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Methods, bottlenecks, best practices and accompanying descriptions to faults in 3D models

Authors and affiliation:
Alexander Malz, Hans Doornenbal, Christian Olaf Müller, Jacob Wächter, Ewa Szynkaruk, Zbigniew Malolepszy, Christoph Jahnke, Karsten Obst, Tomasz Żuk, Rosibeth Toro, Esther Izquierdo-Llavall, Antonio M. Casas, Conxi Ayala, Emilio L. Pueyo, Fabian Jähne-Klingberg, Hauke Thöle
[LAGB][TNO][BGR][LBGR][IGME][PGI]

E-mail of lead author:
malz@lagb.mw.sachsen-anhalt.de

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		Hans Doornenbal (TNO)
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GENERAL INTRODUCTION

The parametrization and understanding of the subsurface is one of the main challenges in ancient and modern earth sciences. Since late 19th century when classical mapping and shallow drilling campaigns were performed, our knowledge about the earth's interior significantly increased due to enhanced prospecting methods first established by the raw material industry and, more recently, by the digital revolution. In accordance with increasing digitalization and processing power a considerable increase of three-dimensional information and models were developed.

This exponential increase of data led to the necessity of harmonization and unified modelling, generalization and parametrization approaches. Especially in the course of recent socio-economic evolutions like national to international plans for the decarbonization of energy systems, (e.g. United Nations' 2030 Green Agenda), reduction of CO_2 emissions and policies for the extraction and storage of renewable energies, the geologic subsurface as economic space becomes more and more relevant. Thereby, it is needless to say that all these challenges do not stop at political and national borders.

In particular, the geometry, extent and influence of faults play one of the most significant and challenging roles in the understanding, parametrization and thus usability of the subsurface. Thereby, their knowledge is essential for any subsurface usage as they can either disturb or delimit well-suited storage or extraction sites, can connect potential aquifers against each other or provide and prevent potential pathways or geological barriers. A further aspect for future planning efforts is the potential activity of faults; e.g. reactivation potential of inherited faults in relation to the recent or future stress regime, especially in combination with a decrease of fault's shear strength due to fluid/gas extraction or injection.

Often the detection and characterization of faults is highly ambiguous and interdisciplinary and multi-methodological exploration and modelling approaches were needed to produce robust interpretations. If crossing national or international borders the availability of comparable geoscientific data and models is additionally hampered. Hence, in the course of the work package (WP5), presented in this report, faults were specially considered. Thereby, we focus, first, on several exploration approaches, which can improve our understanding of fault's geometry in various geological settings and data. Subsequently, different aspects of fault modelling and cross-border harmonization were tested in the project's pilot areas and case studies from methodological work packages and were described in this report. With a short outlook to aspects like classification, attributation and parametrization we show most recent and future challenges for fault data management in pan-European scales, which is in part handled in other GeoERA projects (e.g. HIKE). At least, this report will try to provide a more complete overview of best practices for fault modelling and data management and may act as a reference for future fault modelling projects.

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1 INTRODUCTION

Consistent modelling and cross-border harmonization of structural models depends significantly on our knowledge and understanding of the regional geologic setting, the structural inventory and the assessment of lateral discontinuities, which separate individual blocks and regions of the structural model from their adjacencies. Faults are the most important discontinuities that are relevant for structural modelling. They form mostly planar features in volumes of rocks across which a significant displacement occurred. Moreover, faults never exist individually but rather form a fractal distribution of single fractures ranging from micro- to macroscopic scales. Depending on the level of knowledge, data density and the scale of observation, modelling of faults is always associated with a distinct amount of abstraction. Geologically, faults are important borders of structural blocks or regions that were displaced relative to each other and which likely underwent an individual geological evolution. Hence, faults and fault networks form the essential framework for 3D models. Faults are also possible sources for geological hazards today and may act as sealing or leaking structures in deep geological reservoirs.

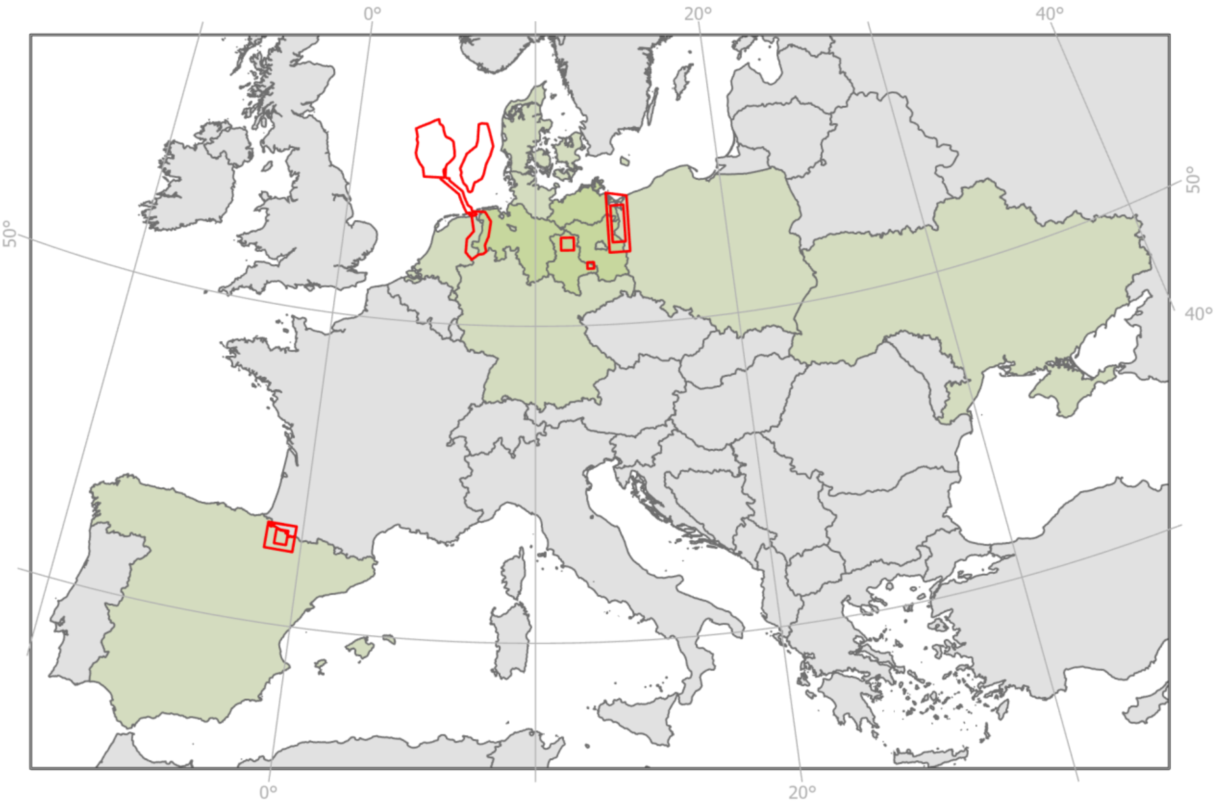


Figure 1 Overview map of participating countries, case study and pilot areas of the work package "Faults" in the 3DGEO-EU project

The knowledge, observability and interpreted geometry of faults strongly depend on the quality, density and type of available data. Additionally, fault interpretations are importantly biased by the subjective impression and experience of the interpreter. Consequently, fault modelling and harmonization, i.e. the conversion towards an abstracted geometrical and digital representation, is often challenging due to ambiguous interpretations. Especially in cross-border areas or in regions with scarce subsurface information, such fault constructions most often do not fit and must be harmonized prior to 3D modelling.

In the framework of several methodological work packages (WPs) of the 3DGEO-EU project faults were observed, mapped at surface, interpreted in depth, modelled and harmonized on the basis of different kinds of data and workflows. Furthermore, an intense discussion about certain and uncertain fault interpretations was performed in WP4. Newly investigated methods and workflows of fault detection and modelling were developed and subsequently tested in three pilot areas (Figure 1), which strongly differ as far as used data, applied methods and geological setting are concerned.

2 OBSERVATION METHODS FOR FAULTS (APPLIED IN THE 3DGEO-EU PROJECT)

The detection and modelling of faults strongly depend on the availability and use of appropriate data sets. The characteristics of these data sets differ depending on the regional geologic setting, the area of interest or territorial or infrastructural conditions. Whereas faults in areas with strong morphological expression are often easy to detect by use of classical geologic mapping, other regions are widely covered by post-kinematic rocks, the water table or infrastructure and thus faults need to be interpreted using subsurface geophysical exploration techniques. In these cases, the most appropriate method must be properly selected in accordance with the geological setting and the distribution of petrophysical parameters. Hence, a high variability of appropriate methods for fault observation and detection exists (Table 1).

Table 1 Methods and preferable settings/conditions for fault observation (not complete) and pilot areas for their application in the 3DGEO-EU project

	Observation method	Description/preferred application	Applying pilot areas in 3DGEO-EU			
			WP1	WP2	WP3	WP6
Direct observation	Field mapping/Geological maps	• Geological units observable at surface (no post-kinematic strata or water column)		✓		✓
	Borehole data		✓	✓	✓	✓
Indirect observation	Seismics (2D)	• (sub-)horizontal bedding of sedimentary rocks • high impedance contrasts • low surface morphology	✓	✓	✓	✓
	Seismics (3D)		✓	✓	✓	
	Gravity data	• distinct density contrasts necessary • limited/ambiguous depth information		✓		✓
	Magnetic data	• distinct contrast in magnetic susceptibility of rocks necessary • limited/ambiguous depth information				
Interpretation	Geological cross-sections	• interpretation of existing data • certainty highly dependent from quality of data and interpreter's experience, concepts and regional geological knowledge		✓		✓
	Seismic depth maps		✓	✓	✓	✓
	Potential field data maps (filtered and gradients)			✓		✓
	Interpreted depth maps (from borehole data)			✓		
	Existing 3D models		✓	✓	✓	

2.1 Direct observation methods

In most areas all over the world direct observation of faults is hampered by some tens to hundreds of meters thick post-kinematic sediments (e.g. the Polish-German border region, WP2), vegetation and soil (e.g. the Gronau-Waldhügel Fault Zone, WP1) or the water column, if offshore areas (e.g. the Central Graben area in the North Sea, WP3) are studied. In other areas, like more recently active orogens or areas of strong uplift, optimal erosion levels, and dry-weather conditions (e.g. the Pyrenees, which form one case study area in WP6), faults can be directly observed at the surface by classical geologic mapping due to the favorable outcropping conditions. Geological maps provide reliable information on the orientation of faults and their relationship to bedding (e.g. main detachment levels, fault ramp angles, etc.) that can guide fault interpretations at depth. To a limited extent, faults can be also directly observed if boreholes or mining shafts penetrated them. Nevertheless, direct observations only provide very localized information of faults and are relatively sparsely available with respect to the extent of regional geologic models, which have to be harmonized on a pan-European scale.

Sparse direct observations can, in some circumstances, be spatially extended with use of other surface observation methods such as lineament detection from remote sensing or aerial surveys and high-resolution digital elevation model analysis. Furthermore, seismites found in Quaternary sediments (e.g. in Polish-German border region, WP2) also provide (semi)direct clues for fault's spatial and temporal extend.

2.2 Indirect observation methods

In areas of sparse surface information, geophysical exploration techniques are the most suitable observation methods to gather two- or three-dimensional information of faults. Next, a brief description on fault identification with applied geophysical methods in the framework of the 3DGEO-EU project is given.

2.2.1 Seismic imaging of faults

Especially in sub-horizontally layered sedimentary bodies, with heterogeneous stratigraphic successions, the high acoustic contrast between individual stratigraphic horizons makes the seismic reflection method most appropriate for structural interpretations. Faults are usually identified in seismic sections as a vertical offset of a discontinuous reflector or hyperbolas resulting from diffraction. Due to disadvantageous reflection angles (i.e. Snell's law) and destructive interference of the seismic signals (complex geologic layering, salt tectonics, etc.) the signal/noise ratio is often low in faulted areas. Therefore, a distinct vertical displacement at the fault and a high resolution of the seismic survey supports reliable fault detection (SCHULTE ET AL. 2019).

Seismic discontinuity attributes are mostly applied for fault detection in 3D seismic cubes. Standard attributes like coherency or semblance measure the similarity between the waveforms or traces and indicate a fault at an abrupt change of the attribute (KINGTON, 2015). The obtained fault indications will be traced across several profiles or time/depth slices to detect the fault's entire extent and shape. However, discontinuity attributes also detect other geological features, steeply dipping strata, collapse structures and data artifacts (KLUESNER AND BROTHERS, 2016). The recognition of faults requires profound insights into the studied data and local geological setting. However, prior knowledge of the seismic specialist may induce a significant bias in the interpretation that has been defined as "conceptual uncertainty" (Bond et al., 2007). A discussion of examples of interpretational bias and other limitations in seismic interpretation is given in Zehner et al. (2021).

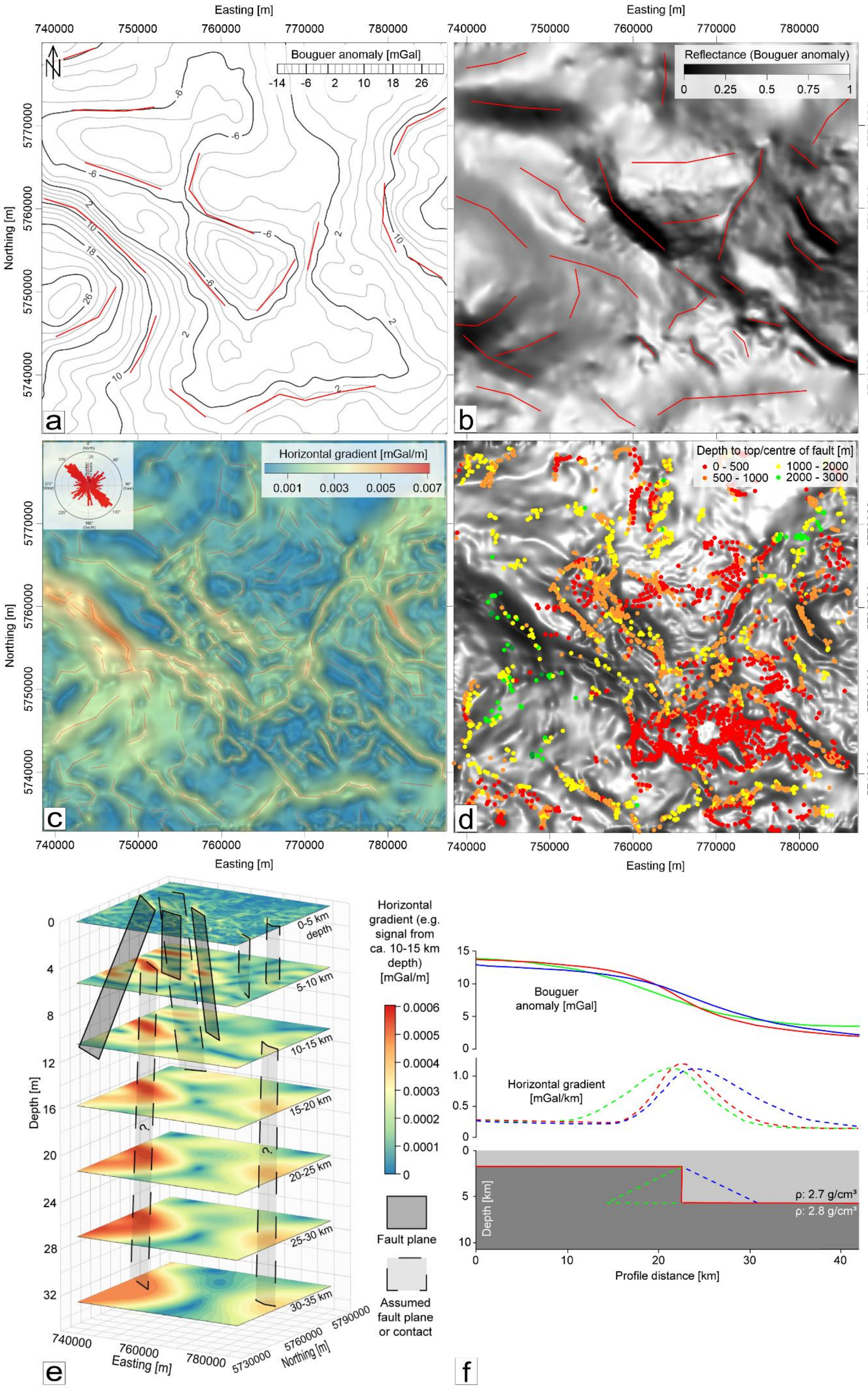
2.2.2 Imaging of faults with potential field methods

The acquisition, processing and interpretation of potential field data (gravity and magnetic) may provide powerful information of the subsurface as long as enough petrophysical contrast among the target formations exists (density, magnetic susceptibility and remanence). Especially in areas where data-driven structural modelling becomes challenging due to ambiguous information, the absence of other subsurface data (e.g. borehole information, seismic reflection data) or in complex geological settings (salt structures or crystalline complexes) the incorporation of potential field data has been proven to significantly decrease a model's uncertainty (e.g. Jacoby and Smilde, 2009). Thereby, studies of the potential field data require a-priori information, which must be accounted for during the interpretation and modelling process. Depending on a fault's depth, extent, geometry and density or susceptibility contrast, the resulting anomalies are characterized by signals of different wavelengths and amplitudes (e.g. Skeels, 1947; Blakely, 1995). A decomposition of the potential field by filtering/enhancement and other techniques allows emphasizing the signals of interest (i.e. parameter contrasts at faults of various depths, geometries and extent) and thus enables the interpretation of structures at various scales. However, as with any other geophysical technique, during interpretation of the potential fields it should be always kept in mind, that the data is subject to the non-uniqueness problem, which indicates that always more than one solution exists to explain the observed signals (Saltus and Blakely, 2011) and that the superposition of two reversed anomaly signals of the same value will erase their anomalous effect.

Fault detection in potential field data interpretation is based on standard anomaly fields (e.g. Bouguer or free-air gravity anomaly, total magnetic intensity anomaly and their residuals) and focuses on clustered isolines (e.g. Militzer and Weber, 1984) (Figure 2 a). A distinct parameter contrast, high fault offsets and steep dips contribute to a pronounced change in the potential field and cause a strong gradient. However, in most cases only the position of the main faults can be roughly identified by means of this approach, due to the method's dependence on the selected increment of plotted isolines as well as the interpreter's ability for visual fault detection. Reflectance or hill-shading effects are often used to increase the visibility of main changes in the anomaly fields (Figure 2 b). Thereby, the illumination angle is changed to highlight faults of different dip and size.

The calculation result of gradients in the anomaly field (first horizontal and/or vertical derivatives including also the tilt angle technique; Hinze et al., 2013 and references therein) is a mathematical presentation of the spatial changes in the anomaly field and allows an improved detection and tracing of faults (Figure 2 c). Theoretically, the gradient will be maximal or zero at the fault location, depending on the inspected or combined gradients. The maxima or zero crossing will be shifted for non-vertical faults. Their true location can be estimated with the approach by Grauch and Cordell (1987). However, the level of detail in fault identification always depends on the resolution of the potential field data, strongly dependent on the density of measured data and the actual petrophysical contrast. Identified faults can be either picked manually or by so-called "ridge-picking" techniques (Pirttijärvi, 2012) (Figure 2 c).

The combination of the anomaly field's gradients with filtered anomaly maps (e.g. second derivatives, Euler deconvolution method; THOMPSON, 1982) are used to reveal additional information on the fault's geometry and to estimate its extent at depth. Therefore, the gradient calculation is applied to residual gravity anomalies (Figure 2 e). Delineating the indications through several depth slices allows a rough estimation of the dip and depth extent. The application of so-called "depth-to-source" techniques (e.g. 3D Euler deconvolution) can provide additional depth information on the fault's top or centre (e.g. REID ET AL., 2014) (Figure 2 d). Finally, geophysical modelling (2D or 3D) of potential field data (especially of gradients) can reveal general information on the fault's geometry and displaced horizons (Figure 2 f), which will be explained in the next sections.



Easting [m]
Northing [m]
Bouguer anomaly [mGal]
Reflectance (Bouguer anomaly)
Horizontal gradient [mGal/m]
Depth to top/centre of fault [m]
0 - 500
500 - 1000
1000 - 2000
2000 - 3000
a
b
c
d
Depth [m]
0-5 km depth
5-10 km
10-15 km
15-20 km
20-25 km
25-30 km
30-35 km
Horizontal gradient (e.g. signal from ca. 10-15 km depth) [mGal/m]
Fault plane
Assumed fault plane or contact
Bouguer anomaly [mGal]
Horizontal gradient [mGal/km]
ρ: 2.7 g/cm³
ρ: 2.8 g/cm³
Depth [km]
Profile distance [km]
e
f

Figure 2 Example of fault detection in gravity data (modified from MUELLER ET AL., in prep). a) Illustration of fault tracing along clustered isolines. The red lines indicate possible fault locations b) Reflectance of Bouguer anomaly (with light illumination from southwest) can support the fault identification based on standard anomaly fields. c) Horizontal gradient with picked fault indications. The rose diagram in the upper left corner reveals the main strike directions of the picked faults. d) Result of 3D Euler deconvolution provides a depth estimation to the top/centre of the fault. e) Horizontal gradient maps of bandpass filtered Bouguer anomaly allow rough tracing of main faults with depth and indication of dip (further explanation in the text). f) Gravity anomaly of a synthetic step fault with different dips. A vertical fault causes a symmetric anomaly in the horizontal gravity gradient with the maximal gradient above the fault. A tilted fault is characterized by a wider gradient above the fault and a steeper flank at the opposite side as well as a shift of the gradient's maximum towards the centre of the fault.

2.2.3 Imaging of faults from combined structural and geophysical data (including inversion)

Combined integration of standard surface geological information (fault traces, dip angles, etc.), derived interpretation (i.e. balanced cross-sections) and geophysical data (potential fields, seismic, etc.) is also able to reasonably image faults in 2D and 3D particularly in regions with scarce geophysical information and/or poor outcropping conditions. This may be the case in vast areas where seismic exploration is absent or ambiguous (see e.g. MALZ ET AL., 2015 for combined cross-section balancing and seismic interpretation approach).

Serial balanced cross-sections (honoring surface structural data and including seismic information if available) using various algorithms of back stripping and/or geometrical forward modeling (cf. JUDGE AND ALLMENDINGER, 2011, LOPEZ-MIR, 2019; MALZ ET AL., 2019a; PUEYO ET AL., in prep. for detailed explanations) can be used as preliminary data to perform a subsequent modelling with the potential field data (gravimetry and/or magnetism). The resulting information represents a robust solution of the subsurface where available geometrical, petrophysical and geophysical properties are all integrated and made consistent in a series of 2D vertical slices. The lateral correlation of these vertical slices using geological and geophysical maps can be very useful to reconstruct faults in 3D (IZQUIERDO-LLAVALL et al., 2019; SANTOLARIA et al., 2020).

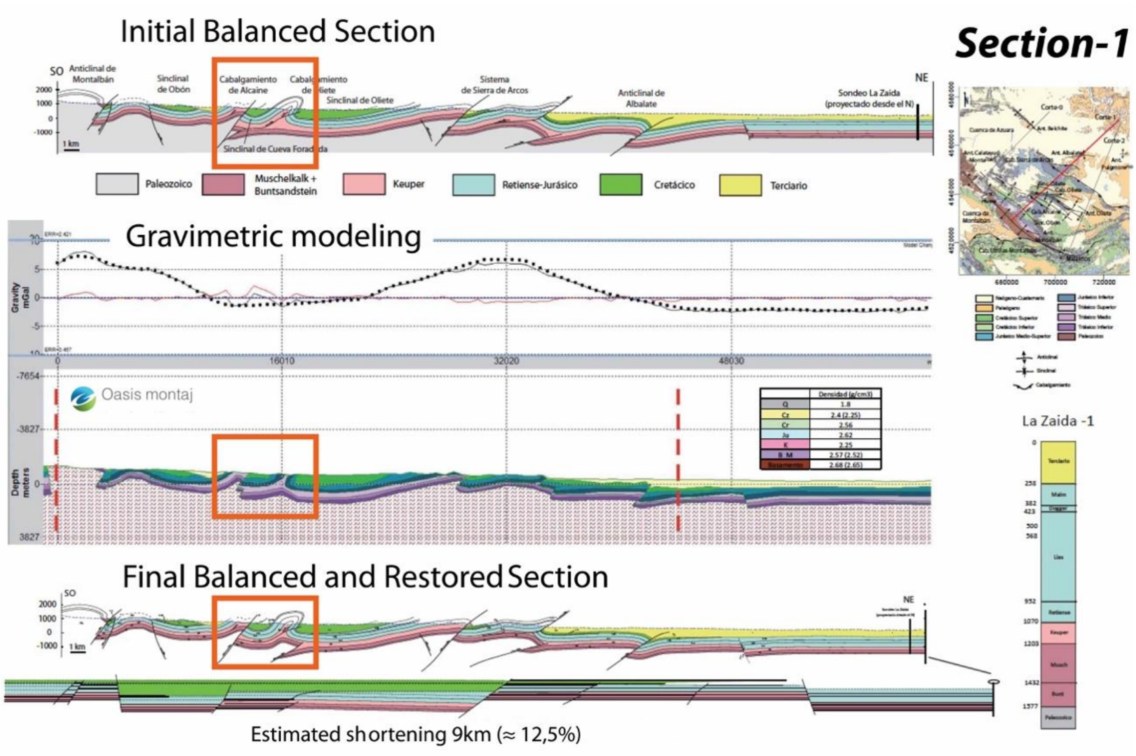


Figure 3 Deduction of basement thrust sheets in the Iberian Range, South of the Pyrenean case-study (IZQUIERDO-LLAVALL ET AL., 2019). Gravity modeling was a keystone to decipher at depth between thin and thick-skin tectonics in this region.

Additionally, joint inversion in 3D of geological (surface maps, balanced sections, stratigraphic thicknesses, etc.) and potential field (gravity, magnetics) data with surficial coverage as well as petrophysical data (surface or borehole data) also allow reconstructing fault systems in 3D (BARBOSA et al., 2007).

2.3 Faults originating from interpretation data

In wide areas across the earth's surface, valuable geological and structural interpretations still exist that must be used in recent collection, analysis and modelling of faults and integration into 3D geological models. These interpretations show a high heterogeneity with regard to their quality and resolution, which depends on the data used and the geological complexity of the area of interest. Without claiming to be exhaustive, in the following section a brief insight into possible existing fault interpretations is provided.

In classical geology based on geological mapping and surface observations, the three-dimensional structure of an area may be effectively illustrated by the combination of a geological map and one or more (serial) cross-sections, which serve to clarify the subsurface structure (e.g., WEIJERMARS, 1997). As most geological maps are accompanied by cross-sections, such data sets are widely available. The construction of geological cross-sections is typically based on surface outcrop observations and additional data like boreholes and, depending on the region, on geophysical data (e.g. seismic reflection). Observed geological structures from the surface (e.g. faults, folds or stratigraphic contacts) were extrapolated to depth by use of geometrical constraints (e.g. dip values, thickness assumptions). In some cases, these constructions were enhanced by additional fault and fold geometrical models (DAHLSTROM, 1969; SUPPE, 1983; SUPPE AND MEDWEDEFF, 1990), kinematic and regional geologic assumptions and construction methods resulting in geologically sound and admissible two-dimensional representations of the earth's subsurface (see WOODWARD ET AL. 1985, ELLIOT 1983; for further explanations); balanced and restored cross-sections. Serial cross sections (based or not on seismic data) have been widely used to image faults in 3D (e.g., DIXON, 1982; BOYER & ELLIOT, 1982). However, the additional uncertainty sources implicit in the construction of balanced sections may be large and must be considered (JUDGE ET AL., 2011).

In addition to classical geological maps, which only show the surface expression of geology, valuable interpretations are included in maps and map series of the subsurface that must be considered for 3D modelling as well. An adequate way of representing the shape of subsurface geological structures is by means of structural and contour maps. Such maps use contour lines for visualization of a distinct parameter (e.g., depth of geological surfaces, thickness of stratigraphic units, seismic travel time, interpolated values of the potential field). Depending on the data source used for map construction, such maps include either a single geological or geophysical parameter (e.g., the Regional Map Series of Seismic Reflection, REINHARD & GRUPPE REGIONALES KARTENWERK, 1968-1991; cf. RAPPSILBER ET AL., 2019 for further information), show a combined interpretation of geophysics and borehole information (e.g., the Geotectonic Atlas of Northwestern Germany and the German North Sea Sector, BALDSCHUHN ET AL. 2001; cf. MÜLLER ET AL., 2016 for further information) or represent large-scale compilations and generalizations of existing map information (e.g. the Petroleum Geological Atlas of the Southern Permian Basin Area, DOORNENBAL & STEVENSON, 2010). Furthermore, across Europe, several hundreds of maps and compilations exist that were constructed for specific prospecting areas reaching from outcrop scale (centimeters to several meters) up to continental crustal-scale observations from potential field data. The GeoERA GeoConnect³d – project (e.g. PIESSENS ET AL. 2020) developed approaches to present all these structural data in a structural framework adapted to the respective scale of geoscientific theme maps. Another approach is given by the GeoERA HIKE project, where multi-scale fault data of various degrees of generalization was collected, attributed and arranged in a semantic network.

3D modelling has become more and more established in geological survey organizations, which led to various kinds and scales of 3D geological models (e.g. GEORG-PROJEKTTEAM, 2013; BOMBIEN ET AL., 2012; GRATACÓS ET AL., 2015; SCHILLING ET AL., 2018). These 3D models aim to provide significant and internally harmonized fault information and are highly appreciated for cross-border model harmonization efforts. Although modern prospection methods (e.g. 3D seismics) allow highly detailed imaging of complex structures with dozens of small-scale faults (e.g. IACOPINI ET AL. 2016 and references therein) along one structural lineament (e.g. crestal faults of salt structures) or of whole regions with sometimes 1000 and more fault segments, 3D structural models are yet not able to fully represent these subtleties of subsurface structures and thus still represent scale-dependent generalisations. However, most 3D models suggest to provide a homogeneous and continuous representation of the subsurface. The representation of heterogeneous data density and quality is most often not emphasized and only little insight into the determinacy of the interpreted fault or tectonic structure (e.g. salt structures) is given. Such information, only if systematically considered during the 3D modelling work, is most often only available from internal documentation reports and not presented in the model itself.

Hence, seemingly consistent and complete 3D models challenge conveying the actual real state of knowledge. Methods and applications for the visualization of such uncertainties are still the matter of debate and ongoing research (see e.g. ZEHNER, 2019, 2021 for a summary of the current state of possible visualisation methods and practical suggestions).

3 3D MODELLING OF FAULTS

A fault modelling workflow is usually described by a series of complex and heterogeneous processes. Depending on the underlying database and supporting information the fault modelling process in general includes poly-dimensional data: one-dimensional points taken from boreholes, two-dimensional polylines taken from maps, cross sections or 2D seismic profiles and even three-dimensional data like point clouds from, e.g., interpreted 3D seismics. Additionally, regional interpretations and often subjective assumptions on fault kinematics and timing can be integrated in the fault modelling process.

For research areas in the 3DGEO-EU project, fault modelling was always based on heterogeneous data sets, but in general the modelling process focuses on the interpolation of polyline and point information attributed with three-dimensional properties. Therefore, interpreted fault sticks (e.g. from 2D or 3D seismics) or polylines at various estimated depth levels (e.g. surface expressions/fault traces from geological maps, depth maps or interpreted gravity maps) were imported into the modelling environment[1].

In some cases, e.g. if formerly printed fault maps of stratigraphic horizons or the surface were used, it becomes necessary to perform spatial referencing of polylines. In these cases, where depth information was available from interpolated depth maps or the surface, fault traces must be projected into their stratigraphic level or into a digital terrain model, respectively, to generate 3D polylines prior to fault modelling.

After georeferencing and preparation of a first order polyline network consisting of fault sticks and fault traces, it is possible to establish a draft fault network with interpolated surfaces. Depending on the software used such interpolations are either represented by triangular meshes or by regular grids. Depending on the heterogeneity of data used, the interpolated fault surfaces require modification; especially if strongly undulating, wavy or highly curved surfaces were produced in overview scales. Although analyses based on recent 3D seismics show that an undulation of the fault plane can be of real origin and may provide significant insights into fault kinematics (e.g., GENT ET AL., 2009), such modelling results must be treated with caution and maybe the careful validation and modification of raw data (e.g., deleting or including additional constraints) becomes necessary. In the case of geometrically plausible surfaces the interpolation results can be connected to a geologically consistent fault network, where single faults are connected or offset by each other. During that modelling step, which requires a considerable amount of modeler's experience and workload, regional geologic knowledge and thus subjectivity, one-dimensional information like fault-borehole intersections and in minor cases earthquake focal solutions can be integrated into the geometrical modelling process.

3.1 3D fault modelling at the Gronau-Waldhügel Fault Zone (WP1)

The harmonisation work in WP1 is based on three existing 3D models: DGM-deep and DGM-NNL on the Dutch side and GTA3D on the German side (see Table 2). After comparing these 3D

[1] Software solutions used in the 3DGEO-EU project and supporting fault modelling are e.g. Schlumberger Petrel E&P Software Platform, Paradigm SKUA-GOCAD, PETEX Move™, JewelSuite, Intrepid 3D Geomodeller, Oasis Montaj and IGMAS+.

models, similar and correlatable geological structures appear present on both sides of the Netherlands-German border. Several parts of the original models could not be harmonized because of one or more of the following reasons:

- the density of the input data was too low
- different reflectors were picked during seismic interpretation
- different geological concepts were used for the formation of structure, such as saltdomes, anti-/synclines, faults etc.

It was agreed to preserve these discrepancies and not to re-model the cross-border regions. Finally, a new harmonised 3D model with gaps was created: NLS3D (Table 2). To create a harmonized 3D model without gaps, it is inevitable to re-interpret the original data, especially with regard to structural features such as faults and salt domes.

Table 2 Existing and the new harmonized 3D model and its treatment of faults

3D Model - acronym	3D Model - full name	Country	Year	Representation of faults
GTA3D	Geotektonischer Atlas 3D	Germany	2012	No fault surfaces or correlation of fault traces were included; the vertical displacement on the stratigraphic horizons show indirectly the existence of faults.
DGM-deep V5.0	Digitaal Geologisch Model: DGM- diep	Netherlands	2019	Fault surfaces have been mapped in seismics and partly modeled in 3D
DGM-NNL	Digitaal Geologisch Model Noord-Nederland	Netherlands	2019	Fault surfaces have been mapped in seismics and modeled in detail in 3D
NLS3D	Netherlands Lower Saxony 3D Model	Netherlands – Germany cross-border	2020	At the Dutch side the faults have been modelled in 3D, at German side the fault traces for different horizon levels have not been correlated

Faults have been treated differently in the existing 3D models (see Table 2). In the Dutch models the faults have been mapped during seismic interpretation and have been modelled in 3D by using Petrel software. The fault traces on the original German GTA horizon maps have not been correlated between the stratigraphic horizons and have been transferred as vertical displacements into the German GTA3D model.

3.2 3D fault modelling of German-Polish cross-border region (WP2)

3.2.1 Introduction

The harmonisation work in WP2 is based on four 3D models: Brandenburg and Mecklenburg-Western Pomerania models on German side and Gorzów Block and Szczecin Trough models on Polish side (Figure 4). The semi-detailed, full 3D, multi-parameter voxel model of Gorzów Block next to Brandenburg (full 3D layer model) was completed, first, under the framework of parallel national projects. These two models were harmonized, permitting construction of WP2's pilot area 1 model submitted in January 2020 as the deliverable D2.3a. Then, Mecklenburg-Western

Pomerania model was completed within a separate national project and, slightly later, corresponding horizons and faults were compiled on the Polish side of the border over the area so-called Szczecin Trough – both represent WP2's pilot area 2. the combination of these models allowed us to build a harmonized cross-border 3D subsurface model comprising nine stratigraphic horizons from base Zechstein to base Quaternary and numerous fault planes. Harmonization of models benefited greatly from concurrent model building, as results were fit to this side of the border where data was more abundant, notwithstanding the possibility to compare and coordinate interpretations.

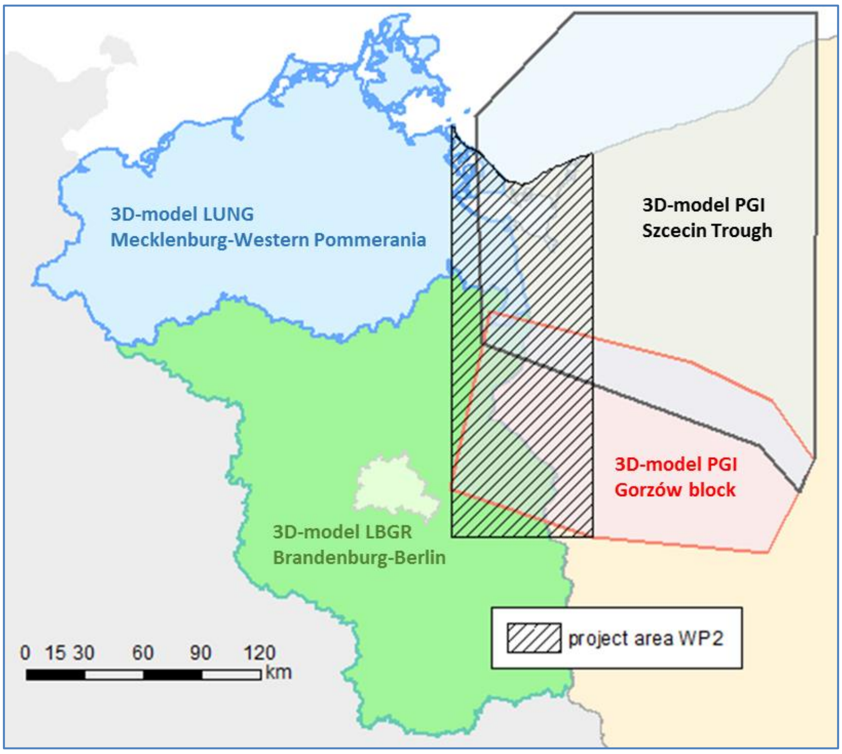


Figure 4: An outline map of the four models used for harmonization.

Fault (and horizon) modelling in all four cases was mainly based on 2D seismic data, except in the Gorzów Block model, where numerous 3D seismic surveys were available. Wherever possible, fault modelling was done by considering the available geological maps. Those were especially helpful in Western Pomerania and in Szczecin Trough area where the fault network is largely controlled by faults belonging to the important fault zones often sub-parallel to (not so distant) East European Craton edge (Figure 5).

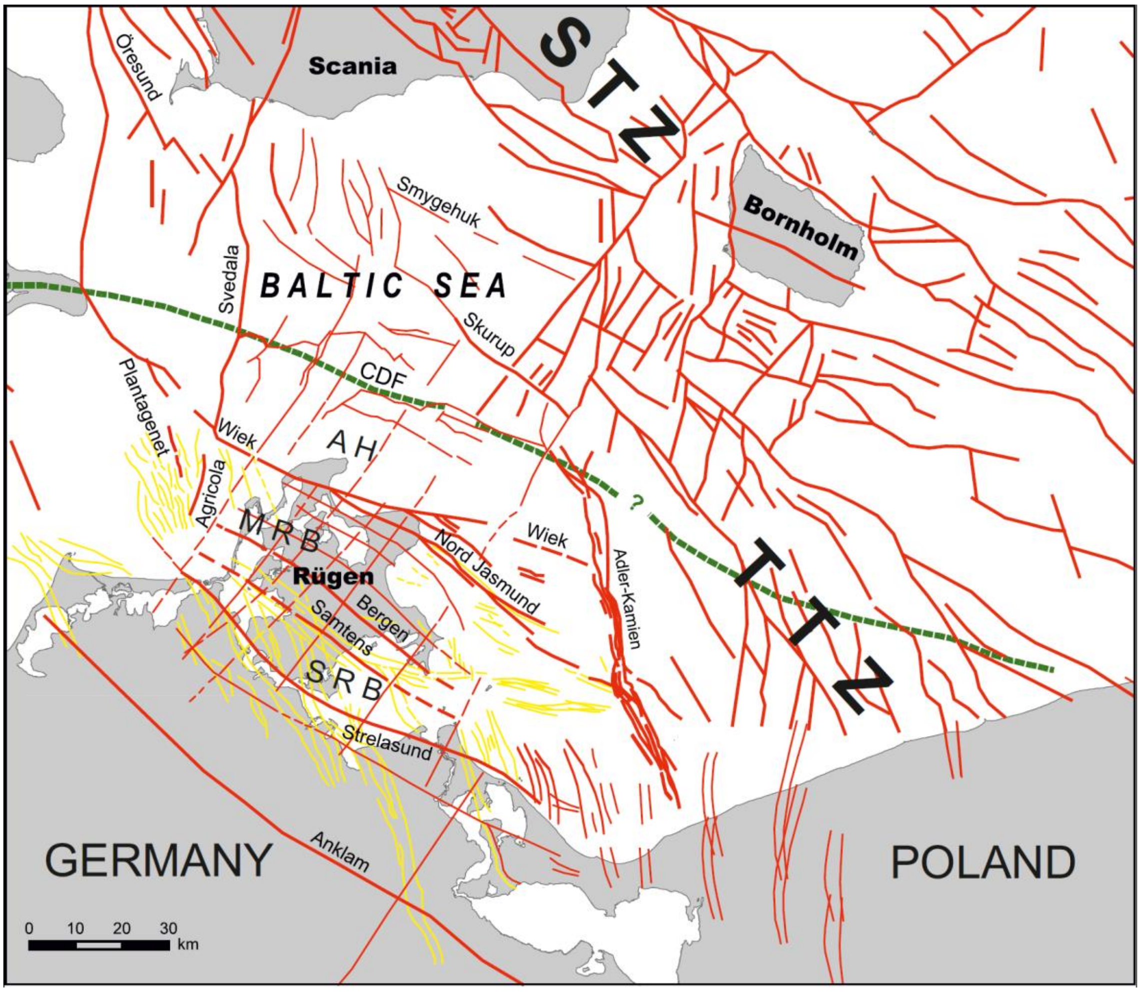


Figure 5: Compilation of major and minor faults of the Tornquist zone and Tornquist Fan (thick and thin red lines) and of the Western Pomeranian Fault System (thin yellow lines) in the southern Baltic Sea and adjacent coastal areas (for data sources, see SEIDEL ET AL., 2018, and references therein). The Caledonian Deformation Front (CDF; green dashed line) outlines the northern rim of an accretionary wedge between the Baltica and Avalonia crustal plates. STZ=Sorgenfrei-Tornquist Zone, TTZ=Tornquist-Teisseyre zone; AH=Arkona High, MRB=Middle Rügen Block, SRB=South Rügen Block.

Series of intracontinental basins developed throughout the study area during Permian to Cenozoic times. Beginning with the evolution of the Southern Permian Basin c. 300 Myrs ago, the area underwent several deformation phases under varying stress regimes, including the contraction and inversion of sub-basins during the Late Cretaceous/Early Cenozoic (see KLEY, 2018 and references therein). A major factor in the structural evolution were thick Late Permian (Zechstein) evaporites; dominantly salt with thicknesses of up to 2,500 metres in the basin center (KIERSNOWSKI ET AL., 2017). Due to enhanced halokinesis, today, the Zechstein sequence within the highest salt diapir in the study area is up to 4,000 meters thick and the diapir roof amplitude reaches 3,300 meters.

These thick Zechstein salts commonly decouple deformation beneath and above the salt layers leading to different shape and pattern of faults in the Mesozoic cover and the Palaeozoic basement. Hence, faults were modelled separately for the base Zechstein and for the Mesozoic to Cenozoic cover. The reason for that is tracing faults across several hundreds of meters (or more) of salt layer would be both impossible and counter-productive given that although fault zones sometimes show spatial correlations, the individual fault planes usually cannot be traced from one structural level to another across the salt-bearing formations or are clearly shifted and may easily display opposite throws and dips.

3.2.2 PGI Gorzów block model and Szczecin Trough model

In Gorzów Block model faults were traced mainly in 3D seismics as fault pillars and fault polygons supplied by Polish Oil and Gas Company together with seismic volumes. These interpretations were reviewed, filtered, generalized and partially supplemented by interpreting 2D seismics. 3D fault planes were built separately for sub-salt and supra-salt layers. For two seismic horizons traceable within Zechstein, faults were interpreted and included in the model as fault lines only, because their vertical continuation could not be established. Traceable sub-salt faults are relatively minor in the western part of the Gorzów Block model that was the subject of 3DGEO-EU harmonization efforts, for which reason they didn't appear in the final, generalized 3D model. Faults affecting the Mesozoic layers are relatively few, mostly confined to Triassic and located in the central and eastern part of the Gorzów Block model beyond the extent of the final 3DGEO-EU model. Therefore, the southern part of the harmonized model does not include faults on the Polish side of the border.

A similar approach for fault modelling was used for the Szczecin Trough model. Unfortunately, this area is less-constrained by 3D seismics, more recent 2D seismic data is missing and previous modelling efforts, forming the basis for the present study, did not produce full 3D models. Available fault and horizon surfaces from these previous studies were evaluated and reinterpreted based on vintage seismic profiles (some from the 1960s) and calibrated with well data to better constrain them within the c. 20 km wide strip on the Polish side of the Polish–German border, where newer data is all but inexistent. Legacy geological maps were also used, especially in the northeastern part of the area where uplifted Cretaceous and Jurassic strata crop out at the base of the Quaternary sequence.

The reinterpretation allowed us to build new fault surfaces for sub-salt and supra-salt layers (Figure 6). Modelling was carried out by use of the Gocad Structural Modelling workflow. Due to decoupling of deformation across the salt-bearing Zechstein sequence, two models were made for Polish side of the border. The first model comprises two horizons, the: base Zechstein and the intra-salt layer (top of Stassfurt Anhydrite), and faults affecting both horizons, although with less displacements in the intra-salt layer due to partial compensation by halokinesis. The second model comprised horizons from top salt/base Triassic up to the base Cenozoic and faults affecting this sequence, oblique to base Zechstain faults and concentrated in the northeastern part of the area. These models were then combined and the fault's vertical extend was fitted to faulted horizon geometries.

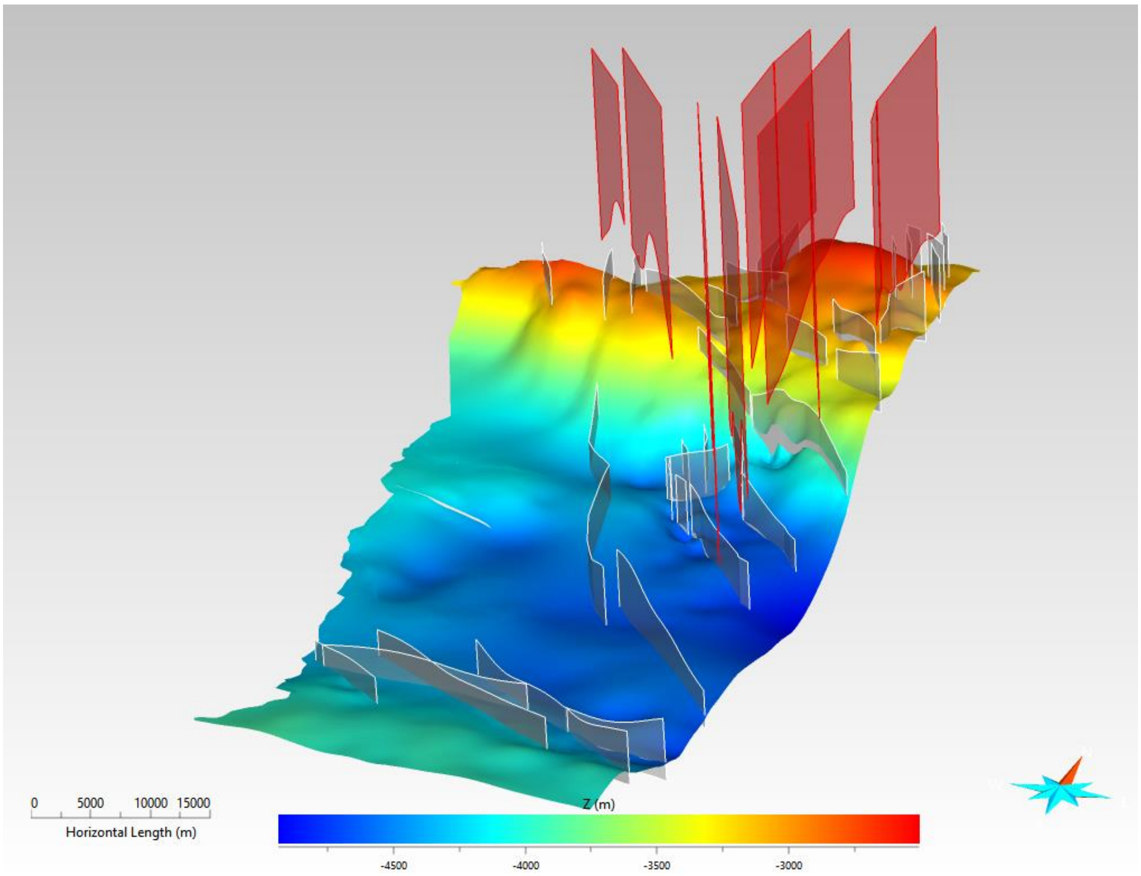


Figure 6: Northern part (Szczecin Trough) sub-salt (base Zechstein) horizon cut by fault planes (transparent grey) with supra-salt faults displayed in transparent red. Note different fault strikes and extends in the two structural levels.

3.2.3 LBGR Brandenburg & LUNG Mecklenburg-Western Pomerania

The Permian, Mesozoic and Lower Cenozoic units, which are the main objectives of the harmonized cross-border model of WP2, are covered by post-kinematic unconsolidated Upper Cenozoic rocks. Nearly no outcrops of Pre-Cenozoic strata exist (with a few local exceptions at the top of diapirs and due to glacial dislocation) in the pilot areas. Therefore, direct observation of faults is usually hampered. All fault information originates from borehole data, seismic investigations, and interpretations encompassing (1) fault markers from wells, (2) fault traces/sticks from 2D seismic reflection (vintage seismics acquired during the 1970s till 1990s available in the depth domain) and (3) fault traces in interpretation data (especially seismic reflector maps; e.g. Regional Map Series of Seismic Reflection, REINHARD & GRUPPE REGIONALES KARTENWERK, 1968-1991).

The available data were digitized, transferred to 3D and assigned to fault objects representing specific fault planes (Figure 7). The fault modeling was carried out in GOCAD/SKUA with the SKUA-workflow “Structure and Stratigraphy”, which needs further parameters to be defined for the generation of a consistent fault network. Thus, in addition to the primary data the following parameters were defined for every fault:

- Fault type/character based on its dip-slip displacement (normal or reverse fault)
- kind of contact to other faults
    - primary/secondary fault in a contact,
    - kind of the contact (branching or crossing)
- youngest horizon not affected by folding (erosion of the fault by unconformities)
- technical modeling parameters to define the shape of a fault plane
    - outline building method,
    - connection distance to other faults,
    - fitting/smoothing factor for the modeled plane

These parameters were optimized in an iterative process combined with horizon modeling that follows in a second step. The resulting fault network is kinematically defined and the displacement of stratigraphic horizons constrained.

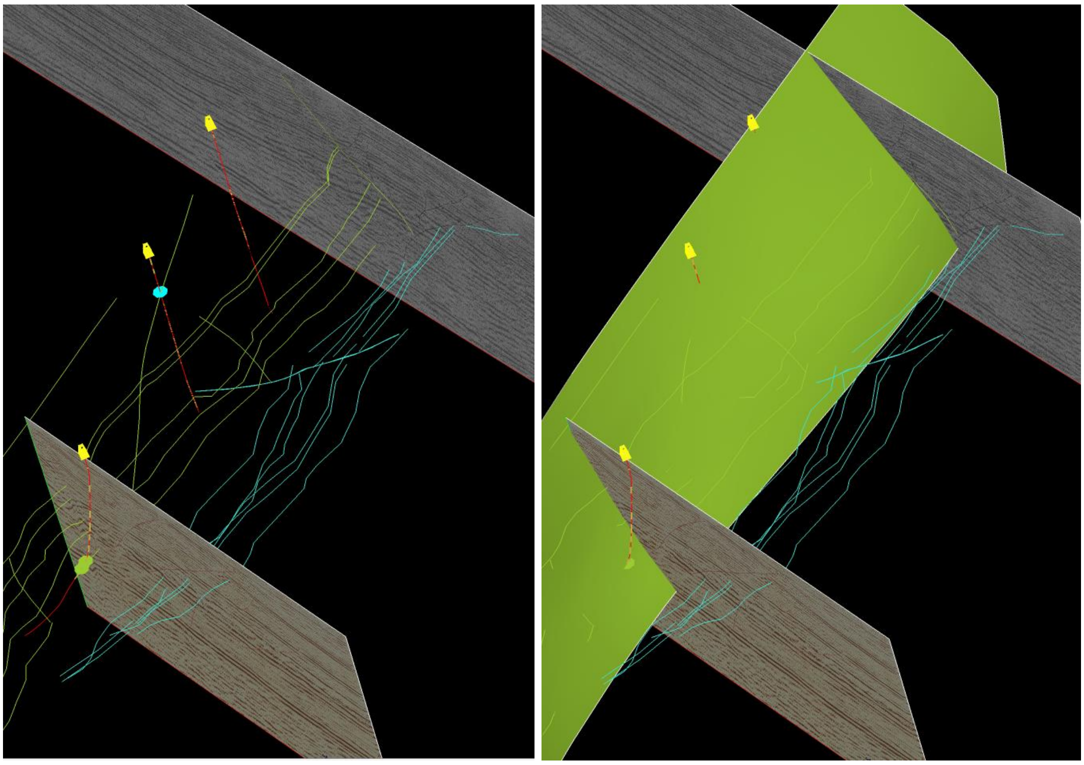


Figure 7: Example for the handling of different fault data (well marker, fault traces from seismic profiles, fault traces from horizon maps) and modelled fault surface.

Modelling of faults that evolved and were active under various stress regimes over geologic times is challenging. Due to the fact that fault activity and parameters significantly change under different stress regimes (e.g. stress directions, amount of strain, deformation rates) single faults or entire fault systems might show a strongly variable behavior (e.g., reverse reactivation of normal faults). During the development of the North German Basin and the Mid-Polish Trough different tectonic phases can be distinguished. After an initial phase of rifting during Carboniferous to Early Permian times the major subsidence phase occurred from Permian to Late Triassic times. Subsequently, during Late Triassic to Cretaceous times, basin differentiation lead to the evolution of several sub-basins. During the Latest Cretaceous to Early Cenozoic, the entire basin system underwent a phase of intraplate contraction resulting in basin inversion. Additionally, these phases are locally superimposed by halokinetic processes (especially during the differentiation and inversion phase). In order to model the different character and activity of faults during the geological evolution and considering the decoupling of the deformation beneath and above the Zechstein salt, two models of faults and horizons were developed: (1) A Lower model that includes faults in the sub-saliniferous strata and horizons at the base and in the Lower Zechstein and (2) a Mesozoic-Cenozoic model that includes faults in the strata above the salt-bearing Zechstein and supra-saliniferous horizons (Zechstein salt top, Triassic, Jurassic, Cretaceous and Cenozoic bases). Faults that cross sub-saliniferous and supra-saliniferous strata are included in both models as objects with similar geometry but different displacement. Finally, the faults and horizons were joined in one model (Figure 8).

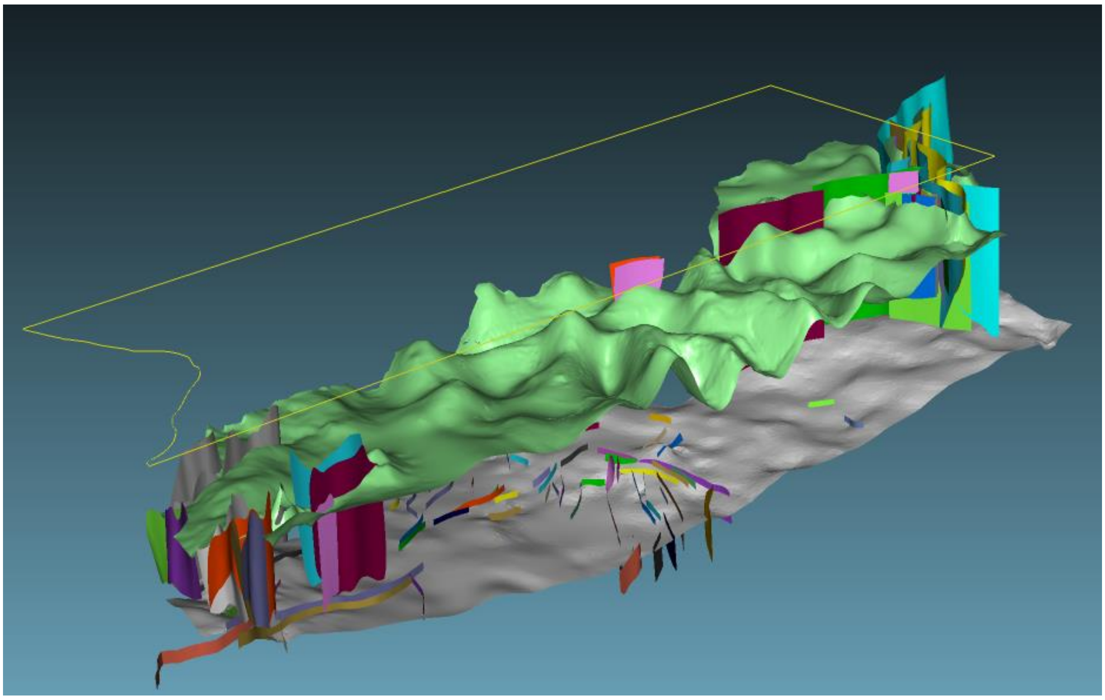


Figure 8: Base Zechstein (grey) and base Jurassic (green) and fault planes in the sub-saliniferous and supra-saliniferous strata in the German part of the Pilot areas of WP2 (harmonized models of Brandenburg and Mecklenburg-Western Pomerania, view from NW, vertical exaggeration 10x).

3.3 3D fault modelling of Danish-German-Dutch cross-border regions within the North Sea (WP3)

The geological surveys GEUS, TNO and BGR have so far followed different approaches for mapping and modelling of faults. The identification of faults that displace the horizons to be mapped is itself comparable between the partners due to a nearly similar data basis and comparable used software solutions. The most important data base for fault mapping within the North Sea is seismic data. Since several years, the availability of 3D seismic data sets gave the possibility to massively increase the level of detail to improve the consistency of fault interpretations in general. However, most national fault and structural maps are still based on the earlier evaluation of 2D seismic data, and the fault interpretations are simply supplementing the seismic horizon mapping. Studies focusing on the regional analysis of fault parameters are rather rare. Depending on the age of the fault mapping and used data, the interpretation results are very diverse and modelling based on them requires regionally different approaches. Typically, 3D modelling is based on the following initial data: (1) Interpretations derived from 2D-seismics (typical formats: e.g. xyz-ASCII, .cps3, .zmap) are typically aligned to vertical cross-sections and represented by polylines or points (fault picks). Based on the fault picks, intersections with horizon surfaces are also defined (fault-horizon contacts) and, based on these, the fault outcrop within a horizon is defined (fault horizon boundaries). Due to the fact that 2D seismics are not necessarily arranged perpendicular to the strike of the fault, interpretation is, in parts, only based on unfavorable profile alignment. In such cases, structures cannot be mapped geometrically correct. Furthermore, between single cross-sections structural trends are mostly linearly interpolated. (2) Interpretations derived from 3D-Seismic (typical formats: e.g. xyz-ASCII, .cps3, .zmap) consist of fault-contacts picked in vertical, horizontal and self-selected orientations (slices in the seismic cube). More recent 3D imaging greatly improved displaying and understanding of the subsurface, which promotes more consistent three-dimensional fault interpretations. The 3D processing of seismic data also enables more precise imaging of the subsurface, especially when complex structures are analyzed. The calculation of additional seismic attributes (e.g. variance) provide further significant support for the detection of faults. (3) Interpretations derived from map compilations (typical formats: e.g. georeferenced images, polyline or point shapes/vector data) are typically subject to strong generalization and cannot unambiguously translate into 3D by means of received interpretative concepts in order to close data gaps. Typically, they are represented by generalized fault traces per horizon as part of horizon maps or more generalized as one fault lineament within structural overview maps. In some cases, even horizon offset maps showing vertical and horizontal fault offsets or maps with additional kinematic (normal or reverse offset) and/or geometric properties (e.g. dip angles) are available.

Especially in regional fault mapping studies, where interpretation results of different seismic surveys must be integrated, first fault analysis is mostly performed in the time domain. Angular relationships between horizons and faults or basic geometric properties, which act as indications for fault kinematics, are, however, skewed in the time domain and must be considered with care. Hence, only by implementing harmonized regional cross-border velocity models fault data and interpretations be consistently transferred to the depth domain which allows consistent kinematic analysis and geometrical modeling in the depth domain (e.g. DOORNENBAL ET AL., 2021). A regional all-encompassing fault modelling in an overview scale has not yet been done for the study region. The currently available interpretation and model basis is briefly described below. Here, as explained earlier, the information often corresponds to the main horizon map compilations of the region (see THÖLE ET AL., 2019 for a comparison).

3.3.1 Published fault interpretations and models in the Danish North Sea offshore

For the Danish North Sea, no fault interpretation directly derived from seismic data (seismic picks) or fault models are published yet. The overview map compilations Southern Permian Basin Atlas (DOORNENBAL & STEVENSON, 2010) and the Millennium Atlas (EVANS ET AL., 2003) are based on several studies, which focused on mapping of distribution, travel time and depths of specific formations (e.g. VEJBÆK & BRITZE, 1994; BRITZE ET AL., 1995 a, b, c, d; JAPSEN ET AL., 2003; VEJBÆK ET

AL., 2007). DOORNENBAL & STEVENSON (2010) includes generalized fault lineaments for some Late Paleozoic to Cenozoic horizons.

3.3.2 Published fault interpretations and models in the German North Sea offshore

The first comprehensive fault analysis within the German North Sea was done in the framework of the Gaspotential Deutsche Nordsee Project (Förderungsvorhaben 03 E 6336 A) in the 1980ties in a scale of 1:100’000. Faults were interpreted on the base of printed (analogue) seismics and the interpreted fault-horizon contacts were projected to the corresponding CDP/SP position on a map. With the exception of a few faults with very large horizontal offsets or those coinciding with diapirs and salt walls, only the vertical offsets were plotted. The results of this work were subsequently published as part of the Geotectonic Atlas of Northwest Germany and the German North Sea Sector (BALDSCHUHN ET AL., 1996, 2001) within a scale of 1:300’000. The Geotectonic Atlas also formed a basis for the supra-regional compilation of the Southern Permian Basin Atlas (DOORNENBAL & STEVENSON, 2010) in a scale of 1:1’000’000.

Within the framework of the GPDN-project (https://www.gpdn.de/; Geopotenzial Deutsche Nordsee; 2009-2013) the previously existing 2D map series were supplemented and expanded by 3D models. Furthermore, seismic mapping of the Entenschnabel was done for the first time (ARFAI ET AL., 2014) and results were subsequently transferred into a detailed structural model. For this 155 km x 30 km area in the northwestern most part of the German North Sea sector, 14 reflection seismic horizons, c. 800 faults and more than 20 salt diapirs were interpreted in a high level of detail (Figure 9 a). Due to the high structural complexity and associated challenges in the modelling process, a generalization (c. 300 faults and simplified salt structures) of the structural pattern became necessary (Figure 9 b).

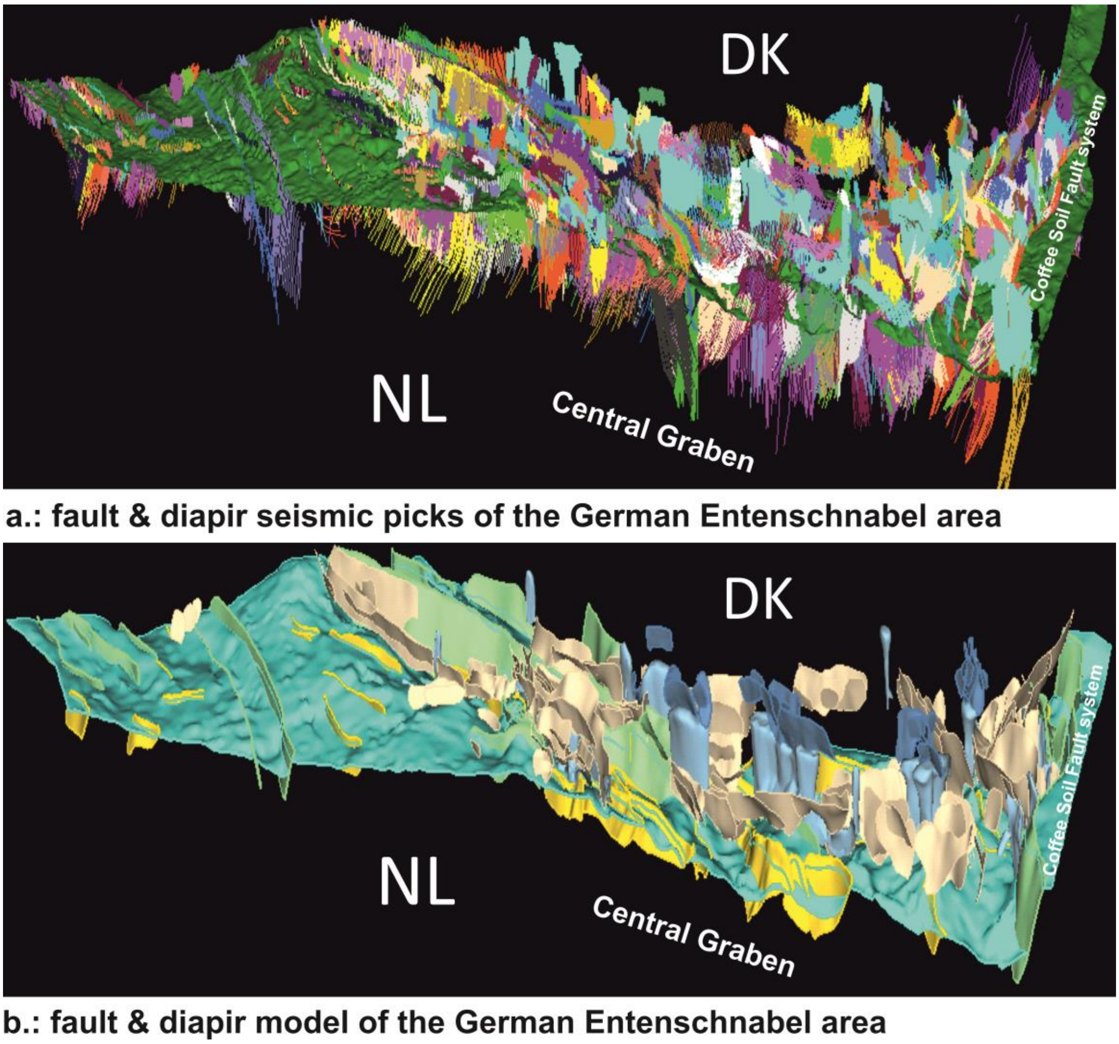


Figure 9 Seismic Interpretation data (a) & (b) derived 3D structural model of the German Entenschnabel area (ARFAI ET AL., 2014). The model shows a strongly deformed part of the Central Graben and surrounding areas. Halotectonics, a multiphase rift evolution as well as inversion tectonics resulted in a complex structural pattern of intersecting and interleaving structures. The model was developed with GOCAD/Skua. (Legend for Figure 9 b: Green faults = faults connecting basement and Mesozoic cover; yellow faults = basement faults; dark blue = faults in the top or related to diapirs and diapiric growth; beige faults = faults only traceable within the Mesozoic to Cenozoic overburden; light blue = diapirs)

Another structural model (KAUFMANN ET AL., 2014) was created in the GPDN-project for the central German North Sea based on the horizon maps of the Geotectonic Atlas (BALDSCHUHN ET AL., 2001). Since this model is the basis for further volume modelling and therefore a low level of structural complexity was necessary for implementation, the more than 1'000 interpreted faults in this area according to BALDSCHUHN ET AL. (2001) were generalized to c. 30 major sub-Zechstein faults and c. 80 faults in the Mesozoic to Cenozoic overburden (Figure 10).

These models are in turn an essential basis for an overall model of the German North Sea, which was compiled in the course of the TUNB project from 2014 to 2021 (model available via https://gst.bgr.de/). Even though a consistent 3D model of the region is present after the end of the TUNB project for the first time, this model is only a generalized representation of the subsurface and in some cases shows major differences and discrepancies to more recent seismic data and interpretations.

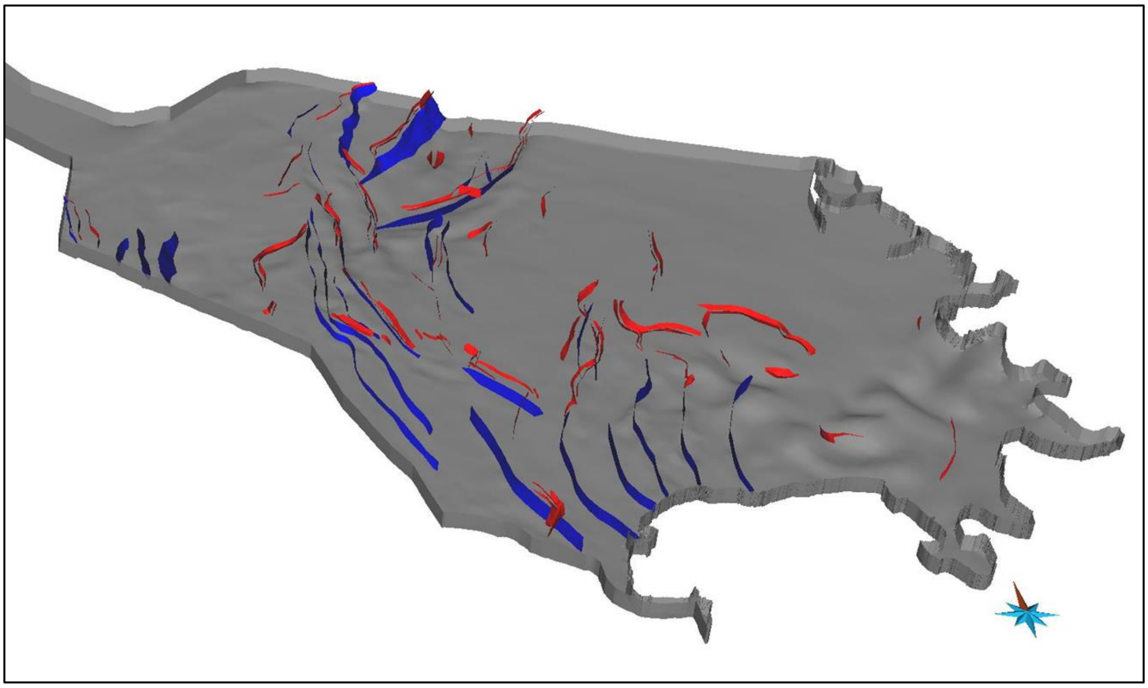


Figure 10 Generalized structural model of the central German North Sea sector (view from South). In blue generalized main fault zones of the Base Zechstein and the Sub-Zechstein. In red the most prominent fault zones of the Mesozoic to Cenozoic overburden. The model was developed with GOCAD/Skua

The integration of these findings, as well as the aim to increase the level of detail of the German North Sea regional model, are future goals of BGR's 3D modelling strategy. Furthermore, the progress made in cross-border harmonization between Danish, German and Dutch offshore (3DGEO-EU WP3 North Sea) will be transferred to future models.

3.3.3 Published fault interpretations and models in the Dutch North Sea offshore

Various studies also including fault interpretations for the Dutch North Sea sector were carried out during the past years (BOURELLEC ET AL., 2016a & b, 2017, 2018, 2019a & b; DE BRUIN ET AL., 2015; DOORNENBAL et al., 2019; HOUBEN ET AL., 2020; TEN VEEN ET AL., 2019; VERREUSSEL ET AL., 2018; VAN WINDEN ET AL., 2018). However, their main focus was to enhance the understanding of tectonostratigraphy, salt tectonics and palaeofacies of important oil & gas source rocks. For some seismic 3D-surveys detailed interpretation data is published on the Nederlandse Olie- en Gasportaal (www.nlog.nl).

In the framework of web-publishing of 3D-subsurface models 3D-fault modeling became an important part of the workflow. The resulting regional to sub-regional subsurface model

(DGMdeep; accessible via https://www.dinoloket.nl/) was continuously enhanced and updated since the beginning 21th century (Table 3). In the early versions (V2.0 and V3.0) fault modeling was a significant aspect and part of the workflow. In V3.0 subregions were modeled with 3D fault planes. Some of these subregions were modelled in the time domain using Petrel software while other subregions were modelled in the depth domain using JewelSuite. In V4.0, which, first, uses an automated, scripted workflow, it is possible to include fault-horizon intersection lines, as fault-centerlines or fault gaps in the grid calculation. However, with the total amount of fault data (fault lines and fault gap outlines of variable time, depth and quality) the workflow was no longer feasible due to significantly increased processing time, which made a pragmatic choice necessary. Since this decision was made, highly variable data is omitted and fault interpretations in first order are based on seismic interpretation, which to most extent come from 3D seismics covering large areas of the Dutch area. Nevertheless, TNO has huge experience in 3D-fault modelling of the entire onshore and offshore area of the Netherlands, which is performed since DGM-deep V2.0 released in 2006. The current results of that ongoing fault modeling are input data for the Dutch contribution to the HIKE project.

Table 3 Published DGMdeep model versions and their specifics. The latest model version V5.0 is not yet available from the DINOloket platform.

DGM-deep Version	Release digital data	Year of publica-tion	Area	Project	Projecti on	Velocity model	Fault lines	3D fault planes	Dino *loket*
v1.0	2002	2004	Onshore	GEO-atlas	RD-Bessel 1841	Various	Yes	No	
v2.0	2006	2006	Offshore	NCP-1	ED50-UTM31	VELMOD -1	Yes	Yes	
v3.0	2010	2012	Offshore	NCP-2	ED50-UTM31	VELMOD -2	Yes (Subregi ons A-G)	Yes	
v4.0	2014		Onshore		RD-Bessel 1841	VELMOD -3.0	No	No	Yes
v5.0	2019		On-/Offshor e		ED50-UTM31	VELMOD -3.1		No	
			Onshore		RD-Bessel 1841				

3.4 3D fault modelling in the Pyrenees (WP6)

The Pyrenean case-study is located in the southwestern region of the so-called Isthmius Zone, in the border region between Aragon and Navarre a few kilometers south of the French national border. This zone belongs to the Alpine orogenic belt, which evolved due to the convergence between the African and Euroasiatic plates during Late Cretaceous to Miocene times. The present-day geometry is built by the interaction of cover (Meso-Cenozoic; mostly Cretaceous) structures and basement (Paleozoic) thrust sheets, which are separated by a detachment in Late Triassic (Keuper) strata or, if absent, in Late Cretaceous shale. The “basement” in any case is a variable Paleozoic (meta-)sedimentary pile including some granites. In the western region this basement is low-grade metamorphosed. They draw a complex fold-and-thrust system involving multiple and laterally changing detachments mostly associated with Triassic evaporites, Cretaceous shale and marlstone as well as Eocene turbidites.

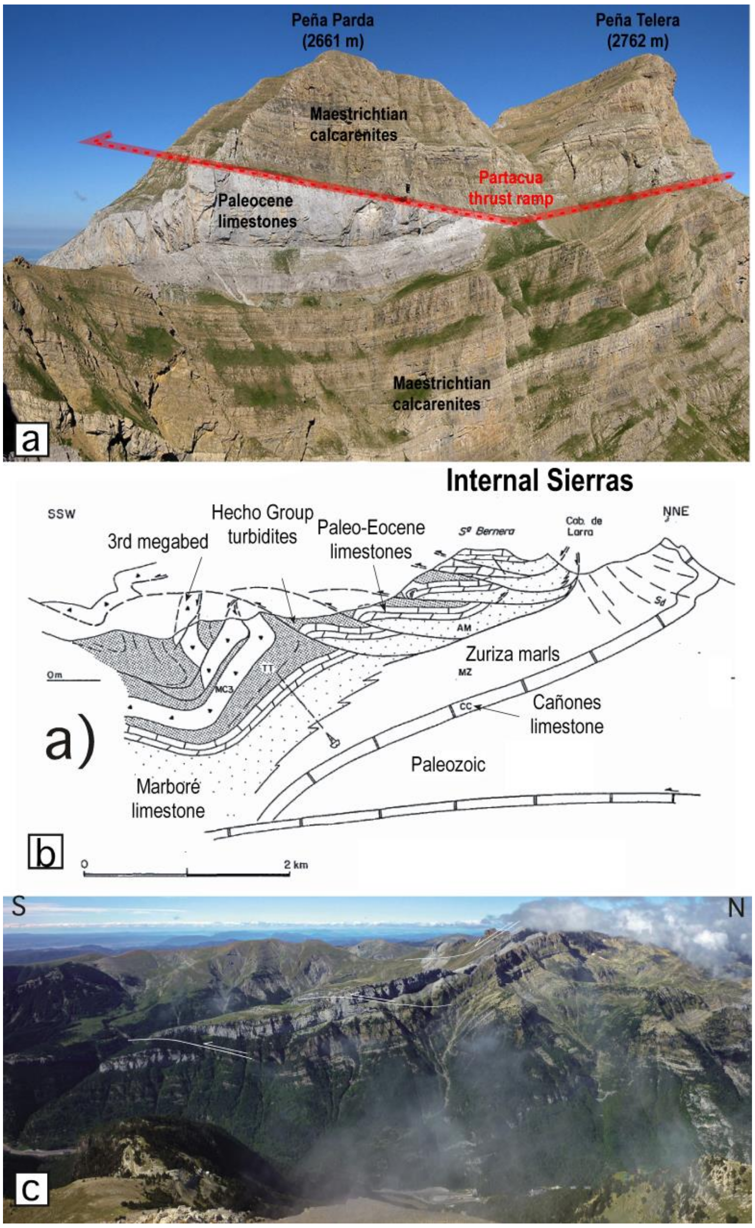


Figure 11: Examples of mapped faults in the Western Pyrenees. Upper: accurate tracing a of a thrust plane (hanging wall flat on footwall ramp) from the Internal Sierras in Partacua Range (eastern portion of the study area). Middle and lower: panoramic view in the GeoERA study case were several thrust sheets can be drawn

Outstanding outcropping conditions (Figure 11) had historically allowed for a reliable mapping of surface faults (MAGNA Geological Map Plan 1:50.000 scale) (Figure 12 A). The most important cover faults (and many other structural features) affecting the Mesozoic-Cenozoic cover system can be accurately tracked over tens of kilometers along-strike.

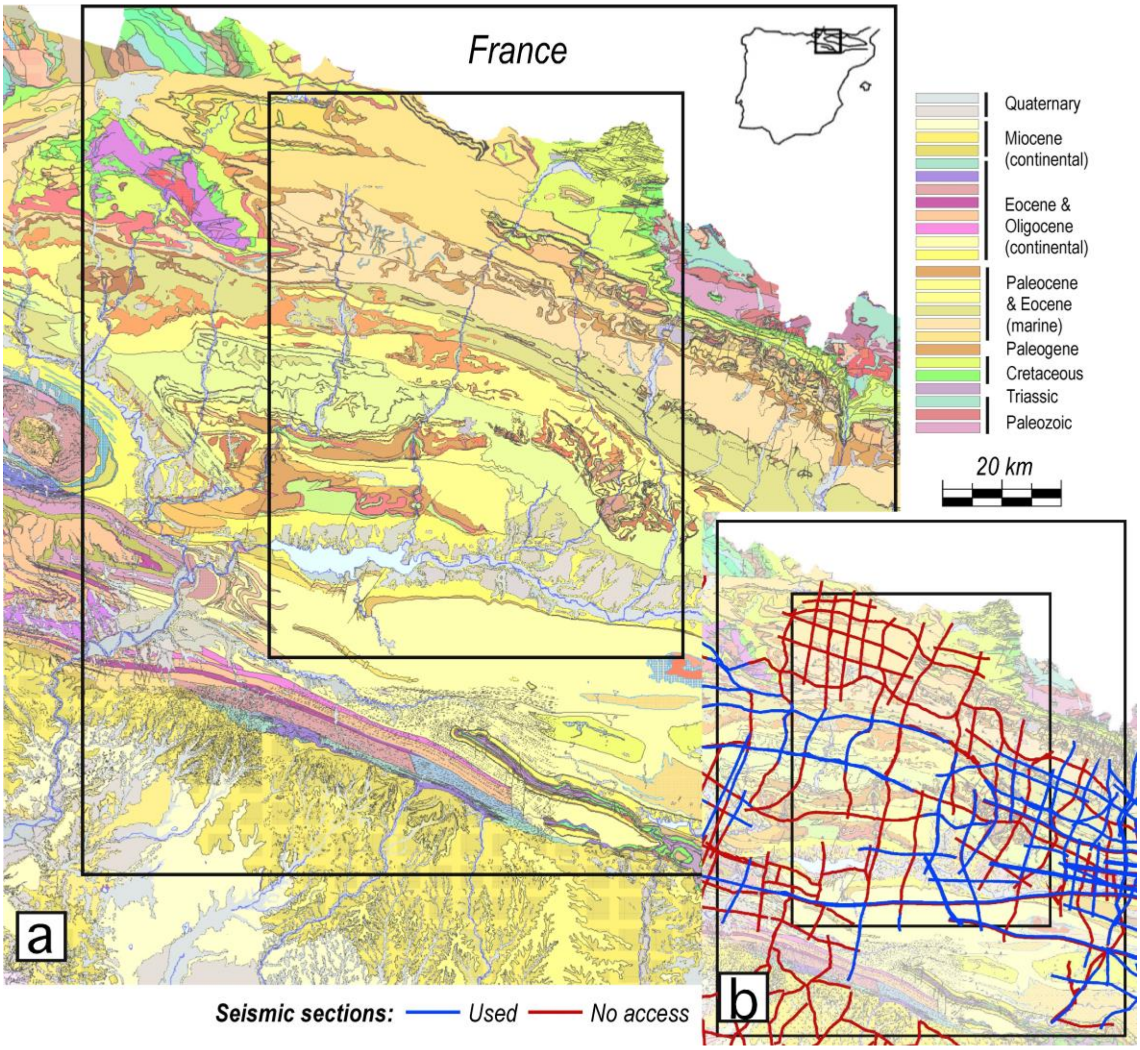


Figure 12 A) Geological map of the Pyrenean case study. GEODE digital map (1:200.000 scale, derived from MAGNA maps; ROBADOR ET AL., 2009). Main thrusts affecting the Meso-Cenozoic cover units are shown (black lines with triangles). B) Seismic coverage in the Pyrenean case study. Red sections are not available due to data access restrictions managed by private (formerly public) companies. Blue sections are mostly vintage seismic information (scanned images in TIFF format) in the time domain. They reach maximum depths of 4 to 5 s.

In this kind of settings, sets of serial balanced and restored cross-sections can be relatively rapidly built from surface elements and thus, most important faults can be interpreted down to a certain depth using geometrical assumptions (e.g. depth-to-detachment estimations) or the available seismic data. Additionally, well data locally pinpoint the position of faults at depth along or beside seismic profiles and cross-sections.

Some problems arise if the relationship of basement and cover systems and the overall geometry down to 5-6 km will be reconstructed: (1) A large number of available seismic sections with a relatively good coverage is owned private energy companies (formerly public) that sometimes not grant access to the data. (2) Data are vintage seismics (acquired during the 1960s to 1970s), which are very often only available as high-resolution TIFF files and thus, preclude reprocessing and enhancement techniques. (3) Seismic images may show a very low signal-noise ratio, especially at depths below 2.5 - 3 s.

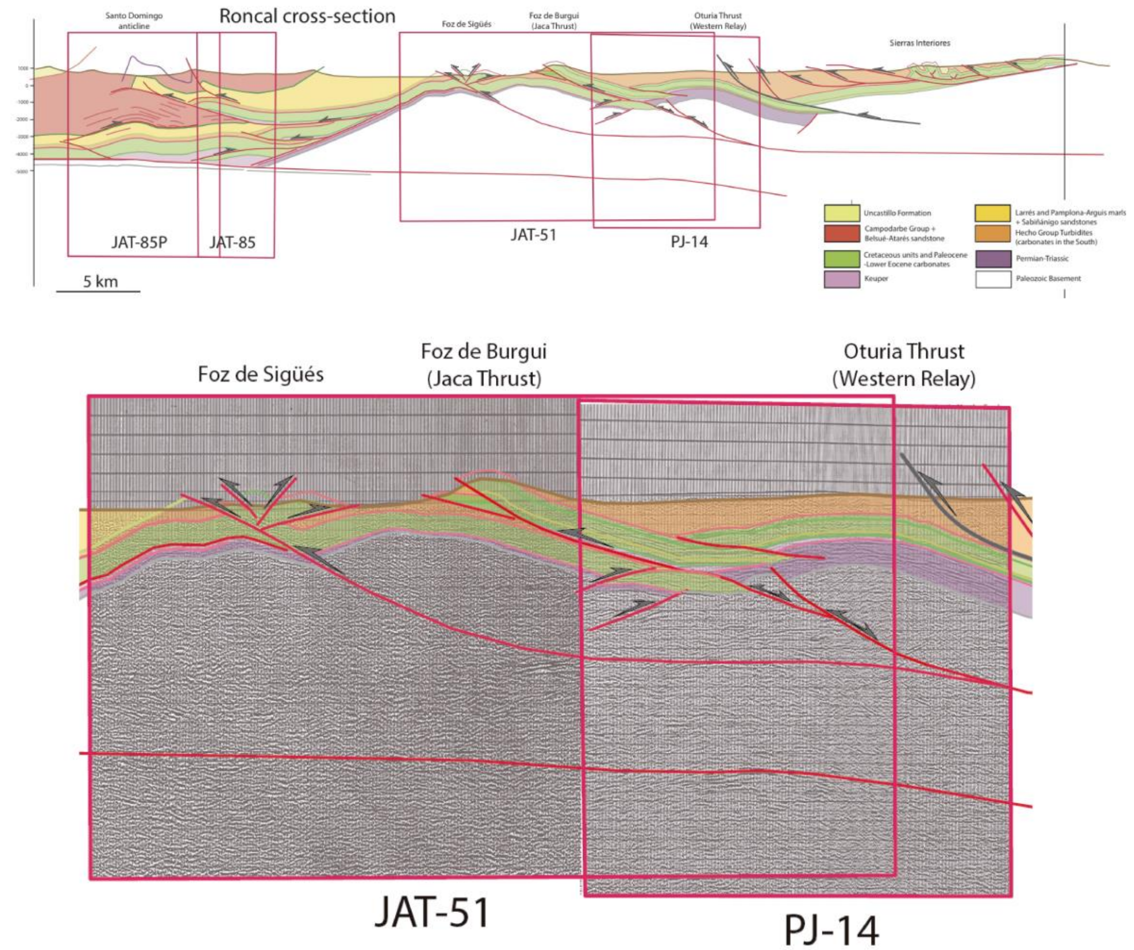


Figure 13 Roncal balanced cross-section (Western sector of the study area) without (upper) and with seismic information (lower part). These seismic sections (JAT51 and PJ14) illustrate the quality of the available information.

In WP6 we have built a 3D model of some target horizons and major faults using the available seismic and well information together with the digital geological map (GEODE). We had only access to less than 50 % of the existent seismic sections (6.3% in SEGY format and 43.2% in TIFF format). Therefore, our 3D model is discrete, incomplete and uneven. Besides, it relies on a depth conversion of time domain interpretations (main horizons and faults) that is based on a limited amount of sonic log data (4 sonic logs from wells in the western part of the study area were considered). For these reasons, we proposed to use gravimetric data to further constrain and harmonize the 3D model. Following the workflow for 3D reconstruction using balanced sections, petrophysical and gravimetric data (Deliverable D6.5 of this project), we built three balanced cross-sections (Figure 13) and compiled and improved the petrophysical (more than

300 sites Figure 14 a) and gravimetric (Figure 14 b) data (>2500 new plus 3350 stations from previous projects and databases).

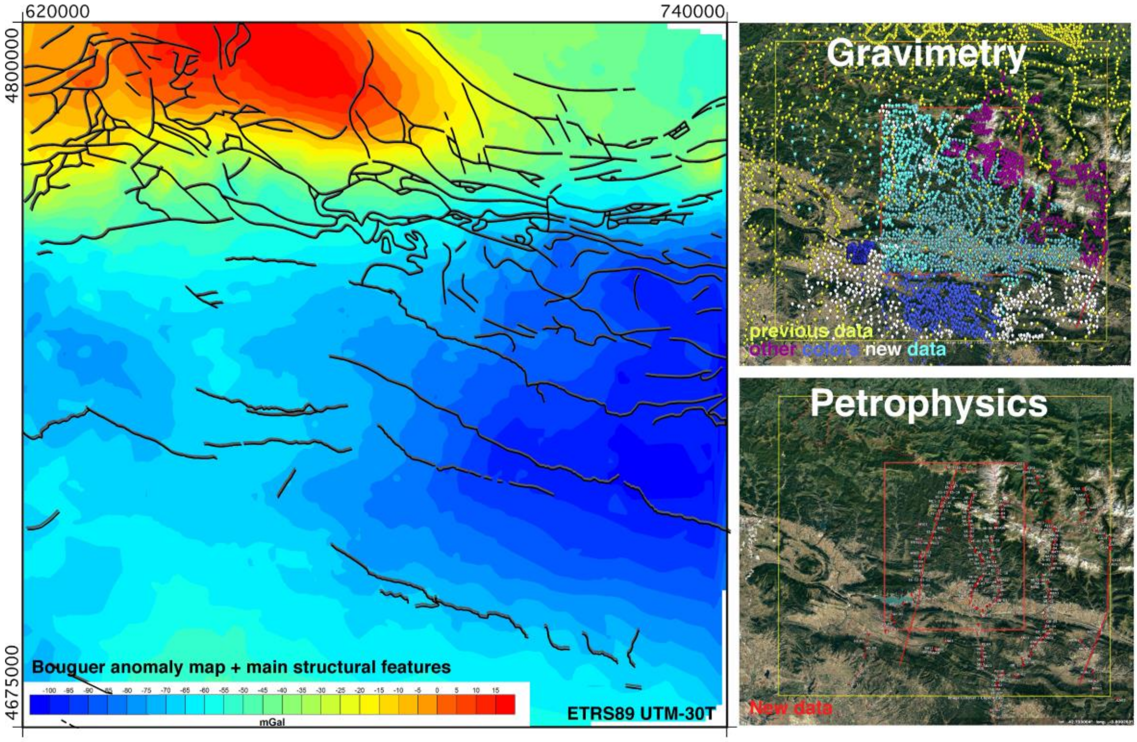


Figure 14 A) Location of the petrophysical data used in the modeling (left). B) Gravimetric stations. Yellow points, from previous databases (IGN+SITOPO), Blue points: Previous recent projects (IGME and mining campaigns). Red points: Newly acquired in the project. Purple points: New data acquired in rough and highly mountainous terrains. The new Bouguer anomaly map is shown in the background.

Our modeling workflow was firstly based on the simultaneous balancing of geometric (structural sections based on seismic profiles and surface elements), petrophysical and gravimetric data altogether in three serial cross-sections (2D). Then, these robust 2D reconstructions were implemented in 3D together with fault traces, stratigraphic thicknesses, dip domains (based on several hundreds of dip values measured in the field) and the entire gravimetric database (a Bouguer residual anomaly grid built from > 2500 stations). A joint 3D inversion (Oasis GMSYS3D) considering all these elements, allow for an integrated 3D model of target horizons and faults to be achieved.

Fault meshes were constructed from the lateral correlation of (1) fault polylines in seismic profiles and cross-sections and from (2) three-dimensional fault traces at the surface, obtained from the projection of faults in map view onto the digital elevation model. This required the depth conversion of the fault polylines interpreted in the time domain in 2D seismic profiles. All polylines were first converted to data points and then interpolated by ordinary kriging using the software Move® (Petroleum Experts).

3.5 3D fault modelling of the Saxony-Anhalt/Brandenburg cross-border region (WP6)

In the Saxony-Anhalt - Brandenburg cross-border region, 3D modelling was performed using the software Paradigm SKUA-GOCAD. Initially, individual fault- and 3D structural models were constructed for the Saxony-Anhalt and Brandenburg parts of the model.

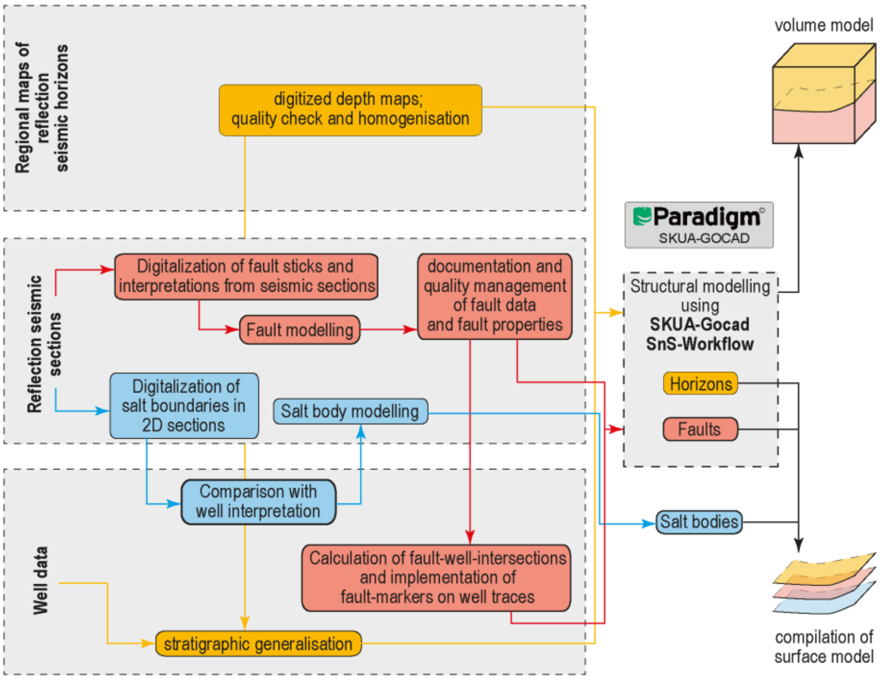


Figure 15 Flowchart of the modelling workflow performed to generate the structure models in the Saxony-Anhalt cross-border region (MALZ ET AL., 2020)

In a first step, the complete data set consisting of interpreted and digitized 2D reflection seismic interpretations, depth contour maps and boreholes was imported into the modelling environment (Figure 15). Fault traces from depth contour maps (2D polygons), which were previously projected to their stratigraphic level were combined with digitized fault sticks from reflection seismic sections. The resulting polyline network formed the origin of manually modeled fault surfaces, which were cut by the highest and deepest stratigraphic affected horizons. If geologically sound, fault surfaces were connected to each other to form fault zones. By calculating intersections between well paths and fault surfaces we determined boreholes that penetrate a faulted stratigraphic sequence. After an extensive quality check with regard to their original documents and repeated modelling and validation cycles a completely revised 3D fault network existed. The main 3D modelling process was performed by use of the 'Structure and Stratigraphy (SnS) workflow' of SKUA-GOCAD. Used parameters were an approximate cell size of 400 to 500 meters, a unified modelling stratigraphy in both modelling areas and an overlap of 10 km. Within this buffer area information from adjacent model parts and data were integrated. In a first iteration we used the complete data set, which was checked during each modelling cycle and step. Inconsistent data was successively deleted, corrected or completed with additional information. Emphasis was placed on hard data (borehole data and seismic sections) while depth maps were regarded to be more uncertain. During every modelling cycle individual horizons and complete stratigraphic sequences were checked in map view, section view and in 3D.

4 FAULT HARMONIZATION METHODS

4.1 Fault harmonization at the Gronau–Waldhügel Fault Zone (WP1)

An attempt has been made to harmonize the Gronau-Waldhügel fault zone that was chosen because of its complexity. If harmonization appears successful, a working proof of concept could converge toward a working method for the entire Netherlands-Germany cross-border area. Due to the absence of 3D fault surfaces in GTA3D it is only possible to harmonize the main faults or fault systems, i.e. faults that have a sufficient horizontal length or a big vertical offset. Since no fault model is present in the German GTA3D model, unfortunately the basis for a harmonized fault model is scarcely constrained. For the faults on the German side of the cross-border area, reconstructed fault planes deduced from fault-gaps would have to be made that could serve as a fault model surrogate. Not only would this be a laborious activity, it would also result in a subpar fault model and an unsatisfactory harmonized, cross-border fault model.

It is not possible to harmonize the faults from the existing 3D models, due to the fact that the Dutch 3D models include interpreted and modeled fault planes in 3D and the fault planes at the GTA3D model will have to be reconstructed and deduced from fault-gaps at horizon levels.

4.2 Fault harmonization in the German-Polish cross-border region (WP2)

Initially, while producing the original models, every partner used his or her own database, workflows and modelling software. Thus, in the first step, separate models were developed by all partners (see chapter 3.2). The most important problem during the modelling workflow was that primary data (well data, seismics) could not be exchanged between the partners due to legal restrictions (with some exceptions). Only a principle comparison of data bases was possible (e.g., velocity models and reflector interpretation at the German and Polish sides). So, only interpretations (modelled horizons and faults) were exchanged and were thus usable to constrain models. This approach was used to construct the first version of pilot area 1 model and, once modelling was finished, in pilot area 2 version one model. The pre-adjusted modelled data from all three partners was finally imported into SKUA/GOCAD to develop a joined harmonized model using the SKUA/GOCAD "Structure and Stratigraphy" workflow. Under the assumption of a similar tectonic evolution on both sides of the border, similar principles and parameters were used to model the faults. In all primary models faults that cross Permian and Post-Permian strata were modeled separately due to the decoupling of deformation across the salt-bearing Zechstein sequence. Only in the final step, the faults and horizons were joined in one model (Figure 16). Therefore, the harmonization of faults was constrained by aspects, which will be described in the following chapters.

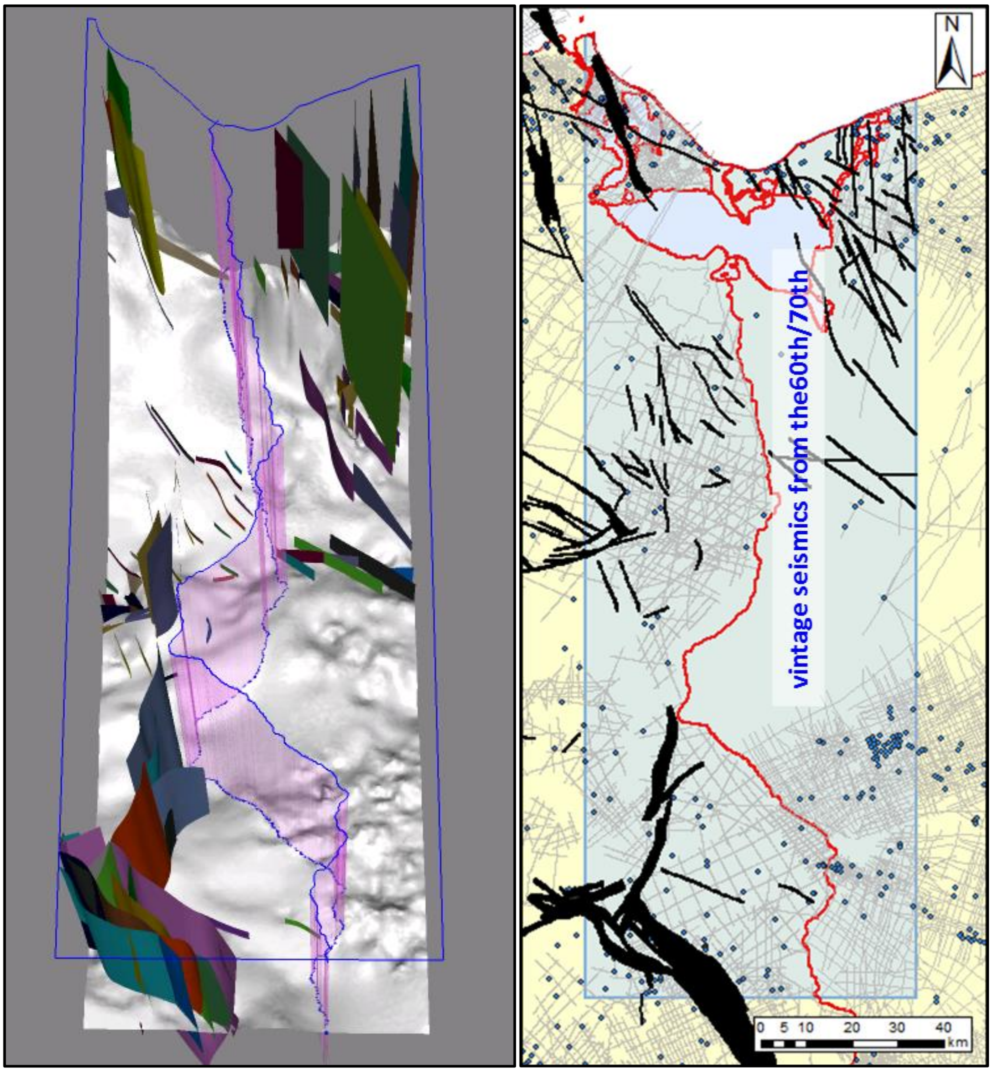


Figure 16: Harmonized fault model showing sub-salt faults and supra-salt faults in the Polish-German border region. Left: perspective view from south with fault planes and the base of Zechstein horizon (German-Polish border is marked as a transparent purple wall). Right: 2D vertical view with fault traces (black), 2D-seismic lines (grey) and deep wells (blue dots)

4.2.1 Faults/fault zones (sub-)parallel to the border

The major fault directions are NW-SE to NNW-SSE in the north of the cross-border model, following the regional trend of the Caledonian front and the southwestern rim of the East European Craton (cf. regional overview in Figure 5), and NNE-SSW and NW-SE in the south of the model. In the studied area the German-Polish border follows the river Oder/Odra, which follows similar directions (NW-SE, NE-SW) and seems to be crossed by no or only a few individual faults. The Oder/Odra river valley is supposed to follow some deep tectonic structures, the inferred Oder/Odra fault-zone, respectively. Here, most faults are arranged parallel to these major deep faults with strike directions roughly coinciding with the Oder/Odra river and, consequently, fault lineaments are often (sub-)parallel to the border without crossing it. This becomes obvious in the northern part (islands of Usedom and Wolin, Szczecin lagoon) or in the southern part of the model where the Buckow Fault Zone striking NE-SW in the sub-salt and supra-salt ends right before the German-Polish border. An extension of this fault zone to the northeast (parallel to the border) is supposed in deeper crustal levels but could not observed in the sparse, available data (Figure 16, left).

4.2.2 Lack of exploration activity in the cross-border area

Modeling of faults in the cross-border area was hampered by lack of data stemming from restricted access. Seismic information, which is the major source for subsurface interpretation, is significantly reduced. Seismic profiles and surveys crossing the border are completely absent and sections usually end at a distance of at least 100 meters from the border at both sides. Furthermore, seismic coverage and information is reduced at the end of profiles in a range of some 100 meters to kilometers depending form the technical configuration. Consequently, a 1 to 2 kilometers wide corridor at both sides of the border has no or limited seismic information. Other aspects that affect and hamper the detection, interpretation and modelling of faults in the study area originate from the following: (1) a lot of seismic profiles run (sub-)parallel to fault's strike directions or cross them under small angles resulting in limited seismic imaging of faults, (2) only vintage seismics cover large areas (analogue seismics form the 1960s and 1970s) due to reduced exploration interests since the 1980s (especially southwest of the Szczecin Trough, cf. Figure 16, right) and vintage seismics is particularly not appropriate for the detection of sub-salt faults due to low source energies and a wide spectrum of seismic frequencies.

For the modelling of horizons, the information gap along the border is usually not so important because the horizons follow regional scale trends, but the modelling of discontinuities like faults or also diapirs needs a more detailed data resolution. An example is the fault system in the middle of the project area developed in the sub-salt sequence, striking NW-SE at both sides of the border. Some individual faults of this systems end close to the border according to the current database. However, they could probably be prolonged and connected to traces at the opposite side of the border if appropriate information would be available.

4.2.3 Large scale faults in the deeper Pre-Permian strata

The most important fault zones crossing the border occur in the Pre-Permian succession (e.g., the Variscan front or fault zones sub-parallel to the southwestern rim of the East European Craton). Nevertheless, these deep faults are not analyzed in the scope of the presented modelling project based on well data and seismics. Locating and harmonizing these deep faults would require further investigation possibly including some cross-border seismic experiments focused on deeper strata.

To try to overcome problems with cross-border fault harmonization, the next step is to use potential field methods. The necessary gravimetric data is available on both sides of the border. Hence, it is possible to create a joint, cross-border Bouguer anomaly map and density maps for modelled layers and, afterwards, gravimetric modelling can be proceeded. Further constraints for fault locations and geometries can probably be derived from this gravimetric modeling, which incorporates existing information for the geometry of faults and horizons in the cover and in the basement. During these gravimetric modelling efforts, it will become possible to modify existing geometries between data points, to fit them into a gravimetrically consistent model and thus to fine-tune the structural model where hard data (i.e. seismic and borehole data) is not available. This work is still ongoing and results will be presented in deliverable D6.3, which will be finalized in October 2021 (project 3DGEO-EU, work package WP6 “Optimizing reconstructions of the subsurface to reduce structural uncertainty in 3D models”).

4.3 Fault harmonization of Danish-German-Dutch cross-border regions within the North Sea (WP3)

The Southern and Central North Sea is a highly structural differentiated area with a multiphase and multidirectional extensional history. Additionally, the Mesozoic and Cenozoic overburden is extensively influenced by halotectonics, which has largely affected subsidence patterns and facies distribution since the Triassic. Furthermore, Late Cretaceous NNE-SSW directed contraction overprinted or inverted earlier (Mesozoic) rift-structures and diapirs leading to a complex and heterogeneously distributed structural pattern of crossing and interlocking structural directions (Figure 17), in particular along the Central Graben main fault (Coffee Soil Fault/Nordschillgrund Fault). The majority of cross-border structures are either rift-related normal/oblique-faults, in parts transpressionally overprinted or dip-slip inverted, or fault zones related to diapirism (e.g. crestal faults). Often both, extensional tectonics and halotectonics, are equally important for the development, kinematics and geometry of the structures.

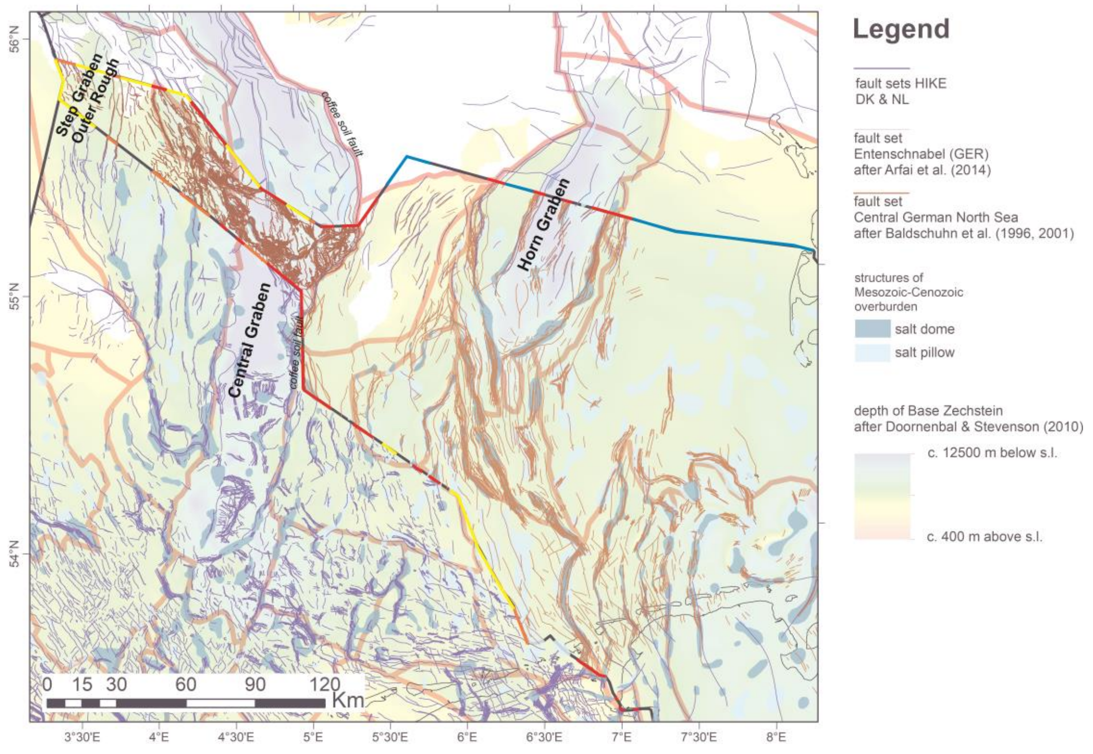


Figure 17: Fault lineaments of DK, GER & NL of the North Sea for the HIKE-project. The fault interpretations have a different degree of detail and generalization. For the German Entenschnabel a high detailed fault analysis with offset outlines for 13 horizons is available (Figure 9). In contrast, only generalized fault lineaments of major faults are freely available for the Danish Sector. Along the border the different colors of the border-line highlight areas of different structural complexity across the borders. Very high structural complexity (red), high structural complexity (orange), moderate complexity (yellow), low complexity (blue)

The highest density of structures and degree of complexity occur in the Horn Graben and the Central Graben areas (Figure 17 and Figure 18), which are both within WP3 study areas. As indicated by the different degree of detail and differing concepts leading to the available interpretations, fault harmonization of derived models or even of the interpreted lineaments is hardly possible and can only be guaranteed by strong generalization. Therefore, cross-border harmonization of faults in detail is only possible through prior harmonization work on seismic stratigraphic concepts (D3.5; THÖLE ET AL., 2020), interpretations of prominent seismic horizons in the time domain (D3.6; THÖLE ET AL., 2021) and by application of a harmonized velocity model (D3.7; DOORNENBAL ET AL., 2021).

Due to the large amount of structures whose consistent modeling requires cross-border harmonization as well as the challenges in harmonizing existing structural interpretations and creating cross-border 3D structural models in depth, the project partners GEUS, BGR and TNO agreed to test and evaluate possible approaches for fault harmonization using the example of the probably most prominent fault zone in the southern and central North Sea, the Coffee Soil Fault and the Nordschillgrund Fault, respectively. This fault zone is the eastern main fault of the North Sea Central Graben, a 500 km long, N-S-trending half-graben straddling the Dutch, German, Danish as well as the British and Norwegian offshore sectors. The study region (Figure 19) covers a c. 80 km long section in the middle segment of the Central Graben, which crosses the border region (Entenschnabel area) of the Netherlands, Germany and Denmark offshore sectors. In addition, this segment of the fault zone is of particularly interest, because fundamental characteristics of the fault zone change in this region (e.g. halotectonics, inversion tectonics, strike and dip of main faults, depth of horizons). Therefore, a fault harmonization in this area can also contribute to a better understanding of the structural development of the entire rift structure.

As part of 3DGEO-EU WP3 Deliverable D3.8 we will test workflows for cross-border harmonization of faults. On the base of detailed seismic interpretation and plausibility checks for the fault geometry we will provide a generalized model of the Coffee Soil Fault/Nordschillgrund Fault. This study is intended to contribute to the standardization of workflows for future harmonization of cross-border structures of GEUS, BGR and TNO.

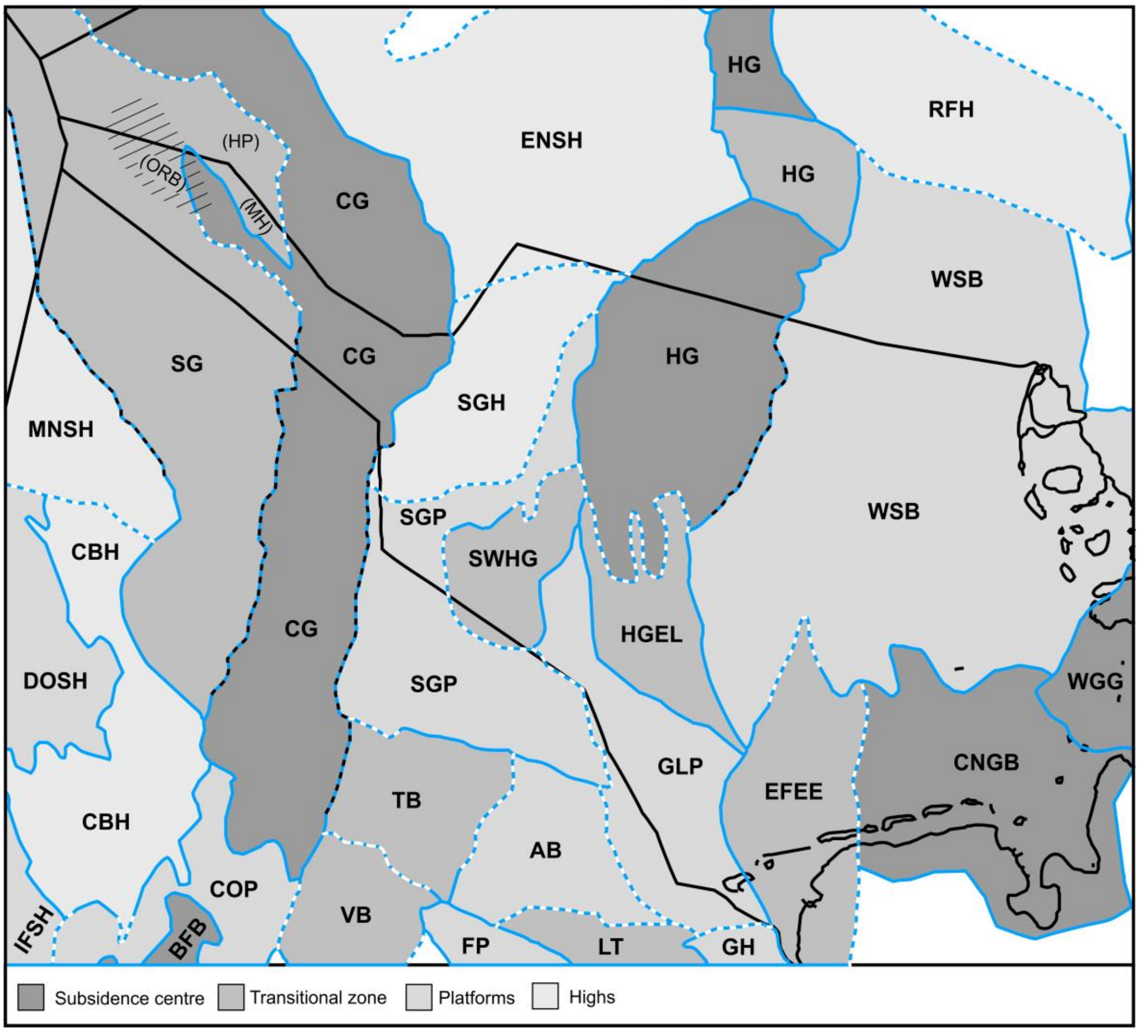


Figure 18 Preliminary map of main structural elements in the area of the Dutch, German and Danish North Sea. Uncertain limits of structural elements which are currently under review in the project (see Deliverable 3.8) are indicated by dashed lines. Blue-black dashed lines: uncertain limits due to differing concepts in defining the boundaries, e.g. according to basement structures or distributional pattern. Blue-white dashed lines: boundaries difficult to define due to e.g. diffuse trends in distributional patterns or no clear basement structures.

Abbreviations of main structural elements: SG = Step Graben / CG = Central Graben / ENSH = East North Sea High / HG = Horn Graben / RFH = Ringkøbing-Fyn High / MNSH = Mid North Sea High / SGH = Schillgrund High / SGP = Schillgrund Platform / SWHG = southwestern branch Horn Graben / HGEL = southern branch Horn Graben – Ems Lineament / WSB = West Schleswig Block / GLP = G- and L-Platform / EFEE = East Frisia – Ems Estuary Region / CNGB = NW part of the Central North German Basin / DOSH = Dogger Shelf / CBH = Cleaver Bank High / COB = Central offshore Platform / VB = Vlieland Basin / TB = Terschelling Basin / BFB = Broad Fourteens Basin / FP = Friesland Platform / IFSH = Indefatigable Shelf / GH = Groningen High / AB = Ameland Block / LT = Lauwerszee Trough / WGG = Western Glückstadt Graben. <u>Subordinate structural elements:</u> ORB = Outer Rough Basin / MH = Mads High / HP = Heno Plateau.

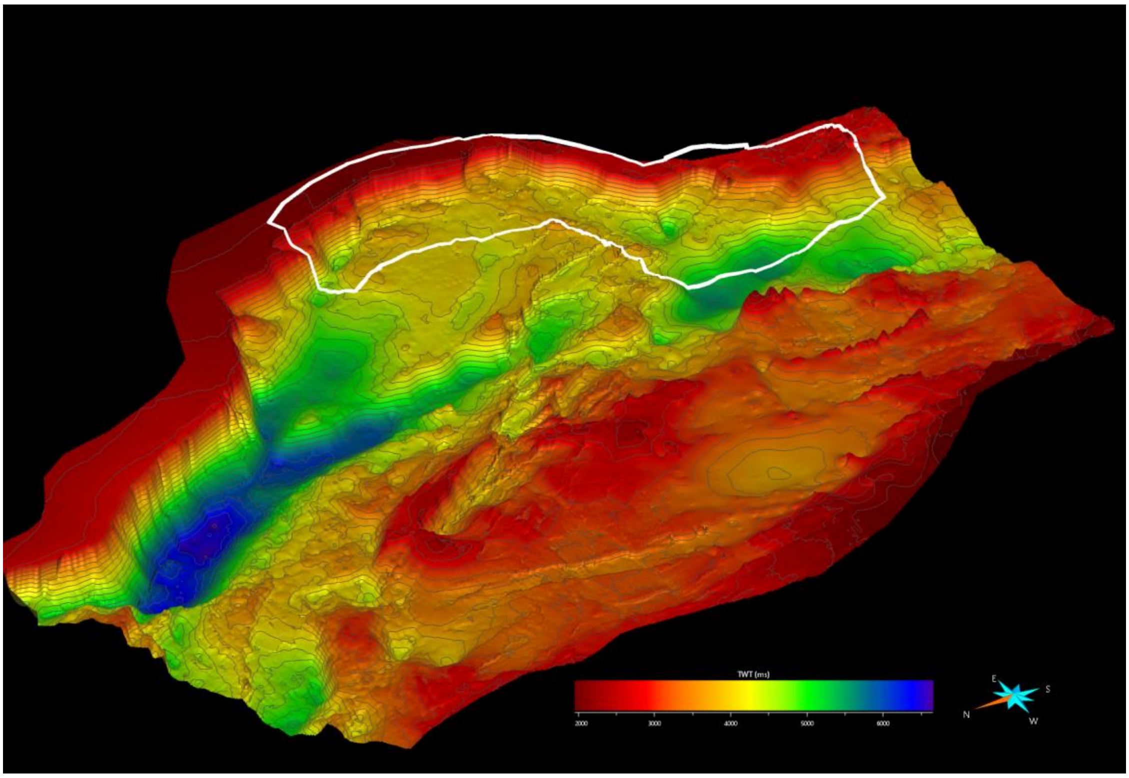


Figure 19 View from NW on the middle segment of the North Sea Central Graben. Shown is the color-coded Top Pre-Zechstein (Deliverable D3.6/D3.7) and the white outline of the study area of the Coffee Soil fault study that will be presented in Deliverable D3.8 (3DGEO-EU)

4.4 Fault harmonization in the Saxony-Anhalt/Brandenburg cross-border region (WP6)

Fault harmonization in the Saxony-Anhalt/Brandenburg cross-border regions follows a completely different approach. The existing 3D models for both sides of the border, which were yet not fully harmonized, were additionally analysed by a harmonized and integrated gravimetric modelling approach. Therefore, not only the existing 3D model data was shared between the partners but even raw data (gravity measurements) were exchanged. All shared data does not underly any legal restrictions thus enabling the harmonized modelling; i.e. modelling was performed by one partner and results were discussed and evaluated in close corporation of both participating geological surveys.

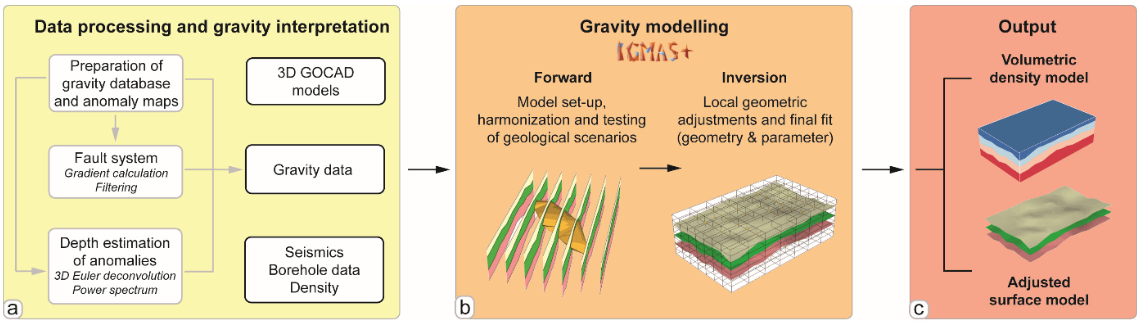


Figure 20: Flow chart of our modelling workflow (MUELLER ET AL., 2021): a) preparation and processing of input data and fault detection in the cross-border region by gravity interpretation, b) merging and harmonization of independent geological models (incl. faults) in the scope of 3D forward and inverse gravity modelling, c) interpretation and utilization of output models.

The harmonized and integrated gravimetric modelling (see MUELLER ET AL., 2021. for a detailed description) in general followed several steps (Figure 20). First, a unified processing was performed for gravity measurements (same gravity system, height reference system, correction formulas, reduction parameters and topographic correction). Wavelength filtering and gradient calculation were applied for calculation of derivative gravity maps, which allow the interpretation and tracing of faults in the cross-border region (Figure 2 c, e). 3D Euler deconvolution was used for rough depth information of main gravity anomalies and faults (Figure 2 d). Afterwards, structural information from both existing models and all a-priori information (seismic profiles, borehole data, gravity data and results from gravity interpretation) were imported in the gravity modelling environment (IGMAS+). Fault and model harmonization, model parametrization as well as tests of different geological scenarios were performed in the scope of 3D forward and inverse gravity and gravity gradient modelling. Finally, the horizons and faults from gravity modelling were retransferred to the geological model.

On one hand, this gravity modelling approach allows the identification and tracking of faults across the state border in the derivative gravity maps and the orientation of fault indications in seismic data. On the other hand, gravity gradient modelling provides rough information on the faults dip and offset and the set-up of a single geological model, which satisfies the observed gravity data (Figure 21). These new information on the fault characteristics allowed a detailed study of the fault system in the Saxony-Anhalt/Brandenburg cross-border region and a harmonization of the faults and model layers. Furthermore, the fault identifications helped to outline main geological structures (contrasting density or elevated blocks) and zones of different facies (Figure 21). However, the use of gravity data for fault inspection is limited to steep (≥ 45°) normal or reverse faults with a pronounced density contrast. Consequently, shallow dipping faults or transform faults will mostly be not observed in gravity data, as these do not cause a significant change in the observed gravity field.

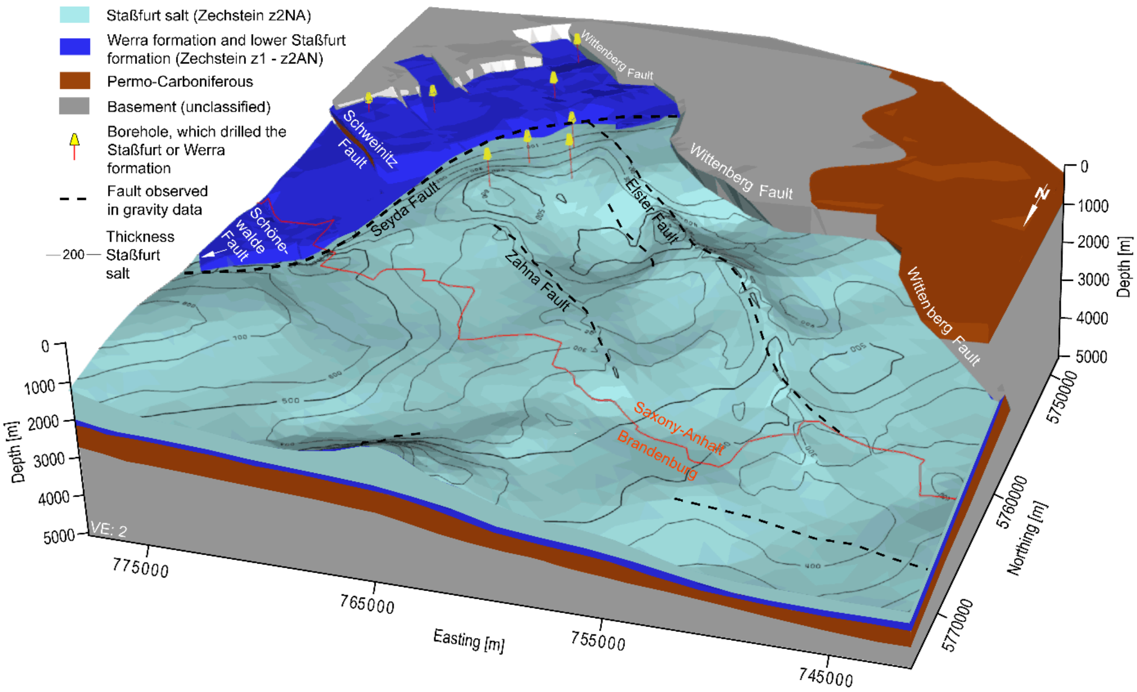


Figure 21: 3D perspective view of modelled Zechstein layers z1 – z2NA and their displacing main faults (Mueller et al. (in prep)). 3D gravity modelling revealed new information on the orientation and dip of the main faults as well as zones of different facies.

5 CLASSIFYING AND ATTRIBUTING FAULT DATA

Classifying and attributing fault data during or subsequently to fault interpretation and modelling is of significant importance, especially if faults must be harmonized across national and international borders. With absence of a unified nomenclature and strictly defined parameters and properties each harmonization effort must naturally fail due to linguistic or descriptive discrepancies. At that point even a geologically sound and geometrically harmonized fault network across borders cannot be fully harmonized if its attributes and parameters do not fit. For this purpose, the Infrastructure for Spatial Information in the European Community (INSPIRE) first developed unified code lists for the description of a wide spectrum of data and information related to geosciences. Furthermore, with special regard to structural information and faults, the European Fault Database (FDB), established and enhanced in the HIKE project, provides harmonized, pan-European vocabularies arranged in a semantic network to handle faults and their related attributes in various scales and levels of detail. Although, recently most of this fault information are simply two-dimensional objects (generalized to detailed fault lines), the integration and incorporation of parameterized three-dimensional objects is planned in the future. Hence, additional to simple fault attributes describing complete fault objects, fault parametrization in 3D space based on cross-border harmonized models will become more and more important.

5.1 Fault attributes

The European FDB framework was presented and discussed with the HIKE partners and other projects during the GeoERA Technical Workshop in Vienna (March 11-12, 2019). The technical specifications of this European FDB have been described in Deliverable 5.1 of the HIKE project.

The general framework is shown in Figure 22, which defines a fault object in a schematic overview. The individual fault data elements (attributes) and their mutual relationship could be subdivided in the following four levels:

Fault geometry and spatial definition (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. Fault geometry can be provided, stored and disseminated in 2D and 3D.

Fault semantic definition and hierarchy (concept level as part of the project vocabulary):

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*.

Fault attributes (in geoscientific context as part of fault attribute database):

These attributes describe the fault object in the geoscientific context. These attributes are independent from the geometrical representation of the fault.

Metadata (on the fault dataset level):

On the fault dataset level these attributes (metadata) describe the dataset as a whole and not the individual fault. The metadata are used to reference the source of the dataset. Furthermore, the metadata are enabling the dataset to be found.

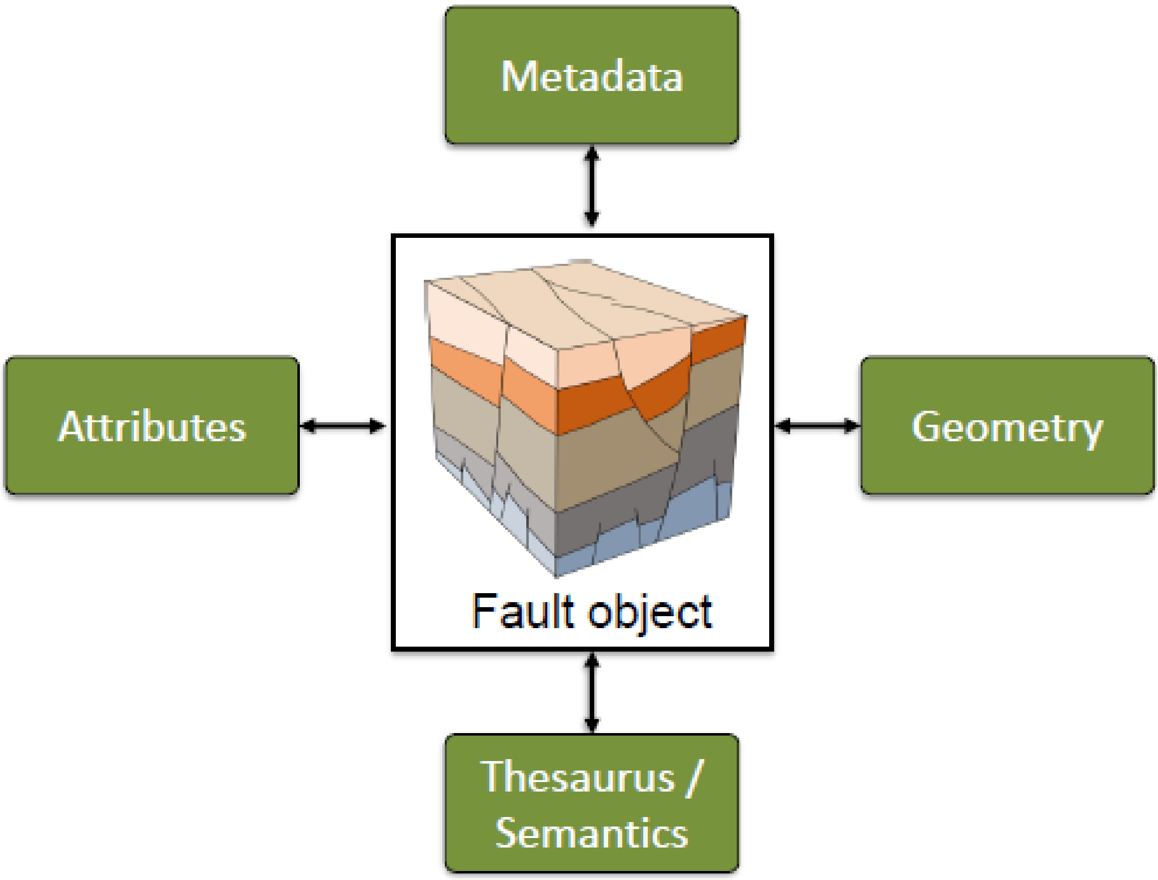


Figure 22 Subdivision of a fault object in four levels.

Although fault data management and attributation is of broad interest, especially for national to pan-European spatial and strategic planning efforts of the subsurface, available attributes are highly variable and to a distinct amount still stored in regional maps or local 3D models. Therefore, to enhance the availability of fault information it will become more and more important to focus even on the possibilities to extract fault information from such technical impasses (e.g. closed modelling environments and software solutions), which will be described in the following.

5.2 Extraction of fault attributes from 3D models

Fault attributes extracted from existing 3D geological models can be stored in databases (e.g. the European Fault Database established in the HIKE project) such that fault data is accessible and searchable for various end-users and usable for, amongst others, spatial planning efforts. Three-dimensional, geometric fault information as well as selected fault parameters and attributes can be generated by most of the above-mentioned modelling approaches (Table 4) and can be harmonized across national borders to a distinct amount. Thereby, many parameters were still used as constraints during the modelling workflow and are thus available in the modelling environment. Hence, it seems a meaningful approach to use this still available information.

Table 4 Selection of properties derivable from 3D geological models

Property	Type	*Use in European Fault Database?*
Displacement	Real number (continuous)	*Yes*
Dip & Azimuth	Real number (continuous)	*Yes*
Throw type	Discrete (Category)	*Yes*
Name of horizon/fault/fault zone	Discrete (Category)	*Yes*
Juxtaposition (if facies properties are defined)	*Discrete (Category)*	*No*
Seal properties	*Real number (continuous)*	*No*

In the following, selected parameters of horizon-fault-contacts (fault cut-off lines) as well as fault-to-fault-contacts, which were modelled and defined during the modelling process, will be described. For sake of simplicity, we herein concentrate on these parameters exemplified by use of the SKUA-GOCAD software, but other spatial modelling software may provide similar functionality.

5.2.1 Determination of kinematic properties

In the "Structure and Stratigraphy" (SnS) workflow of SKUA-GOCAD, fault contacts were defined and the displacement of stratigraphic horizons is defined (to a distinct amount) during the modelling process and the distribution of its values is computed automatically. For that reason, SKUA generates several fault displacement properties in reference to a layered stratigraphic succession (i.e. "Formation" in the SnS workflow), which is defined in the stratigraphic column. The displacement value is the stratigraphic throw, which is defined as the distance between hanging wall and footwall cut-offs. It is calculated along vectors, that are defined for every point on the fault plane. These vectors represent the true displacement and are written as the sum of three orthogonal vectors (Figure 23). The displacement values have a sign that depends on throw type (positive values for normal offsets and negative values for reverse offsets). In addition, values for dip, azimuth and strike can be calculated for each node of the triangular mesh of the modelled fault.

By use of scripts coming with the SKUA-GOCAD software also names of horizons, faults and fault zones can be stored as node-related properties in the form of uniquely defined IDs, which is an important feature for subsequent transfer of information into GIS and database systems. Preservation of IDs during the whole modelling process allows later management processes. Hence, the SKUA-GOCAD software provides several types of data, which can be stored on nodes of modelled fault surfaces.

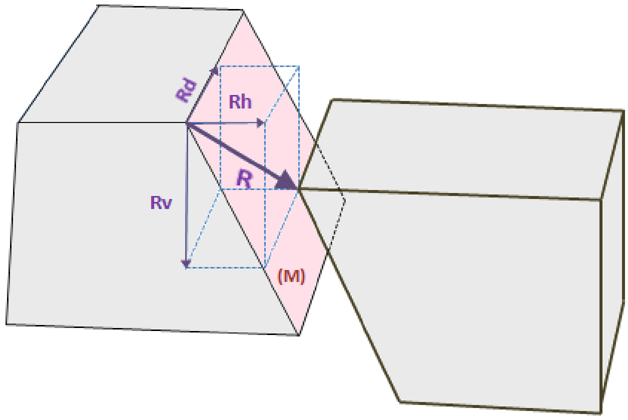


Figure 23 Determination of fault displacement (R) on fault plane (M) in SKUA-GOCAD, where R is defined as the sum of the three orthogonal vectors total strike (Rd), total heave (Rh) and total throw (Rv). Modified from BOUZIAT 2012.

5.2.2 Parametrization of 3D fault planes

Besides still existing kinematic and geometric properties the further parametrization of fault planes and thus the generation of additional properties seems to be a challenging but meaningful goal according to faults. Thereby, the possibility to gather further information strongly depends on the available data as well as the model type and geological content. If only a structural model (with main geometric boundaries) exists, fault attributation and parametrization is limited to geometrical and kinematic properties. On the other hand, if even parametrized volume models are present, there is a wide range of possible attributes that can be transferred to single fault planes. In the following, the general approach of fault parametrization is exemplified with regard to a fault sealing analysis. Due to the fact that faults represent the most important discontinuities in the geological subsurface, such an analysis is applicable and necessary for a wide range of applications (e.g. geothermal plays, storage sites and reservoirs for hydrocarbons, green gas or waste), where potential pathways or barriers across faults are necessary to know.

The basis for the analysis presented, herein, is a parametrized volume model. For this purpose, information from a series of lithological-paleogeographic maps were transferred to the volume model. The maps were prepared between the late 1960s and late 1970s and represent an extensive and consistent data base for parts of the North German Basin (NÖLDEKE AND DIENER 1972). The dataset reveals spatial information on lithology, paleogeography and primary thickness, which was systematically digitized (MALZ ET AL., 2019b) and transferred to a Structural Grid (SGrid) using SKUA-GOCAD (WÄCHTER ET AL., in prep.). Due to the fact that the structural information in these maps (e.g. thicknesses) is based on structural maps used for 3D structural modelling (see RAPPSILBER ET AL., 2019 for a discussion) there is a great fit of structural data and parameters. If such a well-constrained, parameterized 3D volume model exists, fault parametrisation and analysis can be performed.

The juxtaposition is a first, qualitative parameter for the estimation of permeabilities across a fault pane. A simplified petrography derived from the lithofacies model allowed to identify areas at the fault, where high permeable sediments are juxtaposed against low-permeability units. Therefore, lithologies in the hanging wall and the footwall were compared across the fault plane, based on the method referred to as 'Allan maps' (ALLAN, 1989). Six lithotypes were defined leading to 21 possible 2-pair-combinations (Figure 24).

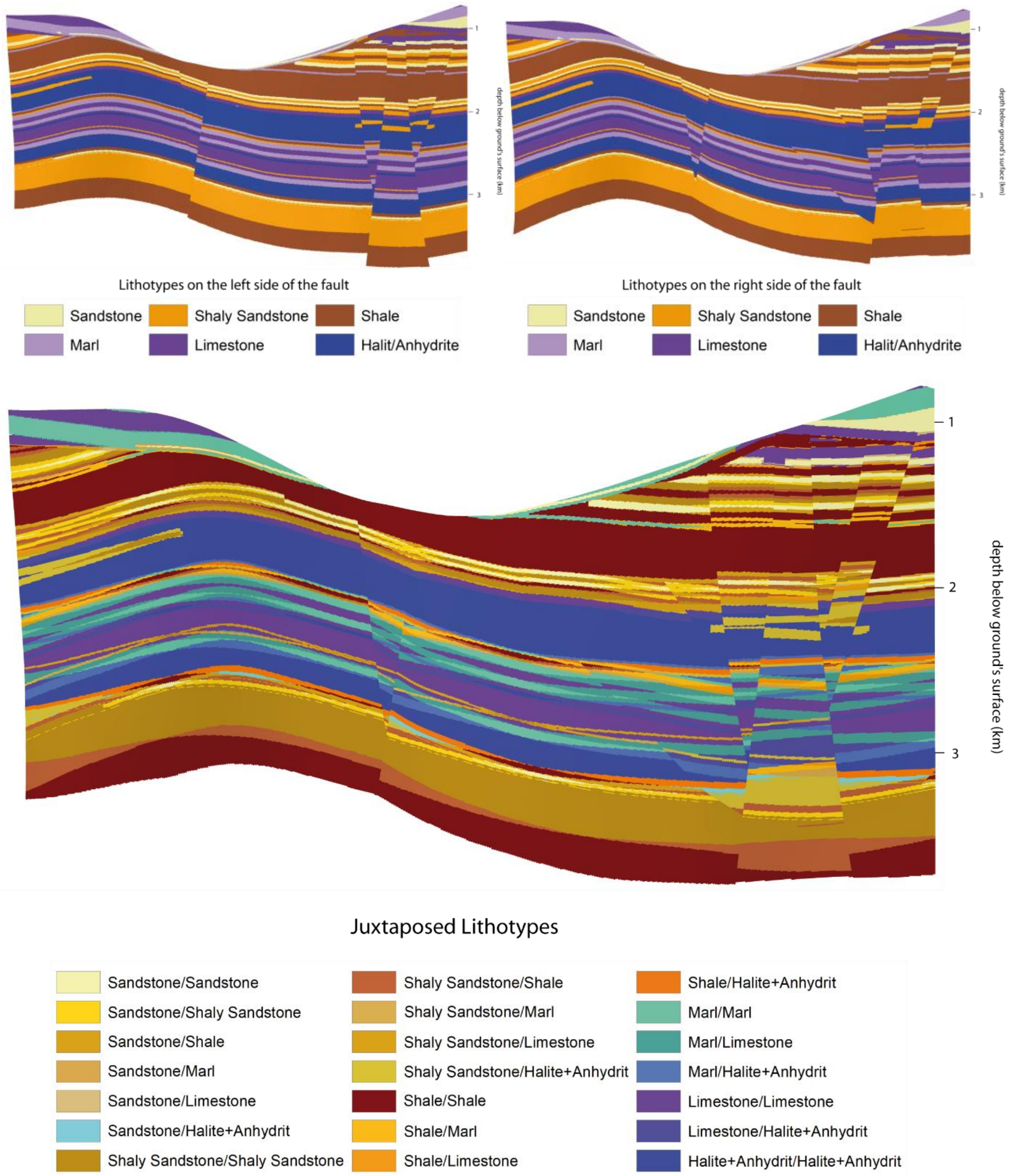


Figure 24 Juxtaposition of lithotypes across the fault plane

5.2.2.1 Determination of clay content

To enable a quantitative characterization of possible permeable and sealing sections and, thus, potential pathways and barriers for fluids and gases across the fault plane, we first derived clay content values from the detailed petrographic descriptions. For validation, we used gamma-ray logs to determine average clay contents for each unit, considering the effects of compaction with increasing depth and lithological and facial differences.

The clay content can be described by the Shale volume (V_{sh}) parameter, which can be equated to the gamma-ray index (GRI) after SCHLUMBERGER (1972):

$$V_{sh} = GRI = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

where:

V_{sh} = volume of shale

GRI = gamma-ray index

GR_{log} = gamma-ray log reading

GR_{min}= gamma-ray log reading in clay-free zone

GR_{max}= gamma-ray log reading in pure-clay zone

These values can used as a parameter in a 3D volume model and, afterwards transferred to single fault planes ().

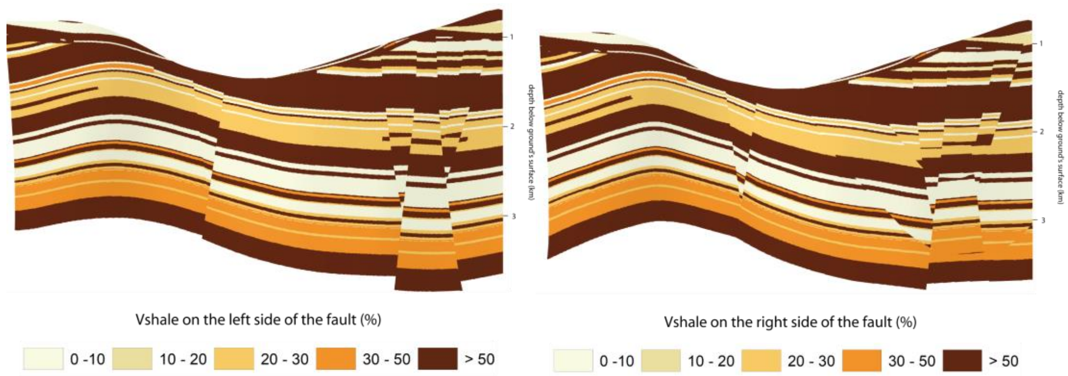


Figure 25: Shale volume (V_{Sh}) from a parametrized 3D volume model plotted on both sides of a fault plane (left: left side of the fault; right: right side of the fault)

5.2.2.2 Shale Gouge Ratio and Clay Smear Potential

Observations by WEBER ET AL. (1978) showed, that faulting can form clay gouge with effective sealing functions along permeable sections of a fault plane. It primarily depends on the distance to the clay source and its thickness. This clay smearing effect can be described by several parameters. The Shale Gouge Ratio (SGR; YIELDING ET AL., 1997) simply describes the percentage of shale in the slipped interval. A weighting by the clay content of each unit leads to following equation:

$$\frac{\sum[(Zone\ thickness) \times (Zone\ clay\ fraction)]}{Fault\ throw}$$

To consider the fact, that the clay gouge gradually becomes thinner with increasing distance to the clay source, a Clay Smear Potential (CSP) can be defined (FULLJAMES, 1996):

$$CSP = \sum \frac{[(Zone\ thickness) \times (Zone\ shale\ fraction)]^2}{Distance\ from\ source\ bed}$$

for distances less than fault throw.

SGR and CSP have values between 0 and 1. The higher these parameters, the more likely the fault is sealing. These values can be, furthermore, transferred to single fault planes ().

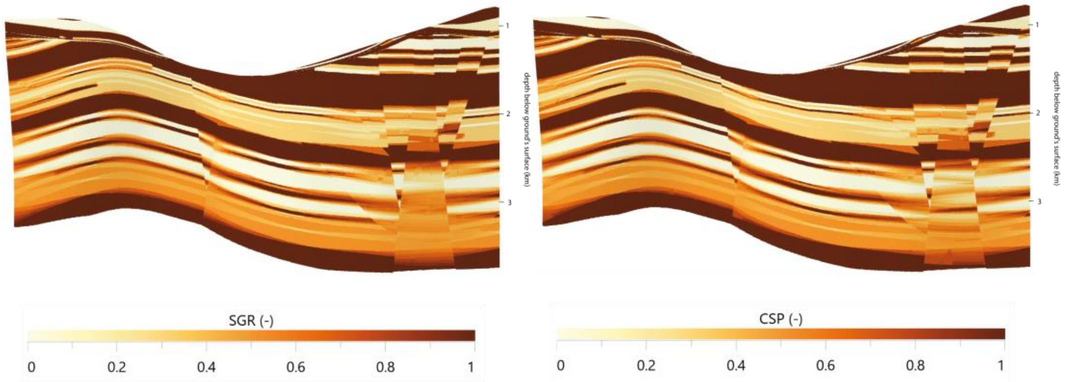


Figure 26: Shale Gouge Ratio (SGR; left) and Clay Smear Potential (CSP; right) calculated on a fault plane

5.2.3 Generation of 2D fault representations (fault cut-off lines)

The result of the "Structure and Stratigraphy" workflow of SKUA-GOCAD is a structural model and an appropriate 'water-proof' volume grid with a defined cell size. Horizons and faults are stored as so-called horizon grids, which must be converted into triangulated surfaces. For that, SKUA determines intersections between grids and a tetraeder model representing the whole model's volume. This method ensures that both, horizons and faults, will share common points (nodes) at their intersections. By calculating intersections of faults and horizons appropriate 2.5D representations of footwall and hanging wall cut-off lines can be generated. Afterwards, properties can be transferred from surfaces to intersection lines by querying XYZ locations (displacement value according to definition of a respective horizon in the stratigraphic column, Figure 27).

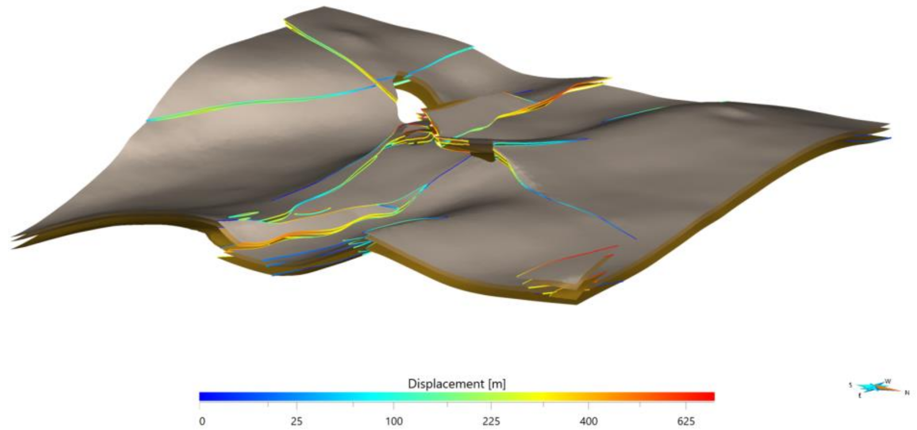


Figure 27 Horizon-fault-contacts with displacement values, derived from SKUA model

After generation of 2.5D polyline features in SKUA-GOCAD the resulting objects can be transferred to geographic information systems (e.g., ArcGIS). The most comprehensible solution of data transfer is to export pure ASCII files including XYZ coordinates of polyline nodes. The only solution, which preserves all geometry information and can be directly imported into ArcGIS, is the use of the DXF data format. Other export tools do not support storage of numerical values. Hence, we decided to export pure point data, including their XYZ location and all properties. These data can be imported as ArcGIS point features. Afterwards, line objects can be generated again using GIS-Tool 'Points to line' with the automatically exported Part-ID as Line Feature (Figure 28). This ensures the generation of fault objects similar to the ones modelled in SKUA-GOCAD.

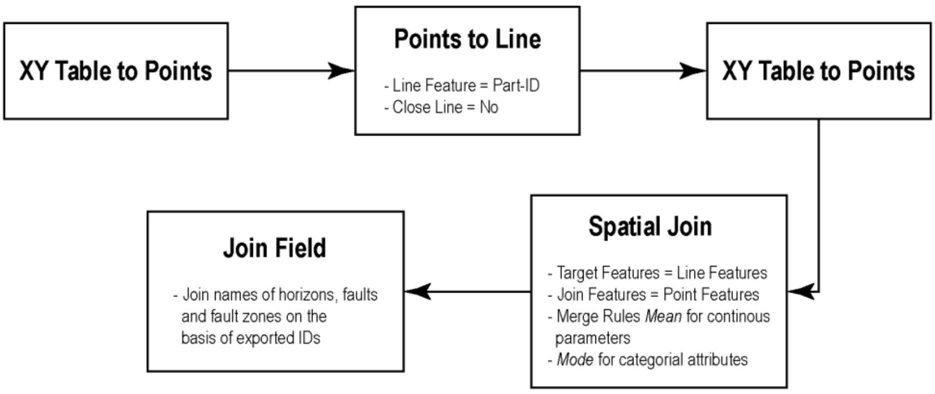


Figure 28 Workflow for transferring parameters (algorithms usable in ArcGIS Pro)

A general problem of the property transfer process is the storage position of values. In SKUA-GOCAD properties are stored on single nodes and interpolated between them. In contrast, GIS stores values on line segments between nodes. Therefore, value transfer must be executed carefully. Nevertheless, the most appropriate method for data and property transfer from points to polylines is the use of a 'Spatial Join' algorithm. To ensure a transfer without losing continuous parameter information, lines have to be splitted at their vertices to separate features. To overcome issues of the storage position, mean values of continuous values have to be calculated between points with spatial relationship to line feature, which mark beginning and end of line segments. The spatial relationship is herein defined as an exact intersection without search radius. For discrete properties (e. g. horizon name), the value with highest frequency has to be used, which is necessary because points with identical positions and different categorial information usually occur at intersections between lines (Figure 29).

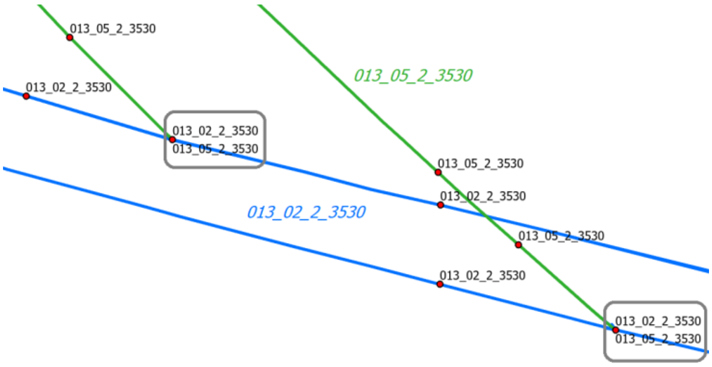


Figure 29 Occurrence of different categorical attributes (here: fault names) on same point location and resulting spatial join using merge rule 'mode'

The exemplarily described fault data and property transfer workflow results in a comprehensive dataset of 2.5D polylines derived directly from the 3D geological model. The dataset includes all information about the spatial distribution and additional properties of faults in the investigated area (Figure 30). The initially use of point data enables the visualization of continuous parameters (displacement, strike) and the query of their statistical characteristics, like minimum and maximum values, for each fault or fault zone. Furthermore, by transferring data from the 3D modelling environment to the geographical information system (GIS), the complete functionality of a GIS system (e.g. calculation of fault lengths, strike directions) can be used to generate fault attributes, the results are storable in database systems (e.g., the pan-European Fault Database established in the HIKE project) and thus are accessible for a broad community. Additionally, extracted data can by searched and selected using well-established GIS routines and algorithms, which enables users to perform further analysis of the fault network.

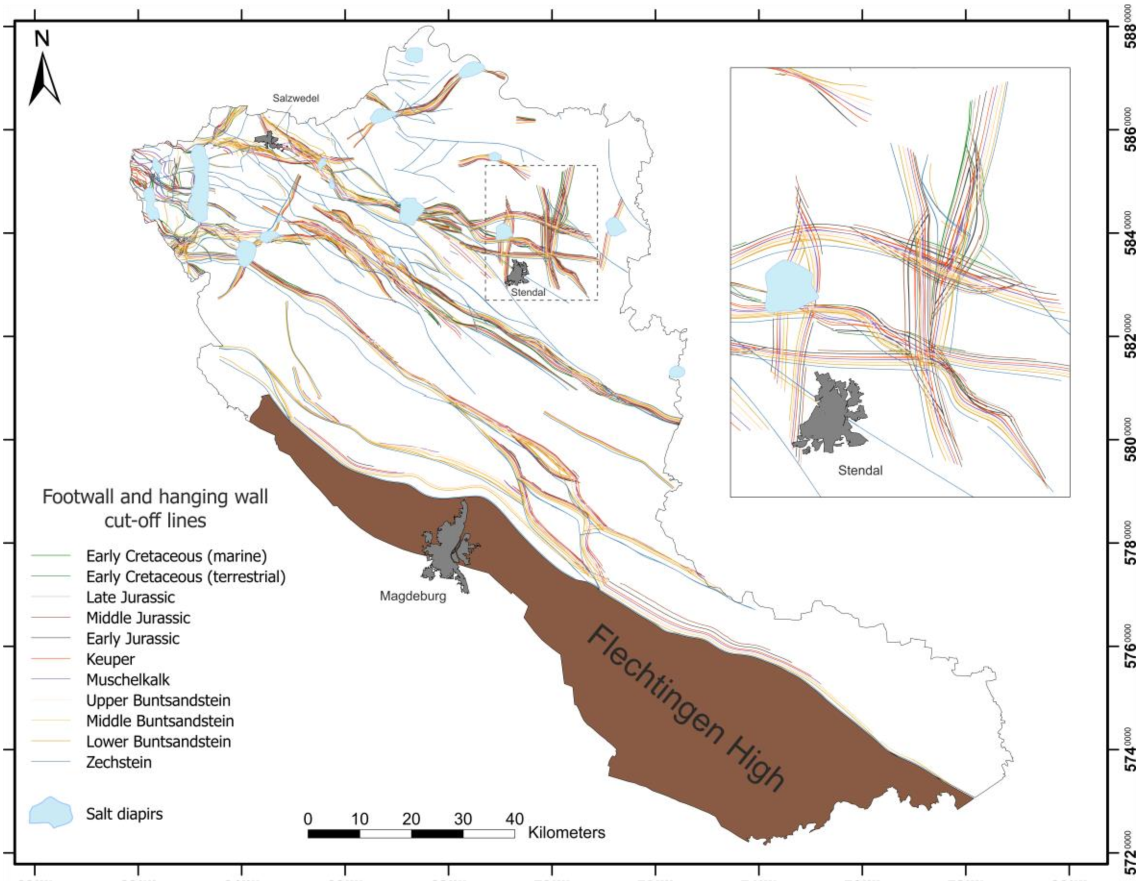


Figure 30 Derived footwall and hanging wall cut-off lines, marking intersections of faults and stratigraphic horizons

6 LESSONS LEARNED AND BEST PRACTICES

The cross-border harmonization of geological 3D models in most cases is a challenging issue for the 3D modelling community and must be carefully planned and performed. Especially the harmonization of faults as geological discontinuities is hampered by various conditions like political and legal restrictions, different classifications and nomenclatures, technical issues concerning the modelling environment and, last but not least, the used data, processing and interpretation. In the following chapters, these conditions and possible solutions will be briefly discussed.

6.1 Political boundaries and legal restrictions

During the work in 3DGEO-EU it became obvious that one of the most limiting factors for an efficient cross-border harmonization is given by political and legal restrictions. These restrictions limited the exchange of data and geological knowledge across borders since many decades and is even hampering consistent geological interpretations. In many cases (e.g. the Netherlands-German border in WP1, the Polish-German border in WP2, or even the former inner-German border) the exchange of data did not occur and thus interpretations on both sides of a political border were done individually. Thereby, exploration at these political boundaries were done with less intensity often leading to large data gaps and artifacts in the interpretation or interpolations (e.g. opposing trends and dips on both sides of the border). Depending from the used data (e.g. interpreted depth maps or finalized models) indicating and reproducing such artifacts is often only possible, if raw data will be considered and interpreted in corporative and communicative projects (e.g. the GeoERA 3DGEO-EU project). Furthermore, individual restrictions and permissions for participating in knowledge exchange meetings (e.g. travel restrictions during the Covid-19 pandemic) must even be considered as limiting factors.

6.2 Legitime interpretational bias and structural regions

During the cross-border harmonization work in 3DGEO-EU (especially in the Polish-German border region; WP2) it became obvious that political borders often retrace even geological boundaries. This is given by the fact that political boundaries were often defined by geomorphological or strategically important incidents in historical times. Especially large mountain ranges (e.g. the Pyrenees) or rivers (e.g. the Oder/Odra river) played an important role for the definition of political boundaries. Nevertheless, these boundaries are triggered by geological units and often coincide with faults; either large thrusts in mountain ranges or tectonically weakened zones were rivers incised.

In the latter case, which became obvious along the German-Polish border, cross-border harmonization of faults is simplified due to the fact that deep faults in the subsurface trending parallel to the border (Oder/Odra river valley) separate two large tectonic units, the North German Basin in the west and the Mid-Polish Trough in the east. Although affected by similar tectonic regimes during Paleozoic-Mesozoic times, both units show a significantly different structural pattern; widely distributed deformation structures and faults in the west and large, spatially concentrated basins and troughs in the east. In such cases, a different interpretational bias on both sides of a border seems legitime and necessary, even if visible in the resulting cross-border model. Nevertheless, even then it should always be kept in mind that, despite only few (or no) faults straddling the border are known, large structural discontinuities in the deep subsurface exist, which may or may not have strong influence on the potential economical use and are hard to detect without unified cross-border exploration and data harmonization efforts (e.g. unified potential field maps as planned in the further process of cross-border harmonization in the Polish-German border region; combined seismic processing and interpretation efforts as done in the North Sea area).

6.3 Definition and assignment of structural regions

The harmonization of fault models & data or of structural concepts is not only important in detailed local studies but also in an overview-scale. For describing and the categorization of faults as well as the understanding of specific structures in a regional context, faults and areas with similar characteristic, subsidence and similar tectonostratigraphic history are often combined into one structural region. Such regions are often separated by large fault systems trending parallel to political borders as described above.

In a map view, the border between different structural regions is usually shown as a discrete line. Switching to the three-dimensional observation as necessary for structural analysis and 3D modelling, this 2D line became substituted by a tilted three-dimensional plane or, if analyzed in detail, a fractal collection of planes, which often underwent generalization for regional categorization efforts. Hence, a preliminary categorization (e.g. as done for the Southern and Central North Sea; see Figure 18) often show uncertainly defined transitions between neighboring structural regions. An incorrect or generalized designation of regions of similar tectonostratigraphic history can consequently also lead to a misattribution of fault characteristics, which should actually be assigned to a neighboring structural region. For cross-border comparison and categorization of fault data implemented in e.g. the European Fault Database concept (HIKE project), the implemented fault data should also be linked to a consistent cross-border definition of structural regions. If there is a clear assignment of all faults and other structural elements (e.g. diapirs, intrusions) to a next higher-level structural region, then there is also an essential basis for the creation of a cross-scale structural framework (GeoERA GeoConnect³d). A more in-depth discussion of the challenges of creating structural maps and defining structural regions within the North Sea area is provided in Deliverable D3.8.

6.4 Challenges from different data processing and interpretation

The essential method for subsurface mapping in areas with widely distributed post-kinematic sediments or water (e.g. the North Sea area; WP3) is the interpretation of reflection seismic data. The quality and interpretability of these data is strongly influenced by the geologic conditions, which should be imaged. Pronounced salt tectonics, which is present in all pilot areas in the 3DGEO-EU project, cause very complex structural features in general providing challenges in seismic processing and interpretation techniques. In a similar manner, deep grabens, might be poorly imaged in seismic reflection data, due to long travel times of seismic waves, the distortion of signal with travel time and steep flanks causing complex reflection patterns and signal scattering. Furthermore, the graben fill is seldom completely penetrated by drilling and thus depth and velocity constraints for the deeper parts are uncertain. Hence, special challenges in the interpretation and consistent modelling of regions like the North Sea area or the Polish-German border region arise, which originate from the variable data density and quality. Depending on the seismic acquisition and processing parameters, faults are differently imaged, thus leading to different interpretations from one survey to another (Figure 31), especially if the interpreter is unfamiliar with the other data set.

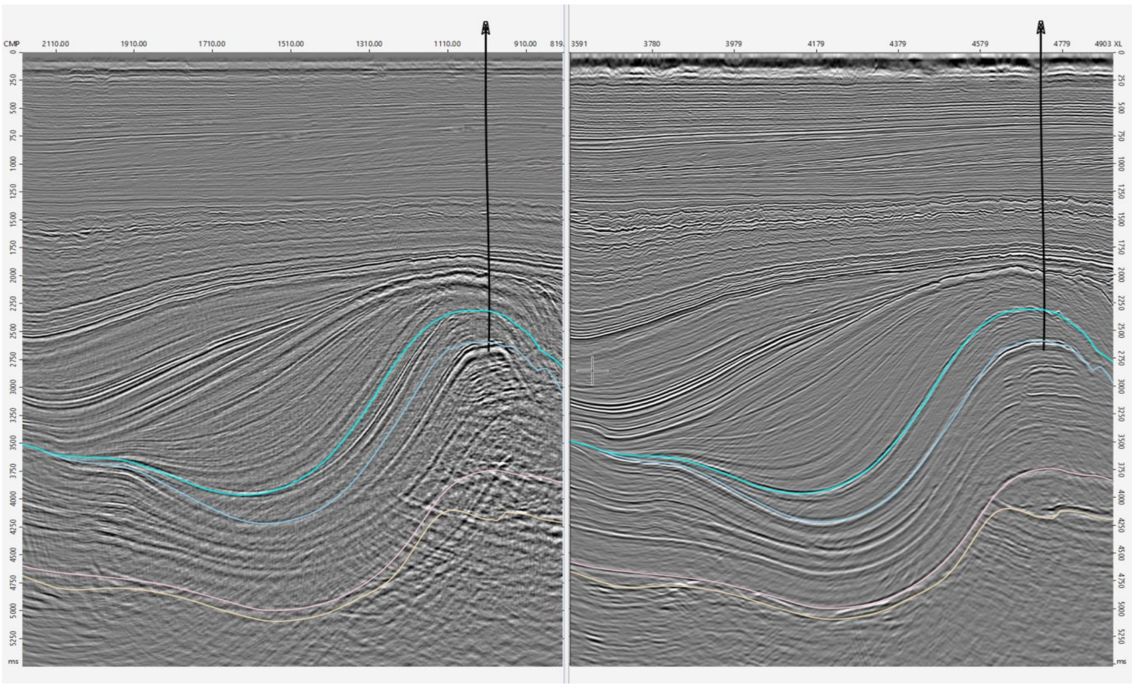


Figure 31 *Two nearly parallel seismic profiles from different surveys. Left: 2D seismic profile from the 1980ties; Right: Vertical slice from a 3D-seismic survey from the beginning of the 21th century. The seismic interpretation plotted on both images (blue, pink, beige) was developed based on the 3D-seismic dataset (right). The partly strong deviations of the interpretation to the 2D seismic (left) are due to a different processing of the surveys.*

The accurate imaging of complex structures like faults and salt diapirs requires a precise and target-oriented adaption of reflection seismic acquisition parameters and processing steps, which is rarely warranted for regional seismic surveys. Especially for steeply dipping features (tilted bedding, faults and outlines of salt diapirs) variable seismic migration approaches result in striking differences in the final interpretation (Figure 31). Although the evolution of 3D seismics and associated processing techniques significantly improved seismic imaging, these striking discrepancies are still present.

Differences between independently developed fault interpretations in the depth domain are often strongly affected by different velocity models, especially in cross-border areas with variable scientific knowledge, economic interests, political decisions and data restrictions (e.g. THÖLE ET AL., 2019; THÖLE ET AL., 2021). The evaluation of their effect requires tracing the data back to the time domain, which is often challenging, especially if vintage map series and seismics with limited (or often only available analogue isoline maps) information about the underlying velocity model have to be reconverted. However, an interpretation model in the time domain is usually the basis for model harmonization but have a strong influence on the derived velocity model, which ideally should incorporate the geological structure of the survey.

6.5 Challenges arising from different interpretation concepts

Depending on the objective of seismic surveys and the depth of a potential exploration target, acquisition and processing parameters are individually selected. Hence, different depth/time ranges are imaged differently with regard to resolution, sharpness and artificial features, while quality is limited in sequences not fitting the defined depth interval. In surveys designed for shallow exploration, deeper sections are imaged in less quality and detail. Additionally, the quality of seismic imaging generally decreases with depth, especially if lithologies with high acoustic resistance occur in shallow depths thus hampering the penetration of seismic waves to greater depths. Without access to the results of individual processing steps its impact is hard to determine and must be considered to avoid over-interpretations. As described by THÖLE ET AL., 2021, different picking concepts (e.g. of reflection seismic horizons) often manipulate the final interpretation, which prevents their comparison across borders without great effort, and inevitably influences fault mapping. In work package 3, GEUS, TNO and BGR have in some cases taken a significantly different approach to the designation of faults in their published products. Thus, at least for the Entenschnabel region, BGR has attempted to represent faults and cut-off lines of horizons chronostratigraphically. In contrast, fault interpretations from TNO and GEUS are fitted either to a top horizon model or to base surfaces of lithostratigraphic formations. Since the study region of work package 3 is characterised by thin-skinned salt tectonics and the hanging wall often represents extensive roll-over structures, different interpretation concepts of the seismic horizons usually have a significant influence on the corresponding fault model.

6.6 Data density and interpolation distances

Data density, the orientation of existing 2D seismic surveys or the selected picking distance in 3D seismics often necessitate different degrees of generalisation along a fault. Thereby, the interpolation of single fault interpretations with different distances and point densities along-strike ultimately results in a false overall impression. Hence, a robust, comprehensible and ideally uniform generalisation concept should be applied for the entire fault and all steps should be comprehensibly documented, which is often associated with a high level of effort. Depending from the exploration target in some studies only fault offsets of single formations (e.g. the selected geothermal or petroleum reservoir) are mapped. In these cases, only punctual information is available and a comprehensive fault harmonisation is prevented without executing additional mapping for further formations. The interpretational bias is also tied to the quality or ambiguity of used data as well as its density and distribution (see ZEHNER ET AL., 2021 for a discussion). Greater distances between single profiles and ambiguous depth information furthermore provoke and necessitate interpretative concepts (e.g. multiple geometries of detachment geometries are possible, if only fault ramp geometries are well-imaged by seismic reflection). Such concepts incorporating regional geologic aspects, admissible geometries and kinematics (e.g. structural restorations) are most often only possible in the depth domain, which in turn requires well-constrained time-depth-conversion.

6.7 Technical limitations

Additional to challenges like the availability of data, associated legal restrictions, data density, quality and processing as well as interpretational discrepancies across borders, some limitations arise from technical limitations (e.g. the availability of appropriate software). Often, the decision for one 3D modelling environment was made years to decades ago, a number of 3D models exist in proprietary data formats and thus models cannot be exchanged across borders or manipulated by all partners in a cross-border model harmonization campaign. Furthermore, depending from the main objectives for past modelling efforts, highly variable models exist (structural models with triangularly meshed surfaces vs. 3D volume or grid models). In all these cases, cross-border harmonization is challenging and much effort must be concerned for sometimes interminable model transformation work.

6.8 Best practices – sharing data vs. sharing models

Resulting from the experiences made in the GeoERA 3DGEO-EU project there are various ways for efficient data exchange between partners in neighboring countries and geological surveys. In general, it has to be noticed that cross-border fault harmonization is most efficient if not only final or preliminary modelling results were exchanged between partners but to even share uniformly processed data to enable each modeler to cross-check existing interpretations and to get a good knowledge about the area of interest. Nevertheless, such data exchange is often hampered by legal restrictions and only interpretation data (e.g. preliminary models) can be shared. In these cases, the only way to overcome misinterpretations and contractionary modelling results is given by enhanced communication, frequent meetings and knowledge transfer to communicate the validity of model parts, the density of data and possible uncertainties in the interpretation and modelling process.

If data exchange is not restricted and information is allowed and possible to be shared with all project partners, harmonized and uniform workflows for data processing, interpretation and modelling can be applied along both sides of a border. Thereby, it can be ensured that the resulting individual models are harmonized to a distinct amount. Subsequently, in the resulting models only minor deviations and distances are present and only geometrical adjustments (e.g. shift of single nodes) are necessary for final model harmonization.

6.9 Best practices – Model harmonization vs. harmonized modelling

Besides the above-mentioned bottle necks and requirements for efficient cross-border 3D model harmonization basically treating the exchange of data (raw data or even interpreted data and preliminary models) it should be always kept in mind that the most efficient way to generate cross-border harmonized models is an integrated and corporate harmonized modelling approach meaning that individual models will not only be harmonized but were rather modelled together. If raw information, model parts and knowledge are available for all partners, or one (independent) partner or contractor who executes the modelling (cf. fault harmonization in the Saxony-Anhalt/Brandenburg cross-border region), the modelling itself can be done without recognition of political boundaries during the practical work. Hence, the resulting 3D model will be harmonized by definition and subsequent harmonization is not needed.

7 CONCLUSION

The interpretation and modelling of faults is an essential step during the process of 3D geological modelling, because faults form the most important discontinuities separating blocks of different properties and behavior. Furthermore, in most modelling environments and software solutions, faults (or fault networks) build the structural framework for further modelling steps (i.e. horizon interpolation, volume generation). Nevertheless, interpretation and modelling of faults, which is most often performed during an early stage of model generation is challenging, especially if cross-border regions are analyzed. Heterogeneous data sets, independent exploration concepts, technical limitations and legal restrictions often exclude the existence of a uniform data base. Consequently, inconsistent data, variable processing techniques as well as interpretational and regional geological concepts provide various challenging issues for cross-border fault harmonization.

To perform an efficient cross-border fault harmonization project the following questions have to be clarified during an early phase of the project: (1) Are there any legal restrictions or technical discrepancies between the project partners? If raw data and large parts of existing models can be exchanged across political borders, this information can be made available for all partners. Hence, all partners are enabled to check the consistency of their interpretations, data and modelling results across borders. (2) Which situation and state of knowledge exist in each project partners research at the beginning of the harmonization process? Are there any discrepancies in the nomenclature of structural elements? If geological interpretations were performed individually, often various kinds of fault interpretations (e.g. interpreted depth maps vs. 3D structural models; WP1) exist. Depending on the level of detail and scales of maps often different nomenclatures are used for structural elements. Furthermore, earlier generalization processes lead to significantly variant data. Hence, these data cannot directly be compared. A very efficient way to solve such discrepancies is to establish a structural framework (cf. the GeoERA GeoConnect³d project) or to link all existing data in databases, which provide the possibility to semantically link all existing fault objects (cf. GeoERA HIKE project). (3) Which kind of raw data is available on both sides of the border? How was the data processed and interpreted? In many cross-border areas the target for exploration and thus used methods (e.g. detailed seismic reflection vs. potential geophysics) and data acquisition (e.g. different target horizons for prospection; cf. WP3) strongly differs. In such scenarios it would be best to only use raw data and, first, establish unified and harmonized processing algorithms (e.g. cross-border harmonized velocity models usable for time-depth conversion of seismic reflection; WP3). Nevertheless, such unified algorithms need much effort, especially if several hundreds of seismic sections must be analyzed and reprocessed. (4) Are there any discrepancies between interpretational and regional geologic concepts across borders? In some cases, political borders even follow regional geologic boundaries. Hence, significant changes in interpretational and regional geologic concepts probably become obvious in cross-border areas. The most efficient solution to overcome these issues is an enhanced transfer of knowledge across borders. Only, if all partners are able to understand the geological situation on both sides of a border, unified and harmonized interpretations are possible. Furthermore, the integration of additional data (e.g. harmonized geophysical potential field data; WP2, WP6) and interpretational concepts and methods (e.g. cross-section balancing and restoration techniques; WP6) significantly constrain individual interpretations.

As shown in all work packages of the 3DGEO-EU project, there is a wide range of challenges for fault harmonization. All these issues typically evolve from independent data sets, interpretations and concepts and are hampered by legal restrictions and technical limitations. Only if an efficient exchange of data and, if the latter is not possible, a transfer of knowledge is enabled, cross-border fault harmonization can be performed successfully. Thereby, fault (and model) harmonization across political borders strongly depends from technical, interpretational and legal limitations. An efficient harmonization thus needs a huge amount of communication, the possibility of data and knowledge exchange, scientific independence across borders and political decisions and frameworks, which help to establish cross-border to pan-European research areas where scientists can come together to perform joined and integrated research projects without political limitations.

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