fault System (LFS) if their extent and impact on the orogenic evolution are of transregional importance (i.e. the Periadraric-Mid-Hungarian Large-scale Fault system for the Alpine Orogen).

5.2.2.8 Fault Domain:

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/867
Fault domain describes an area/terrain of similar pattern of fault array implying a similar tectonic regime. Direct subsets can be Subdomains, Fault Systems and/or Faults. In contrast to Large-scale Fault Systems (LFS) which are more or less linear alignment of (sub-)parallel faults or fault systems, the term 'Fault Domain' applies for areal (non-linear) terrains of similar fault pattern. If any confusion with geological domains would arise, the term 'fault realm' could be used for clarification purposes.

5.2.2.9 Fault Subdomain:

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/868
Fault subdomains describes distinguishable areas of closely similar pattern of fault array within a Fault domain. Fault Subdomain is a subset of Fault domain. This category can be used to distinguish between areas of (subordinate) differences of fault pattern within a Fault domain. If linear arrays of faults are distinguished, the term 'Fault System' applies.

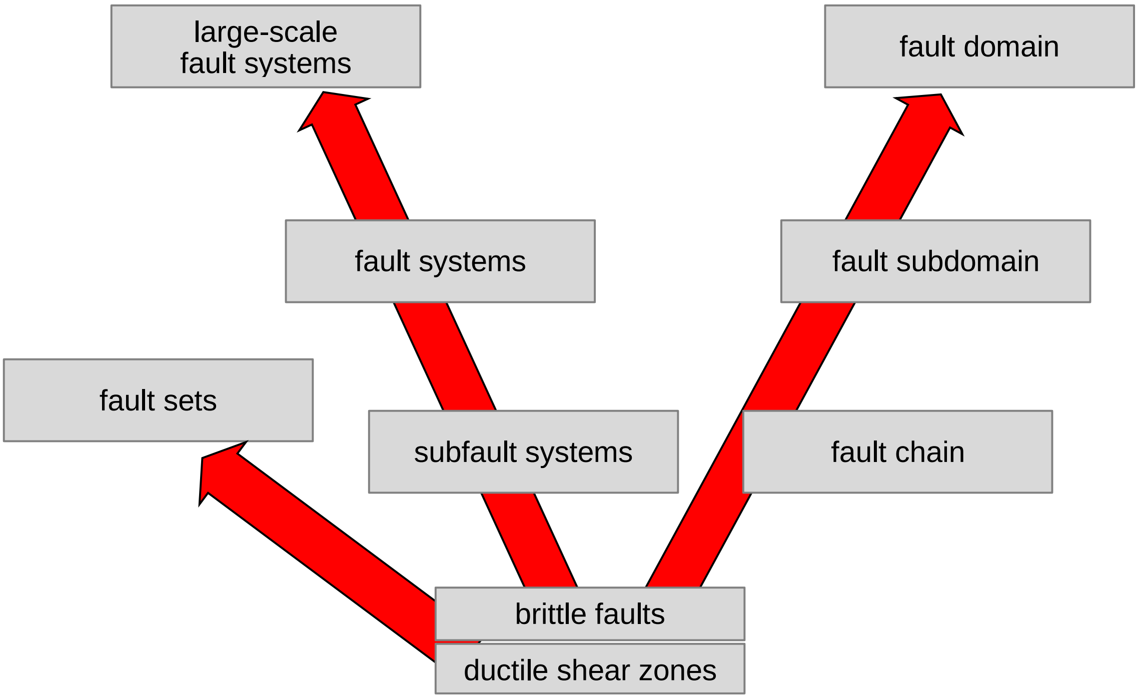

Figure 5.1: Exemplary ranking possibilities for the classification terms. Note that not all hierarchical levels must be used.

5.2.3 Hierarchical order of volcanic systems

In Iceland, a specific fault type is used to describe the features there, the fissure. Analog to faults, fissures can also be grouped into fissure sets. These can be combined with fault sets to volcanic systems.

5.2.3.1 Fissure

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/872
Fissures are volcanic vents. They present as linear features on the surface and are created by the non-explosive eruption of lava. In some cases, the fissures make rows of craters.

5.2.3.2 Fissure Set

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/871
Fissure sets are groups of fissures which are found within the volcanic systems. They can be sorted into fissure swarms which can usually be associated with central volcanoes. The fissure swarms extend outwards from the central volcano, aligned sub-parallel to the axis of the hosting volcanic zone.

5.2.3.3 Volcanic system

Link to Vocabulary: https://data.geoscience.earth/ncl/geoera/hike/category/870
Volcanic systems are the principal geological features in the volcanic zones in Iceland. Each volcanic system contains a fissure swarm or a central volcano or both and younger

systems are associated with swarms of tension fractures and normal faults. The volcanic systems are the formed by the interaction of the divergent plate boundary associated with the Mid-Atlantic Ridge and the mantle plume located under Iceland.

5.3 Tectonic boundary objects in Europe

Link to Vocabulary: https://schmar00.github.io/HIKE/
In this scheme, the actual fault objects that form the FDB are defined by their geographic extend and name. The scheme is subdivided into several top concepts reflecting the national/regional fault inventory of each GSO (e.g. Tectonic Boundaries in Austria, Tectonic boundary in the Netherlands, Tectonic Boundaries in Bavaria, etc.). These top concepts are also the default value in case that no specific descriptions of faults are delivered during the project time (eg., Tectonic Boundary in France). Below these top concepts, GSO's have determined the hierarchy of fault domains, fault systems, faults, etc. that are representative for their areas. These concepts have in certain instances been related to similar tectonic boundary objects in adjacent countries. In total, over 2500 fault descriptions from all partner GSO have been included, making it the largest vocabulary of named fault objects worldwide.

The concepts were provided via a template spreadsheet which is explained in the GIP WP4 github page[27]. In Figure 5.2, an example of a vocabulary entry is shown with a short description of the functionalities. Below a brief explanation of the vocabulary elements is provided:

(1) The title of the vocabulary entry consists of the preferred (English) name of the respective tectonic boundary object.
(2) The (final) URI of the concept is provided here.
(3) Alternative names in English and in local languages are provided here. If border-crossing faults are associated with different local names, both English derivates are provided (e.g., Lavanttal Fault, derived from German "Lavanttal-Störung" and "Labot Fault", derived from Slovenian "Labotski prelom").
(4) The Fault ID of the FDB (see section 4.3.2) is listed under "Notation". Note that more than one Fault ID can be listed here, especially in case of border-crossing faults where the fault has an ID in each country. Hierarchically higher vocabulary entries are not necessarily directly linked to a geometry in the FDB, especially if there are narrower concepts available.
(5) Definition of the fault, describing at least its geographic location. Additional information not included in the attribute table of the FDB can be provided in an unstructured text.
(6) Bibliographic references for the respective fault. A blue sign at the end of the reference provides the link to the respective pdf.
(7) The semantic relations are listed here, with the direct relations within the HIKE vocabulary in dark grey and the matches to other structured vocabularies in light grey. The transitive SKOS[28] relations "narrower" and "broader" are used to create a direct hierarchy of the tectonic boundary objects, e.g., the Pöls-Lavanttal Fault System is the hierarchically higher level (e.g., the broader concept) of the Lavanttal Fault, whereas the Lavanttal Fault is the narrower concept of the Pöls-

[27] https://github.com/GeoEra-GIP/WP4-Semantics/tree/master/Project%20Vocabularies
[28] https://www.w3.org/TR/skos-reference/#semantic-relations

Lavanttal Fault System. Polyhierarchy is possible, i.e., a fault can belong to several broader concepts, and vice versa, a fault system can consists of several narrower concepts. The possible mapping to other structured vocabularies are obtained by using “exactMatch”, “closeMatch”, “relatedMatch”, “broadMatch”, “narrowMatch”[29].

(8) Under the “read more” arrow, technical information in form of all used triples is provided. For detailed explanation, refer to GeoERA GIP-IP Deliverable 4.3[30].

(9) Under the title of the vocabulary “Tectonic Boundary Objects in Europe”, all vocabulary entries are listed in alphabetic order.

(10) The paperclip provides the link to other online resources, e.g. the same fault represented in other European fault databases, e.g., EDSF/SHARE, or national fault data bases, e.g. ITHACA.

(11) Link to the rdf-file listing all semantic triples used for this specific vocabulary entry

(12) HTML list of this vocabulary entry and all narrower concepts.

(13) Link to FDB, where all fault geometries linked to this vocabulary entry are shown, including all narrower concepts.

(14) Link to the overview home page of all GeoERA vocabularies.

(15) Search function for all GeoERA vocabularies.

(16) Description of the GeoERA project that provided the vocabulary entry. Note that within the HIKE vocabulary “Tectonic Boundary Objects in Europe”, vocabulary entries provided by other GeoERA projects are used, especially from HotLime[31] and GeoConnect3D[32].

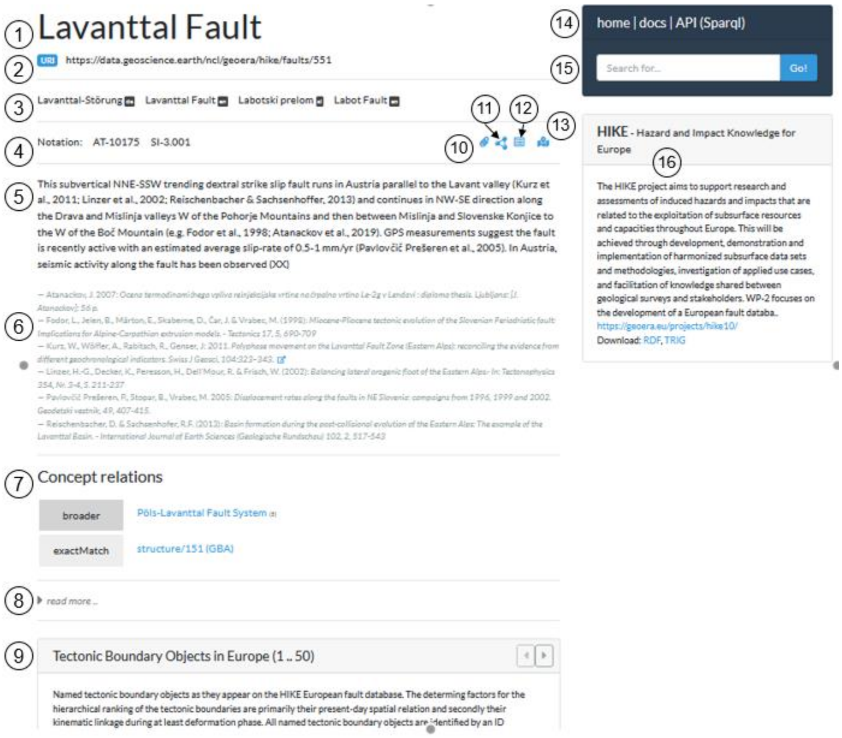

Figure 5.2: Exemplary GeoERA HIKE vocabulary entry with all functionalities as they are shown at the moment (subject to change).

[29] https://www.w3.org/TR/skos-reference/#mapping
[30] https://geoera.eu/wp-content/uploads/2019/11/D4.3-GeoERA-Project-Vocabularies.pdf
[31] https://geoera.eu/projects/hotlime6/
[32] https://geoera.eu/projects/geoconnect3d6/

6 RECOMMENDATIONS

The FDB is a first and major step towards a comprehensive European administration of geological data on subsurface faults and includes links to other existing fault repositories (e.g. EDSF/SHARE for seismogenic faults). Its development has triggered an under-represented area of EU geological research and mapping. For many surveys the development of the FDB has been a major step and support for fault research. The specifications have helped to reach a more uniform state-of-art across Europe which may see continued development in future national programmes. The embedding within the European Geo-Data Infrastructure (EGDI) supports long-term accessibility, better integration with other geological datasets and implementation of future updates.

While the GeoERA-HIKE project will end in 2021, there are still many opportunities to improve the database architecture and specifications. In this chapter, recommendations on the use of the FDB are made, together with comments on possible further developments and improvements.

6.1 Status quo, maintenance and updates

- Faults are included based on common standards and data formats. While the level of detail is still different between countries, these standards and formats have already led to a more uniform representation and registration of fault data.
- A large part of Europe is already included, but several countries are still missing. Some of the countries represented in the database still provide mainly basic information of their fault data.
- The FDB requires continued development to reach a more mature status needed for advanced applications.
- It is recommended to further embed the developed procedures and specifications in the regular national geological programmes and GSO tool sets. While this will be key to extending the database in the coming years, the tools and specifications will also facilitate the fault research capacities and capabilities of individual surveys. This has already been proven during the HIKE project.
- Continued promotion within the geoscience community should attract new data providers (also non-GSO) and lead to a better data coverage (both spatially and in terms of qualitative and quantitative characterization). This will largely depend on the visibility of the database and the demonstrated applicability. It is recommended that the partner surveys continue to use the database for future research projects to stimulate further development.
- It is recommended to develop and maintain an overlay map which represents the current state-of-art per country and highlights eventual areas with low/sparse data coverage. This map may be a guideline for future policy and research programmes.

6.2 Specifications and standards

- While the user-base grows, there will also be a growing demand for new specifications including new attribute types, new formats to represent geometries (e.g. 3D, raw interpretation data) and new visualization and selection tools.
- The HIKE European FDB provides more information than the basic mandatory attributes for a shear displacement structure within the INSPIRE data model.

Thus, the database by itself is not completely INSPIRE-compliant, but an INSPIRE-compliant dataset could be extracted by the information provided by the FDB. The mandatory INSPIRE attributes inspireID, faultType, and mappingFrame can be derived from the FDB attributes ID (see section 4.3.2), FAULT_TYPE (section 4.4.4) and the combination of REF_TYPE (section 4.9.1.) and REF_SURF (section 4.9.2), respectively.

- In general, existing INSPIRE and GeoSciML standard code lists have been used, where possible – and extended or repurposed, if needed. For more detailed information see respective sections in Chapter 4. Nevertheless, further extension of the respective code lists beyond the HIKE usage must be discussed in a case-by-case manner and was **not** the purpose of the project.
- Currently, many attribute values have value-categories instead of more accurate numerical values (e.g., strike, dip direction, dip angle etc.). This reflects the associated uncertainties of these values. As maturity of fault data improves, it is recommended to add numerical attribute fields next to the category-based attributes. This will enhance the applicability for research.
- Confidence levels are now defined at a generic level in the meta-data (non-specific for the entire database). In addition, the attributes EVAL_METH (section 4.4.1) and OBSERV_METH (section 4.4.2) should give an estimate on the quality and reliability of the provided information. If more precise information will become available for more countries, it is recommended to include and represent uncertainties at the individual attribute level. This would be important for a justified application of the FDB.

6.3 Inter-operability and applicability

- Links to other existing fault databases and other online resources are organized via the HIKE project vocabulary entries (see section 5.3 (10)). At the moment, the links are set exemplary, but they already create the bridge between the different fault databases. In future, this network between the fault databases can be extended by a more systematic inclusion of the links. In addition, this route could be a possibility to include nations with already existing national fault databases, which were not part of the HIKE project (e.g., Spain, Greece).
- The applicability and visibility of the FDB will grow with a better integration of external datasets. It is recommended to add new links to external datasets via the vocabulary system and to develop a more advanced integration which allows direct data exchange (e.g. combining datasets, linking/conversion of attributes in different databases, joint representation, etc.)
- A major point of improvement is the across-border harmonisation. This FDB compilation provides the opportunity to explore the different national views and provides starting points for cross-border synergy investigations in order to work towards a seamless harmonisation within Europe.
- As the data of the FDB is provided under the creative commons licence CC BY 4.0[33], it can be directly downloaded or used embedded via WMS and WFS by users via the EDGI platform[34].

[33] https://creativecommons.org/licenses/by/4.0/
[34] https://geoera.eu/projects/hike10/faultdatabase/

6.4 Miscellaneous features

- The FDB provides an extensive view on geological structures in Europe. A recommended future step would be the combination with geological and/or lithotectonic units. As example, the fault data could be used as base for a Europe-wide application test of the structural/geological framework as provided by the GeoERA project GeoConnect³d, as envisioned in the planned CSA-GSE project proposal.
- In the FDB, two scale ranges have been applied: a pan-European overview ranging between the scales of 1:15.000.000 and 1:1.000.000 and a detailed view between the scales of 1:1.000.000 and 1:25.000. However, this is only applied in a few countries (see section 3.2.1). Even though it was not used in the current application, the infrastructure for a true scale dependency on a fault-to-fault level is given: Each fault can be associated with several fault geometries, linked together via the fault ID. For each fault geometry, a scale range can be provided via the attributes SCALE_TO and SCALE_FROM (sections 4.9.5 and 4.9.6). Thus, it is recommended to include more scale-dependent fault geometries in the future.
- As fault characteristics, such as sense of movement, the amount and type of displacement and offset, and even the dip angle, are prone to change over time, time-dependency of the related attributes are necessary to represent accurately the deformation history of faults. At the moment, time-dependency is mainly applied for the FAULT_TYPE (section 4.4.4). It is recommended to extent time-dependency to other attribute values in order to reflect the detailed information available for some faults.
- 3D fault data is now provided through the information in metadata and links. It is recommended support direct inclusion (and representation) of 3D data in the future.
- At the moment, additional analysis and visualization tools (e.g. rose-diagrams, statistics,…) are not included on the EDGI platform. In the future, it is recommended to include basic structural geological diagrams for the better analyzation and visualization of the extensive information provided by the FDB.