



ARBEITSBERICHT NAB 23-17

3D Seismic Interpretation of Stratigraphic
Horizons and Structures in Time Domain
Jura Ost

September 2024

**Nagra | National Cooperative for the
Disposal of Radioactive Waste**

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KEYWORDS

Seismic, seismic interpretation, 3D, site comparison, faults,
undisturbed area, JO, Jura Ost

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

Abstract

A 3D seismic evaluation was carried out for the Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) siting regions in the course of the repository site selection process. The aim is to identify and map the most undisturbed area for each of these three siting regions. It is important to highlight that this report focuses on seismic-scale observations. The development of geological concepts and the abstraction to subseismic scale interpretation is part of a multi-scale and multi-disciplinary integration and is captured in NTB 24-17 (Nagra 2024d).

While 3D seismic data greatly improve the imaging of the subsurface, the challenge of separating seismic reflections associated with geological features and seismic artefacts represents the key pitfall in the interpretation results, especially for onshore data with complex and heterogeneous shallow geology. Interpreting 3D seismic data is therefore a complex process that involves multiple steps. These can include some looping or repetition of the workflow steps, and require a deep understanding of geophysics, geology and seismic data processing.

In addition, for the purpose of site selection, emphasis was placed on the comparability of the seismic interpretation results. Despite being located in the Molasse Basin and being ~20 km apart, the Jura Ost, Nördlich Lägern and Zürich Nordost siting regions are demonstrably characterised by a different subsurface architecture. Therefore, to ensure a comparable and balanced evaluation, not only was seismic data reprocessing designed such that all the processing input parameters and workflows were consistent across the three seismic surveys, but also an interpretation approach with rigorous criteria was established and implemented in the interpretation of the seismic surveys, covering the three siting regions. Consequently, importance was given to the methodology section, which is repeated in the three seismic interpretation reports for the respective siting regions (NAB 23-17, NAB 23-18 and NAB 23-19), where the applied workflow is illustrated based on site-specific examples.

The resulting horizon - fault framework in JO siting region includes the interpretation of 7 key horizon markers:

- (i) 159.8 Oxf 700 – Intra Wildegg
- (ii) 159.8 Oxf 975 – Top Dogger
- (iii) 170.9 Aal 300 – Top Opalinus
- (iv) 192.9 Sin 200 – Near Top Klettgau
- (v) 227 Car 200 – Near Top Bänkerjoch
- (vi) 237 Lad 200 – Intra Bänkerjoch
- (vii) 251.9 Per 100 – Near Base Mesozoic Unconformity

and 3D fault interpretation in the form of fault sticks / planes.

The seven horizons were selected to represent key surfaces for the definition of the host rock (Opalinus Clay) as well as the upper and lower confining geological units, while ensuring interpretability (i.e. imaging continuity) to reduce the picking uncertainty across the structurally complex zones.

Confidence in the interpretation results was established by an in-depth analysis of the uncertainties associated with the interpretation of seismic data. Uncertainties associated with data quality were mitigated by the use and comparison of all the seismic processing vintages, while the impact of human bias was assessed by superimposing all the available interpretations from different interpreters. Different seismic processing datasets interpreted by different interpreters resulted in a technically robust, consistent and comparable image of the three investigated siting regions.

The evaluation performed shows that the Jura Ost siting region can be subdivided into four main structural domains: (i) Northern Fold-and-Thrust Zone (NFTZ, i.e. Mandach Thrust), (ii) Southern Deformation Zone (SDZ, including structures such as the Brugg Structure Zone, Gallenkirch Structure Zone, Villnachern Fault), (iii) the Effingen Fault Zone (EFZ) and (iv) the Central Panel (CP, which includes the Siggenthal Anticline). Seismically undisturbed areas can be recognised across the Central Panel and the northern sector of the Southern Deformation Zone. If only faults affecting the lower Mesozoic succession (i.e. faults tipping up below the 174.7 Toa 100 – Top Lias) are considered, a large undisturbed area with an extent of 31 km² can be delimited.

A divergence in the fault distribution and density is observed when comparing seismic-scale faults mapped in 2023 (this report) with previously proposed structural maps (Nagra 2022, NAB 18-34). Such a divergence is directly connected to the distinction between structural lineaments proposed for the ASR mapping, where “structural” seismic discontinuities (deformation zones) are undifferentiated between faults and folds, and when considering type C faults (attribute response only) from the 2018 interpretation (Nagra 2019). The comparison considering only type A faults (fault interpreted both on amplitude sections and attribute slices: 2018 and 2022 interpretation vintage) results instead in a consistent image with the proposed interpretation of the fault distribution in the JO siting region, suggesting that the observed difference in the seismic fault pattern is controlled by attribute-derived lineaments and their geological interpretation.

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List of Acronyms

AGC	Automatic Gain Control
AOI	Area of Interest
ASR	Auswahl der Standorte für die Vorbereitung der Rahmenbewilligungsgesuche Site Selection in Preparation for General Licence Application
CP	Central Panel
CRS	Common Reflection Surface
DEM	Digital Elevation Model
EFZ	Effingen Fault Zone
GL	Ground Level
JO	Jura Ost
JO-15	Jura Ost seismic survey acquired in 2015
NAB	Nagra Arbeitsbericht (Work Report)
NAGRA	National Cooperative for the Disposal of Radioactive Waste
NFTZ	Northern Fold-and-Thrust Zone
NL	Nördlich Lägern
PreSDM	Pre-Stack Depth Migration
PreSTM	Pre-Stack Time Migration
PreSTM-ref	Pre-Stack Time Migration zero phase used as seismic reference dataset
QC	Quality Control
QLP	Quick Look Processing
REP	Refinement Processing
RMO	Residual Moveout
SDZ	Southern Deformation Zone
SG	Siggenthal Anticline
SRD	Seismic Reference Datum
TDR	Time-Depth Relationship
TWT	Two-Way Travel Time
VSP	Vertical Seismic Profile measured in a borehole
ZNO	Zürich Nordost
ZOVSP	Zero-offset vertical seismic profile

1 Introduction

In the course of the repository site selection process, in-depth 3D seismic investigations were conducted in the three remaining siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) located in the Molasse Basin of Northern Switzerland (Fig. 1-1). The main objective was to identify the most suitable (i.e. undisturbed) areas in these regions based on the integrated analysis of information from multiple data sources.

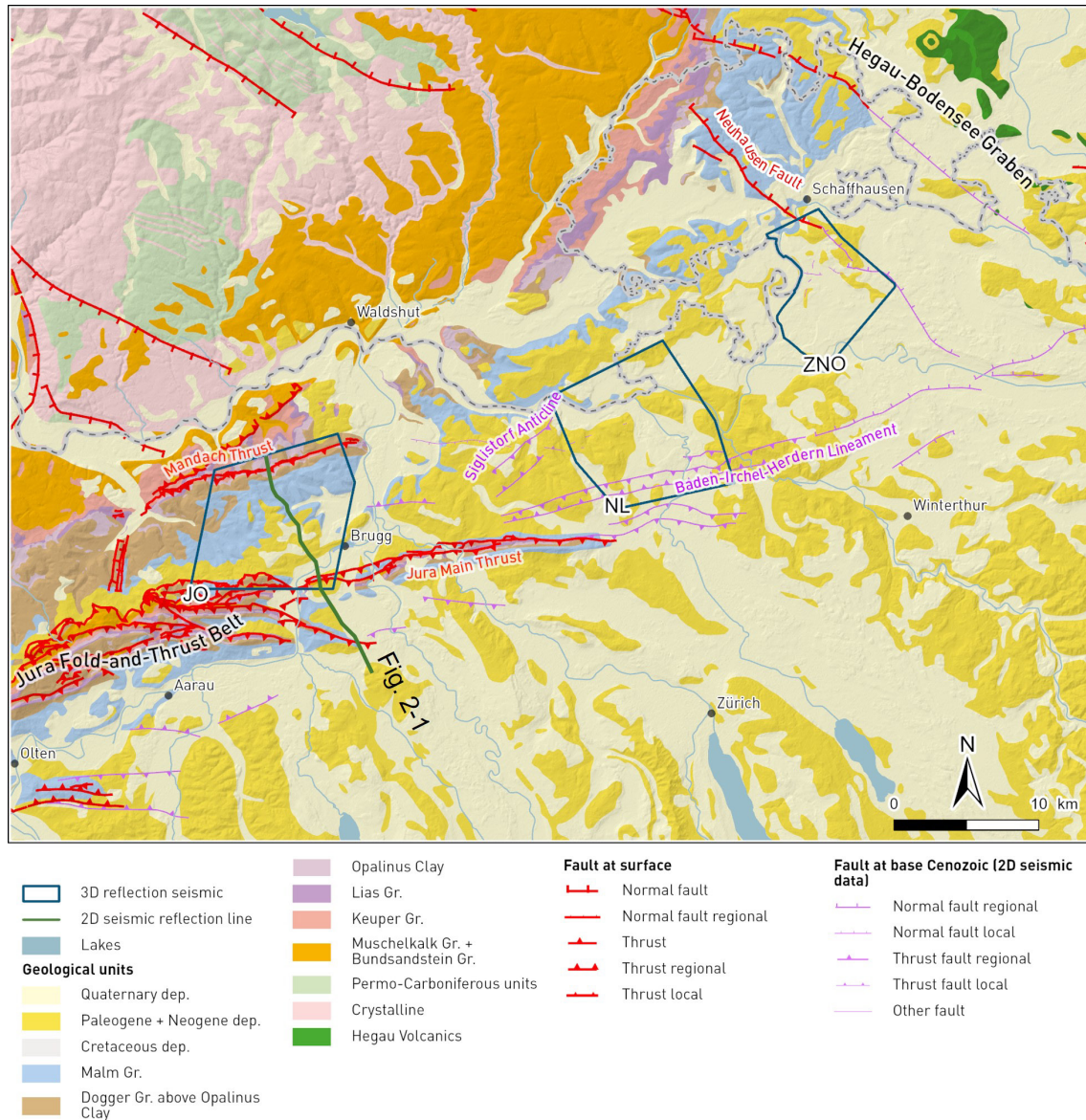


Fig. 1-1: Regional geological map showing the location of the three siting regions: JO, NL and ZNO

Modified after Nagra (2024d)

Green line is the 2D 11-NS-06 regional seismic line shown in Fig. 2-1.

This report will elaborate on the work carried out to seismically characterise the subsurface in the area covered by the JO-15 seismic survey. A critical challenge in the investigation of the three siting regions is matching the requirement of comparability. Seismic surveys were individually acquired in the Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) siting regions. Even if the reference seismic data over the siting regions were processed to mitigate such differences (Nagra, 2024a), the complexity and variability of the subsurface between the siting regions still remain. Similarly, for the strategy followed within the framework of seismic reprocessing (Pre-Stack Time Migration Reference: PreSTM-ref, Nagra 2024a), a critical requirement for the interpretation methodology is the comparability of its application among the three siting regions. Therefore, a standard workflow (Fig. 1-2) with a rigorously structured approach was established showing that the challenges associated with the data were recognised and understood and that the criteria for stratigraphic and fault interpretation were defined, explained and rigorously implemented.

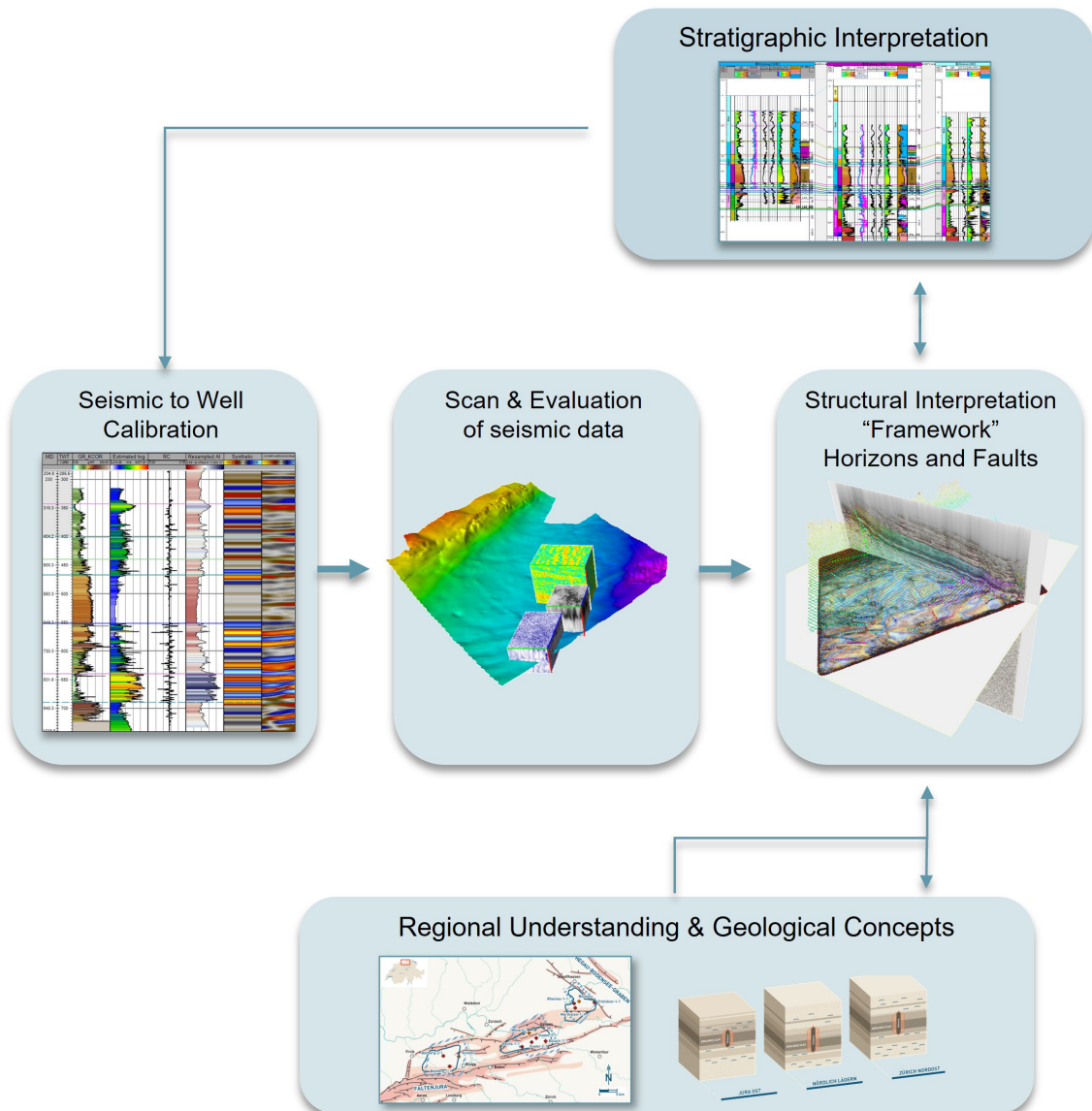


Fig. 1-2: Diagram showing the proposed integrated workflow

Key steps prior to seismic interpretation include the calibration to wells after establishing a robust stratigraphic framework, and the screening of the seismic data to identify major geological features as well as areas that are challenging in terms of interpretation. The regional geological understanding represents the benchmark element for the interpretation results.

The consistency of the methods and criteria applied to the three seismic surveys JO-15, NL-16 and ZNO-97/16, respectively, should provide the pillar for (i) a robust and objective evaluation of the subsurface, overcoming the intrinsic geological variability among the three siting regions, (ii) an understanding of past tectonic disturbances and (iii) the groundwork for predicting future tectonic evolution.

The pillar for comparable analysis across variable subsurface is the developed methodology and its application. Therefore, the other two seismic interpretation reports for the NL and ZNO siting regions (Nagra 2024b, 2024c) are similarly structured and partly feature the same content. Strong emphasis was consequently placed on the description and illustration of the methodology section, while the interpretation results are discussed in the three main sections: (Section 5.1) seismic data quality, where seismic features of uncertain origin are discussed and classified; (Section 5.2) key stratigraphic horizons, and (Section 5.3) fault interpretation, which includes key observations on the distribution, density and style of seismic-scale deformation. As in many seismic interpretation reports, while trying to keep observations and interpretation separate, explaining observations can fall into geological interpretations of the recognised seismic patterns.

It is important to highlight that this report focuses on seismic-scale observations, only. The integrated interpretation, the development of geological concepts and the abstraction to subseismic scale interpretation is part of a multi-scale and multi-disciplinary integration, which is outlined in NTB 24-17 (Nagra, 2024d).

Differently from other Nagra reports, and to ensure consistency in terminology with the seismic interpretation workflow, the term well is preferred over borehole.

2 Geological setting

The Jura Ost siting region is located in Northern Switzerland, just north of the Jura Main Thrust. (Fig. 1-1). The Jura Fold-and-Thrust Belt is part of the detached Alpine foreland. The Molasse Basin, located south of it, is a flexural foreland basin which formed as a result of the building-up of the Alps.

The area covered by the JO-15 seismic survey is delimited by the Jura Main Thrust to the south and by the Mandach Thrust to the north. The Jura Main Thrust is part of the Internal Jura (Fig. 1-1, Fig. 2-1). It accommodates 2 to 5 km of shortening decreasing towards the east (Jordan et al. 2015) and is interpreted to be a system of thrust faults soling out in the Triassic evaporites which acted as a regional detachment. The Mandach Thrust is located approximately 6 km north of the Jura Main Thrust. It strikes roughly E-W and can be traced at the surface for ~15 km (Diebold et al. 2006, Bitterli-Dreher et al. 2007). It is classically interpreted as décollement-based thrust strongly influenced by pre-existing structures (e.g. Laubscher 1986). Major faults underlie the Jura Main Thrust and the Mandach Thrust and are located at the southern and northern border of the Konstanz - Frick Trough, respectively (Madritsch et al. 2018). These inherited ENE-striking basement features (fault step with basement topography) were interpreted as key structures concentrating the deformation and influencing the structural style of the overriding Jura Fold-and-Thrust Belt (Caer et al. 2018).

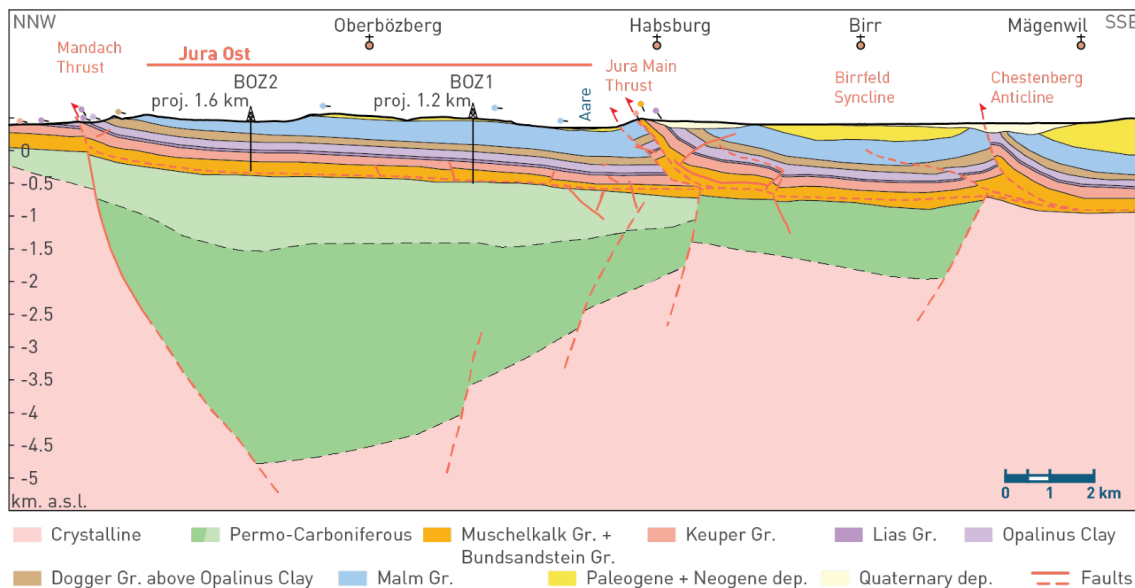


Fig. 2-1: Geological section drawn along the 2D seismic reflection line 11-NS-06

The section is based on Meier et al. (2014). Results from 3D seismic reflection interpretation were integrated within the 3D seismic perimeter. The symbols above the topography indicate bedding dip measured in nearby outcrops. Gr.: Group, Dep.: deposits (Nagra 2024d). Line location shown in Fig. 1-1.

In addition to the inherited basement topography, deformation of the Mesozoic-Cenozoic sedimentary cover is strongly controlled by the presence and distribution (thickness) of salt in the Muschelkalk Group evaporites (Sommaruga et al. 2017). The large-scale Pre-Mesozoic structure in the area of interest is Permo-Carboniferous Konstanz - Frick Trough (Diebold 1991, McCann 2008, Madritsch et al. 2018). The roughly ENE-WSW-striking trough is completely buried by Mesozoic strata. Seismic reflection data and gravity data indicate a more complex architecture with NW-SE-striking and NNE-SSW-striking faults as important segmenting elements (Madritsch et al. 2018, Nagra 2014 and references therein), although the limited well penetrations do not provide a good calibration and estimation of the variability in facies and thickness of the sedimentary fill.

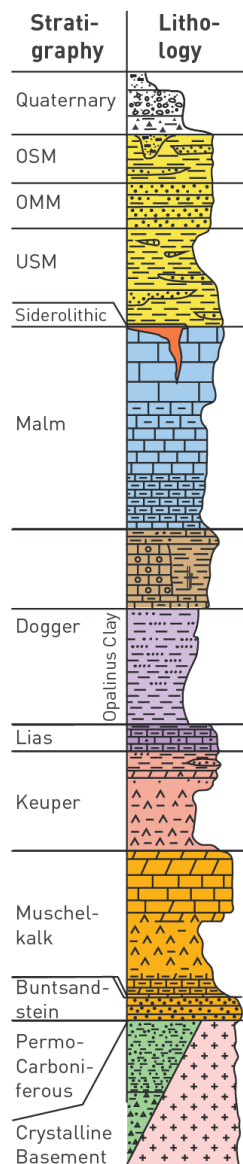


Fig. 2-2: Simplified lithological column of Northern Switzerland

Detailed description of the litho- and stratigraphic units is captured in NTB 24-10 (Nagra 2024d).

The area of interest comprises mainly the Mesozoic sedimentary sequence, which evolved in an epicontinental marine environment (Fig. 2-2; Geyer & Gwinner 1991, Nagra 2024d), with successive periods of marine transgressions and regressions resulting in the deposition of terrestrial, evaporitic and shallow to deep marine sedimentary rocks (marls, claystones, limestones). The Mesozoic time period has long been considered to be characterised by relative tectonic quiescence (Naef et al. 1995). However, several authors have questioned this view and have inferred syndepositional tectonic activity, based mainly on the observation of lateral changes in the sedimentary facies that seem to correlate with Palaeozoic basement structures (Allenbach 2001).

The Molasse Basin is characterised mostly by Cenozoic sediments linked to the formation and erosion of the Alps. It initiated as a flexural foreland trough in Eocene times and, with the initiation of a major décollement within the Middle Triassic salt-rich evaporite series (Muschelkalk and Keuper Groups) in Early-Middle Miocene times, subsequently evolved into a detached and transported wedge-top basin (e.g. Becker 2000). Lower Triassic sandstones lie beneath the main décollement and are therefore part of the mechanical substratum.

In synthesis, the area of investigation is located at the NE edge of the Jura Fold-and-Thrust Belt, in a zone where the décollement tapers out and where basement-involved deformation - including the reactivation of inherited faults - may have occurred (Fig. 2-1, Fig. 2-3, Nagra 2024d). The main inherited structures are linked to pre-existing Permo-Carboniferous graben faults (shoulder-parallel and oblique). However, further extensional faulting / fault reactivation may be linked to both Palaeogene flexure of the foreland plate and development of the Oligocene Rhine Graben rift (which is part of the European Cenozoic Rift System, e.g. Laubscher 1986).

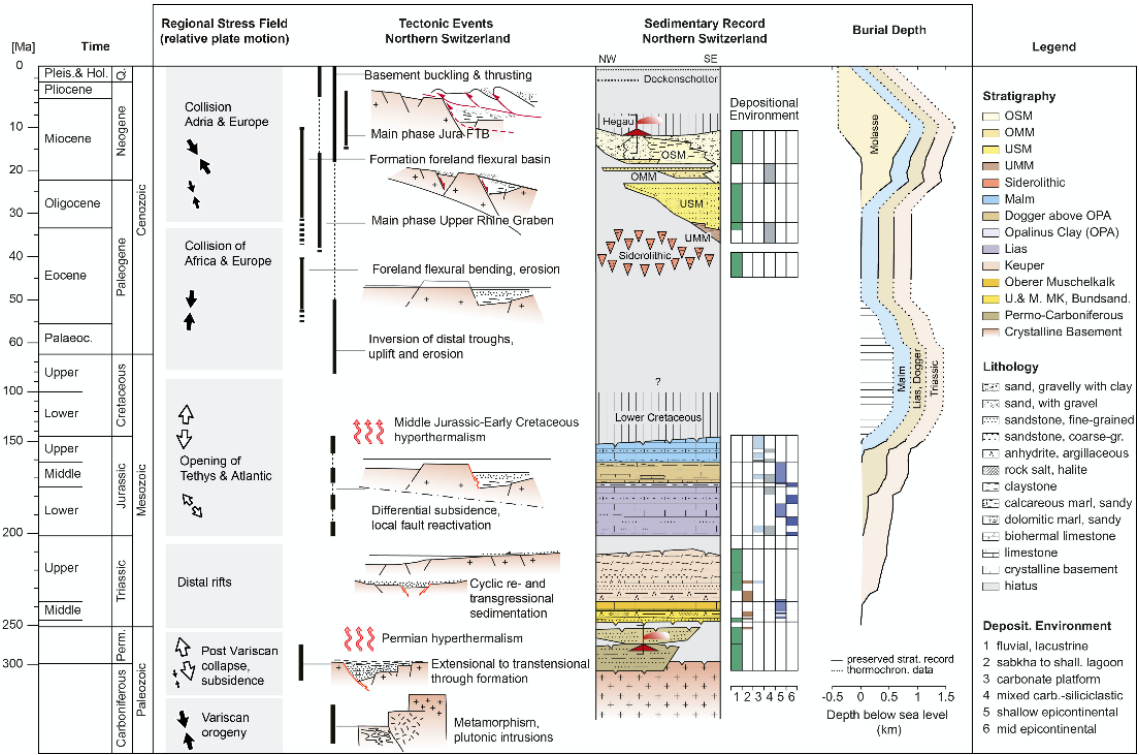


Fig. 2-3: Timeline summarising the geological evolution of Northern Switzerland
Nagra (2024d)

3 Dataset

The seismic interpretation performed in this study relied on the integration of 3D seismic data originating from different seismic processing vintages and the integration with key wells. (Fig. 3-1). Within the seismic survey perimeter, two wells, which were drilled during Nagra's deep borehole campaign (Bözberg-1 and -2, Nagra 2021a, 2021b), and a pre-existing well (Riniken) were selected, together with standard wireline log data and vertical seismic profile (VSP) surveys with reliable data quality available for the Bözberg-1 and -2 wells.

Note that for consistency with the seismic interpretation workflow terminology, the term well is preferred to the term borehole.

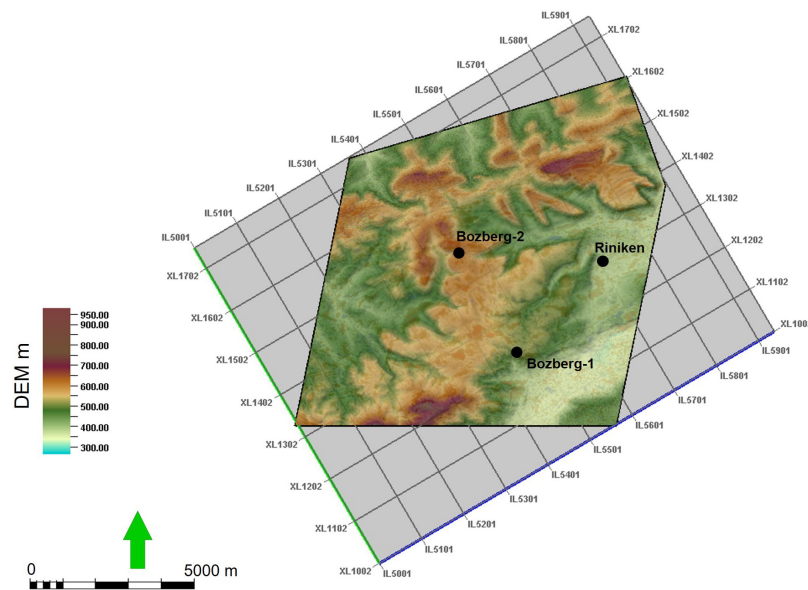


Fig. 3-1: Seismic data and well locations on the Digital Elevation Model (DEM)

Three wells are available within the perimeter covered by the JO-15 seismic survey and were used for seismic interpretation.

The integrated dataset was loaded in Petrel software for interactive interpretation. The Petrel project was set up using a seismic reference datum of 800 m, a replacement velocity of 3,600 m/s and an X/Y coordinate system identical to that of the Swiss Reference System CH1903.

3.1 Seismic dataset

The 3D seismic data was acquired in 2015. The survey covered an area of $\sim 96.3 \text{ km}^2$ and contains 939 inlines, trending $\sim$ -NW-SE, and 749 crosslines, trending $\sim$ -SW-NE, with a line spacing of 15 m (Fig. 3-2).

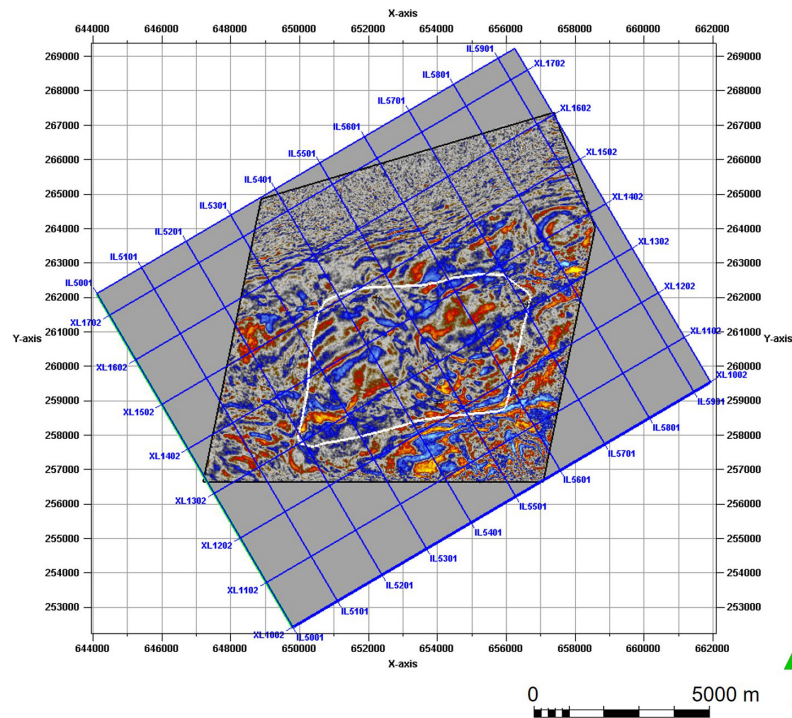


Fig. 3-2: JO-15 seismic survey (with grid coordinates). White polygon shows the perimeter of the PreSDM processing

Since 2018, Nagra has processed and reprocessed 3D seismic data using different imaging technologies and parameterisation. The following seismic processing vintages are available and were used in the interpretation (Tab. 3-1, Fig. 3-3, Fig. 3-4, Nagra 2019, Nagra 2024a).

Tab. 3-1: Summary of the available seismic processing vintages

Category	Data Type	Domain	Details
QLP zero-phase	Post-stacked zero-phase normal SEG polarity	TWT	Data conditioning (deconvolution / noise suppression). Static correction down to flat pseudodatum (100m.a.s.l)
PreSDM minimum- phase	Post-stacked minimum-phase normal SEG polarity	Depth	Migration from topography. Near-surface velocities from first arrival traveltime tomography
PreSTM-ref minimum- phase	Post-stacked minimum-phase normal SEG polarity	TWT	Input data from QLP data conditioning. Static correction to geological pseudodatum. Postprocessing RMO / Trimstatics.
PreSTM-ref zero-phase	Post-stacked zero-phase normal SEG polarity	TWT	As PSTM-ref, with well based zero-phase filter applied

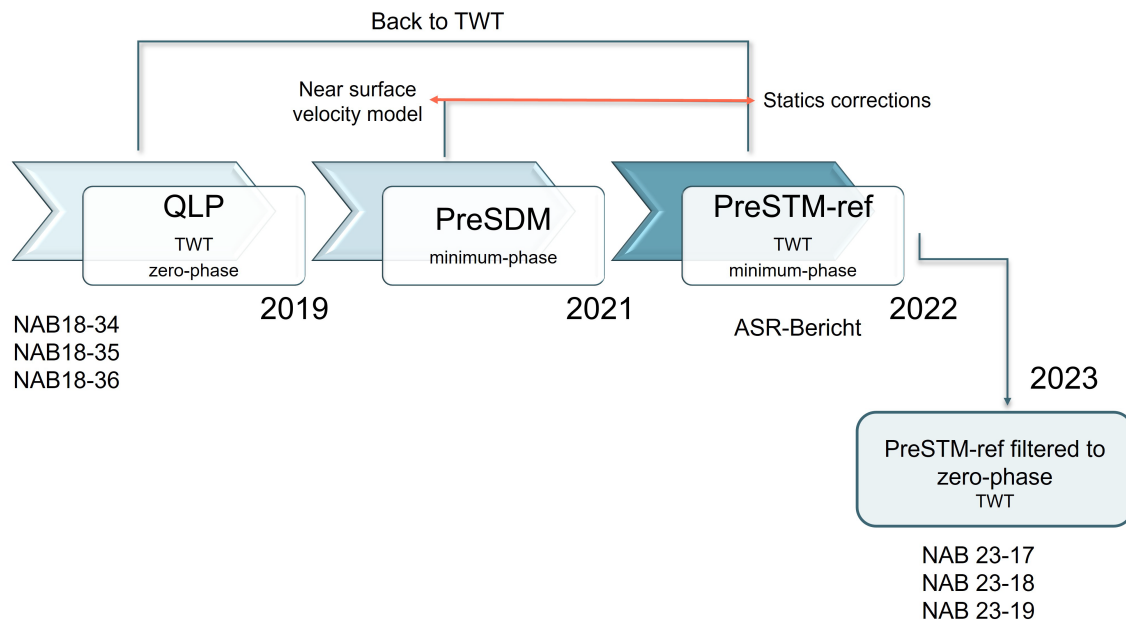


Fig. 3-3: Seismic processing simplified roadmap

The main processing products represent the dataset for the seismic interpretation. QLP is Quick-Look Processing, PreSDM is Pre-Stack Depth Migration, PreSTM is Pre-Stack Time Migration.

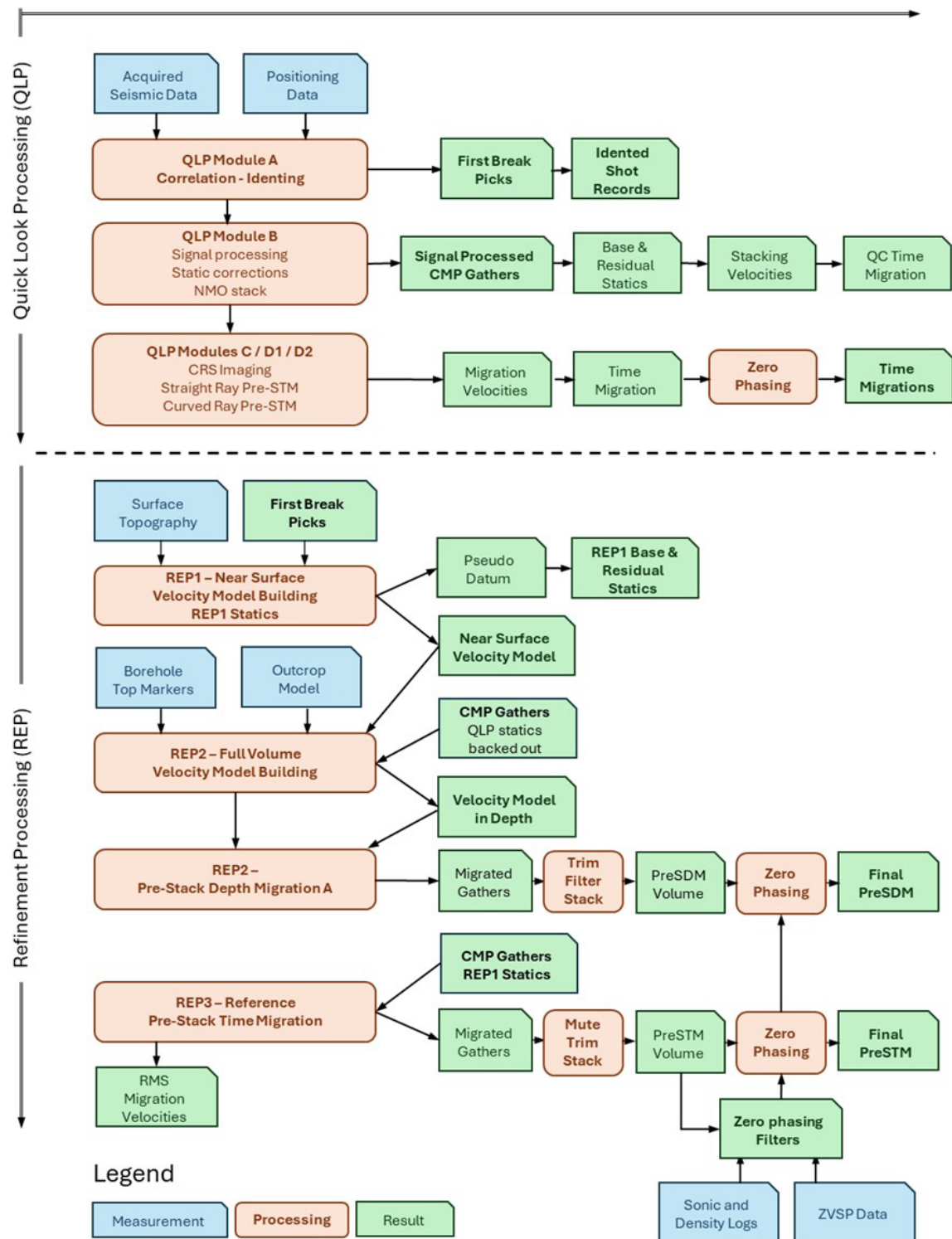


Fig. 3-4: Processing flowchart summarising the processing steps applied in 2017 and 2020/21 Nagra (2024d)

3.1.1 Quick Look Processing (zero-phase)

In 2018, time-domain processing, generally referred to as Quick Look Processing (QLP, Hölker & Birkhäuser 2018) was performed. It follows a modular, multi-method approach particularly aimed at exploring the strengths and weaknesses of various technical approaches and imaging uncertainties and results in several seismic processing products. A number of different seismic imaging products were screened as a result of QLP, and processing vintage C6 was selected since this vintage showed very coherent reflectors in comparison with the other processing products (Nagra 2019). The data were stacked with residual moveout (RMO) correction and post-stack processing, and PreSTM processing was carried out using geometry-regularised data after a common reflection surface (CRS; Nagra 2019). The original seismic data were delivered in minimum-phase. For interpretation purposes, it is advisable to use zero-phase seismic data as these have relative amplitude maxima at impedance contrasts, whereas minimum-phase seismic data have relative amplitude maxima below impedance contrasts. Therefore, zero-phase of the seismic data was achieved by convoluting the minimum-phase seismic data with a zero-phase operator over a length of 2,000 ms (Hölker & Birkhäuser 2018, Nagra 2019).

3.1.2 PreSTM and PreSDM (minimum-phase)

Following the Quick-Look Processing (QLP), a so-called Refinement Processing (REP) was carried out. Starting from the Quick-Look signal processing, a new shallow velocity model and corresponding statics were derived. This was followed by a few iterations of Pre-Stack Depth Migration (PreSDM), and the PreSDM-A volume was generated and selected (here referred simply as PreSDM); and finally, a Pre-Stack Time Migration created the PreSTM-ref volume (Sections 3.1.3 and 3.1.4). For the QLP, a flat pseudo datum at 100 m above sea level was used, above which the derived velocities were replaced with a velocity of 3,600 m/s to calculate the corresponding base (refraction) statics. The considerable lateral variability in shallow velocities in combination with the relatively shallow target implied that the basic vertical ray assumption behind any static model was violated. Therefore, for the refinement processing the pseudo datum level was made spatially variant at a level where the velocity of the derived shallow velocity model was estimated to be equal to the replacement velocity. Key processing workflow steps (Fig. 3-4, Nagra 2024a) include (i) the removal of earlier statics (elevation, refraction, residual) from seismic, (ii) REP tomography using Eikonal solver, (iii) a spatially varying pseudo datum, (iv) the calculation of corresponding refraction static- and station-consistent residuals (based on first-break picks), and (v) seismic-based residual statics calculations (various iterations including velocity picking). Note that for the JO-15 seismic survey, only a post stamp (central area of the survey) was selected for the PreSDM reprocessing (Fig. 3-2, Fig. 3-5).

3.1.3 Pre-Stack Time Migration PreSTM-ref (minimum-phase)

Anomalies (notably in the overburden and Opalinus Clay) were observed in the PreSDM velocity models, which are not supported by well data and regional geological understanding. Such velocity anomalies align with observed local variations of top structure morphologies but they do coincide with geological features (Fig. 3-5), impairing confidence in depth-migrated cube seismic imaging. Several attempts demonstrated that the realisation of a reliable Pre-stack Depth Migration (PreSDM) cannot be easily achieved due to the large variability in shallow geology-associated parameters (statics) and overburden heterogeneities. Such geological variability is even stronger among the three siting regions (Fig. 3-6). Taking into account that the seismic data should provide critical input for the siting region selection (i.e. presence, position and density of structural lineaments and the host rock geometry), comparability of the data among the three siting regions becomes the key parameter to ensure the same level of resolution and uncertainty in the data quality and associated interpretation. Even a perfect PreSDM processing would be strongly

site-tailored, therefore missing the overarching equivalence between the siting regions. PreSTM-ref processing was therefore designed such that all the processing input parameters and workflow were similar across the three seismic surveys over the siting regions.

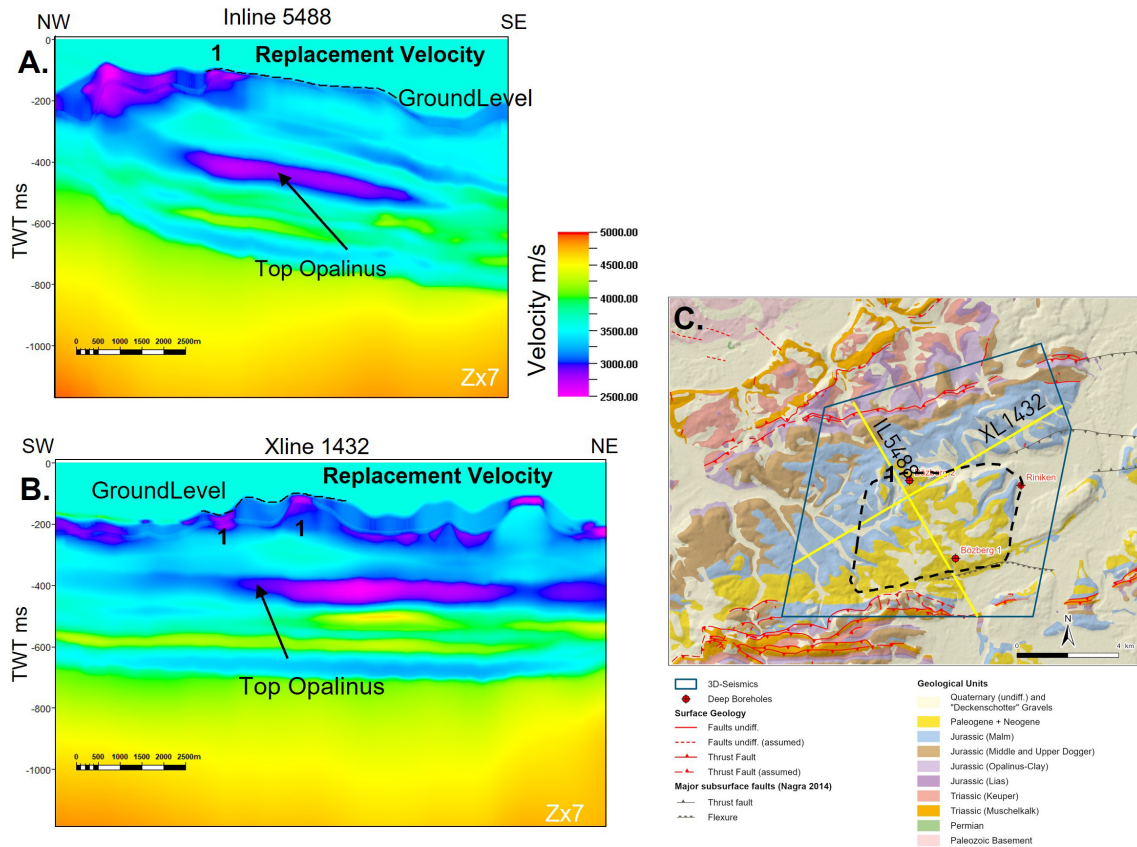


Fig. 3-5: PreSDM velocity model

A. Inline 5488 and B. Crossline 1432 displaying the (smoothed) velocity model from PreSDM showing the major velocity anomalies in the shallow levels and within the Opalinus Clay. The shallow geology anomalies (1) do not directly link to geology. In the geological map (C.) these anomalies seem to correspond to outcropping Malm carbonate, which should have a higher velocity than the surrounding Quaternary and Palaeogene / Neogene deposits. Note that the PreSDM was performed only for the central area of the JO-15 seismic survey (dashed black line in A., B. (plotted at ground level) and C.).

The workflow (Fig. 3-4, Nagra 2024a) includes (i) the implementation of the refinement statics, (ii) data azimuth / offset regularisation with CRS, (iii) migration velocity update, (iv) isotropic (straight ray) migration, (v) RMO picking and application, (vi) trim statics and automatic gain control (AGC; 1,000 ms), (vii) stack and time demigration and depth remigration.

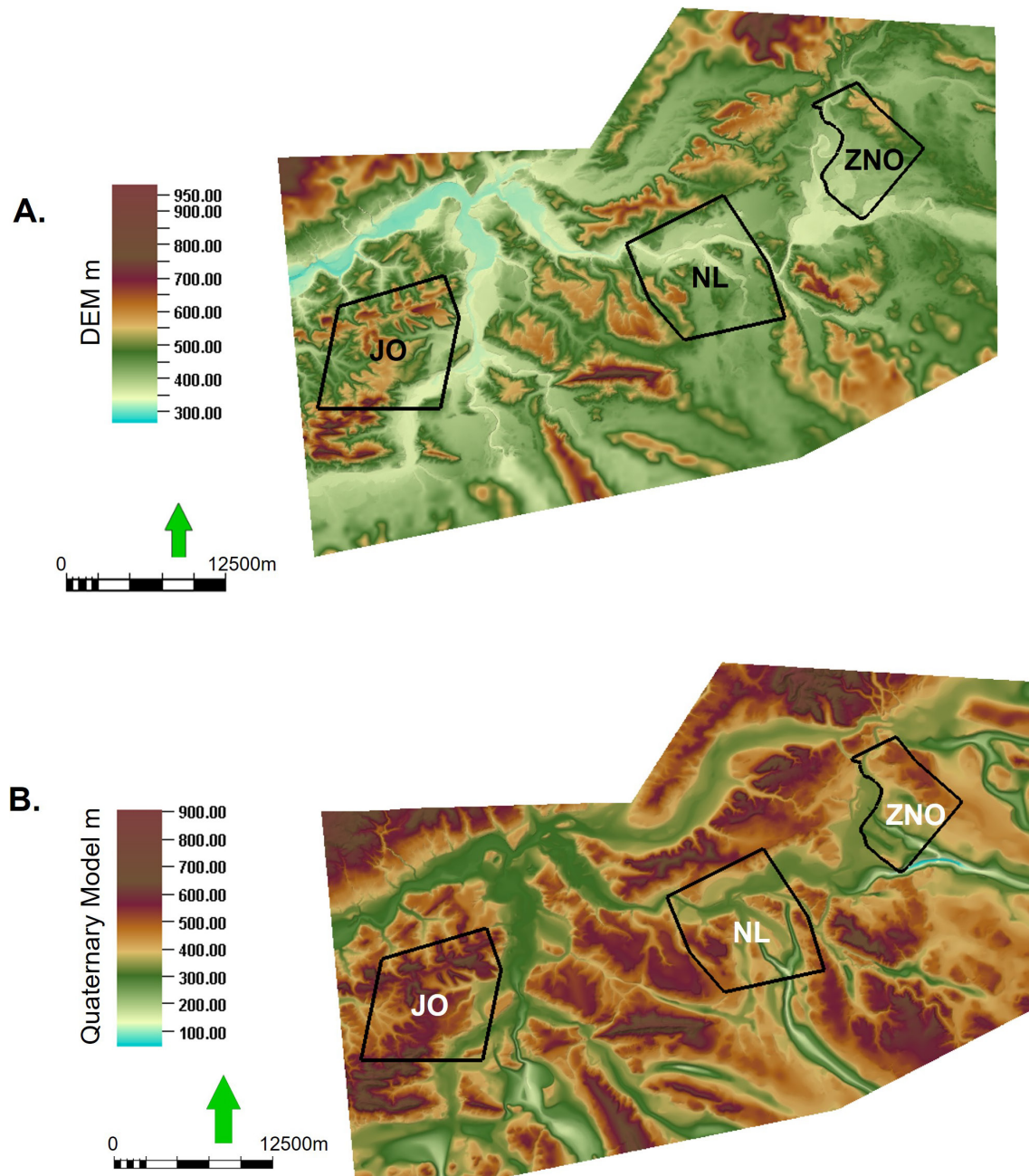


Fig. 3-6: Morphological complexity of the shallow geology has a direct impact on the seismic imaging

A. Surface topography (digital elevation model) and B. Base Quaternary model across the area of the three siting regions.

While this might not be the best seismic processing approach for each individual survey, it best serves the objective of obtaining comparable images for the three siting regions. PreSTM-ref shows a strong improvement in imaging the deformation zones compared to the QLP dataset (Fig. 3-7) and thus was determined adequate for horizon and fault interpretation across undisturbed and structurally complex areas.

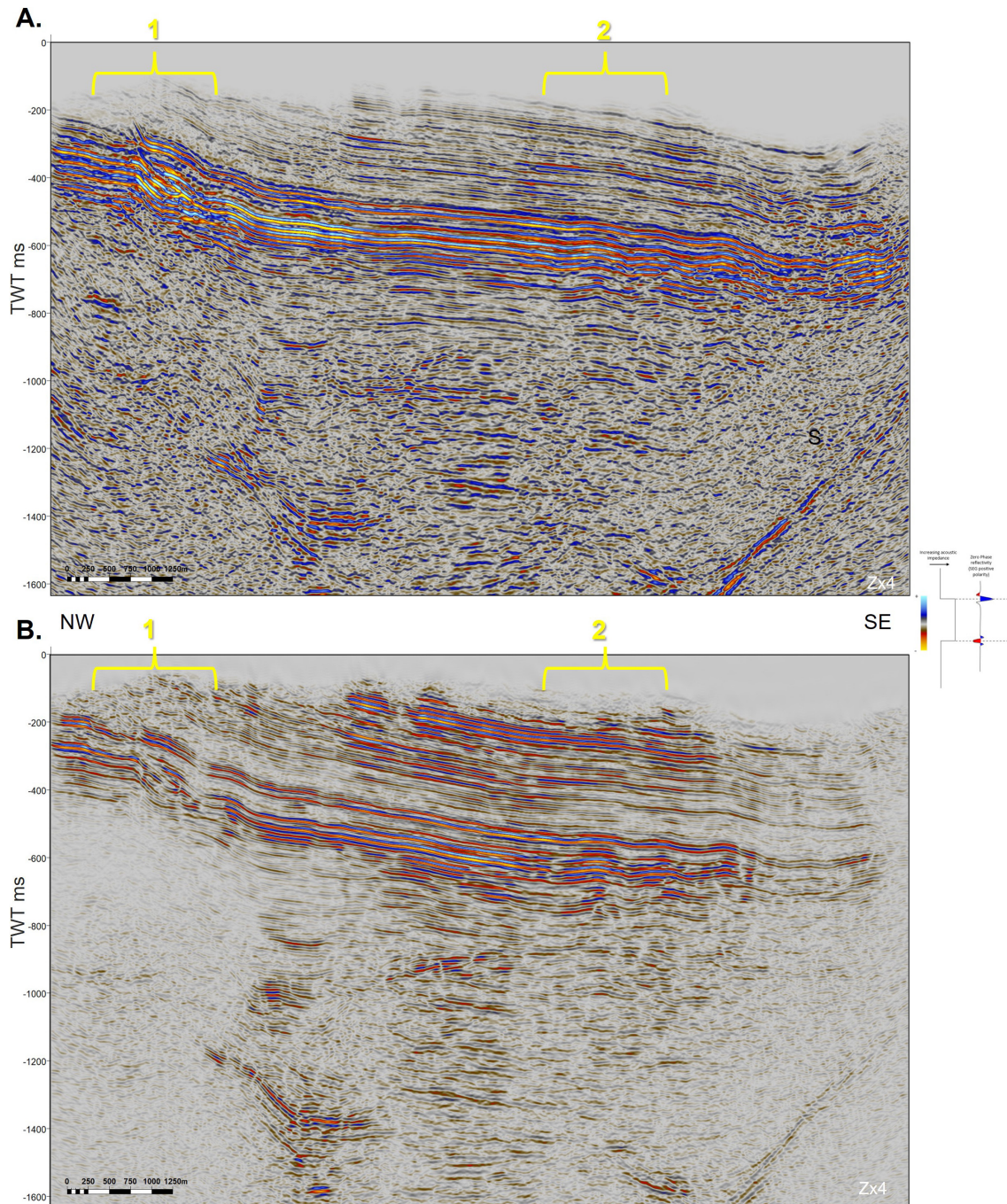


Fig. 3-7: Seismic section showing processing vintage comparison

Inline 5486 from A. QLP and B. PreSTM-ref. Note the improved seismic imaging in the PreSTM-ref data over the northern (1) and central (2) structurally complex zonesa.

3.1.4 Pre-Stack Time Migration PreSTM-ref (zero-phase)

The minimum-phase seismic data were converted to zero-phase by means of a zero-phase operator. As in the case of the QLP dataset, the key objectives of this conversion were: (i) to enable the interpreter to match observed events in the seismic to the correct acoustic impedance contrasts in the well logs, (ii) to shift the seismic data to the roughly correct TWT by applying a best-estimate zero-phase filter. The phase filtering exercise used the following workflow:

- Density and sonic log editing followed by synthetics versus VSPs comparison to verify log quality, generating a zero-phase synthetic matching the VSP corridor stack.
- Generate a minimum-phase synthetic to match the PreSTM seismic using a modelled spectrum to derive the minimum-to-zero-phase filter for this.
- Use the cross-correlation between the PreSTM and the synthetics to derive an additional phase rotation to apply to the synthetic trace.
- Create two synthetic super-traces by combining the zero-phase and the minimum-phase synthetics of individual wells.
- Calculate a shaping filter between the two synthetic super-traces.
- Applying the shaping filter to the minimum-phase data to obtain the zero-phase data.

Despite the use of a single seismic volume by the interpreter is not an uncommon practice, the use of different processing vintages helps to understand how the seismic signatures, diagnostic for geological features, can be differently imaged. Given that each data type has strengths and weaknesses, and despite selecting the PreSTM-ref cube zero-phase as the reference cube for the evaluation of the siting regions, all the other seismic processing vintages were referenced together and/or in series during the interpretation. This approach is critical with regard to mitigating imaging or interpretation uncertainties, particularly when “special” seismic attributes are generated from the parent survey data.

Note that in the text PreSTM-ref zero-phase is always referred to as PreSTM-ref.

3.1.5 Seismic resolution

A critical issue in the interpretation of band-limited seismic data is the fact that there is a lower limit (imposed by bandwidth and wavelet shape) to the bed thickness that can be uniquely resolved. This limit defines the boundary between “thick” beds (above the resolution limit) and “thin” beds (below the resolution limit). This represents the “dimension” of the geological features that a seismic signature (i.e. measure of minimum vertical or lateral distance between two features) required to resolve the beds separately (Sheriff 1997, Brown 1996, 2011). The vertical resolution has two limits, both resulting from the interaction of the wavelets from adjacent reflecting interfaces:

- (i) Limit of separability: for practical purposes, the tuning thickness can be considered as an indication of the vertical resolution. Fundamentally, the tuning thickness is determined by the compressional velocity of the unit and the wavelength of the seismic pulse (λ), and it is equal to a quarter of a wavelength ($\lambda/4$; Brown 2011)
- (ii) Limit of visibility (Brown 2011), or detectability: the reflection signal merges with the background noise. The limit of visibility depends essentially on the acoustic impedance contrast and the signal-to-noise ratio of the seismic data. As a general rule of thumb, for low impedance contrast with reasonable data quality (high signal-to-noise ratio), the limit of detectability can be around $\lambda/20$ to $\lambda/30$ (Sheriff & Geldart 1995, Sheriff 1997, Brown 2011, Simm & Bacon 2014).

Lateral seismic resolution results from constructive interference over an area of the wavefront called the Fresnel zone (Sheriff 1977, Simm & Bacon 2014). It is, however, not as important for amplitude interpretation as vertical resolution, particularly since 3D migration collapses the Fresnel zone to a small circle (ideally around one half of the wavelength in diameter, i.e. about $\lambda/2$; Sheriff 1985, Herron, 2011).

For the QLP dataset, based on its dominant frequency and velocity, a theoretical vertical resolution of around $\lambda/4$ was estimated, i.e. around 12 m for the Opalinus Clay interval and 25 m for the Triassic Top Muschelkalk – Top Stubensandstein interval (Nagra 2019). Similar calculations were performed for the PreSTM-ref vintage. The limits of separability ($\lambda/4$) and visibility (conservatively assumed to be $\lambda/10$ – medium signal-to-noise ratio) are captured for key stratigraphic intervals in Tab. 3-2.

Tab. 3-2: Estimated vertical resolution (tuning thickness, $\lambda/4$) and detectability ($\lambda/10$) for key stratigraphic intervals

Strat. Name	Formation Name	Frequency mean and bulk max	Velocity (Aver.)	$\lambda/4$	$\lambda/10$
170.9 Aal 300	Top Opalinus	54	2900 m/s	13 m	5 m
		70		10 m	4 m
237 Lad 200	Intra Bänkerjoch	50	3450 m/s	17 m	7 m
		70		12 m	4.9 m
Below 237 Lad 500	Within Muschelkalk Fm	52	5000 m/s	24 m	9.6 m
		104		12 m	4.8 m

3.2 Well dataset

The available wireline logs include typical log suites (e.g. gamma ray, density, porosity, sonic, neutron and caliper from the three vertical wells Bözberg-1, Bözberg-2 and Riniken (Nagra 2021a, 2021b, 1990) and were complemented by edited and quality-checked density and sonic logs using zero-offset VSP (ZOVSP) results for Bözberg-1, Bözberg-2 and Riniken wells.

Unfortunately, the Riniken VSP could not be reconciled with the PreSTM-ref due to the very low-quality data, and therefore only VSP corridors from Bözberg-1 and -2 were used. VSPs are useful in the well-to-seismic tie process because they provide a link between wells and seismic data at the correct scale. The benefits of VSP are numerous (e.g. high-density data sampling that provides high-quality control over the time-depth relationship, phase control, a largely multiple-free upwave corridor stack; Campbell et al. 2005). However, they might not tie exactly to seismic data when different volumes of rock were sampled or/and when a different processing sequence might have been applied.

4 Methodology

Seismic interpretation is the extraction of subsurface information from seismic data. The danger in seismic interpretation is in assuming that everything that it is imaged is geology-related (Brown 2011). Reflection seismic data comprise (i) continuity of reflections indicating geological structures, (ii) variability of reflections indicating stratigraphy, fluids and reservoir fabric, and (iii) noise of various kinds and data defects (generically referred to as seismic artefacts, e.g. acquisition footprints, imprints, multiples, migration smiles). Interpreting 3D seismic data is therefore a complex process that involves multiple steps, including some looping or repetition of the workflow steps, and requires a deep understanding of geophysics, geology, and seismic data processing. For the purpose of the siting region investigations, the analysis and interpretation of the available data followed an integrated multi-step approach (Fig. 1-2): (i) data screening and seismic attribute generation aiming to display and understand the data from different angles and perspectives and to highlight key seismic patterns (ii) seismic-to-well ties providing key input on how to interpret seismic data, (iii) a seismic data interpretation framework resulting in a structural framework (key stratigraphic horizons and faults) and (iv) calibration of the interpretation within a regional framework.

4.1 Data screening

In Step 1, all the available processed seismic vintages are visualised in 3D space. Seismic attributes, which are measurements derived from seismic data, are calculated and analysed (Fig. 4-1). These can provide additional information about the subsurface, such as structural features, depositional architecture up to the lithology and fluid content.

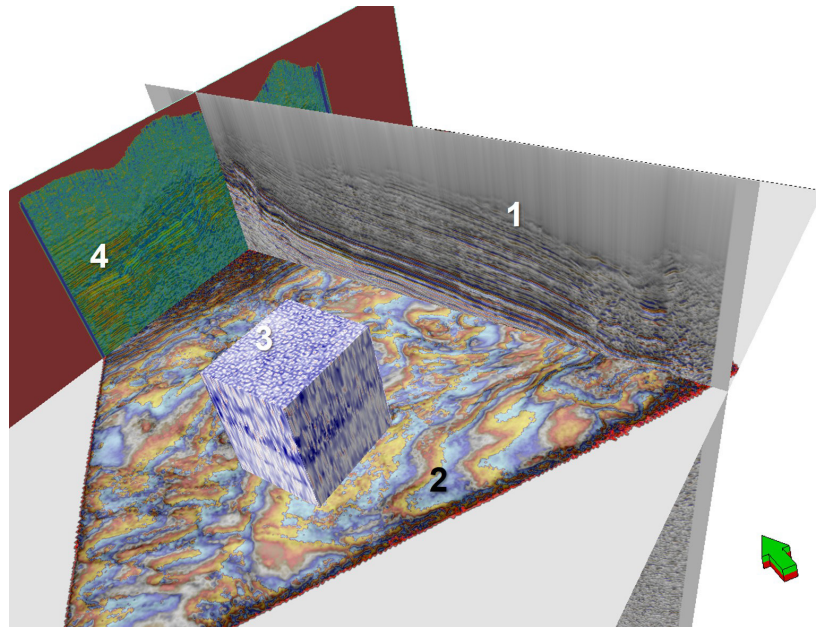
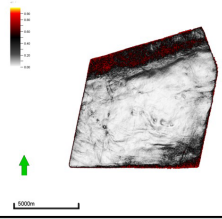
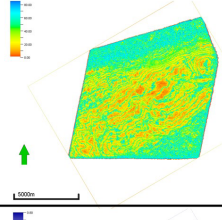
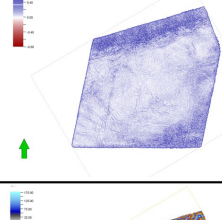
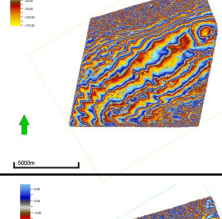
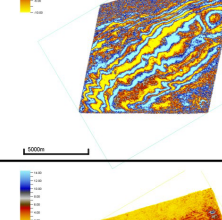
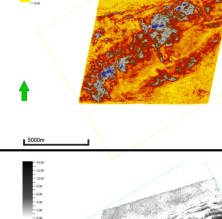
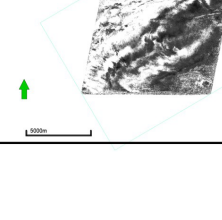


Fig. 4-1: Example of 3D visualisation and screening of attributes

Several attributes are combined and interrogated to gain confidence in the seismic imaging: 1. inline with outcrop look; 2. time slice combination of instantaneous phases and variance; 3. cropped cube of 3D curvature and 4. combo crossline of reflectivity and dip. Green arrow points towards north.

In reflection seismology, a seismic attribute is a quantity extracted or derived from seismic data that can be analysed to enhance information that might be more subtle in a traditional seismic image. This leads to a better geological or geophysical interpretation of the data. Seismic attributes typically provide information related to amplitude, shape and position of the seismic waveforms derived from multi-trace (lateral variations in seismic data) and frequency domain analyses. The selected seismic attributes used in this study are described in Tab. 4-1.

Tab. 4-1: Seismic attributes used in this study

Attribute	Purpose	Impact on fault interpretation	Time slice – 580 ms TWT
Variance	Discontinuity measurements	Fault pattern at a glance on time slide ideal correlation guide	
Structural Dip	Change in reflection dips	Image overall structural trends	
3D curvature	Enhance reflection discontinuity	Small discontinuity but extremely more noisy	
Instantaneous Phase	Lateral continuity of reflectors	Better image of fault cut-offs – better for bigger faults	
RAI (Relative acoustic impedance)	Display acoustic impedance contrast	Highlight trace disruption when used as overlay for reflectivity	
RMS (Root Mean Square)	Enhance amplitude contrasts	Dimming of amplitude	
Envelope-Phase shift 90°	Outcrop look	Enhanced imaging of mechanical breaks	

4.2 Seismic-to-well tie

The three wells (Bözberg-1, Bözberg-2 and Riniken) were used for detailed seismic-to-well ties. The goal for this correlation is to be able to locate the key well markers in the time domain with the highest interpretation confidence (i.e. highest traceability) and to guide their interpretation in order to assess the relationship between the seismic signal and well data. This can be achieved by generating synthetic seismograms. Synthetic seismograms allow to: (i) tie geological markers to seismic horizons, (ii) understand the seismic response to seismic markers (stratigraphy) and define whether these events are single, doublets, or more complex reflections and determine how to pick them, (iii) understand phase and frequency characteristics of seismic data and (iv) generate accurate time-depth relationships (as part of the overall process). A critical and fundamental step, before starting the seismic-to-well tie workflow (or any seismic interpretation), is to define and fully establish (freeze) a complete set of geologically sound stratigraphic markers. Since the 1970s (Sheriff 1977, Vail et al. 1977, van Wagoner et al. 1990, Tipper 1993, Nielsen & Van Weering 1998), it has been well recognised that the most ideal marker types to be used in seismic interpretation are those that subdivide geological time intervals into “genetically related” stratigraphic units and thus identify “time-evolving” depositional sequences. A sequence stratigraphic framework was therefore developed, applying a cross-discipline and multi-scale approach (Fig. 4-2) integrating depositional facies characterisation, vertical stacking pattern, key stratal boundaries identification (core data) with biostratigraphic calibration (i.e. chronostratigraphy and associated timelines) and log calibration (i.e. physical properties and log response character).



In 2023, a consistent stratigraphic framework across the three siting regions was established incorporating the lithostratigraphic knowledge from decades of published studies of outcrops and cores, with the standardised well logs-based formation tops and criteria, with the petrophysical analysis of the logs, and with the depositional / facies interpretation of cores and logs as commonly used in sequence stratigraphy (Fig. 4-3, Nagra 2024d). Stratigraphic tops are coded using: << absolute_age_stage name_sequential number >>, with the sequential number increases from top to bottom (usually from 100 to 999).

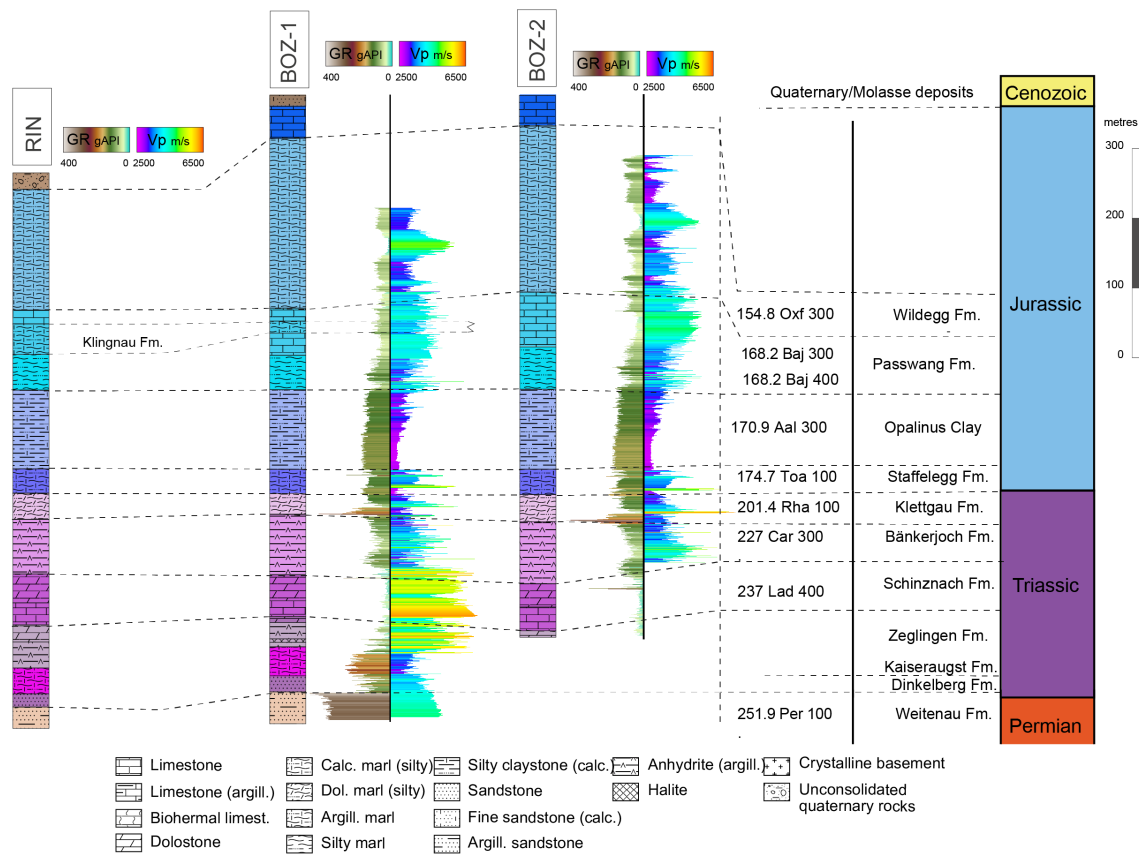


Fig. 4-3: Proposed sequence stratigraphic scheme referenced to lithological formation and petrophysical signature

Well correlation panel flattened on 170.9 Aal 300 – Top Opalinus. Well locations as shown in Fig. 3-1.

Once the stratigraphic framework had been established, synthetic seismograms were generated in Petrel software following a standard workflow (Fig. 4-4, Simm & Bacon 2014).

- Log quality was controlled and edited. Gaps were filled and log spikes corrected.
- The time-depth relationship (TDR) was calculated, directly derived from the VSP dataset. Since the seismic reference datum (SRD, i.e. the datum from which all two-way time (TWT) depth values are measured) and the reference level of the VSPs (ground level) differ, a bulk shift was calculated and applied using a replacement velocity.
- Wavelet was extracted from the seismic data at well location using a statistical approach. The wavelet amplitude spectrum is derived from scanning of seismic traces at intervals of interest, and it is as for seismic data. Phase is assumed to be constant and equal to zero.

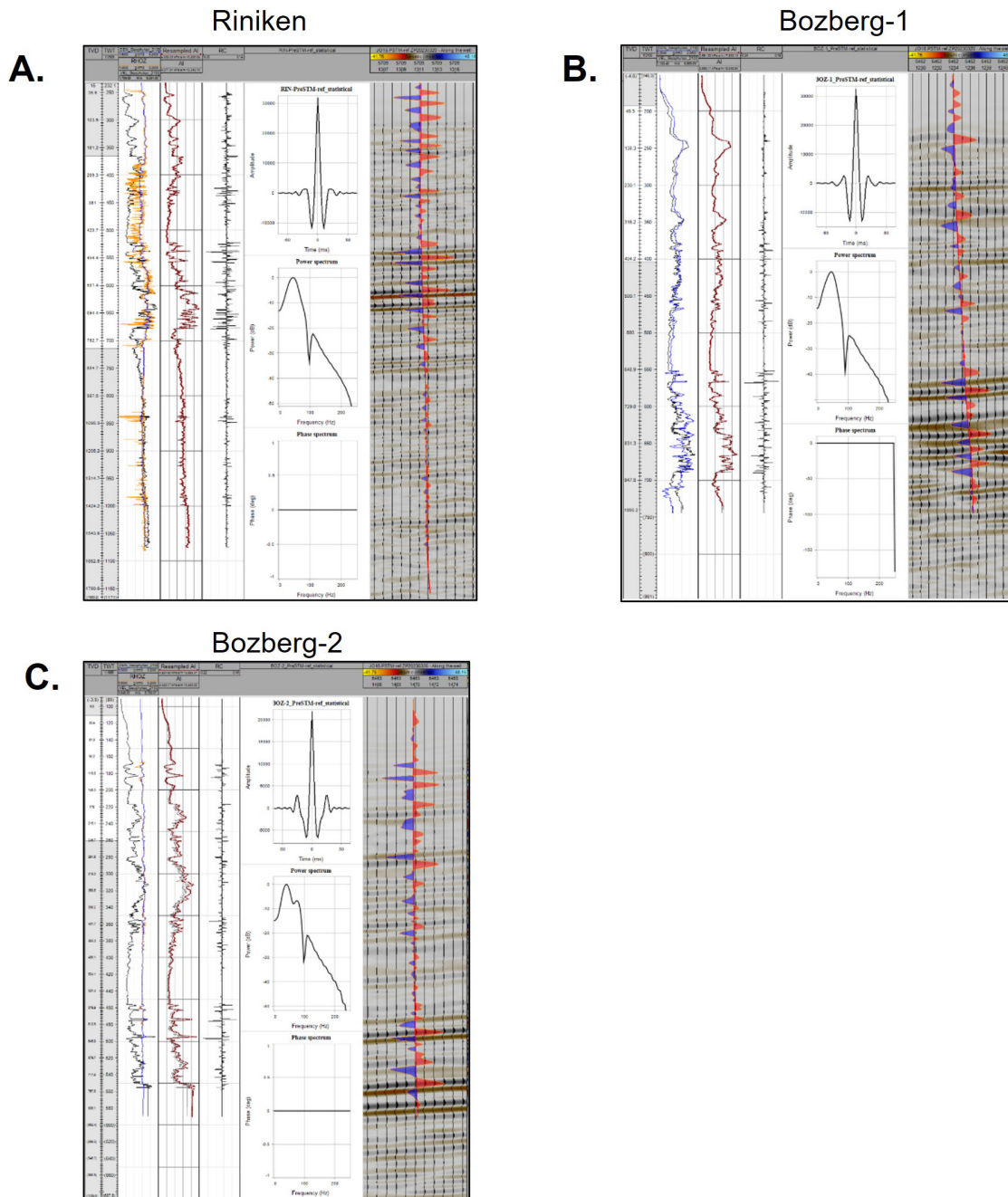


Fig. 4-4: Synthetic panels for the three wells

A. Riniken, B. Bözberg-1, and C. Bözberg-2.

Note that, in the first column, the VSP velocity for Riniken (orange) is of very low quality. The colour code in the synthetic logs is flipped for display reason.

To ensure the reliability of the seismic-to-well tie and the subsequent interpretation, a quality check of the seismic-to-well tie was performed by comparing the matches in the correlation panel, the drift of input/output velocities (i.e. drift calculations denote the difference in two-way travel time (TWT) between the checkshots) and a comparison with the processing (phase-filter) synthetics.

For the wells located in the NL and ZNO siting regions, synthetics were anchored to the Top Malm (Kim-100) reflector since this is the shallowest major acoustic boundary. Due to the surface geological setting, this was not possible in the JO siting region (Fig. 3-5), where a deeper reference level showing a good continuity (154.8 Oxf 975 – Top Dogger Group) was instead selected as the anchor. Since it was consciously decided not to apply ad hoc stretches of the synthetic seismograms to specific stratigraphic levels, some mismatches among the three wells in the JO siting region were observed, particularly at shallow levels. Because of the better VSP correlation, higher weight in the tie was assigned to the Bözberg-1 well.

During the processing stage, the phase rotations required to achieve a perfect match, are often quite significant. This indicates that after application of the spectrum derived zero-phase filter, the data does not have a complete zero-phase characteristic. Therefore, key stratigraphic markers horizons do not always perfectly tie to a seismic loop in the seismic data and zero-crossing is in cases preferred to perform the interpretation.

4.3 Horizon interpretation

During horizon interpretation, subtle geological details, fault lines, tuning effects and other features critical to a comprehensive understanding of the subsurface can be uncovered and identified by integrating the geological knowledge with a detailed analysis of the seismic data. For horizon interpretation, a standard approach was applied (Fig. 4-5). The flexibility of manual interpretation, which allows the recognition of geological patterns, is combined with automated algorithms to efficiently identify and track horizons.

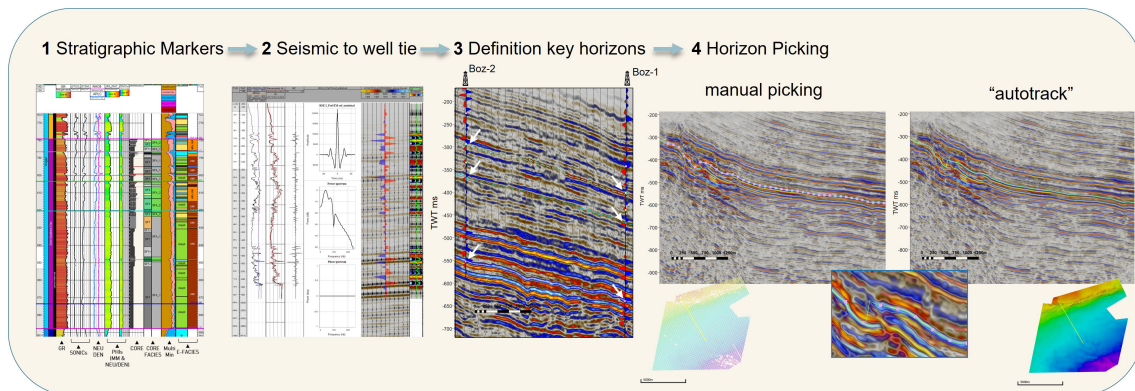


Fig. 4-5: Horizon interpretation workflow

Step 1 requires the stratigraphic markers to be defined, quality controlled and frozen. Through synthetic seismograms (Step 2), the markers are then translated into seismic reflections (Step 3). Subsequently, the stratigraphic layers are interpreted by applying a two-phase seismic picking approach: (i) manual picking of incremental inlines and crosslines in an 8 x 8 line-grid and (ii) survey autotracking of the horizon using manually picked seismic lines as seedlines.

Seismic-to-well ties resulted in the calibration of the key stratigraphic markers with seismic reflections and the determination of their seismic phases. The developed stratigraphic scheme is therefore related to a particular interface or sequence of interfaces (Sheriff 1977). To achieve a coherent structural framework (fault horizon) interpretation, particularly in structurally complex areas, the selection of key stratigraphic markers is strongly driven by the reflector characteristics (continuity and amplitude). The uncertainty associated with fault interpretation can be mitigated by the confidence in the horizon-picking continuity, which allows a further constraint in the imaging interruptions / discontinuities caused by the horizon cut-offs associated with faults or minor tectonic lineaments. Limitation of the traditional fault-picking algorithm becomes critical across the major deformation zones (specifically in the case of reverse faults), where the horizon multi-z (i.e. multi-depth) values at the hanging wall and footwall across the fault are not tolerated.

4.3.1 Horizon interpretation strategy

After identifying the continuous seismic reflector events, the reflector was interpreted in areas where it is coherent and clear, and then infilled in areas with moderate noise and finally interpolated / manually pushed across patches of poor data quality. Interpretation was carried out by means of the seedline square approach. Inlines and crosslines were interpreted at an initial grid interval of 32×32 lines, which was first decreased to 16×16 lines and eventually to 8×8 lines. This narrowing-down seedline grid approach allowed for a consistent horizon pick between inlines and crosslines (Fig. 4-6). Interpretation started from the inlines and crosslines at the Bözberg-1 and Bözberg-2 wells (Fig. 4-6 A) and closed the “square” at the Riniken (Fig. 4-6 D). The latter well was used as a blind quality check for horizon interpretation. The seedlines were manually picked using both Petrel manual and 2D autotrack options.

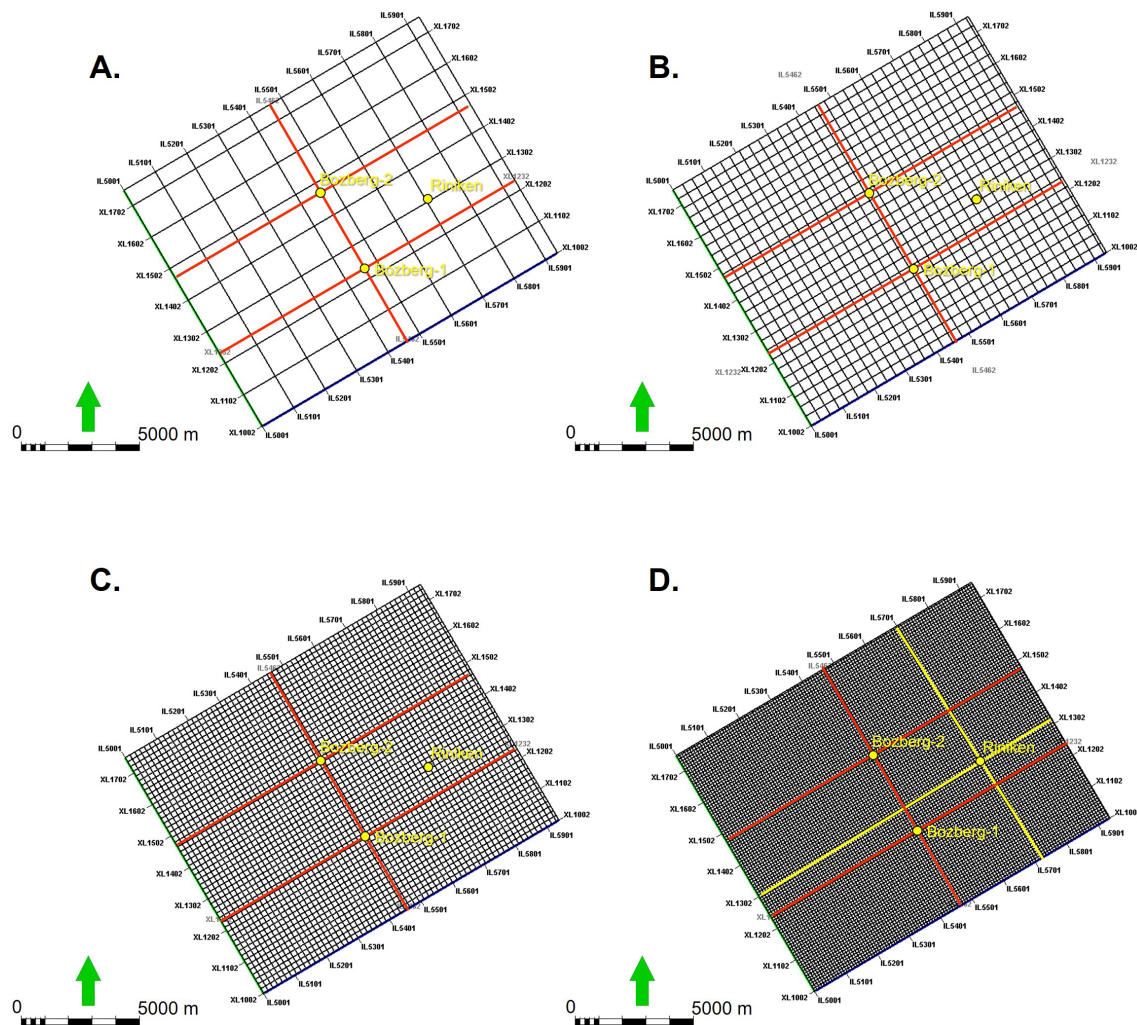


Fig. 4-6: Interpretation seedline methodology and grid building

A. Horizon interpretation is calibrated at inlines and crosslines (red lines) crossing the Böberg 1 and Böberg-2 wells; B. interpretation is then performed with the initial grid of 32×32 lines; C. decreasing to 16×16 lines and finally to 8×8 lines (D.), and finally checked along the inline and crosslines crossing the Riniken well (yellow lines in D.).

The interpretation gaps between the 8×8 line-grid were filled using the Petrel autotrack algorithm. Autotracking used the 8×8 line-grid as seedpoint input, locked at a z (depth)-value (i.e. not overwritten by the autotracking run) with a correlation of 0.8, a basic 3×3 expansion coefficient (i.e. cross-correlation among adjacent lines; Fig. 4-6D), and an amplitude confidence (i.e. percentage representing the amount of amplitude value variation between seedlines and adjacent lines) of 30%. The autotracked horizons were automatically (autotrack confidence attribute) and manually checked for errors and inconsistencies using 3D viewer interactive inspection and surface generation (i.e. anomalous contour lines; Fig. 4-7).

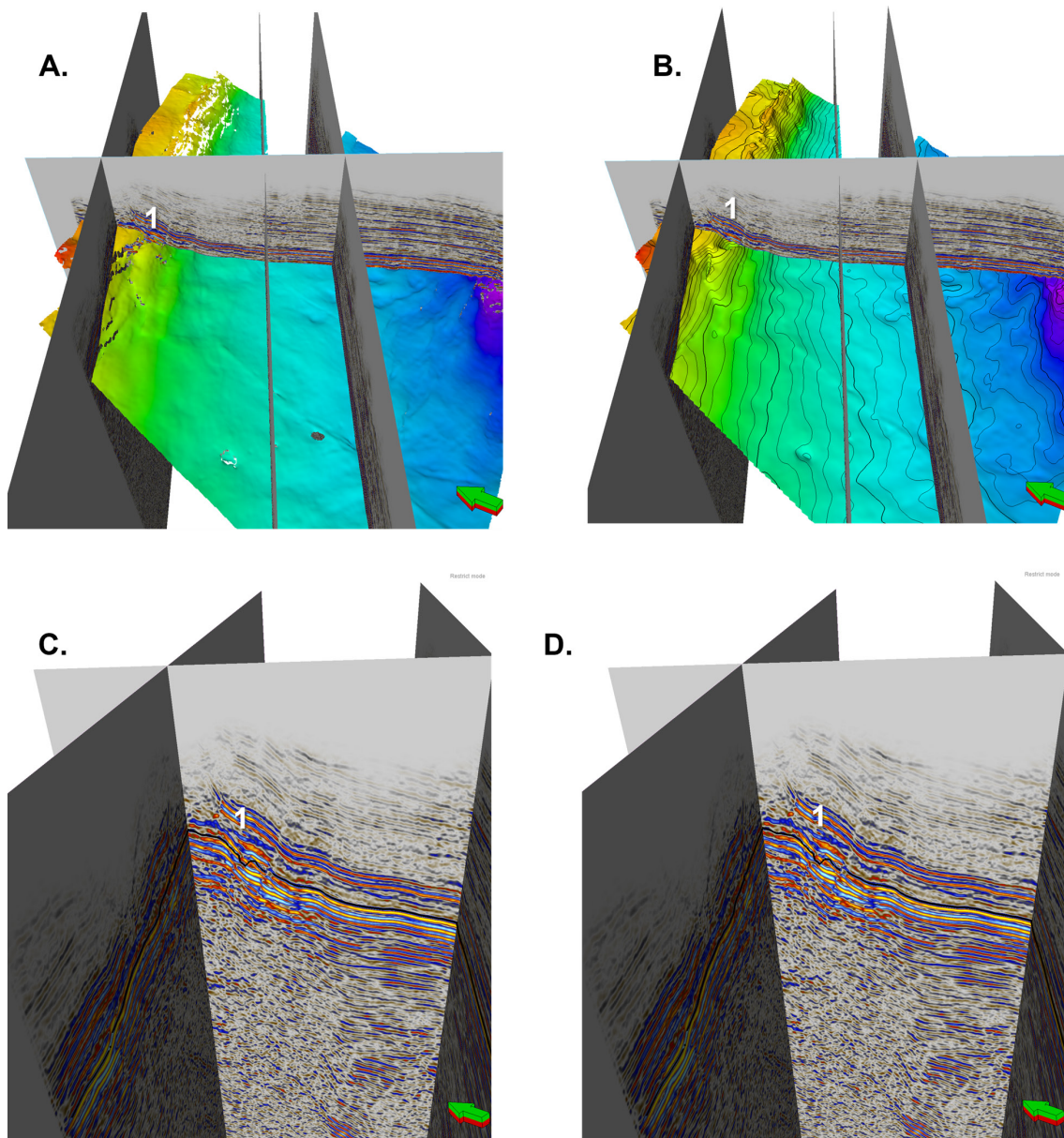


Fig. 4-7: Quality control of autotracked horizon in 3D viewer

A. 3D autotrack horizon screening and identification of problematic areas using the horizon as well as inlines and crosslines (1). B. Screening of gridded surfaces (complex / erroneous contour lines (1). C. Horizon display in restricted mode to quality check and correlate the horizon pick in the inline-crossline intersection. D. Identification of mispick and 3D correction. Green arrow points towards north.

4.4 Fault interpretation

Fault interpretation was performed using a 3D phased approach. The workflow was broken down into two basic elements (Fig. 4-8):

Phase 1 – Reconnaissance: Aiming to interrogate the data to identify its field-scale structural architecture via 3D seismic attribute generation and screening (Tab. 4-1). Discrimination of seismic discontinuities as structural elements, stratigraphic features, seismic noise or artefacts (acquisition footprints and overburden geology imprints, multiples and velocity effects; Fig. 4-9). The resulting interpretation is 2D-based (maps), where the mapped lineaments represent undifferentiated structural features (i.e. faults and folds (deformation zones); Nagra 2022).

Phase 2 – 3D mapping: Main phase of 3D fault interpretation, i.e. mapping the fault arrays defining the field-scale architecture of fault blocks as fault sticks or segments and forming the basis for understanding the structural geology framework of the area of interest (Fig. 4-10). In this phase, the picking (interpretation) criteria were defined to ensure comparability among the three siting regions. The resulted interpretation is only 3D fault sticks (planes); no deformation associated with folding is captured.

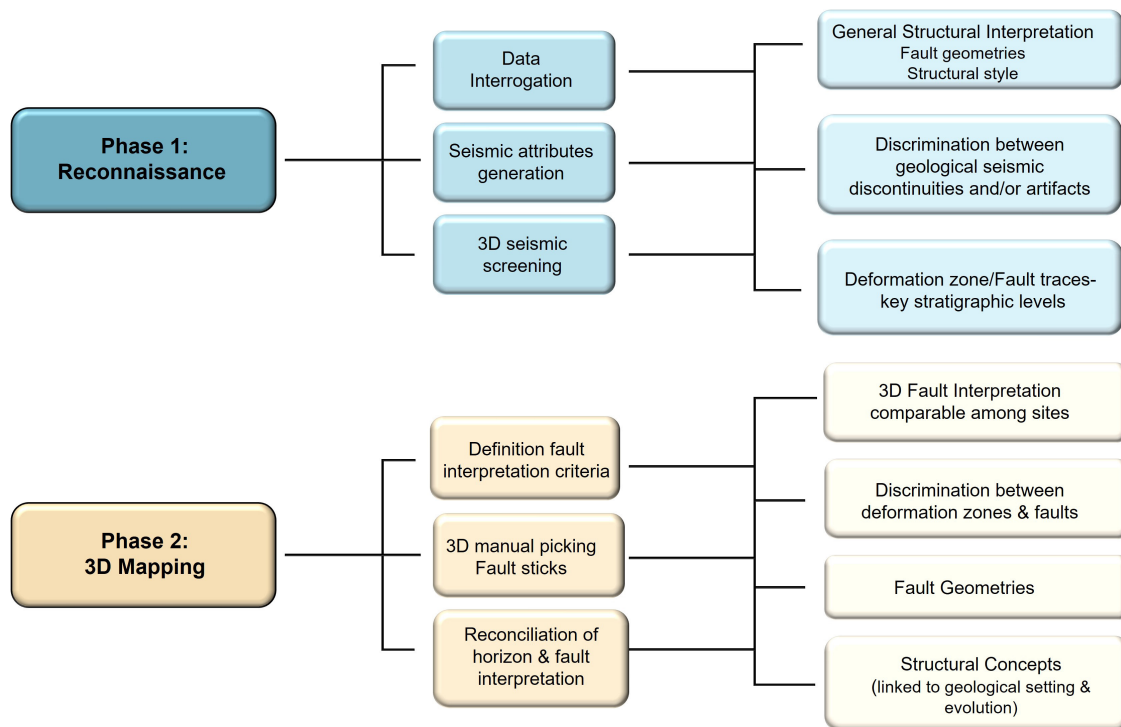


Fig. 4-8: Fault interpretation carried out using a two-phase approach

In Phase 1 (reconnaissance), the seismic data were screened and interrogated. An initial discrimination was carried out between structural lineaments (faults and folds), sedimentological features and artefacts. 3D fault mapping was then performed (Phase 2), which involved picking fault sticks / planes based on the defined criteria and allowing the separation of the deformation zones into faults and folds.

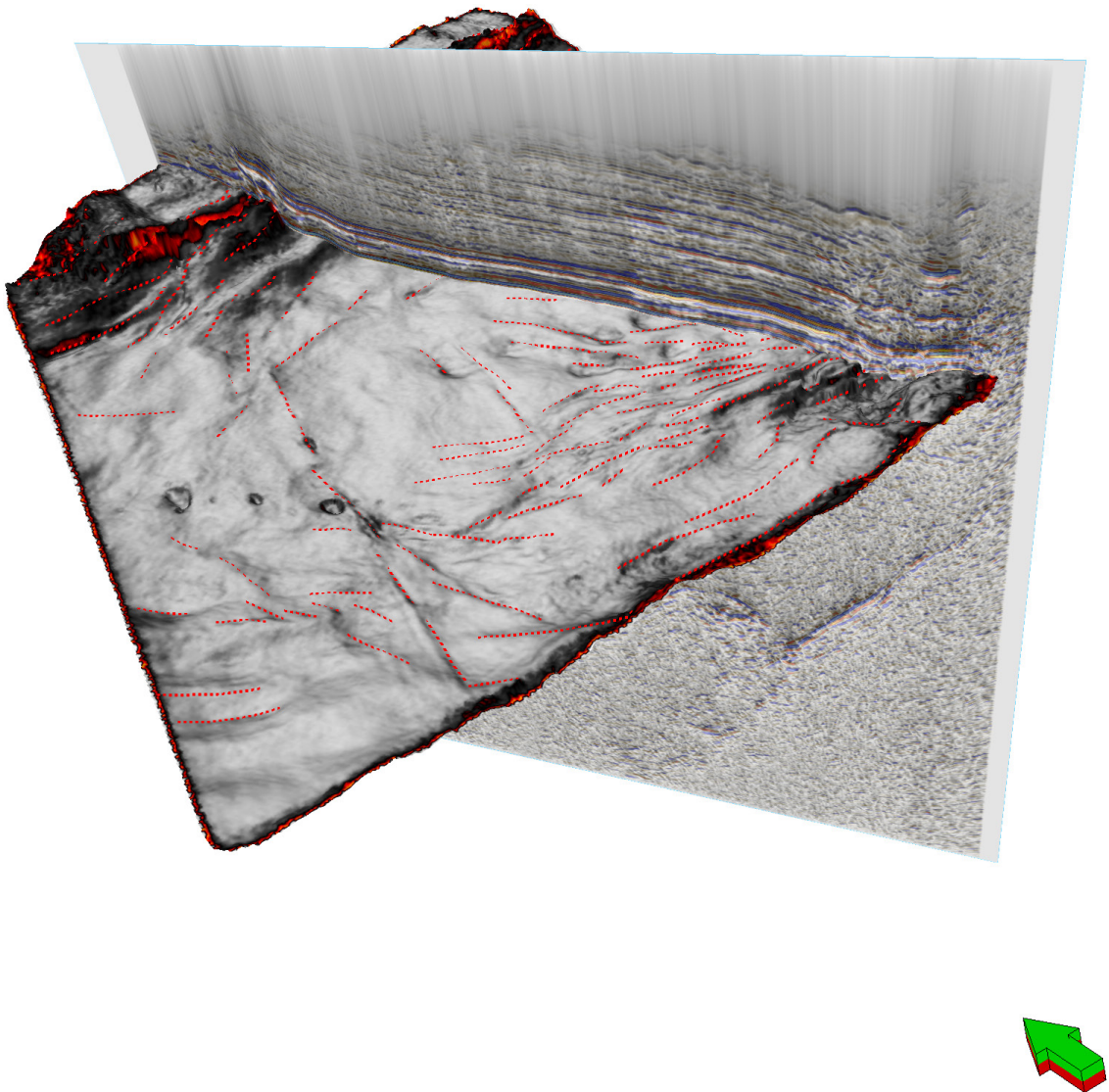


Fig. 4-9: 3D display for Phase 1 fault interpretation workflow

237 Lad 200 – Intra Bänkerjoch variance horizon and inline outcrop view, showing the approach and results. Structural lineaments (i.e. deformation zones as for Nagra 2022; red dashed lines) could be discriminated from seismic artefacts and sedimentological features via seismic attribute analysis and quality check using 3D screening with vertical amplitude sections. Seismic display is PreSTM-ref. Green arrow points towards north.

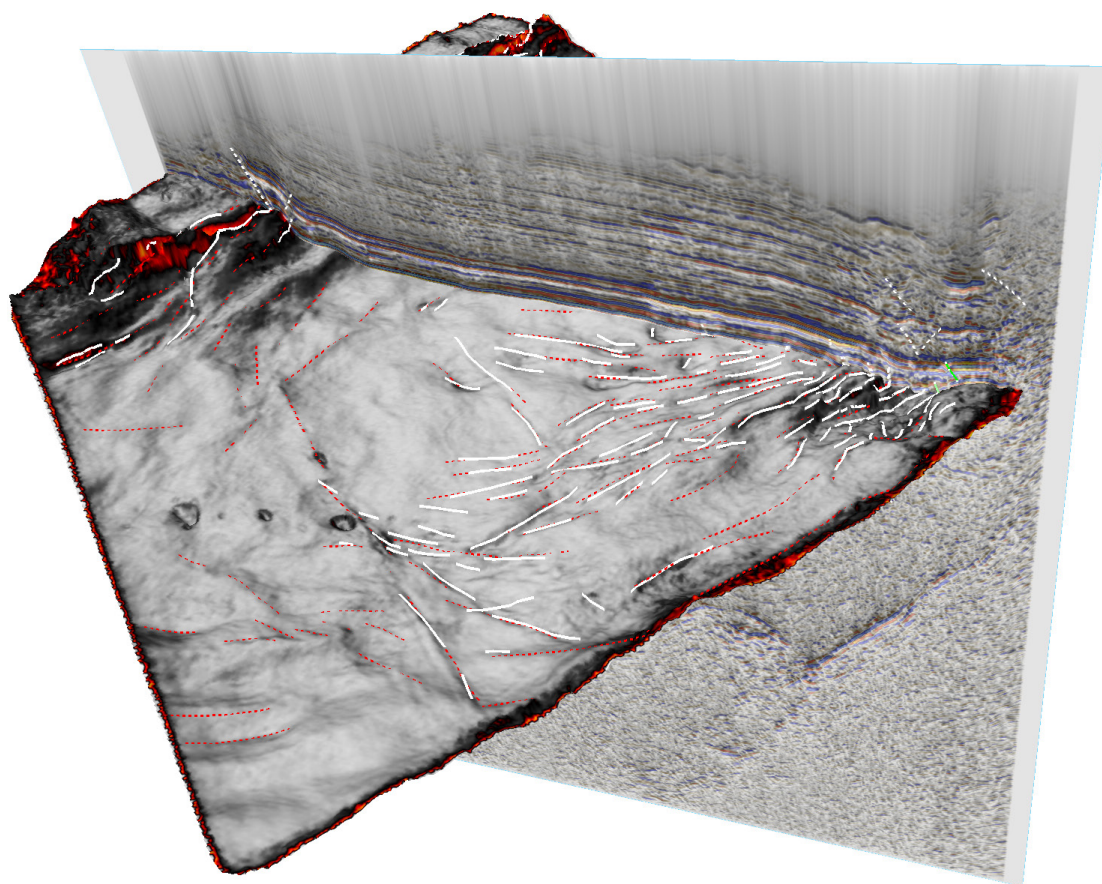


Fig. 4-10: 3D display for Phase 2 fault interpretation workflow

237 Lad 200 – Intra Bänkerjoch variance horizon and inline outcrop view, showing the approach and results. Seismic scale faults could be interpreted as 3D sticks (white vertical lines on seismic section), allowing the separation of fault traces (white lines in the horizon slice) from the structural lineaments of Phase 1 (i.e. deformation zones as for Nagra 2022; red dashed lines). Seismic display is PreSTM-ref. Green arrow points towards north.

4.4.1 Fault signature in seismic interpretation criteria

The disruption of stratigraphy by faulting is recorded in the seismic data by a number of diagnostic signatures. Faults can be loosely subdivided into (i) those with throws large enough to offset the two-way-time (TWT) arrivals of reflections (seismic loops), enabling them to be identified on traditional section-and-time-slice data displays, and (ii) those with smaller throws close to the detection limits of the seismic survey, which can only be imaged by seismic data “attribute” variations. Depending upon the geology, the seismic dataset in use, and the scale of the fault(s) concerned, these signatures are present in various combinations. A fault interpretation should attempt to recognise and “overlay” as many indicative diagnostics as possible. In addition, the seismic signature for a fault was compared across several seismic processing vintages, increasing the confidence in the fault pick and in the lineament position by using the Pre-stack Depth Migration (PreSDM) cube. The PreSDM takes into account ray bending and produces a corrected lateral position of events. Several seismic attributes measure different aspects of the seismic reflection response to a fault break (Tab. 4-1). Confidence in the pattern of faults can be increased by mapping fault lines on each attribute surface separately, and then “overlying” them to correlate a final map pattern with cross-reference to section views, picking and assigning segments as appropriate (Fig. 4-11). As the fault throw diminishes towards the resolution limits of the seismic data, fault detection becomes a matter of cross-referencing these techniques, such that no individual volume or attribute type is used for picking or relied upon in isolation.

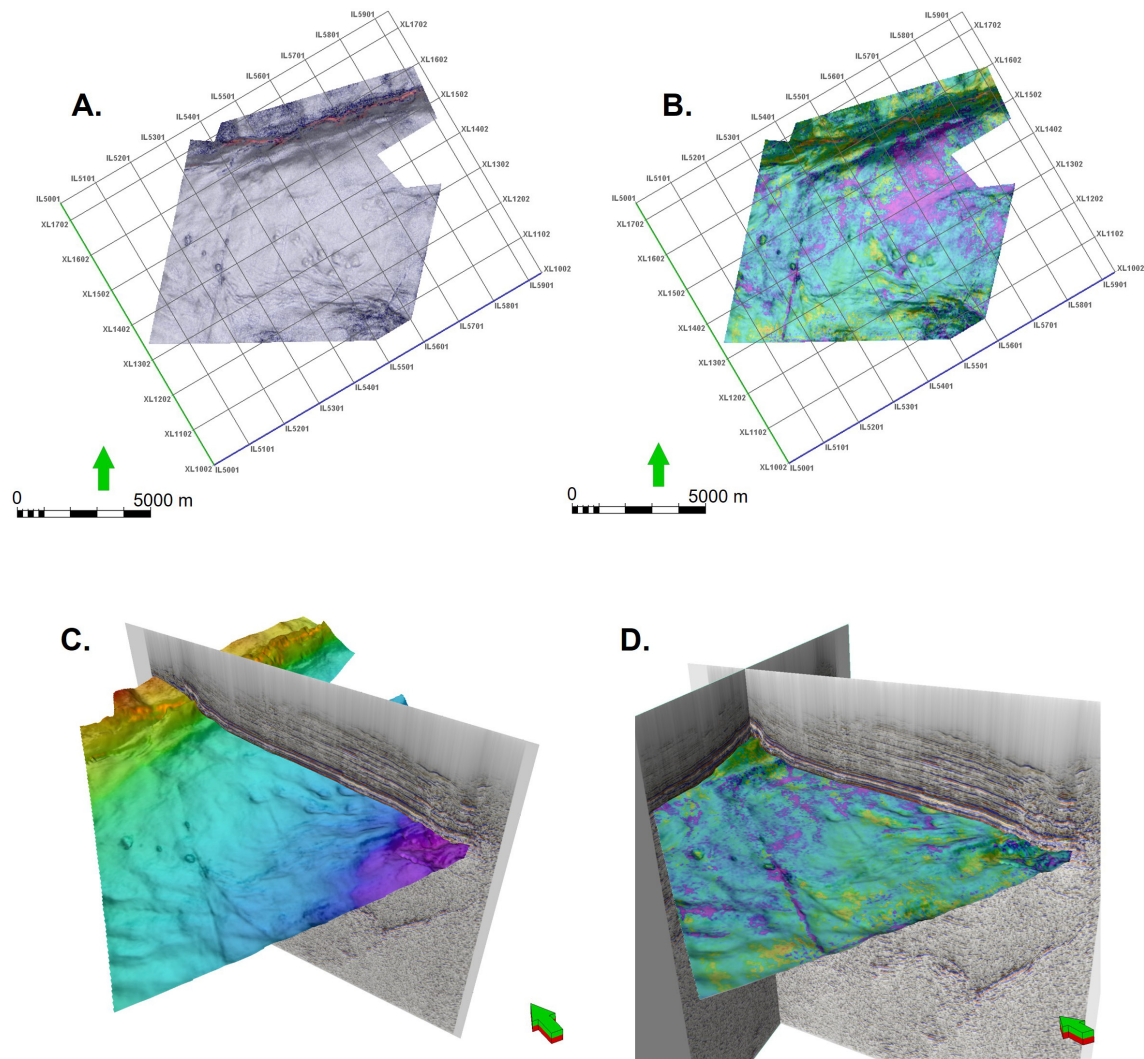


Fig. 4-11: Displays showing the multi-attribute fault identification and interpretation workflow approach in 2D and 3D views

The combination of several seismic attributes and 3D correlation with section and top structure trend increases the level of confidence in the fault pick. A. 237 Lad 200 – Intra Bänkerjoch horizon variance and 3D curvature; B. 237 Lad 200 – Intra Bänkerjoch horizon variance and frequency; C. 237 Lad 200 – Intra Bänkerjoch horizon combining top structure and variance with vertical inline in outcrop view; D. 237 Lad 200 – Intra Bänkerjoch horizon combining variance and frequency with vertical inline and crossline. Seismic display is PreSTM-ref. Green arrow points towards north.

The most common seismic signatures include (Fig. 4-12):

1. Reflection displacement/TWT offsets: offset of reflectors across a discrete plane is the simplest and most obvious expression of a fault within seismic data. The presence of a fault and its displacement can be verified by comparing the character of reflection series on both sides.
2. Reflection character changes / amplitude dimming: a seismic reflection recorded at the surface is derived from a disc-shaped region of reflected energy known as the “Fresnel zone”, which is related to the frequency content and therefore increases in size with depth. If the Fresnel zone traverses a normal fault, for example, part of the reflection response comes from the hanging wall stratigraphy and part from the footwall. As such, with the centre of the Fresnel zone located directly above the hanging-wall fault contact, the returning energy (amplitude) of the reflection is greatly reduced. Reduced amplitudes (dimming) are therefore seen in the loops adjacent to faults.
3. Reflection deflection (dip change): the prevailing stratigraphic dip often changes across a fault in response to flexure of the rocks accompanying faulting deformation.
4. Fault-plane reflections: these may become visible if the juxtaposed lithologies generate an acoustic impedance contrast and the migration operator is insufficiently wide to migrate the reflections from steep features. Essentially, they indicate the presence of an acoustic impedance contrast across the faults. This can work in “binary” layering stratigraphies, where the fault alternately juxtaposes sand-shale layers, and in larger faults, where the lithologies in hanging wall and footwall differ markedly from each other over a large area of the fault contact. This contrast can change along the fault, making consistent and accurate interpretation of the fault plane reflections difficult. A few pitfalls exist, e.g. the interpreter should be aware that reflection multiples, diffraction patterns, and in some cases igneous intrusives (dykes) can produce similar responses.

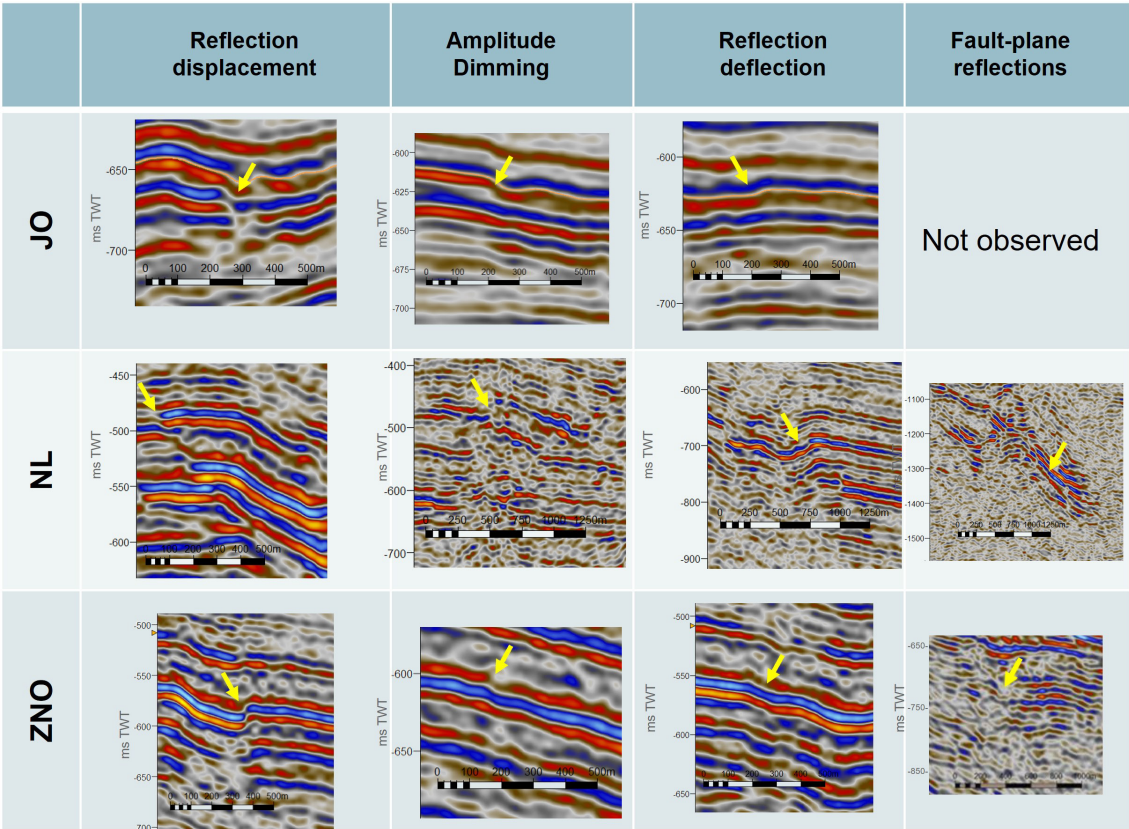


Fig. 4-12: Examples of the most common fault signatures in seismic sections for the three siting regions

1. Reflection displacement (TWT offsets); 2. Reflection character change (i.e. dimming, growth strata); 3. Dip changes (as panel or reflectivity deflection); 4. Fault-plane reflections. These diagnostic features are commonly calibrated with variance (i.e. coherence) linears and edges in the time / horizon slices. Fault signatures were used in a similar manner for JO, NL and ZNO seismic data in order to facilitate comparability in the interpretation. Seismic display is PreSTM-ref.

4.4.2 Fault interpretation strategy

Following reconnaissance phase, the larger fault arrays which define the field-scale architecture of fault blocks / compartments are interpreted as fault “sticks” or “segments”.

Fault interpretation was carried out only for the Mesozoic succession, and fault sticks were vertically traced between the Intra Wildegg (159.8 Oxf 700) and Near Base Mesozoic (251.9 Perm 100) stratigraphic interval. For the shallow section, horizon 159.8 Oxf 975 – Top Dogger represents the reference horizon to identify fault seismic signature. Seismic faults were mapped to follow the seismic diagnostic fault signatures (e.g. reflector offsets, amplitude dimming). Fault identification was performed by cycling among different colour displays, different seismic attributes, continuously changing / referring to different seismic volumes, and changing the vertical exaggeration on section and volume viewers to make shallower dipping faults easier to identify (Fig. 4-13).

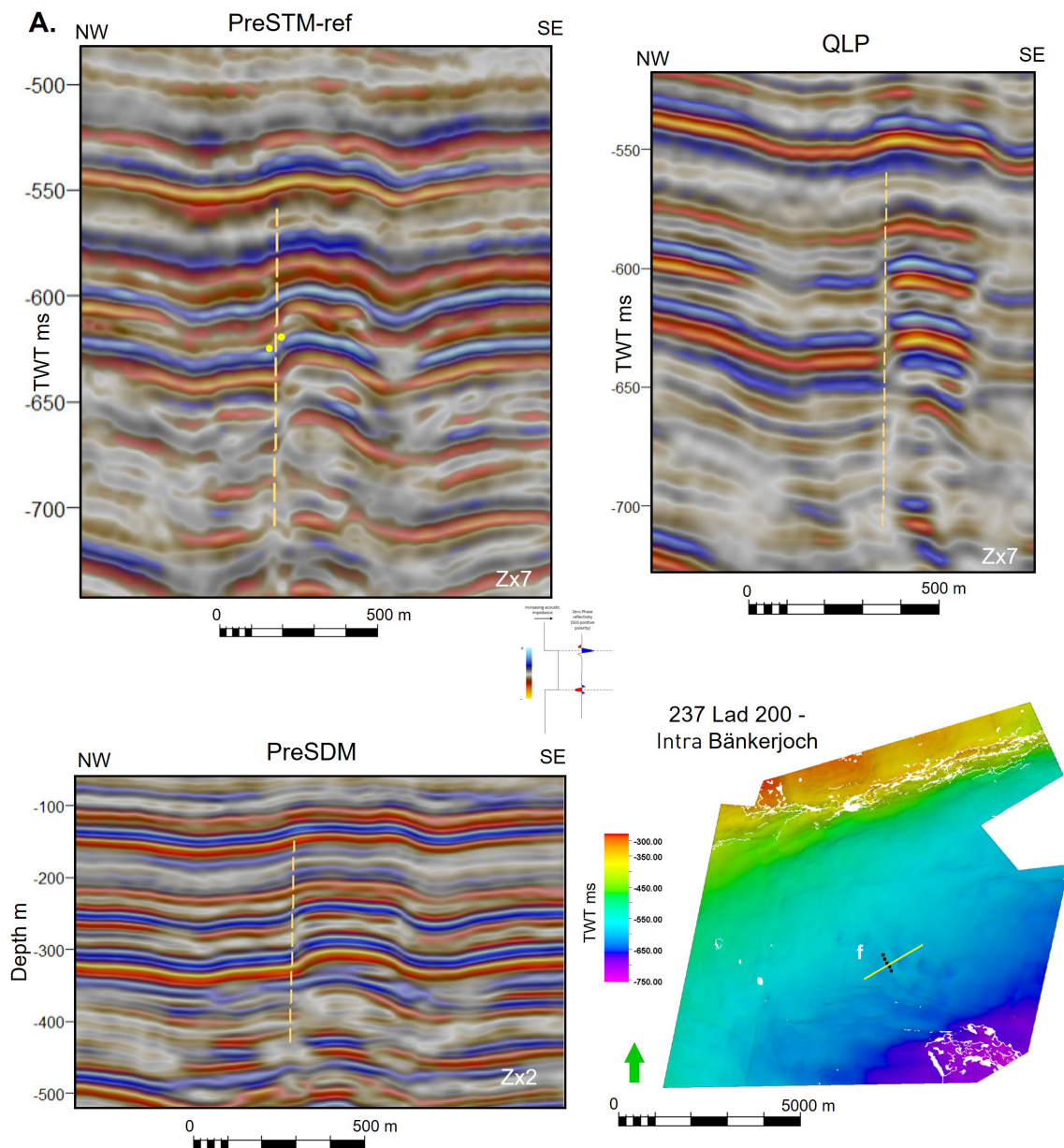


Fig. 4-13: Fault interpretation by comparing fault signatures in available seismic vintages

The recognised fault signatures were compared in all the available seismic vintages thus increasing the interpretation confidence. The fault stick interpreted in the PreSTM-ref was projected in the QLP and (after depth conversion) in the PreSDM data. Example from a NW-SE random line. In this example, the seismic fault is recognised based on reflection offset (yellow dots) and reflection deflection. B. Example from a E-W random line, where the seismic fault is interpreted based on reflection offset (coloured dots-red arrows and dimming (red arrows) associated with a linear edge in the variance extraction. Yellow line on map views represents the location of the seismic line.

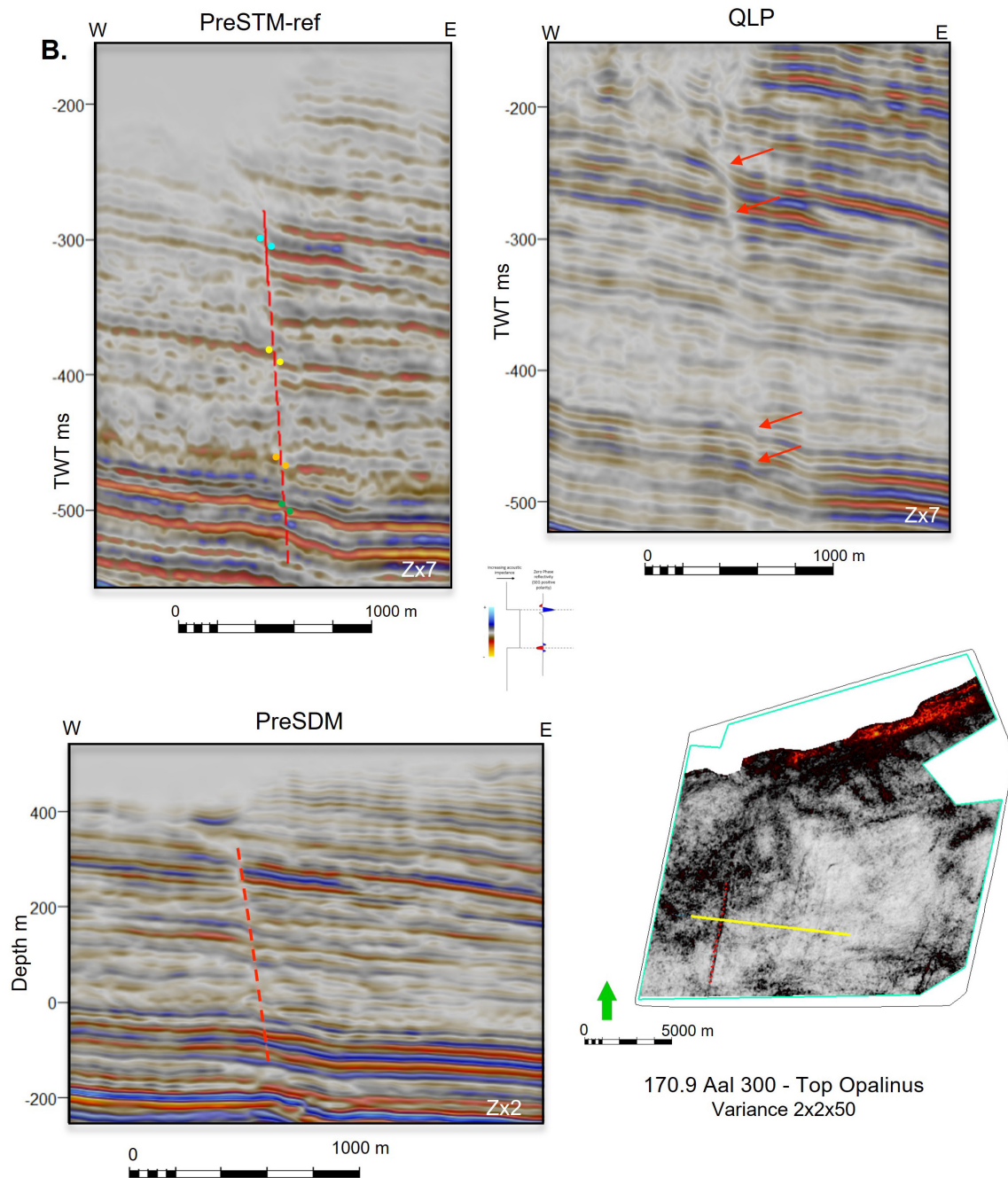


Fig. 4-13: Cont.

Fault stick picking was manually performed predominantly along inlines and crosslines (8×8 line-grid) since the acquisition orientation in the JO-15 seismic survey is almost orthogonal to the main structural grains. For lineaments where the angles are below 60 degrees between the seismic grid section and the fault plane (i.e. potential for misinterpretations due to apparent dip), random lines were traced to generate sections perpendicular to the fault strike. Fault interpretation was conducted with iterative cross-reference to a 3D visualiser. Viewing the faults in the 3D space by simultaneously correlating attribute time / horizon slices and vertical sections enhances the 3D geometrical understanding of the structure, guides segment interpretation and highlights segment shape and position inconsistencies (Fig. 4-14).

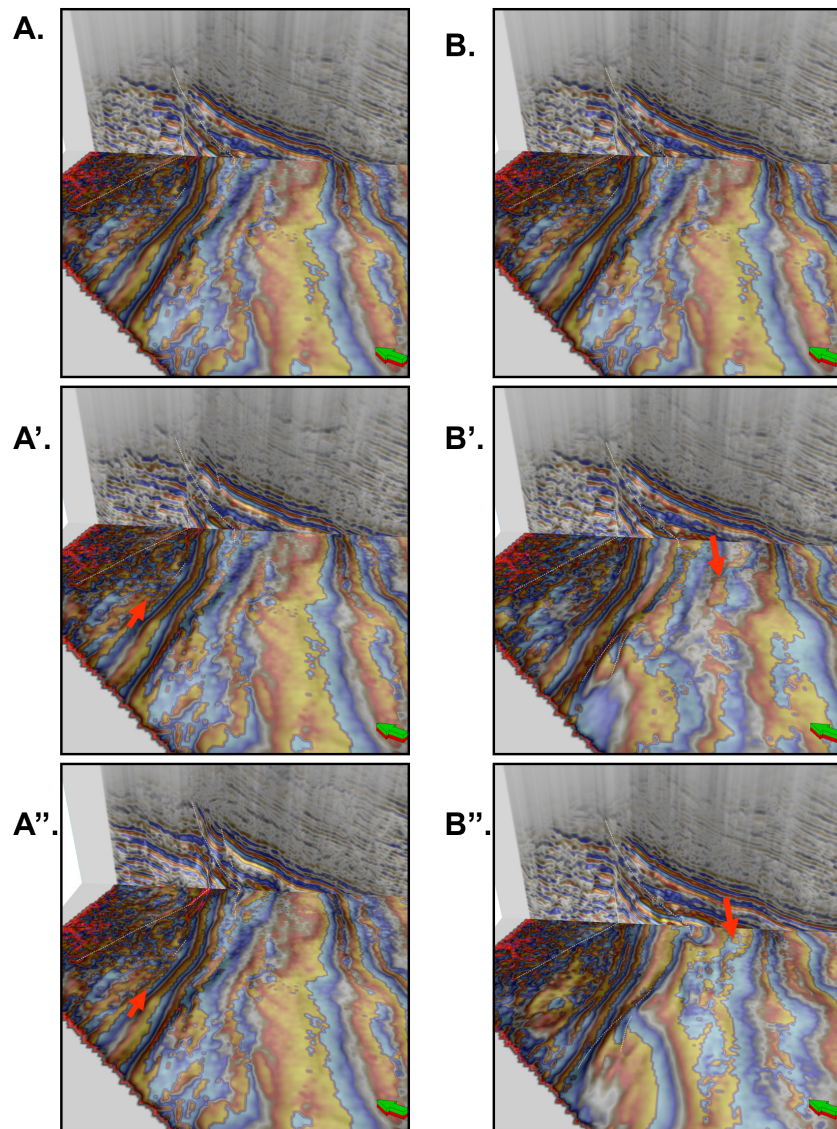


Fig. 4-14: Sets of 3D displays showing the 3D quality check performed for fault interpretation

Instantaneous phase and variance mixer time slice and section with outlook view. Faults are projected in the seismic section and time slice; inlines and time slices are moved in the 3D space in order to check the lateral and vertical consistency of the fault picking. A. Inline 5434; A'. Inline 5448; A''. Inline 5460; B. Time slice 412 ms TWT; B'. Time slice 424 ms TWT and B''. Time slice 442 ms TWT. Seismic display is PreSTM-ref. Red arrows indicate the direction of seismic section (A', A'') and time slice (B', B'') sliding relatively to A. and B. Green arrow points towards north.

A scaled-down approach was applied for the 3D fault interpretation. First, the larger faults were mapped to create a structural framework of primary kinematic family, followed by a second phase of interpretation where smaller structures infill the detailed fault architecture of the larger field-scale deformation compartments.

In summary, the following steps were consistently applied:

1. Lateral mapping:

1.1 Lateral picking of fault sticks constrained by:

- Fault imaging indicator in section → different processing vintages.
- Discontinuity in horizon slice (if horizon available) - time slice between interpreted horizons → multiple attributes.
- Surface morphology (top structure step).
- Multiple seismic processing vintages and attributes.

1.2 Fault sticks interpreted every 8 lines (4 lines for subtle and/or complex geometry).

1.3 Discontinuities shorter than ~120 m (2 fault sticks) were not interpreted.

2. Vertical interpretation:

2.1 Vertical extension for fault sticks: Intra Wildegg to Near-Base Mesozoic Unconformity.

2.2 Initial picking: fault sticks extended down to and up to reflections with fault imaging indicators (section + discontinuity in horizon slice and time slice).

2.3 Fault stick simplification - vertical extent of fault sticks across thicker reflection packages.

2.4 Fault sticks displacing top and base of thick clay intervals with identical strikes despite representing segments of the same fault are not connected across the clay interval (e.g. Opalinus Clay) despite the implemented vertical simplification approach. The Opalinus Clay interval is characterised by the presence of seismic multiples (see Section 5.1). Therefore, the fault plane cannot be traced with confidence. In addition, due to the rheological behaviour of the clay, deformation is expected to be accommodated without evident fault displacement at seismic scale. However, to capture the fault presence across the entire sequence, sticks representing the segments were singularly mapped and referred to by a progressive naming convention. Exceptions are thrust faults, where the structural style implies the propagation across weak mechanical layers.

Faults are usually picked as two-dimensional lines and discrete (simplified) planes, which do not capture the complexity of fault architecture as observed in outcrops (Fig. 4-15, Wibberley et al. 2008, Childs et al. 2009, Braathen et al. 2009, Faleide et al. 2021). The level of detail in the interpretation can directly impact the complexity of the fault geometry even at seismic scale. Such detail strongly depends on the purpose of the interpretation (Richard et al. 2014). For siting regions comparison purposes, fault segmentation was simplified. Such simplification comes with some limitations in the interpretation products.

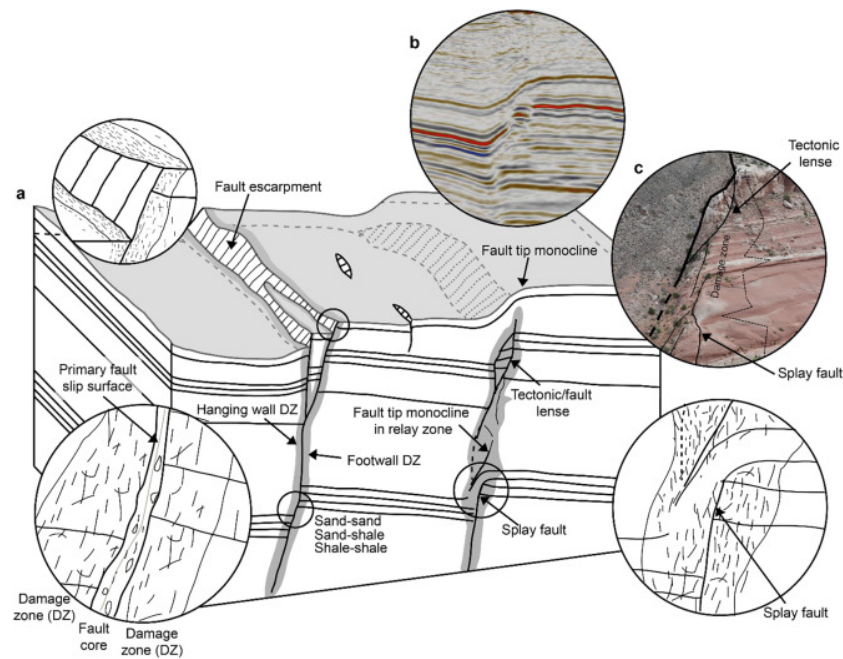


Fig. 4-15: Schematic 3D fault block model showing the complex architecture of a fault zone comparing the scale of detail between b. (fault in seismic) and c. (fault in outcrop)

Figure from Faleide et al. 2021.

Limitations include: (i) increased fault dimensions (i.e. reduced number of faults), (ii) more gentle fault plane dips (average trend), (iii) typical length / throw of quality check relationship not always applicable, and (iv) simplification of fault plane geometry (fault plane gridding) with one-to-one matches of the stick in the seismic in-between sections. Further segmentation and complexity of the interpreted fault zones are expected within stratigraphic levels and associated with lithological changes (Childs et al. 1996, Roche et al. 2021). Nevertheless, while compromising on “fault architecture”, the applied simplification still captures the key characteristics, complexity and distribution of the deformation zones.

5 Results

5.1 Seismic data quality

A first step to determine the confidence in the resulting seismic interpretation is to understand the seismic signal quality. The 3D seismic data were therefore qualitatively screened based on overall event continuity and amplitude fidelity (signal / noise, clarity of reflections, internal depositional / structural features, bandwidth / seismic character preservation, remnant multiples and noise trains). Since 1997, it was established that using a 3D approach to evaluate reflectivity continuity and geometry allows discrimination between discontinuities, which represent geological features from those discontinuities that are associated with seismic artefacts (Hesthammer & Fossen 1997a, 1997b). Such an evaluation was conducted during the reconnaissance phase of the integrated workflow (Fig. 4-9) by identifying, checking and mapping seismic patterns that could be related to typical artefacts. Typical subcategories of seismic artefacts were recognised in all the available processing vintages. They were subsequently mapped as low-confidence areas where amplitude fidelity and continuity as well as imaging can be reduced (Fig. 5-1).

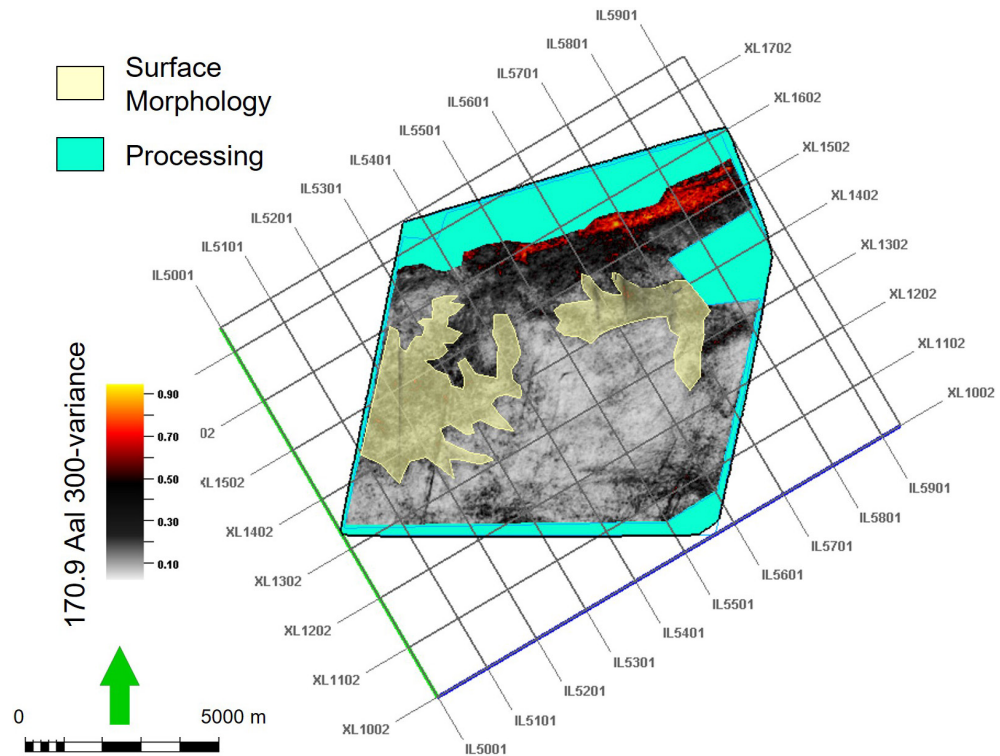


Fig. 5-1: Areas impacted by seismic signal disturbance (artefacts) were recognised and mapped

The observed seismic artefacts are mainly driven by seismic processing and the complex surface geology (incisions and positive erosional morphologies). Areas affected by processing artefacts strongly impaired the interpretation and were not considered. Therefore, a new survey boundary for interpretation was implemented. Surface geology imprints are visible at shallow stratigraphic levels (170.9 Aal 300 – Top Opalinus), but hardly visible also in seismic attribute displays at deeper level.

Areas where interpretation can be impaired due to lack of signal and/or noise masking geological features are predominantly associated with three categories, namely (i) processing artefacts, (ii) imprints caused by overlying geological features, and (iii) seismic acquisition related footprints:

1 – Processing artefacts (i.e. errors in signals in the processing and imaging processes or velocity models). Fig. 5-2 shows a cross-section where dimmed dipping patterns display similar characteristics as interpreted seismic faults. Hesthammer & Fossen (1997) and Hesthammer et al. (2001) indicate that noise-interference lineaments interfere at high angles with real reflections and cause disruption of the weaker signal (Fig. 5-2A; Hesthammer et al. 2001). These dipping features may, in part, be a result of imperfect migration of the seismic data. Within the JO-15 seismic survey, such vertically dimming stripes coincide with the presence of articulated surface and Quaternary morphology (Fig. 5-2B) and could represent dipping noise. While those dipping noise features were not captured as an artefact polygon (confined within specific shallow stratigraphic intervals), awareness of the presence of such discontinuities is critical when interpreting faults.

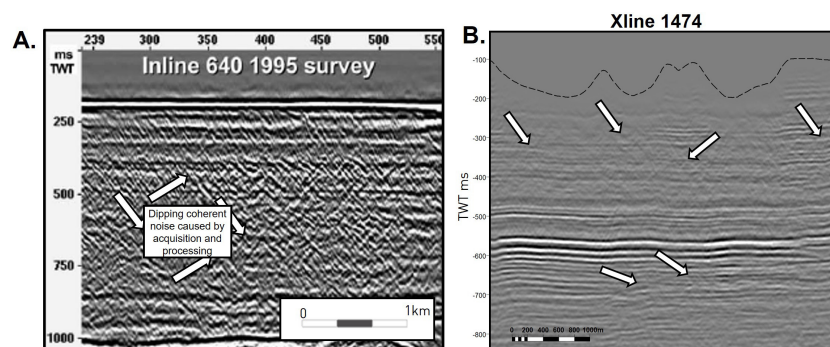


Fig. 5-2: Example of seismic processing artefacts, which can directly impair fault recognition and interpretation

A. North Sea seismics showing dimmed dipping patterns displaying similar characteristics as interpreted faults. It is important to avoid the misinterpretation of offsets caused by noise interference as real faults (after Hesthammer et al. 2001) and B. example from JO-15 PreSTM-ref dataset. Whereas the use of a colour palette is useful to recognise disruptions of reflections, a grey scale is best suited for the identification of the dipping noise. Dashed black line is ground level.

Multiples are reflections created by acoustic waves that are travelling several times between two strong reflectors before being intercepted by a geophone. Multiples are mostly treated as artefacts that need to be removed during seismic data processing (Backus 1959) and were therefore included here in the processing artefact category. Multiple reflections were identified within the Opalinus Clay (Fig. 5-3) do not support the observed relatively high-amplitude reflectivity patterns (consistently with observations gained from the re-processing exercise). This is partly supported by the VSP dataset (Fig. 5-3 B.). The VSP response suggests that primary reflections could still be present in the upper part of the clay interval, however their separation from the multiple reflections results extremely challenging.

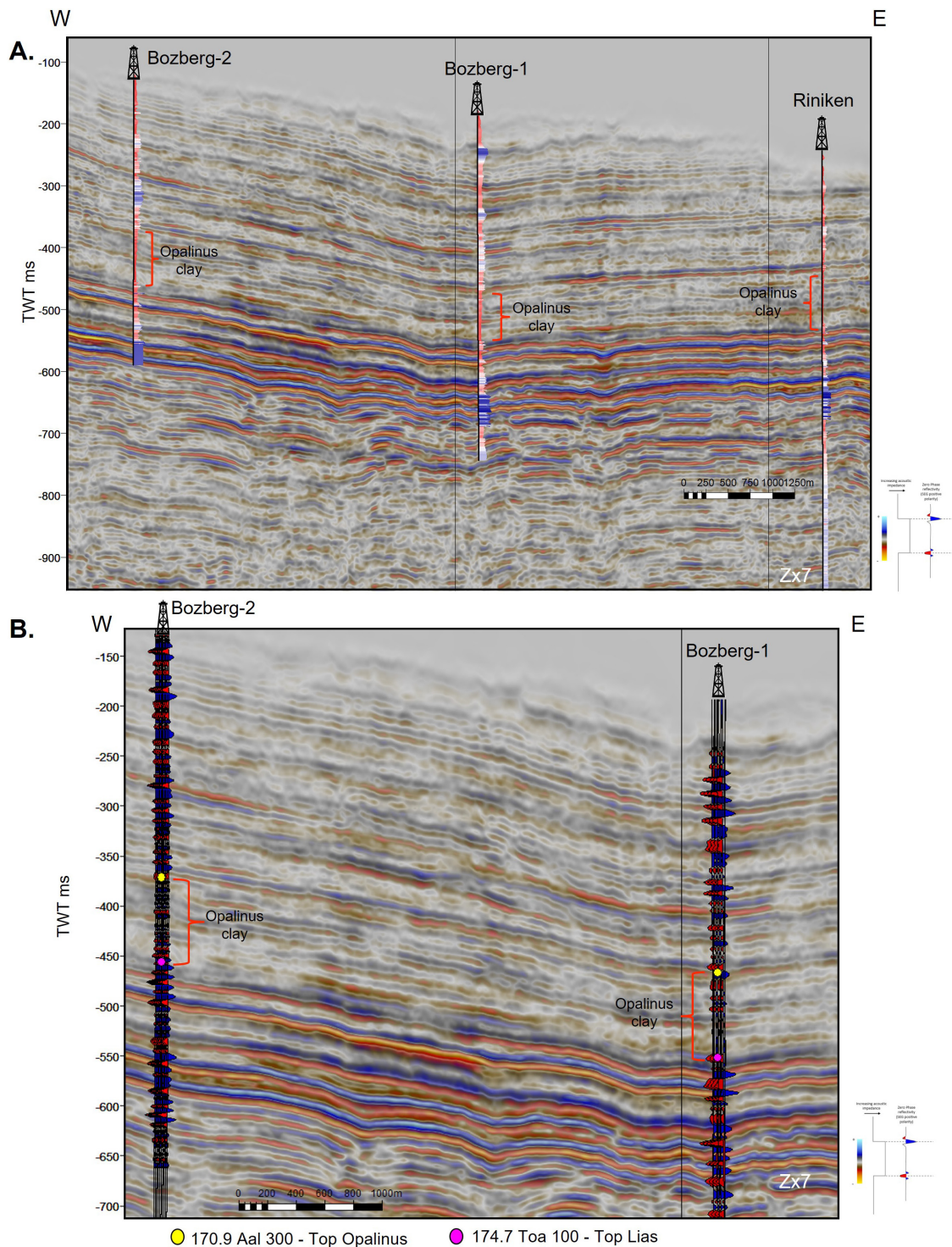


Fig. 5-3: Seismic section (reflectivity and structural smoothing) across the three wells in JO siting region

A. Acoustic impedance logs showing the acoustically weak Opalinus Clay interval. B. Zoom in at Bözberg-1 and -2 VSPs showing that most of the Opalinus Clay interval lacks acoustic contrast, suggesting the presence of secondary energy (seismic multiples) affecting the geometry of primary reflections. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. Note VSP corridor at Bözberg-1 well has opposite polarity to the seismic data.

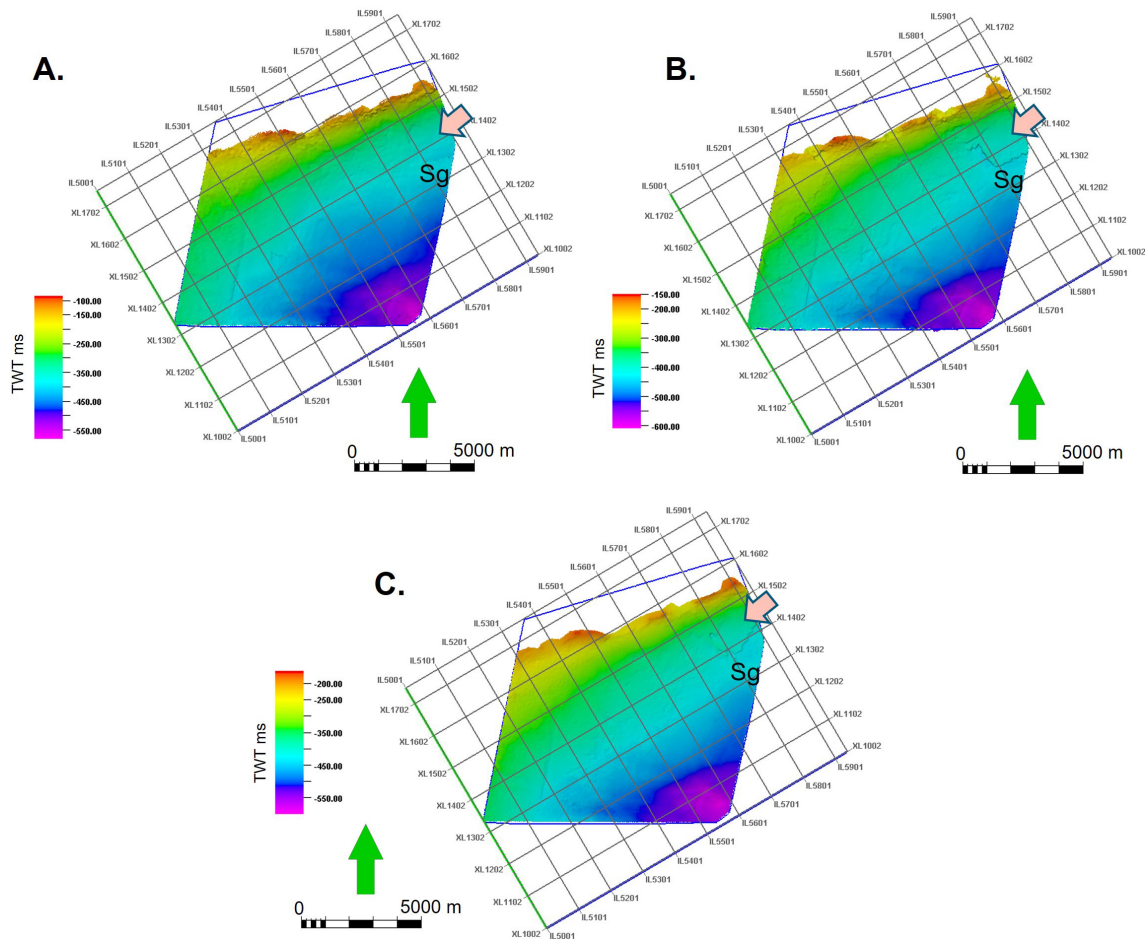


Fig. 5-4: A square-shaped area representing a seismic processing artefact observed in the northeastern corner of the survey (pink arrow), just north of the Siggenthal Anticline (Sg)

A. Top Opalinus QLP B. 170.9 Aal 300 – Top Opalinus PreSTM-ref minimum-phase and C. 170.9 Aal 300 – Top Opalinus PreSTM-ref zero-phase.

In the northeastern corner, a square-shaped area with sharp edges is visible in all the seismic vintages (Fig. 5-5; Nagra 2019). The shape and the character of this area is generated by the fact that there is a jump between inlines and crosslines when tracing a continuous reflection from north to south and east to west (Fig. 5-5, Fig. 5-6). This area is located north of Siggenthal Anticline. Detailed interpretation excludes the presence of faults bounding this area (Fig. 5-6), and a seismic processing-related artefact appears to represent the most reasonable explanation, because of the superimposed presence of a similar shaped feature at the surface (Fig. 5-6). Because of this artefact, a new bounding polygon was proposed to delimit the interpretation perimeter of the survey excluding major processing artefacts. This also includes a frame around the edge of the survey, where the seismic imaging is extremely poor (Fig. 5-1, Fig. 5-5).

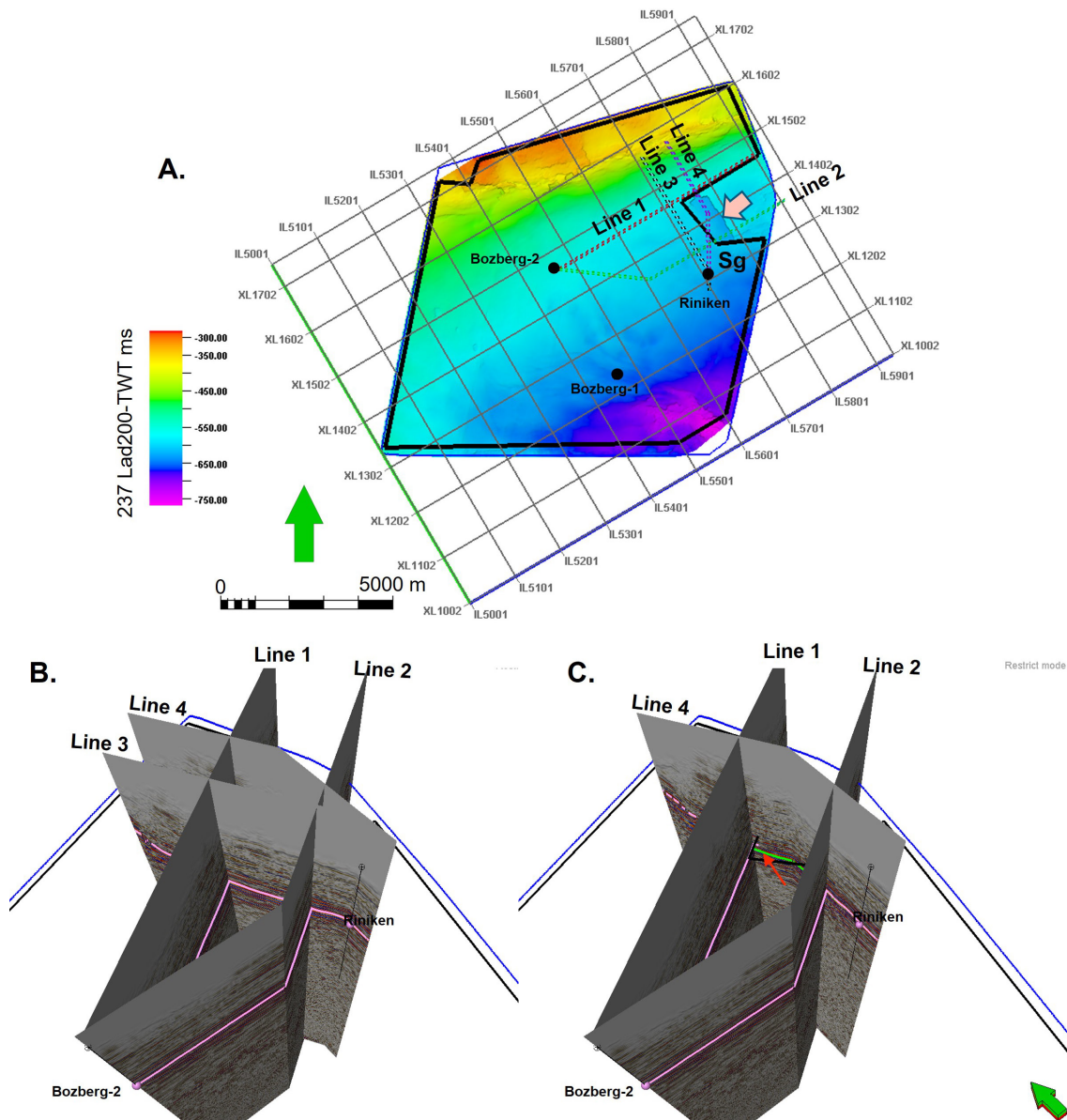


Fig. 5-5: 2D and 3D displays imaging the seismic processing artefact identified in the north-eastern corner of the JO-15 3D seismic survey

TWT top structure of 237 Lad 200 – Intra Bänkerjoch showing the artefact area (pink arrow) north of the Siggenthal Anticline (Sg). Four random lines (Lines 1 to 4) were generated from the Riniken and Bözberg-2 wells across this area. By moving from Line 3 eastwards towards Line 4 the area with the processing artefact becomes visible (B. and C. respectively). In Line 4 the 237 Lad 200 – Intra Bänkerjoch horizon within the artefact perimeter was coloured in green to show the step (red arrow) that it is needed to reconcile the horizon coming from the north and tied to the Bözberg-2 well and the same horizon coming from the south and tied to the Riniken well (pink). A new interpretation boundary was introduced to avoid this artefact (black line). Seismic display is PreSTM-ref reflectivity. Green arrow points towards north. See Fig. 5-6 for section display.

2 – Imprints are amplitude morphologies that appear in sections, time slices or horizon slices produced by geological features in overlying intervals. In the JO-15 seismic survey, the topography and Quaternary morphology, while being quite articulate, do not include important features (i.e. the Strassberg Valley in Nördlich Lägern perimeter). Therefore, while some mild amplitude wash-out zones are recognisable in association with small, incised valleys, the degradation of amplitude is not dramatic and therefore does not impair the confidence in the interpretation. Two areas associated with more complex shallow geology were identified. While the imprints are almost invisible in amplitude cross-section displays, they generate discontinuity ghosts in attribute extractions. Therefore, attention should be paid when looking at seismic discontinuities based solely on attribute time / horizon slices especially at shallow stratigraphic levels (Fig. 5-1).

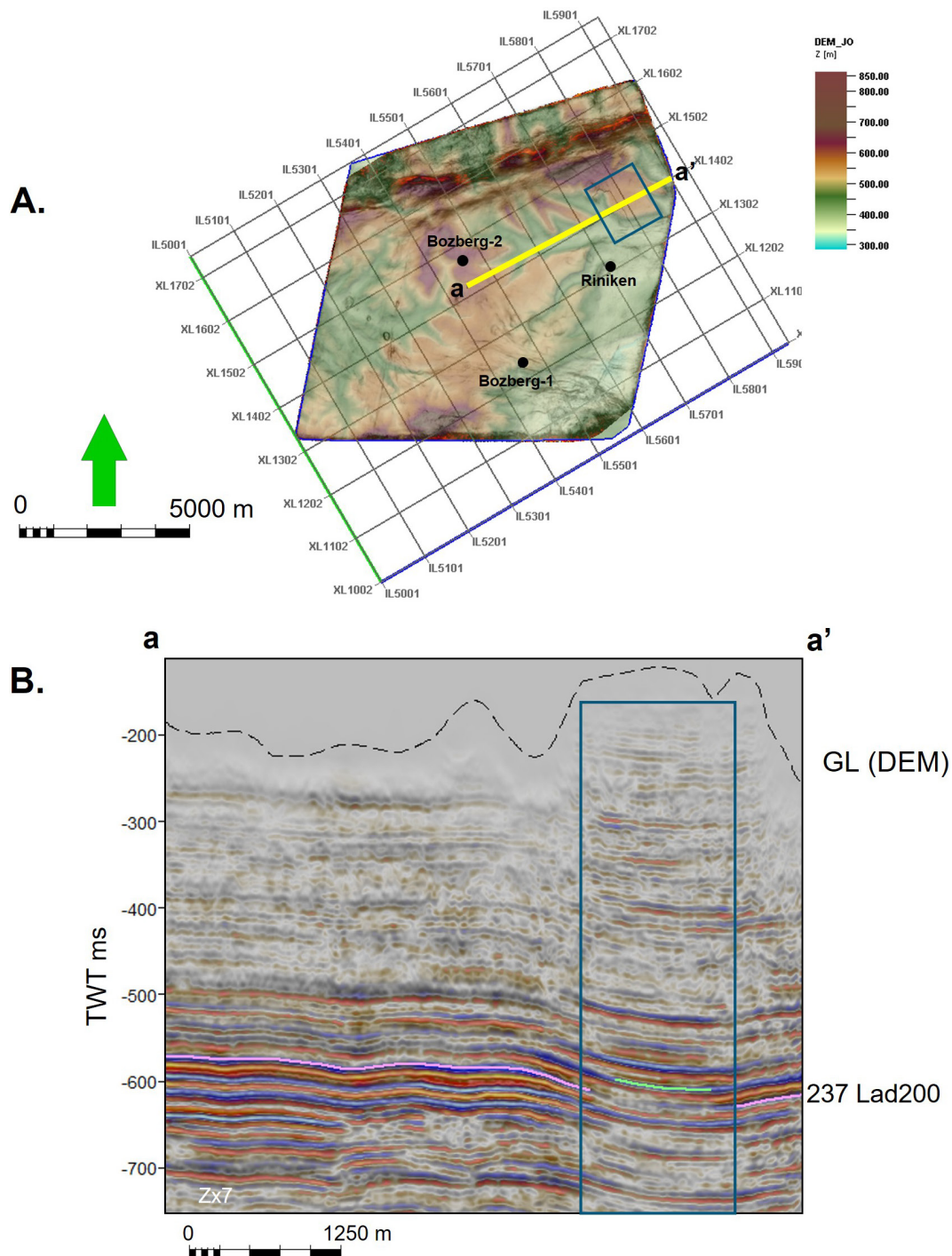


Fig. 5-6: Topographic map overlying the identified area of seismic processing artefact

Map view of the topography overlying the 237 Lad 200 – Intra Bänkerjoch variance horizon slice showing the occurrence of a surface positive morphology mimicking the boundary of the artefact area (blue polygon). B. Random seismic line perpendicular to the artefact “break” showing the continuity of the reflectivity and the lack of seismic signature for faults at the location where the resulting 3D loop mapping of 237 Lad 200 – Intra Bänkerjoch requires a jump of the horizon. Colour was changed to green from pink in the artefact area (blue polygon). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. GL is ground level.

3 – Footprints are not visible in the JO-15 seismic dataset. No clear indications of acquisition-related noise are detectable even on 3D curvature attribute displays.

5.2 Stratigraphic interpretation

Seismic interpretation of stratigraphic sequences has been traditionally conducted by identifying key seismic reflections, whether due to their interpretability (i.e. seismic horizon (reflection) and amplitude continuity over broad areas) or because of associated reflection terminations that defined unconformable surfaces (unconformities).

Within the framework of the site selection process, seismic interpretation was performed solely for the Mesozoic succession (Top Malm - Base Mesozoic Unconformity), since it contains the three major units (upper confining unit, host rock and lower confining unit, Nagra 2024d). Seven regional markers comprising and defining the above units were mapped across the entire survey (Fig. 5-7). To deliver a geometrically robust structural framework (i.e. horizons and faults), the choice of key reflections to be interpreted relies on the interpretability (continuity and amplitude stability) of the marker reflections. Therefore, a continuous reflection near the stratigraphic markers of interest is preferred to ensure reliability, consistency and confidence in the interpretation and to reduce the uncertainty associated with the picking.

Tab. 5-1: Key stratigraphic horizons with seismic phase and seismic resolution / mapping quality

Strat. Name	Formation Name	Phase	Quality
159.8 Oxf 700	Intra Wildegg	 Z-crossing	
159.8 Oxf 975	Top Dogger		
170.9 Aal 300	Top Opalinus		
192.9 Sin 200	Top Beggingen Mb		
227 Car 200	Near Top Bänkerjoch		
237 Lad 200	Intra Bänkerjoch		
251.9 Per 100	Near Base Mesozoic Unc.		

A traffic light approach was used to show the quality (interpretability) of the resulting horizons (Tab. 5-1). Green horizons are reflections that can be mapped with confidence across the entire seismic dataset and do not show major changes in reflectivity, variation in loop thickness and/or presence of doublets (Fig. 5-7 B).

In contrast to the other two siting regions (NL and ZNO), the Malm carbonate / marly carbonates are outcropping or subcropping in the JO siting region, with the Bözberg-1 well encountering ~100 m of Molasse and Quaternary deposits. The shallow, high velocity lithology impacts the imaging of the upper confining unit, resulting in a reduced seismic resolution.

Also, the Herrenwis carbonate platform (Nagra 2024b) and associated clay wedge (overlying the Opalinus Clay), which hampered the Top Opalinus reflection, are not present in JO siting region. Therefore, the Top Opalinus Clay reflection could be recognised and mapped in the JO-15 seismic survey (Fig. 5-7). Due to its seismic discontinuous / transparent characteristics, the Top Liassic (base of the Opalinus Clay interval) could not be mapped across the entire area of the seismic survey. Instead, the nearest confidence pick was selected (192.9 Sin 200 – Near Top Klettgau).

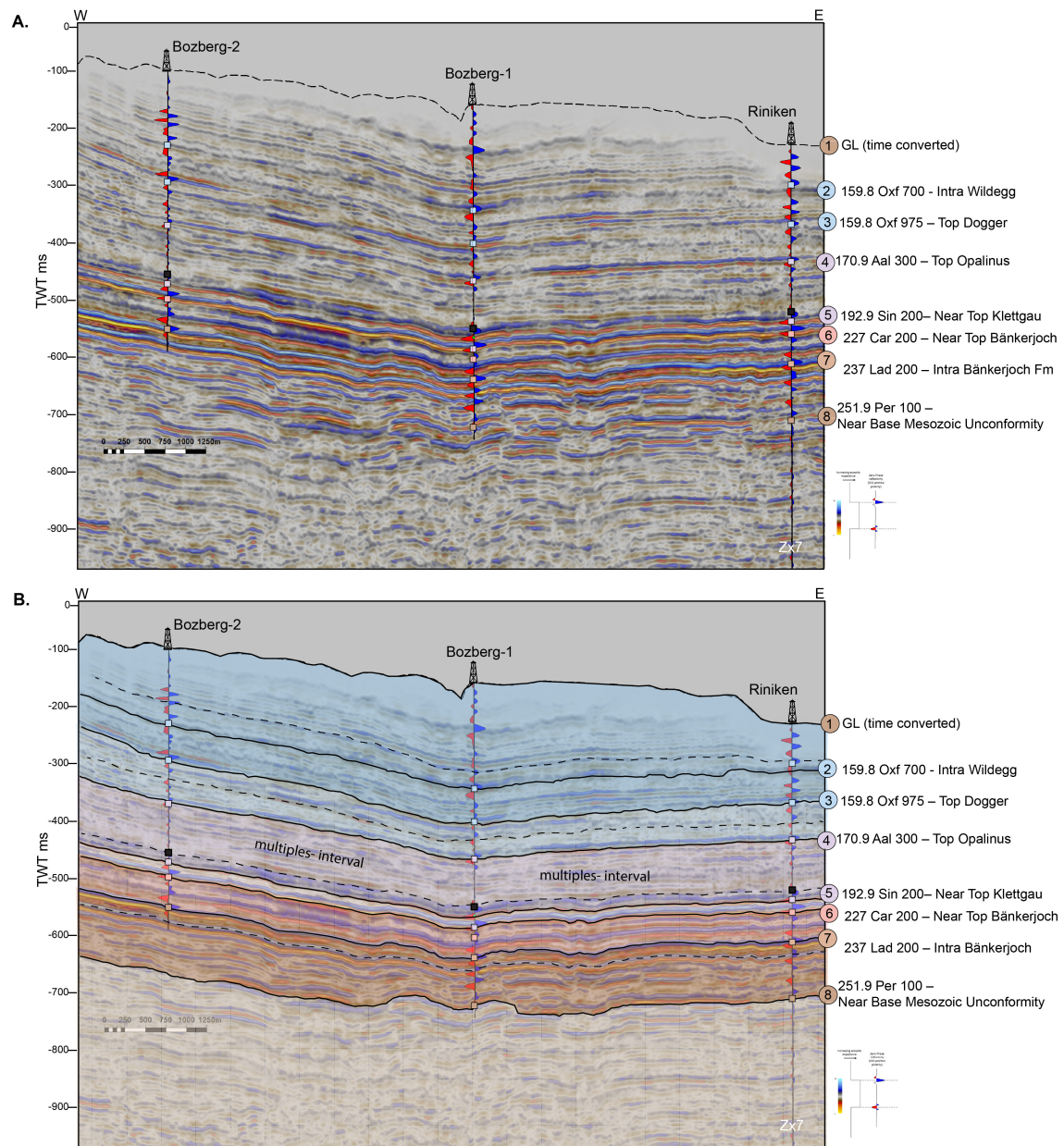


Fig. 5-7: Seismic section across the wells with key stratigraphic horizons

A. Uninterpreted and, B. Interpreted seismic line showing the seismic-to-well tie and the seven key stratigraphic horizons interpreted across the entire JO-15 seismic survey. The dashed horizon tied to the well marker (black dot) is 174.7 Toa 100 – Top Lias (base host rock), characterised by the weak acoustic response with the overlying Opalinus Clay. Here, the presence of seismic multiples makes this horizon very low confidence and challenging to interpret particularly in structurally complex areas. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.1 159.8 Oxf 700 – Intra Wildegg

The Intra Wildegg (159.8 Oxf 700) is a relatively shallow horizon. Its variable amplitude content yields low continuity and consequently low confidence in the interpretation, particularly in the degraded amplitude curtains associated with articulated topography (Fig. 5-8).

In the JO siting region, the Wildegg Formation is partly eroded. Furthermore, in many areas, the seismic data were muted near the surface and therefore it becomes challenging to discriminate when the interpreted horizon is eroded and when it is simply not imaged (Fig. 5-8A and Fig. 5-9).

The interpreted horizon 159.8 Oxf 700 corresponds to the Gerstenhübel Bed, here generally referred as Intra Wildegg for simplicity, a carbonate layer that may even be correlated across the three siting regions, although its thickness and facies show lateral changes (Nagra 2024d). The Wildegg Formation was deposited during the Late Jurassic in a shallow marine epicontinental setting with the Tethys Ocean to the south and was formed in a mixed carbonate-siliciclastic environment. The interval below the Gerstenhübel Bed is interpreted to represent highstand deposits, with more siliciclastic material trapped on the flooded coastal plains and increased carbonate production due to the increased accommodation space (Nagra 2024d).

Wells penetrating this interval in the JO perimeter indicate that, below the Gerstenhübel Bed, limestone beds are rare and thin, and the lithology is dominated by alternation of calcareous marls and argillaceous limestone (Nagra 2024d). A thicker interval of argillaceous limestone at Bözberg-1 compared to Bözberg-2 might explain the lateral change from chaotic low-amplitude reflections to relatively higher-amplitude continuous stacked reflections (Fig. 5-8).

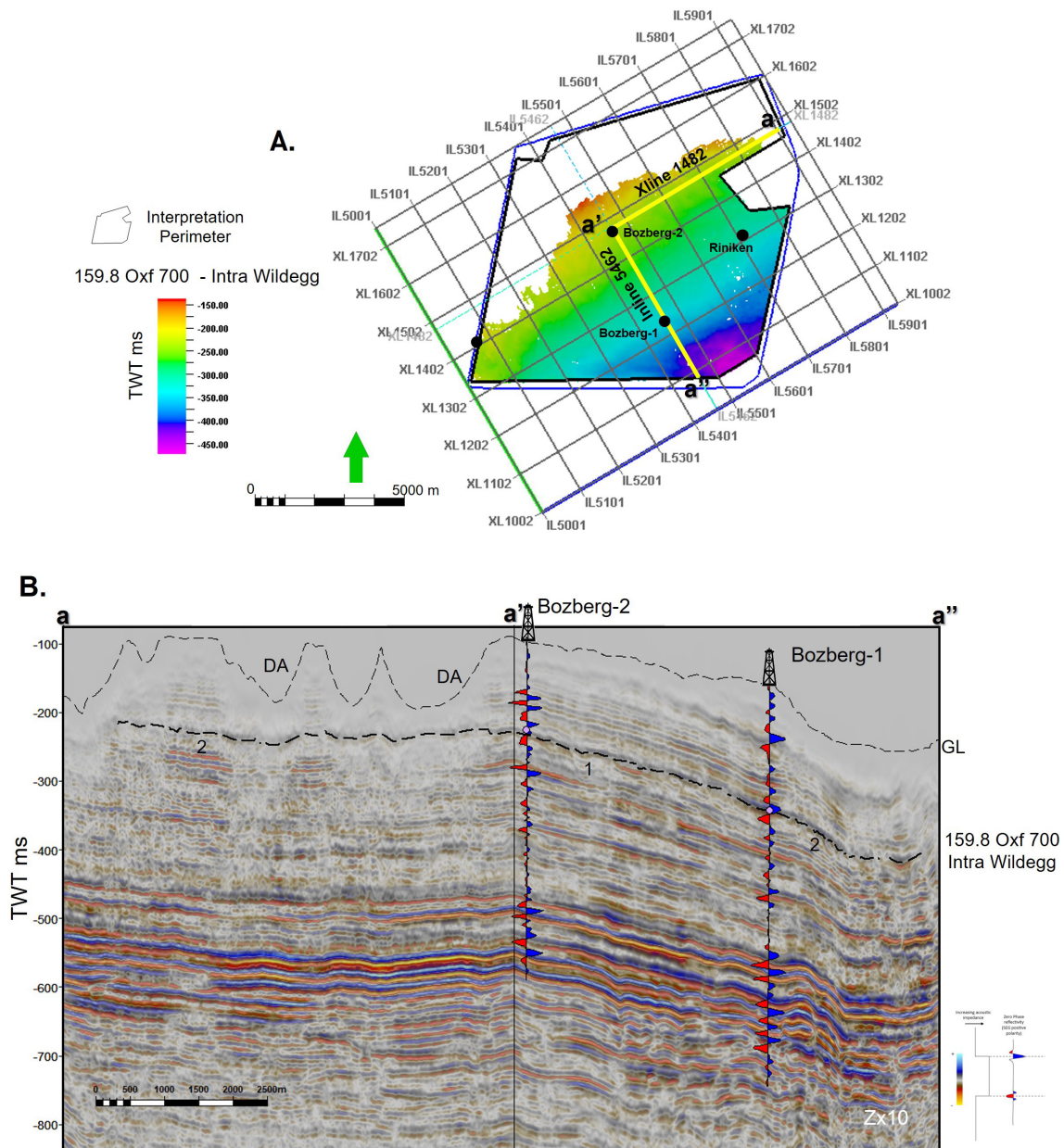


Fig. 5-8: 159.8 Oxf 700 – Intra Wildegg horizon interpretation

A. TWT top structure of horizon 159.8 Oxf 700 – Intra Wildegg; B. Inline-crossline composite across the Bözberg-1 and Bözberg-2 wells. 159.8 Oxf 700 – Intra Wildegg is interpreted as a zero-crossing below the peak that marks the limestone layer of the Gerstenhübel Bed. Changes in amplitude content and reflection pattern from areas with chaotic seismic facies (1) and more continuous reflectors (2) could be related to the lithological variability of this stratigraphic interval. Amplitude degraded areas (DA) are identified and are associated with the presence of topographic valleys. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

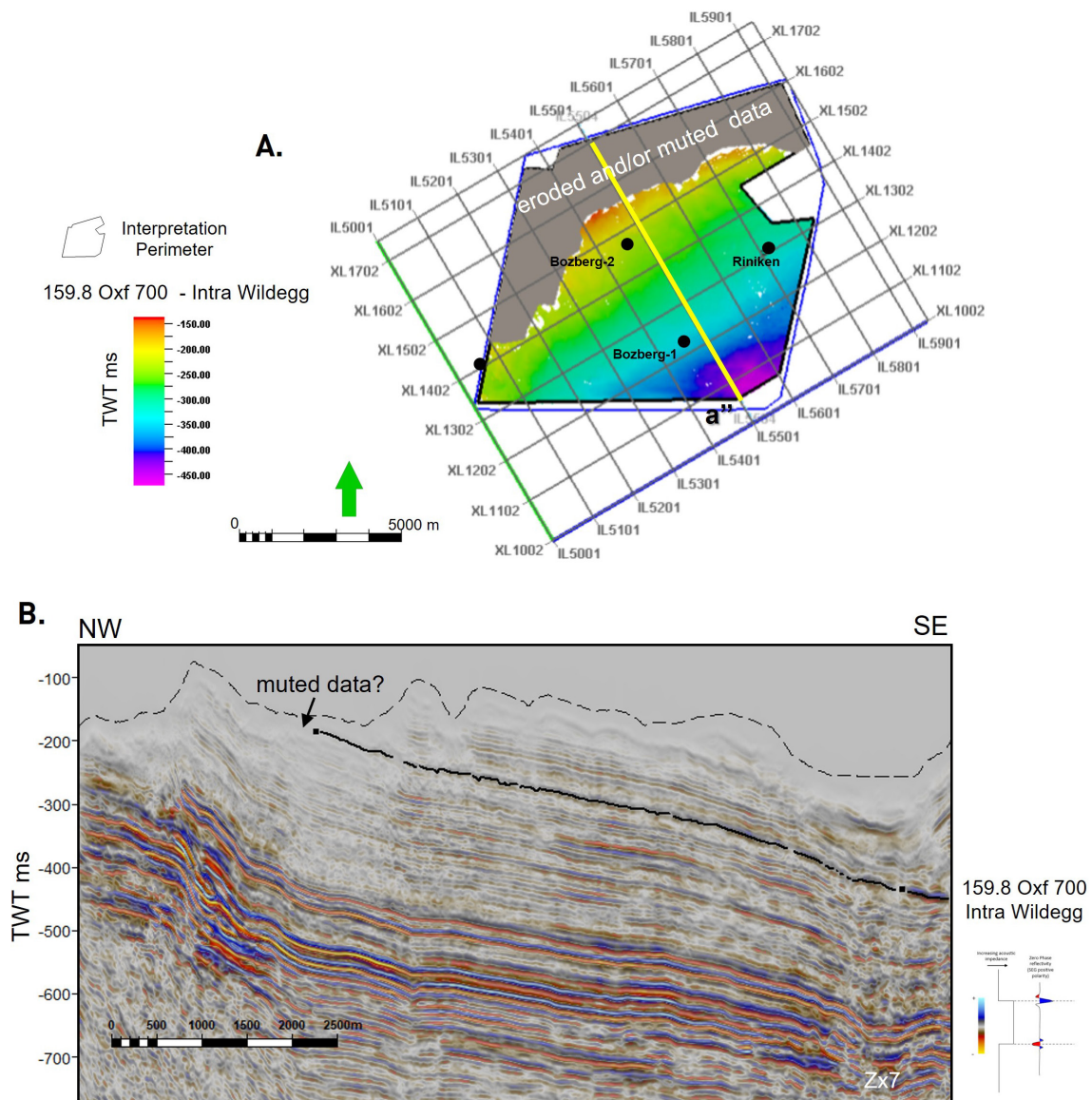


Fig. 5-9: Area where 159.8 Oxf 700 – Intra Wildegg horizon is eroded and/or not imaged

A. TWT top structure of horizon 159.8 Oxf 700 – Intra Wildegg showing the area where this stratigraphic layer is eroded. However, the seismic data appear muted at shallow level. Therefore, a clear boundary of erosion cannot be determined. B. inline 5504 showing the interpretation termination towards the north. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.2 159.8 Oxf 975 – Top Dogger

Horizon 159.8 Oxf 975 coincides with the Top Dogger Group and was interpreted following a relatively continuous trough (Fig. 5-7, Fig. 5-10). Towards the north, the Top Dogger is eroded. Similar to the horizon 159.8 Oxf 700 – Intra Wildegg, the limit of the erosion is impaired by the data muting near the surface. The Dogger Group, from bottom (Top Opalinus Clay) to top comprises the Passwang Formation (168.2 Baj 100), consisting mostly of silty claystone, argillaceous siltstone and silty to sandy marl with non-porous, calcareous and iron-oolitic interbeds, with an inferred decreasing thickness trend towards the east. The 168.2 Baj 100 – Top Passwang Formation is overlain by the carbonate platform of the Hauptrogenstein, which consist mostly of bedded oolitic and bioclastic limestone and some calcareous marl. The Hauptrogenstein platform interfingers towards the east with its more basinal counterpart of the Klingnau Formation. The summed thickness of the Hauptrogenstein decreases from ca. 80 m in the west to 8 m (Riniken well) in the east. The Ifenthal Formation, which consists of a 5 – 10 m thick interval of partly iron-oolitic limestone and calcareous marl, completes the Dogger Group (Nagra 2024d).

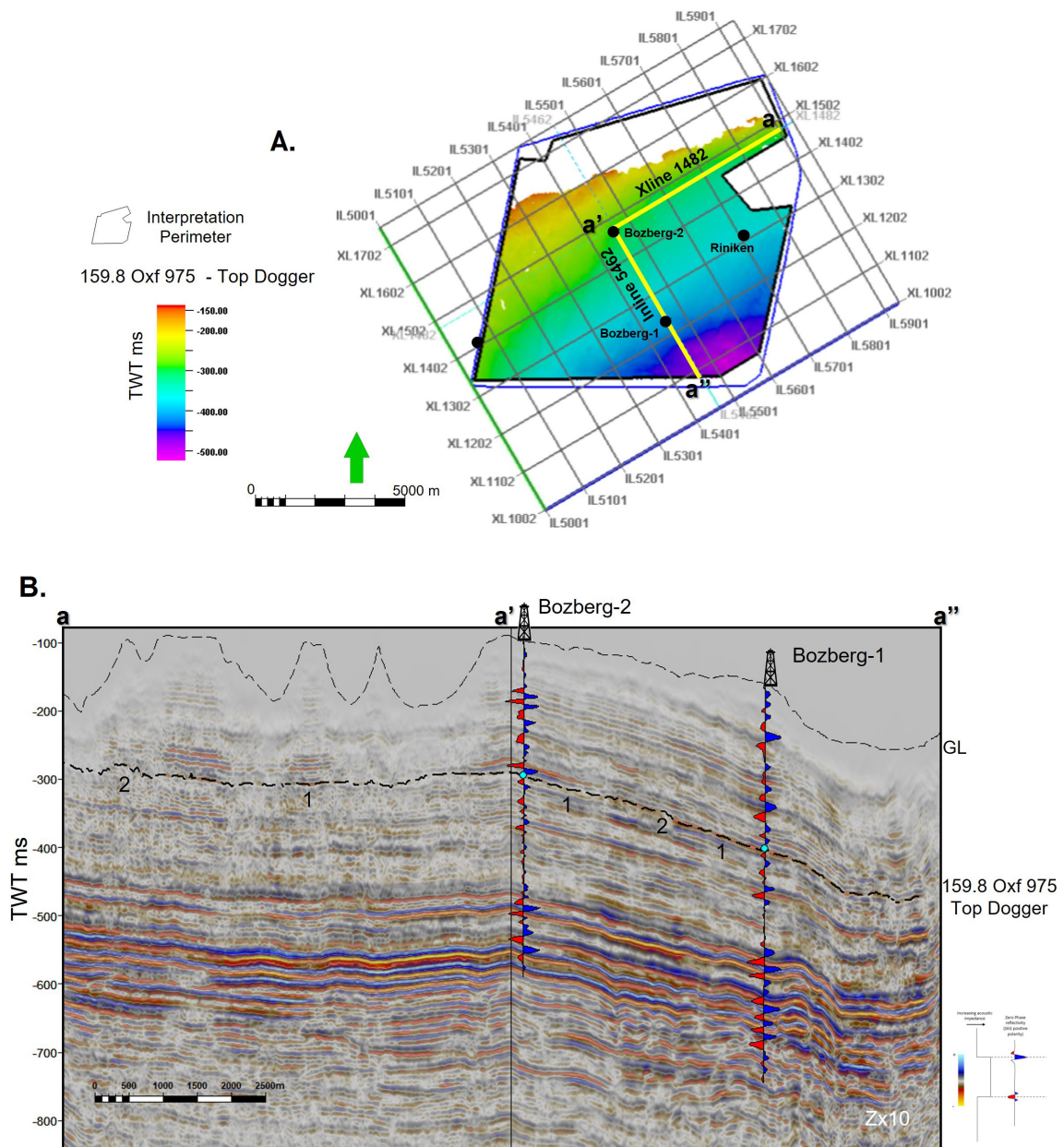


Fig. 5-10: 159.8 Oxf 975 – Top Dogger horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Bozberg-2 and Bozberg-1 wells. Horizon 159.8 Oxf 975 – Top Dogger is a horizon with variable amplitude content. The variability of the acoustic response appears to be related to the underlying seismic facies. Higher amplitudes are observed with continuous stratified reflectivity stack (1), while dimmed amplitude is associated with chaotic low-amplitude seismic facies (2). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The articulated sedimentological architecture of the Dogger interval is reflected in the complex seismic response. The top horizon (159.8 Oxf 975 – Top Dogger) shows a change in amplitude appearance along this horizon that seems to be controlled by the acoustic contrast with the underlying layer. The transition (interfingering) between the Hauptrogenstein platform with its more basinal counterpart of the Klingnau Formation towards the east appears to be imaged by the change in seismic facies with a transparently chaotic response at the Riniken well (Fig. 5-11). The 168.2 Baj 100 – Top Passwang Formation is a very challenging horizon to interpret. The interval below this horizon is characterised by variable seismic facies from low-amplitude discontinuous mound-shaped reflections to a well stratified high-amplitude reflection package, which laterally and vertically incorporates mound-shaped or inclined low-amplitude internal reflections (Fig. 5-10, Fig. 5-11). Seismically, the eastwards decreasing thickness trend inferred from the sedimentology can be recognised, however the thickness pattern appears more irregular with localised thickening and thinning (Fig. 5-11B).

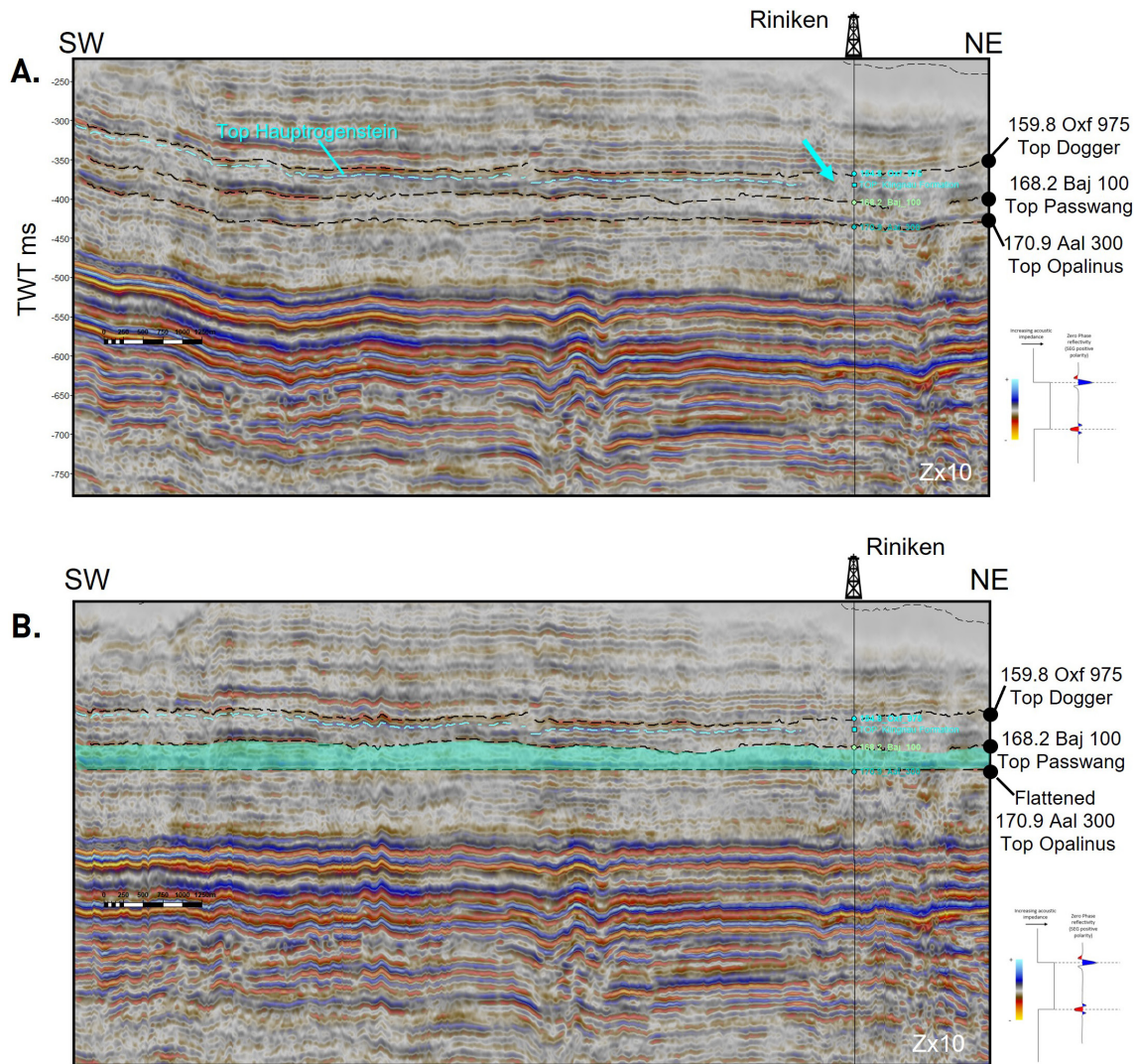


Fig. 5-11: Crossline 1314 across the Riniken well showing Dogger Group seismic facies variability

A. Crossline 1314 across the Riniken well; B. Crossline 1314 across the Riniken well flattened at horizon 170.9 Aal 300 – Top Opalinus, which represents the bottom horizon of the Dogger Group stratigraphic unit. The 168.2 Baj 100 – Top Passwang Formation is an extremely challenging horizon to map, showing a lot of lateral variability in the seismic response. Sedimentological evaluation suggests thickness decreasing trend towards the east. This trend is recognisable in the flattened seismic section (B.), but the thickness variability appears to follow a less linear pattern (light green transparent polygon). Despite the complicated seismic response of the Dogger Group interval, the transition (interfingering) between the Hauptrogenstein platform with its more basinal counterpart of the Klingnau Formation towards the east appears to be imaged by the change in seismic facies (A.; light blue arrow). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.3 170.9 Aal 300 – Top Opalinus

The Top Opalinus (170.9 Aal 300 well marker (Tab. 5-1, Fig. 5-7, Fig. 5-12) represents the top of the host rock and seismically shows as a clearly marked soft acoustic response above the transparent acoustic impedance zone where seismic multiples interfere with primary reflectivity (Fig. 5-3). The lack of acoustic response is strongly driven by the Opalinus Clay composition of mostly claystone to fine sandy and silty claystone. Consequently, while the internal architecture of the Opalinus Clay cannot be unlocked, its top can be interpreted with confidence. In the northern area of the JO-15 seismic survey perimeter, the 170.9 Aal 300 – Top Opalinus is eroded. As described for horizons 159.8 Oxf 700 – Intra Wildegg and 159.8 Oxf 975 – Top Dogger, the exact erosional limit cannot be mapped since the very shallow part of seismic data is muted (Fig. 5-9).

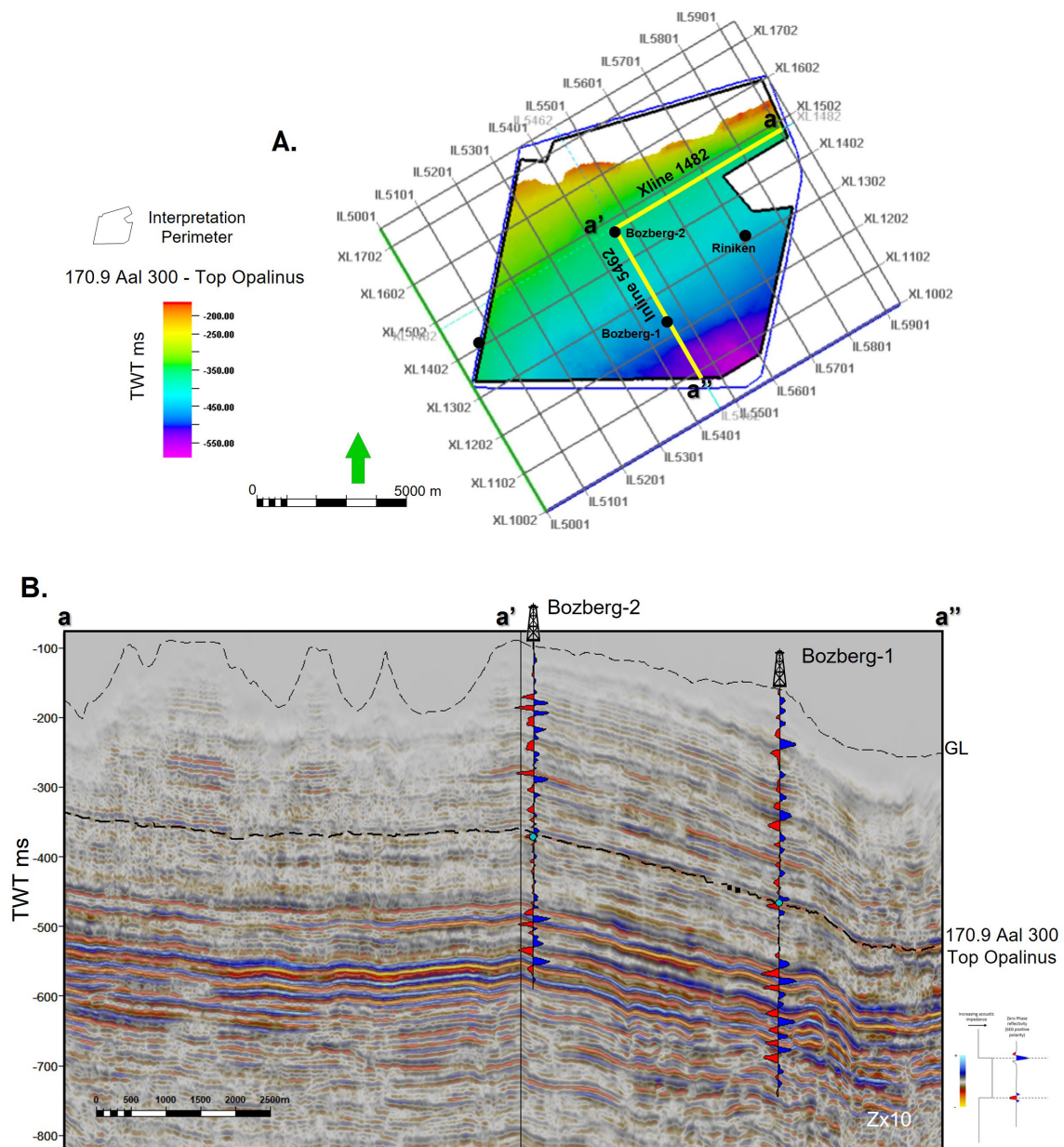


Fig. 5-12: 170.9 Aal 300 – Top Opalinus clay horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Bözberg-2 and Bözberg-1 wells. Horizon 170.9 Aal 300 – Top Opalinus marks the top of the homogeneous interval of the Opalinus Clay as reflected by the soft acoustic contrast. Such a horizon can be traced with confidence across the JO-15 seismic survey. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.4 192.9 Sin 200 – Near Top Klettgau (as Proxy for 174.7 Toa 100 – Top Lias)

Clear challenges were identified in the interpretation of the Top Lias (174.7 Toa 100) even in the most undisturbed central area (Tab. 5-1, Fig. 5-7, Fig. 5-13). In this area, the Top Lias seismic event shows a strong lateral variability in amplitude strength and reflection shape, which is not consistent with the described homogeneous rock properties (Nagra 2024d, 2022a, 2022b).

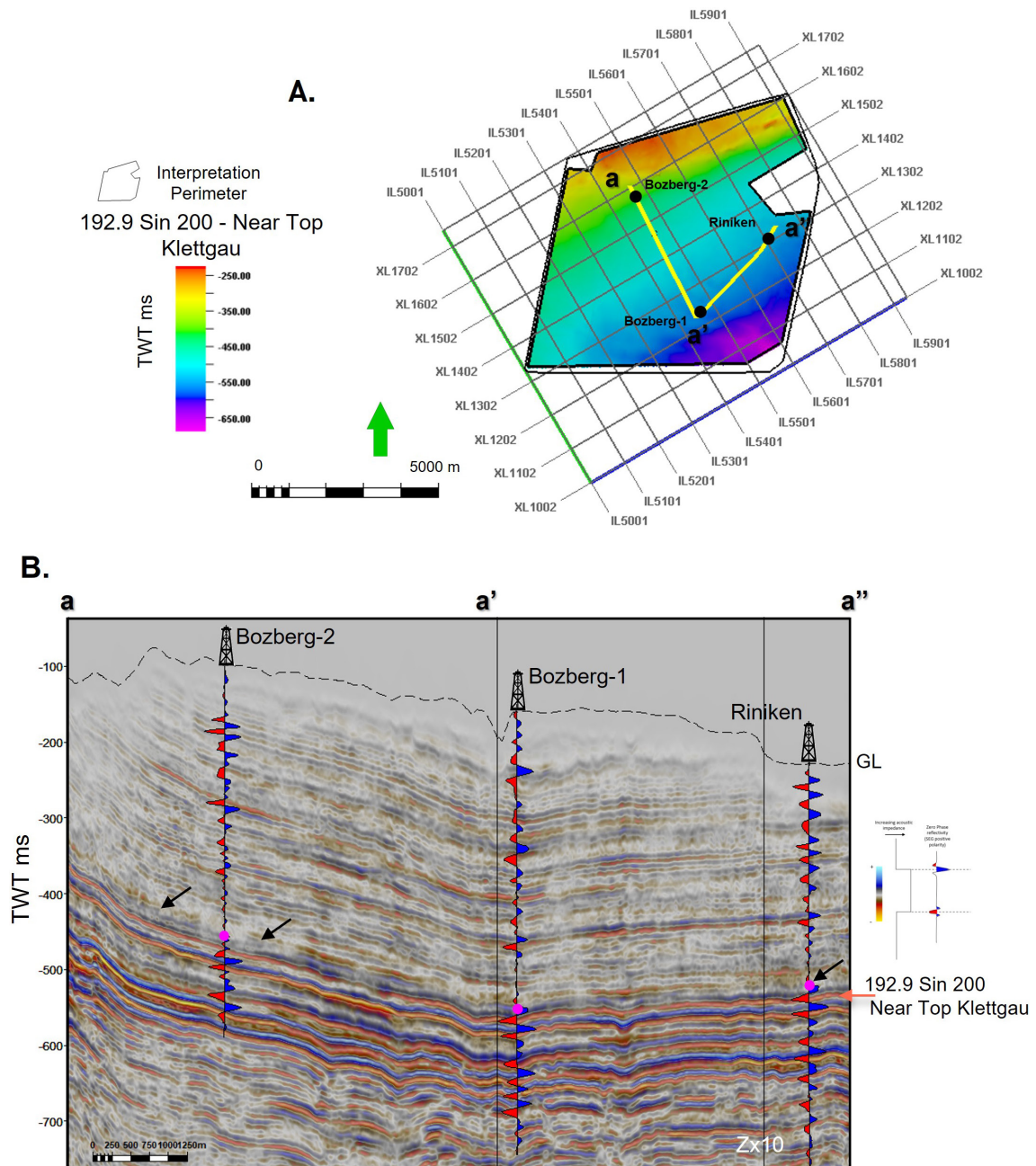


Fig. 5-13: Seismic section across the three wells showing seismic-to-well ties (synthetics) and the correlation of 174.7 Toa 100 – Top Lias well tops (purple circles)

A. Line location plotted over 192.9 Sin 200 – Near Top Klettgau horizon interpretation;
B. Seismic section showing the clear challenges in the interpretation of the 174.7 Toa 100 – Top Lias (Base Opalinus) even in the most undisturbed central area, where a strong lateral variability in amplitude strength and width is observed (black arrows). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

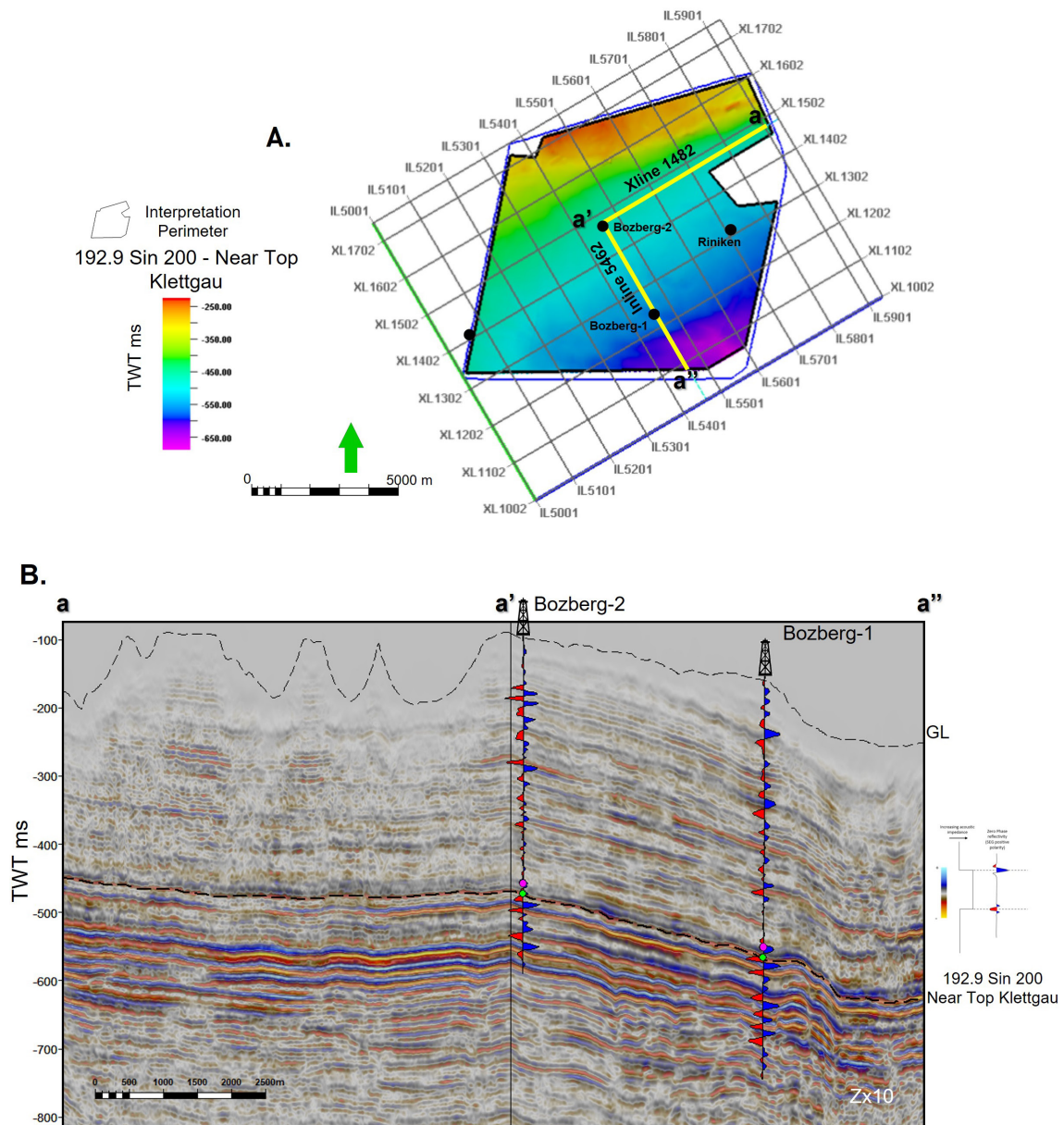


Fig. 5-14: 192.9 Sin 200 – Near Top Klettgau horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Bözberg-2 and Bözberg-1 wells. Clear challenges were identified in the interpretation of the Base Opalinus Clay (174.7 Toa 100 - purple well marker). Therefore, 192.9 Sin 200 – Near Top Klettgau (green well marker) was selected as it represents the most continuous horizon below the Base Opalinus Clay. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

At this specific stratigraphic level, confidence (interpretability) in the horizon picking is a critical factor to establish the vertical upward propagation of the faults affecting the deeper Mesozoic succession (i.e. lower confining unit) and their impact on host rock integrity. Consequently, the 192.9 Sin 200 – Top Beggingen Member marker, for simplicity referred to as Near Top Klettgau, was selected as it represents the most continuous horizon below the Top Lias (Tab. 5-1, Fig. 5-7, Fig. 5-14). Since horizon 192.9 Sin 200 – Near Top Klettgau is a very continuous and high-amplitude through, it maximises the effectiveness and confidence of the event continuity for the autotrack algorithm, while being as close as possible to the base of the Opalinus Clay host rock interval (Tab. 5-1, Fig. 5-14).

5.2.5 227 Car 200 – Near Top Bänkerjoch

Together with the overlying Klettgau Formation, the Bänkerjoch Formation forms the Keuper Group. It is a heterogeneous succession dominated by dolomitic and argillaceous marls with intercalations of dolostones and sandstones. Seismically, such heterogeneity is revealed by the lateral variability of the amplitude strength and thickness of the seismic event. The horizon 227 Car 200 – Near Top Bänkerjoch is a high-amplitude, continuous reflection (Tab. 5-1, Fig. 5-7, Fig. 5-15) and was therefore interpreted since it will act as calibration event to differentiate amplitude dimming associated with sedimentological facies variations from the amplitude dimming, indicating the presence of faults.

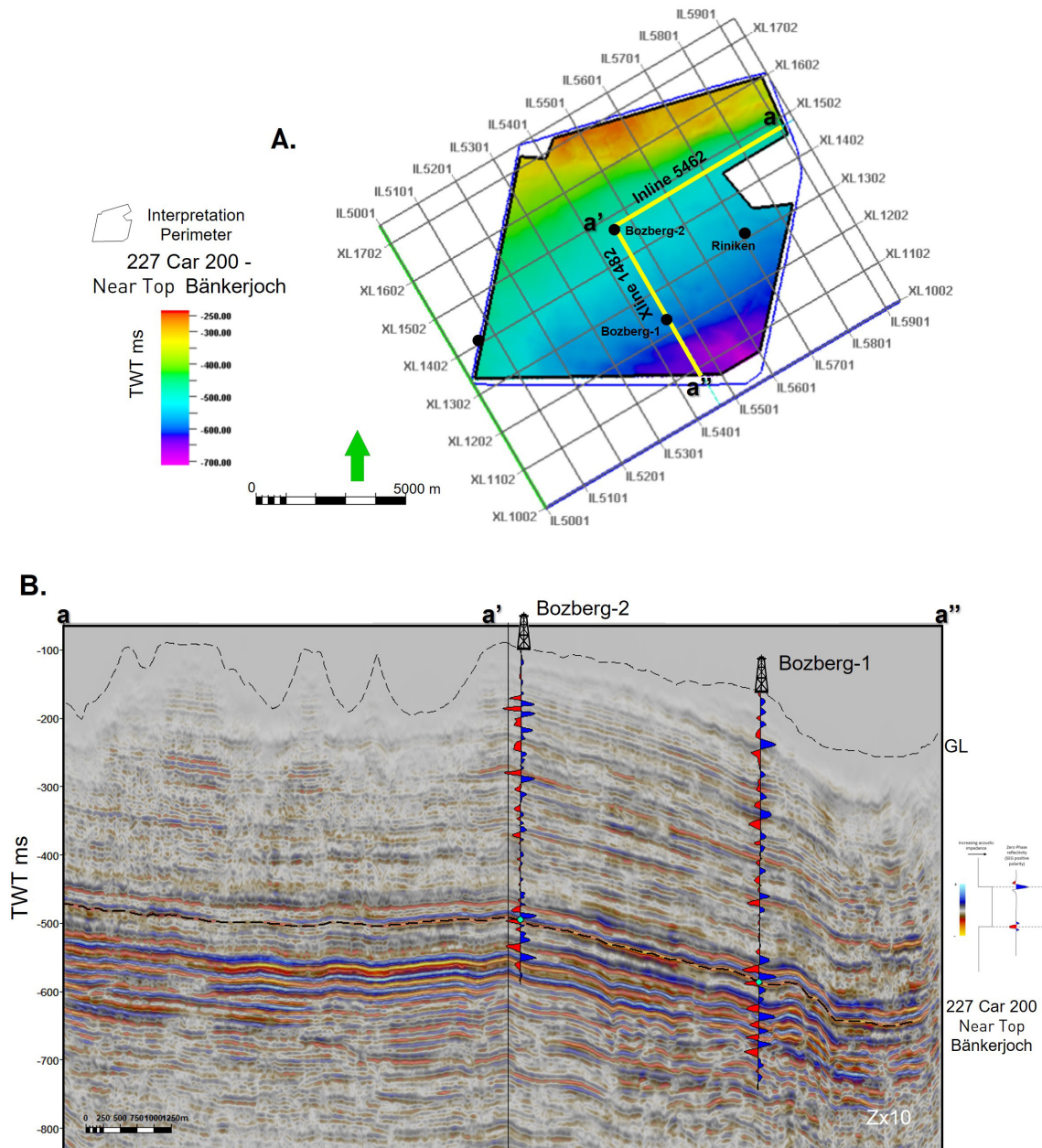


Fig. 5-15: 227 Car 200 – Near Top Bänkerjoch horizon interpretation

A. TWT top structure of 227 Car 200 – Near Top Bänkerjoch; B. Inline-crossline composite across the Bözberg-2 and Bözberg-1 wells. This horizon is seismically imaged by a continuous soft acoustic contrast bounding the Bänkerjoch Formation and it is an important event for discriminating facies variation versus presence of faults (amplitude dimming). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.6 237 Lad 200 – Intra Bänkerjoch

As proxy for the stratigraphic marker 237 Lad 400, which correlates with the Top of the Muschelkalk Group (Fig. 5-7; Jordan, 2016), horizon 237 Lad 200 – Intra Bänkerjoch was selected since it represents a high-amplitude and very continuous positive reflection, associated with the soft contrast with the underlying Muschelkalk Formation (Tab. 5-1, Fig. 5-16).

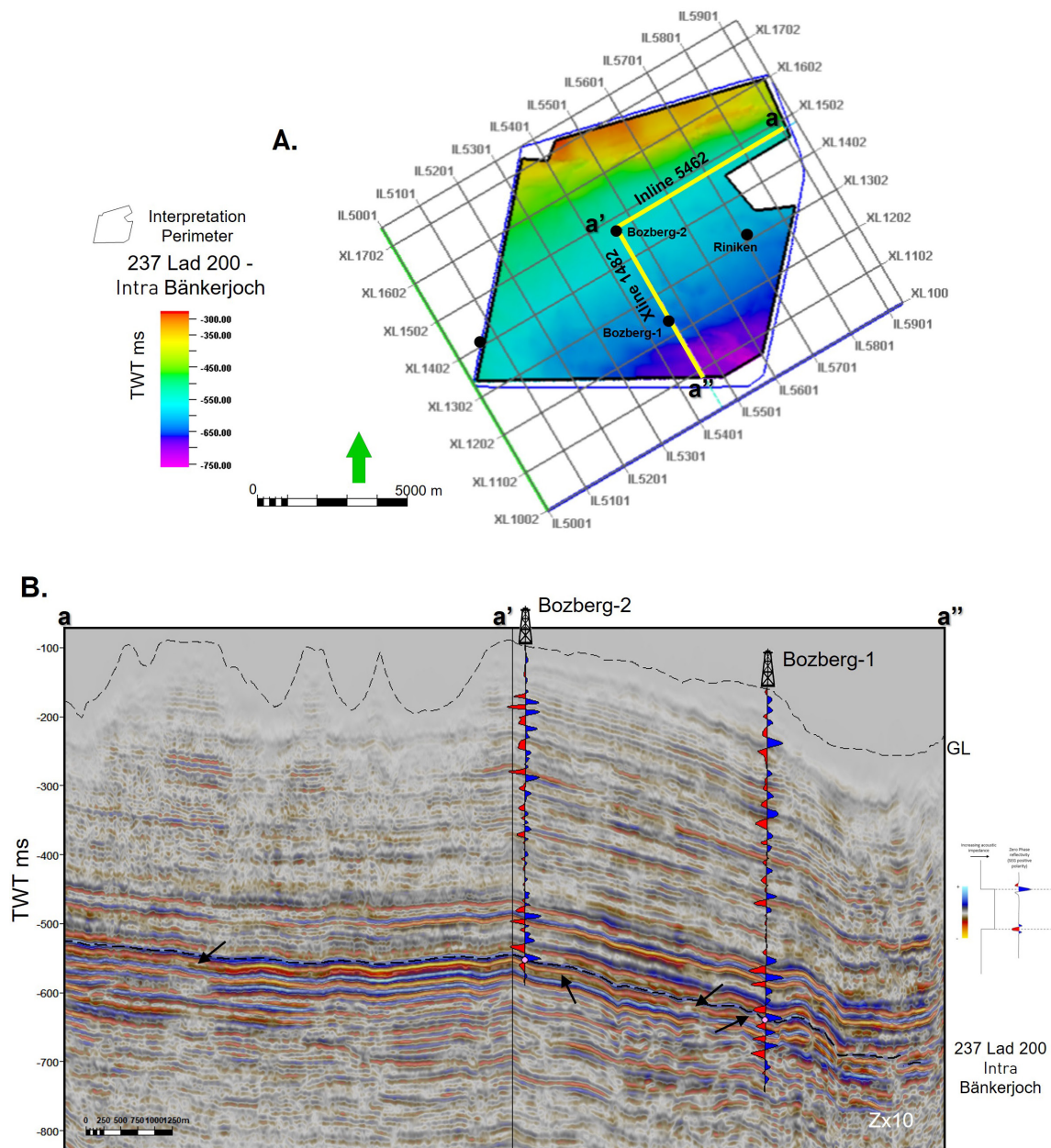


Fig. 5-16: 237 Lad 200 – Intra Bänkerjoch horizon interpretation

A. TWT top structure of horizon; B. Inline-crossline composite across the Bözberg-2 and Bözberg-1 wells. This horizon was selected in place of Top Muschelkalk since it is seismically very continuous. The soft loop associated with the Muschelkalk Group shows, on the other hand, strong variability in amplitude contents and wavelet shape (black arrows). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The zero-crossing and the soft loop marking the Top Muschelkalk Group, as well as the reflection package below, are characterised by lateral variation of the seismic response, with changes in amplitude content and wavelet shape (i.e. doublets; Fig. 5-16), reducing the confidence in the fault interpretation. This observation is consistent with previous interpretation efforts (Nagra 2019), where the Top Muschelkalk horizon interpretation was guided by the overlying strong reflection package. The observed heterogeneous response (Fig. 5-17) might mimic the complex geology of the Muschelkalk Group (Nagra 2024d). The three depositional phases distinguished in the Muschelkalk Group recorded a variability in depositional environments from (i) a transgressive phase characterised by silty, sandy, marly and calcareous / dolomitic deposits, to (ii) a sabkha environment dominated by evaporites (dolostones, marl, claystone, anhydrite) to (iii) a marine transgression and regression phase where shallow marine micrite and intermittent bioclastic beds (transgression) underlay oolitic micrite locally deposited during the regression phase. In the latter depositional environment, almost no halite was recorded in the wells in the JO siting region (in contrast to the wells in the NL siting region; Nagra 2024d).

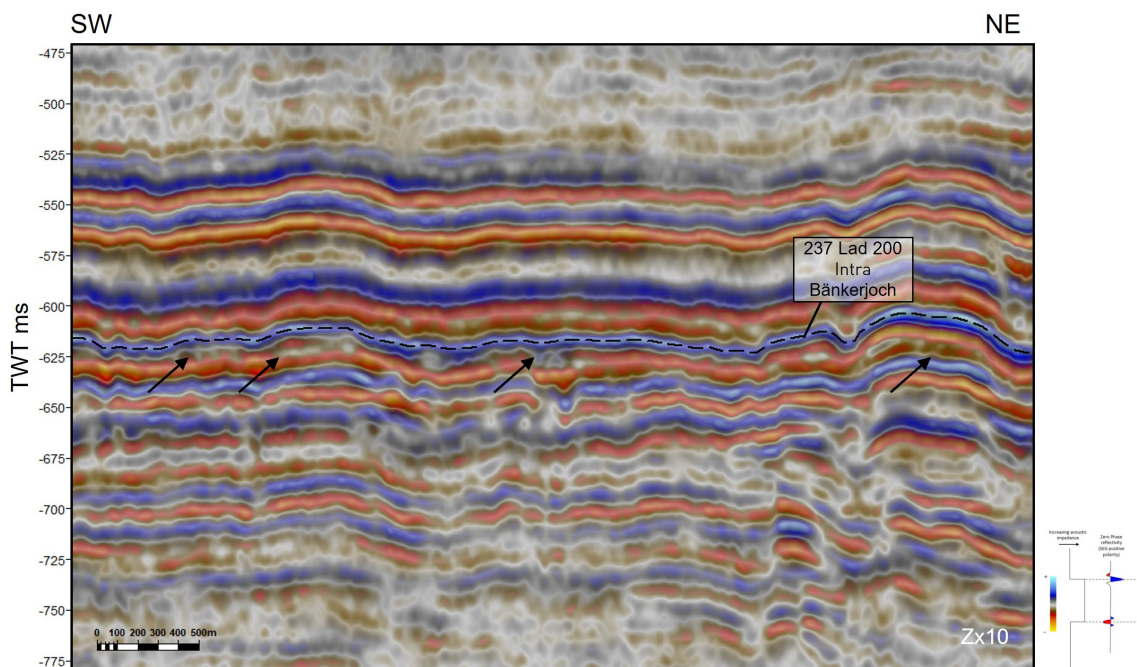


Fig. 5-17: Crossline 1290 showing the variability of the Top Muschelkalk reflection

Zoom-in on crossline 1290 located in the central area of the JO-15 seismic survey showing the variability in amplitude and wavelet shape (black arrows) of the soft loop (trough) associated with the Top Muschelkalk, just below the 237 Lad 200 – Intra Bänkerjoch. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.7 251.9 Per 100 – Near Base Mesozoic Unconformity

Horizon 251.9 Per 100 – Base Mesozoic Unconformity has the lowest confidence among the interpreted surfaces, since it represents a major unconformity (Tab. 5-1, Fig. 5-18). The seismic response to an unconformity depends on the nature of the contact between pre-unconformity and post-unconformity sections. For an unconformity, the pre-unconformity and post-unconformity sections are in angular contact, and the seismic response to an unconformity appears as a reflection of terminations or discontinuities between groups of reflections (Fig. 5-19). Due to the variability in properties of pre-unconformity and post-unconformity deposits, a change in reflection polarity can be expected.

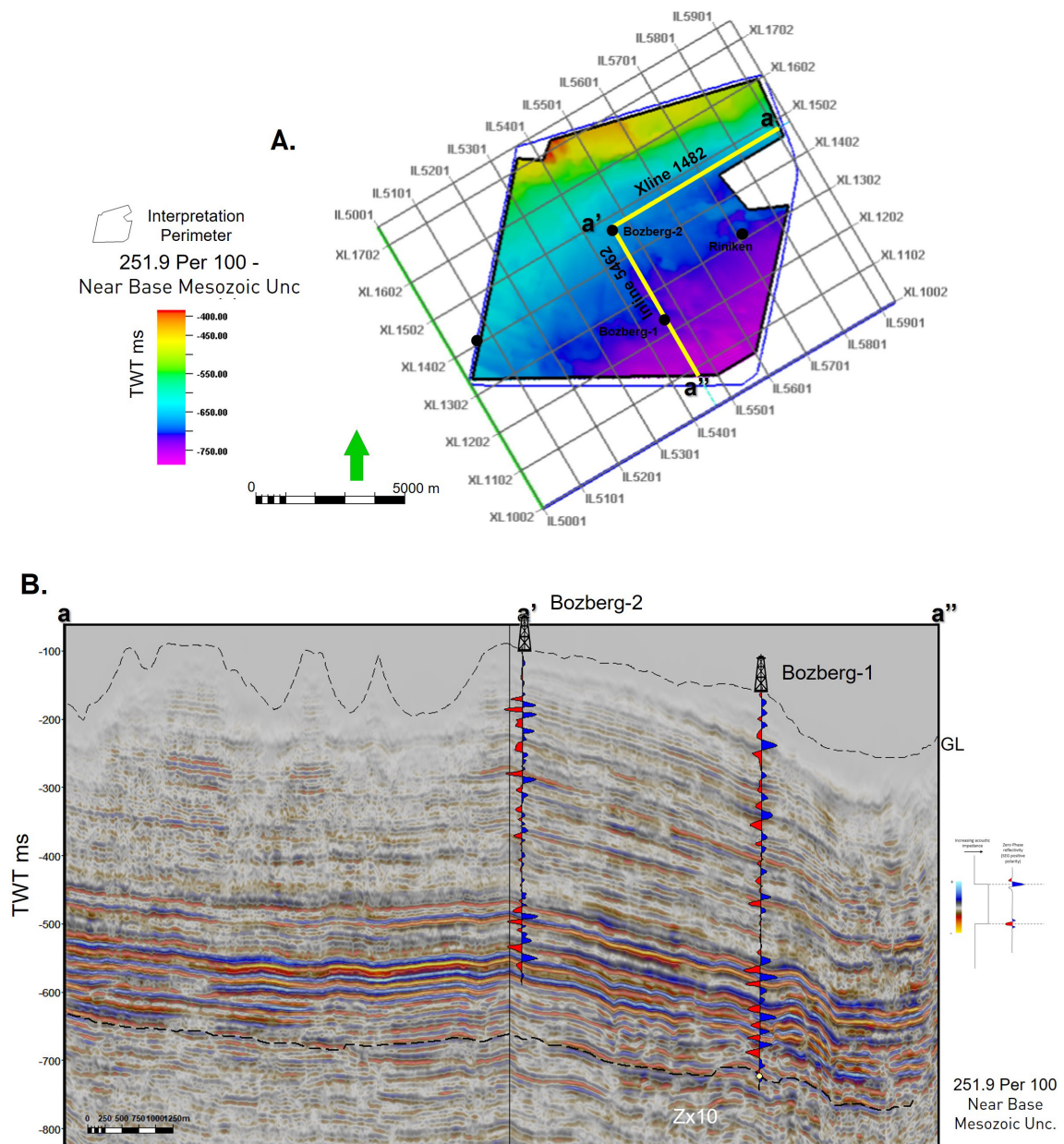


Fig. 5-18: 251.9 Per 100 – Near Base Mesozoic Unconformity horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Bözberg-1 and Bözberg-2 wells. Note that Bözberg-2 well does not penetrate the 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The Base Mesozoic unconformity was interpreted with challenges recognised by previous interpretation attempts (Nagra 2019, Madritsch et al. 2013) and in the other two siting regions (Nagra 2024b, 2024c). To mitigate the picking uncertainty, despite considering the limitation of the approach, this horizon was traced following a zero-crossing (Z-crossing; Fig. 5-7, Fig. 5-18, Tab. 5-1) that consistently correlated at wells to the stratigraphic marker 251.9 Per 100. Not representing the unconformable boundary, but rather the nearest continuous peak, the resulting interpreted horizon was referred to, therefore, as the Near Base Mesozoic Unconformity. Rare potential reflection geometries that could be related to unconformity truncation are observed deeper than the interpreted horizon (Fig. 5-19). Despite the interpretation uncertainty, the Near Base Mesozoic Unconformity represents, as for the other two siting regions, a key marker since it was demonstrated to play a key role in unlocking the interaction and influence of the deeper structural grains (basement and Permo-Carboniferous faults) on the Mesozoic deformation (Nagra 2024d, 2019, Zambrano et al. 2024, Madritsch et al. 2013).

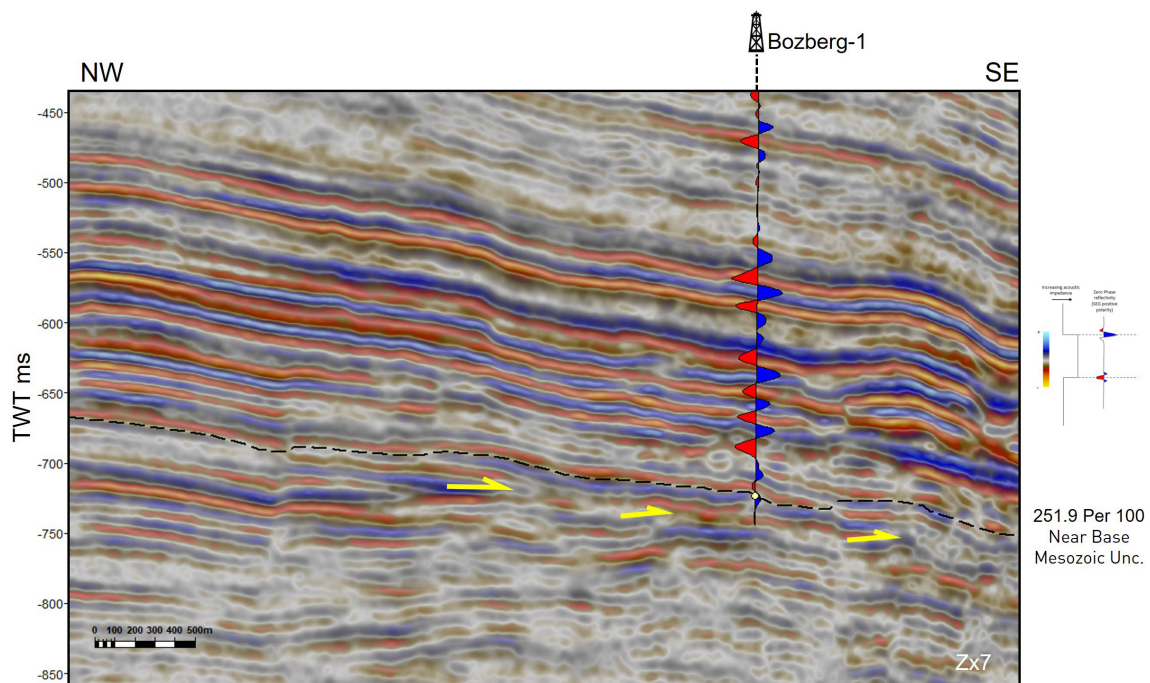


Fig. 5-19: Potential strata truncation (yellow arrows) below 251.9 Per 100 – Near Base Mesozoic Unconformity

5.3 Fault interpretation

Fault interpretation was carried out using a 3D multi-phase approach (Fig. 4-8). The screening phase resulted in structural maps where structural lineaments (faults and folds; ASR 2022 deformation zones, Nagra 2022) were discriminated from other geological features and seismic artefacts and captured as traces for the four main stratigraphic horizons (Fig. 5-20 Fig. 5-21).

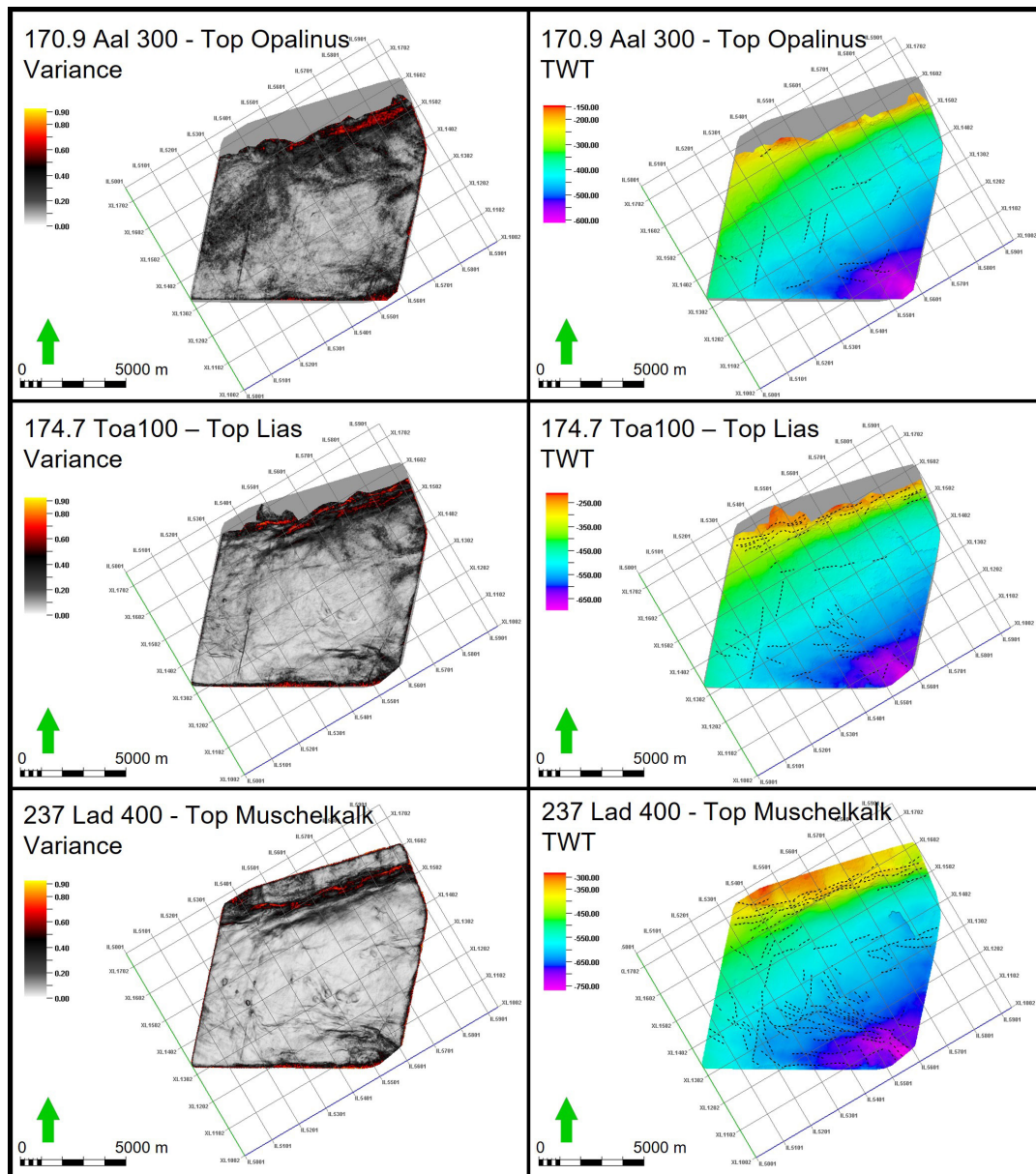


Fig. 5-20: ASR structural interpretation matrix based on PreSTM-ref minimum-phase
Nagra (2022)

Displays of the variance attribute horizon slices and the structural lineaments (dashed black lines-fault interpretation workflow Phase 1; interpreted seismic discontinuities represent deformation zones: faults and folds) on top of TWT structural maps of the three main stratigraphic horizons. In the JO siting region, Top Villigen is mostly eroded and therefore structural lineament mapping at this level is not shown. Input as for ASR. Definition of structural lineament as in Figure 5-22. Seismic data is PreSTM minimum-phase.

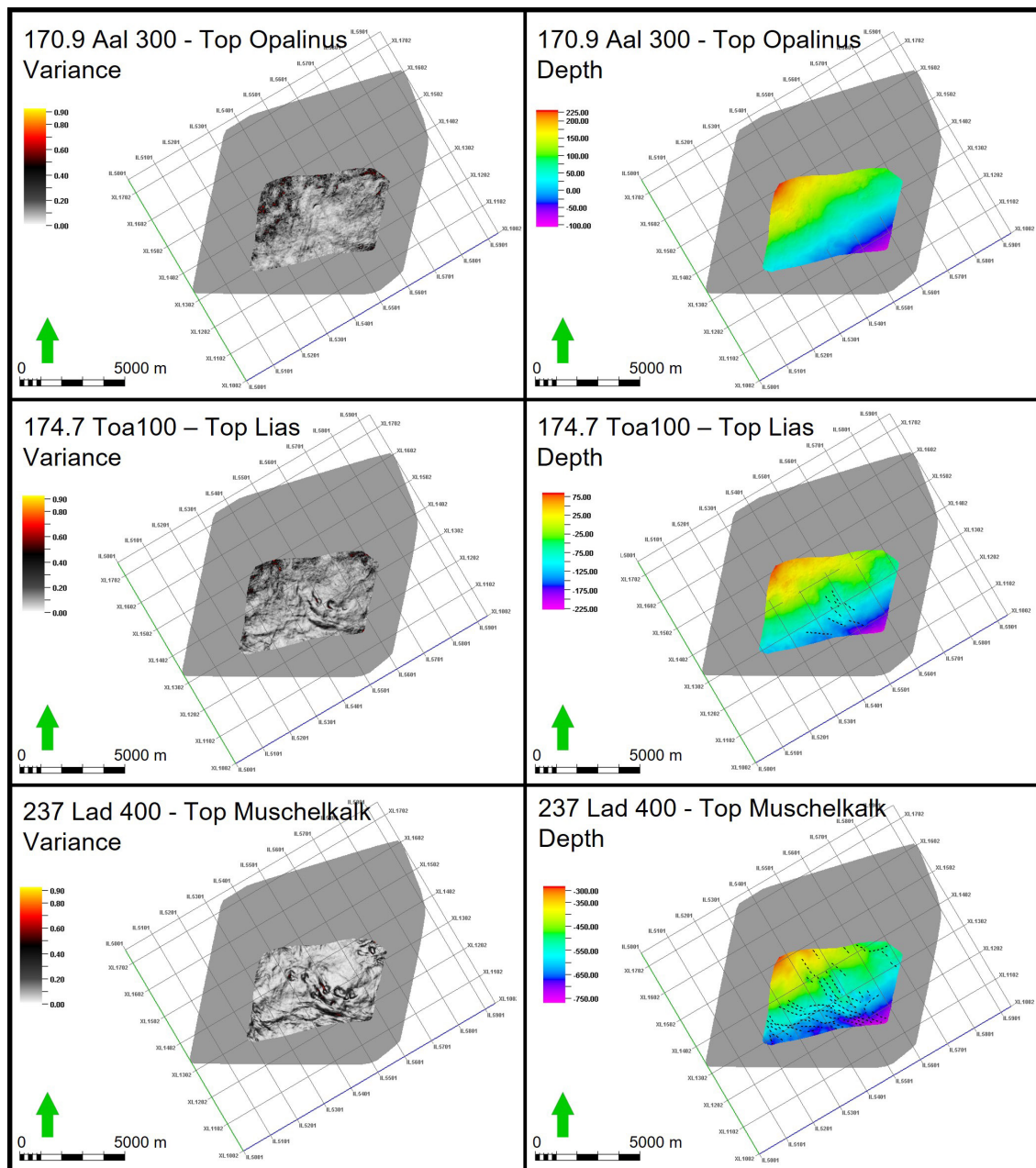


Fig. 5-21: Pre-ASR 2021 structural interpretation matrix based on PreSDM-ref minimum-phase

Displays of the variance attribute horizon slices and the structural lineaments (dashed black lines-fault interpretation workflow Phase 1; interpreted seismic discontinuities represent deformation zones: faults and folds) on top of TWT structural maps of the three main stratigraphic horizons. In the JO siting region, Top Villigen is mostly eroded and therefore structural lineament mapping at this level is not shown. Definition of structural lineament as in Fig. 5-22. Seismic data is PreSDM minimum-phase. Note that for JO-15 survey the PreSDM processing was performed only for the central part of the survey.

The interpreted structural lineaments at this stage of the interpretation workflow are considered (structurally) to be undifferentiated seismic discontinuities that can be attributed indiscriminately to faults or fault-related folds (i.e. fault-tip monoclines; Fig. 5-22). Since, on attribute maps, the identified seismic deformation zones appear to have similar seismic expression that make them indistinguishable from fold- and fault-related traces (Fig. 5-20, Fig. 5-21), the recognition and separation of seismic faults from folds was carried out following the defined seismic fault diagnostic criteria (Fig. 4-12) in a detailed 3D fault mapping performed during Phase 2.

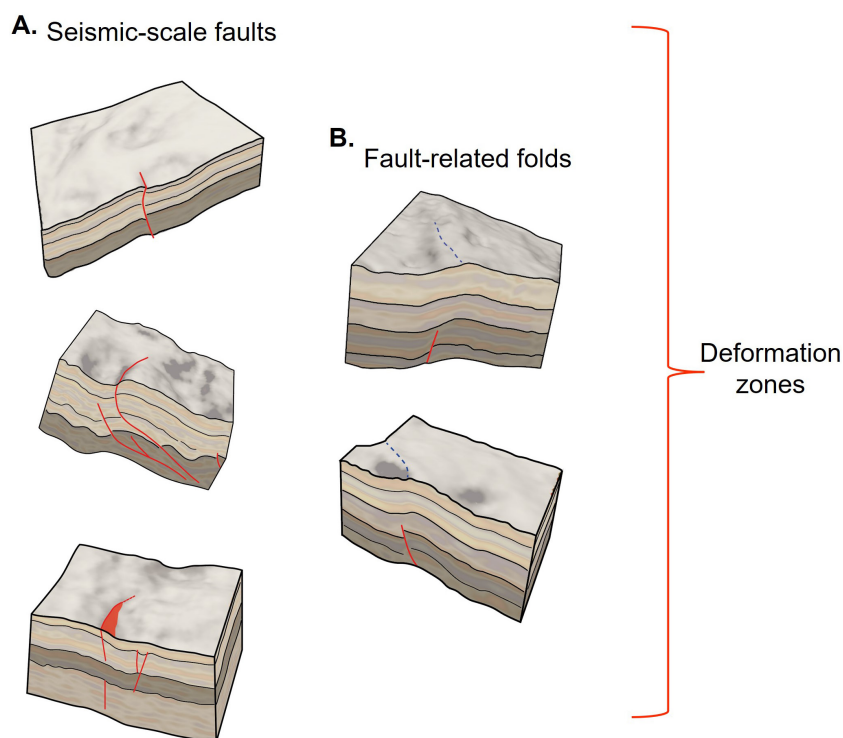


Fig. 5-22: Conceptual diagrams of the deformation zones as for Phase 1 interpretation

The seismic structural lineament mapping does not differentiate between faults and fault-related folds (i.e. drape-folds / fault-tip monoclines) and they are generally referred to as deformation zones. Definition of seismic fault signatures and 3D fault stick interpretation result in being able to distinguish between seismic faults and fault-related folds. This distinction is more challenging in the structurally complex zones (fold-and-thrust zones) since the definition of fault tip can occasionally be uncertain. A. Simplified conceptual diagram of seismic scale faults (red solid lines) for the different fault kinematics observed in the three siting regions; B. Simplified conceptual diagram of seismic-scale fault-related folds (blue dashed lines, i.e. fault-tip monoclines / drape-folds).

The resulting mapping of Phase 2 is a filtered image of the seismic structural lineaments of Phase 1 (Fig. 5-23) where solely fault traces are displayed and with some of the lineament trends adjusted to fully honour the vertical (section) criteria. To extract fault traces and generate fault maps at the base of the Opalinus Clay interval (174.7 Toa 100 – Top Lias), the high confidence 192.9 Sin 200 – Near Top Klettgau was shifted upwards (18 ms TWT) to match the 174.7 Toa 100 well tops (Fig. 5-24). The resulting fault traces are derived from the intersection of the fault sticks and the shifted horizon 192.9 Sin 200 – Near Top Klettgau and therefore they are referred as Near 174.7 Toa 100 – Top Lias.

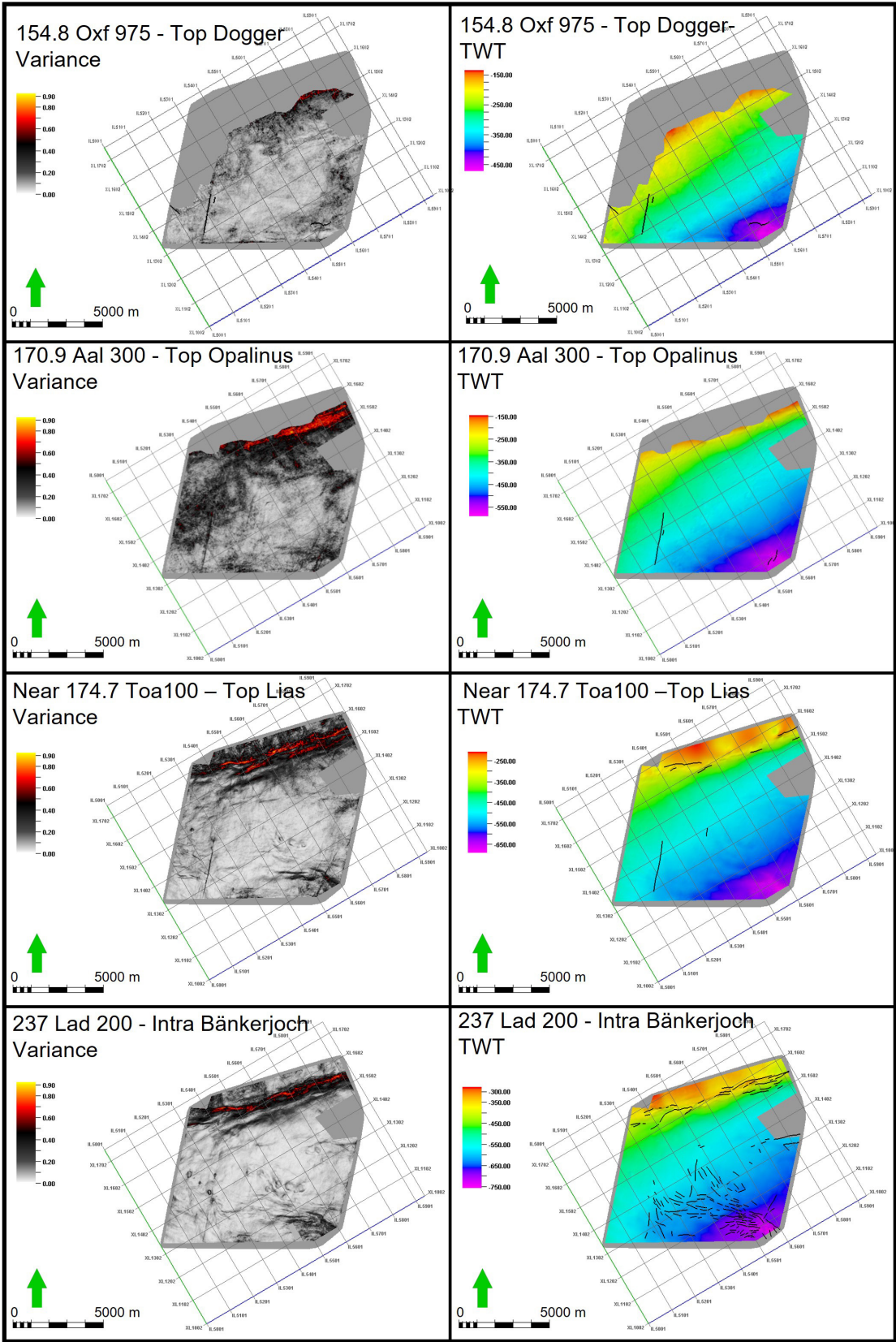


Fig. 5-23: 2023 (this report) fault interpretation matrix

For caption see next page

Displays of the variance attribute horizon slices and fault traces (black lines - fault interpretation workflow Phase 2) on top of TWT structural maps for the four main stratigraphic horizons. Compared to the ASR deformation zones, which use 3D stick interpretation, only lineaments interpreted as faults were selected. Note that horizon 174.7 Toa 100 – Top Lias is referred to as Near 174.7 Toa 100 – Top Lias since it is a “calculated” horizon derived from the isochroned up 192.9 Sin 200 – Intra Wildegg horizon. Furthermore, note that horizon 237 Lad 200 – Intra Bänkerjoch was preferred to 237 Lad 400 – Top Muschelkalk because of higher confidence in the picking continuity. Definition of structural lineament as illustrated in Fig 5-22. Seismic data is PreSTM-ref.

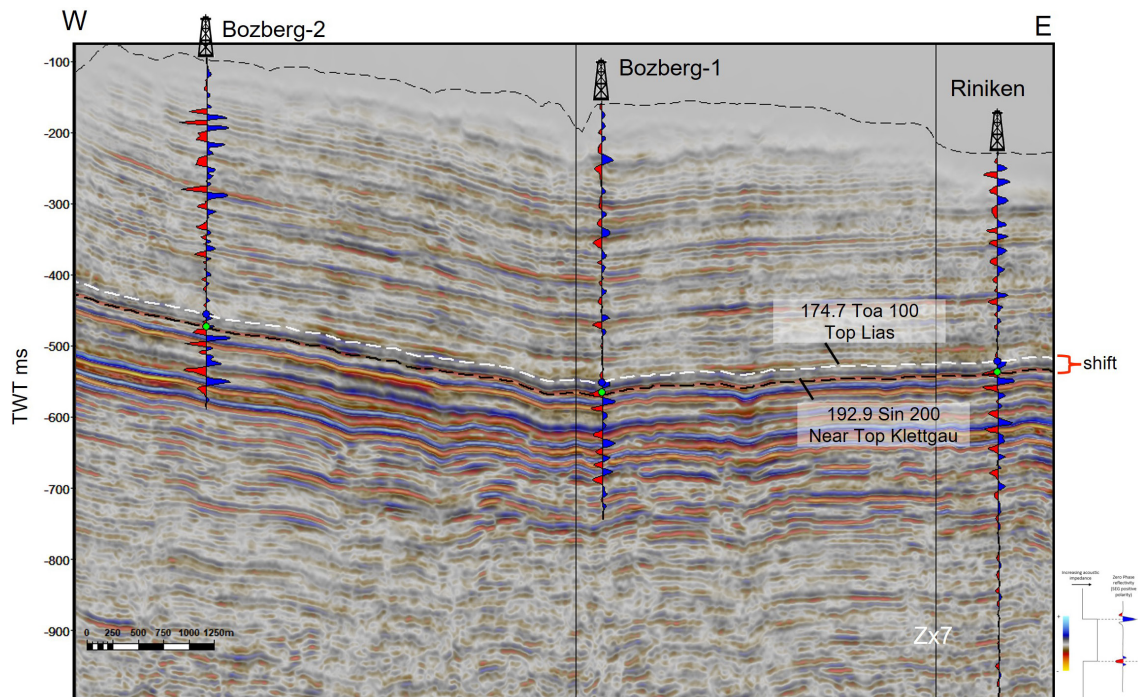


Fig. 5-24: Seismic line across the three wells showing the high confidence horizon 192.9 Sin 200 – Near Top Klettgau (black dashed line - green well top) shifted upwards to mimic the horizon 174.7 Toa 100 – Top Lias (white dashed line- blue well top)

This surface was used to extract fault traces affecting the base host rock (174.7 Toa 100 – Top Lias). Since it is a “calculated” horizon, it will be referred in this report as Near 174.7 Toa 100 – Top Lias. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The distribution and style of the interpreted seismic faults are also captured in key cross-sections (Fig. 5-25, Fig. 5-26, Fig. 5-27, Fig. 5-28). Seismic-scale faults appear to be systematically identified through the different vintages of seismic data and interpretations.

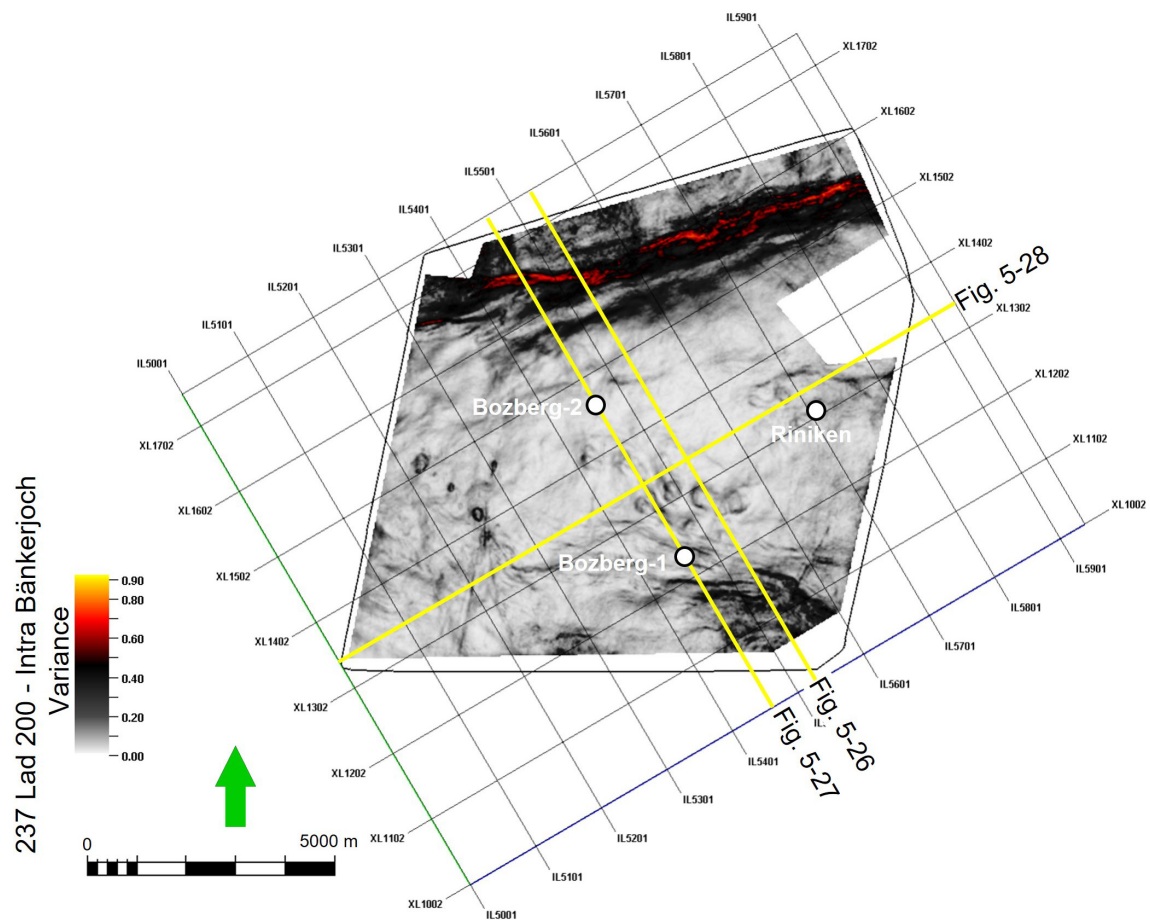


Fig. 5-25: 237 Lad 200 – Intra Bänkerjoch variance showing the three wells and the three key seismic sections illustrated in Fig. 5-26, Fig. 5-27, and Fig. 5-28

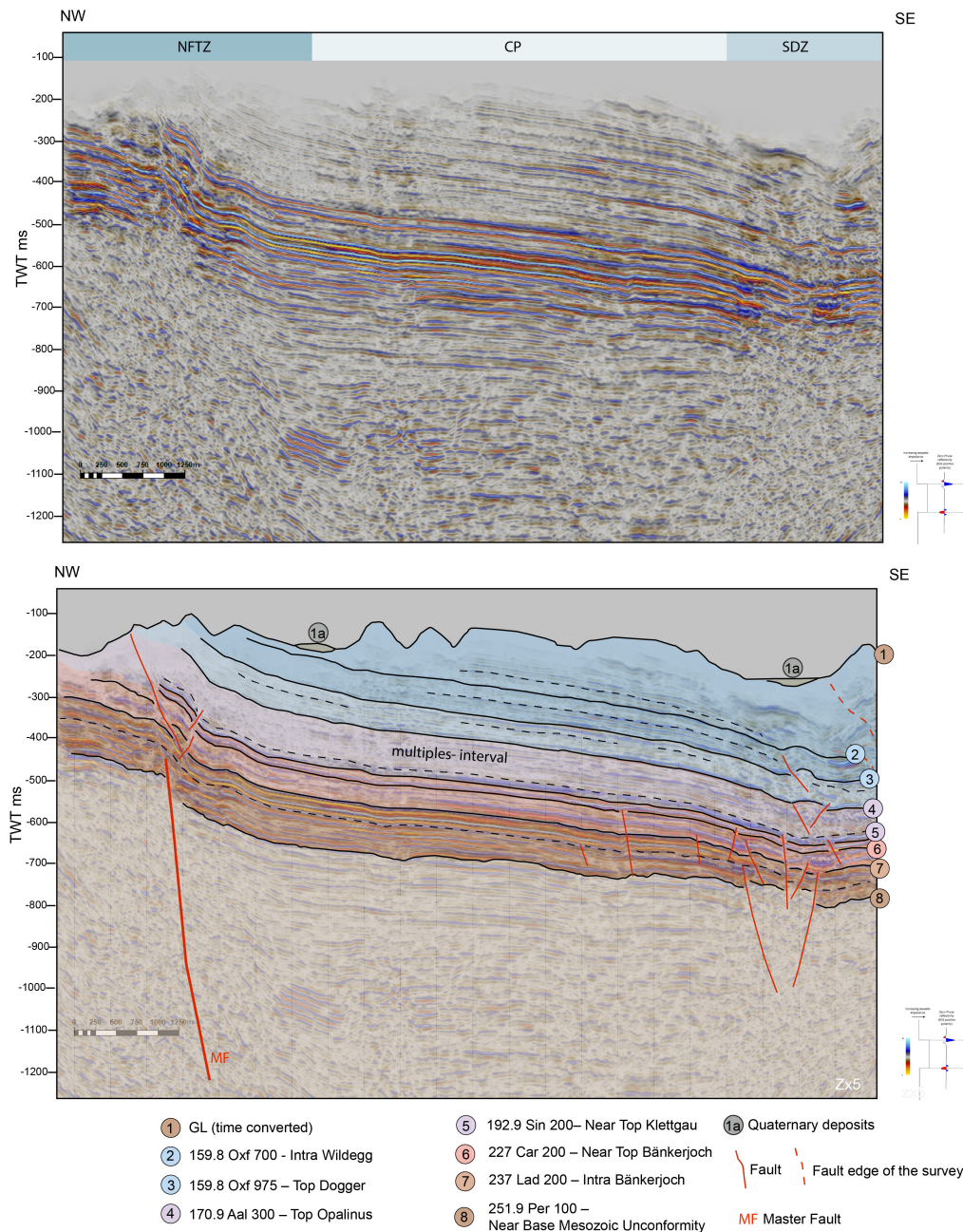


Fig. 5-26: Inline 5533 showing the fault interpretation and structural geometry and complexity across the JO siting region

A. Uninterpreted. B. Interpreted. Key structural element is the master fault (MF) forming the northern boundary of the Konstanz-Frick Trough. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by the presence of seismic multiples. Line location is shown in Fig. 5-25. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

NFTZ: Northern Fold-and-Thrust Zone, CP: Central Panel, SDZ: Southern Deformation Zone.

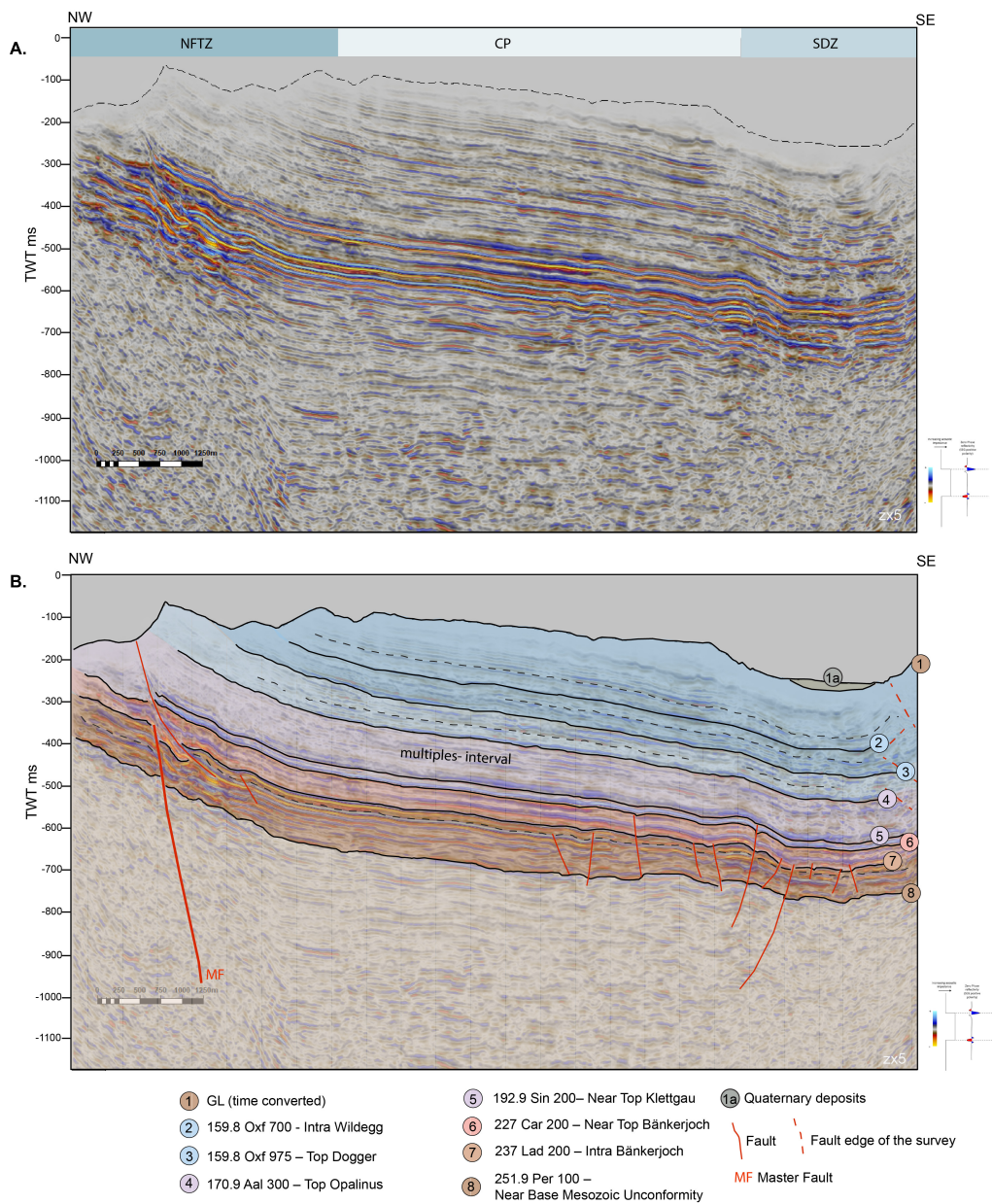


Fig. 5-27: Inline 5467 showing the fault interpretation and structural geometry and complexity across the JO siting region

A. Uninterpreted. B. Interpreted. Key structural element is the master fault (MF) forming the northern boundary of the Konstanz-Frick Trough. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by presence of seismic multiples. Line location is shown in Fig. 5-25. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

NFTZ: Northern Fold-and-Thrust Zone, CP: Central Panel, SDZ: Southern Deformation Zone.

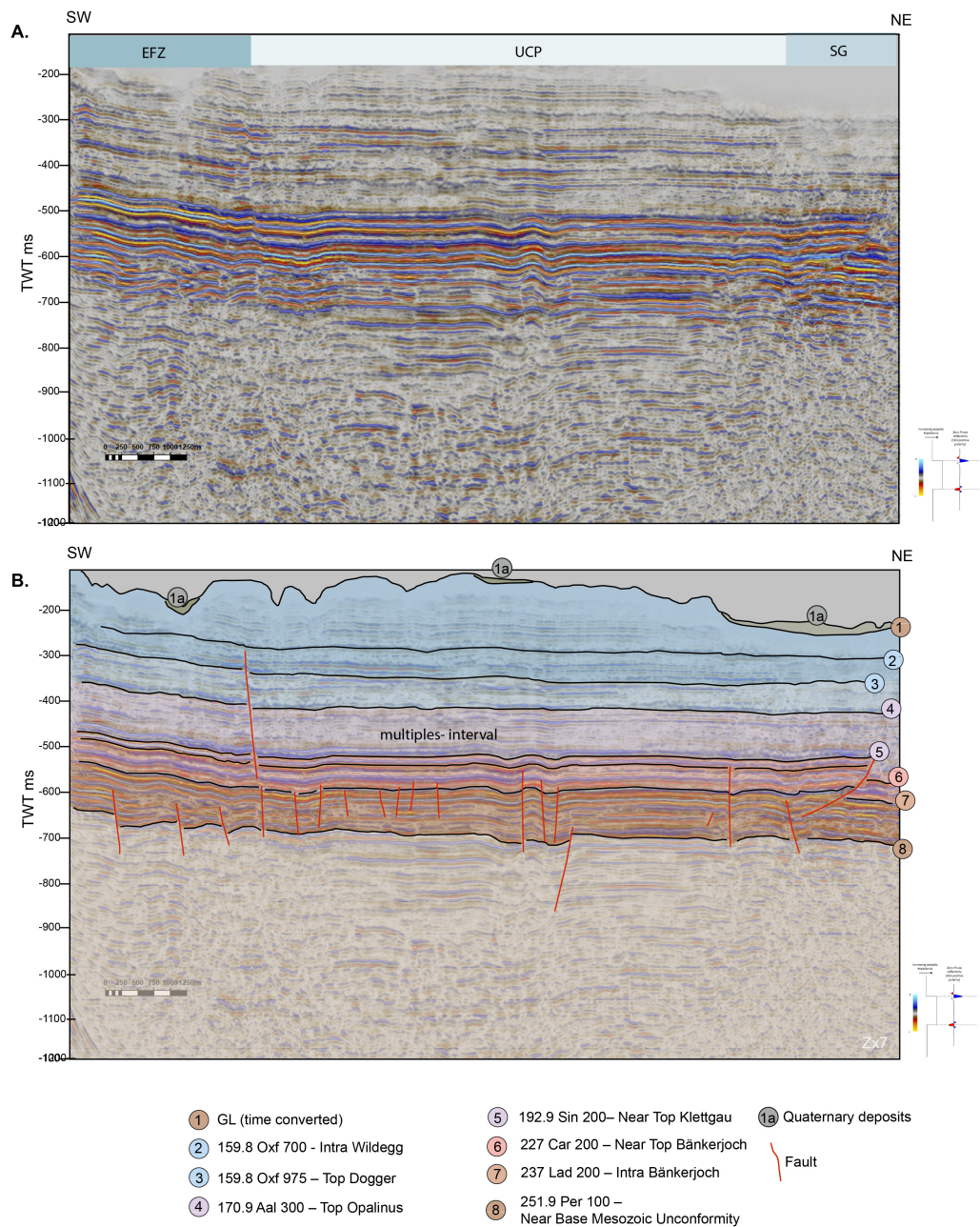


Fig. 5-28: Crossline 1338 showing the fault interpretation and structural geometry and complexity across the JO siting region

A. Uninterpreted. B. Interpreted. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by the presence of seismic multiples. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Line location is shown in Fig. 5-25. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

EFZ: Effingen Fault Zone, CP: Central Panel with SG (Siggenthal Anticline).

When comparing the resulting structural maps (Fig. 5-20, Fig. 5-21, Fig. 5-23) with the pre-existing interpretation (Nagra 2019, Fig. 5-29), differences in spatial distribution, geometry and density of faults can be observed, particularly at Top Opalinus and Top Lias stratigraphic levels and they are mainly related to the so called “Class C Faults” from the 2018 interpretation (Nagra 2019). Different available interpretations will be discussed in Chapter 6.

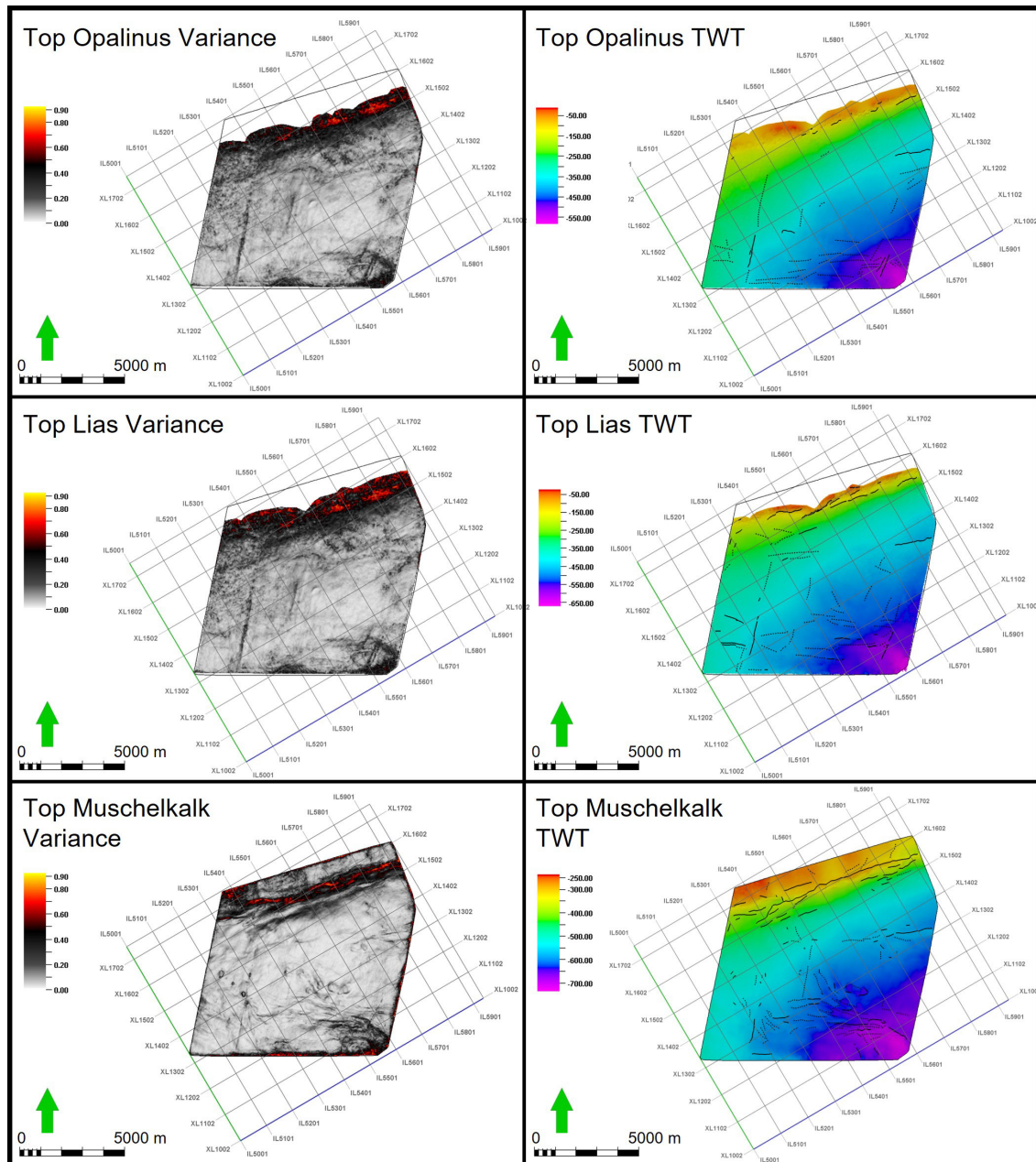


Fig. 5-29: Fault interpretation matrix from the 2018 evaluation (Nagra 2019)

Similar matrix to Fig. 5-20, Fig. 5-21, Fig. 5-23 (variance horizon slices and TWT top structure), reproducing the 2018 fault interpretation (black lines) on a QLP dataset from NAB 18-35.

Black solid lines are class A faults and dashed lines are class C (lower confidence). For more details regarding definition of class A and class C faults, see NAB 18-34.

5.3.1 Structural domains

Based on the 3D structural interpretation, tectonic deformation affecting the Mesozoic succession appears to cluster along major deformation zones. The JO siting region can be subdivided into four main structural domains (Fig. 5-25, Fig. 5-26, Fig. 5-27, Fig. 5-28, Fig. 5-30):

1. Southern Deformation Zone (SDZ),
2. Northern Fold-and-Thrust Zone (NFTZ),
3. Effingen Fault Zone (EFZ),
4. Central Panel (CP).

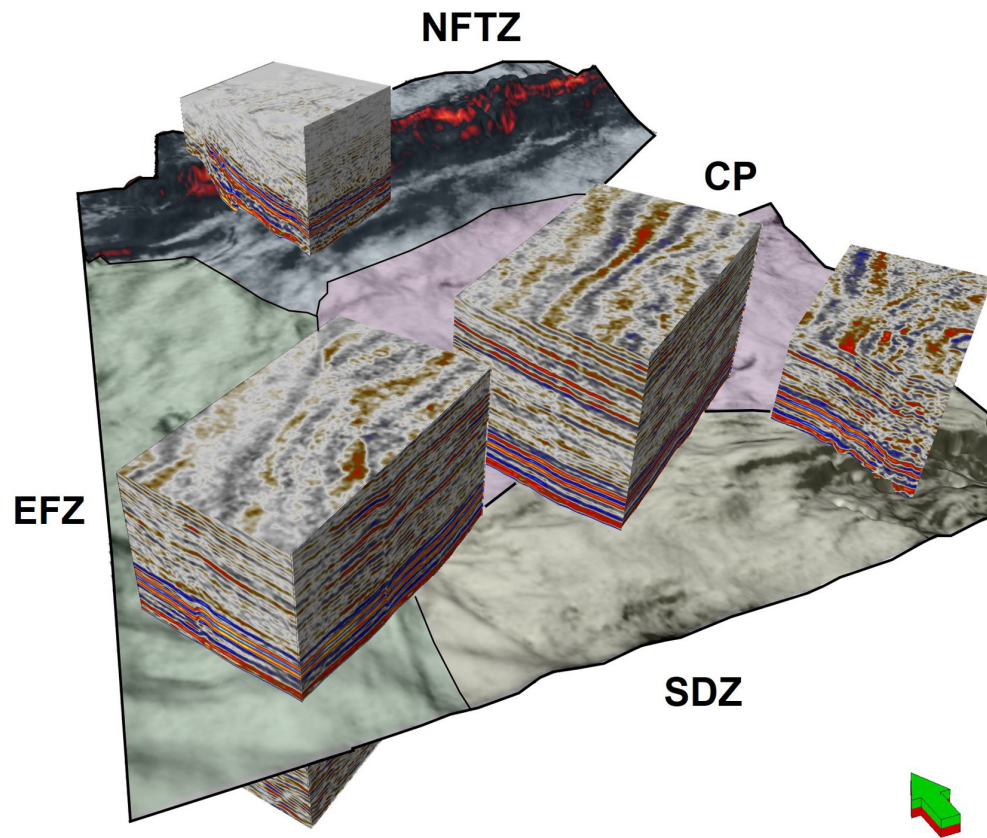


Fig. 5-30: Four structural domains defined for the JO siting region

NFTZ: Northern Fold-and-Thrust Zone (blue), EFZ: Effingen Fault Zone (green), CP: Central Panel (pink), SDZ: Southern Deformation Zone (yellow). Green arrow points towards north.

5.3.1.1 Southern Deformation Zone

The Southern Deformation Zone (SDZ) is bounded by the outcropping Jura Main Thrust (Fig. 5-31). Seismic interpretation of this structure in the JO-15 seismic survey was recognised to be challenging due to the poor seismic imaging where structural complexity combines with the extremely low-resolution seismic survey edge. This area was also excluded by the interpretation perimeter defined in this study, since the seismic data were considered to be unreliable. Such consideration is in accordance with previous interpretation work carried out on QLP seismic vintage (Nagra 2019).

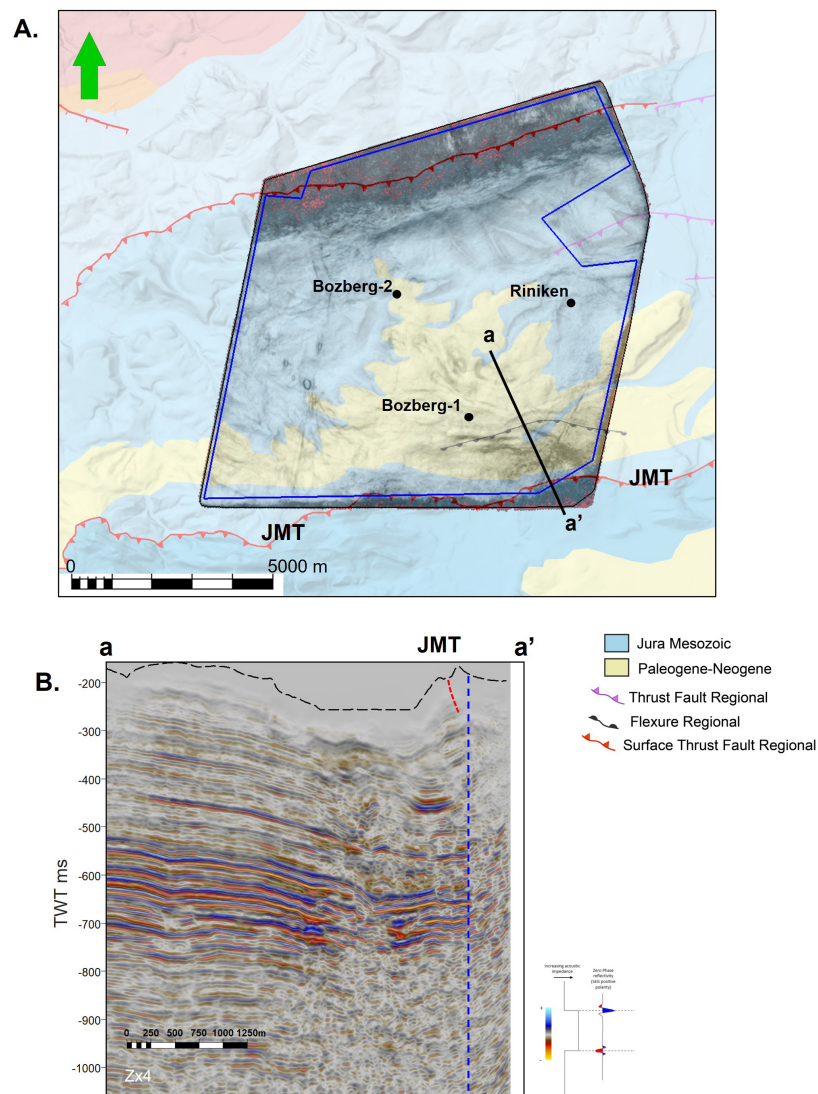


Fig. 5-31: A. Surface geology map, and B. seismic line showing the Jura Main Thrust (JMT) at the southern edge of the JO-15 seismic survey

This structure was not included in the interpretation area (A. blue polygon) because it coincides with a strip of very poor seismic imaging associated with survey edge effects, where no confident interpretation can be carried out. B. NNW-SSE section showing the poor seismic image. The JMT surface (red dashed line) cannot be traced in the subsurface across the survey edge strip (blue dashed line). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. Black dashed line in seismic display represents ground level. Line location shown in A.

In the SDZ, the observed seismic-scale deformation appears to cluster along a major fault system with fault segments mostly ranging from NW-SE to ~E-W striking (to NNW-SSE striking at the western termination of the SDZ; Fig. 5-32).

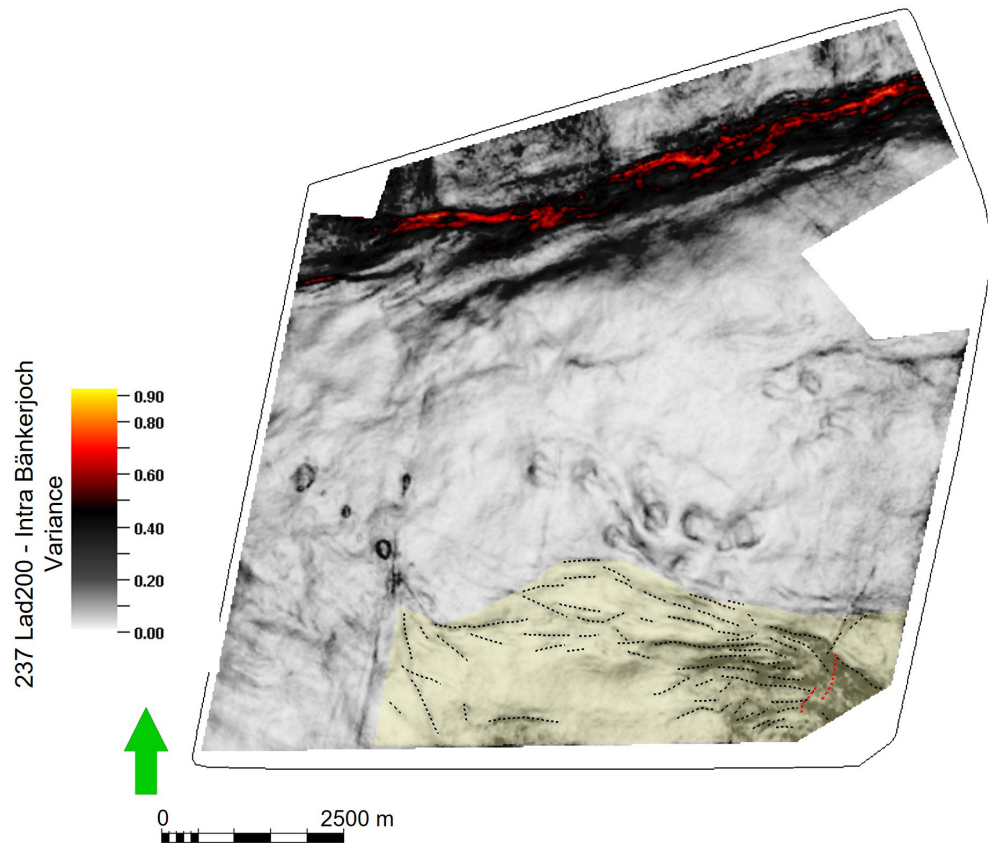


Fig. 5-32: Overview of the Southern Deformation Zone

237 Lad 200 – Intra Bänkerjoch variance horizon slice with the Southern Deformation Zone highlighted in yellow. Black dashed lines are fault traces at horizon 237 Lad 200 – Intra Bänkerjoch with superimposed in red (dashed) fault traces at overlying horizon 170.9 Aal 300 – Top Opalinus. Note the variability in fault strike (from NW-SE to ~E-W) at deeper levels and the lack of structures at shallower stratigraphic levels.

Such variations in observed fault strikes (Fig. 5-32) are accompanied by structures observed in cross-section that are consistent with strike-slip faulting. For example, following a single curved fault that changes in strike from SE-NW to roughly E-W along its length, structural features are observed that could be associated with negative (Fig. 5-33) and positive (Fig. 5-34) flower structures, respectively. Such structures are interpreted to have developed at a releasing bend (NW-SE striking segment) and at a restraining bend (roughly E-W striking segment) of a right-lateral slip fault.

Seismic-scale faulting appears to be vertically constrained below the base of the clay-rich interval of the Opalinus Clay (Fig. 5-26, Fig. 5-27). Even in densely faulted areas, the closely spaced (~150 – 200 m) relatively high-angle faults appear not to propagate across the Opalinus Clay interval; rather, they appear to tip-up at horizon 192.9 Sin 20 – Near Top Klettgau, hardly affecting horizon 174.7 Toa 100 – Top Lias (base host rock). When faults are present in the upper confining unit (above horizon 170.9 Aal 300 – Top Opalinus), no obvious hard linkage is observed between fault segments across the Opalinus Clay interval, even in the more intensively deformed area (Fig. 5-26).

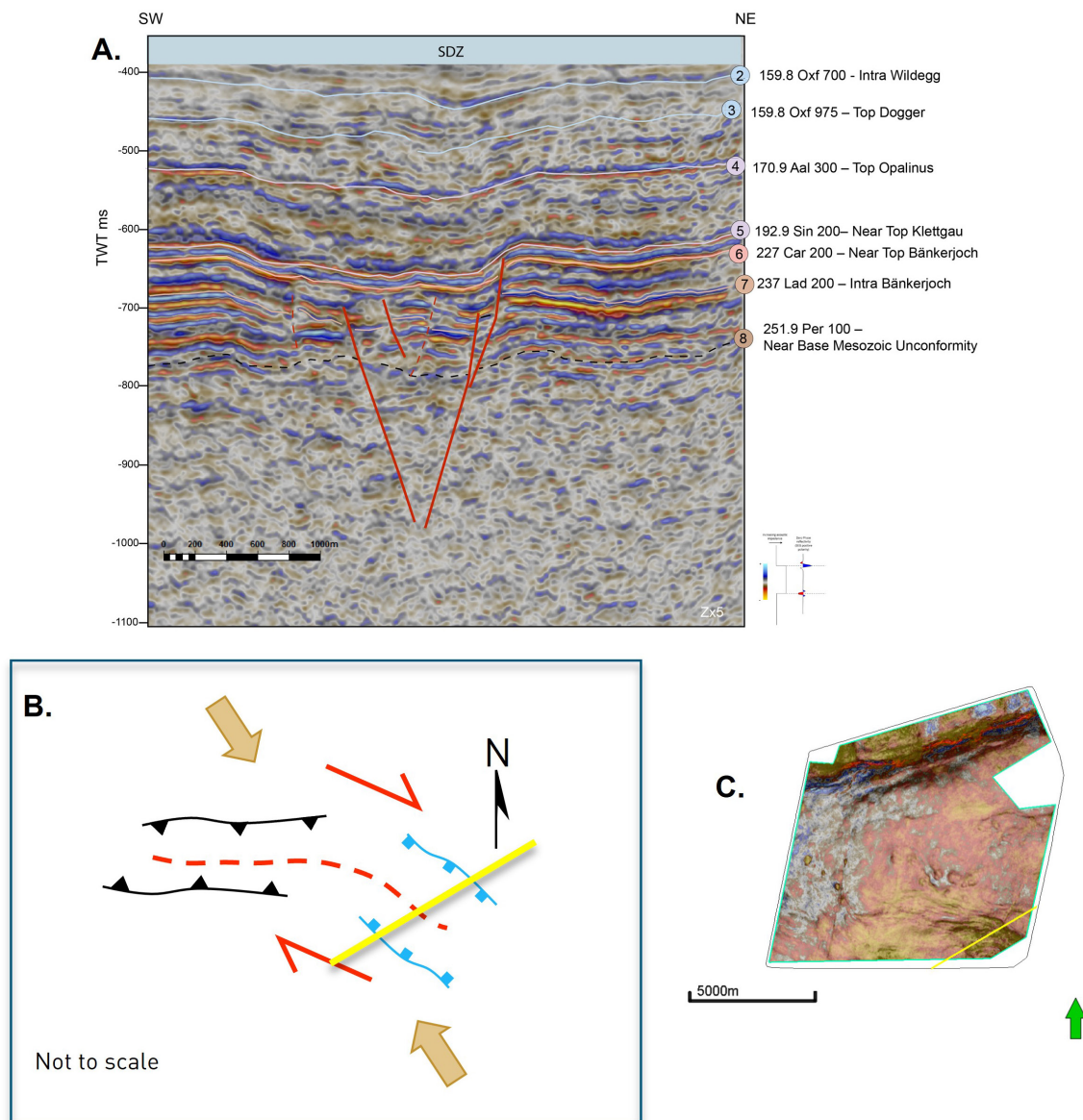


Fig. 5-33: Crossline 1118 showing a structural feature that could be interpreted as a negative flower structure (A.)

Such a structure could develop at a releasing bend (WNW striking fault segment) of a right-lateral strike-slip fault (B., schematic interpretation). C. Line location shown on 237 Lad 200 – Intra Bänkerjoch RMS and variance horizon slice. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

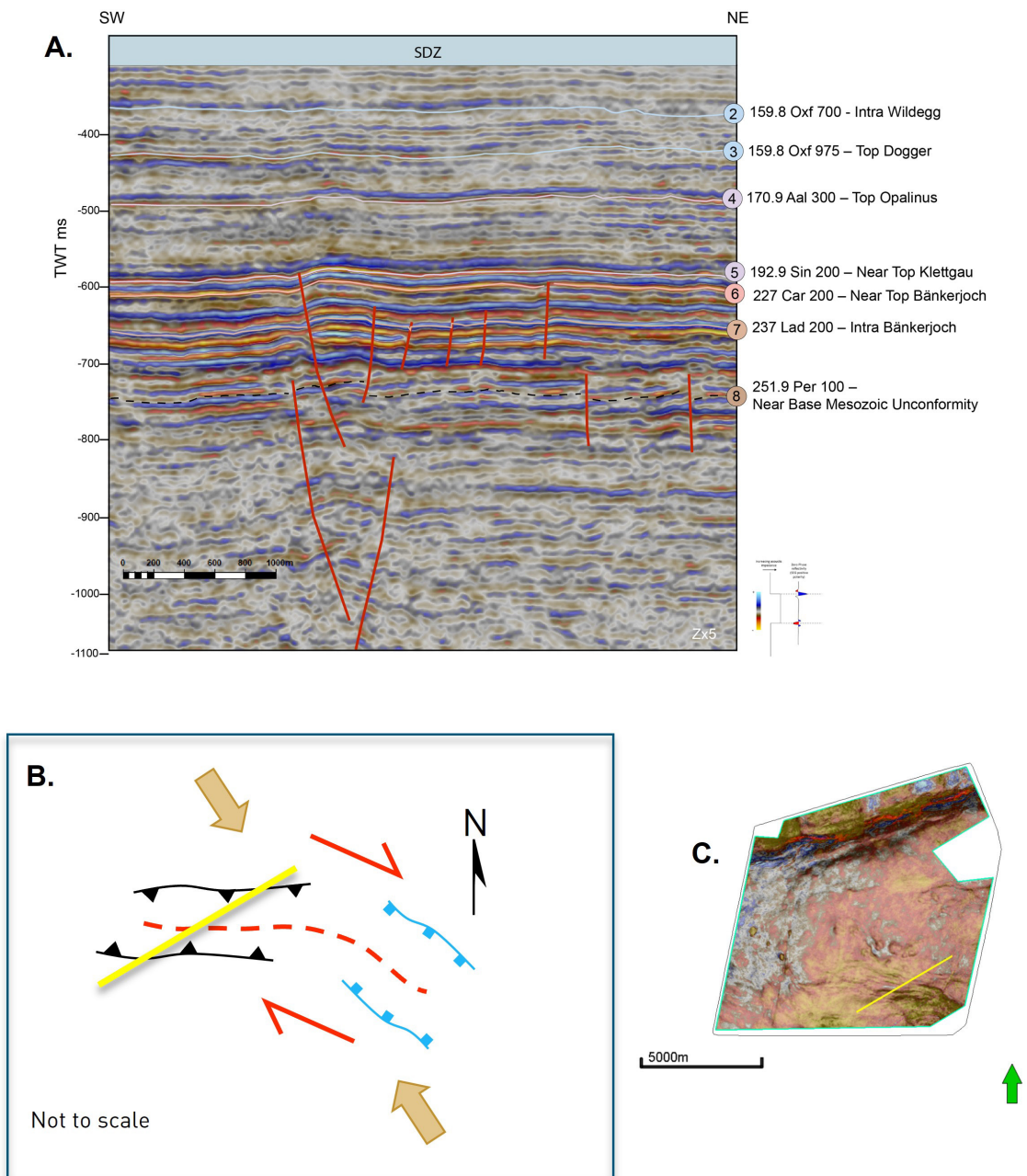


Fig. 5-34: Crossline 1194 showing a structural feature that could be interpreted as a positive flower structure (A.)

Such a structure could develop at a restraining bend (roughly E-W striking fault segment) of a right-lateral strike-slip fault (B., schematic interpretation). C. Line location shown on RMS and variance horizon slice at 237 Lad 200 – Intra Bänkerjoch. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

A previous interpretation (Nagra 2019) characterised the SDZ with a series of (in cases newly) identified structure zones and faults (Brugg Structure Zone, Gallenkirch Structure Zone, Villnachern Fault). Based on seismic observations, it appears that all the single structures are instead part of the same dextral strike-slip fault system and the separation of single structures is not representative of, and does not capture, the complexity of the observed fault system in the Southern Deformation Zone.

5.3.1.2 Northern Fold-and-Thrust Zone (Mandach Thrust)

The Northern Fold-and-Thrust Zone (NFTZ) is manifested at the surface by the intensively studied Mandach Thrust (Bitterli-Brunner 1987, Laubscher 1986, Diebold et al. 2006, Graf et al. 2006, Malz et al. 2019) and is referred as Northern Fold-Thrust Zone consistently with the definition proposed for the NL region (Nagra 2024b). The ENE-WSW striking Mandach Thrust is the most prominent structure within the JO perimeter and is interpreted to be associated with the Jura Fold-and-Thrust Belt. This structure extends for the entire length (in a SW-NE direction) of the JO-15 survey (Fig. 5-35) but its structural setting is variable both across- and along-strike (Fig. 5-26, Fig. 5-27, Fig. 5-35, Fig. 5-35), with thrusting transferring to folding and vice versa.

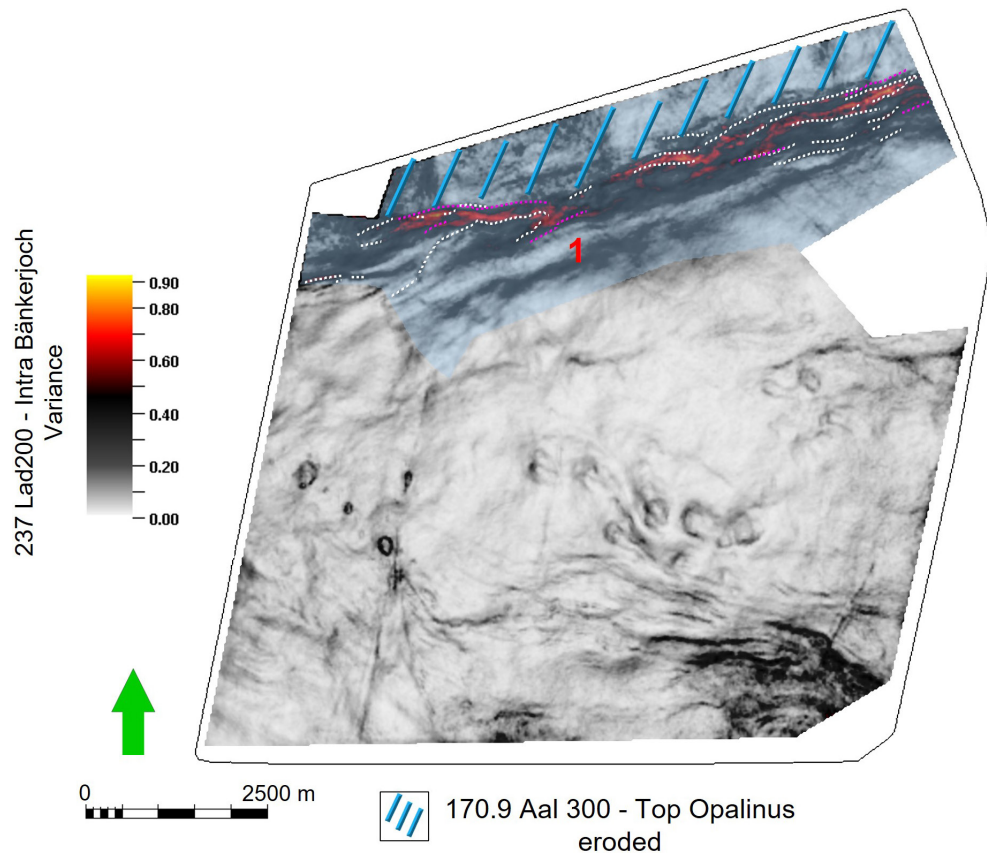


Fig. 5-35: Overview of the Northern Fold-and-Thrust Zone

237 Lad 200 – Intra Bänkerjoch variance horizon slice with the Northern Fold-and-Thrust Zone highlighted in blue. White dashed lines are fault traces at 237 Lad 200 – Intra Bänkerjoch with superimposed in violet (dashed) fault traces at 174.7 Toa 100 – Top Lias. Despite affecting the entire length of the JO-15 seismic survey, the structure shows a more complex and segmented architecture, where, particularly at shallower stratigraphic levels, thrusting transitions to folding and vice versa. Note that the Top Opalinus Clay is eroded towards the north; the lack of the surface does not allow fault trace extraction, although the Mandach Thrust crops out. A southern structure is observed (1), which is interpreted predominantly as a fold.

Typical observed geometry consists of a composite (relatively narrow) pop-up structure (Fig. 5-26, Fig. 5-36) including highly segmented thrust and backthrust splays, transitioning to a simpler imbricate geometry along strike (Fig. 5-27, Fig. 5-37) and detaching along the Mesozoic (Muschelkalk) evaporitic interval. The pop-up structure (and associated imbricate structures) appears to develop at the basement step associated with the Master Fault (MF) that forms the northern boundary of Konstanz-Frick Trough in the JO siting region (Fig. 5-26, Fig. 5-27).

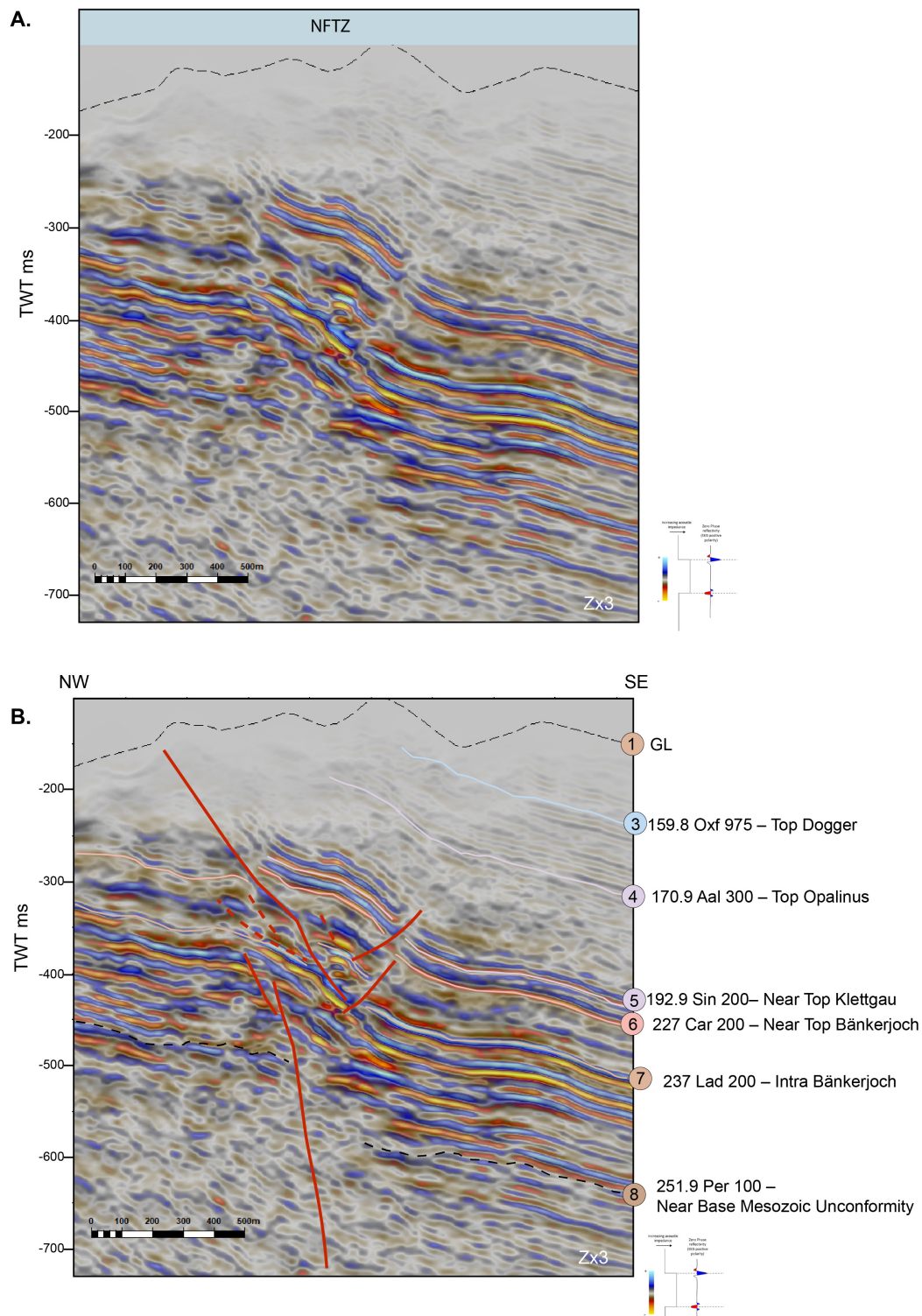


Fig. 5-36: Zoom-in of inline 5533 showing the pop-up structure of the Northern Fold-and-Thrust Zone

The pop-up structure represents a localised deformation at a basement step. Red lines are major faults. Dashed red lines are secondary (infill) faults. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. Entire section of inline 5533 is shown in Fig. 5-26. Line location is shown in Fig. 5-25.

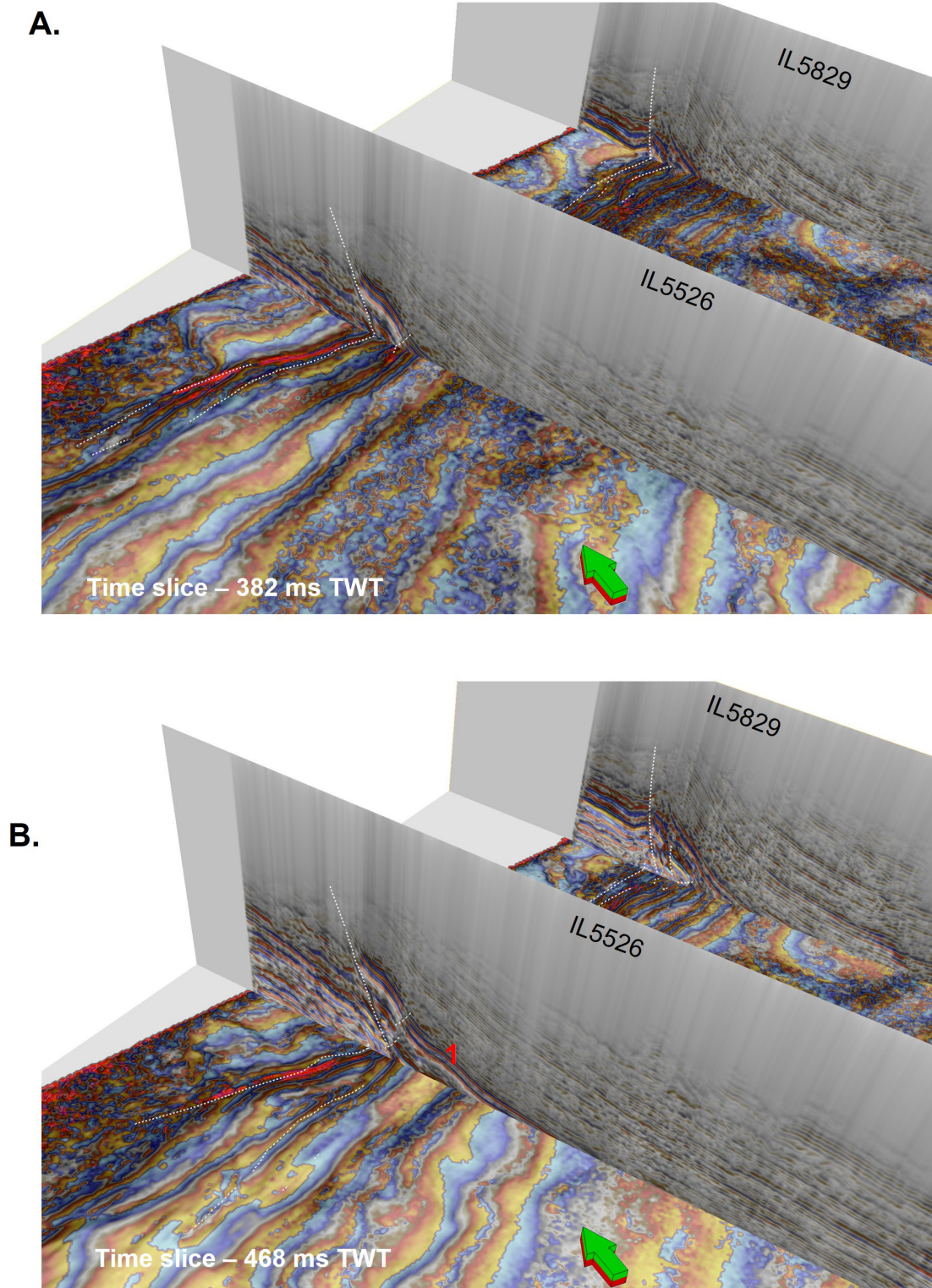


Fig. 5-37: 3D displays across the Northern Fold-and-Thrust Zone

Inlines 5526 and 5829 (outcrop look) and time slice (RMS and variance) at -382 ms TWT (A) and -468 ms TWT (B) showing the variability of the NFTZ. From a narrow pop-up structure in the west, to an imbricate structure in the east. The southern structure is interpreted to be related to folding (1). Seismic display is PreSTM-ref. Green arrow points towards north.

The presence of a basement thrust was observed beneath the pop-up structure in the eastern sector of the JO-15 seismic volume. Such a basement thrust may be interpreted as a footwall shortcut associated with a shortening-related reactivation (with a reverse component of motion) of a deeper section of the Late Palaeozoic basin-bounding fault (MF, Fig. 5-38).

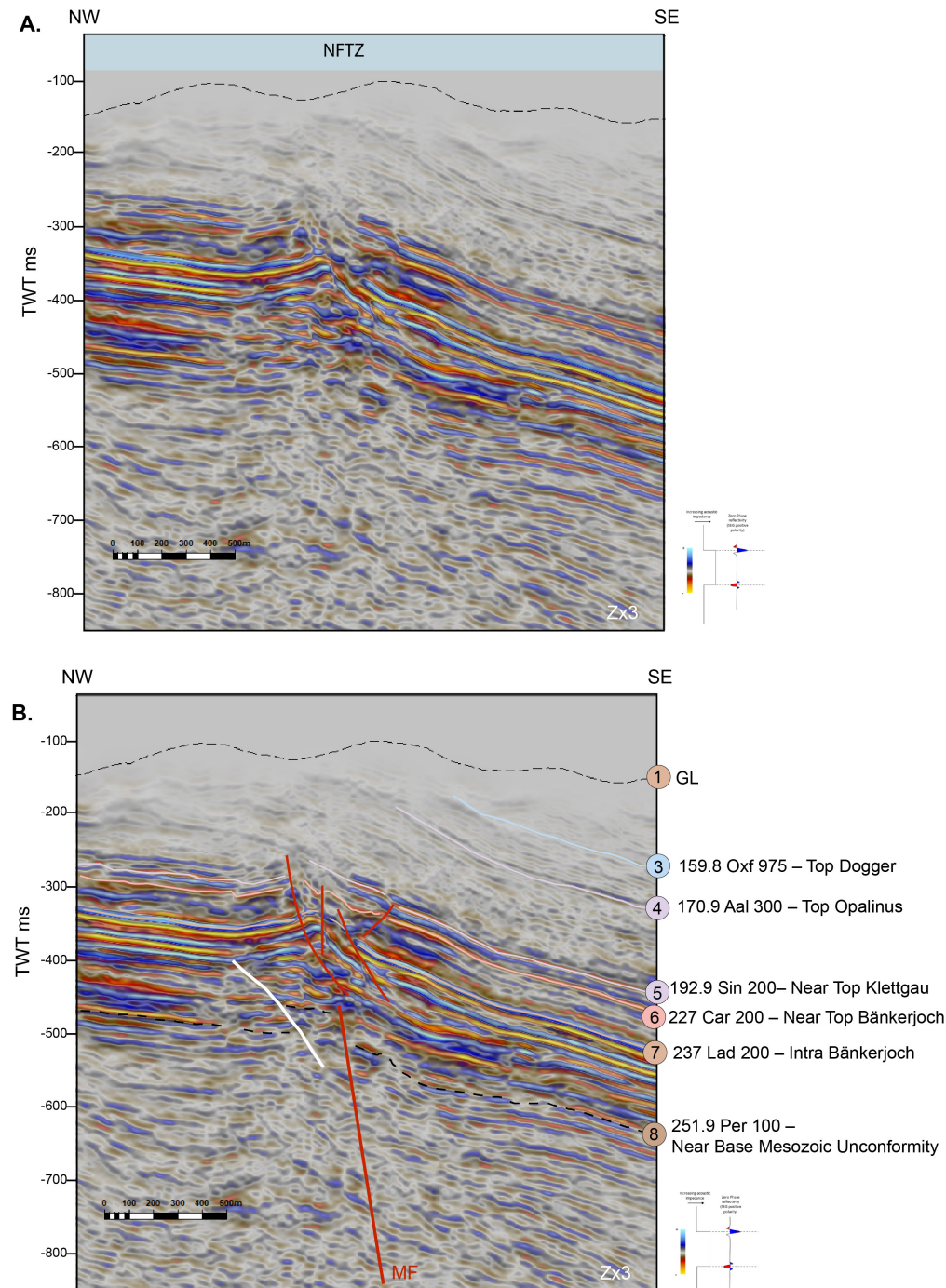


Fig. 5-38: Part of inline 5663 showing a basement thrust interpreted as a footwall shortcut

The basement fault (white line) may be interpreted as a footwall shortcut associated with the shortening-related reactivation of the Late Palaeozoic basin-bounding fault (MF).

Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The Mesozoic succession appears to be downthrown below regional level in the hanging-wall block of the Late Palaeozoic basin-bounding fault (MF, Fig. 5-38). Such a geometrical relationship is consistent with the interpretation proposed by Laubscher (1986). According to this author, the Master Fault forming the northern boundary of the Late Palaeozoic graben was extensionally reactivated during the Palaeogene producing a major flexure of the Mesozoic succession clearly observable on the seismic data.

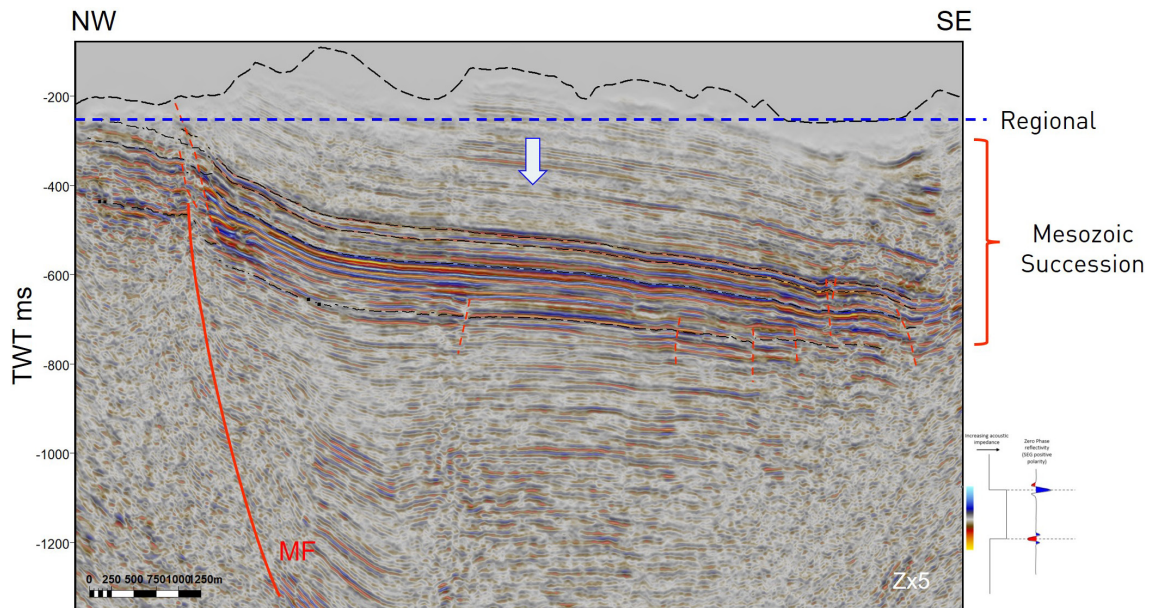


Fig. 5-39: Inline 5589 showing flexure of the Mesozoic multi-layer succession, which is depressed below regional level in the hanging wall of the basin-bounding fault (MF). This indicates that the Late Palaeozoic fault was extensionally reactivated during the Palaeogene. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.3.1.3 Effingen Fault Zone

The Effingen Fault Zone structural domain includes the area west of the prominent lineament referred to as the Effingen Fault (EF, Fig. 5-40; Nagra 2019). The ~N-S trending Effingen Fault is a relatively steep fault showing limited vertical displacement. In horizon and time slices it is characterised by a continuous linear discontinuity in shallow stratigraphic units in all the seismic vintages (Fig. 5-20, Fig. 5-23). In the Lower Mesozoic interval (horizon 237 Lad 200 – Intra Bänkerjoch) it is characterised by an array of segmented lineaments (Fig. 5-20). Such segmentation is also imaged vertically in seismic section (Fig. 5-28, Fig. 5-41), where the evaporites of the Bänkerjoch Fm appear to behave as a key mechanical level decoupling the brittle deformation below and above it.

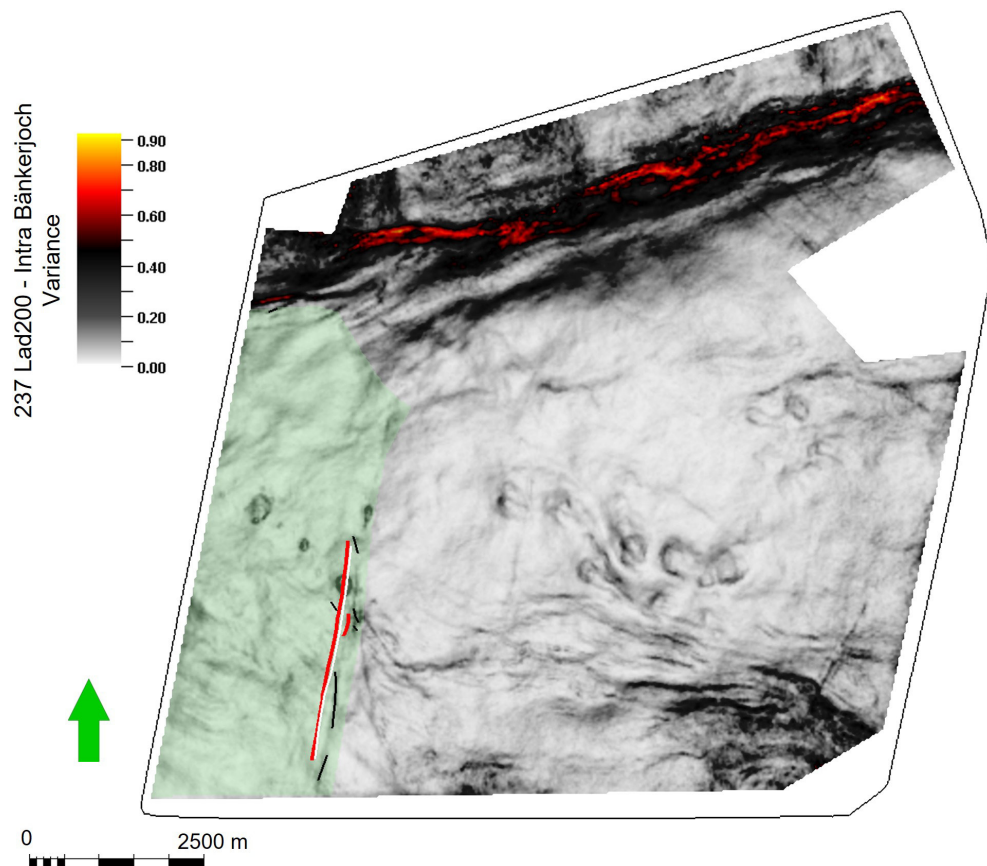


Fig. 5-40: Overview of the Effingen Fault Zone (structural domain)

237 Lad 200 – Intra Bänkerjoch variance horizon slice with highlighted in green the Effingen Fault Zone (structural domain). Black lines are fault traces at horizon 237 Lad 200 – Intra Bänkerjoch with superimposed in white fault traces at overlying horizon 174.7 Toa 100 – Top Lias and in red fault traces at horizon Top 170.9 Aal 300 – Top Opalinus. The Effingen Fault is a steep fault, which affects mainly the shallower stratigraphic units and appears extremely segmented at the level of the Muschelkalk Fm. Discontinuities are visible in this region, which is also affected by a strong imprint associated by articulated topography, and these were not interpreted as seismic faults.

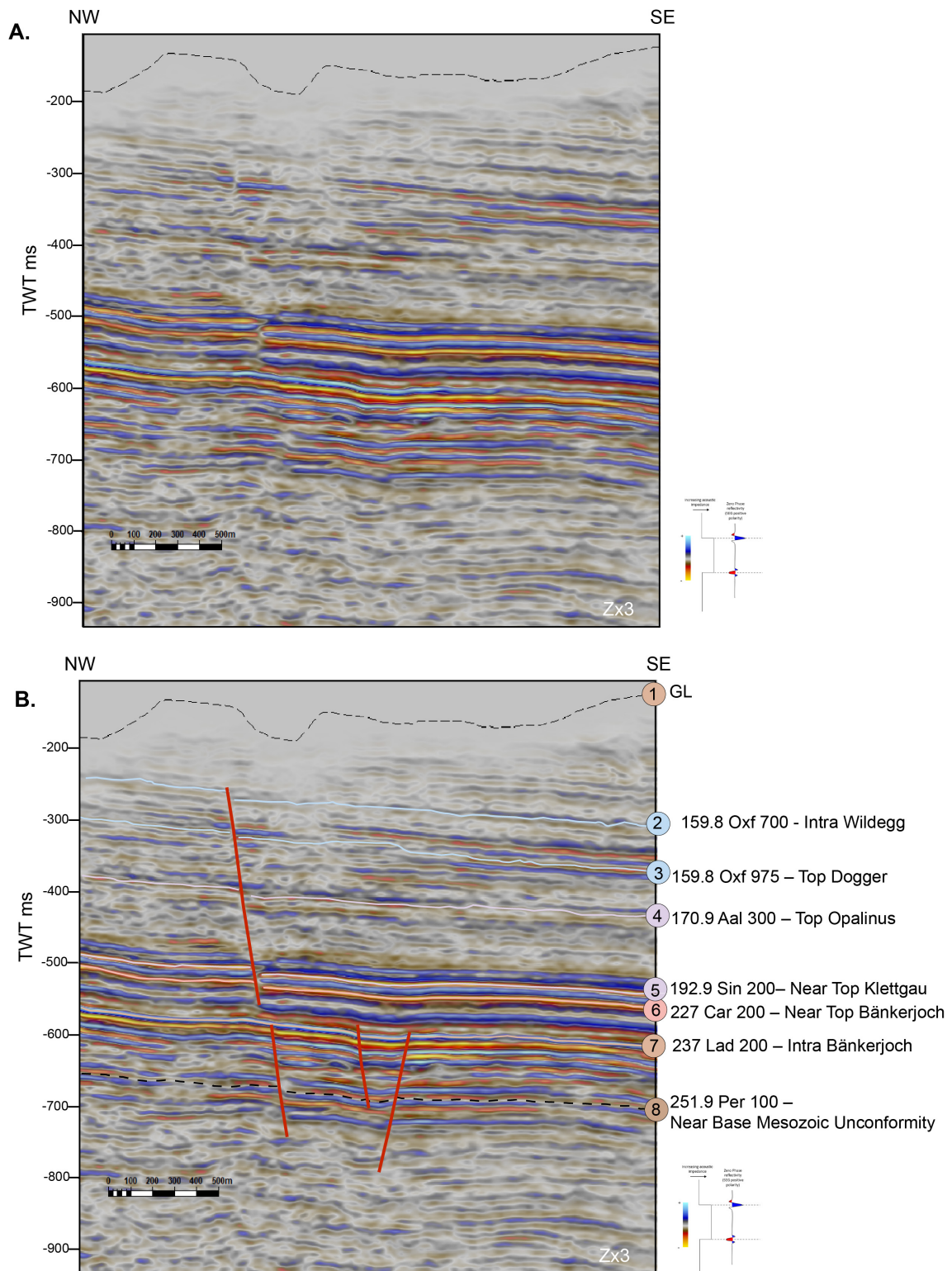


Fig. 5-41: Random line showing the Effingen Fault

The fault appears to be vertically segmented, with breaks mainly coinciding with the Bänkerjoch evaporitic interval. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. Note that the Effingen Fault stick is simplified across the Opalinus Clay.

West from of the Effingen Fault (Fig. 5-1, Fig. 5-40), the complex surface geology, particularly the presence of narrow valleys, weakens the seismic imaging over the area. Therefore, fault interpretation in this domain remains of relatively lower confidence, specifically at shallower stratigraphic levels above the Opalinus Clay. However, several discontinuities as well as sub-circular features are imaged by the seismic attributes (Fig. 5-40). WNW-ESE striking, steeper reverse faults and gently dipping thrusts associated with the folding of the Top Muschelkalk horizon (237 Lad 200 – Intra Bänkerjoch is proxy horizon for Top Muschelkalk), but best recognisable at the level of the Base Mesozoic, were interpreted and referred to as the Zeihen Structure Zone in NAB 18-34 (Nagra 2019). 3D seismic evaluation indicates that such discontinuities coincide with muted or degraded seismic data and do not appear to be associated with the proposed seismic diagnostic fault signatures. Consequently, these discontinuities are not interpreted to represent seismic-scale faults within the Mesozoic succession. Some evidence of faulting with minor normal offset can be observed at the level of the Base Mesozoic Unconformity (Fig. 5-41).

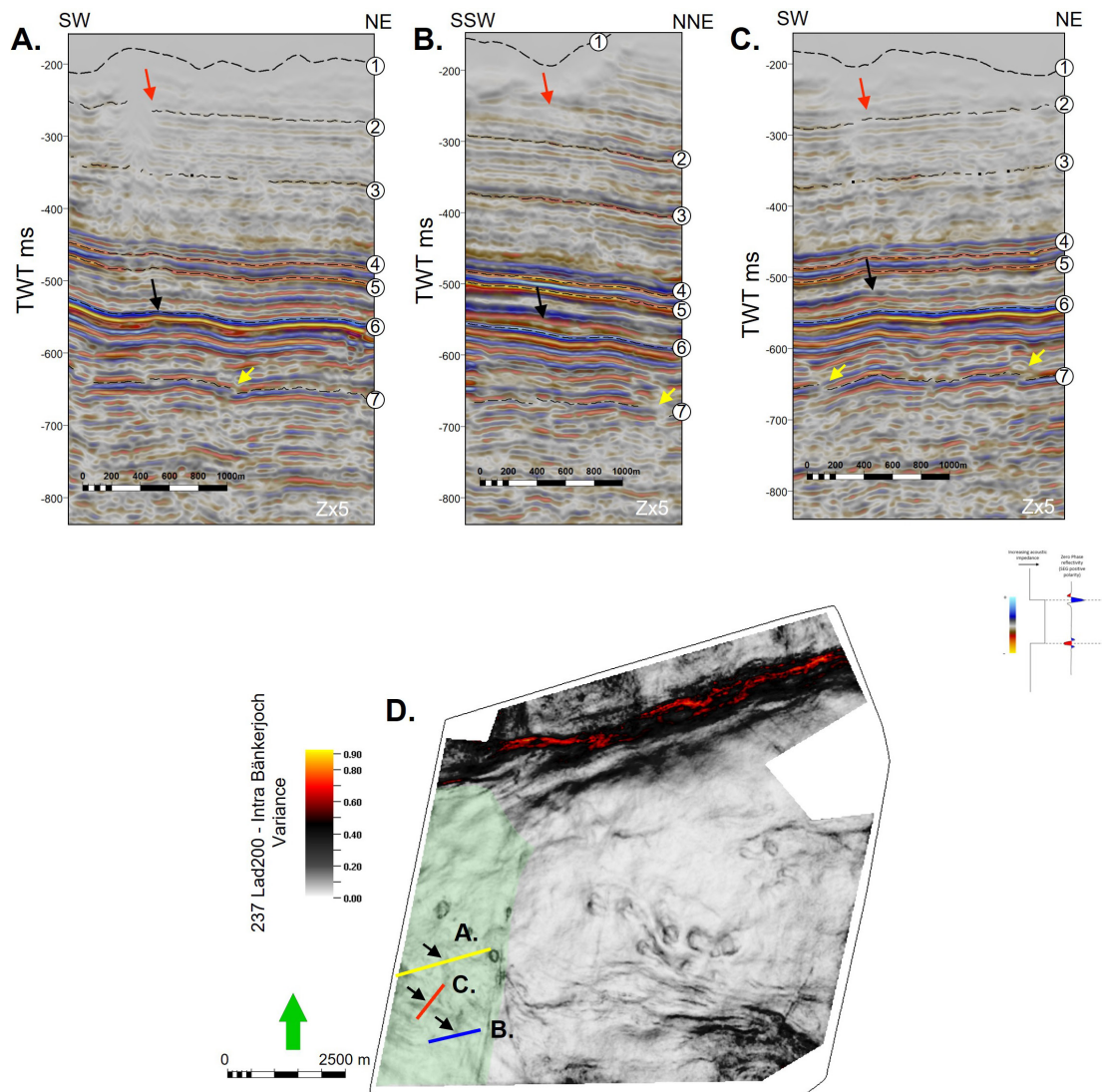


Fig. 5-42: Random seismic sections across observed discontinuities

In vertical sections (A.), no clear indications of seismic faults are visible. The discontinuities observed in the variance display (B., black arrows) appear to correlate with areas of muted or degraded seismic data associated with the complex topography (red arrows). Evidence of faulting (with minor normal offsets) occurs at the Base Mesozoic Unconformity level (yellow arrows). B. 237 Lad 200 – Intra Bänkerjoch variance horizon slice showing the Effingen Fault Zone structural domain perimeter (green transparency), line locations and linear discontinuities (black arrows).

Horizon legend (A.): 1 is Ground Level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The subcircular features observed in the discontinuity maps are characterised by disrupted and transparent seismic facies within the Bänkerjoch Fm (Fig. 5-43). Such features may reveal the complex depositional history of this interval, which might have undergone one or more evaporite dissolution events.

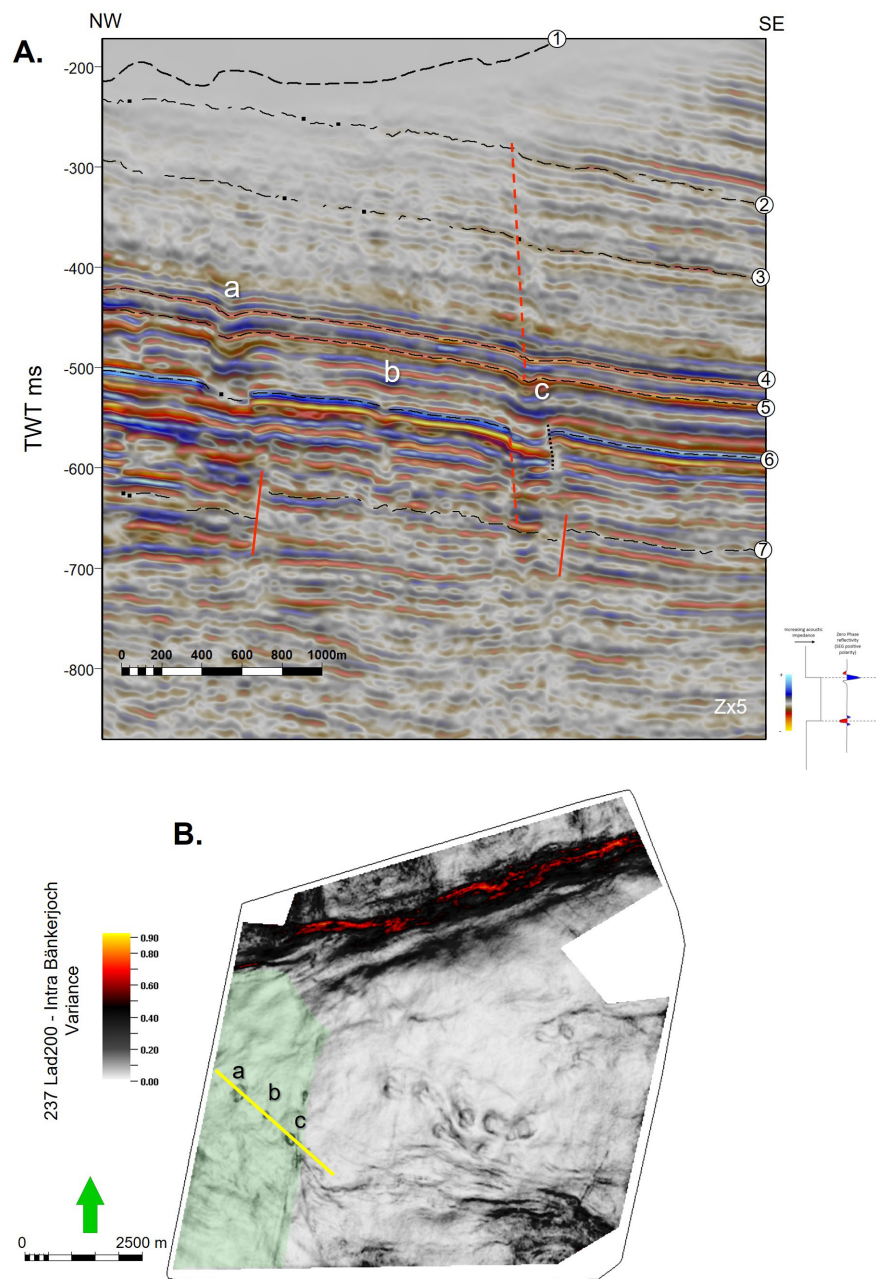


Fig. 5-43: The observed subcircular features (a, b and c) are interpreted as dissolution features of the evaporitic interval of the Bänkerjoch Fm

A. In seismic vertical display, discontinuous, chaotic reflections form concave shape geometries laterally transitioning to continuous reflectivity packages. Dissolution features show varying size and vertical distribution. Features a and b appears to be not fault controlled. Clear continuous reflections can be observed below them (a and b). Feature c is located near the Effingen Fault (dashed red lines) and the interaction between faulting and dissolution cannot be excluded. Black dotted line is a seismic fault which is not interpreted since cannot be mapped by two fault sticks at a distance of 8 lines.

Horizon legend (A.): 1 is Ground Level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.3.1.4 Central Panel

The Central Panel is the area bounded by the Effingen Fault to the west, by the deformation zone associated with the NFTZ to the north and by the high-density faulted area associated with a dextral strike-slip zone of the SDZ to the south (Fig. 5-44).

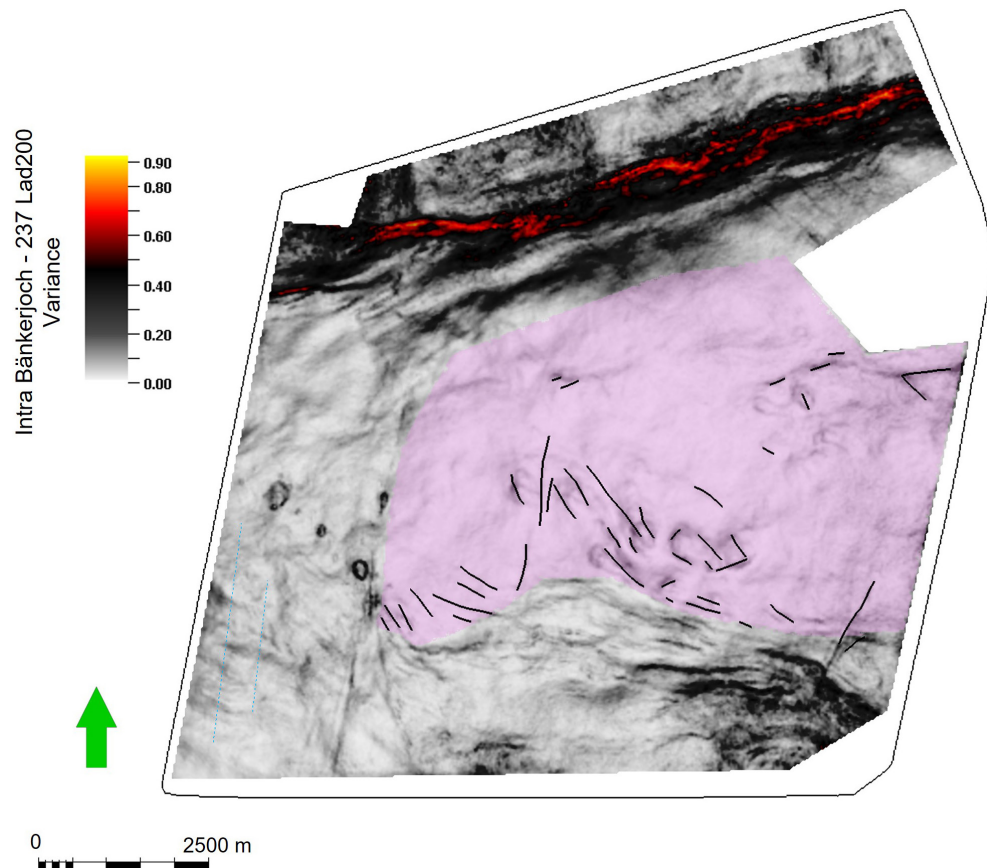


Fig. 5-44: Overview of the Central Panel

237 Lad 200 – Intra Bänkerjoch variance horizon slice with highlighted in pink the Central Panel. Black lines are fault traces at horizon 237 Lad 200 – Intra Bänkerjoch. No seismic-scale faults were recognised affecting overlying horizons 174.7 Toa 100 – Top Lias and 170.9 Aal 300 – Top Opalinus.

Seismic-scale deformation is associated with predominantly NNE-SSW to NW-SE striking and ~N-S (Effingen Fault trend) striking high-angle faults, which mainly affect the lower part of the Mesozoic succession (i.e. the succession underlying the Opalinus Clay; Fig. 5-44, Fig. 5-28). Some of the faults propagate down section, also offsetting the Near Base Mesozoic Unconformity and the underlying Permo-Carboniferous units, whereas several of them tip out downwards before reaching the Near Base Mesozoic Unconformity (Fig. 5-45).

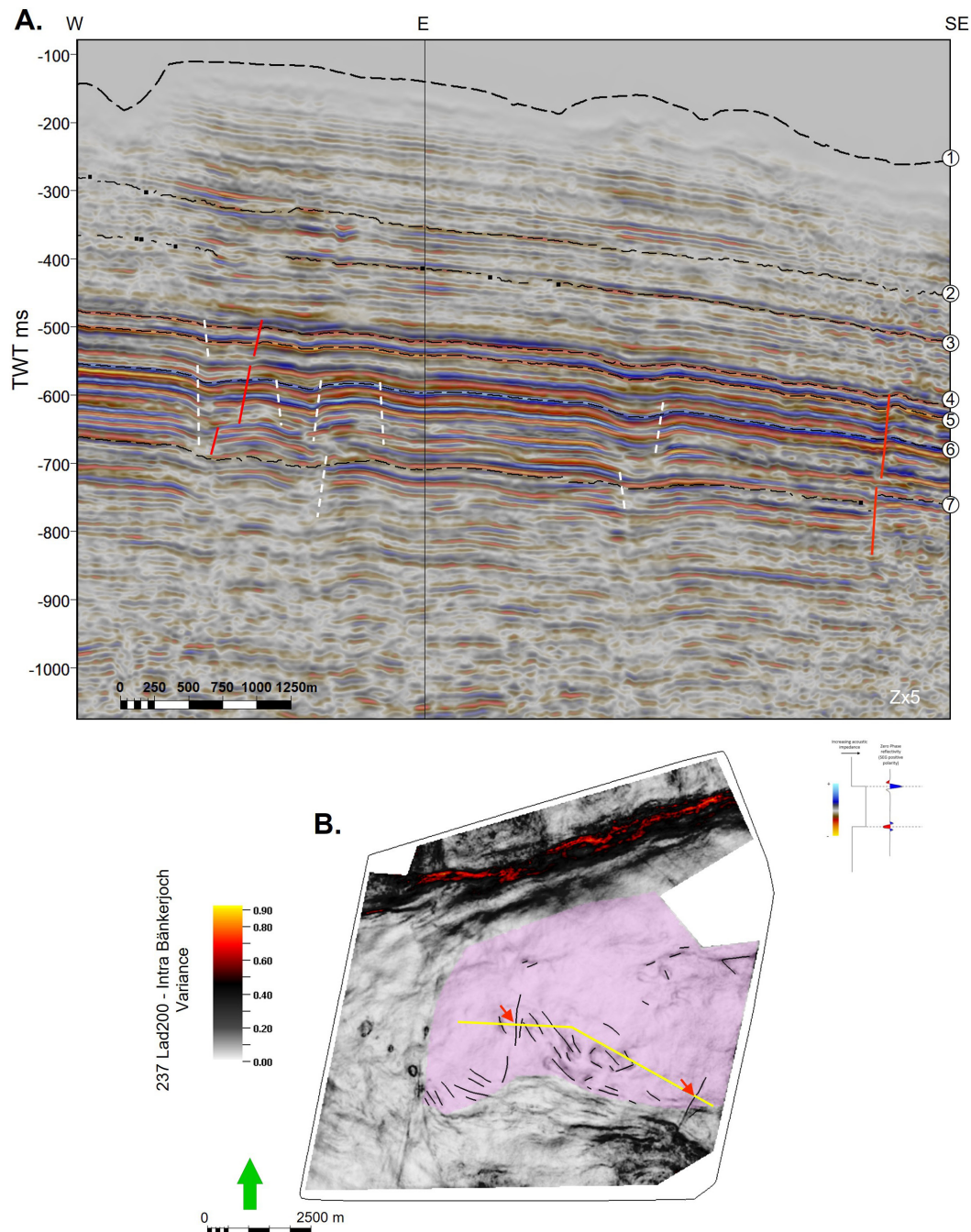


Fig. 5-45: Seismic random sections across interpreted faults

A. NNE-SSW to NW-SE (white dashed lines) striking and ~N-S (red lines -Effingen Fault trend) striking high-angle faults (red arrows, B.), which affect mainly the lower part of the Mesozoic succession. B. 237 Lad 200 – Intra Bänkerjoch variance horizon slice showing line location, the structural domain perimeter (pink transparency), fault traces at horizon 237 Lad 200 – Intra Bänkerjoch (black lines) and Effeling Fault trend faults (red arrows).

Horizon legend (A.): 1 is Ground Level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

As for the Effingen Fault structural domain, subcircular features are observed in the Central Panel. The zone encompassing these circular features was referred to as Unterbözberg Structure Zone (Nagra 2019) and was interpreted to be associated with N-S and WNW-ESE striking smaller-scale faults forming a polygonal pattern at the Muschelkalk level.

Based on their seismic character and in analogy with the nearby Effingen Fault features, despite occurring predominantly in concomitance with faults, dissolution of the Bänkerjoch evaporitic interval is proposed to represent the driving process for the generation of the observed subcircular features (Fig. 5-46).

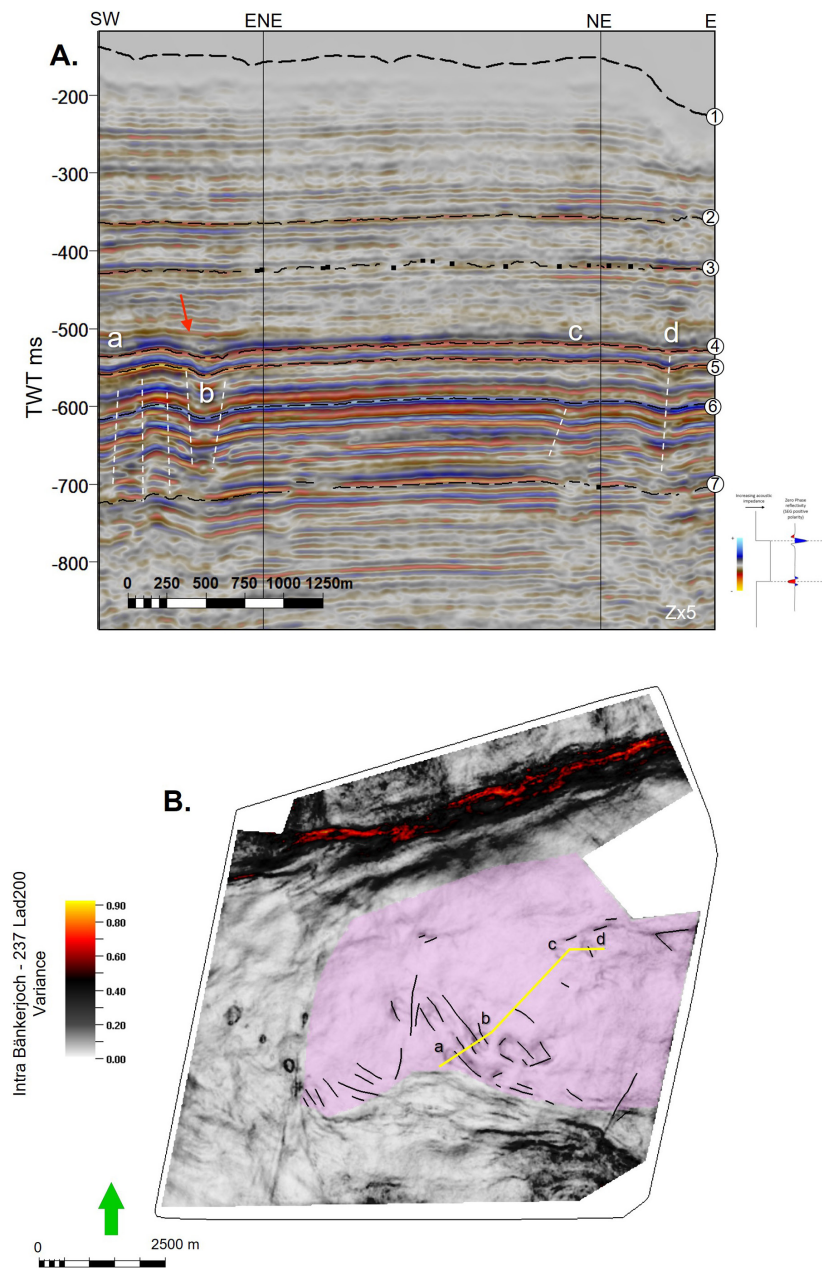


Fig. 5-46: The observed subcircular features (a, b, c and d) are interpreted as dissolution features of the evaporitic interval of the Bänkerjoch Fm

A. In seismic vertical display, discontinuous, chaotic reflections form concave shape geometries laterally transitioning to continuous reflectivity packages. Dissolution features show different size and vertical distribution. Concomitance of faults and dissolution features are observed; however, the dissolution is interpreted to be the main process. B. 237 Lad 200 – Intra Bänkerjoch variance horizon slice showing line location, the structural domain perimeter (pink transparency), fault traces at horizon 237 Lad 200 – Intra Bänkerjoch (black lines) and subcircular features (a-d).

Horizon legend (A.): 1 is Ground Level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Within the Central Panel, a regional structure, the Siggenthal Anticline, was previously described as a north-verging thrust fault associated with the Jura Fold-and-Thrust Belt (Bitterli-Dreher et al. 2007, NAB 23-18, Fig. 5-47). The footwall of the previously interpreted thrust fault falls within the area affected by processing artefacts and it is not included within the interpretation perimeter (Fig. 5-1, Fig. 5-5, Fig. 5-28, Fig. 5-47). Consequently, an in-depth interpretation of this structure was not performed in this study.

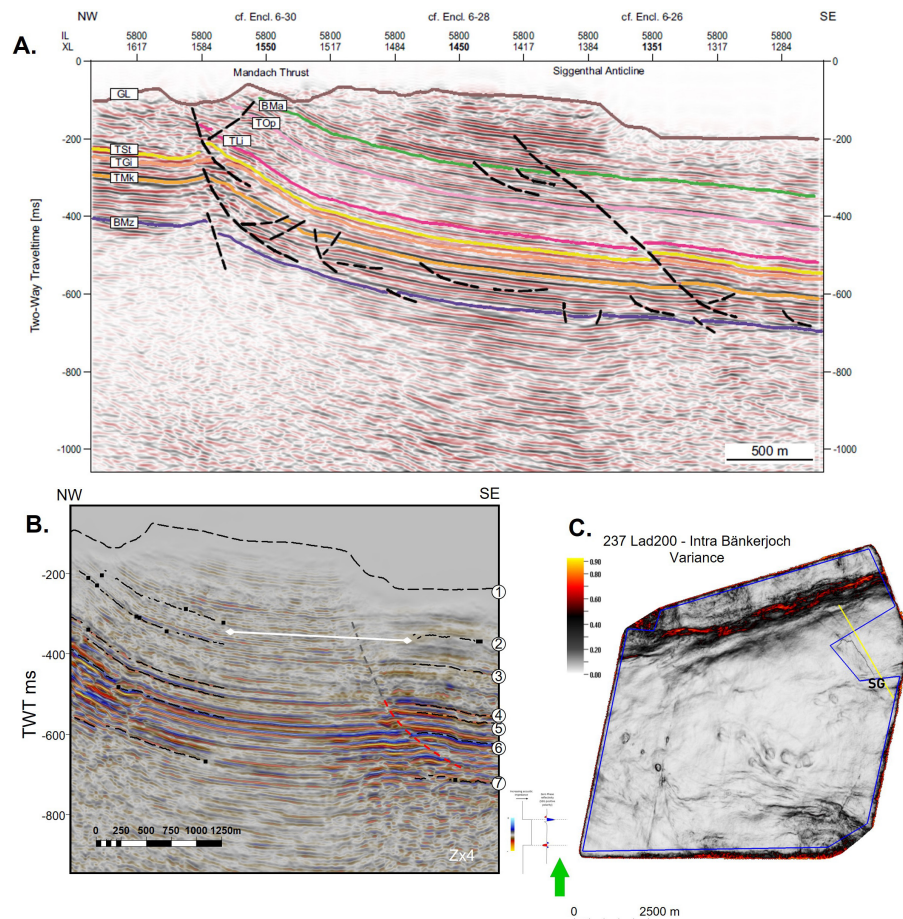


Fig. 5-47: Siggenthal Anticline

A. Inline 5800 showing the interpretation of the Siggenthal Anticline as a structure associated with a thrust soling out at the Muschelkalk evaporite proposed in previous study NAB 18-34 (Enclosure 6-17, Nagra 2019); B. Part of the same line with 2023 interpretation and PreSTM-ref dataset. The footwall and as well as the upper part of the thrust (grey dashed line) are located within the area excluded in the interpretation (white bar) due to processing artefacts; C. Top Muschelkalk variance horizon slice (Nagra 2022) showing the location of the Siggenthal structure (SG), the location of the seismic line (yellow line) and the perimeter of the interpretation (blue polygon).

Horizon legend (A.): GL is Ground Level, BMa is Base Malm. Top is Top Opalinus, TLI is Top Liassic., TSt is Top Stubensandstein, TGi is Top Gipskeuper, TMk is Top Muschelkalk, BMz is Base Mesozoic.

Horizon legend (B.): 1 is Ground Level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch (is proxy horizon for Top Muschelkalk), 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity.

Comparison among the different seismic vintages suggests that in the Central Panel structural domain seismic-scale faults do not affect the Opalinus Clay and its overburden (Fig. 5-48). The PreSDM seismic data appears, however, to be characterised by a more discontinuous seismic response compared to the TWT seismic data (Fig. 5-48 C.). The shape of the observed discontinuities in the depth cube seems to be related more to seismic processing (i.e. noise) than to geology, therefore the Central Panel structural domain could be considered a proxy for the undisturbed area in the JO siting region. However, if taking into account also seismic-scale faulting affecting the deeper stratigraphic levels (below Opalinus Clay), the undisturbed area is dissected into two smaller undisturbed zones that are located eastwards and westwards of the Unterbözberg Structure (Fig. 5-48).

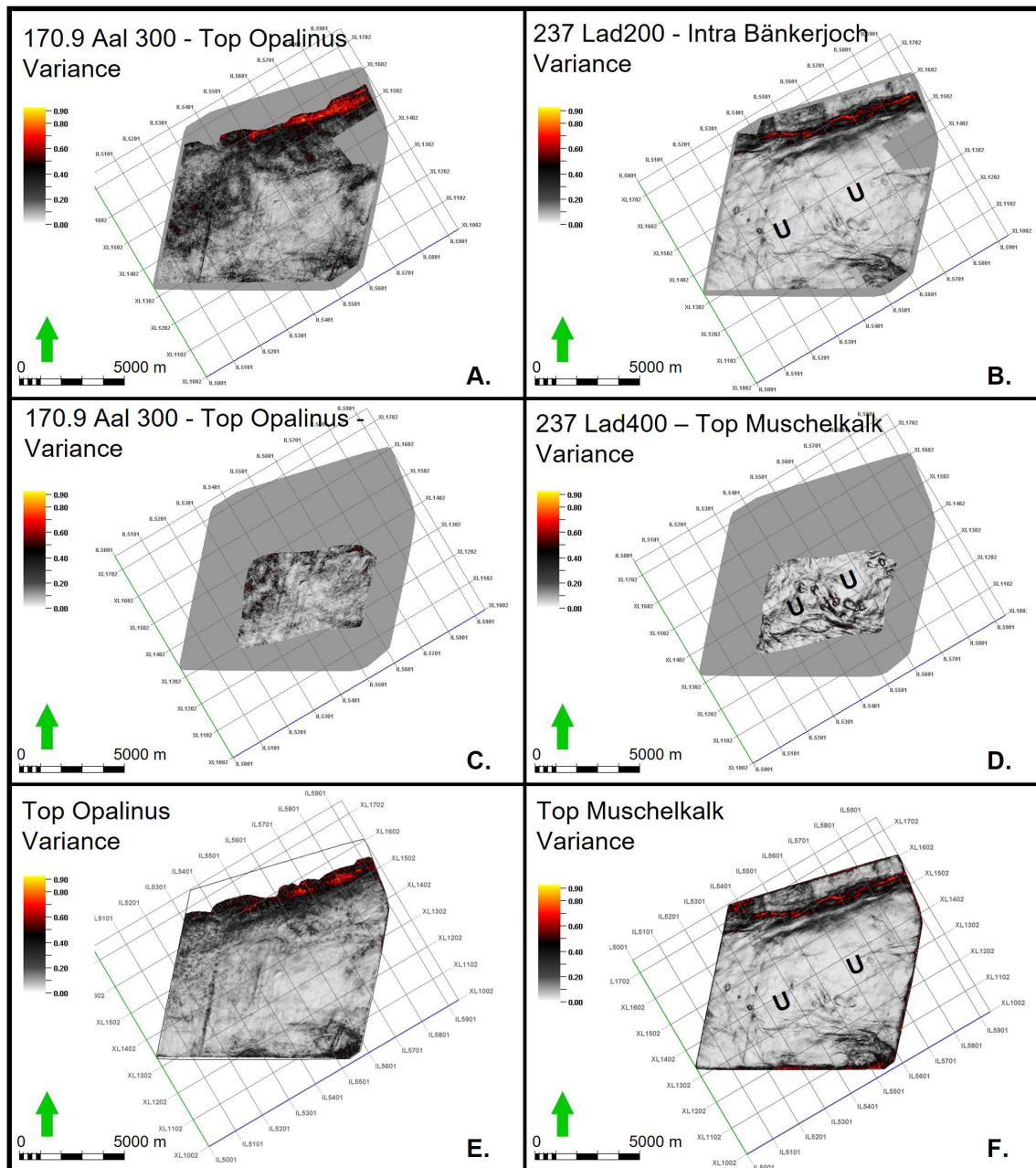


Fig. 5-48: Comparison of two key variance horizon slices for the three seismic vintages

237 Lad 200 – Intra Bänkerjoch / 237 Lad 400 -Top Muschelkalk and 170.9 Aal 300 -Top Clay unit - (Top Opalinus for QLP)

A. and B. PreSTM-ref zero-phase; C. and D. PreSDM; and E. and F. QLP. Note the consistent seismic response and the lack of major discontinuities at Opalinus Clay level, while at deeper stratigraphic level two smaller undisturbed areas can be recognised (U). More chaotic response in the PreSDM data is interpreted to represent seismic noise.

Subseismic deformation (cm-to-mm-scale shear planes) was documented in core data of the Bözberg-1 and Bözberg-2 wells (Fig. 5-49; Nagra 2024d) located in the Southern Deformation Zone and in the Central Panel, respectively. Interpreted structure density tends to decrease upwards, consistently with the observed seismic-scale deformation. Subseismic deformation is interpreted to accommodate the bulk coaxial strain (homogeneous shortening) associated with the main Jura shortening phase by localised non-coaxial deformation zones (i.e. shear planes) at meso- and micro-scales (i.e. at core scale). The Bözberg-1 well is located near a highly faulted zone in the SDZ, and a fault breccia was cored within the lower interval of the Mesozoic succession (Nagra 2024d).

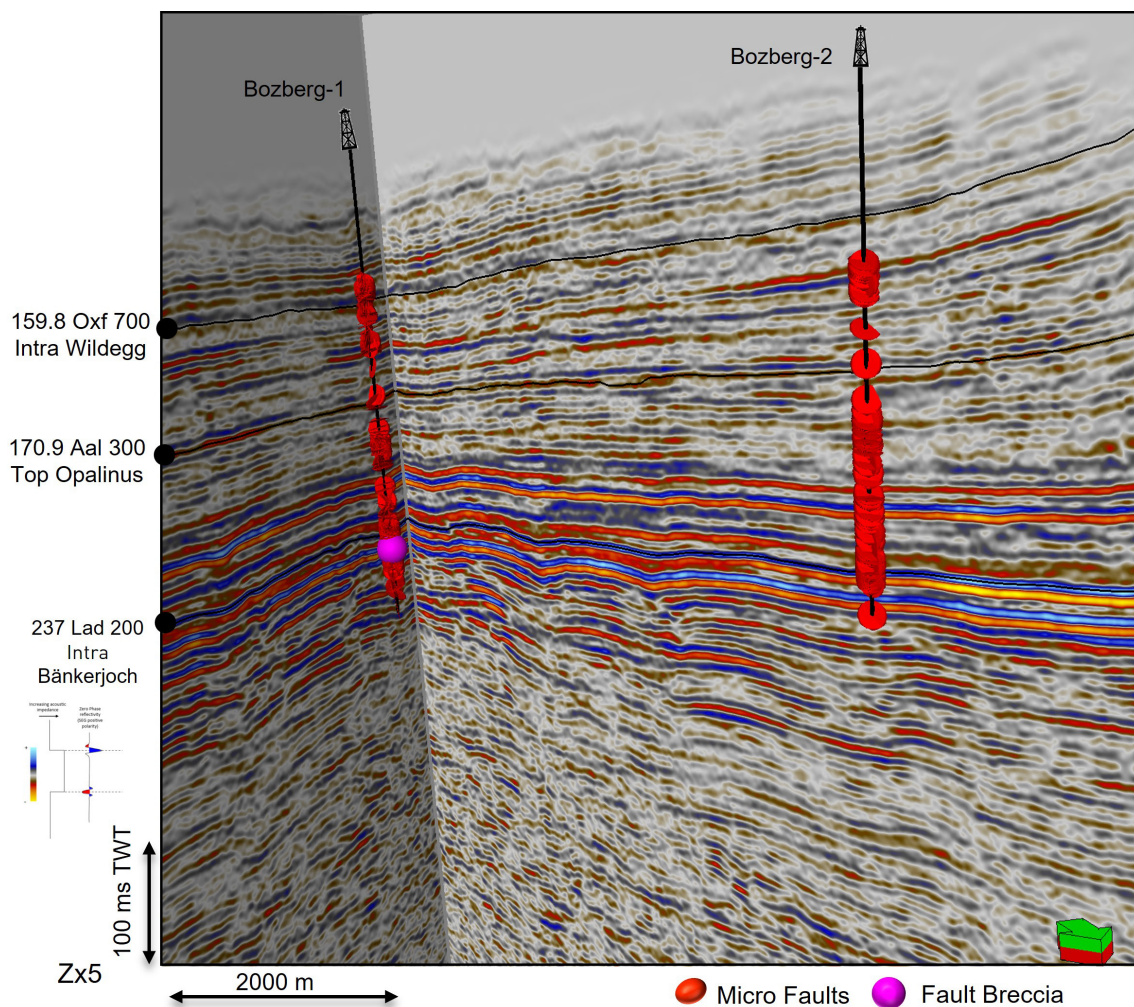


Fig. 5-49: 3D display of seismic and wells with core microstructure interpretation

The seismic random line (PreSTM-ref reflectivity) with well microstructures from core description across the Bözberg-1 and Bözberg-2 wells, located in the SDZ and in the CP structural domains, respectively. Note the presence of fault breccia in the lower interval of the Mesozoic succession. Green arrow points towards north.

6 Discussion

6.1 Fault interpretation uncertainty

Faults were interpreted as two-dimensional lines and discrete planes in 3D seismic data which do not capture the complex fault architecture observed in outcrop geology (e.g. segments, splays and lenses, and damage zones Fig. 4-15, Faleide et al. 2021) and which are commonly below seismic detection levels (Wibberley et al. 2008, Childs et al. 2009, Braathen et al. 2009). Furthermore, the source of some interpretation constraints is directly derived from the actual seismic data, e.g. its resolution (i.e. depth interval where the faults are picked) and from fault imaging itself that allow larger faults to be identified more easily than smaller faults due to the larger offsets of seismic horizons (Misra & Mukherjee 2018). Uncertainty associated with seismic interpretation falls into two different categories: objective and subjective (Tannert et al. 2007, Bond et al. 2007, Allenbach et al. 2019, Schaaf & Bond 2019). Objective uncertainties relate to limitations of seismic data in terms of resolution and quality, imaging issues of complex subsurface geometries, as well as uncertainties in seismic velocities used for depth conversion (Bond 2015, Alcalde et al. 2019, Schaaf & Bond 2019). Specifically, considering that the reference seismic data are time migrated and therefore do not fully consider ray bending in the overburden, the seismic events could be laterally mispositioned. Subjective uncertainties, or human bias, depend on the interpreters' fault picks. These will vary based on their experience and background as well as the amount of time invested in the task (Bond et al. 2007, Bond 2015, Schaaf & Bond, 2019, Alcalde et al. 2019, Michie et al. 2022). Uncertainties and pitfalls associated with data quality were investigated by qualitatively comparing seismic discontinuity imaging in the available seismic datasets. This comparison method was established as one of the key steps of the applied interpretation methodology (Fig. 4-13, Section 4.4). When referring to lateral positioning of the interpreted faults and other seismic features, higher weight has been given to interpretations carried out on the pre-stack depth migration cube (PreSDM). Since ray bending was taken into account, PreSDM should result in a corrected lateral position of the interpreted events, despite some issues with the applied velocity model. The distance between fault seismic signatures was manually calculated among the different seismic vintages both in vertical sections and in variance key horizon, with measured lateral shifts generally lower than 50 m (Fig. 6-1, Fig. 6-2). Few cases were observed where the lateral distance between the same mapped fault on different seismic vintages reaches values up to 70 m. In these cases, due to the geometry of the faults, it is speculated whether the higher lateral distance is influenced more by the interpretation (human pick) itself than by the seismic signal. Global examples from the North Sea indicate that, in areas with a complex overburden (Evans et al. 2005, van Der Velde 2006), a PreSDM may shift fault position by around 30 m to a maximum of 100 m relative to the pre-stack time migrated (PreSTM) image. Examples from time-migrated seismic datasets of the Middle East where fault cuts observed in deviated and long, horizontal wells were calibrated against seismically mapped faults indicate that lateral shifts generally do not exceed 50 m, even in datasets with complex overburden (Li et al. 2009, Hoch et al. 2010, Lorenzen et al. 2014, Zampetti et al. 2014, Zampetti & Emang 2014).

Subjective uncertainties associated with interpreter (human) biases were assessed in the comparison of different vintages of interpretation and are described in the next section.

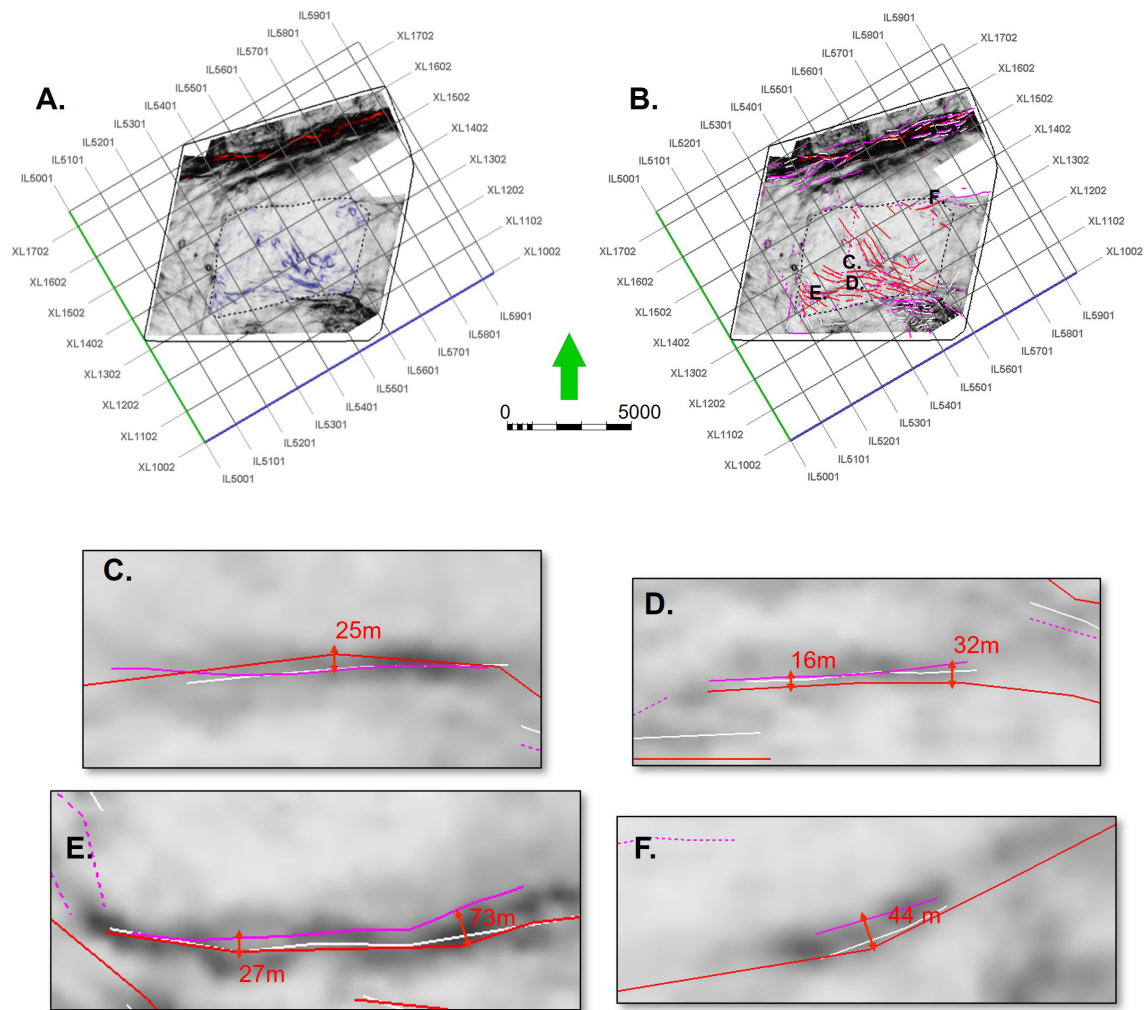


Fig. 6-1: Estimation of fault lateral position across the different seismic vintages

A. Overlay of 237 Lad 400 – Top Muschelkalk variance horizon slice extracted from PreSDM (black dashed polygon) on 237 Lad 200 – Intra Bänkerjoch variance slice extracted from PreSTM-ref; discontinuity. PreSDM is plotted in blue over the black-and-white scale of the PreSTM-ref. B. Lad 200 – Intra Bänkerjoch variance horizon slice extracted from PreSTM-ref with fault traces and structural lineaments at 237 Lad 200 – Intra Bänkerjoch / 237 Lad 400 – Top Muschelkalk from different seismic vintages: (1) NAB 18-35 in pink (solid are A faults and dashed C faults as defined in NAB 18-34), (2) PreSDM ASR 2022 deformation zones (undifferentiated faults and folds) in red and (3) PreSTM-ref 2023 fault traces in white. C. to F. Zoomed-in windows from B. on key fault locations to estimate lateral shifts of the fault traces among the different interpretation vintages.

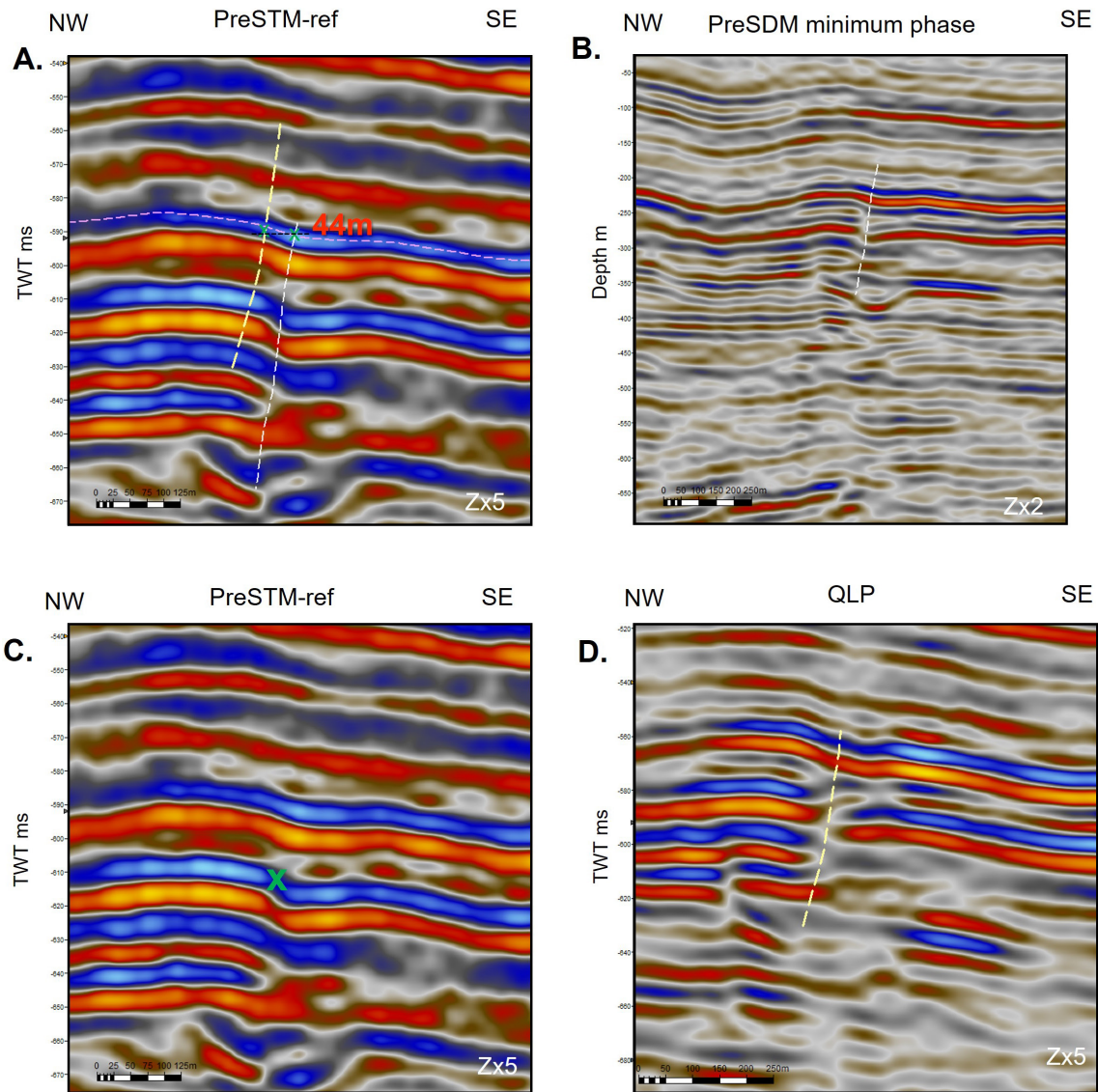


Fig. 6-2: Estimation of fault lateral position uncertainty across the different seismic vintages by comparing seismic fault signature across the different seismic cubes

Inline 5674: A. Comparison between fault interpretations from PreSTM-ref (white dashed line) and NAB 18-34 QLP (yellow dashed line); B. Depth-converted fault from PreSTM-ref to PreSDM minimum-phase diagnostic (note a slight vertical shift due to both different velocity model and phase shift); C. QC of fault signature (green cross) on PreSTM-ref; D. fault interpretation performed in QLP (dashed yellow line) over QLP seismic data. Estimated lateral uncertainty between the PSTM-ref and QLP seismic datasets is ~44 m (A.), whereas there is good fault position overlay between the PreSTM-ref and the PreSDM seismic datasets (B.).

6.2 Comparison with Previous Interpretations

Since the first seismic processing product (2018), Nagra has invested continuous effort in seismic interpretation, with a strong focus on fault mapping. Several interpretation products from different interpreters covering different seismic vintages were produced (Tab. 6-1).

The available fault interpretations were performed based on different seismic vintages and/or by different interpreters applying different approaches and criteria, but they are all based on the 3D integration of amplitude sections and seismic attribute horizon / time slices.

The fault interpretation in 2018 on the QLP seismic vintage (Fig. 5-29, Nagra 2019) was performed along a 5×5 interpretation seedline grid, and followed two interpretation criteria, resulting in the identification of two classes of faults, namely class A and class C faults. The identification of class A faults relied on a first-order criterion of reflection discontinuity in the seismic sections, i.e. (i) as a reflection displacement or (ii) as the presence of a narrow flexure, solely, for at least one of the mapped horizons and on a minimum of two neighbouring seedlines (Nagra 2019). The traces of the faults identified during the manual seedline interpretation were subsequently also mapped on relevant time slices of seismic amplitude cubes, as well as on horizon extracts of seismic attribute volumes. The class C faults were considered as less robust since the structures were solely mapped based on seismic attribute response. These structures showed hardly any fault throw and narrow flexure in the seismic amplitude sections but a consistent expression in seismic attribute maps (Nagra 2019).

Tab. 6-1: Summary table of all the available seismic interpretation vintages and products

Interpretation Vintage	Seismic Data	Workflow	Products	Interpreter
NAB 18-34	QLP zero-phase	3D interpretation → sections and attribute horizon slices	3D fault sticks/planes Fault traces at key horizons	Interpreter A Contractor
Pre-ASR 2021	PreSDM minimum-phase	3D screening → attribute time and horizon slices – QC via vertical sections	Structural lineament traces (i.e. faults and folds)	Nagra
PreSTM-ref 2022	PSTM-ref minimum-phase	3D interpretation → sections and attribute horizon slices	3D fault sticks/planes Fault traces at key horizons	Interpreter A Contractor
ASR 2022	PreSTM-ref minimum-phase	3D screening → attribute time and horizon slices – QC via vertical sections	Structural lineament traces (i.e. faults and folds)	Nagra
NAB 23-17	PreSTM-ref zero-phase	3D interpretation → sections and attribute horizon slices	3D fault sticks/planes Fault traces at key horizons	Interpreter B Contractor

In 2022, the same fault interpretation criteria, as defined for the 2018 interpretation of the QLP seismic vintage (Nagra 2019), were used by the same interpreter contractor (see Table 6.1) in the fault interpretation carried out on the PreSTM-ref minimum-phase seismic vintage (Fig. 6-3). In this interpretation product, however, only A class faults were mapped.

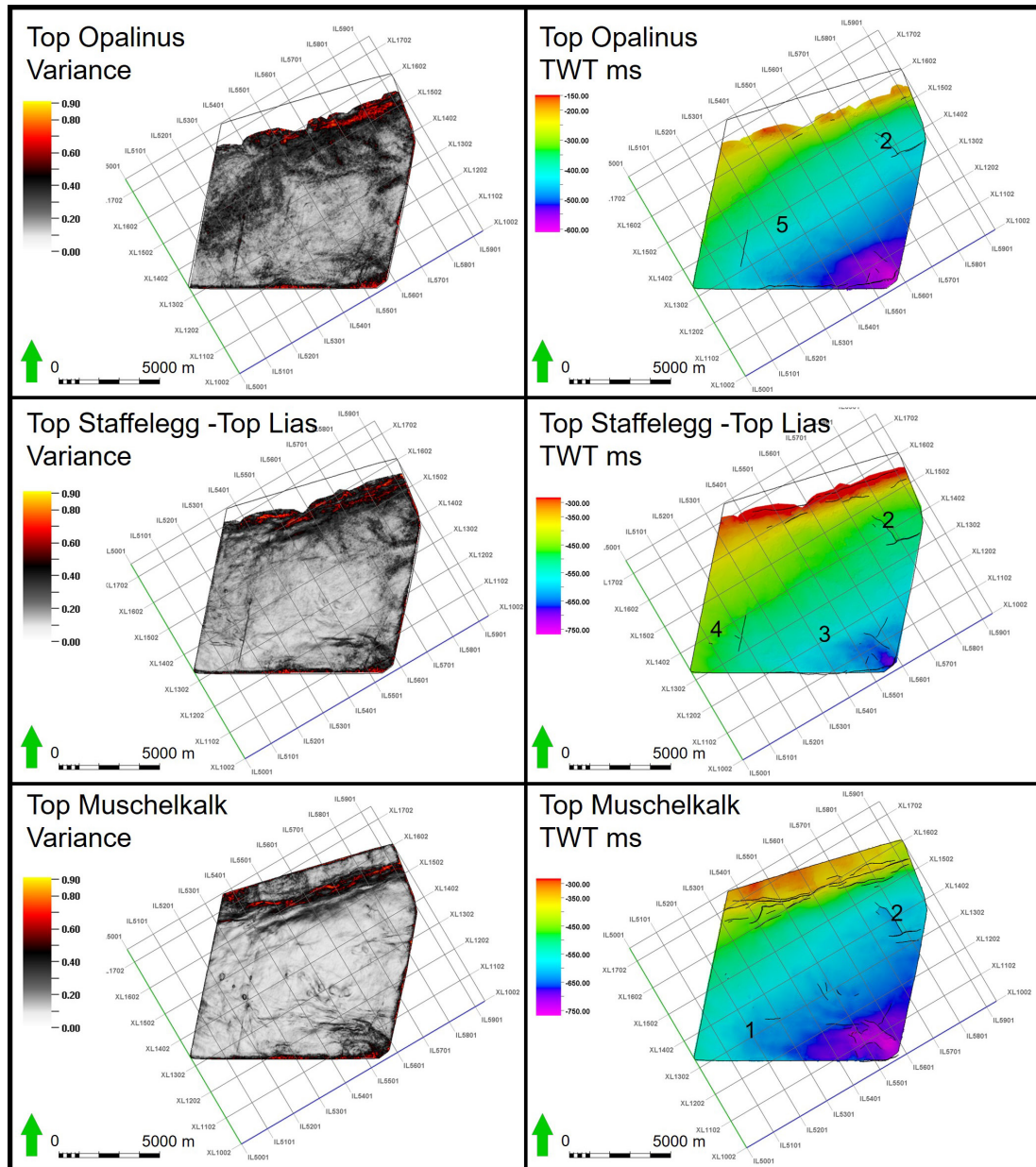


Fig. 6-3: Fault interpretation matrix - PreSTM-ref-minimum-phase (interpreter A contractor, 2022 evaluation)

Similar matrix to Figs. 5-20, 5-21, 5-23 and 5-29 (variance horizon slices and TWT top structure). Black lines are fault polygons.

When comparing with the previous evaluation of the same interpreter (contractor A) on the QLP dataset (Tab. 6-1, Fig. 5-29), note: 1: the Effingen Fault is no longer interpreted at level Top Muschelkalk; 2: the artefact is now interpreted as a fault affecting the entire Mesozoic stratigraphy; 3 and 4: ~E-W striking faults at Top Lias are no longer interpreted, 5 minor faults in the Central Panel (CP) area at Top Opalinus are also no longer recognised.

As input for the ASR evaluation (Nagra 2022), a structural interpretation was carried out based both on a PreSDM-A, PreSTM-ref minimum-phase seismic vintages (Fig. 5-20, Fig. 5-21). The 3D screening approach was described in the methodology section (Fig. 4-8, Fig. 4-9) and allowed discrimination among (i) structural lineaments, (ii) stratigraphic features (i.e. channels, incisions, karsts and carbonate platform margins), and (iii) seismic artefacts. Seismic discontinuities interpreted to represent structural lineaments were mapped and displayed in a 2D map view of three key stratigraphic horizons. Such lineaments are generically referred as deformation zones and include indistinctively seismic faults and fault-tip monoclines (drape-folds on top of blind normal or reverse faults; Fig. 5-22, Nagra 2022).

Fault maps for all the available interpretations (Tab. 6-1) were captured in a graphic matrix (Fig. 5-20, Fig. 5-21, Fig. 5-23, Fig. 5-29, Fig. 6-3).

Interpretations from different interpreters and different seismic processing vintages are displayed over the interpretation proposed in the report (referred to as 2023) for easy comparison. When comparing all the interpretation results (Fig. 6-4, Fig. 6-5, Fig. 6-6, Fig. 6-7), it becomes clear that the main contrast in fault distribution is associated with the distinctions in definition of the seismic discontinuities. This is evident in Fig. 6-4, where the difference between the fault interpretation performed in 2023 and in 2018 is predominantly related to the class C faults (faults interpreted based solely on attribute map displays) and in Fig. 6-5 (2023 versus ASR 2022) where only part of the undifferentiated deformation zones (i.e. faults and folds) is selected to represent fault polygons (resulting from 3D fault (stick) interpretation). Strong similarity in the distribution is observed when comparable products are correlated. The deformation pattern outlook appears quite consistent when comparing the ASR 2022 deformation zones with the 2018 class A and class C faults (Nagra 2019), and the 2023 class A faults and the 2022 interpretation (Fig. 6-4, Fig. 6-7, Fig. 6-8). This suggests that most of the class C faults (Nagra 2019) might represent folds more than faults.

The observed deformation style, with seismic-scale faults tipping-up into drape folding (fault-tip monocline) and the “definition / terminology” used for the seismic discontinuities seems to be the source of the apparent interpretation divergence. Seismic discontinuities in 2D (map) attribute displays represent both folds and faults, a differentiation not fully elaborated during the 2018 investigation.

Nevertheless, despite the different spatial distribution and density, a consistent trend can be inferred with a net decrease in deformation amount towards the shallow stratigraphic levels, specifically from the Base Opalinus Clay (174.7 Toa 100 – Top Lias) interval upwards and in the Central Panel structural domain.

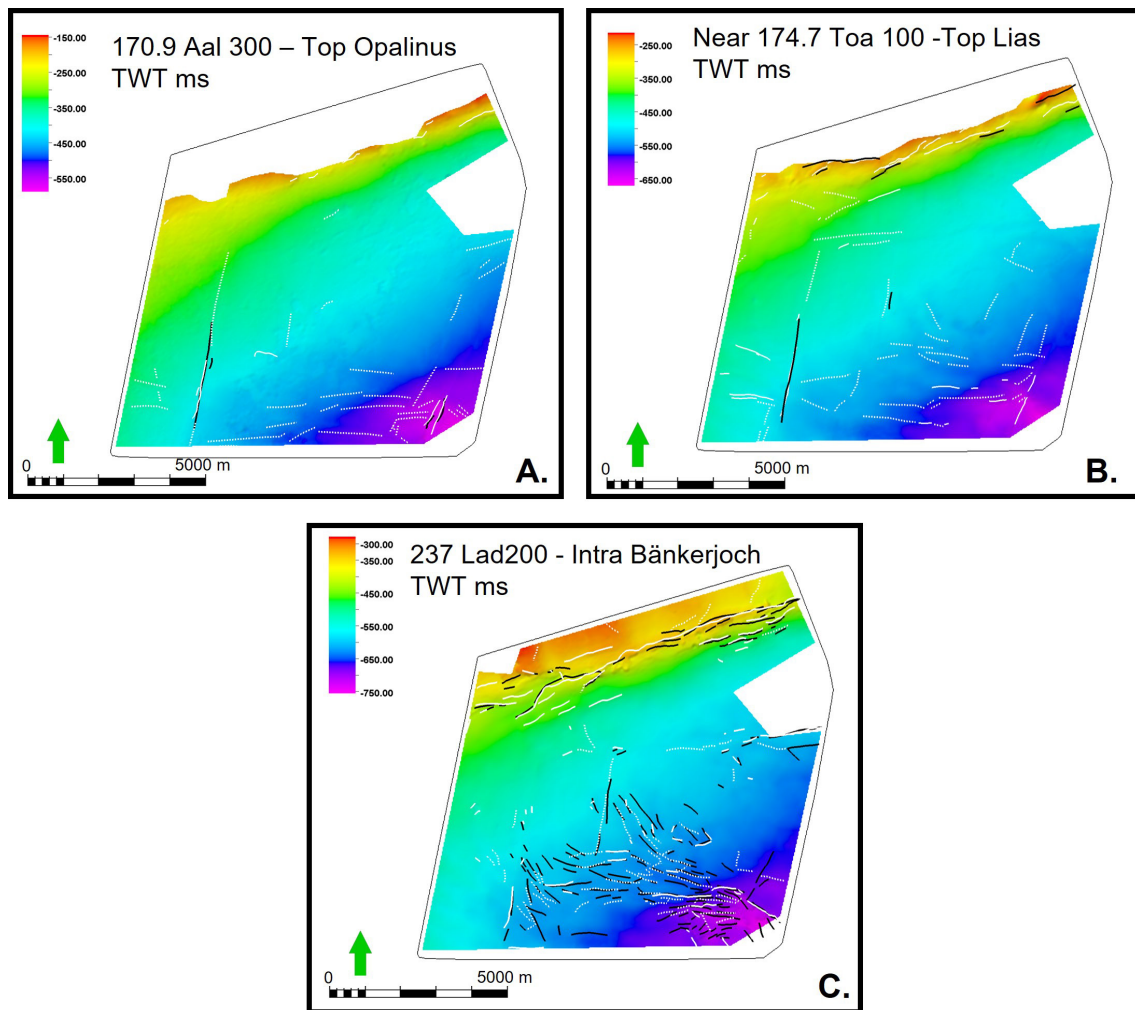


Fig. 6-4: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2018 QLP (NAB 18-34)

Overlay of 2023 fault traces (black lines = this report) and NAB 18-34 (white solid lines = class A faults, and white dashed lines = class C faults) for the three key stratigraphic levels A. 170.9 Aal 300 – Top Opalinus; B. Near 174.7 Toa 100 – Top Lias; C. 237 Lad 200 – Intra Bänkerjoch. Refer to Tab. 6-1 for seismic vintage and interpreter details.

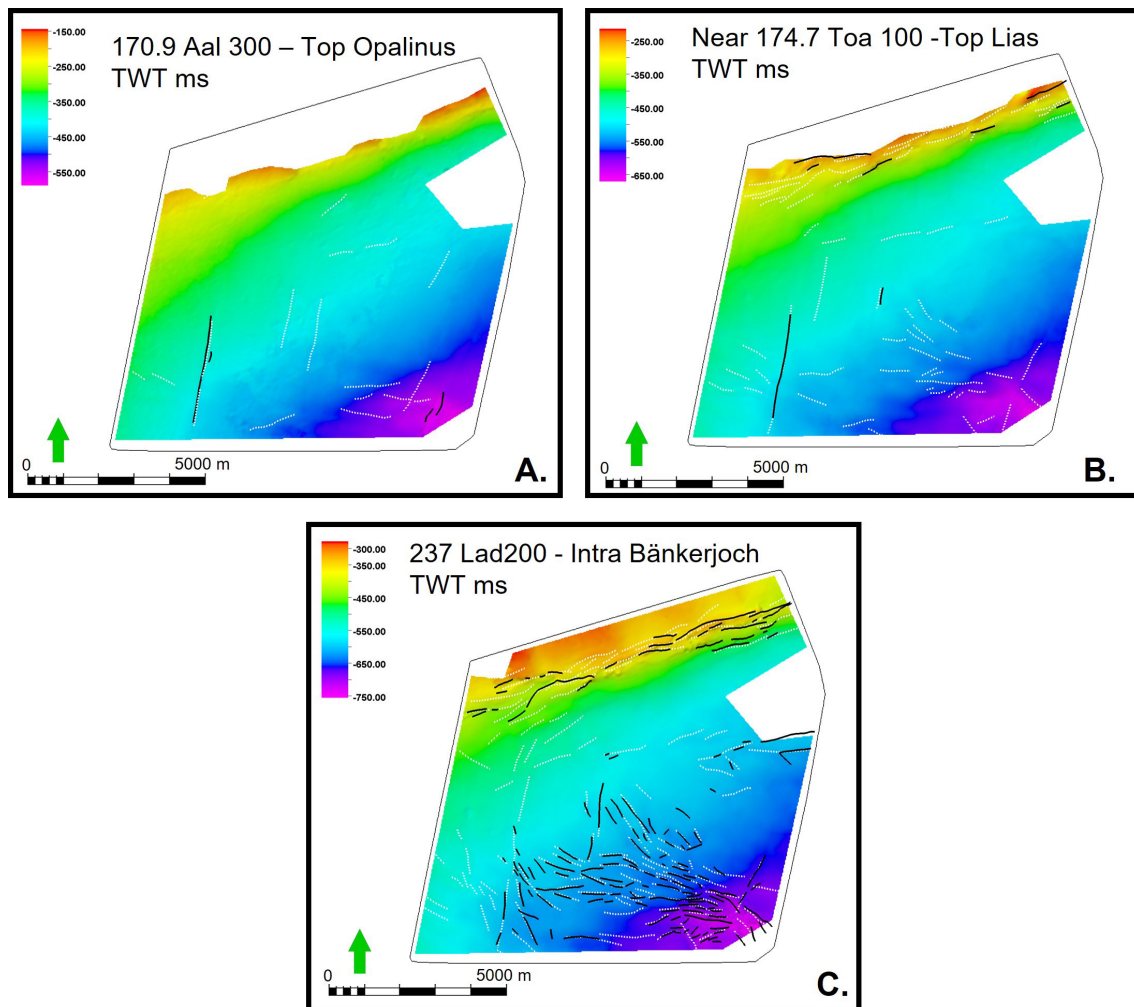


Fig. 6-5: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (ASR)

Overlay of 2023 fault traces (black lines = this report) and ASR structural lineaments (white dashed lines = PreSTM-ref minimum-phase) for the three key stratigraphic levels. A. 170.9 Aal 300 – Top Opalinus; B. Near 174.7 Toa 100 – Top Lias; C. 237 Lad 200 – Intra Bänkerjoch. For the ASR interpretation no distinction was made between faults and folds. Refer to Tab. 6-1 for seismic vintage and interpreter details.

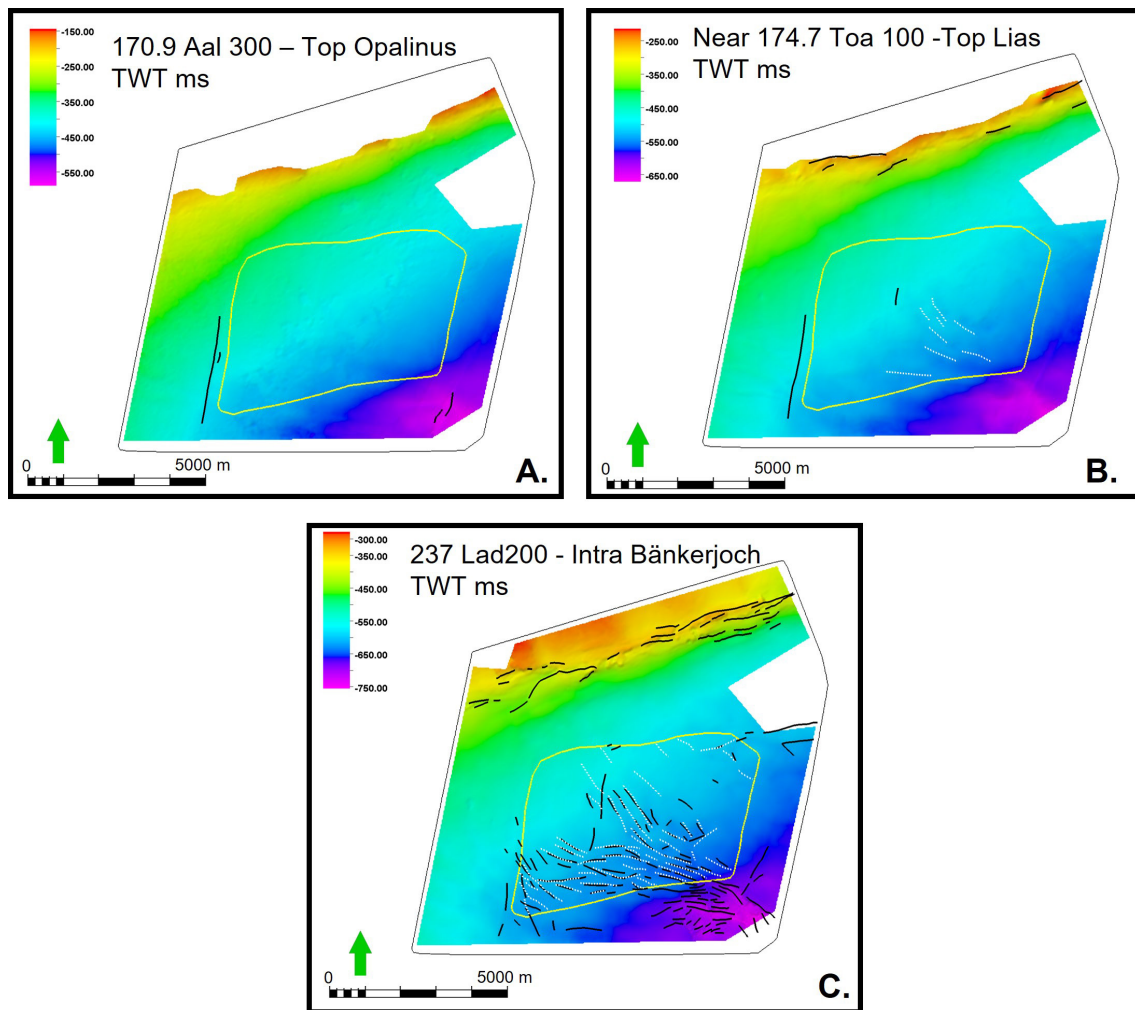


Fig. 6-6: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2021 PreSDM (Pre-ASR)

Overlay of 2023 fault traces (black lines = this report) and ASR structural lineaments (white dashed lines = PreSDM-A) for the three key stratigraphic levels. A. 170.9 Aal 300 – Top Opalinus; B. Near 174.7 Toa 100 – Near Top Lias; C. 237 Lad 200 – Intra Bänkerjoch. For the ASR interpretation no distinction was made between faults and folds. This might contribute to the difference at the Near 174.7 Toa 100 – Top Lias horizon, where the presence of deformation zones could be associated with folding at fault tips. Refer to Tab. 6-1 for seismic vintage and interpreter details. PreSDM processing was carried out only for the central part of the survey (yellow polygon)

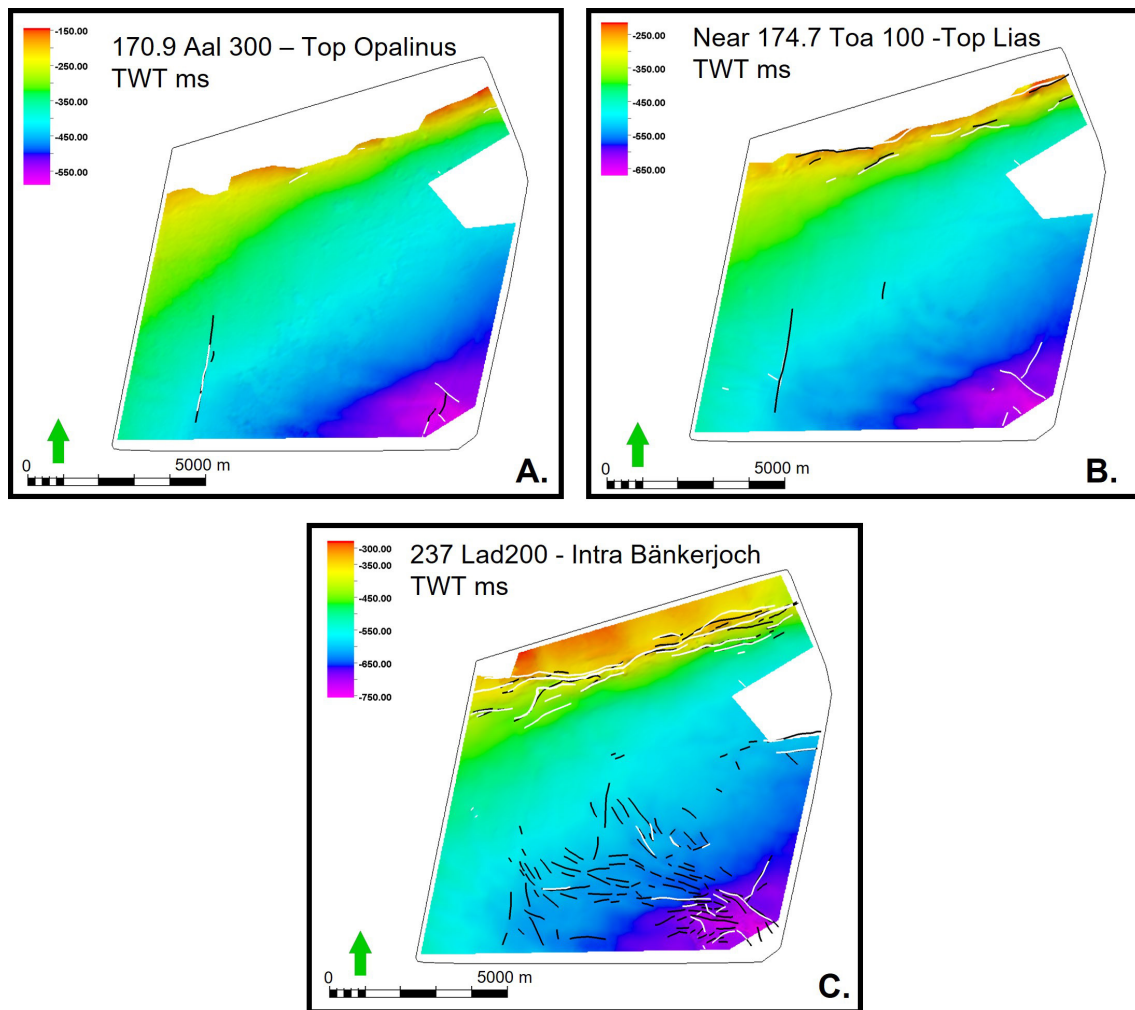


Fig. 6-7: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (interpreter A contractor)

Overlay of 2023 fault traces (black lines = this report) and 2022 (white dashed lines = PreSTM-ref minimum-phase) for the three key stratigraphic levels. A. 170.9 Aal 300 – Top Opalinus; B. Near 174.7 Toa 100 – Near Top Lias; C. 237 Lad 200 – Intra Bänkerjoch. Different interpreters on PreSTM-ref data. Refer to Tab. 6-1 for seismic vintage and interpreter details.

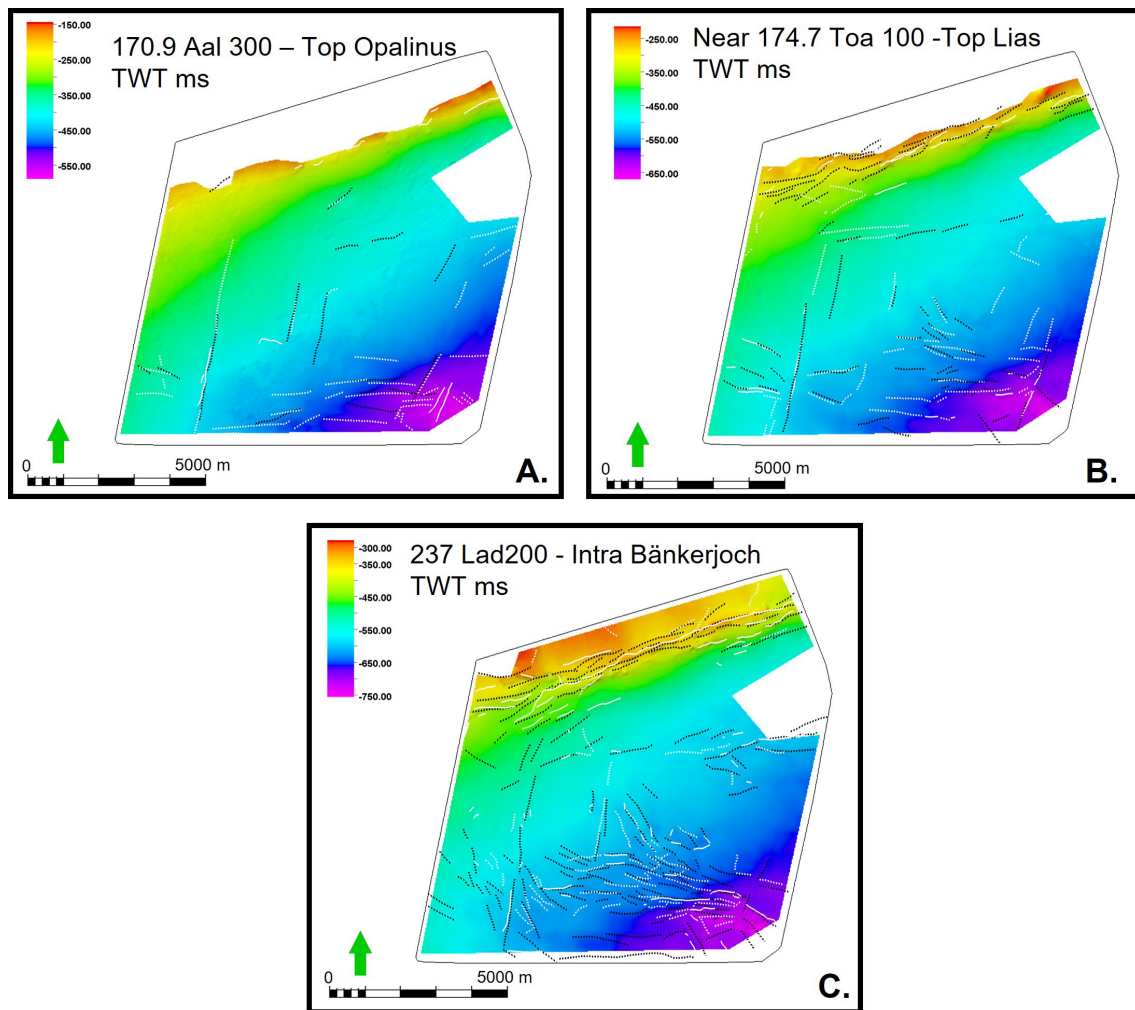


Fig. 6-8: Fault interpretation vintage comparison: 2022 PreSTM-ref minimum-phase (ASR) versus 2018 QLP (NAB 18-34)

Overlay of ASR structural lineaments (black dashed lines) and NAB 18-34 faults (white line = class A faults, white dashed lines = class C faults) for the three key stratigraphic levels. A. 170.9 Aal 300 – Top Opalinus; B. Near 174.7 Toa 100 – Near Top Lias; C. 237 Lad 200 – Intra Bänkerjoch. For the ASR interpretation no distinction was made between faults and folds. This might yield to the difference at Near174.7 Toa 100 – Top Lias horizon, where the presence of deformation zones could be associated with folding at fault tips. Note similar fault density and distribution. Refer to Tab. 6-1 for seismic vintage and interpreter details.

Discounting the faults which do not reach the base of the Opalinus Clay (171.4 Toa 100 – Top Lias), a large undisturbed area can be recognised in the central area of JO siting region, covering the Central Panel (CP) and part of the Southern Deformation Zone (SDZ). In the definition of a perimeter for the undisturbed area, few lineaments become critical at the level of base and top Opalinus Clay, lineaments which also represent the main differences among the several vintages of interpretation. Such lineaments were further investigated, and their seismic expression is captured in Fig. 6-9 and Fig. 6-10. A curved fault trace was interpreted in 2018 affecting the Top Opalinus, only (Nagra 2019). Faults with similar geometry and occurrence were proposed in the 2018 interpretation (located within structurally more complex areas) and were defined as intra-interval faults (Nagra 2019). These faults appear to affect only the reflection marking the Top Opalinus, and to quickly sole out at an extremely low angle within the Top Opalinus reflection itself (Fig. 6-9) without displacing any overlying reflections. Based on their seismic geometry (hummocky shape), the lack of clear seismic fault signature / geometry, the restricted vertical occurrence such features are inferred to represent more likely sedimentary features (reworked sediment bodies) than faults.

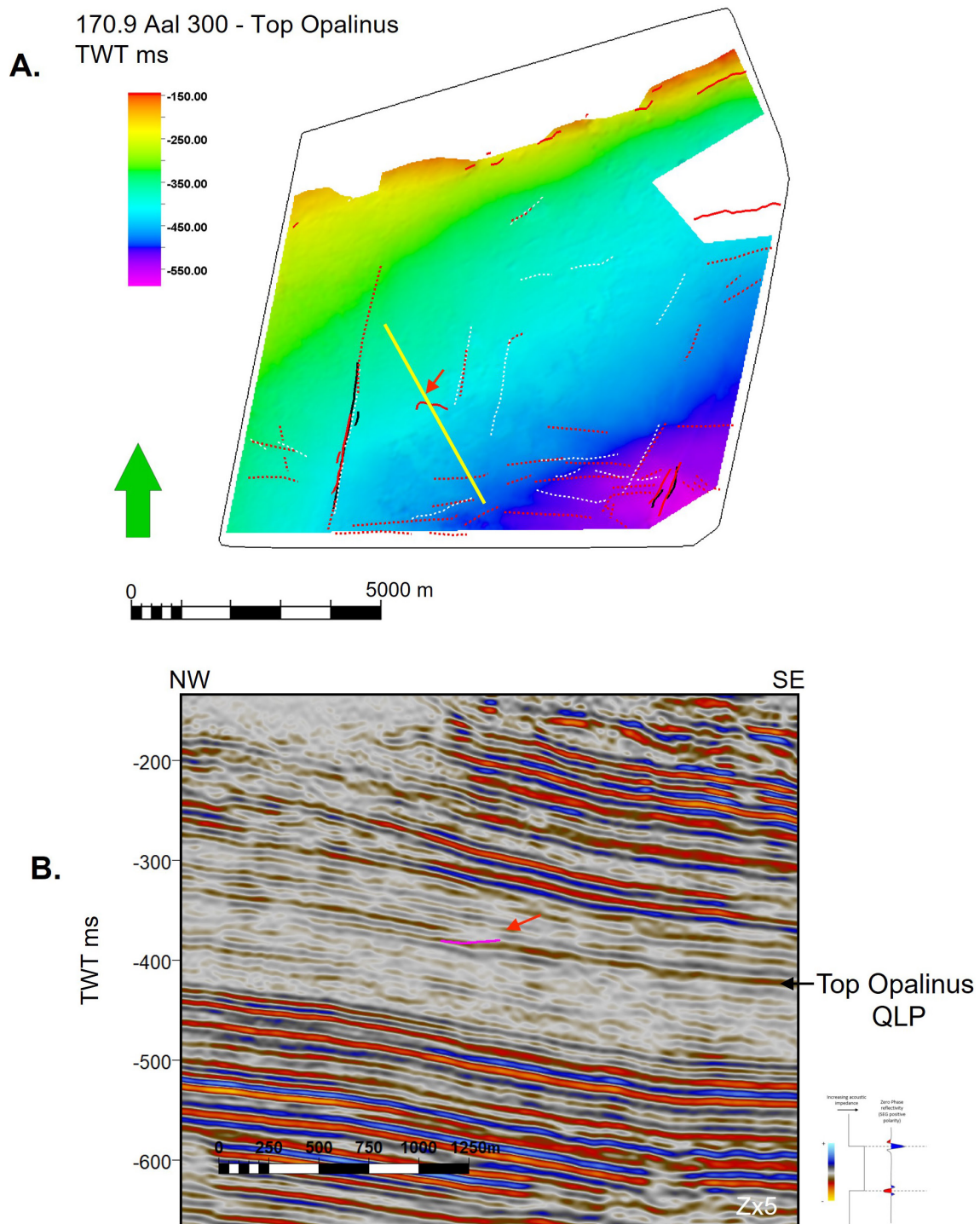


Fig. 6-9: Intra-Opalinus fault from 2018 interpretation (NAB 18-34)

A. TWT horizon slice of 170.9 Aal 300 – Top Opalinus with different vintages of fault / structural lineament interpretations: NAB 18-34 (red solid lines are class A faults, red dashed lines are class C faults), ASR (2022) structural lineaments (dashed white lines) and 2023 interpretation (black solid lines). A curved fault trace (class A fault type, 2018) was interpreted in the central area representing an intra-Opalinus fault. B. Inline 5330 showing the NAB 18-34 fault interpretation on a section view. The absence of clear seismic fault signature and extremely low fault dip (vertical exaggeration is 5) might lead to a sedimentological explanation instead. Seismic data is QLP.

Two linear discontinuities were recognised during the Phase 1 screening (Nagra 2022; Fig. 6-11). Those features were interpreted to be associated with structural lineaments because of their linear appearance in horizon and time slices. Detailed 3D investigation and evaluation of seismic reflection geometries associated with them indicate that they are more likely to represent sedimentological features associated with facies variation near (below) Top Opalinus and with potential imprints related to the undulations mimicking the Top Dogger unconformity reflection, and therefore they were dismissed in the 2023 fault mapping.

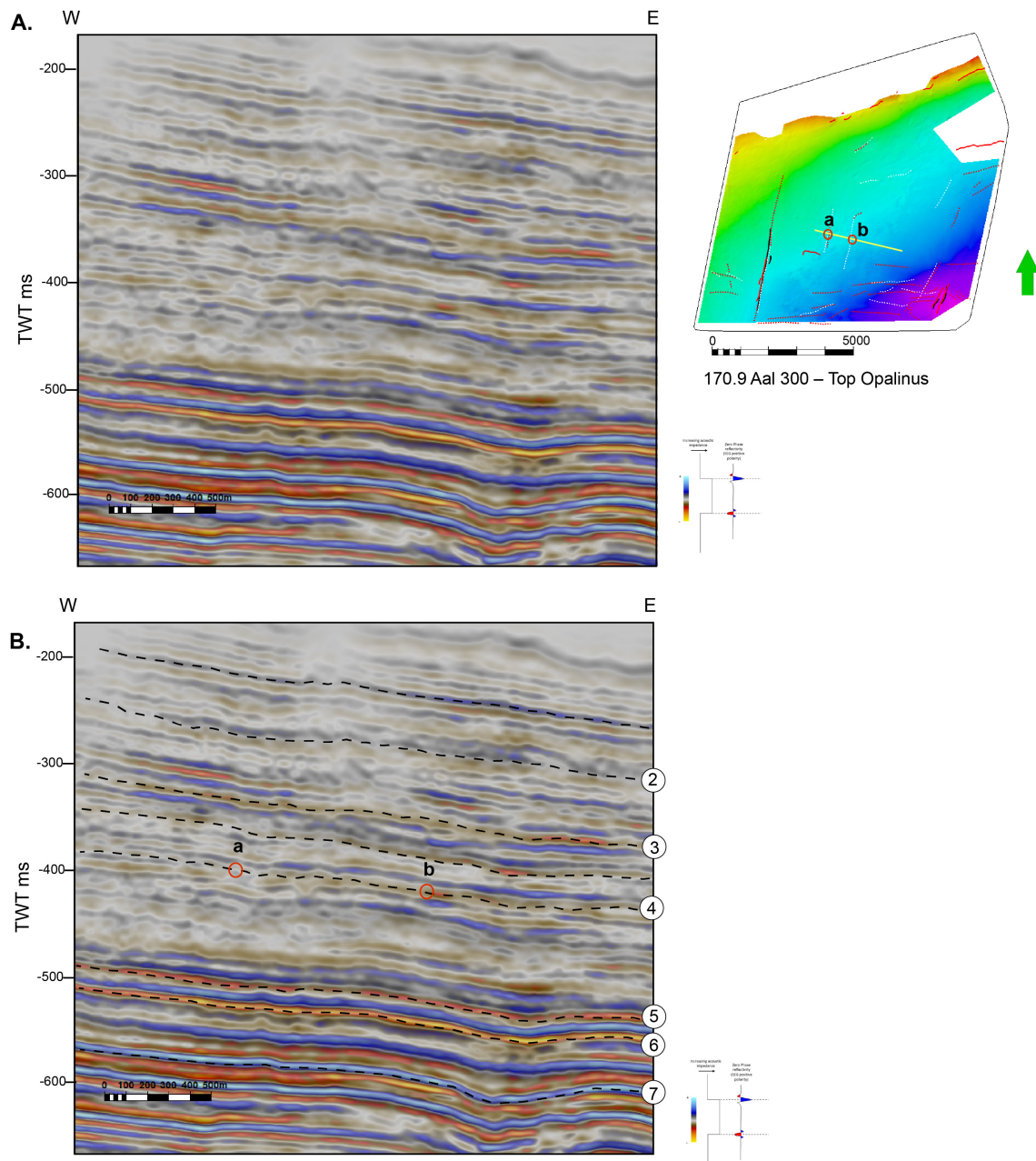


Fig. 6-10: Random line across the two lineaments interpreted in 2022 (ASR) as structural lineaments

A. Uninterpreted and B. interpreted seismic line showing the two linear features interpreted as structural lineaments at Top Opalinus Clay (ASR 2022). Detailed 3D interpretation and section displays indicate that the attributes discontinuities (a. and b. - red circles) are more likely to represent sedimentological features associated with facies transition in the Opalinus Clay with a potential component of imprint associated with the Top Dogger wavy reflection and Intra-Dogger complex reflectivity pattern.

Horizon legend (B.): 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300 – Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

At the level of 174.7 Toa 100 – Near Top Lias, a short fault segment was mapped in 2023 and was previously recognised in the 2022 ASR screening phase (Fig. 6-11). The presence of this lineament can be confirmed by 3D investigation. It represents part of a deeper and larger fault that extends upwards to the 174.7 Toa 100 – Near Top Lias level. The fault is described in Section 5.3.1.4 and represents a fault located in the Central Panel but with similar orientation to the Effingen Fault.

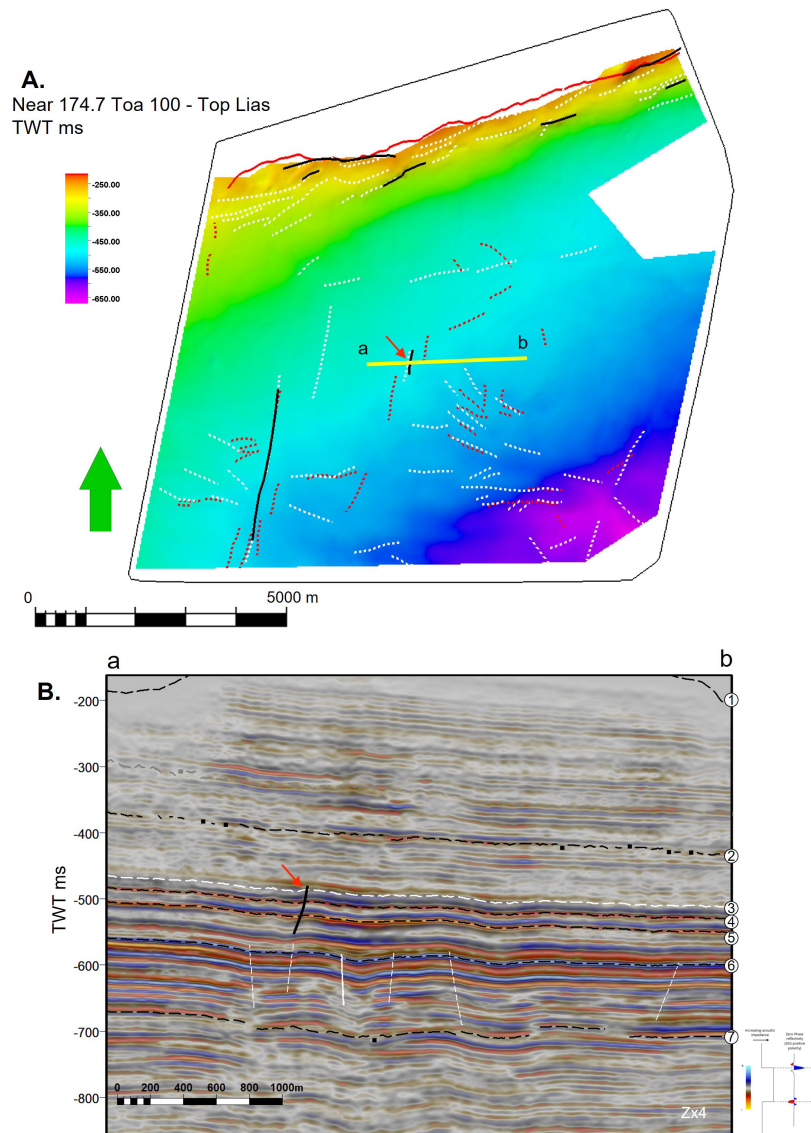


Fig. 6-11: Random line across the fault affecting the Near 174.7 Toa 100 – Top Lias in the Central Panel

A. TWT horizon slice of 174.7 Toa 100 – Near Top Lias with different vintages of fault / structural lineament interpretations: 2018 NAB 18-23 (red dashed lines are class C faults), 2022 ASR structural lineaments (dashed white lines) and 2023 interpretation (black solid lines). In 2023 a short fault segment (black solid line indicated by red arrow) was interpreted in the central area. B. Random line showing 2023 fault interpretation (white dashed sticks) on a section view. The short fault segment is highlighted in black. In section, it appears to offset (red arrow) the 174.7 Toa 100 – Near Top Lias (white dashed horizon line). Such fault segment is softly linked to a deeper structure. Vertical segmentation appears to occur at the Intra Bänkerjoch evaporitic level.

Horizon legend (B.): 1 is ground level, 2 is 159.8 Oxf 975 – Top Dogger, 3 is 170.9 Aal 300– Top Opalinus, 4 is 192.9 Sin 200 – Near Top Klettgau, 5 is 227 Car 200 – Near Top Bänkerjoch, 6 is 237 Lad 200 – Intra Bänkerjoch, 7 is 251.9 Per 100 – Near Base Mesozoic Unconformity. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

7 Conclusions

A dedicated seismic evaluation matching the requirements at the scale of the siting region selection process and ensuring comparability among the three siting regions was carried out for the JO siting region. For this seismic evaluation, all the available seismic processing datasets were evaluated using a rigorously structured approach in line with standard workflows and established criteria. Challenges that impaired interpretation confidence were recognised and understood, and the uncertainties in the geological evaluation were captured and their impact estimated (both qualitatively and quantitatively).

While using all the seismic datasets (Tab. 3-1), the interpretation results were captured in the PreSTM-ref seismic data. The seismic processing was designed such that all the processing input parameters and workflows were similar across the seismic surveys of the three siting regions. While this might not have resulted in the best processing approach for each of the individual surveys, it best serves the aim of comparing the three siting regions through consistent seismic imaging.

A robust and comparable horizon-fault framework was established for the JO siting region. Confidence in the resulting subsurface image was bolstered by a detailed evaluation of the uncertainties associated with the interpretation of seismic data. Uncertainties and pitfalls associated with data quality were mitigated by the use and comparison of all the seismic processing vintages (Tab. 3-1), while the impact of human bias was assessed by the superimposition all the available interpretations (Tab. 3-1). When comparing different vintages of interpretations, the length and orientation of individually interpreted fault segments might vary across the different products. The fault maps resulted from the seismic interpretation carried out in this evaluation differ in distribution and density from previous products (i.e. ASR as for Nagra 2022 and NAB 18-34). The difference with the 2022 ASR interpretation is related to the ASR mapping approach, where the “structural” seismic discontinuities (deformation zones) captured in the maps represent both faults and folds. A similar observation can be made relatively to the 2018 interpretation results. In the 2018 interpretation vintage two classes of seismic faults were considered: class A faults with fault signature visible in both amplitude sections and attribute displays and class C faults only associated with the attribute map displays (Nagra 2019). When considering only class A faults, fault distribution does not deviate from the proposed (2023) interpretation. The higher density related to the incorporation of class C fault traces, particularly at shallower stratigraphic levels, resemble the ASR 2022 maps. This suggests that the majority of the 2018 class C faults are more likely to represent folds than faults.

The complex geological architecture of the upper interval of the Mesozoic succession poses a challenge in the recognition of subtle faults in the stratigraphic level overlying the Opalinus Clay interval. Despite this, the evaluation of the seismic facies and geometries indicates that the observed subtle and linear seismic discontinuities correspond to sedimentological patterns rather than tectonic lineaments, although a level of uncertainty remains.

The performed evaluation shows that the Jura Ost siting region can be subdivided into four main structural domains: (i) Northern Fold-and-Thrust Zone (NFTZ, i.e. Mandach Thrust), (ii) Southern Deformation Zone (SDZ, including structures such as the Brugg Structure Zone, Gallenkirch Structure Zone, Villnachern Fault), (iii) the Effingen Fault (EF) and (iv) the Central Panel (CP, including the Siggenthal Anticline). Such structural configuration resulted in the identification of isolated sectors of seismically undisturbed areas for the entire Mesozoic succession.

However, if only the upper interval of the Mesozoic succession (Opalinus Clay and units above the Opalinus Clay) is considered, since faulting is mainly affecting the Bänkerjoch and the Muschelkalk Formations, a large seismically undisturbed area can be identified. This area covers a perimeter of 31 km² (Fig. 7.-1). This area is bounded by major structural lineaments: the

Effingen Fault to the east, the Jura Main Thrust to the south and the Mandach Thrust to the north. Towards the west, a seismic-scale fault was interpreted to affect the 174.7 Toa 100 -Top Lias horizon (base Opalinus Clay) and therefore a buffer area of 500 m around ($\sim 1 \text{ km}^2$) the interpreted fault should be further considered when abstracting the undisturbed area perimeter (Fig. 7-1).

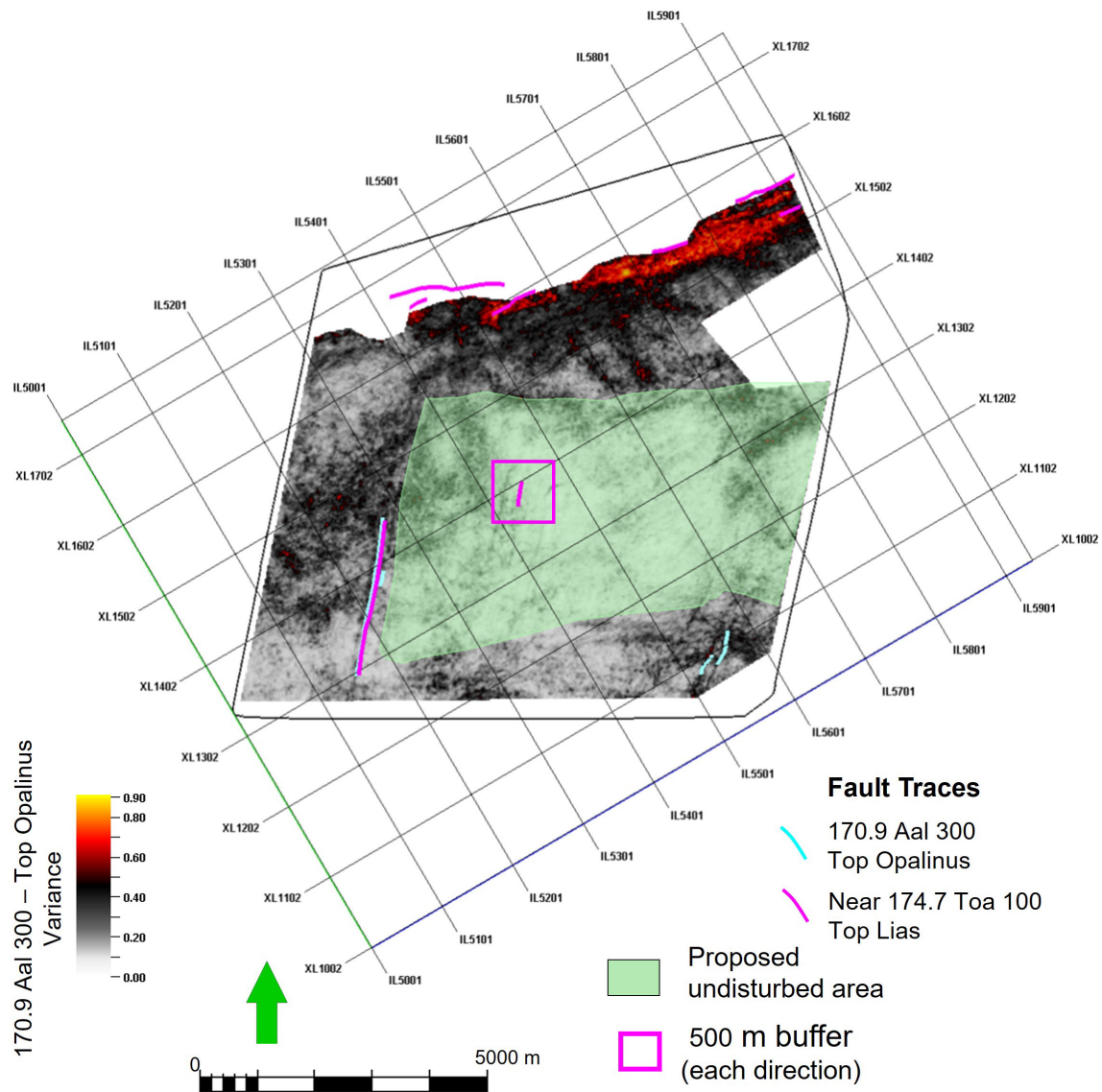


Fig. 7-1: Identification of a seismically undisturbed area for the Opalinus Clay host rock
Based on a detailed seismic analysis, a large undisturbed area can be identified in the JO siting region, when considering faulting affecting the Opalinus Clay and its overburden, only.

8 References

- Alcalde, J., Bond, C.E., Johnson, G., Kloppenburg, A., Ferrer, O., Bell, R. & Ayarza, P. (2019): Fault interpretation in seismic reflection data: an experiment analysing the impact of conceptual model anchoring and vertical exaggeration. *Solid earth*, 10(5), 1651-1662.
- Allenbach, R.P. (2001): Synsedimentary tectonics in an epicontinental sea: a new interpretation of the Oxfordian basins of northern Switzerland *Eclogae Geologicae Helveticae*, 94, 265-287.
- Backus, M.M. (1959): Water reverberations – their nature and elimination. *Geophysics*, 24(2), 233-261.
- Becker, A. (2000): Der Faltenjura: geologischer Rahmen, Bau und Entwicklung seit dem Miozän. *Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins. Neue Folge* 82, 317-336-4.
- Bitterli-Dreher, P., Graf, H.R., Naef, H., Diebold, P., Matousek, F. & Burger, H. (2007): Blatt 1070 Baden. *Geologischer Atlas der Schweiz 1:25 000, Erläuterungen Blatt 120*. Bundesamt für Landestopografie Swisstopo, Wabern (Bern).
- Birkhäuser, P., Roth, P., Meier, B. & Naef, H. (2001): 3-D Seismik: Räumliche Erkundung des mesozoischen Sedimentschichten im Zürcher Weinland. *Nagra Technischer Bericht NTB 00-03*.
- Bond, C., Robledo, F. & Butler, R. (2023): The Jura Fold-Thrust Belt, Switzerland - a contractional deformation setting for nuclear waste disposal. *EGU General Assembly Conference Abstracts*, EGU23-9905.
- Bond, C.E., Gibbs, A. D., Shipton, Z.K. & Jones, S. (2007): What do you think this is? “Conceptual uncertainty” in geoscience interpretation. *GSA today*, 17(11), 4-10.
- Bond, C.E., Johnson, G. & Ellis, J.F. (2015a): Structural model creation: the impact of data type and creative space on geological reasoning and interpretation. *Geological Society of London, Special Publications*, 421(1), 83-97.
- Bond, C.E. (2015b): Uncertainty in structural interpretation: Lessons to be learnt. *Journal of Structural Geology*, 74, 185-200.
- Braathen, A., Tveranger, J., Fossen, H., Skar, T., Cardozo, N., Semshaug, S.E., Bastesen, E. & Sverdrup, E. (2009): Fault facies and its application to sandstone reservoirs. *AAPG bulletin*, 93(7), 891-917.
- Brown, A.R. (1996): Seismic attributes and their classification. *The leading edge*, 15(10), 1090-1090.
- Brown, A.R. (2011): Interpretation of three-dimensional seismic data. *Society of Exploration Geophysicists and American Association of Petroleum Geologists. AAPG Memoirs*, 42 / SEG Investigations in Geophysics, No. 9.
- Caër, T., Souloumiac, P., Maillot, B., Leturmy, P. & Nussbaum, C. (2018): Propagation of a fold-and-thrust belt over a basement graben. *Journal of Structural Geology*, 115, 121-131.

- Campbell, A., Fryer, A., Isaacson, L. & Wendt, B. (2005): Successful imaging in a structurally complex environment, using a Look-Ahead VSP. SEG Technical Program Expanded Abstracts 2005.
- Childs, C., Nicol, A., Walsh, J.J. & Watterson, J. (1996): Growth of vertically segmented normal faults. *Journal of Structural Geology*, 18(12), 1389-1397.
- Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A. & Schöpfer, M.P. (2009): A geometric model of fault zone and fault rock thickness variations. *Journal of Structural Geology*, 31(2), 117-127.
- Diebold, P., Naef, H. & Amman, M. (1991): Zur Tektonik der Zentralen Nordschweiz: Interpretation aufgrund regionaler Seismik, Oberflächengeologie und Tiefbohrungen. Textband. Nagra Technischer Bericht NTB 90-04.
- Diebold, P., Bitterli-Brunner, P. & Naef, H. (2006): Blatt 1069/1049 Frick-Laufenburg. Geologischer Atlas der Schweiz 1:25'000, Erläuterungen Blatt 110. Bundesamt für Landestopografie Swisstopo, Wabern (Bern).
- Evans, E., Papouin, M., Abedi, S., Gauer, M., Smith, P. & Jones, I.F. (2005): Southern North Sea PreSDM imaging using hybrid gridded tomography. SEG Technical Program Expanded Abstracts 2005.
- Faleide, T.S., Braathen, A., Lecomte, I., Mulrooney, M. J., Midtkandal, I., Bugge, A. J. & Planke, S. (2021): Impacts of seismic resolution on fault interpretation: Insights from seismic modelling. *Tectonophysics*, 816, 229008.
- Geyer, O.F. & Gwinner, M.P. (1991): Geologie von Baden-Württemberg. 4., neubearb. Aufl. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
- Gygi, R.A. (2000): Annotated index of lithostratigraphic units currently used in the Upper Jurassic of northern Switzerland. *Eclogae Geologicae Helveticae* 93/1, 125-146.
- Herron, D. A. (2011): First steps in seismic interpretation. Society of Exploration Geophysicists.
- Hesthammer, J. & Fossen, H. (1997a): The influence of seismic noise in structural interpretation of seismic attribute maps. *First Break*, 15(6).
- Hesthammer, J. & Fossen, H. (1997b): Seismic attribute analysis in structural interpretation of the Gullfaks Field, northern North Sea. *Petroleum Geoscience*, 3(1), 13-26.
- Hesthammer, J., Landrø, M. & Fossen, H. (2001): Use and abuse of seismic data in reservoir characterisation. *Marine and Petroleum Geology*, 18(5), 635-655.
- Hoch, E., Ohrt, H.B., Brink, D.I., Flikkema, J. & Noman, R. (2010): Pushing the limits for field development. Abu Dhabi International Petroleum Exhibition and Conference SPE-138301-MS.
- Hölker, A. & Birkhäuser, P. (2018): 3D Seismik Datenbearbeitung 2016-2017: Jura Ost, JO-15: Nördlich Lägern, NL-16: Zürich Nordost, ZNO-97 /16-4 Nagra Arbeitsbericht NAB 17-36.

- Jordan, P., Pietsch, J., Kündig, N., Bläsi, H.R. & Deplazes, G. (2016): Grundlagen zur Definition und Unterteilung der Klettgau- und Bänkerjoch-Formation (vormals Oberer und Mittlerer Keuper) in der Nordschweiz. Nagra Arbeitsbericht NAB 16-62.
- Jordan, P., Malz, A., Heuberger, S., Pietsch, J., Kley, J. & Madritsch, H. (2015): Regionale geologische Profile durch die Nordschweiz und 2D-Bilanzierung der Fernschubdeformation im östlichen Faltenjura: Arbeitsbericht zu SGT Etappe 2. Nagra Arbeitsbericht NAB 14-105.
- Laubscher, H. (1986): The eastern Jura - Relations between thin-skinned and basement tectonics, local and regional. *Geologische Rundschau* 75/3, 535-553.
- Li, B., Al-Awadi, M., Perrin, C., Al-Khabbaz, M., Al-Ashwak, S. & Al-Qadeeri, B. (2009): Fracture and Sub-Seismic Fault Characterization for Tight Carbonates in Challenging Oil-Based Mud Environment - Case Study from North Kuwait Jurassic Reservoirs. Middle East Oil and Gas Show and Conference SPE Middle East Oil and Gas Show and Conference, SPE-120424-MS.
- Lorenzen, R., Madsen, L., Huegen, C., Ting, T., Henderson, J.R., Raborn, C. B., Uldall, A., Cromie, H., Zampetti, V. & Emang, M.I. (2014): Applications of Geophysics to the Al Shaheen Field, Qatar, for Reservoir Characterisation and Field Development. IPTC 2014: International Petroleum Technology Conference (Abstract).
- Madritsch, H., Meier, B., Kuhn, P., Roth, P., Zingg, O., Heuberger, S., Naef, H. & Birkhäuser, P. (2013): Regionale strukturgeologische Zeitinterpretation der Nagra 2D-Seismik 2011/12. Nagra Arbeitsbericht NAB 13-10.
- Madritsch, H., Naef, H., Meier, B., Franzke, H.J. & Schreurs, G. (2018): Architecture and Kinematics of the Konstanz-Frick Trough (Northern Switzerland): Implications for the Formation of Post-Variscan Basins in the Foreland of the Alps and Scenarios of their Neogene Reactivation. *Tectonics*, 37(7), 2197-2220.
- Malz, A., Madritsch, H., Meier, B. & Kley, J. (2016): An unusual triangle zone in the external northern Alpine foreland (Switzerland): Structural inheritance, kinematics and implications for the development of the adjacent Jura fold-and-thrust belt. *Tectonophysics*, 670, 127-143.
- McCann, T., Kiersnowski, H., Krainer, K., Vozárová, A., Peryt, T.M., Opluštil, S., Stollhofen H., Schneider, J., Wetzel, A., Boulvain, F., Dusar, M., Török, Á., Haas, J., Tait, J. & Körner, F. (2008): Permian, In McCann T. (Ed.). *The geology of Central Europe*, 1, 531-595.
- Michie, E.A., Alaei, B. & Braathen, A. (2022): Assessing the accuracy of fault interpretation using machine-learning techniques when risking faults for CO2 storage site assessment. *Interpretation*, 10(1), T73-T93.
- Misra, A.A. & Mukherjee, S. (2018): *Atlas of structural geological interpretation from seismic images*. John Wiley & Sons.
- Nagra (1990): Sondierbohrung Riniken Untersuchungsbericht. Textband & Beilagenband. Nagra Technischer Bericht NTB 88-09.
- Nagra (2019): Preliminary horizon and structure mapping of the Nagra 3D seismics JO-15 (Jura Ost) in time domain. Nagra Arbeitsbericht NAB 18-34.

- Nagra (2021): TBO Bözberg-1-1: Data Report. Nagra Arbeitsbericht NAB 21-21.
- Nagra (2021): TBO Bözberg-2-1: Data Report. Nagra Arbeitsbericht NAB 21-22.
- Nagra (2022): Der Standort für das Tiefenlager: Der Vorschlag der Nagra. ASR Bericht.
- Nagra (2024a): Processing 3D Seismic Surveys Jura Ost, Nördlich Lägern and Zürich Nordost. Nagra Arbeitsbericht NAB 23-16.
- Nagra (2024b): 3D Seismic Interpretation of Stratigraphic Horizons and Structures in Time Domain Nördlich Lägern. Nagra Arbeitsbericht NAB 23-18.
- Nagra (2024c): 3D Seismic Interpretation of Stratigraphic Horizons and Structures in Time Domain Zürich Nordost. Nagra Arbeitsbericht NAB 23-19.
- Nagra (2024d): Geosynthesis of Northern Switzerland. Nagra Technical Report. NTB 24-17.
- Naef, H., Birkhäuser, P. & Roth, P. (1995): Interpretation der Reflexionsseismik im Gebiet Nördlich Lägeren - Zürcher Weinland. Nagra Technischer Bericht NTB 94-14.
- Nielsen, T. & Van Weering, T. C. E. (1998): Seismic stratigraphy and sedimentary processes at the Norwegian Sea margin northeast of the Faeroe Islands. *Marine Geology*, 152(1-3), 141-157.
- Roche, V., Camanni, G., Childs, C., Manzocchi, T., Walsh, J., Conneally, J., Saqab, M.M. & Delogkos, E. (2021): Variability in the three-dimensional geometry of segmented normal fault surfaces. *Earth-Science Reviews*, 216, 103523.
- Richard, P., Bazalgette, L. & Al-Kindi, M. (2014): North Oman fault geometries in outcrops, analogues and subsurface. *Geological Society, London, Special Publications*, 392(1), 447-460.
- Sheriff, R.E. (1977): Limitations on resolution of seismic reflections and geologic detail derivable from them. *Seismic stratigraphy - applications to hydrocarbons exploration*. C.E. Payton. *AAPG Memoirs*, 26, 3-14.
- Sheriff, R.E. (1985): Aspects of seismic resolution: Chapter 1. *Seismic stratigraphy II-applications to hydrocarbons exploration*. O.R. Berg & D.G. Woolverton. *AAPG Memoirs*, 39, 1-12.
- Sheriff, R.E. & Geldart, L. P. (1995): *Exploration seismology*. Cambridge University Press.
- Sheriff, R.E. (1997): Seismic resolution a key element. *AAPG Explorer*, 18(10), 44-51.
- Simm, R. & Bacon, M. (2014): *Seismic amplitude: An interpreter's handbook*. Cambridge University Press.
- Tannert, C., Elvers, H.D. & Jandrig, B. (2007): The ethics of uncertainty: In the light of possible dangers, research becomes a moral duty. *EMBO reports*, 8(10), 892-896.

- Vail, P. R., Mitchum Jr, R. M. & Thompson III, S. (1977): Seismic stratigraphy and global changes of sea level: Part 3. Relative changes of sea level from Coastal Onlap: section 2. Application of seismic reflection Configuration to Stratigraphic Interpretation. Seismic stratigraphy - applications to hydrocarbons exploration. C. E. Payton. AAPG Memoirs, 26, 62-82.
- Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. & Rahmanian, V. D. (1990): Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. AAPG Methods in Exploration Series, 7.
- Wibberley, C. A., Yielding, G. & Di Toro, G. (2008): Recent advances in the understanding of fault zone internal structure: a review. Geological Society, London, Special Publications, 299(1), 5-33.
- Zambrano, M., Mazzoli, S. & Mosar, J. (2024). Influence of Inherited Structures on Deformation Patterns in the Eastern Jura Fold and Thrust Belt: Insights from 3D Seismic Data, EGU General Assembly EGU24-13025.
- Zampetti, V., Madsen, L., Cromie, H., Durance, G., Emang, M., Bounoua, N. & Gagigi, T. (2014b): The role of regional basement fabric on Cretaceous structural deformation; a case study from Al Shaheen Field, offshore Qatar. IPTC 2014: International Petroleum Technology Conference, IPTC-17612-MS.