



ARBEITSBERICHT NAB 23-19

3D Seismic Interpretation of Stratigraphic
Horizons and Structures in Time Domain
Zürich Nordost

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, ZNO, Zürich Nordost

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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 has been 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 sub-seismic-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, therefore, is 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 also established and implemented in the interpretation of the seismic surveys covering the three siting regions. Consequently, strong emphasis has been placed on 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 the ZNO siting region includes the interpretation of six key horizon markers:

- (i) 149.2 Kim 100 - Top Malm
- (ii) 149.2 Kim 700 - Top Villigen
- (iii) 170.9 Aal 300 - Top Opalinus
- (iv) 174.7 Toa 100 - Top Lias
- (v) 237 Lad 200 - Intra Bänkerjoch
- (vi) 251.9 Per 100 - Near Base Mesozoic Unconformity

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

The six 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 ZNO siting region can be subdivided into three main structural domains: (i) Neuhausen-Wildensbuch Structural Domain (NWSD) (ii) Niderholz-Marthalen Structural Domain (NMSD), and (iii) the Central Panel (CP, including the Trüllikon Anticline).

The different appearance of the seismic-scale structures observed in the ZNO siting region, compared to Jura Ost (JO) and Nördlich Lägern (NL), is simply the reflection of a very different tectonic configuration. The positioning of the ZNO siting region, with respect to the Permo-Carboniferous Konstanz - Frick Trough, implies a more intense influence of basement faulting on the Mesozoic succession compared to the JO and NL siting regions. Major regional tectonic events are translated into the re-activation and/or generation of high-angle faults, predominantly in a strike-slip motion.

A divergence from a previous interpretation (Nagra 2019) is critically observed for the Central Panel structural domain. Differences arise from the recognised challenge of interpreting seismically subtle faults. Detailed analysis and comparison demonstrated that the NAB 18-36 (Nagra 2019) mapping under-interpreted the seismic-scale deformation in this important area of the ZNO siting region.

A seismically fault-free area cannot be recognised in the ZNO-97/16 merged seismic survey. Nevertheless, a (relative) undisturbed area with an extent of 16.5 km² is considered and coincides with the Central Panel, where subtle faults are widely distributed and interpreted to be vertically and laterally highly segmented.

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List of Acronyms

AGC	Automatic Gain Control
ASR	Auswahl der Standorte für die Vorbereitung der Rahmenbewilligungs- gesuche Site Selection in Preparation for General Licence Application
CP	Central Panel
CRS	Common Reflection Surface
DEM	Digital Elevation Model
GL	Ground Level
JO	Jura Ost
NAB	Nagra Arbeitsbericht (Work Report)
NAGRA	National Cooperative for the Disposal of Radioactive Waste
NL	Nördlich Lägern
NMSD	Niderholz-Marthalen Structural Domain
NWSD	Neuhausen-Wildensbuch Structural Domain
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
SRD	Seismic Reference Datum
TDR	Time-Depth Relationship
TWT	Two-Way Travel Time
VSP	Vertical Seismic Profile measured in a borehole
ZNO	Zürich Nordost
ZNO-97/16	Zürich Nordost merged seismic survey
ZOVSP	Zero-offset vertical seismic profile

1 Introduction

In the course of the site repository 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.

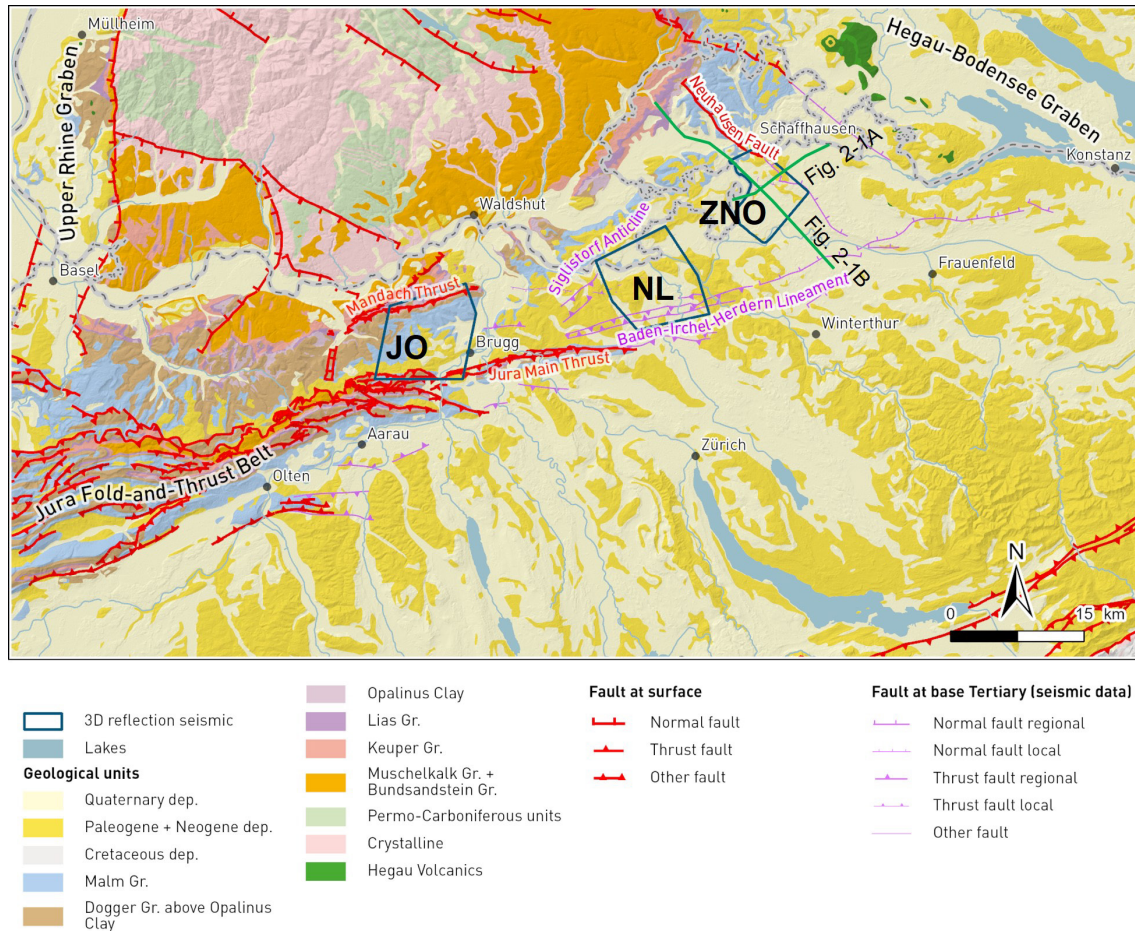


Fig. 1-1: Regional geological map showing the location of the three siting regions: JO, NL and ZNO

Green lines are the 2D 91-NO-77 and 91-NO-68 regional seismic lines 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 ZNO-97/16 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 and, even if the reference seismic data 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), 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 that shows the challenges associated with the data that were recognised and understood and the criteria for stratigraphic and fault interpretation that were clearly defined, explained and rigorously implemented.

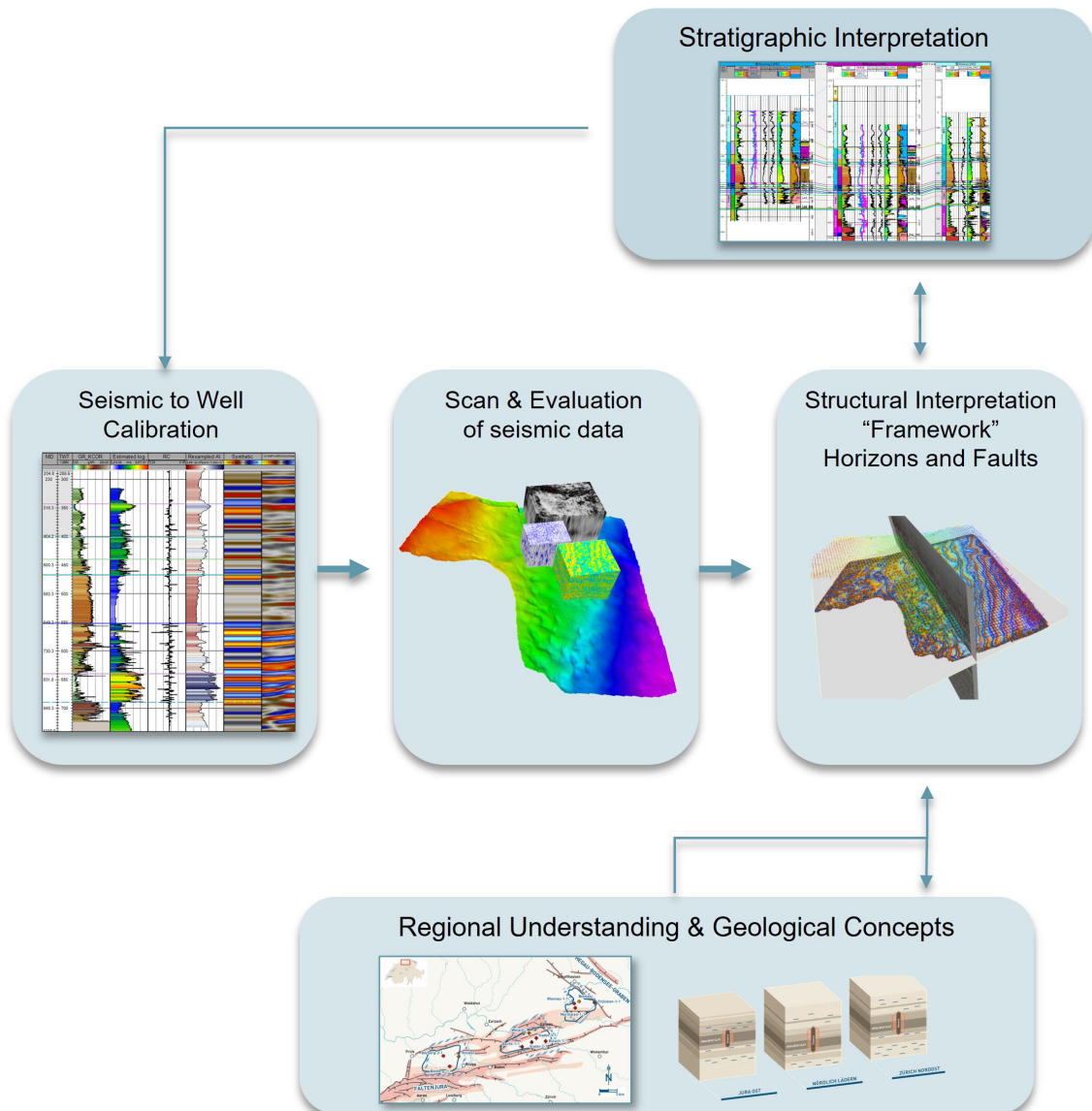


Fig. 1-2: Diagram showing the proposed integrated workflow

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 subsurfaces is the developed methodology and its application. Therefore, the other two seismic interpretation reports for the NL and JO siting regions (Nagra 2024b, 2024c) are similarly structured and partly feature the same content. Strong emphasis has consequently been 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 geological interpretation, the development of geological concepts and the abstraction to subseismic-scale interpretation is part of a multi-scale and multi-disciplinary integration and 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 Zürich Nordost (ZNO) siting region is located in Northern Switzerland, at the northern margin of the Molasse Basin (Fig. 1-1). The Jura Fold-and-Thrust Belt is part of the detached Alpine foreland. The Molasse Basin, located to the south, is a flexural foreland basin which formed as a result of the building-up of the Alps.

The area covered by the ZNO-97/16 merged seismic survey is, from a tectonic point of view, considered to be different from the Jura Ost (JO) and Nördlich Lägern (NL) siting regions, since it is mostly interpreted as an autochthonous area with respect to the Alpine orogeny (NTB 14-02, Birkhäuser et al. 2001). The area is delimited to the northeast by the NW-striking Neuhausen Fault, which forms the western margin of the Tertiary Bonndorf - Hegau- Bodensee Graben zone (Egli et al. 2017). This represents a major fault affecting the entire geological sequence from the Hercynian basement to the Quaternary deposits (Egli et al. 2017) (Fig. 2-1). Towards the south, the Rafz - Marthalen Flexure represents the Mesozoic expression of the northern rim of the Konstanz - Frick Trough or southern border of the Benken Horst (NTB 24-10, NTB 14-02, Birkhäuser et al. 2001). Those inherited ENE-striking basement features (fault step with basement topography) associated with the Konstanz - Frick Trough (Madritsch et al. 2018) were interpreted as key structures concentrating the deformation and influencing the structural style of the overlying Jura Fold-and-Thrust Belt (Caer et al. 2018).

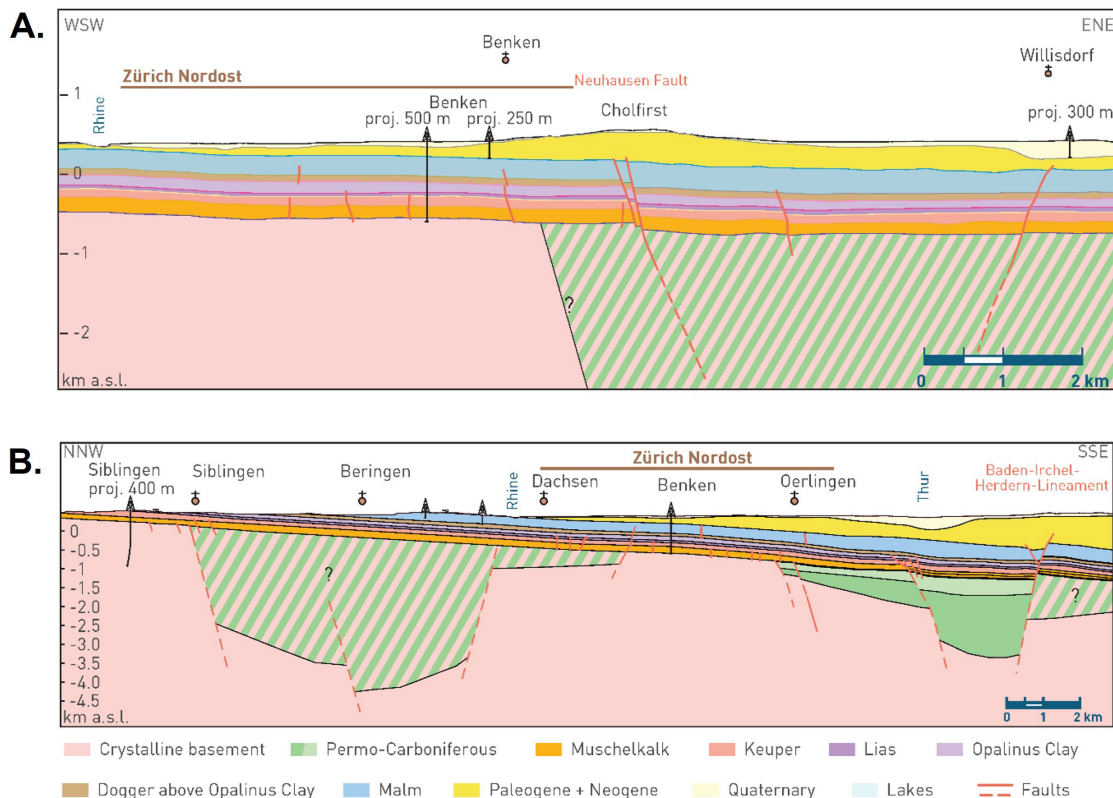


Fig. 2-1: Large-scale geological cross-sections through Zürich Nordost siting region

A. WSW-ENE geological section drawn along the 2D seismic reflection line 91-NO-77 and B. WSW-ENE geological section drawn along the 2D seismic reflection line 91-NO-68. The sections are based on Meier et al. (2014) and Jordan et al. (2015). Results from 3D seismic reflection interpretation were integrated within the seismic perimeter. Gr.: Group, Dep.: deposits (Nagra 2024d). Line locations shown in Fig. 1-1.

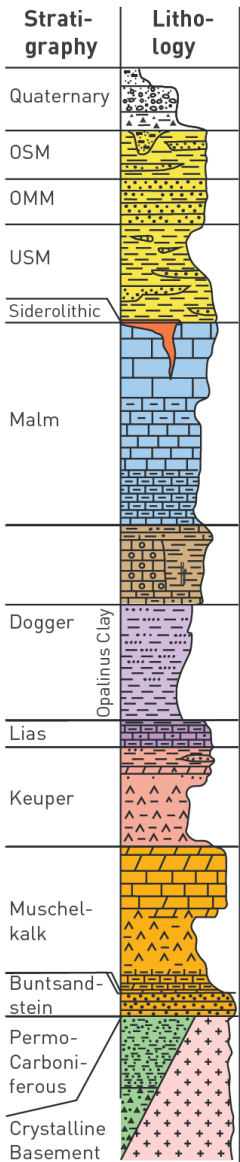


Fig. 2-2: Simplified lithological column of Northern Switzerland
Detailed description of the litho- and stratigraphic units captured in NTB 24-10 (Nagra 2024d).

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) (Fig. 2-2). The large-scale Pre-Mesozoic structure in the area of interest is the 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), although the limited well penetrations do not provide a good calibration and estimation of the variability in facies and thickness of the sedimentary fill.

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 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 extreme 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).

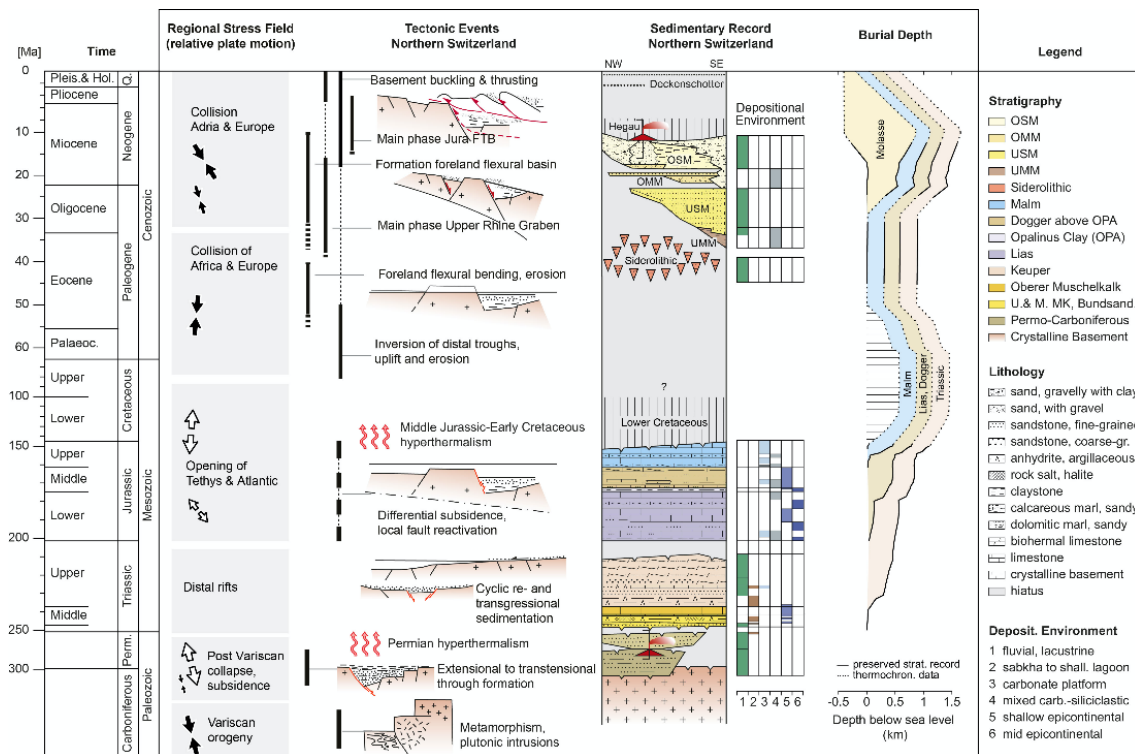


Fig. 2-3: Timeline summarising the geological evolution of Northern Switzerland (Nagra 2024d)

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, four wells, three of which were drilled during Nagra's deep borehole campaign (Marthalen-1, Trüllikon-1 and Rheinau-1; Nagra 2020, 2021, 2023), and a pre-existing well (Benken), were selected, together with comparable wireline log data and vertical seismic profile (VSP) surveys with quality available for Marthalen-1, Trüllikon-1 and Benken. Note that for consistency with the seismic interpretation workflow terminology, the term well is preferred to the term borehole.

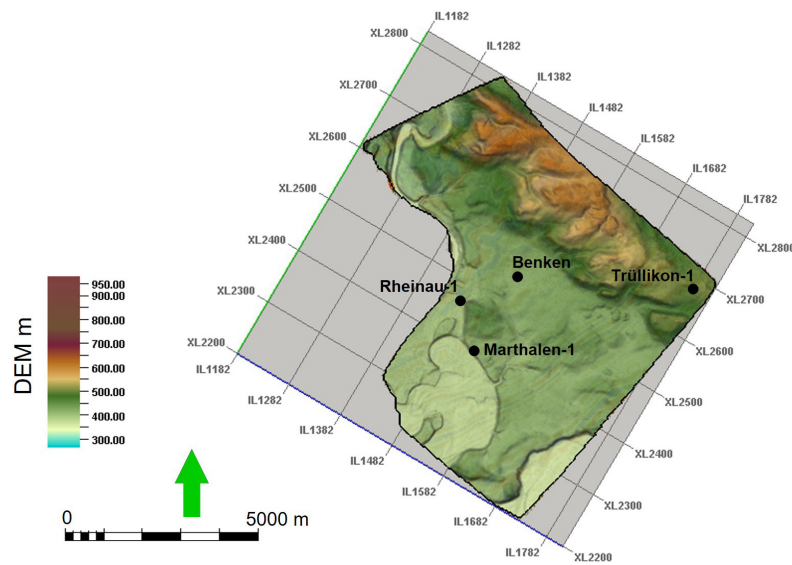


Fig. 3-1: Seismic data and well locations on the Digital Elevation Model (DEM)

Four wells are available within the perimeter covered by the ZNO-97/16 merged 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 600 m, a replacement velocity of 3,500 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 is a merged dataset from two different phases of acquisition, one legacy dataset acquired in 1997, and a second (overlapping) smaller survey acquired in 2016. While the 1997 dataset covers an area of 48.3 km², the 2016 survey perimeter covers an area 18.3 km², resulting in a total areal coverage of the merged dataset of 53 km² with an estimated overlap of 60% between the two seismic datasets. The ZNO-97/16 merged seismic survey contains 634 ~ NE--SW-trending inlines and 628 ~ NW-SE-trending crosslines with a line spacing of 15 m (Fig. 3-2).

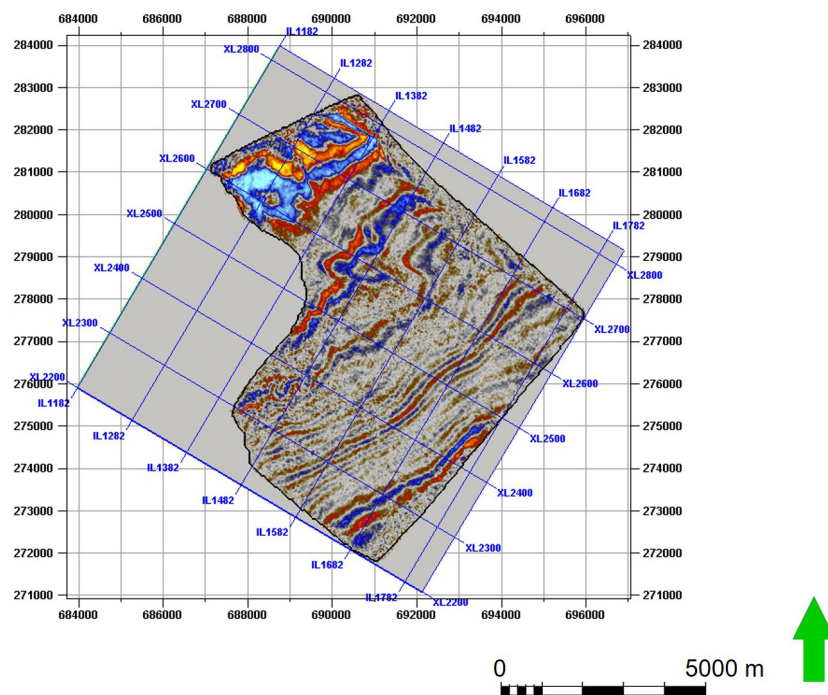


Fig. 3-2: ZNO-97/16 merged seismic survey (with grid coordinates)

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 considered in the interpretation (Tab. 3-1, Fig. 3-3, Fig. 3-4, Nagra 2019, 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 traveltimes 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

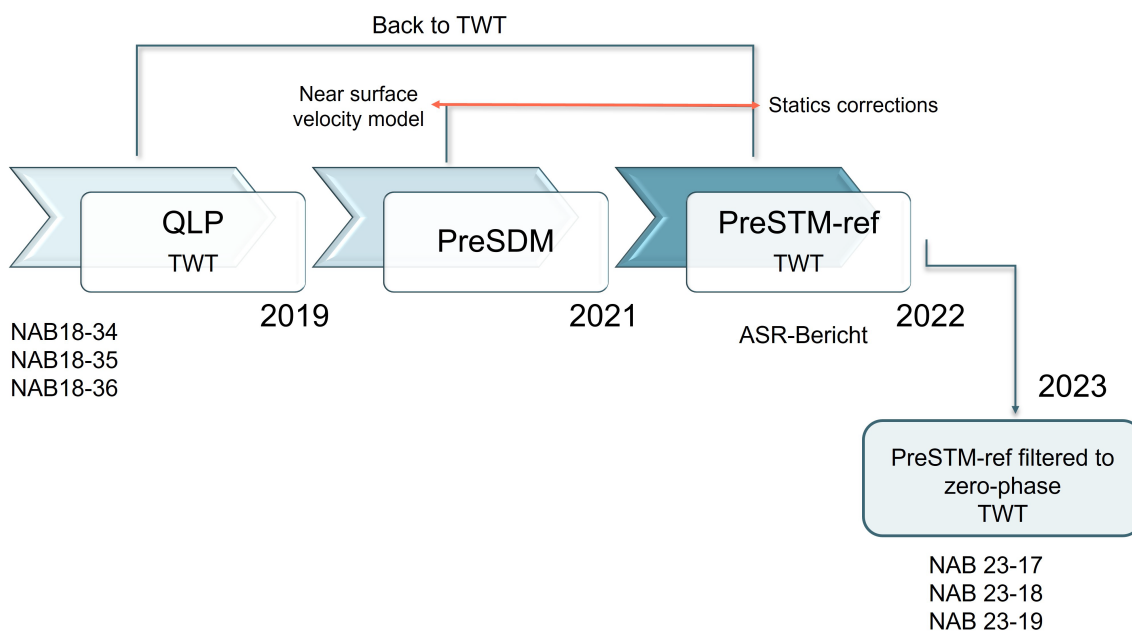


Fig. 3-3: Seismic processing simplified roadmap

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.

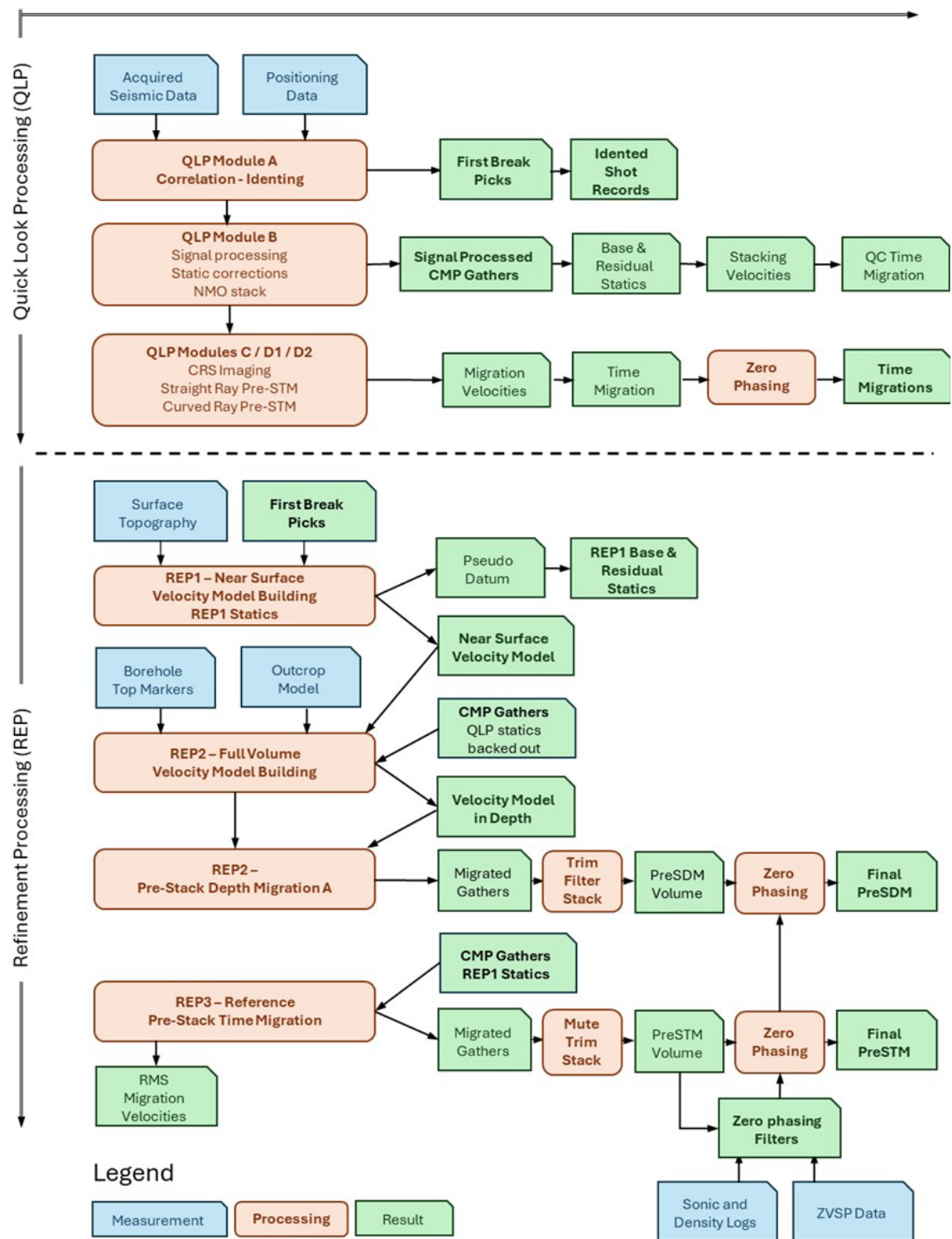


Fig. 3-4: Processing flowchart summarising the processing steps applied in 2017 and 2020/21 (Nagra 2024a)

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 a multitude of 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-phasing of the 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 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 (referred to here simply as PreSDM); 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 3,500 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. For the refinement processing, therefore, 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) 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).

3.1.3 Pre-Stack Time Migration PreSTM-ref (Minimum-Phase)

Anomalies (notably in the overburden and the 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 not coincide with geological features (Fig. 3-5), impairing confidence in depth-migrated cube seismic imaging. Several attempts demonstrated that the realisation of a reliable (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 intensity 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 seismic 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.

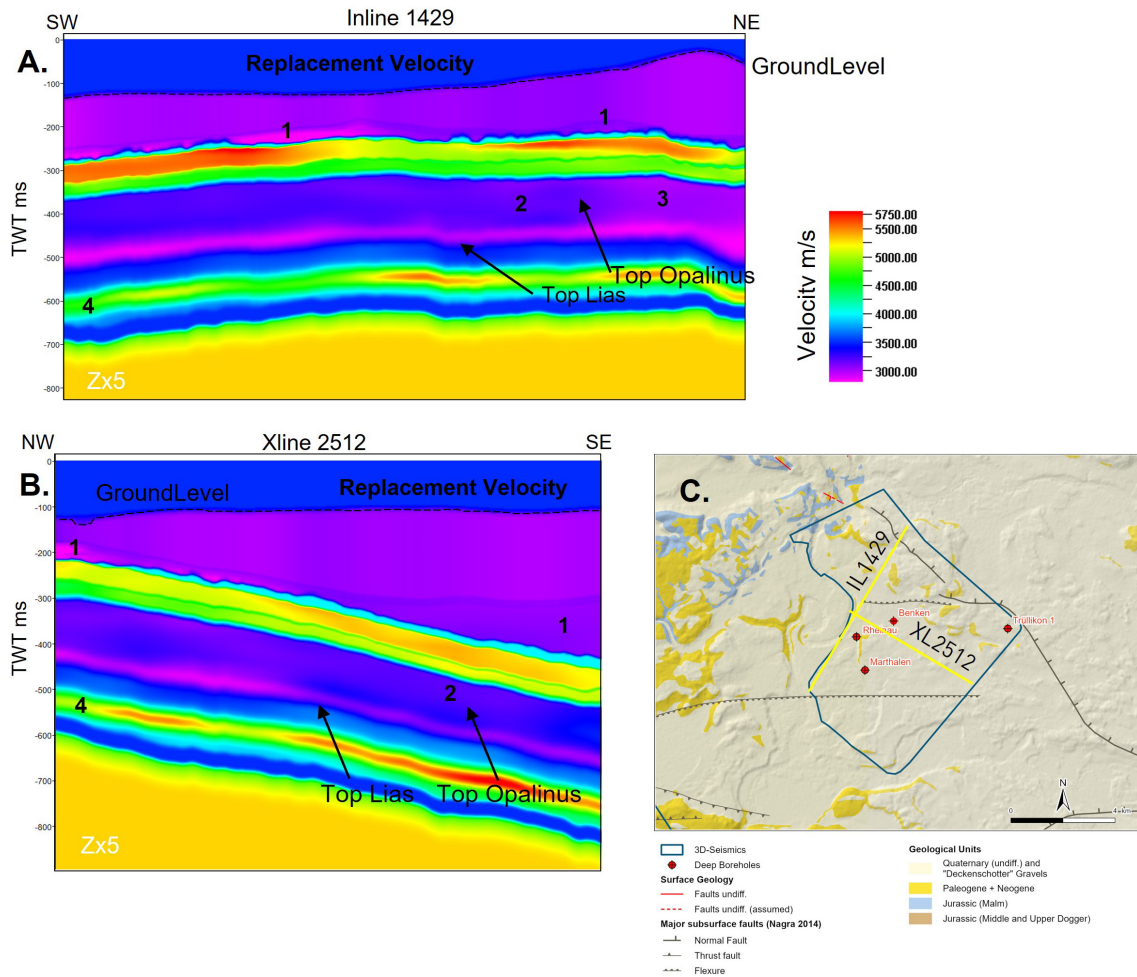


Fig. 3-5: PreSDM velocity model

A. Inline 1429 and B. Crossline 2512 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 or to a consistent depth trend. There is also no clear velocity break for the Opalinus Clay (2), but a transition to lower velocity (3) towards the NE. A clear low-velocity non-uniform layer is present just above the base of the Opalinus Clay interval (Top Lias), which has not been observed in well data. (C.) Line locations displayed over surface geology map.

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.

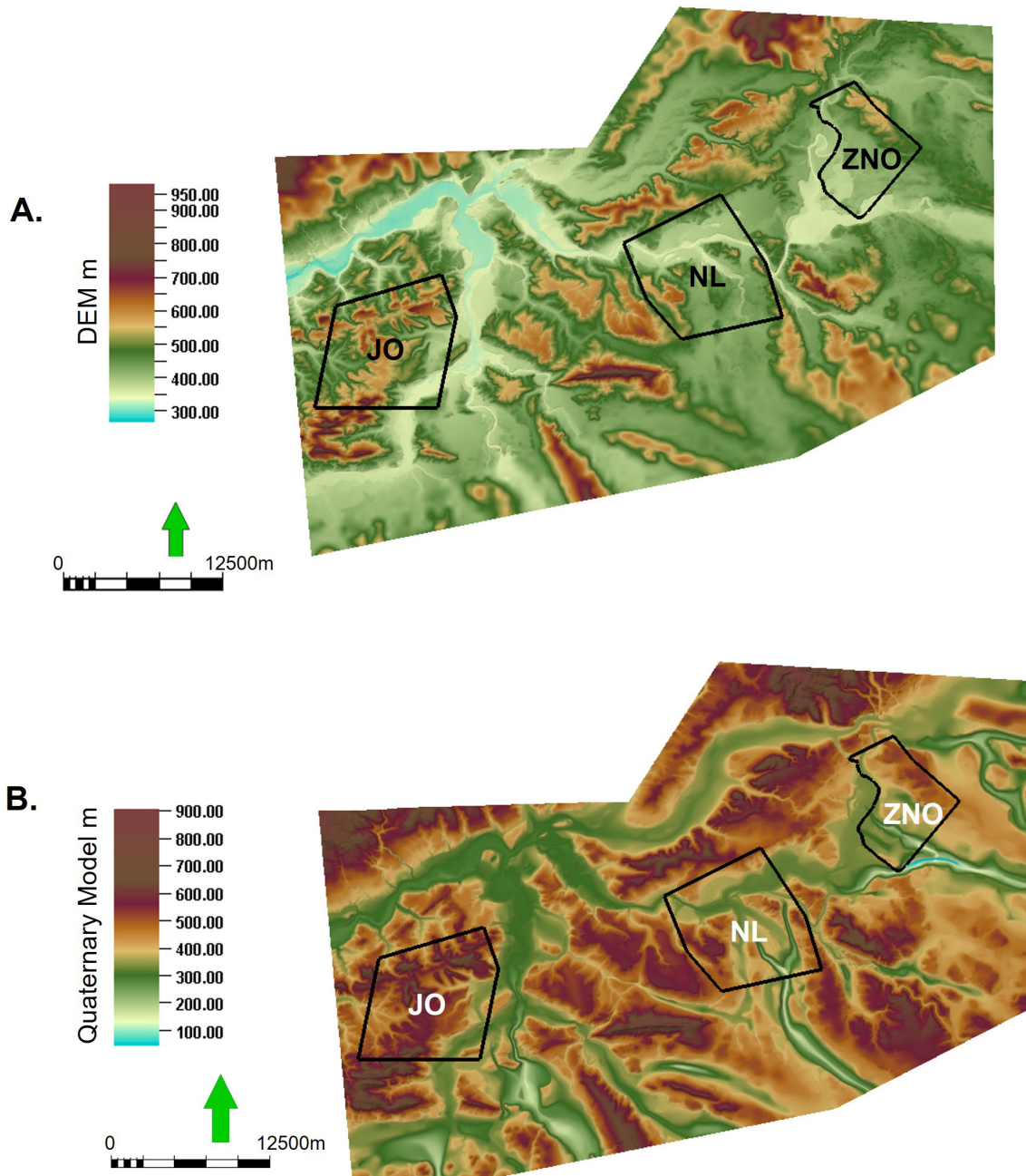


Fig. 3-6: Morphological complexity of the shallow geology has a direct impact on the seismic imaging

A. Surface topography (digital elevation model) and B. 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 similar 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 was thus determined adequate for horizon and fault interpretation across undisturbed and structurally complex areas.

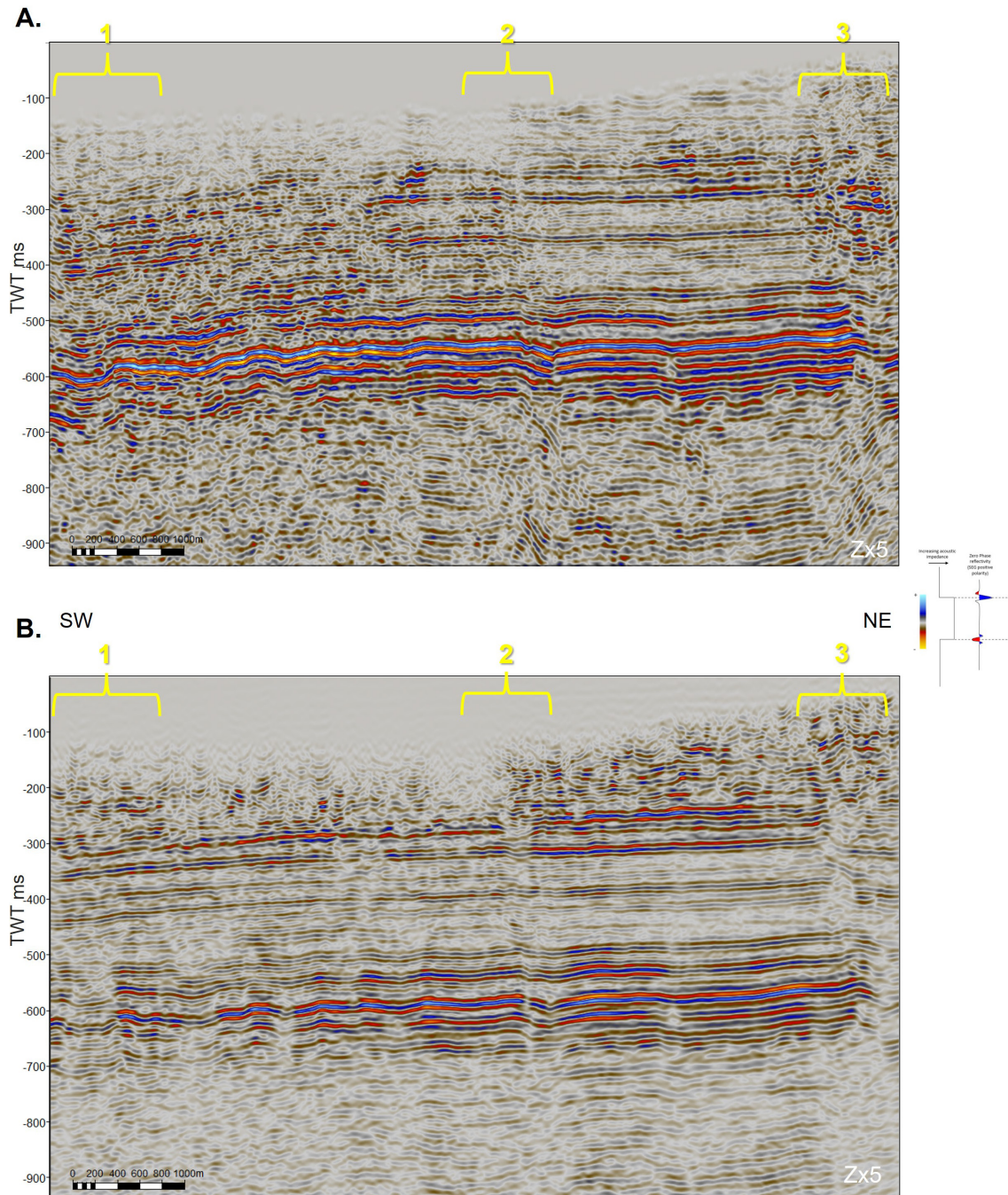


Fig. 3-7: Seismic section showing processing vintage comparison

Inline 1445 from A. QLP and B. PreSTM-ref. Note the improved seismic imaging in the PreSTM-ref data over the three structurally complex zones (1, 2 and 3).

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-phasing filter. The phase filtering exercise used the following workflow:

- Density and sonic log editing followed by synthetics versus VSP 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, which is not an uncommon practice, the use of different processing vintages helps to understand how the seismic signatures that are diagnostic for geological features are 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 seismic 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) requires 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 14 m for the Opalinus Clay interval and 22 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	55	2900 m/s	13 m	5.2 m
		70		10 m	4 m
237 Lad 200	Intra Bänkerjoch	50	3500 m/s	17.5 m	7 m
		60		14 m	4.9 m
Below 237 Lad 500	Within Muschelkalk Fm	50	4900 m/s	24.5 m	9.8 m
		100		12 m	4.9 m

3.2 Well Dataset

The available wireline logs include typical log suites (e.g. gamma ray, density, porosity, sonic and caliper from the three vertical wells Benken, Marthalen -1 and Trüllikon -1 (Nagra 2021, 2020) and one deviated well Rheinau-1 (Nagra 2023), and were complemented by edited and quality-controlled density and sonic logs using zero-offset VSP (ZOVSP) results for the Benken, Marthalen -1 and Trüllikon -1 wells.

Within the ZNO siting region, ZOVSP data were acquired for three wells (Benken, Marthalen -1 and Trüllikon-1). 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 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 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 seismic data followed an integrated multi-step approach (Fig. 1-2): (i) data screening and 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 lithology and fluid content.

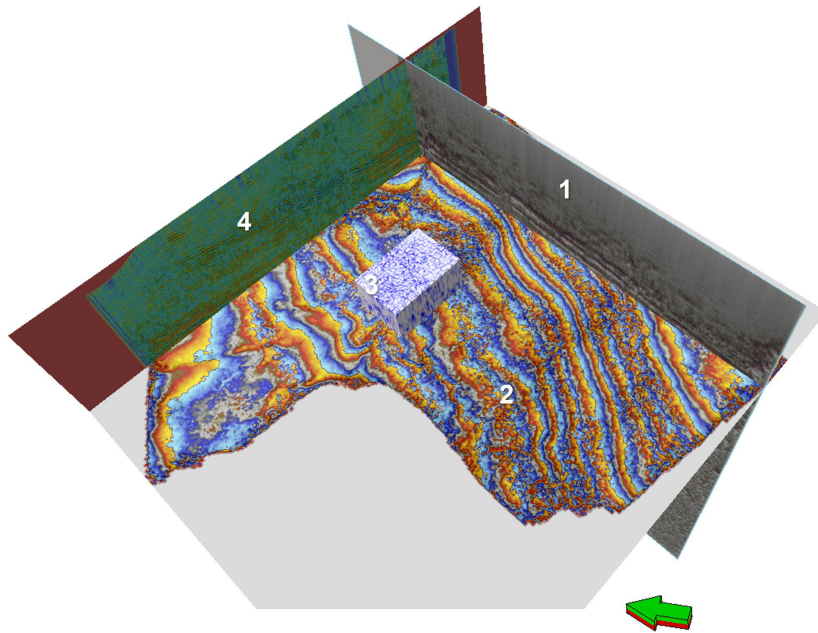
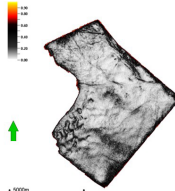
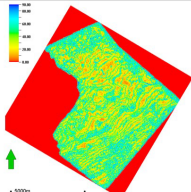
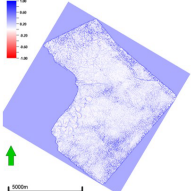
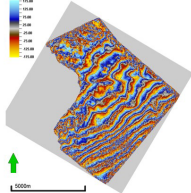
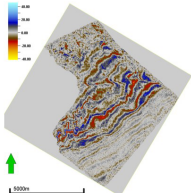
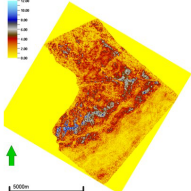
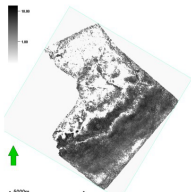


Fig. 4-1: Example of 3D visualisation and screening of attributes

Several attributes are combined or 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 four wells Marthalen-1, Trüllikon-1, Benken and Rheinau-1 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 has therefore been 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). Stratigraphic tops are coded using: << absolute age_stage name_ sequential number >>, with the sequential number increasing from top to bottom (usually from 100 to 999).

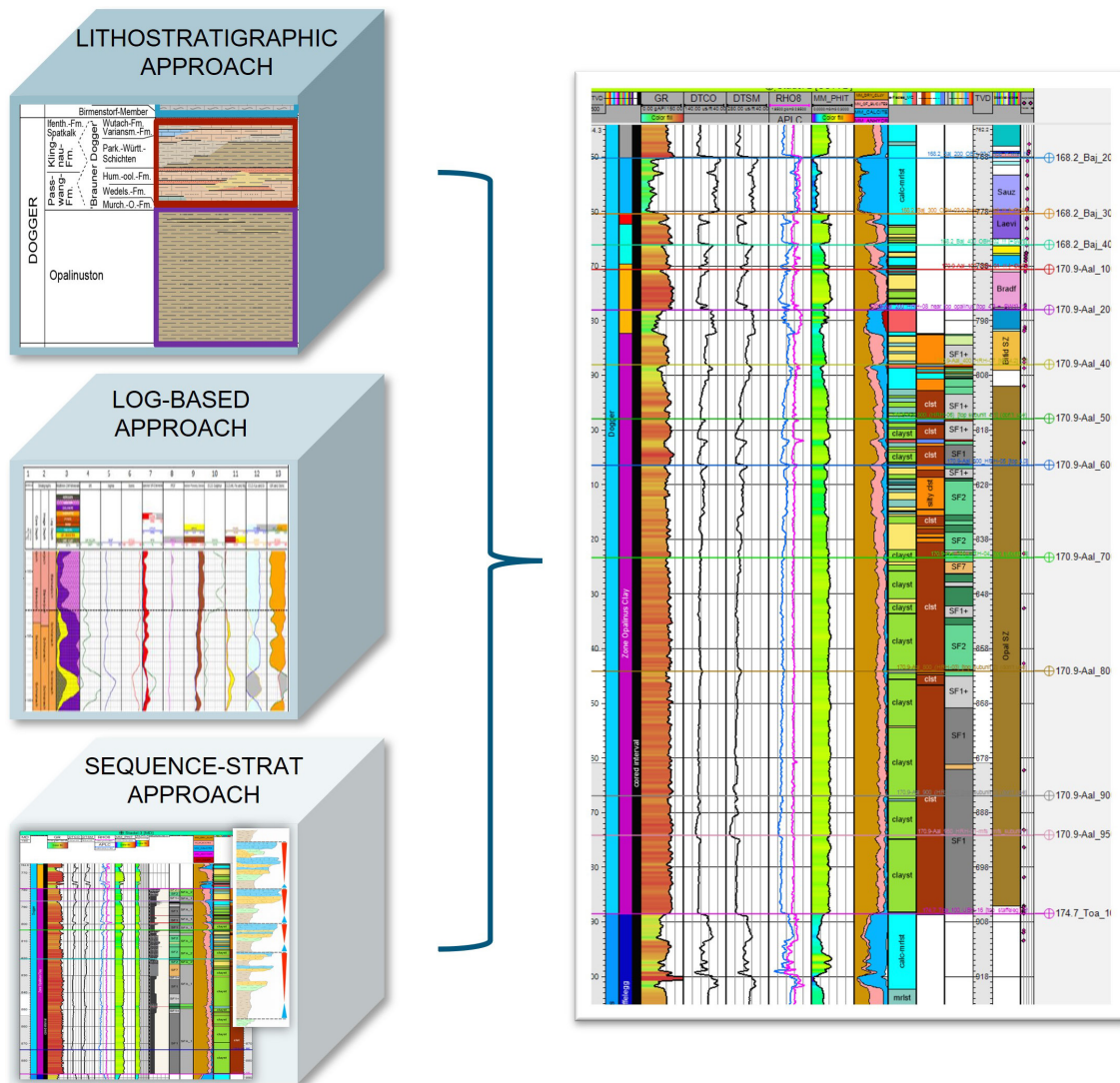


Fig. 4-2: Approach applied to generate the proposed sequence stratigraphy framework

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 log-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 increasing from top to bottom (usually from 100 to 999).

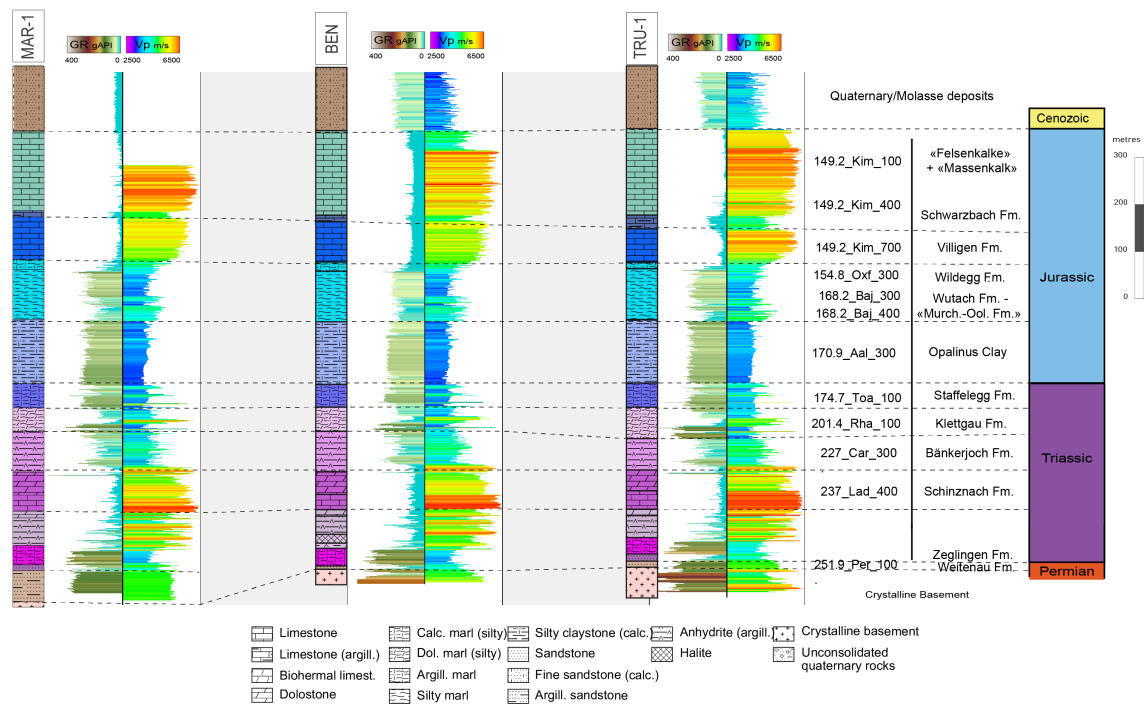


Fig. 4-3: Proposed sequence stratigraphic scheme referenced to lithological formation and petrophysical signature

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

Once the stratigraphic framework was 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 replacement velocity.
- A wavelet was extracted from the seismic data at the 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.

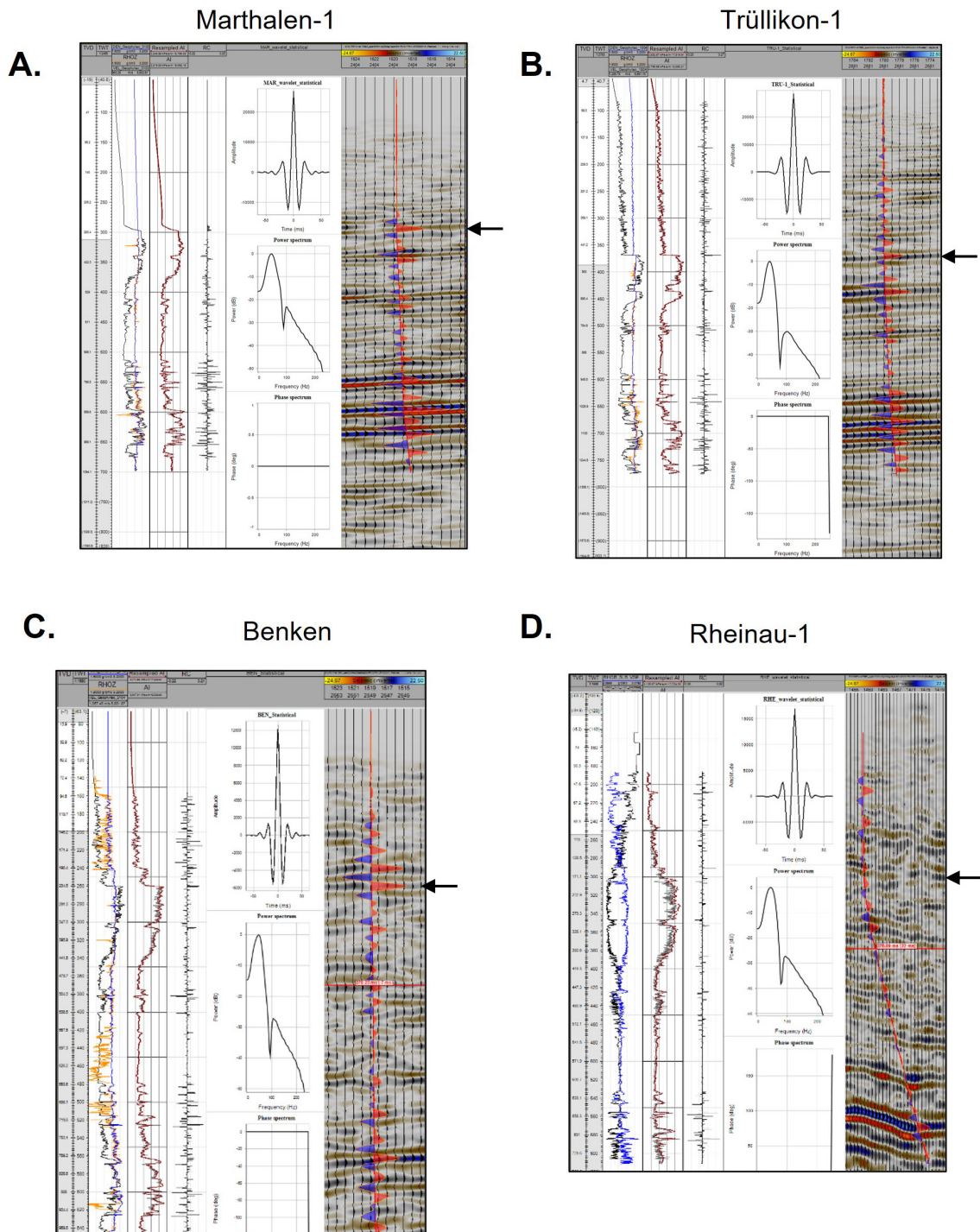


Fig. 4-4: Synthetic panels for the four wells Marthalen-1, Trüllikon-1, Benken and Rheinau-1

A. Marthalen-1, B. Trüllikon-1, C. Benken and D. Rheinau-1

Note, in the first column the comparison is shown between normalised velocity and density logs and edited logs after VSP QC (orange and blue, respectively) for three of the four wells. The colour code in the synthetic logs is flipped for display reasons. Black arrow shows the position of the key Top Malm reflection.

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, particularly at the Top Malm (149.2 Kim 100) reflector (i.e. at anchor level since this is the shallowest major acoustic boundary), 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. 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-phasing filter, the data do 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 some 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.

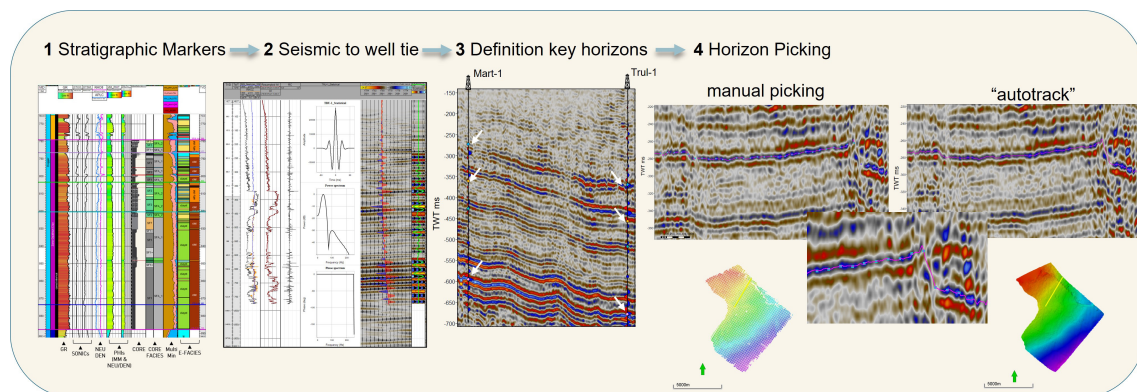


Fig. 4-5: Horizon interpretation workflow

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 8×8 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. The 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 values (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 subsequently areas with moderate noise are infilled and finally interpolated/manually pushed across patches of poor data. 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 Marthalen-1 and Trüllikon-1 wells and with a random line connecting these two wells (Fig. 4-6 A, B) and then closed the “square” at the Benken and Rheinau-1 wells (Fig. 4-6 D). The latter wells were used as a blind QC for horizon interpretation. The seedlines were manually picked using both Petrel manual and 2D autotrack options.

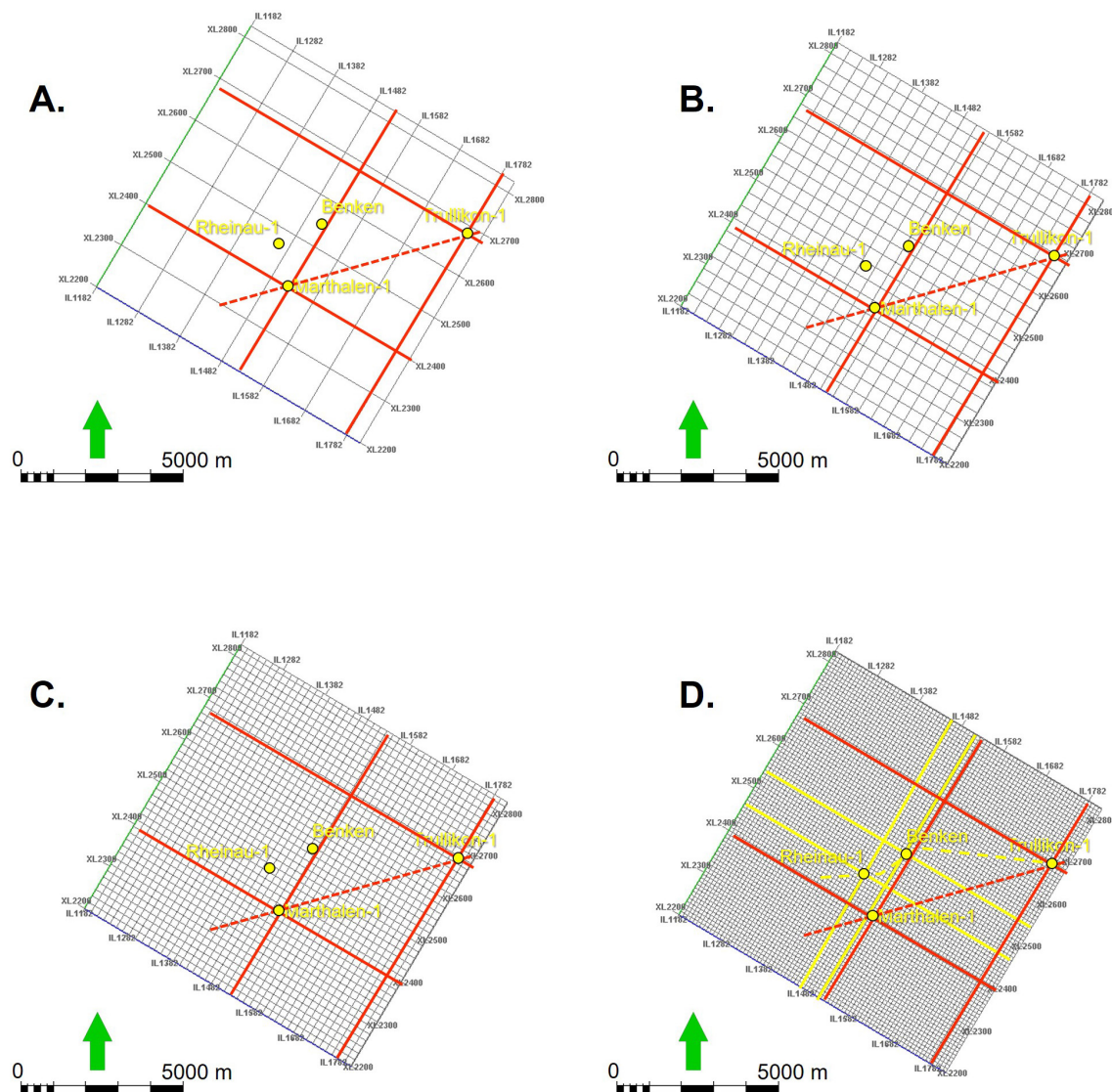


Fig. 4-6: Interpretation seedline methodology and grid building

A. Horizon interpretation is calibrated at inlines and crosslines (red lines) and a random line (dashed red line) crossing the Marthalen-1 and Trüllikon-1 wells; B. interpretation is then performed with the initial grid of 32 x 32 lines; C. decreasing to 16 x 16 lines and finally to 8 x 8 lines (D.) and finally checked along the in-, cross- and random lines crossing the Benken and Rheinau-1 wells (yellow solid and dashed lines in D.).

The interpretation gaps between the 8 x 8 line-grid were filled using the Petrel autotrack algorithm. Autotracking used the 8 x 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 x 3 expansion coefficient (i.e. cross-correlation among adjacent lines), and an amplitude confidence (i.e. percentage representing the amount of amplitude value variation between seed-lines 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).

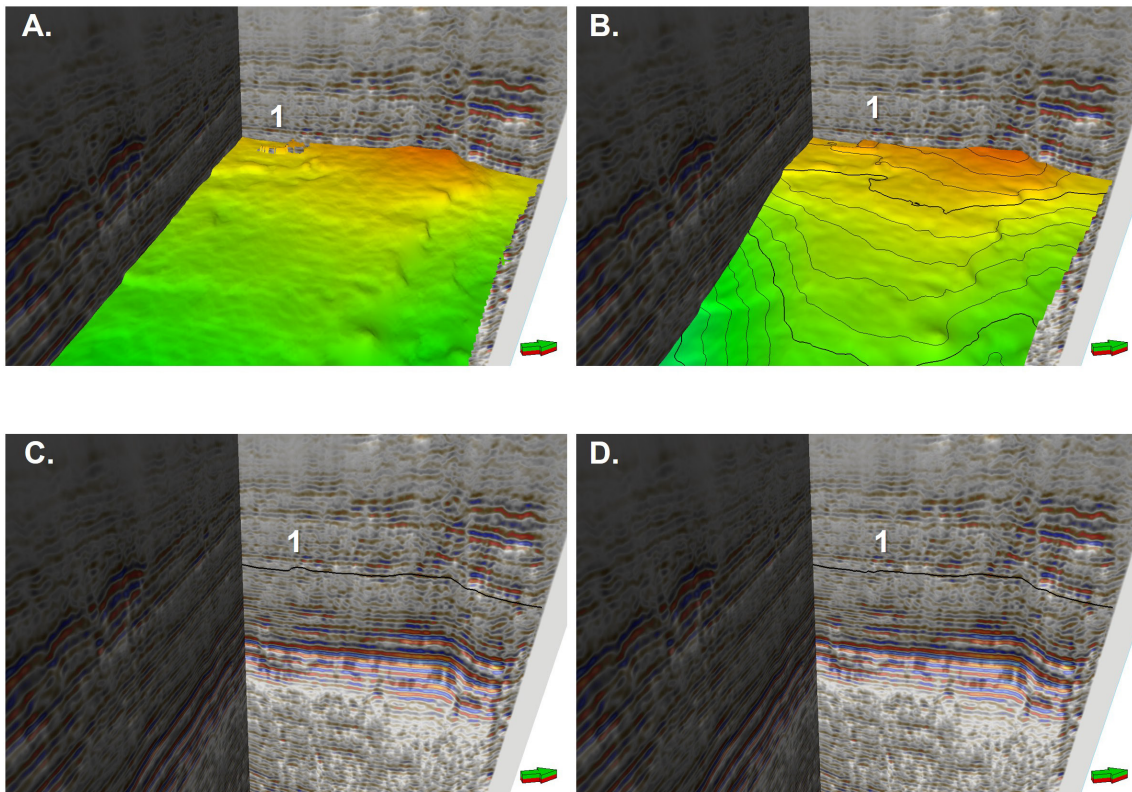


Fig. 4-7: Quality control of autotracked horizon in 3D viewer

A. 3D autotrack horizon screening and identification of problematic areas using the horizon as well inlines and crosslines (1); B. Screening of gridded surfaces (complex/erroneous contour lines) (1); C. Horizon display in restricted mode to QC 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; 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.

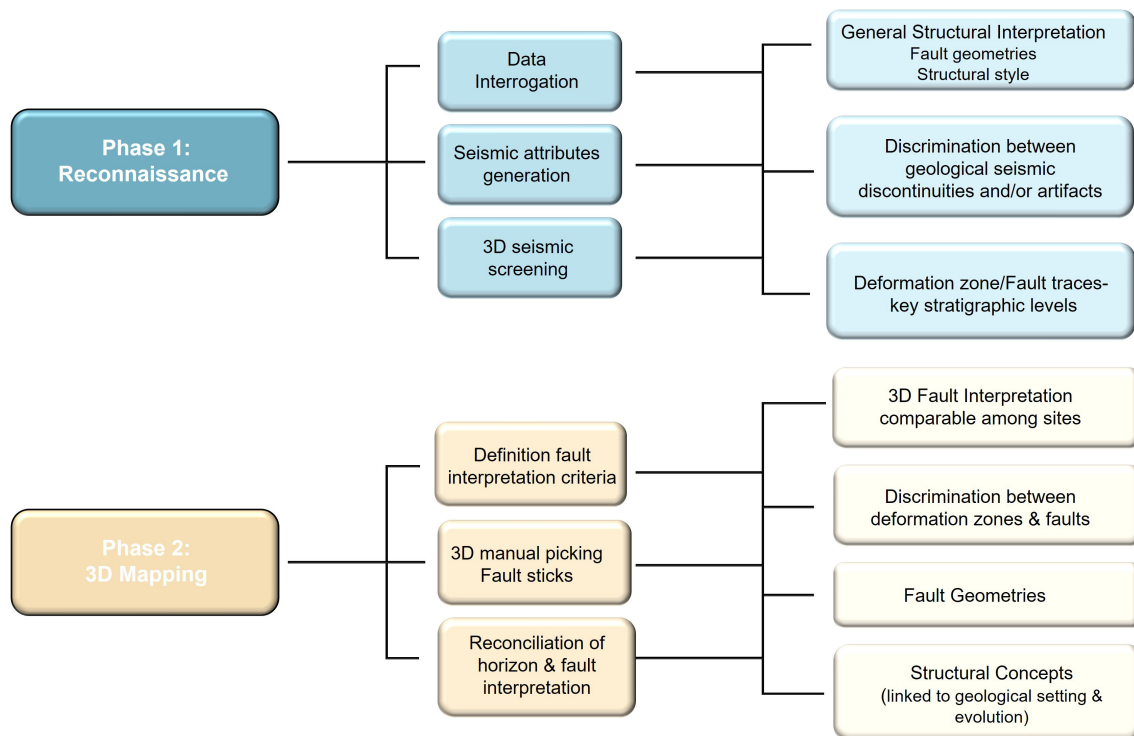


Fig. 4-8: Fault interpretation carried out using a two-phase approach

In Phase 1 (reconnaissance), the seismic data were screened and interrogated. An initial discrimination was carried out between structural lineaments (deformation zones = faults and folds, Nagra 2022), 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 class into faults and folds.

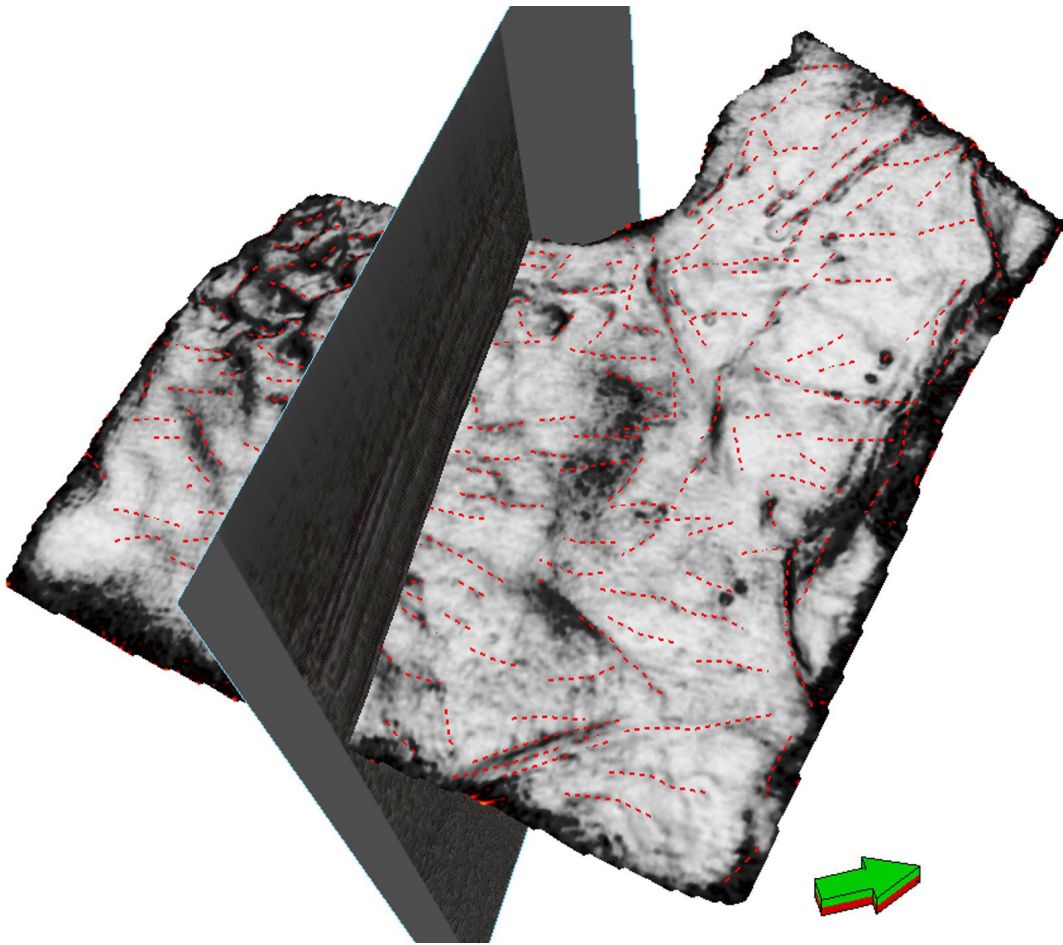


Fig. 4-9: 3D display for Phase 1 fault interpretation workflow

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 attribute analysis and QC using 3D screening with vertical amplitude sections. Seismic display is PreSTM-ref. Green arrow points towards north.

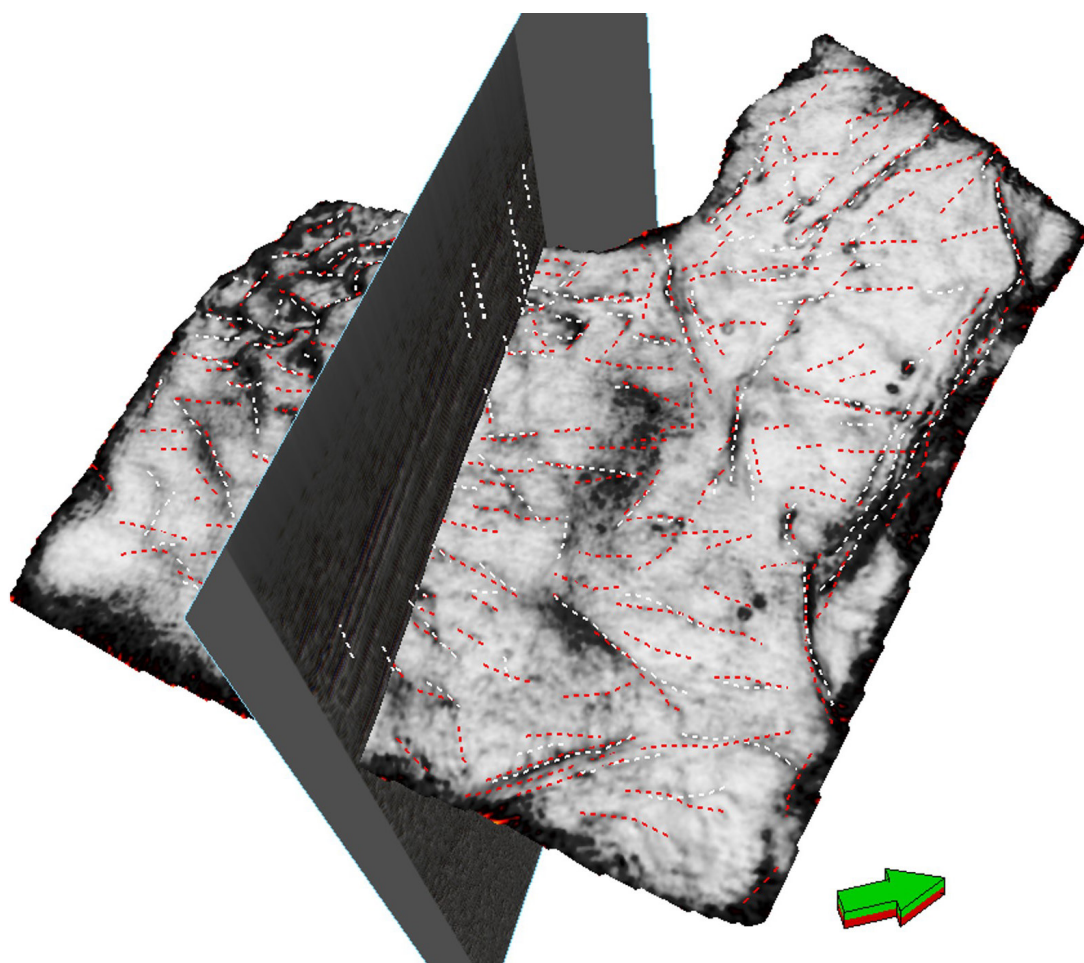


Fig. 4-10: 3D display for Phase 2 fault interpretation workflow

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 2 (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 “overlaying” 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.

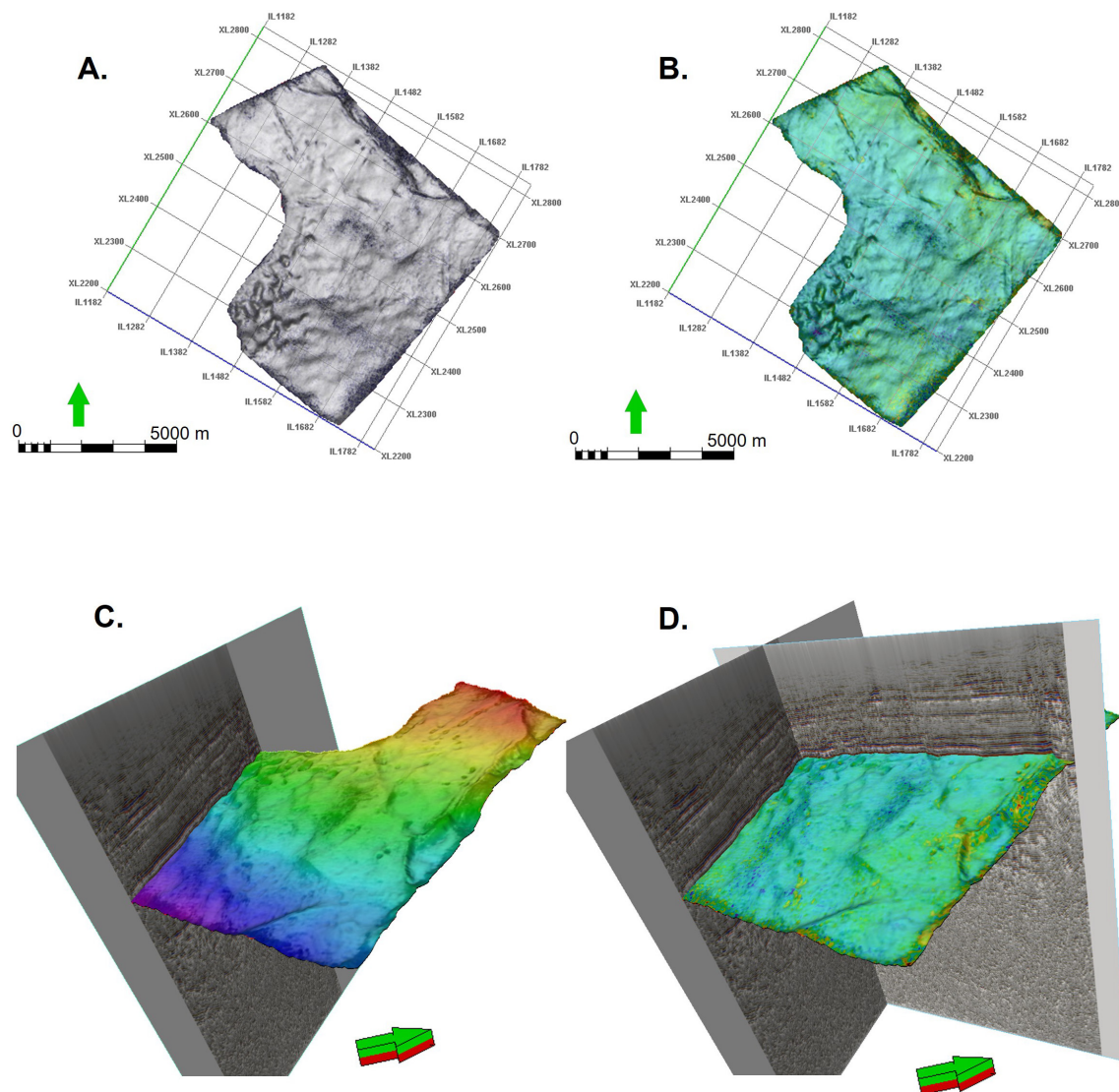


Fig. 4-11: Displays showing the multi-attribute fault identification and interpretation workflow approach in 2D and 3D

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.

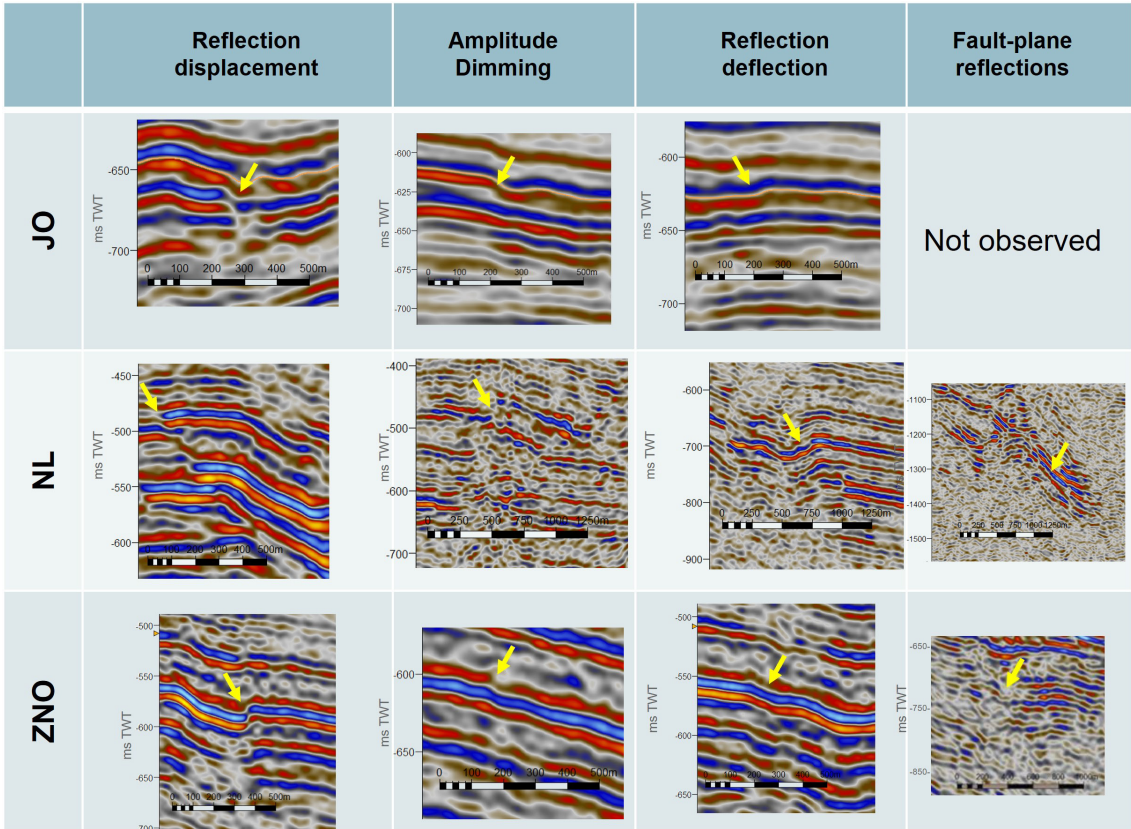


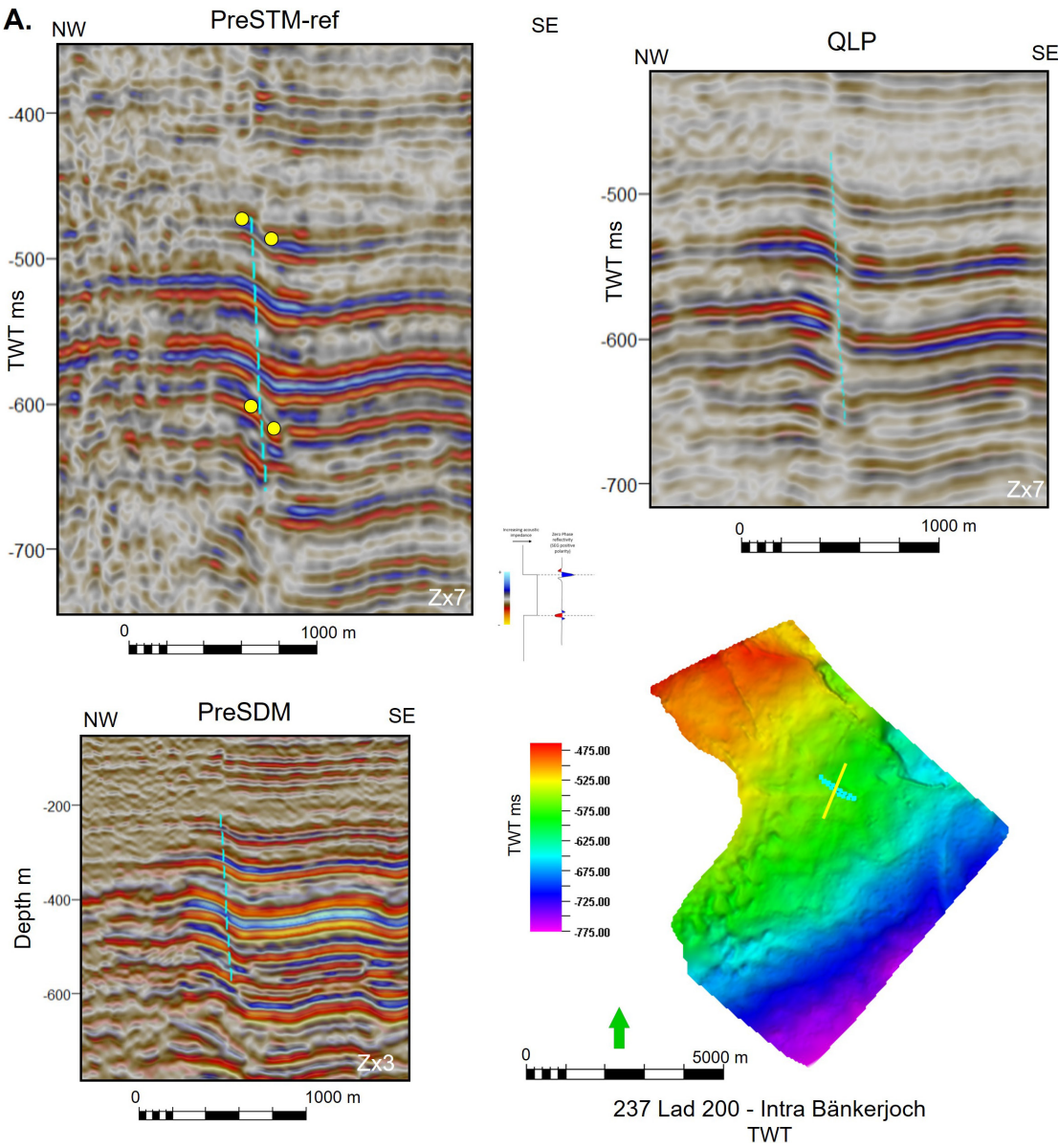
Fig. 4-12: Examples of the most common fault signatures in seismic sections for the three siting regions

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 the 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 Top Malm (149.2 Kim 100) and Near Base Mesozoic (251.9 Perm 100) stratigraphic intervals. 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 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).



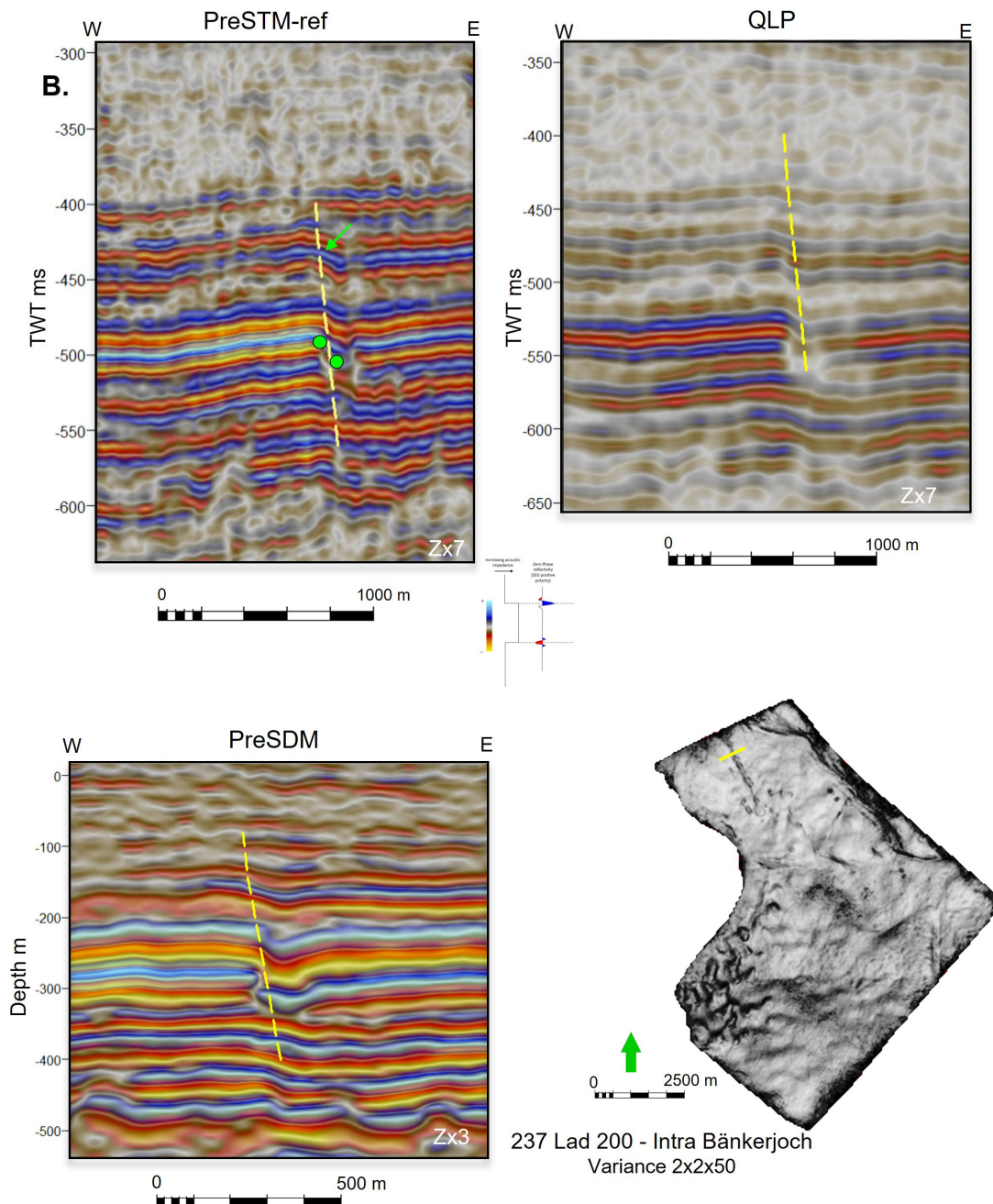


Fig. 4-13: Fault interpretation by comparing fault signatures in available seismic vintages

The recognised fault signatures were compared in all the available seismic vintages, 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. A. Example from NE-SW random line. In this example, the seismic fault is recognised based on reflection offset (green dots) and reflection deflection. B. Example from E-W random line, where the seismic fault is interpreted based on reflection offset (green dots – green arrow) associated with a linear edge in the variance extraction. Yellow line on map views represents the location of the seismic inline.

Fault stick picking was manually performed predominantly along inlines and crosslines (8×8 line-grid) since the acquisition orientation in the ZNO-97/16 merged seismic survey is almost orthogonal to the main structural grains. For lineaments where the angles are below 60 degrees between the 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 geometric understanding of the structure, guides segment interpretation and highlights segment shape and position inconsistencies (Fig. 4-14).

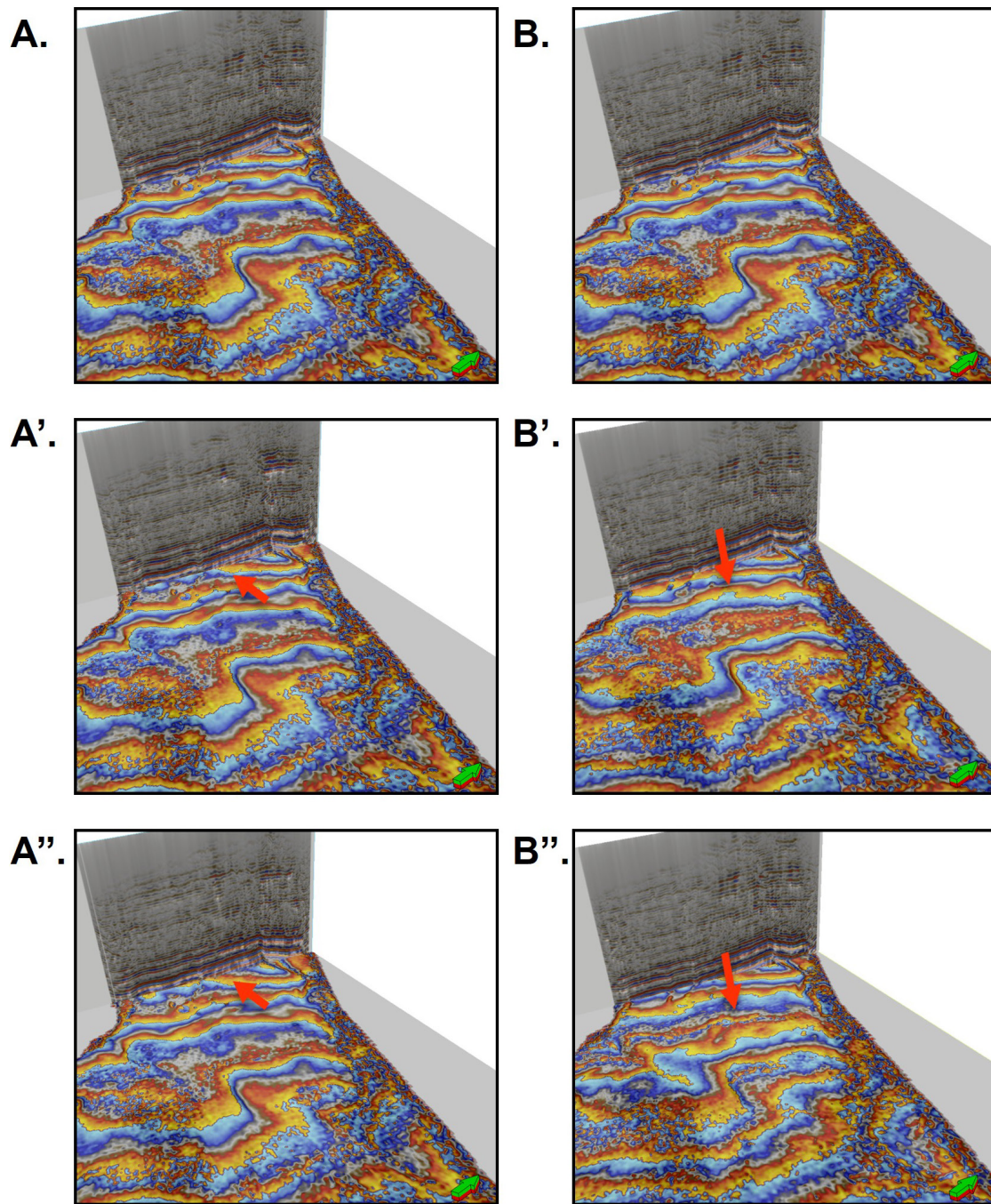


Fig. 4-14: Sets of 3D displays showing the 3D QC performed for fault interpretation

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 picking. A. Inline 1344; A'. Inline 1334; A''. Inline 1324; B. Time slice 532 ms TWT; B'. Time slice 522 ms TWT and B''. Time slice 512 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 the 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) have not been interpreted.

2. Vertical interpretation:

2.1 Vertical extent for fault sticks: Top Malm 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 (e.g. Opalinus Clay) interval despite the implemented vertical simplification approach. The Opalinus Clay interval is characterised by the presence of 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 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 region comparison purposes, fault segmentation has been simplified. Such simplification comes with some limitations in the interpretation products.

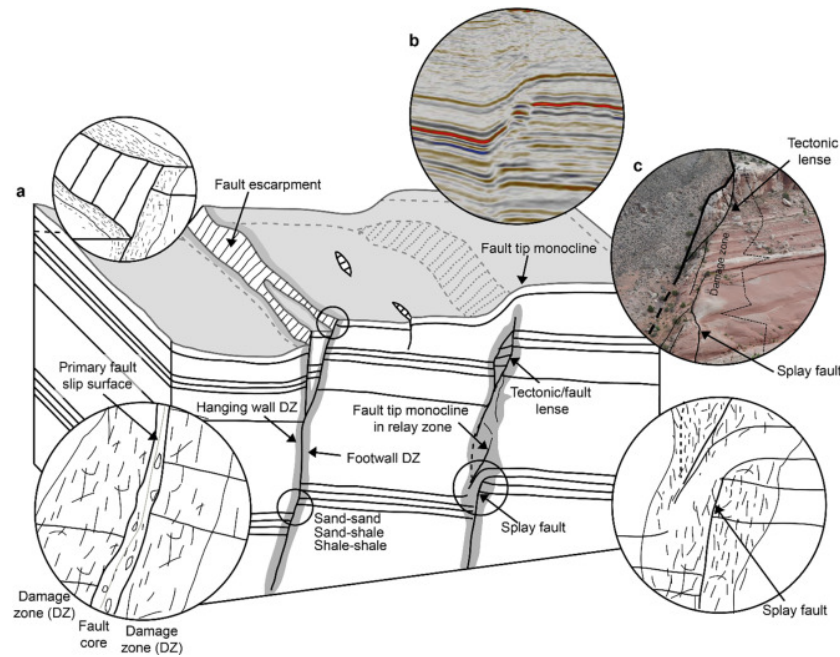


Fig. 4-15: Schematic 3D fault block model showing the complex architecture of a fault zone comparing the scale of detail between b. (fault in seismic) and c. (fault in outcrop)

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 seismics in the 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 has been 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).

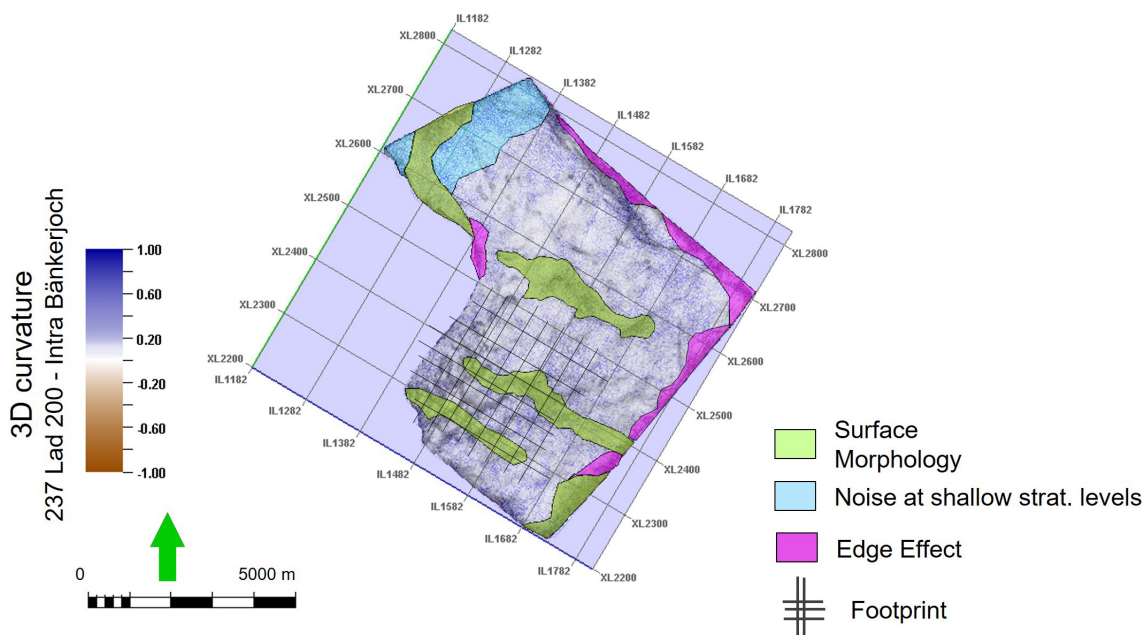


Fig. 5-1: Areas impacted by seismic signal disturbance (artefacts) were recognised and mapped

The observed seismic artefacts are mainly driven by seismic processing and the complex surface geology (surface rivers and morphology, Quaternary valley). Processing artefacts are only associated with localised edge effects, particularly in structurally complex zones. Acquisition footprints are clearly visible at shallow levels, but they can also be recognised at the deeper stratigraphic levels in specific areas. These acquisition footprints represent the key challenge in the fault interpretation, since one (NE-SW) of the regional fault systems has similar orientation to the acquisition direction.

Areas where interpretation can be impaired due to lack of signal and/or noise masking geological features are predominantly associated with three factors, 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 to 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. 5-2 A., Hesthammer et al. 2001). These dipping features may, in part, be a result of imperfect migration of the seismic data. Within the ZNO-97/16 merged seismic survey, such vertically dimming stripes coincide with the presence of articulated Quaternary morphology (Fig. 5-2 B.) and could represent dipping noise. While these dipping noise features were captured as an artefact polygon (confined within specific shallow stratigraphic intervals), awareness of the presence of such discontinuities is critical when interpreting faults.

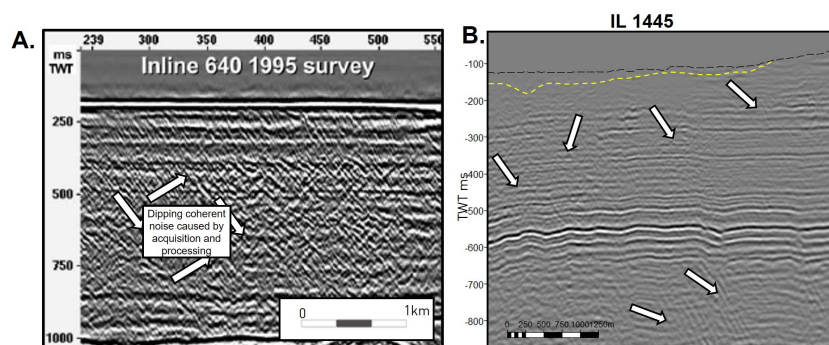


Fig. 5-2: Example of seismic processing artefacts, which can directly impair fault recognition and interpretation

A. North Sea seismics showing dimmed dipping patterns displaying similar characteristics to interpreted faults. It is important to avoid the misinterpretation of offsets caused by noise interference as real faults (after Hesthammer et al. 2001). B. Example from ZNO PreSTM-ref dataset. Base Quaternary morphology is shown by a yellow dashed line. Ground level is shown by black dashed line. While 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.

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 in the processing artefact category. Multiple reflections were identified within the Opalinus Clay interval. The acoustic properties of the Opalinus Clay (Fig. 5-3) do not support the observed relatively high-amplitude reflectivity patterns (consistently with observations gained from the reprocessing 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 Opalinus Clay interval.

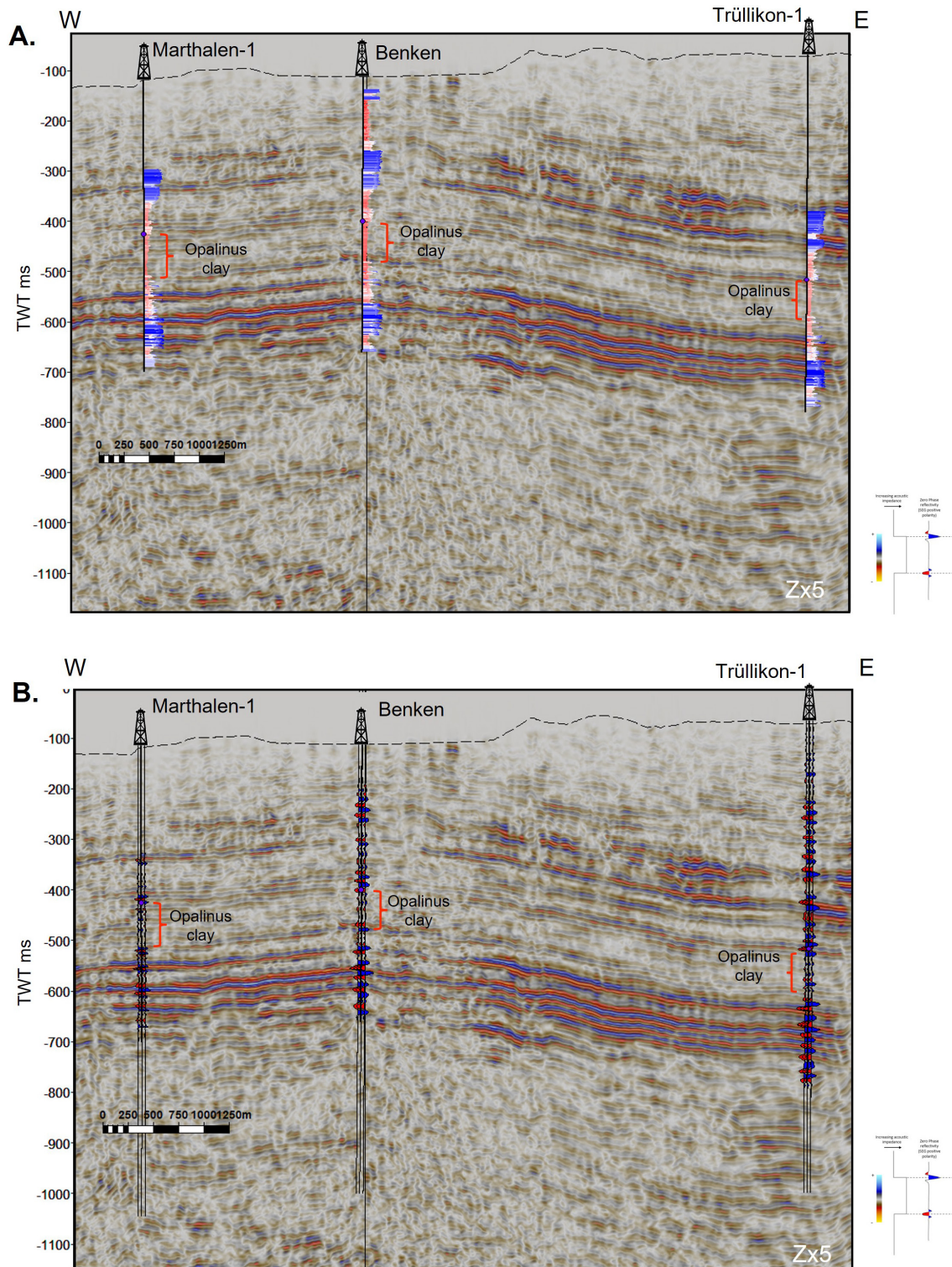


Fig. 5-3: Seismic section (reflectivity and structural smoothing) across three wells in the ZNO siting region

A. Acoustic impedance logs showing the acoustically weak Opalinus Clay interval. B. Similar observations from VSP where most of the clay interval lacks acoustic contrast, suggesting the presence of secondary energy (multiples) affecting the geometry of primary reflections. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

2- Imprints are seismic amplitude morphologies that appear in sections, time slices or horizon slices produced by geological features in overlying intervals. In the ZNO datasets, imprints are represented by zones of amplitude washouts. Degraded seismic data imaging shows that vanished reflection events coincide with major Quaternary valleys (Fig. 5-4).

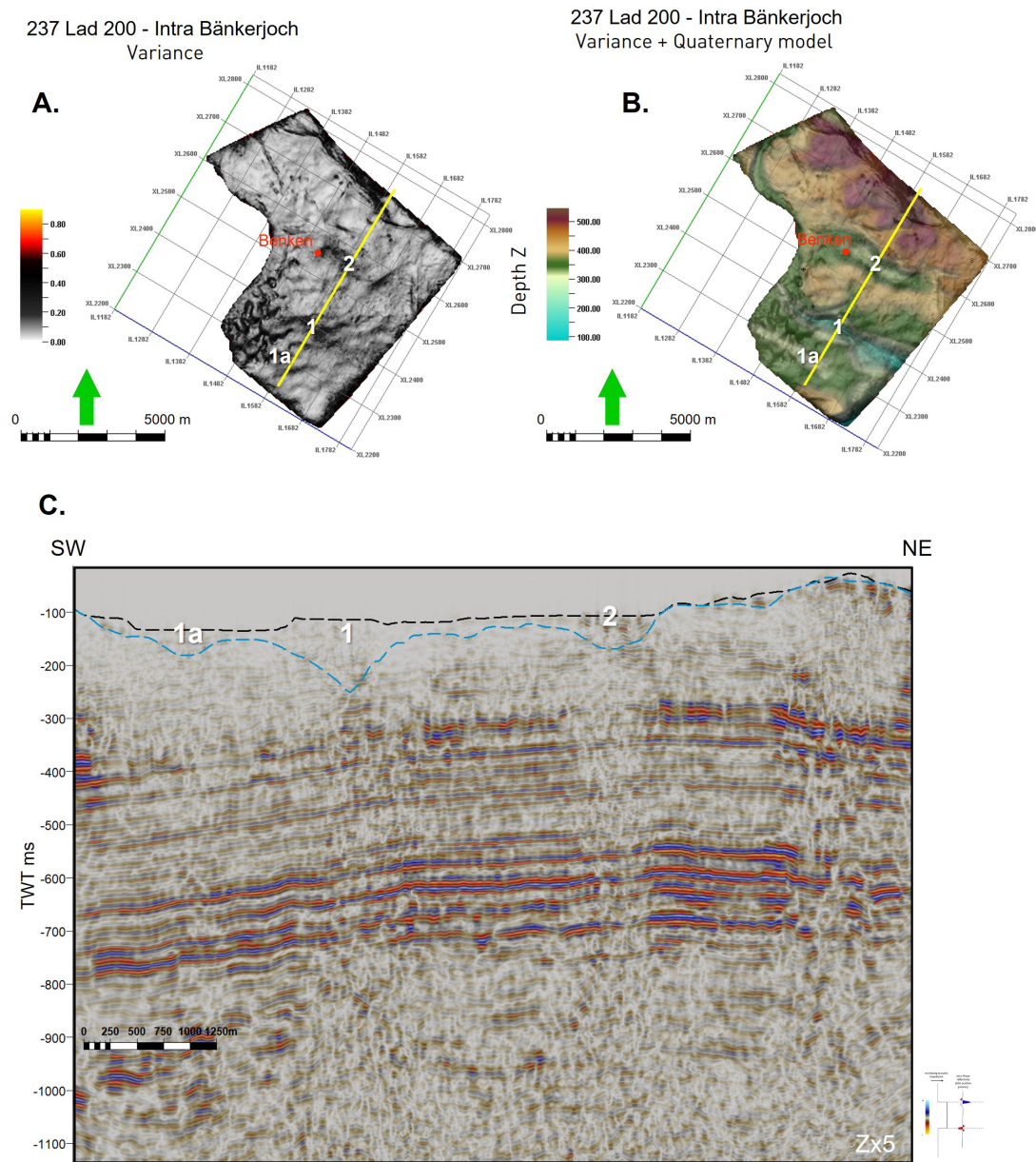


Fig. 5-4: Example of amplitude washout zone coinciding with the presence of Quaternary valleys

Variance display of 237 Lad 200 - Intra Bänkerjoch horizon showing the chaotic seismic pattern associated with the washout zones (1a, 1 and 2), which also affects deeper stratigraphic intervals; B. Same variance display as A. with overlaying Base Quaternary, demonstrating the coincidence of degraded seismic imaging areas with the presence of incised valleys (1 and 2). C. Inline 1595 crossing the two Quaternary valleys with disrupted amplitude continuity below the incisions (1a (minor), 1 and 2). Black dashed line is ground level and blue dashed line Base Quaternary. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

A similar seismic pattern but with more prominent expression is also visible in NL siting region, again in connection with the presence of Quaternary valleys (Nagra 2024c). The degraded seismic imaging below the Quaternary valleys strongly impairs the confidence in the seismic interpretation, particularly for faults, and resulting surfaces might show higher rugosity. This is clearly visible in the area surrounding the Benken well, where the gentle Quaternary incision translates into extremely chaotic response in seismic attribute maps and wider amplitude disrupted curtains in seismic section displays (Fig. 5-5, Fig. 5-6).

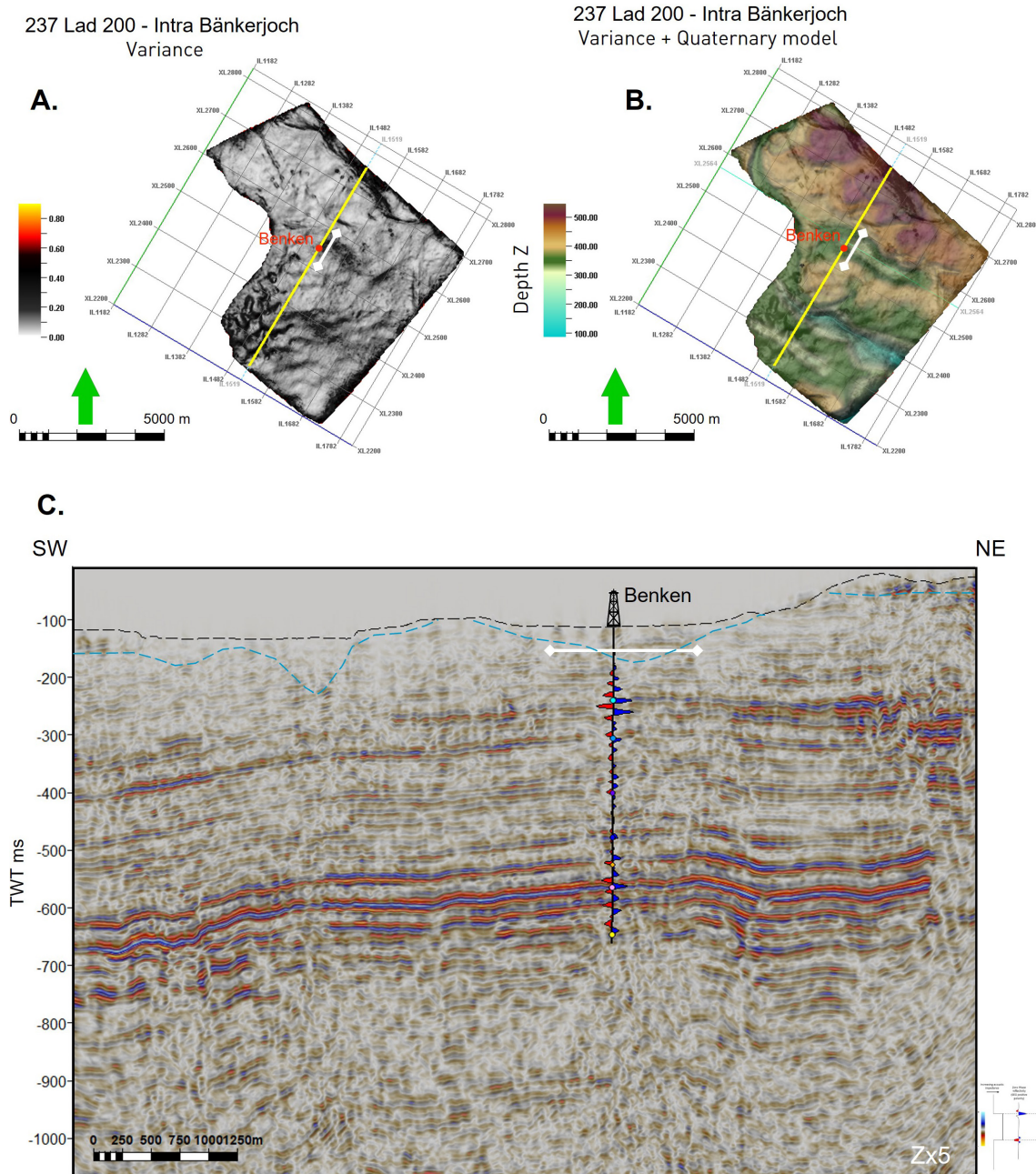


Fig. 5-5: Example of amplitude washout zone around the Benken well

Variance display of 237 Lad 200 - Intra Bänkerjoch horizon showing the chaotic seismic pattern associated with the washout zone in the surroundings of the Benken well B. Same variance display as A. with overlying Base Quaternary demonstrating the concomitance of degraded seismic imaging area with the presence of wide but gentle incised valley. C. Inline 1519 perpendicularly crossing the Quaternary valley. The extent of the seismic amplitude disrupted zone is indicated by the white bar in both map and seismic views. Black dashed line is ground level and blue dashed line Base Quaternary. Seismic display is PreSTM-reflectivity with an overlay of relative acoustic impedance.

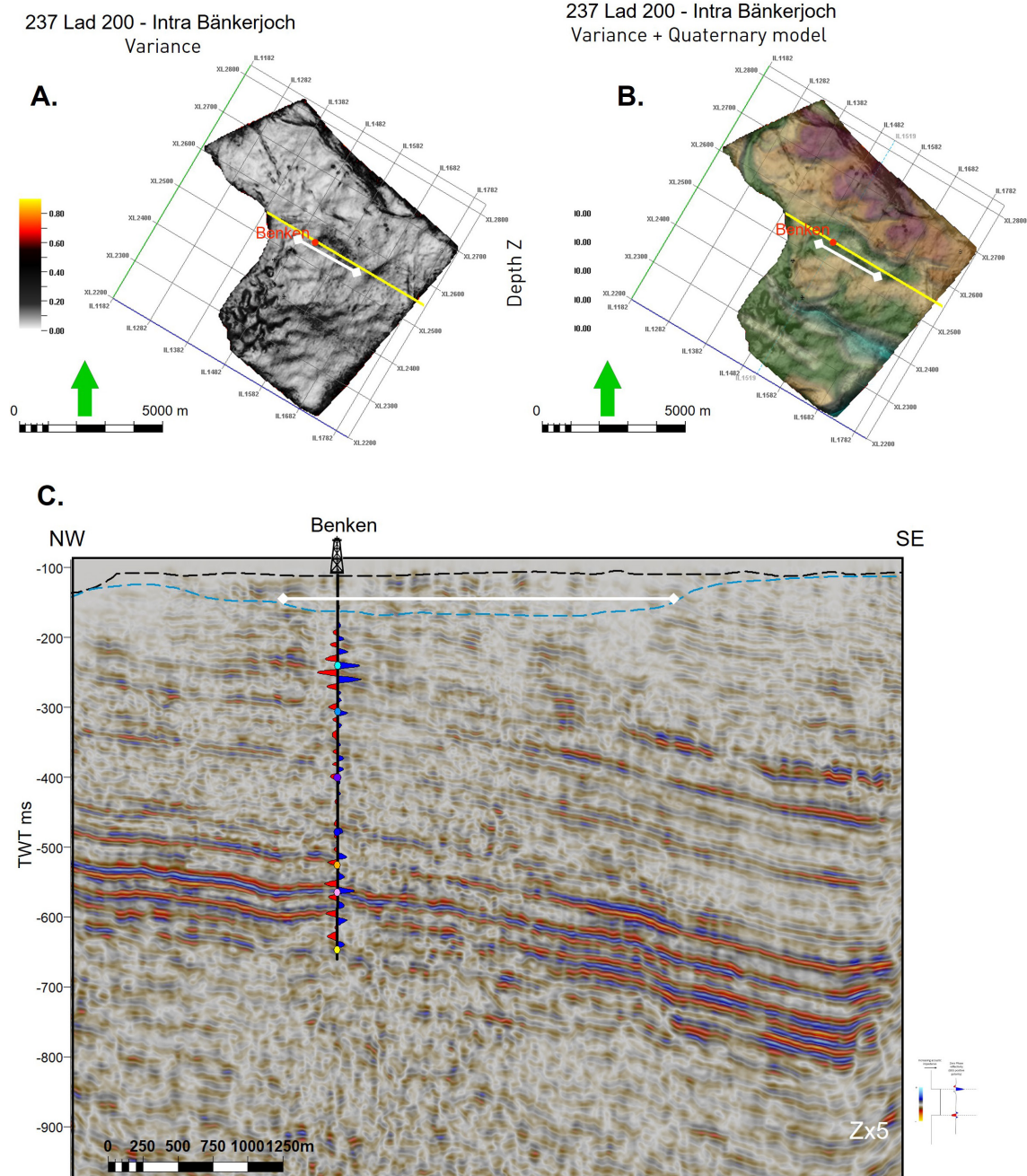


Fig. 5-6: Example of amplitude washout zone around the Benken well

A. Variance display of 237 Lad 200 - Intra Bänkerjoch horizon showing the chaotic seismic pattern associated with the washout zone in the surroundings of the Benken well (white bar). B. Same variance display as A. with overlying Base Quaternary demonstrating the concomitance of degraded seismic imaging area with the presence of a wide but gentle incised valley. C. Crossline 2552 running parallel to the Quaternary valley. The extent of the seismic amplitude disrupted zone is indicated by the white bar in both map and seismic views. Black dashed line is ground level and blue dashed line Base Quaternary. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

3- The term acquisition footprint is commonly used to define patterns in seismic time and horizon slices that are closely correlated to the acquisition geometry. Seismic attributes, particularly variance and curvature, often exacerbate footprint artefacts and may pose pitfalls in the interpretation of seismic discontinuities, particularly if they have similar orientations of regional structural trends or they can mask the more subtle underlying faults. In the ZNO siting region, the acquisition footprint strongly affects the southern part of the 96/17 merged seismic survey, related to the 1996 acquisition perimeter (Fig. 5-1; Nagra 2024a) at shallow stratigraphic levels. In cross-section displays, footprints generate undulations in the shallow section, which could easily be mistaken for geology (Fig. 5-7).

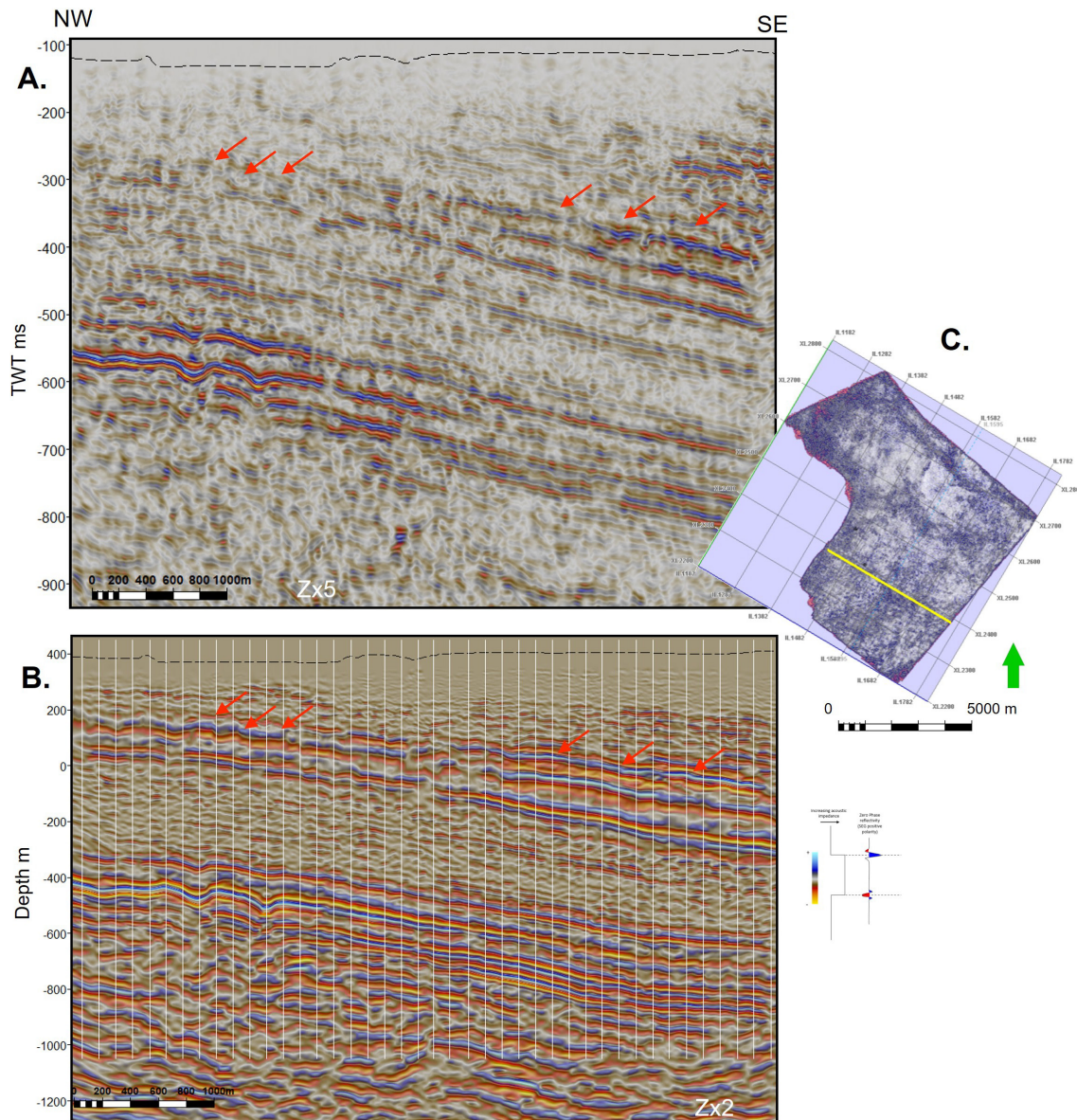


Fig. 5-7: Example of footprint-related undulations in the shallow section (red arrows) that could easily be mistaken for geology

Crossline 2389 on PreSTM-ref (A.) and PreSDM (B.) datasets across the southern area characterised by a strong footprint. C.: curvature-variance time slice at -300 ms TWT with line location. In the ZNO siting region, the presence of footprints represents a key challenge for the recognition and interpretation of subtle faults, which are expected to have similar orientation. Crossline displayed in B. shows the approach used to identify footprints. Vertical planes (white lines) were generated with acquisition spacing, seismic discontinuities matching those planes are dismissed as seismic artefacts and not included in the fault mapping. Seismic display is PreSTM-ref (A.) and PreSDM (B.) reflectivity with an overlay of relative acoustic impedance.

5.2 Stratigraphic Interpretation

Seismic interpretation of stratigraphic sequences has traditionally been 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 siting region selection process, seismic interpretation was performed solely for the Mesozoic succession (Top Malm – Near Base Mesozoic Unconformity since it contains the three major units (upper confining unit, host rock and lower confining unit, Nagra 2024d). Six regional markers comprising and defining the above units were mapped across the entire survey (Tab. 5-1, Fig. 5-8). 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 phase and quality

Strat. Name	Formation Name	Phase	Quality
149.2 Kim 100	Top Malm	 peak	
149.2 Kim 700	Top Villigen	 peak	
170.9 Aal 300	Top Opalinus	 trough	
174.7 Toa 100	Top Lias	 peak	
237 Lad 200	Intra Bänkerjoch	 peak	
251.9 Perm 100	Near Base Mesozoic Unc.	 S-crossing	

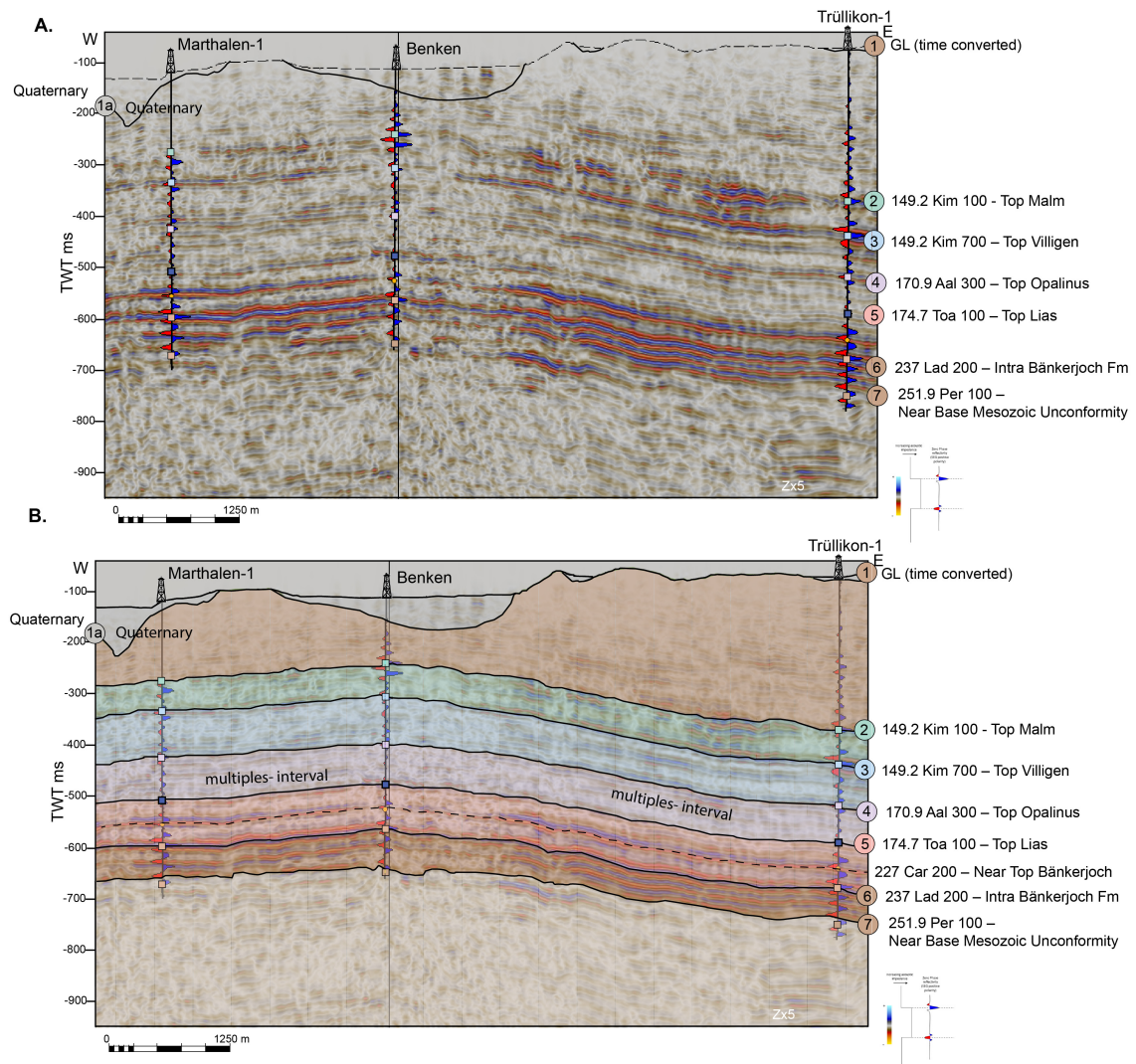


Fig. 5-8: Seismic section across the wells with key stratigraphic horizons

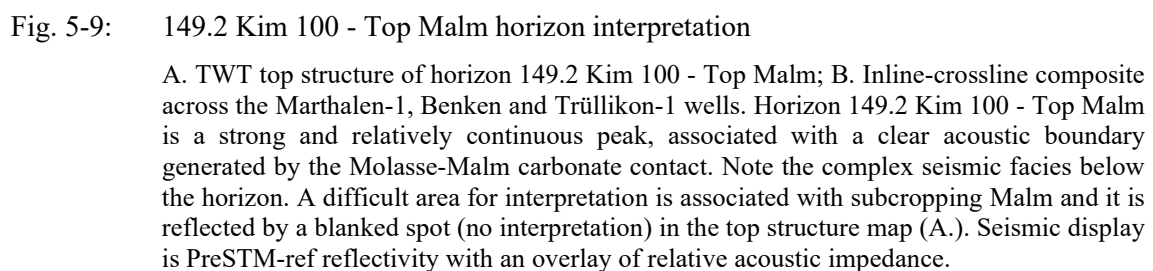
A. Uninterpreted and B., Interpreted showing the seismic-to-well tie and the six key stratigraphic horizons interpreted across the entire ZNO-97/16 merged seismic survey. Due to potentially simpler overburden geology, both 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias (base host rock) can be mapped with a good level of confidence. The 227 Car 200 - Near Top Bänkerjoch (dashed black line) was autotracked to increase the confidence in the Top Lias surface trend. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

In contrast to the NL siting region, the Herrenwis carbonate platform (Nagra 2024c) and associated clay wedge (overlying the Opalinus Clay), which hampered the Top Opalinus reflection, are not present in the ZNO siting region. Therefore, the Top Opalinus Clay reflection could be recognised and mapped in the ZNO-97/16 merged seismic survey (Fig. 5-8). Also, the Top Lias (base of the Opalinus Clay interval) could be mapped with a good degree of confidence across the entire area of the seismic survey, despite its discontinuous and transparent seismic character. To increase the picking confidence of the 174.7 Toa 100 - Top Lias horizon, its interpretation was coupled with the interpretation of a highly continuous stratigraphically deeper horizon, namely the 227 Car 200 – Near Top Bänkerjoch horizon.

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. 5-8 B).

5.2.1 149.2 Kim 100 - Top Malm

The Top Malm (149.2 Kim 100) appears as a comparatively strong positive amplitude (Fig. 5-9, Tab. 5-1). Such good impedance contrast can be related to the geological contact between the overlying Molasse unit characterised by alluvial sand- and siltstones, variegated marls and claystones of terrestrial or lacustrine origin as well as the Malm Siderolithic claystone and the calcareous Malm units (Fig. 5-9, Felsenkalke and Massenkalke Members, Nagra 2024d, 2023, 2021, 2020, 2019). The “Massenkalke” encompasses sponge bioherms and includes closely related, poorly or non-bedded sediments within and adjacent to the bioherms. The “Felsenkalke” represents the mostly well-bedded and sponge-free sediments occurring between the bioherms. The overlying Siderolithic portion is comprised of residual sediments (of various nature and lithological composition) and sits unconformably above the palaeo-karstic landscape of the Top Malm, yielding a highly variable thickness. Lithologies with Siderolithic affinity also occur within the carbonate layers underneath and appear to fill palaeo-karstic cavities. The Top Malm reflection is strong and continuous throughout the seismic survey, apart from areas where seismic imaging is directly compromised by the Quaternary morphologies (Fig. 5-10). Towards the north, the carbonate portion of the Malm subcrops with a few metres with Quaternary cover (Fig. 2-1, Fig. 5-10) and its interpretation becomes extremely difficult. This challenging area is reflected by a blanked interpretation spot in the northeastern corner of the survey (Fig. 5-10 A).



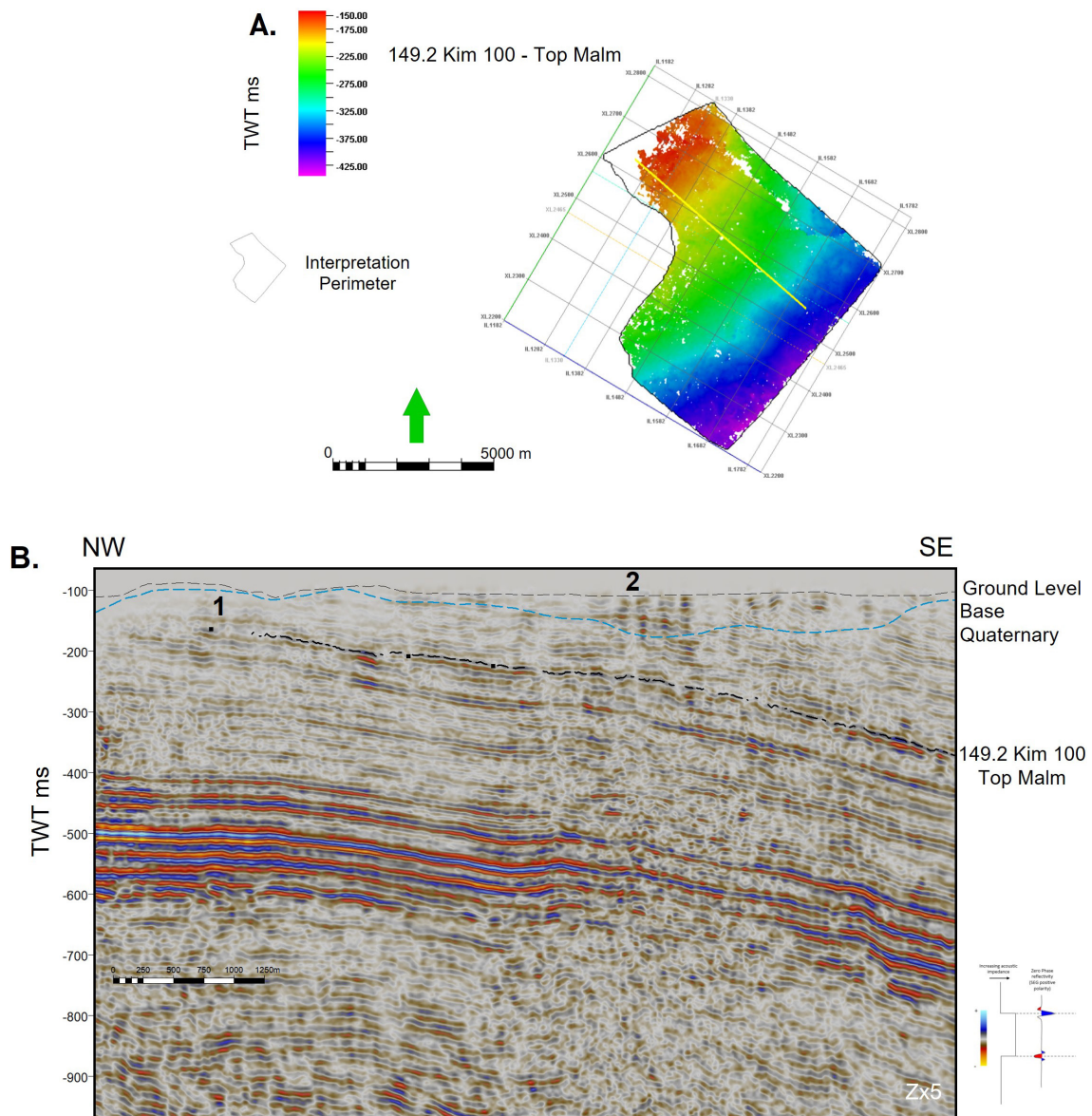


Fig. 5-10: NW-SE seismic line showing 149.2 Kim 100 - Top Malm interpretation challenges

A. 149.2 Kim 100 - Top Malm TWT autotracked horizon showing the area towards the northeast where Top Malm is almost subcropping and the seismic picking of the horizon cannot be performed with confidence. B. NW-SE seismic line showing the subcropping area (1) and the areas impaired by the presence of Quaternary valleys (2). Seismic display is PreSTM ref reflectivity with an overlay of relative acoustic impedance.

At the Trüllikon-1 well location, truncation of reflections below the 149.2 Kim 100 - Top Malm suggests a more prominent dissolution/erosion of the upper Felsenkalke interval (Fig. 5-9, Fig. 5-11). Below such a concave-shape feature, a body characterised by chaotic transparent seismic response is observed (Fig. 5-11). Several authors (Moldovanyi et al. 1995, Wagner et al. 1997, Heubeck et al. 2004, El Awawdeh et al. 2008, Sayago et al. 2012, Zampetti et al. 2014a) relate the presence of chaotic seismic facies to meteoric diagenetic alteration of the carbonate deposits, implying that the irregular shape of large-scale negative dissolution features, such as sink holes, caves, and karst collapse, are reflected by seismic waves in a chaotic matter. However, the geometry (positive convex upwards) of the transparent seismic body seems to indicate the presence of a bioherm build-up. Similar features, but with a less prominent shape, are observed along the same line. The proposed interpretation is consistent with the presence of bioherms in the core of the Trüllikon-1 well, recorded from a depth of ~ 570 m (MD; Nagra 2021).

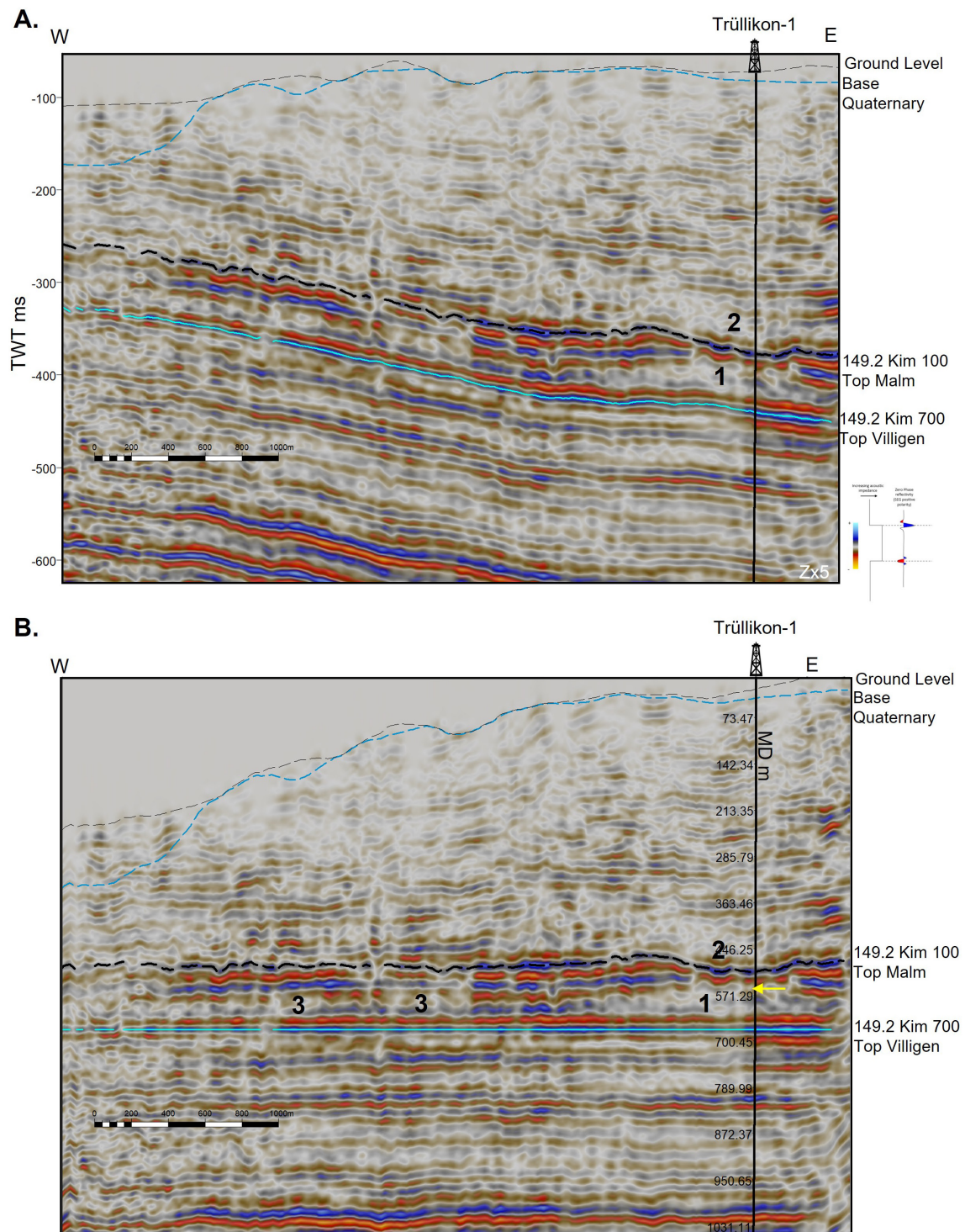


Fig. 5-11: E-W seismic section showing Upper Malm interval seismic expression near the Trüllikon-1 well

A. Seismic section and B. seismic section flattened at 149.2 Kim 700 – Top Villigen. Note the concave shape at 149.2 Kim 100 - Top Malm (1) and the presence of a transparent seismic body (2), which coincides with the appearance of bioherms in the core (~570 m MD, yellow arrow). Note that similar chaotic and transparent features can be observed along the line in similar stratigraphic positions (3). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.2 149.2 Kim 700 - Top Villigen

Horizon 149.2 Kim 700 - Top Villigen represents the most confident horizon in the Opalinus Clay overburden and includes the lowermost part of the Malm aquifer. The Villigen Formation consists mostly of micritic limestone with intervals of fossiliferous (sponges, crinoids, bivalves and ammonites) and glauconitic limestone. This horizon correlates with a clear positive acoustic impedance (peak; Tab. 5-1, Fig. 5-12) that can be consistently observed throughout the entire seismic survey.

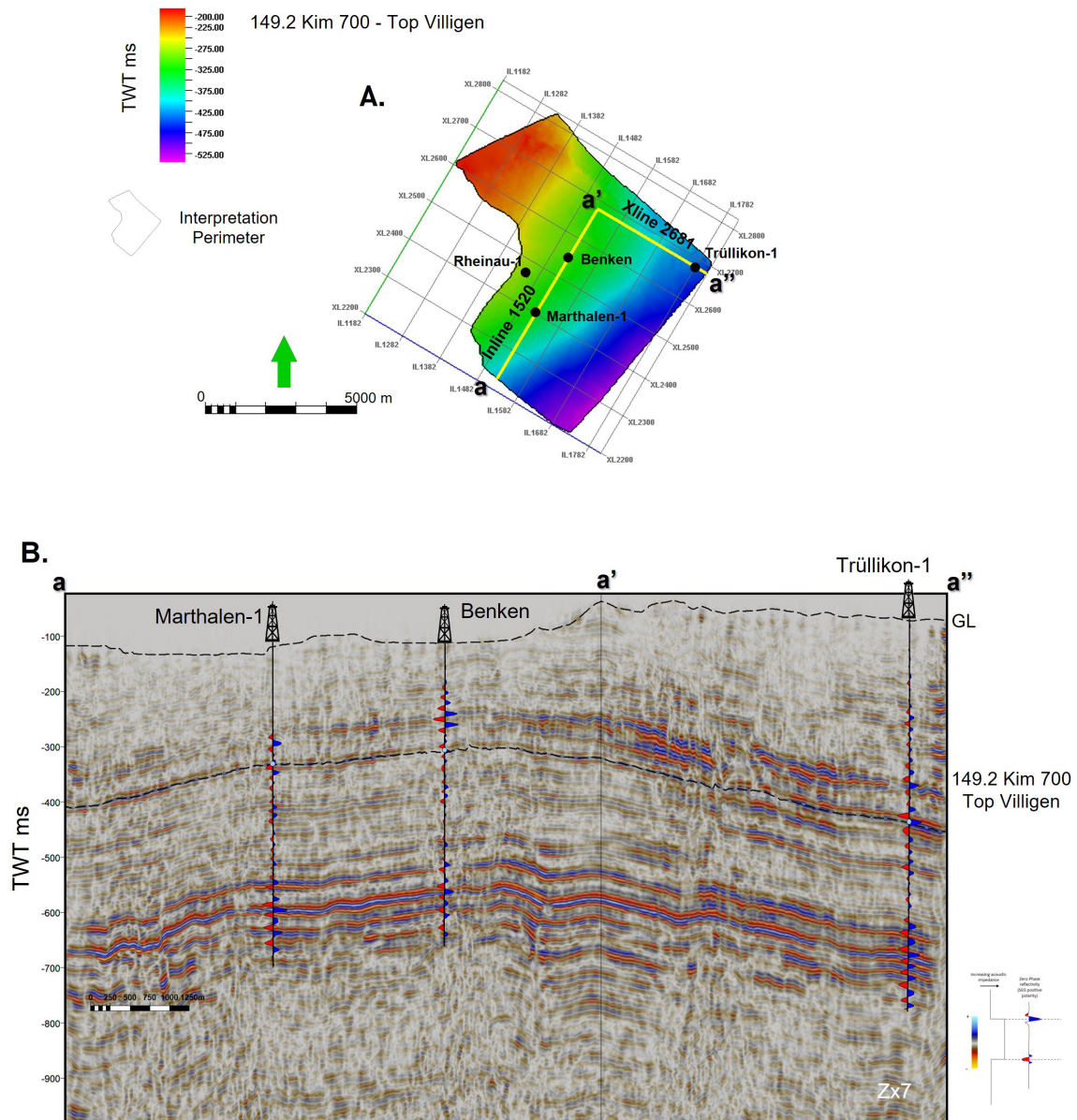


Fig. 5-12: 149.2 Kim 700 - Top Villigen horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-1 wells. Horizon 149.2 Kim 700 - Top Villigen is a strong and continuous peak and is considered the reference horizon for fault mapping in the stratigraphic interval above the Opalinus Clay. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Also, when the overlying Top Malm subcrops or is extremely shallow, the Top Villigen reflector still maintains its continuity, and stability of the reflection pattern (Fig. 5-13). Top Villigen horizon was selected to represent the key horizon marker needed to identify the presence of faults (geometry and cut-offs) in the stratigraphic interval above the Opalinus Clay host rock interval.

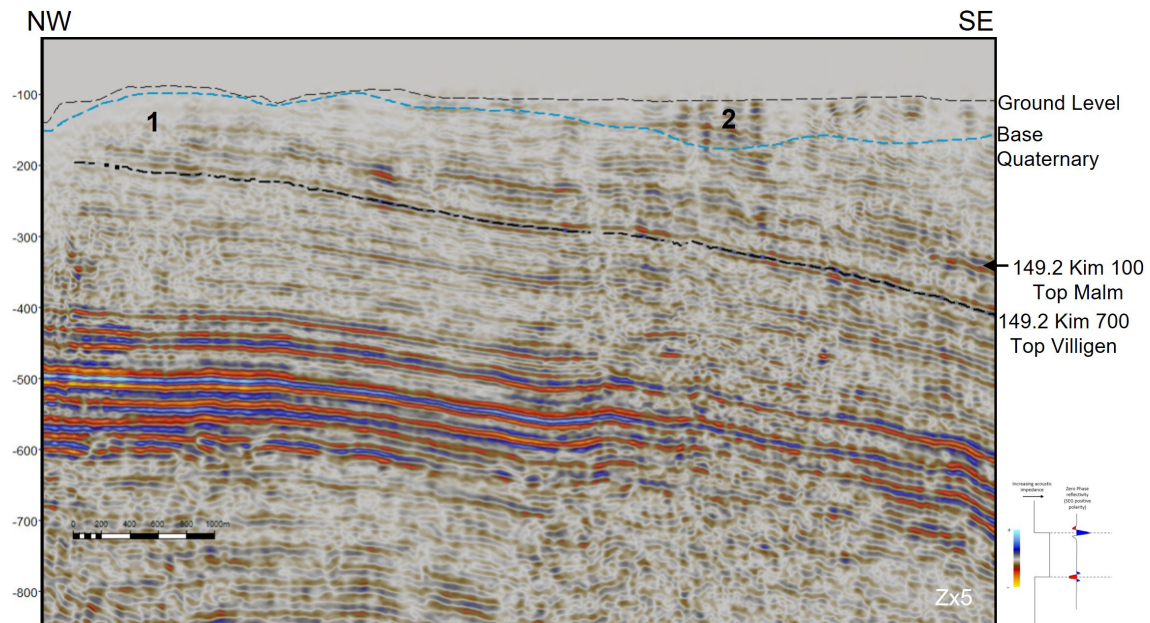
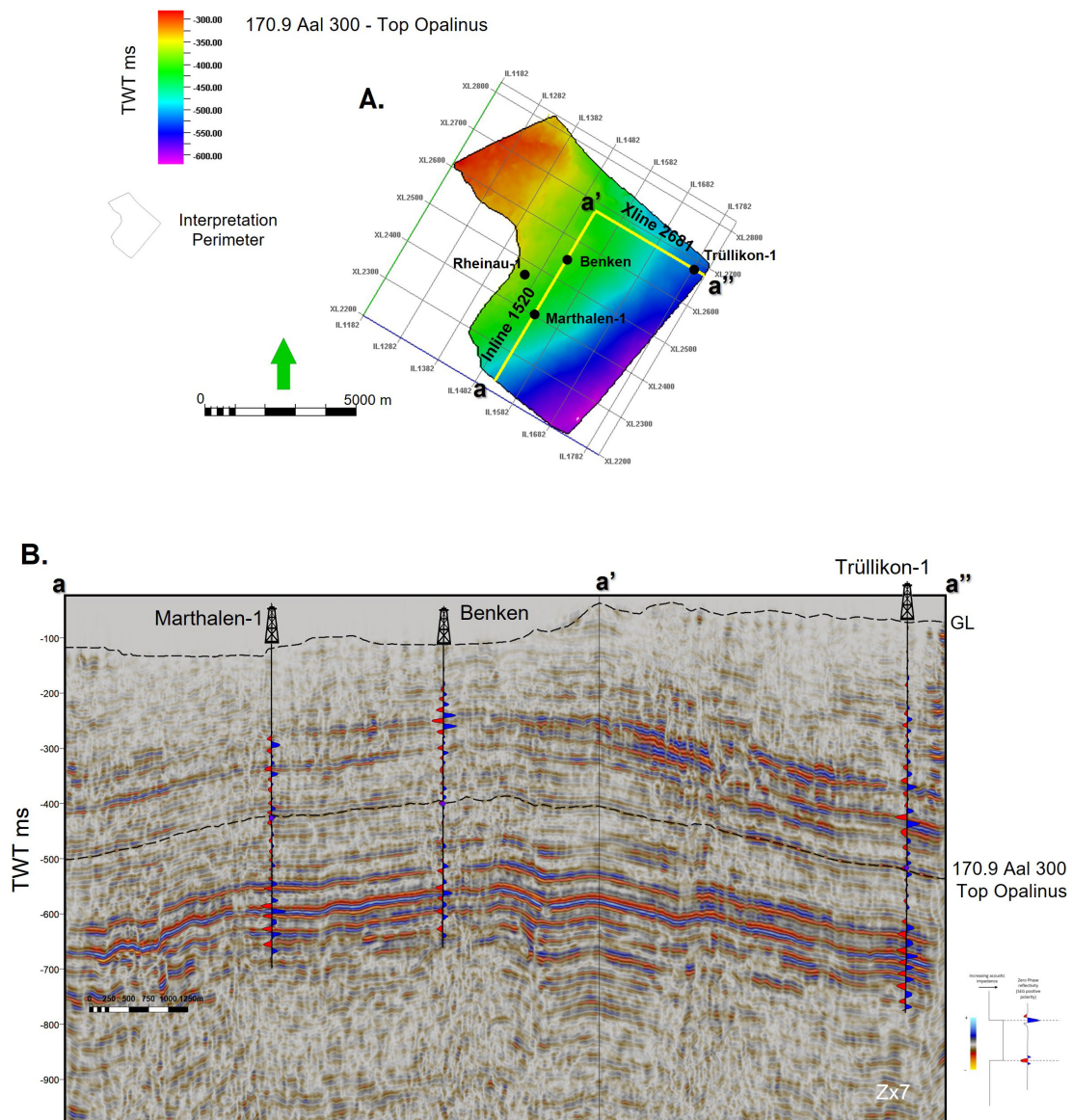


Fig. 5-13: Seismic section as for Fig. 5-10, showing the continuity and stability of the 149.2 Kim 700 - Top Villigen horizon in areas of challenging interpretability of the 149.2 Kim 100 - Top Malm horizon (1 and 2)

Top Opalinus (170.9 Aal 300 well marker, Tab. 5-1, Fig. 5-8, Fig. 5-14) represents the top of the host rock and seismically shows as a clearly marked soft acoustic response above the transparent acoustic impedance zone where multiples interfere with primary reflectivity (Fig. 5-3). Below the Top Opalinus marker, the lack of acoustic response is strongly driven by the Opalinus Clay composition of mostly fine sandy and silty claystone and claystone. Consequently, while the internal architecture of the Opalinus Clay interval cannot be unlocked, its top can be interpreted with confidence.



A. TWT top structure; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-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. This horizon can be traced with confidence across the ZNO seismic survey. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.4 174.7 Toa 100- Top Lias

Horizon 174.7 Toa 100 -Top Lias represents the base of the Opalinus Clay interval. Clear challenges were identified in the interpretation of the Top Lias (174.7 Toa 100), even in the undisturbed central area both in the NL and JO siting regions (Nagra 2024b, 2024c). In the ZNO siting region, Top Lias was interpreted taking into account the strong lateral variability in amplitude strength and reflection shape of this event (Fig. 5-15, Fig. 5-16).

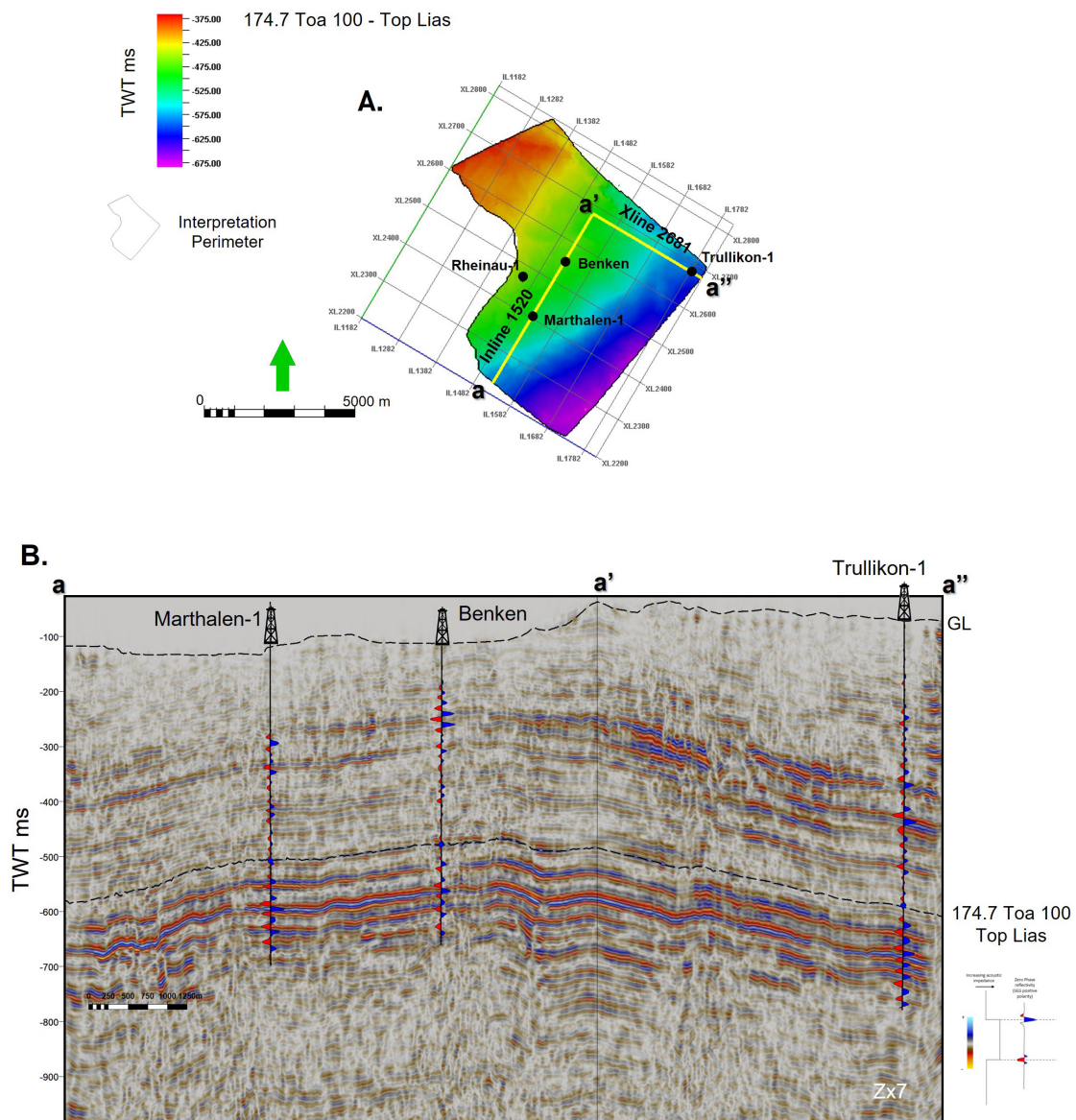


Fig. 5-15: 174.7 Toa 100 - Top Lias horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-1 wells. Horizon 174.7 Toa 100 - Top Lias marks the base of the homogeneous interval of the Opalinus Clay. This horizon can be traced across the ZNO 97/16 merged seismic survey. GL is ground level. 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 extent of the faults affecting the deeper Mesozoic succession (i.e. lower confining unit) and their impact on host rock integrity. To increase the confidence in the Top Lias “pick” in areas where the amplitude appears more discontinuous, the horizon 227 Car 200 - Near Top Bänkerjoch was interpreted as it represents the most continuous horizon below the Top Lias (Fig. 5-16).

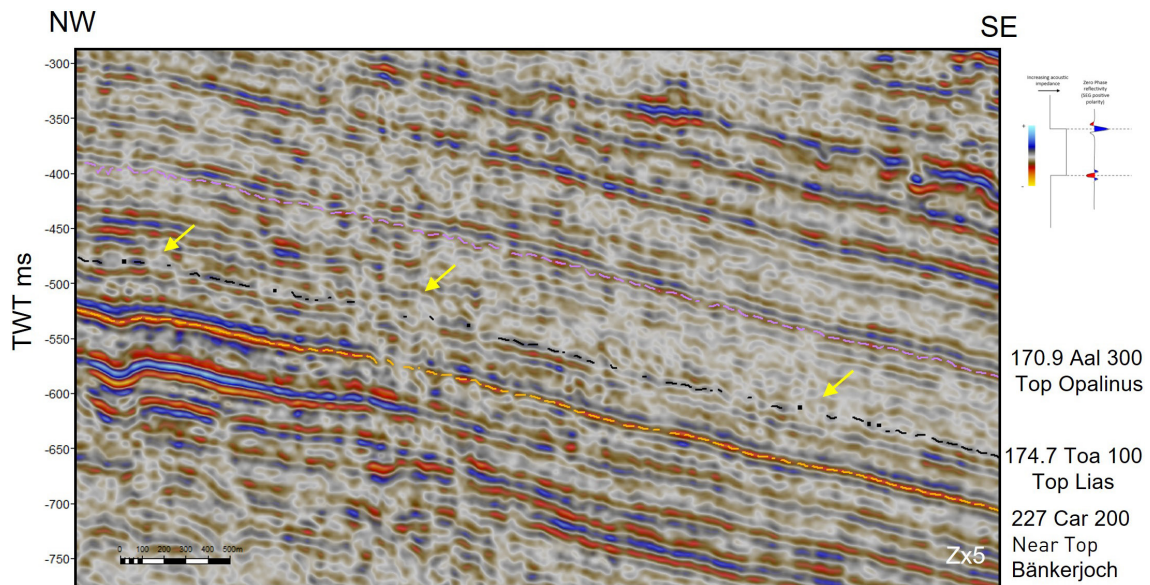


Fig. 5-16: Crossline 2398 showing examples of amplitude discontinuity observed when interpreting horizon 174.7 Toa 100 - Top Lias

Seismic event associated with 174.7 Toa 100 - Top Lias horizon shows in some cases a more discontinuous response (yellow arrows). To better calibrate the interpretation, 227 Car 200 - Near Top Bänkerjoch was also picked.

The 227 Car 200 - Near Top Bänkerjoch reflector is a very continuous and high-amplitude through, hence 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 host rock (Fig. 5-17).

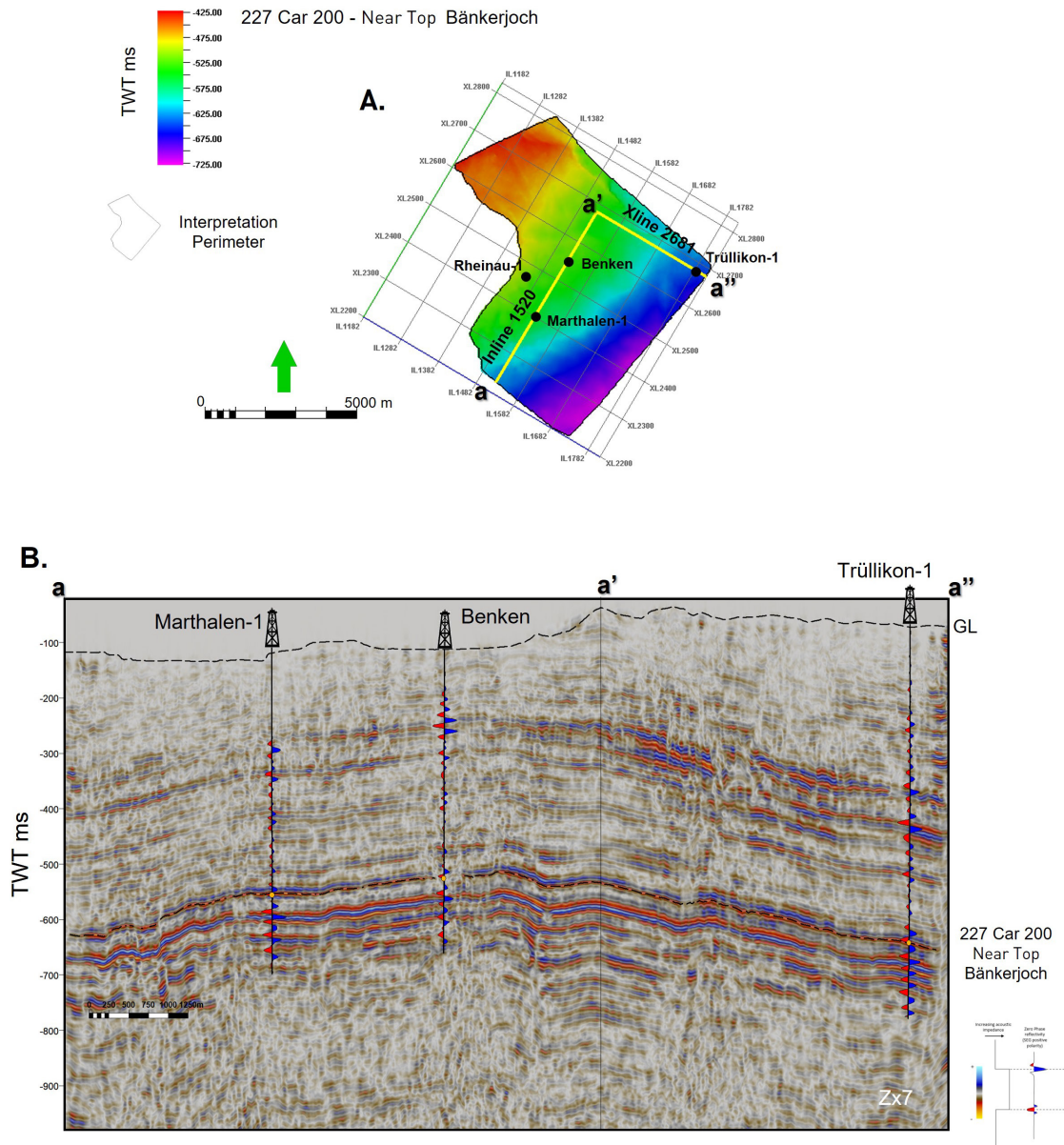


Fig. 5-17: 227 Car 200 - Near Top Bänkerjoch horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-1 wells. Horizon 227 Car 200 - Near Top Bänkerjoch was interpreted to increase confidence in horizon 174.7 Toa 100 - Top Lias. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.5 237 Lad 200 - Intra Bänkerjoch

As proxy for the stratigraphic marker 237 Lad 400, which correlates with the Top of the Muschelkalk Group (Fig. 5-8; Jordan 2016), horizon 237 Lad 200 - Intra Bänkerjoch was selected since it represents a high-amplitude and very continuous positive reflection just above the 237 Lad 400 - Top Muschelkalk well marker (Tab. 5-1, Fig. 5-18, Fig. 5-19).

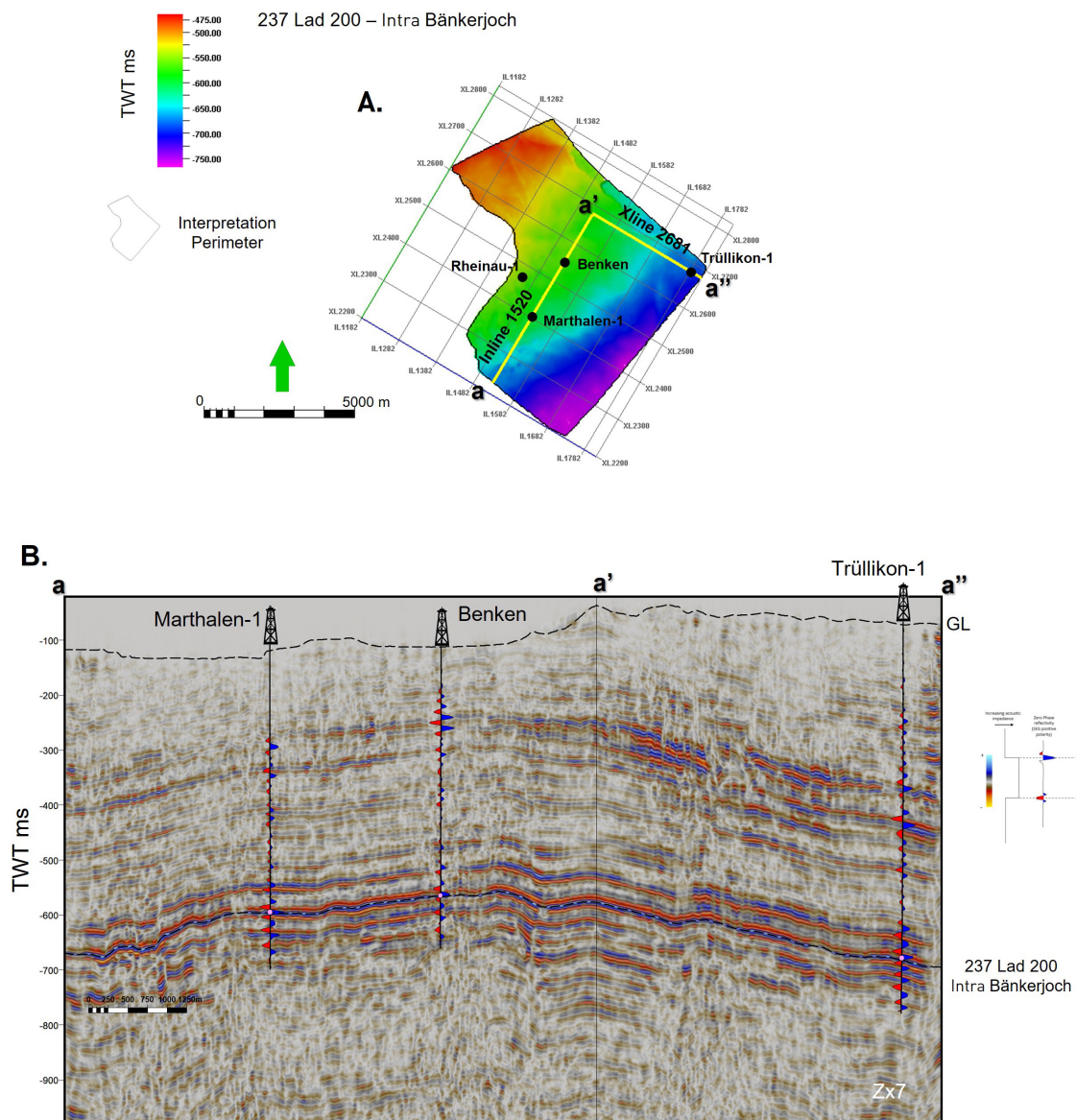


Fig. 5-18: 237 Lad 200 - Intra Bänkerjoch horizon interpretation

A. TWT top structure of horizon; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-1 wells. This horizon was selected in place of horizon 237 Lad 400 - Top Muschelkalk since it is seismically very continuous. Seismic display is PreSTM-reflectivity with an overlay of relative acoustic impedance.

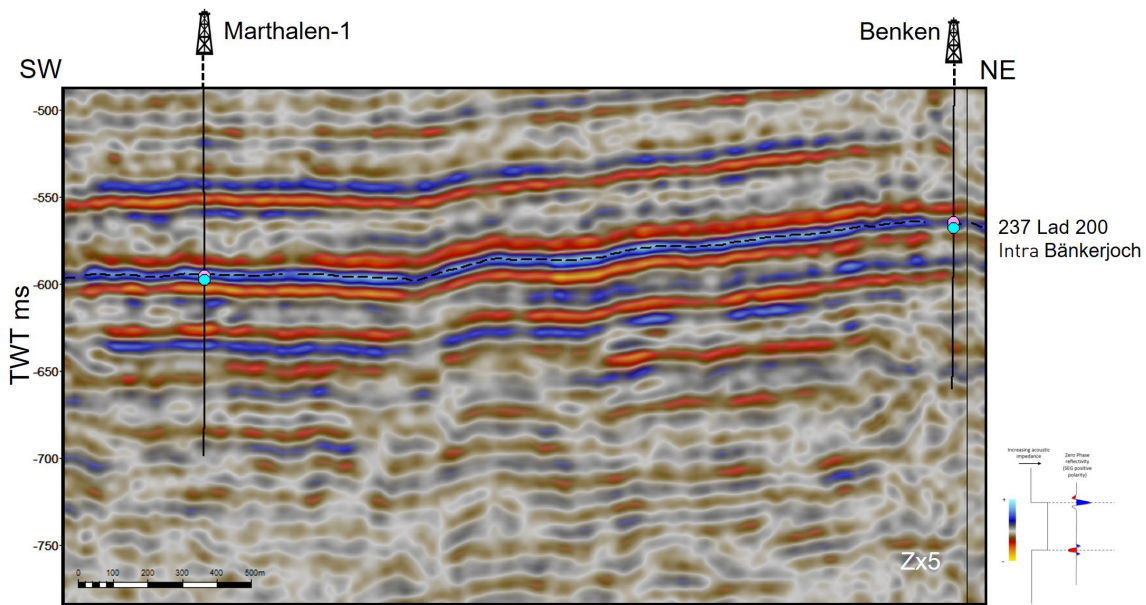


Fig. 5-19: Zoomed-in section across the Marthalen-1 and Benken wells, showing the proximity between the well markers 237 Lad 200 - Intra Bänkerjoch (pink circle) and 237 Lad 400 - Top Muschelkalk (light blue circle)

Horizon 237 Lad 200 - Intra Bänkerjoch was preferred since it is a very continuous, high-amplitude positive reflection.

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 changing amplitude content and wavelet shape (i.e. doublets; Fig. 5-20), reducing the confidence in the fault interpretation. This observation is consistent with previous interpretation efforts (Nagra 2024c), where the Top Muschelkalk horizon interpretation was guided by the overlying strong reflection package. The alternative solution to select Top Bänkerjoch (Top Gipskeuper as for Nagra 2019) instead was not further considered since it was identified in previous interpretation efforts (Nagra 2019) that this horizon represents a rather problematic marker horizon. It was not fully evident if the horizon should be picked on a zero-crossing or on a very weak negative amplitude (Nagra 2019).

The observed heterogeneous seismic response (Fig. 5-20) might mimic the complex geology of the Muschelkalk Group (Nagra 2024d). The three phases distinguished in the Muschelkalk Group recorded a variability in depositional environments from (i) a transgressional 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) underlie oolitic micrite locally deposited during the regression phase (Nagra 2024d). In particular, areas of concave-downward morphology with dimmed, chaotic seismic facies are associated with circular to subcircular features, which can be interpreted as dissolution features related to subaerial exposures (Fig. 5-20).

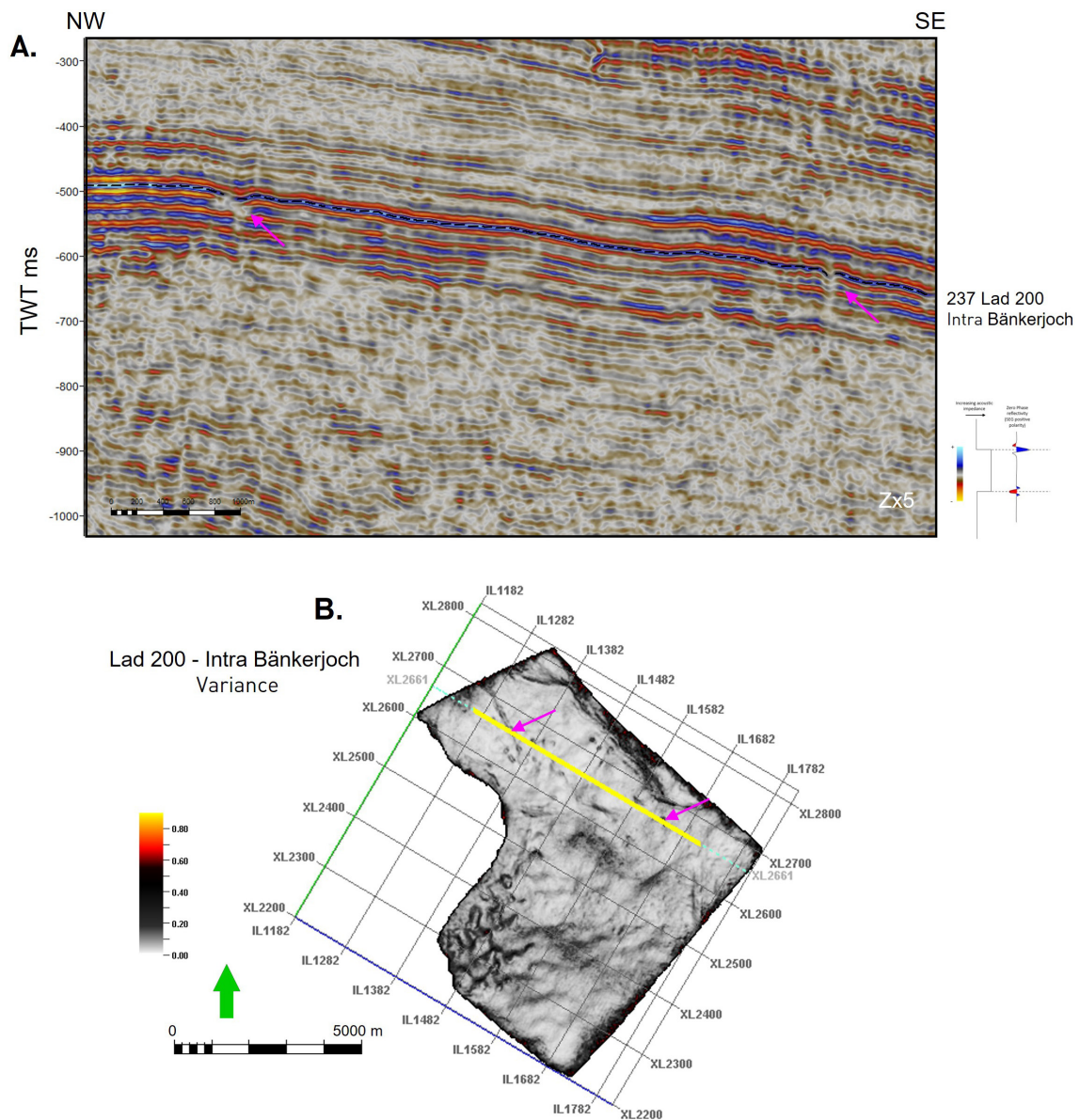


Fig. 5-20: Crossline 2661 showing the variability of the Muschelkalk reflection package

Lateral variability of seismic response within the Muschelkalk Group. Concave-shaped features with dimmed seismic facies (A., pink arrows) correlate to circular/subcircular features in the variance attribute display (pink arrows, B.). The imaging of the subcircular features at 237 Lad 200 - Intra Bänkerjoch might indicate the presence of a collapse feature associated with the Muschelkalk dissolution or superimposed exposure events also affecting the Bänkerjoch Formation. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.6 251.9 Per 100 - Near Base Mesozoic Unconformity

The 251.9 Per 100 - Near Base Mesozoic Unconformity has the lowest confidence among the interpreted horizons, since it represents a major unconformity (Tab. 5-1, Fig. 5-21). The seismic response to an unconformity depends on the nature of the contact between pre-unconformity and post-unconformity sections. For the Base Mesozoic 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. 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 (S-crossing; Fig. 5-8, Fig. 5-21, Tab. 5-1) that correlated to the stratigraphic marker 251.9 Per 100 at the Benken well, but coincides with a reflection shallower than the 251.9 Per 100 well tops at Marthalen-1 and Trüllikon-1 wells. 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. Reflection geometries that could be related to unconformity truncation are observed deeper than the interpreted horizon (Fig. 5-22). 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 2019, 2024d, Zambrano et al. 2024, Madritsch et al. 2013).

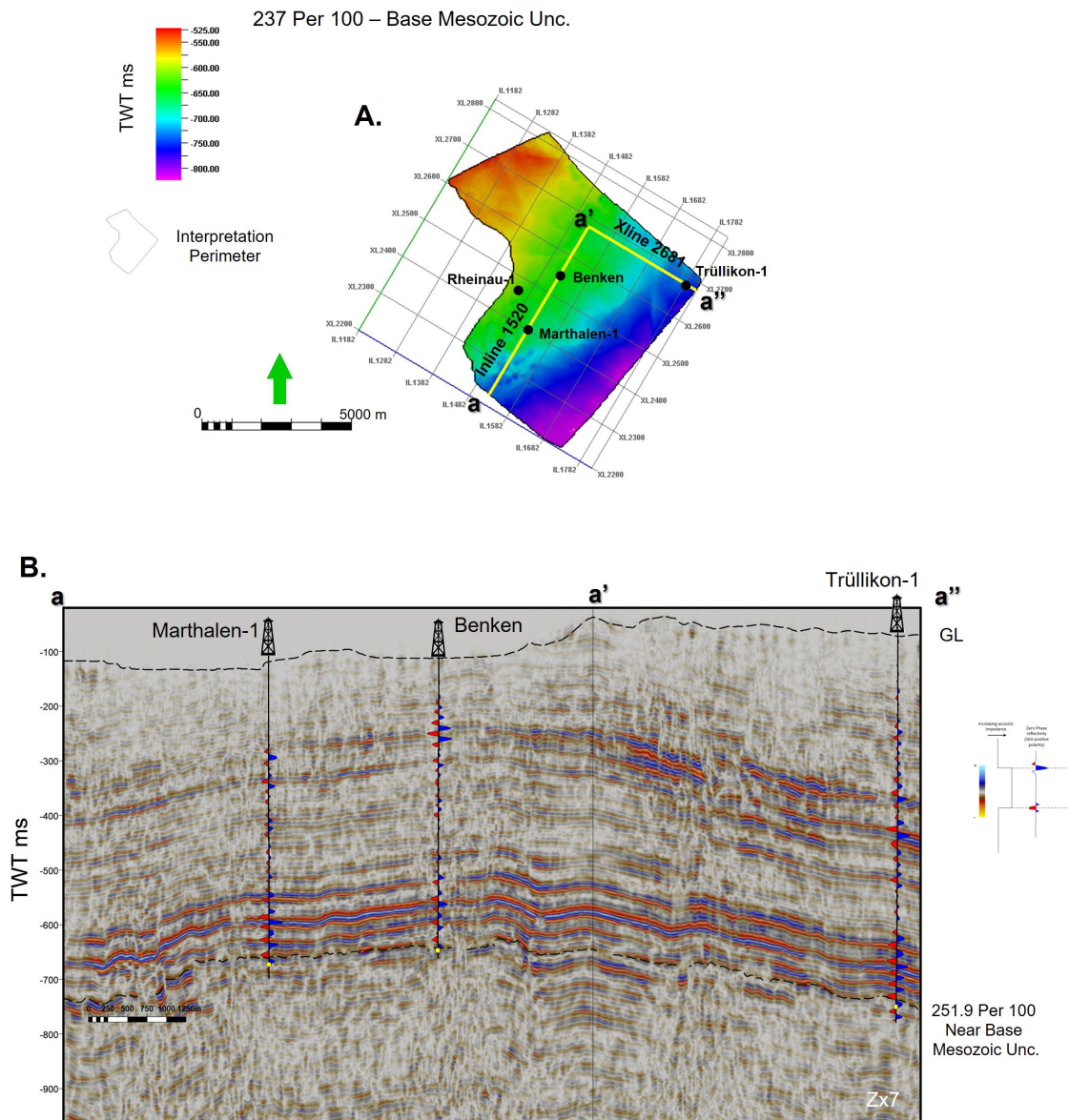


Fig. 5-21: 251.9 Per 100 - Near Base Mesozoic Unconformity horizon interpretation

A. TWT top structure of horizon; B. Inline-crossline composite across the Marthalen-1, Benken and Trüllikon-1 wells. This horizon was selected to represent the 251.9 Per 100 - Near Base Mesozoic Unconformity, even if it appears to be positioned higher than the Base Mesozoic Unconformity encountered in the wells. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

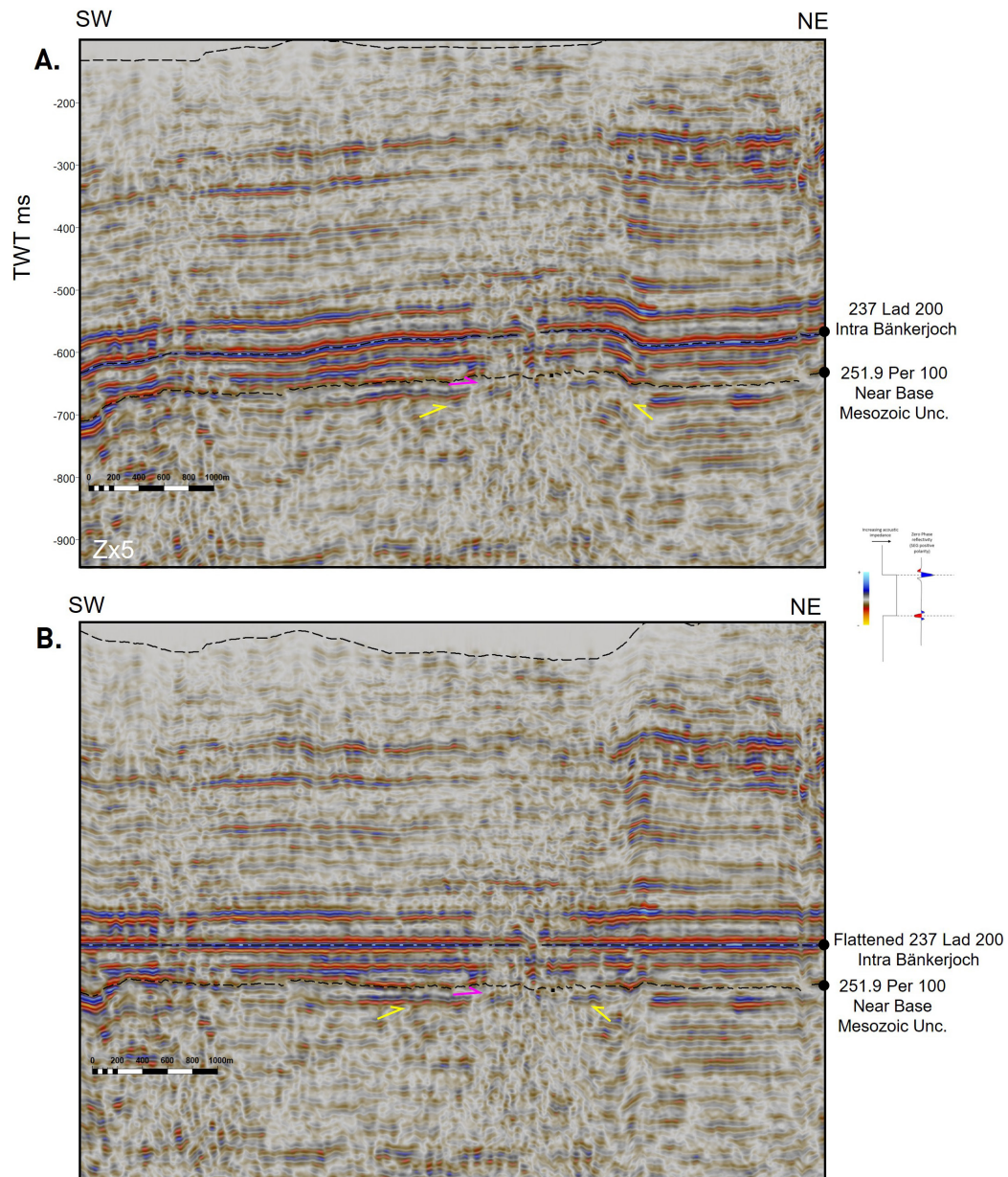


Fig. 5-22: Seismic random line showing evidence of reflection truncation (yellow arrows) and onlapping (pink arrow) below the 251.9 Per 100 - Near Base Mesozoic Unconformity interpreted horizon

A. Seismic section: B. Seismic section flattened at 237 Lad 200 - Intra Bänkerjoch. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

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 deformation zones (i.e. faults and folds, Nagra 2022) were discriminated from other geological features and seismic artefacts and captured as traces for the four main stratigraphic horizons (Fig. 5-23, Fig. 5-24).

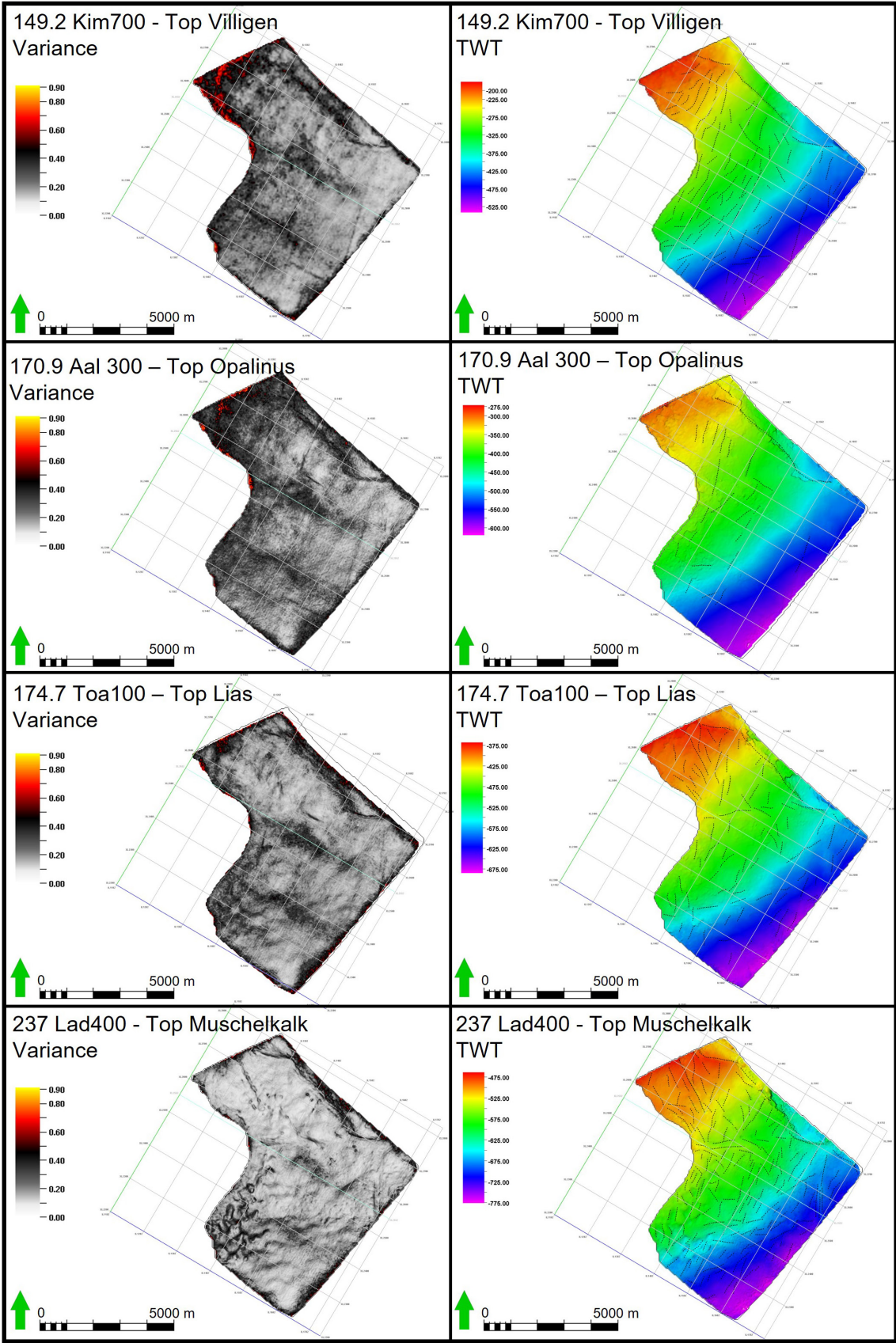


Fig. 5-23: ASR structural interpretation matrix based on PreSTM-ref minimum-phase (Nagra 2022)

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 four main stratigraphic horizons. Seismic data is PreSTM-ref minimum-phase.

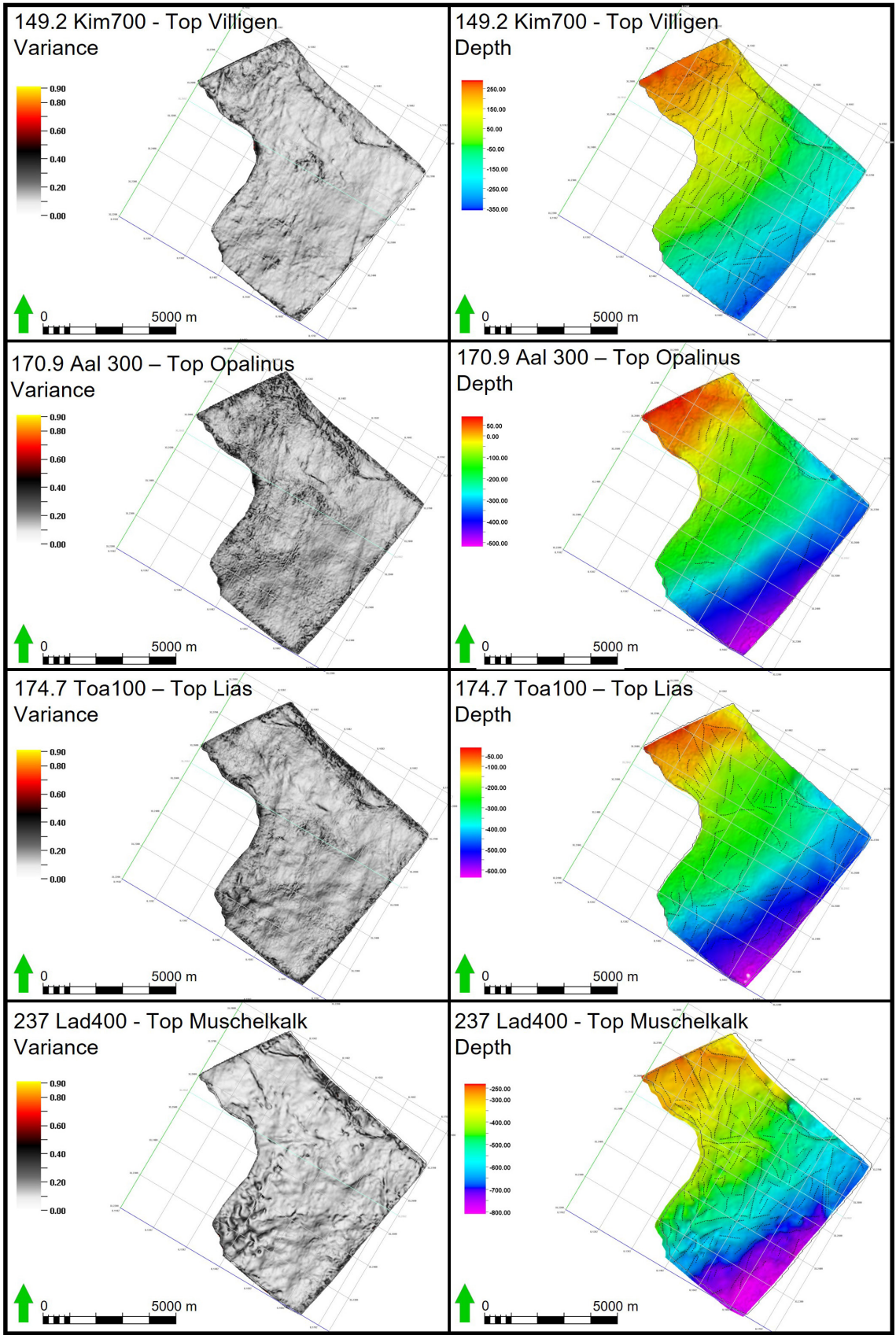
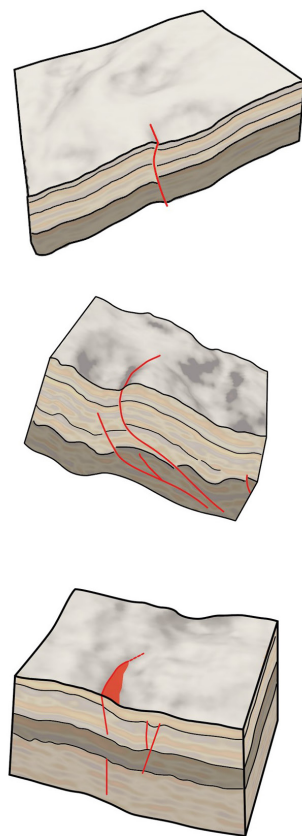


Fig. 5-24: Pre-ASR 2021 structural interpretation matrix based on PreSDM-ref minimum-phase

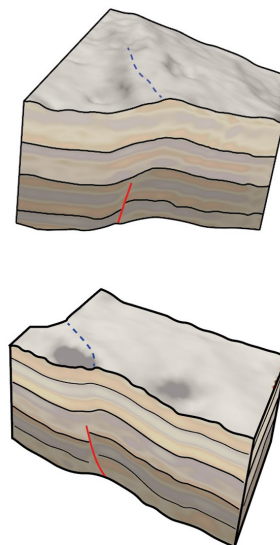
Dashed black lines-fault interpretation workflow Phase 1; interpreted seismic discontinuities represent deformation zones: faults and folds) on top of TWT structural maps of the four main stratigraphic horizons. Seismic data is PreSDM minimum-phase.

At this stage of the interpretation workflow, the interpreted structural lineaments are considered to be (structurally) undifferentiated deformation zones (Nagra 2022) that can be attributed indiscriminately to faults or fault-related folds (i.e. fault-tip monoclines; Fig. 5-25). Since, on attribute maps, the identified seismic discontinuities appear to have similar seismic patterns that make them indistinguishable from fold and fault traces (Fig. 5-23, Fig. 5-24), the recognition and separation of seismic faults to folds was achieved following the defined seismic fault diagnostic criteria (Fig. 4-12) in a detailed 3D fault mapping performed in the Phase 2 workflow.

A. Seismic-scale faults



B. Fault-related folds



Deformation zones

Fig. 5-25: Conceptual diagrams of the deformation zones 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) generally referred to as deformation zones. Definition of seismic fault signatures and 3D fault stick interpretation results 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 for the different fault kinematics observed in the three siting regions; B. Simplified conceptual diagram of seismic-scale fault-related folds (i.e. fault-tip monoclines/drape-folds).

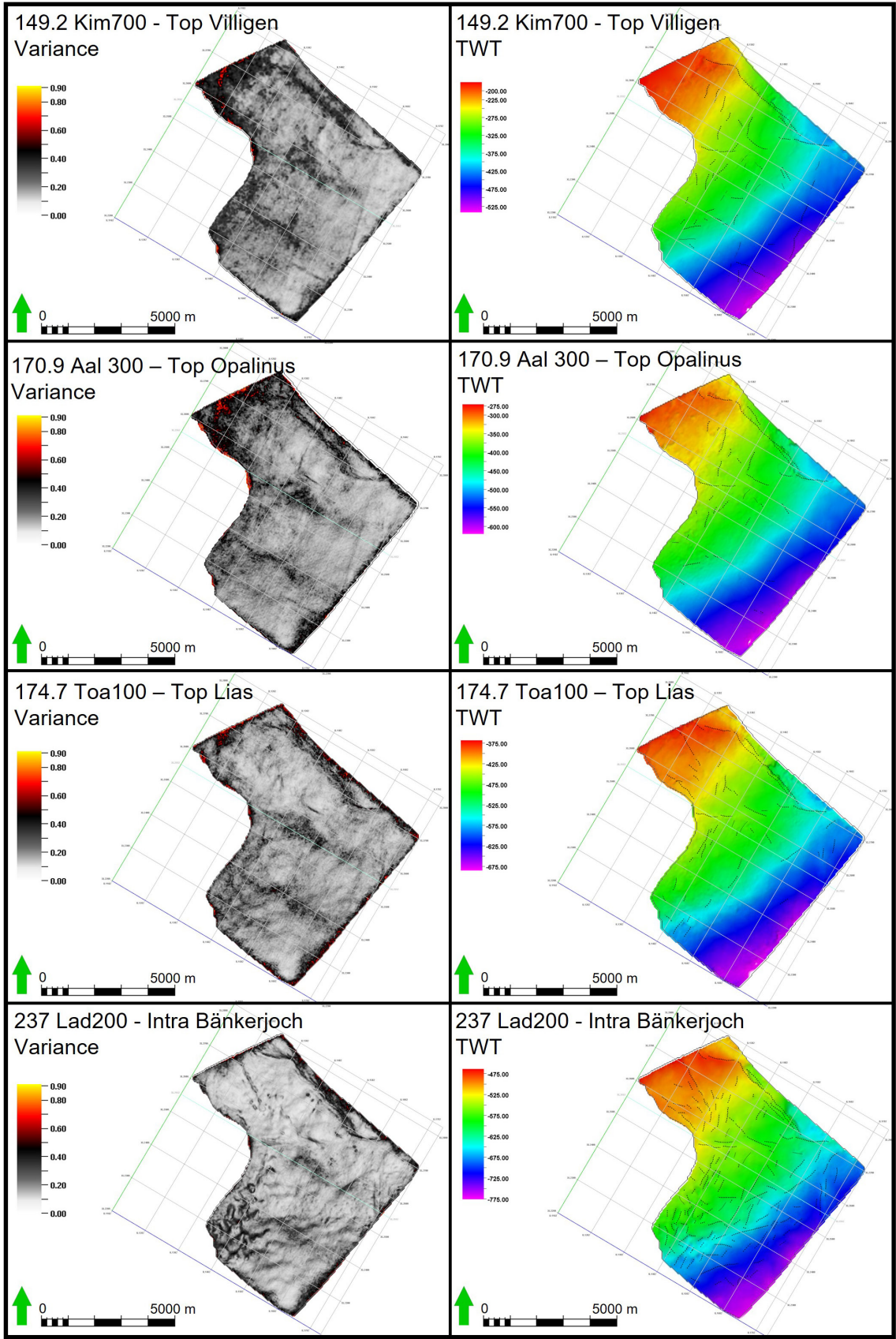


Fig. 5-26: 2023 (this report) fault interpretation matrix

To Fig. 5-26 Displays of the variance attribute horizon slices and fault traces (black lines - fault interpretation workflow Phase 2, lower confidence faults are displayed as thin grey lines) on top of TWT structural maps of the four main stratigraphic horizons. Compared to the ASR deformation zones (Nagra 2022), only lineaments interpreted in 3D as faults were selected. Note that horizon 237 Lad 200 - Intra Bänkerjoch was preferred to 237 Lad 400 - Top Muschelkalk, because of higher confidence in the picking continuity. Seismic data is PreSTM-ref.

The resulting mapping (Fig. 5-26) is a filtered image of the seismic structural lineaments of Phase 1 (Fig. 5-23) where only fault traces are displayed and some of the lineament trends were adjusted to fully honour the vertical (section) criteria.

Distribution and style of the interpreted seismic faults are also captured in key cross-sections (Fig. 5-27 Fig. 5-28, Fig. 5-29, Fig. 5-30).

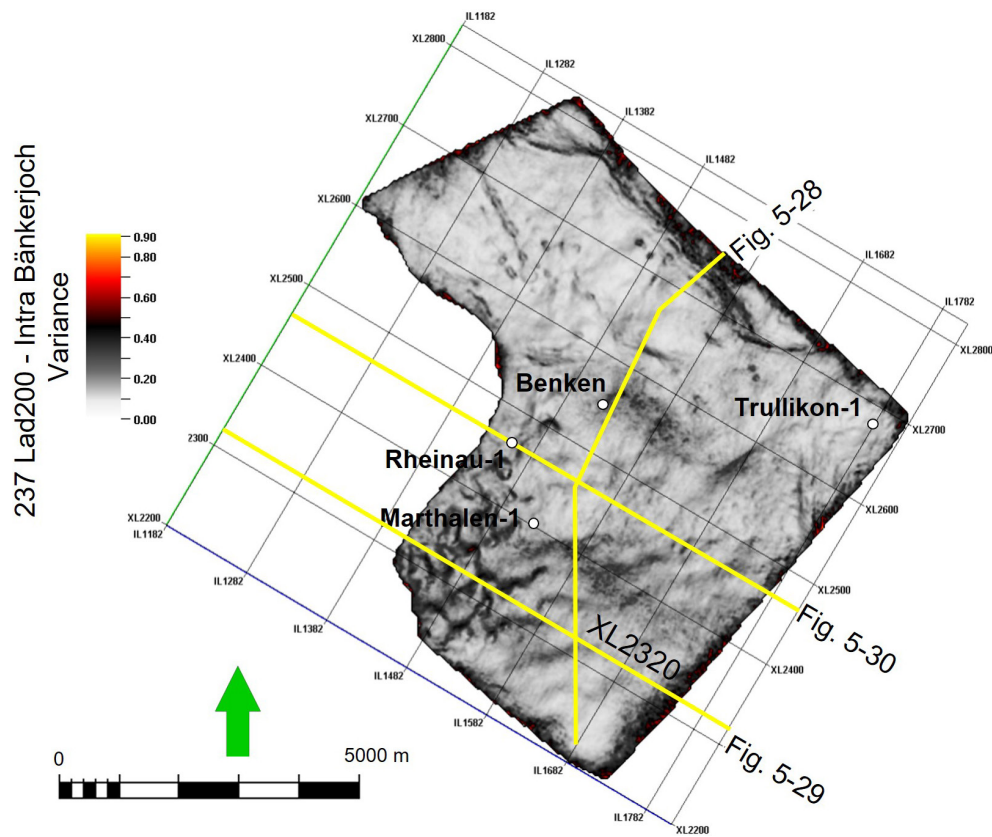


Fig. 5-27: 237 Lad 200 – Intra Bänkerjoch variance showing the position the four wells and the three key seismic sections illustrated in Fig. 5-28, Fig. 5-29 and Fig. 5-30

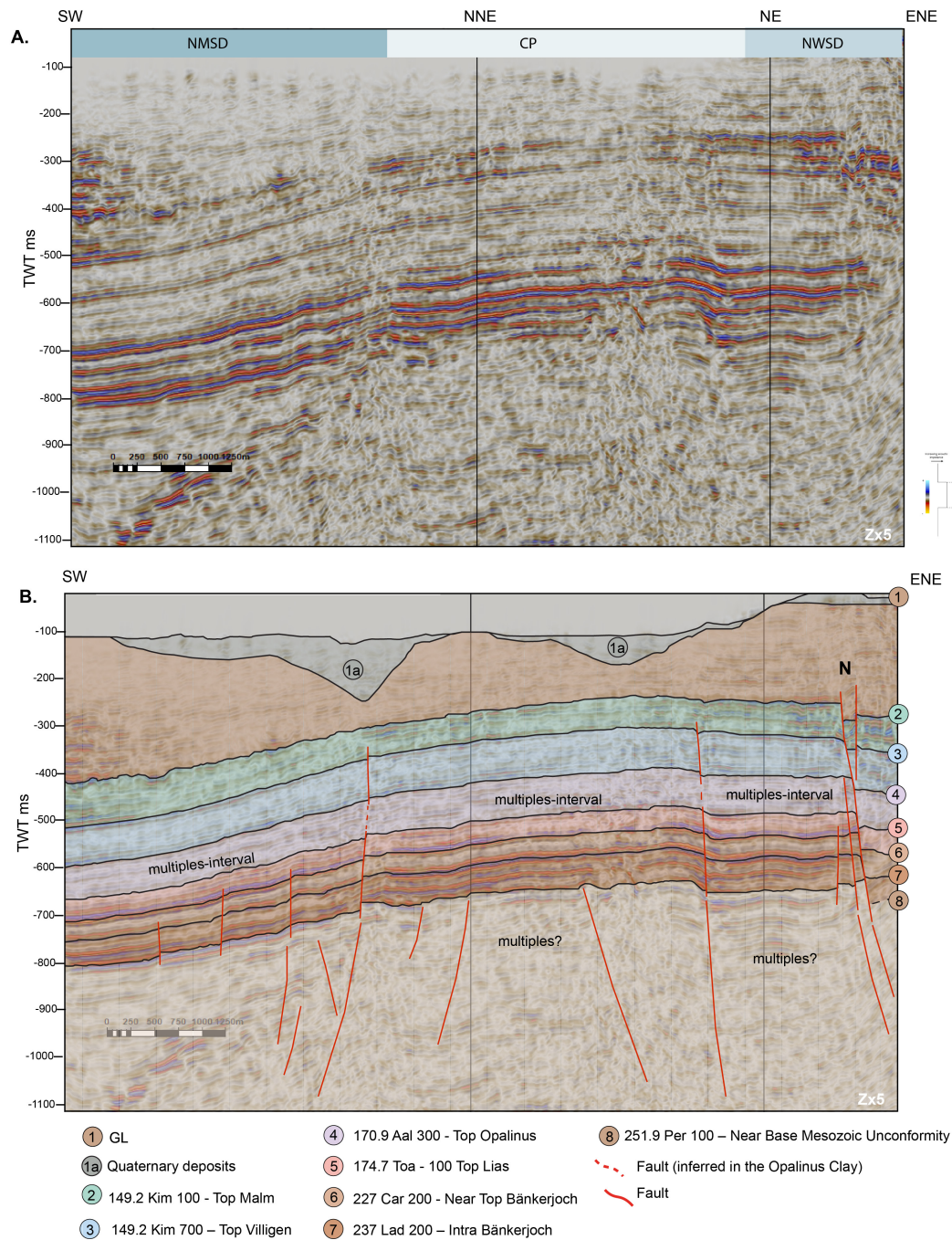


Fig. 5-28: Random line showing the fault interpretation and structural geometry and complexity across the ZNO siting region

A. Uninterpreted. B. interpreted. 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. If seismic faults are observed to displace both Top and Base Opalinus, the seismic fault is traced across the Opalinus Clay with a dashed line. This concept is not applied to the Neuhausen Fault (N), delimiting the eastern boundary of the ZNO 97/16 merged seismic survey. Line location is shown in Fig. 5-27. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. NWSD: Neuhausen-Wildensbuch Structural Domain, CP: Central Panel, NMSD: Niederholz-Marthalen Structural Domain.

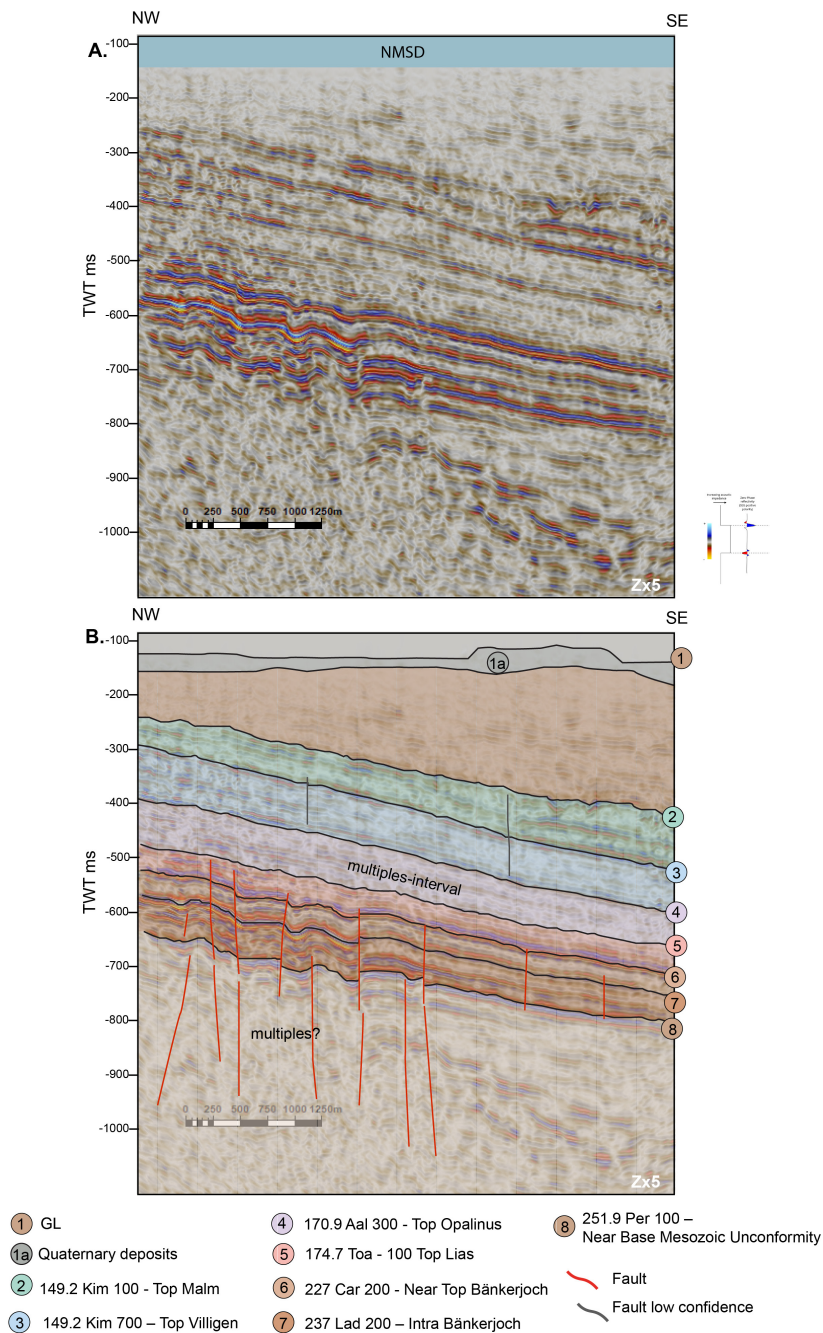


Fig. 5-29: Crossline 2320 showing the fault interpretation and structural geometry of high-angle faults and associated folds (particularly well developed in the Niderholz-Marthalen Structural Domain)

A. Uninterpreted. B. Interpreted. 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. If seismic faults are observed to displace both Top and Base Opalinus, the seismic fault is traced across the Opalinus Clay with a dashed line. Line location is shown in Fig. 5-27. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. NMSD: Niderholz-Marthalen Structural Domain.

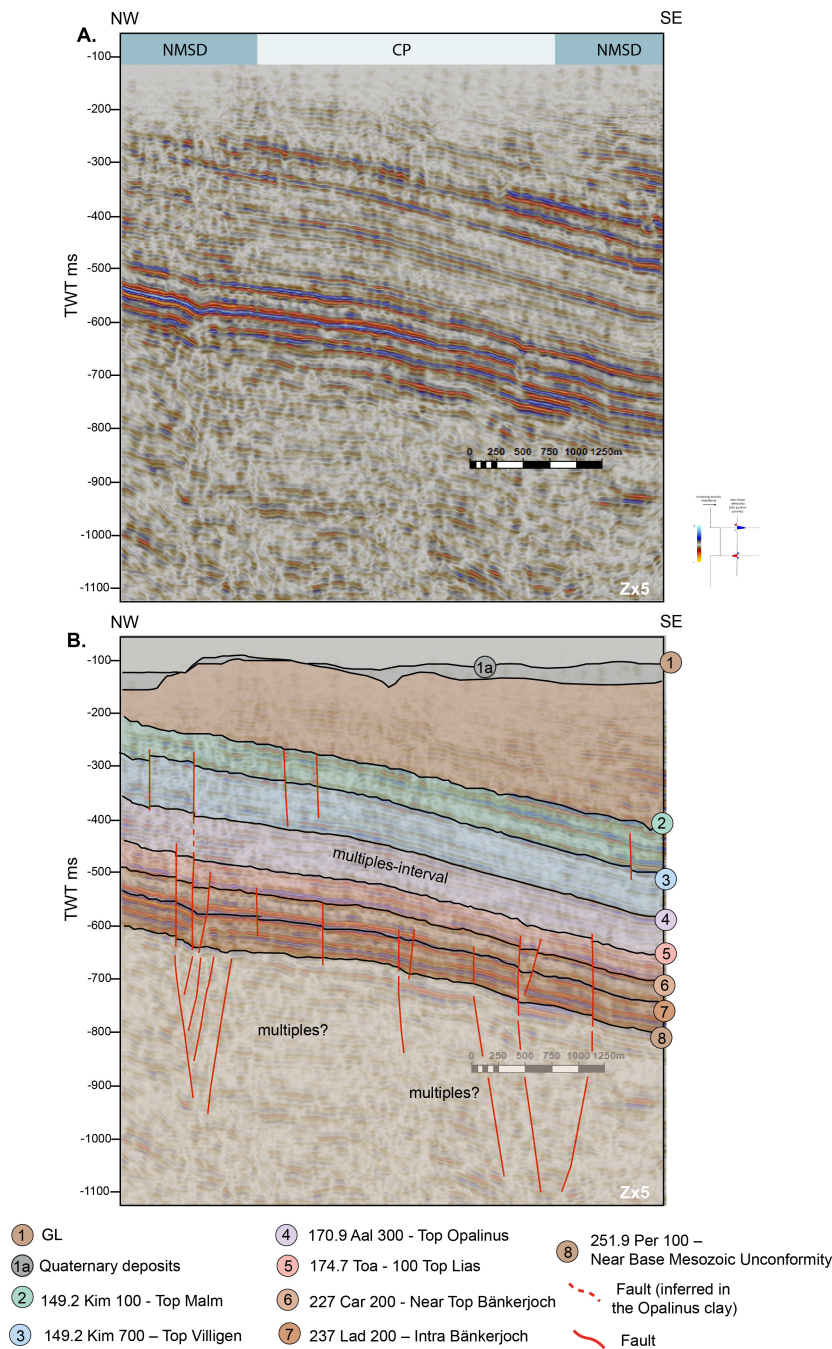


Fig. 5-30: Crossline 2465 showing the fault interpretation and structural geometry and complexity across the ZNO siting region

A. Uninterpreted. B. Interpreted. Only major basement faults were pencilled in 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 multiples. If seismic faults are observed to displace both Top and Base Opalinus, the seismic fault is traced across the Opalinus Clay with a dashed line. Line location is shown in Fig. 5-27. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. NMSD: Niderholz-Marthalen Structural Domain, CP: Central Panel.

When comparing the resulting structural maps (Fig. 5-23, Fig. 5-24, Fig. 5-26) to the preexisting interpretation (Nagra 2019, Fig. 5-31), differences in spatial distribution, geometry and density of faults can be observed, particularly within the central area of the ZNO-97/16 merged seismic survey.

Results from the available interpretations, as well as the observed differences, will be discussed in Chapter 6.

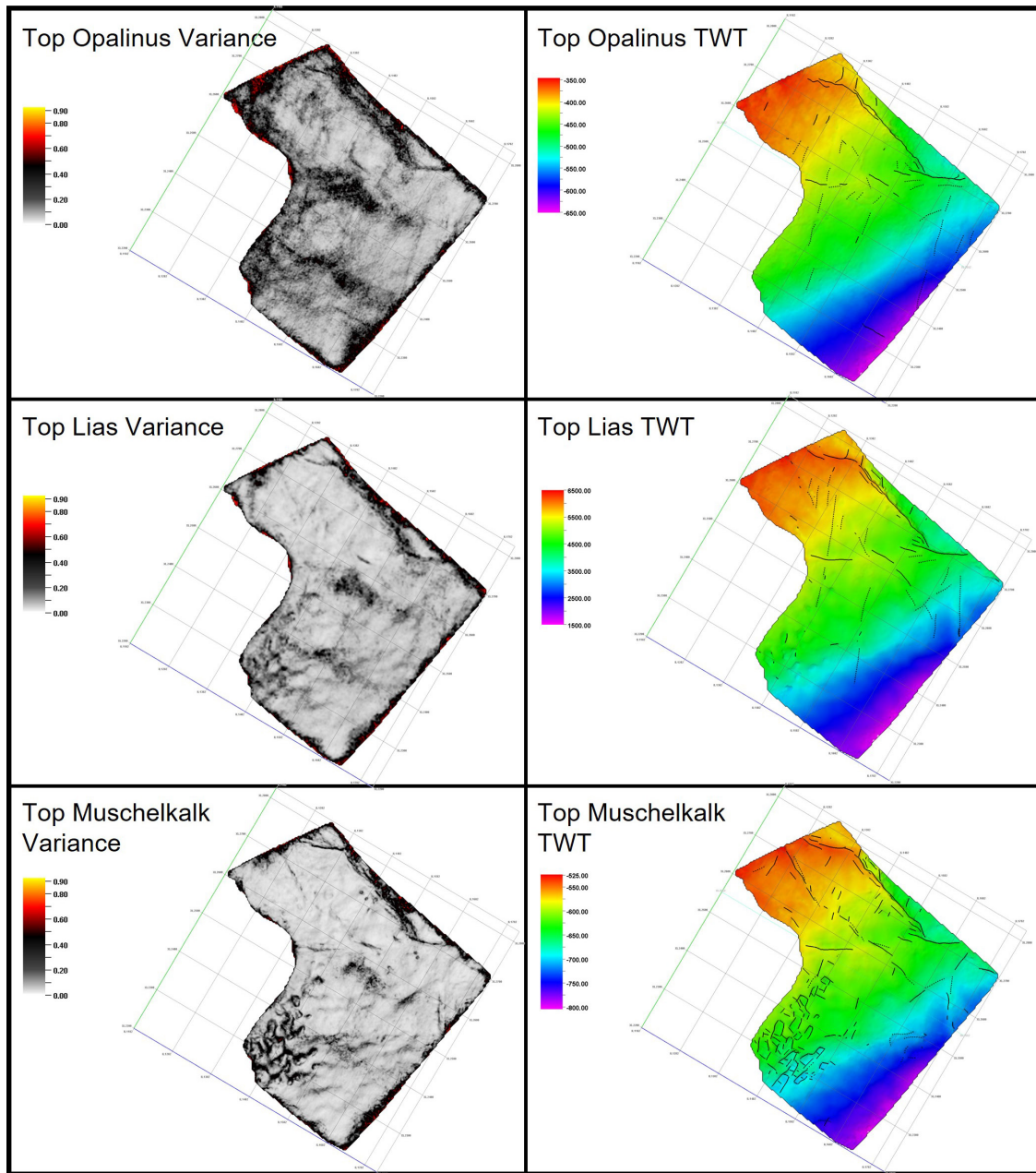


Fig. 5-31: Fault interpretation matrix from the 2018 evaluation (Nagra 2019)

Similar matrix to Figs. 5-28, 5-29 and 5-31 (variance horizon slices and TWT top structure), reproducing the 2018 fault interpretation (black lines) on a QLP dataset (Nagra 2019). Note that in NAB 18-36 only class A faults were shown for Top Muschelkalk, but maps with class A and class C faults were reproduced in this report from the original database. Class C faults are considered of lower confidence.

Black solid lines are class A faults and dashed lines are class C.

5.3.1 Structural Domains

Based on the 3D structural interpretation, structural deformation affecting the Mesozoic succession appears to cluster along major deformation zones. The ZNO siting region can be subdivided into three main structural domains as illustrated in Fig. 5-32, Fig. 5-28, Fig. 5-29 and Fig. 5-30:

1. Neuhausen-Wildensbuch Structural Domain (NWSD)
2. Niederholz-Marthalen Structural Domain (NMSD)
3. Central Panel (CP)

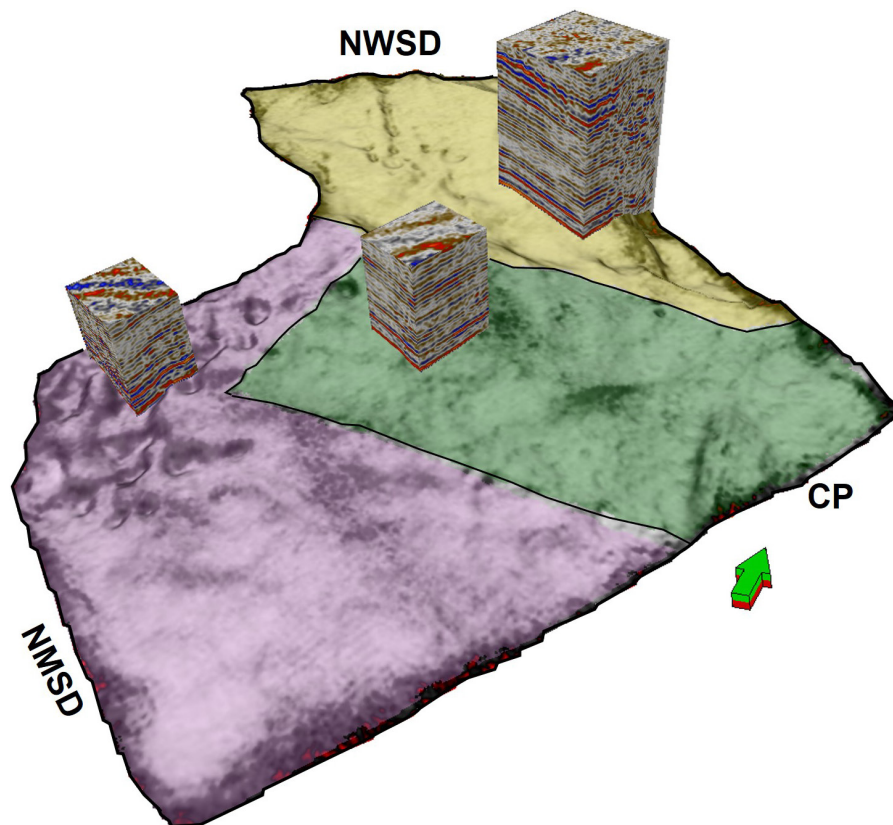


Fig. 5-32: 3D view of the three structural domains defined for the ZNO siting region

Variance horizon slice at horizon 237 Lad 200 - Intra Bänkerjoch illustrating the three structural domains. NWSD: Neuhausen-Wildensbuch Structural Domain (yellow), NMSD: Niederholz-Marthalen Structural Domain (pink), CP: Central Panel (green). Green arrow points toward north.

5.3.1.1 Neuhausen-Wildensbuch Structural Domain (NWSD)

The Neuhausen-Wildensbuch Structural Domain is bounded by the major regional tectonic elements of the Neuhausen Fault (N and N₁) to the east and by the Wildensbuch Flexure to the south (Fig. 5-33). Three main fault systems were recognised: (i) a NNW-striking fault system, parallel to the major segment of the Neuhausen Fault (N) and affecting solely the lower Mesozoic succession, with the exception of the Neuhausen Fault itself; (ii) a WNW-striking fault system, which shows a quite consistent spacing at deeper stratigraphic levels (i.e. below the Opalinus Clay interval) and includes the Wildensbuch Flexure and the Neuhausen Fault northern bend (N₁), and (iii) NE-striking faults affecting the Top Opalinus horizon. These observations are in accordance with previous interpretation work carried out on QLP seismic vintage (Nagra 2019).

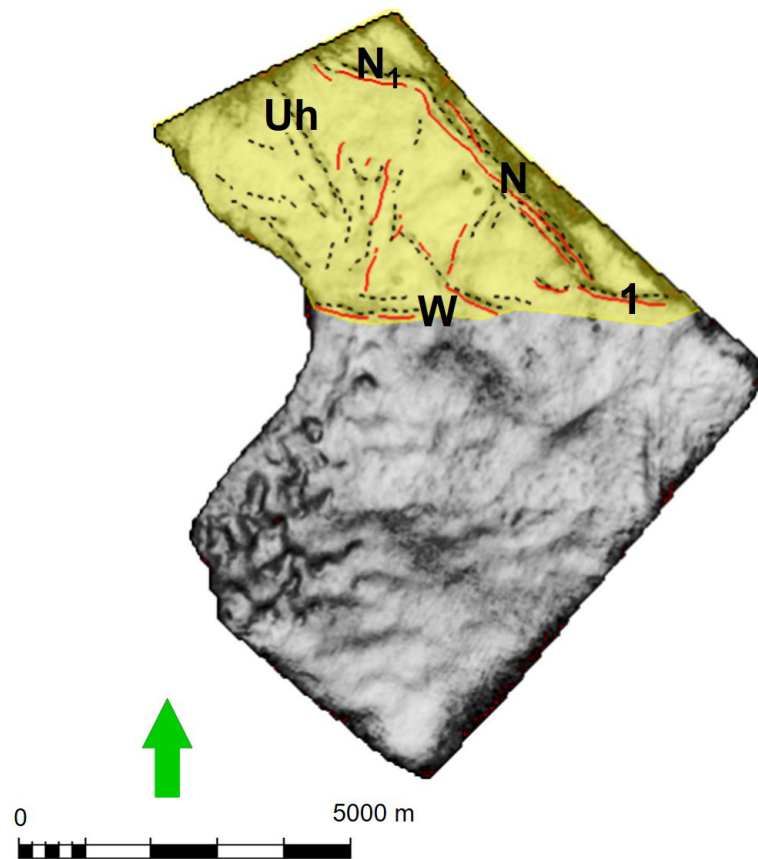


Fig. 5-33: Overview of the fault systems in the Neuhausen-Wildensbuch Structural Domain

237 Lad 200 - Intra Bänkerjoch variance horizon slice with, highlighted in yellow, the Neuhausen-Wildensbuch Structural Domain. Black dashed lines are fault traces at 237 Lad 200 - Intra Bänkerjoch with superimposed in red (solid) fault traces at 170.9 Aal 300 - Top Opalinus.

Key structural features: Neuhausen Fault (N) and its WNW-striking branch (N₁), Wildensbuch Flexure (W), 1 branch of Neuhausen Fault / Wildensbuch Flexure and the Uhwiesen Fault (Uh).

The Neuhausen Fault (Fig. 5-28, Fig. 5-34), was previously described based on geological surface mapping (Hofmann 1981) and in much greater detail by Birkhäuser et al. (2001) and NAB 18-36 (Nagra 2019). It is a NNW-striking fault showing a normal sense of displacement and a complex fault architecture with the presence of splays at different stratigraphic levels (Fig. 5-28, Fig. 5-34).

Its length was regionally estimated up to several tens of kilometres, with the main NNW-striking segment traceable up to 3 km within the seismic survey area. This structure was recognised as a regional fault zone marking the western limit of the Bodensee Graben System (Nagra 2014, Egli et al. 2016). Important vertical displacements around 40 ms TWT can be observed along strike.

Because of the fault dimension and the observed important vertical displacement, the fault stick, representing the fault plane, was not vertically segmented across the Opalinus Clay (as for proposed picking approach), but it was continuously traced (Fig. 5-28, Fig. 5-34).

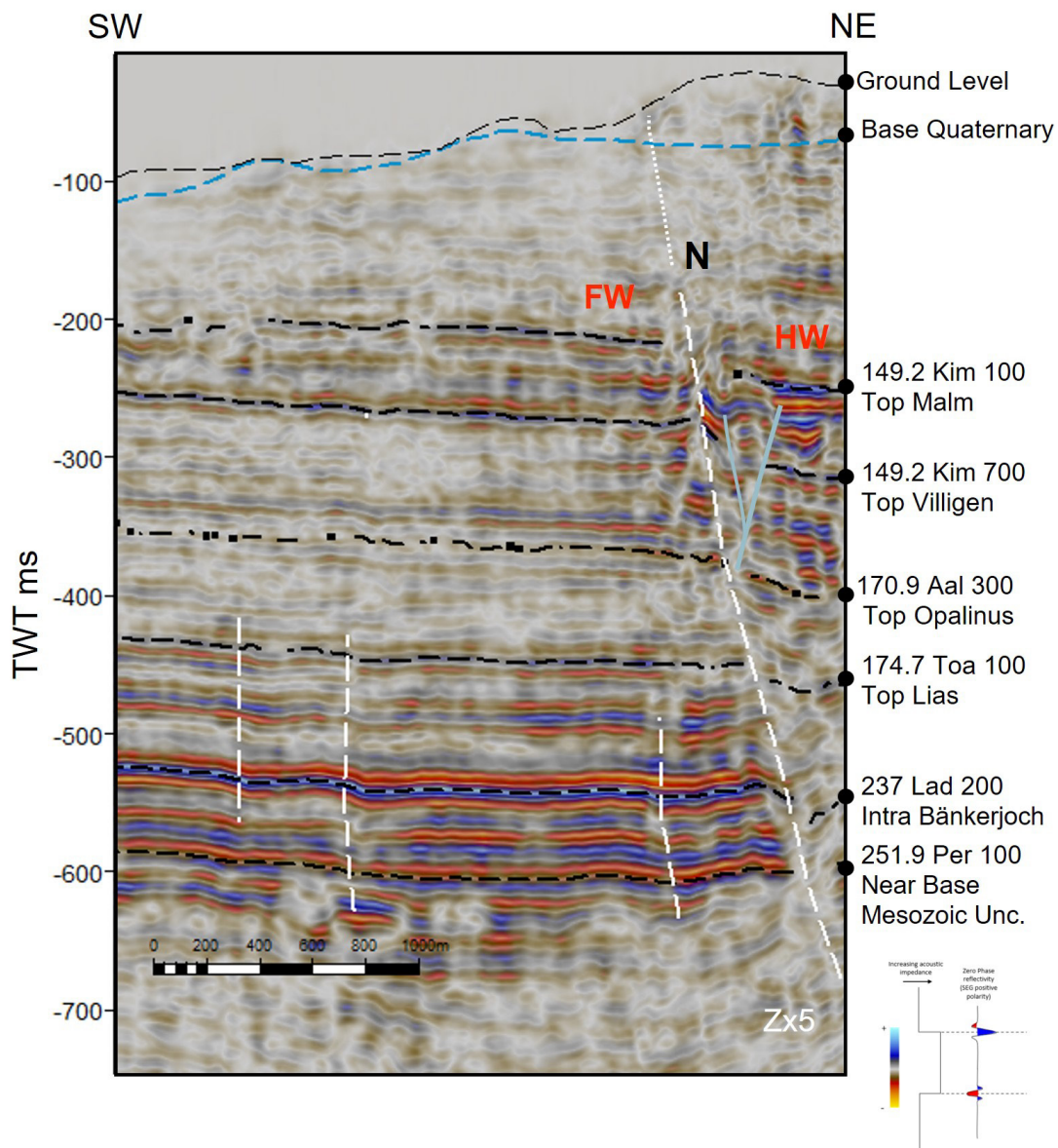


Fig. 5-34: Random seismic line across the Neuhausen Fault

This fault shows a complex architecture along strike, with fault splays at different stratigraphic levels (greyish lines). Sense of slip is generally normal, however the position of its hanging-wall block (HW) at the edge of the seismic survey makes the correlation between footwall (FW) and hanging wall (HW) reflections challenging. Note that the fault is traced up to the surface (thin white point dashed line), consistently with outcrop evidence (Hofmann 1981).

According to the NAB 18-36 interpretation (Nagra 2019), the seismically imaged part of the Neuhausen Fault can be subdivided into three segments along strike. The northern and southern segments were described in 2018 to be characterised by a strike roughly E-W (most likely WNW as referred to in this study, N_1 and 1, Fig. 5-33), whereas the central segment strikes NW-SE. The segments are arranged in a relay geometry and consist of several fault branches. Alternative view to this interpretation is to consider the southernmost segment is considered as part of the Wildensbuch Flexure (Fig. 5-33) as it is on trend with the other fault segments associated with this structure. Unfortunately, in the north, the seismic survey does not cover the lateral extension of the N_1 segment, therefore the presence of a second structure similar to the Wildensbuch Flexure cannot be inferred, and segment N_1 is therefore still considered part of the Neuhausen Fault. The Wildensbuch Flexure, despite being defined as a “flexure”, includes a series of WNW-striking fault segments that affect the entire Mesozoic succession and that are arranged in an en-echelon fashion, as already suggested by previous interpretation. Such en-echelon fault segments are interpreted to form part of a dextral transcurrent shear zone (Roche et al. 2001, Fig. 5-33, Fig. 5-35).

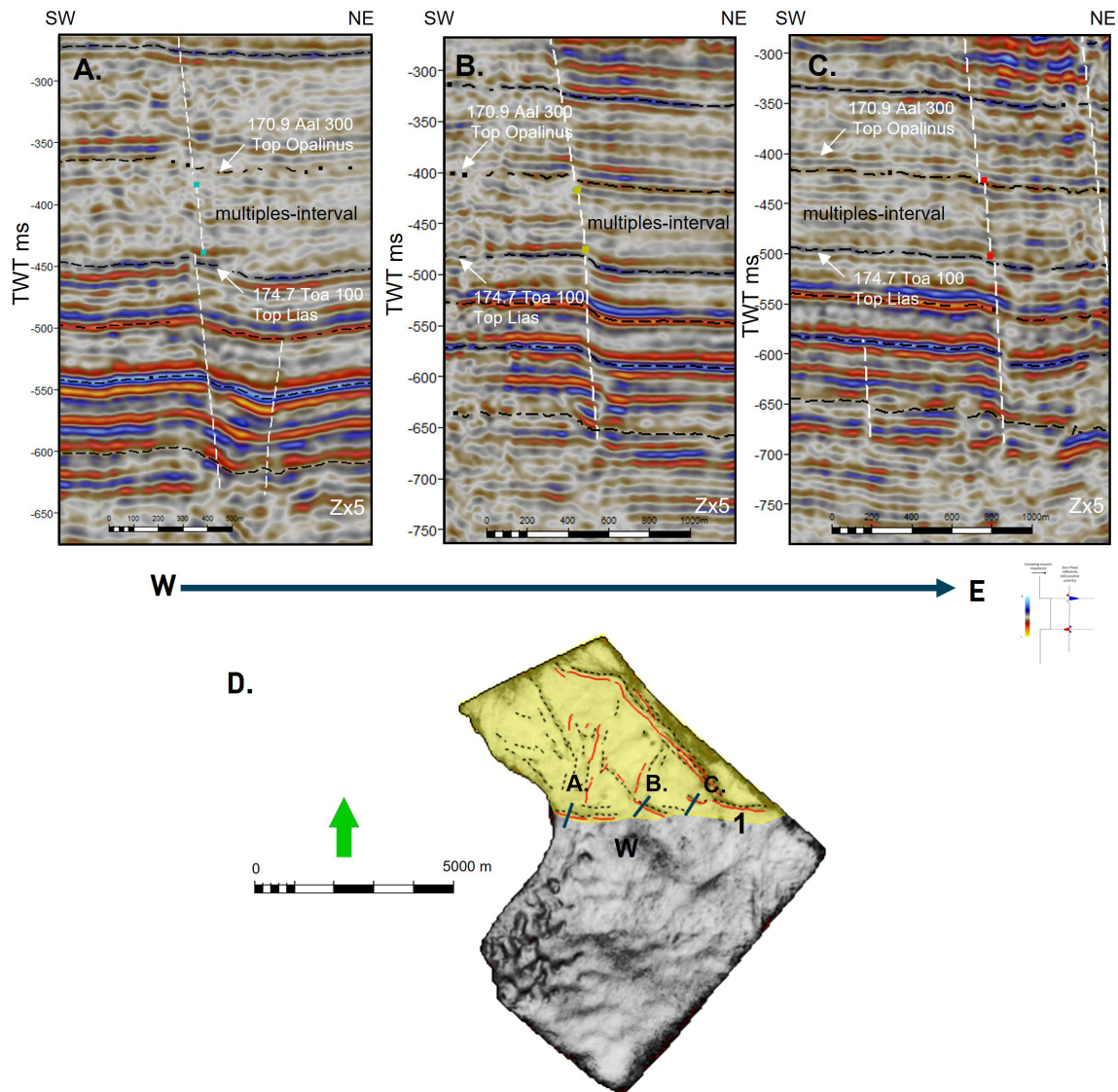


Fig. 5-35: Random seismic lines across the Wildensbuch Flexure fault segments

A., B. and C. NE-SW random seismic lines from west to east, displaying the main fault segments across the Wildensbuch Flexure (W). Note the implementation of the fault picking strategy across the Opalinus Clay interval. The fault was subdivided into three sticks where faults in the upper and lower competent layers were connected with a third stick (white dashed connecting the coloured squares) across the Opalinus Clay, where the presence of seismic multiples does not allow a seismic imaging-based interpretation.

The easternmost fault segment (indicated with 1 on map, B.), previously interpreted as part of the Neuhausen Fault, is considered here to belong to the en-echelon system of the Wildensbuch Flexure. Line locations are shown on 237 Lad 200 - Intra Bänkerjoch variance horizon slice (D). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Black dashed lines on the variance horizon slice are fault traces at 237 Lad 200 - Intra Bänkerjoch with superimposed in red (solid) fault traces at 170.9 Aal 300 - Top Opalinus.

Another key structure has been described within the perimeter of the Neuhausen-Wildensbuch Structural Domain and has been referred to in 2018 as the Uhwiesen Fault (Nagra 2019, Fig. 5-33). This fault strikes NNW-SSE with an orientation subparallel to the Neuhausen Fault and extends for a length of ~2.5 km at Muschelkalk/Bänkerjoch stratigraphic levels (Fig. 5-33), but it does not affect the upper Mesozoic succession - including the Opalinus Clay interval (Fig. 5-36). This fault is associated along strike with subcircular features (Fig. 5-33), which relate to dimmed, concave-downwards reflections at the Muschelkalk/Bänkerjoch stratigraphic levels (Fig. 5-36). Such features can be related to evaporite and/or carbonate dissolution, indicating a relationship between dissolution and faulting (i.e. diagenetic enhanced fault).

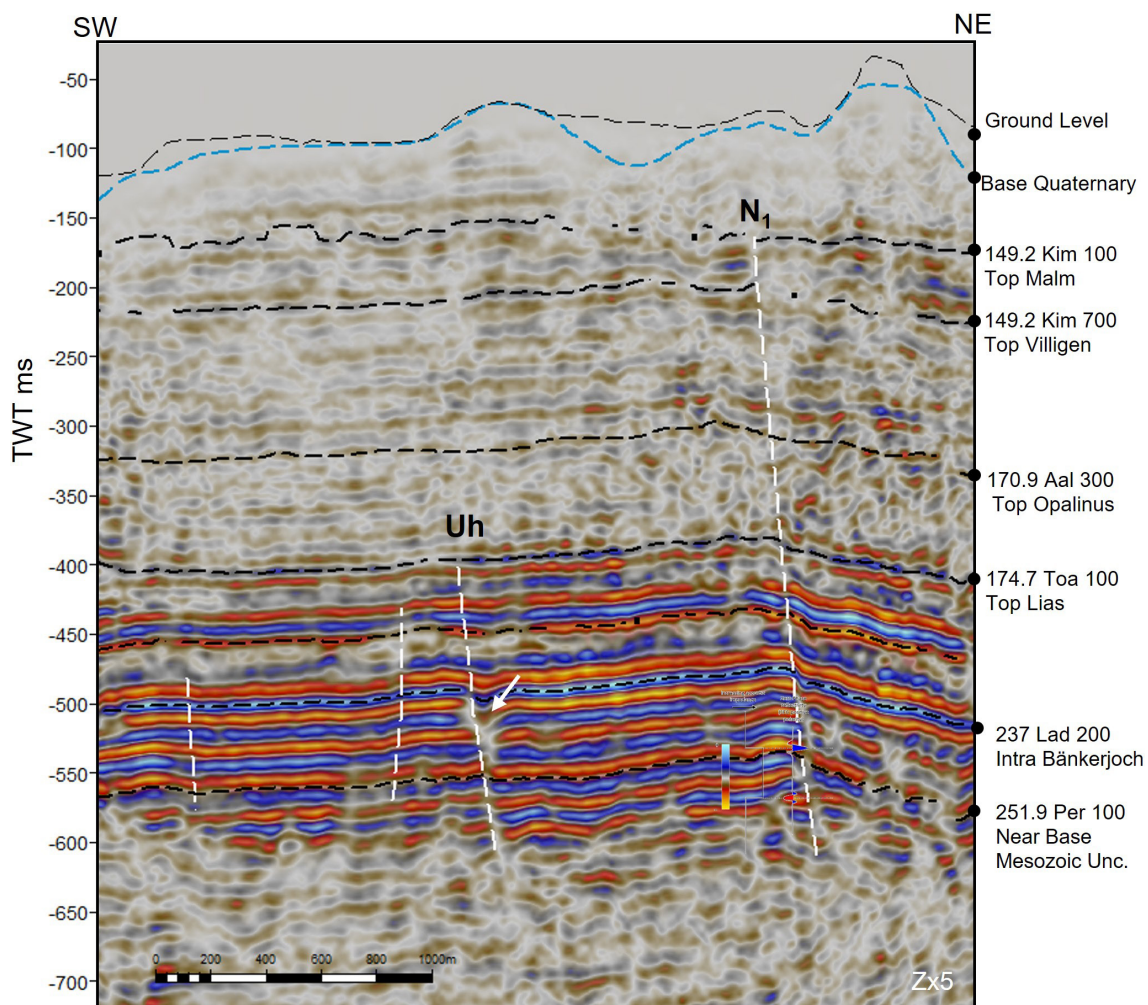


Fig. 5-36: Inline 1314 showing the Uhwiesen Fault

The Uhwiesen Fault (Uh) does not affect the Upper Mesozoic succession and appears to tip at the 174.7 Toa 100 Top Lias horizon (base of the Opalinus Clay interval). Note the dimmed concave-shaped reflection near 237 Lad 200 - Intra Bänkerjoch stratigraphic level (white arrow). N_1 is the WNW-striking segment of the Neuhausen Fault. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.3.1.2 Niderholz-Marthalen Structural Domain (NMSD)

The Niderholz-Marthalen Structural Domain (Fig. 5-29, Fig. 5-30, Fig. 5-37) covers the southern and western corners of the ZNO-97/16 merged seismic survey and includes known regional structures such as the Niderholz Structure Zone and the Rafz-Marthalen Flexure, as well as the northern continuation of the Niderholz Structure Zone, referred to here as the Rheinau Fault since it was penetrated by the Rheinau-1 deviated well.

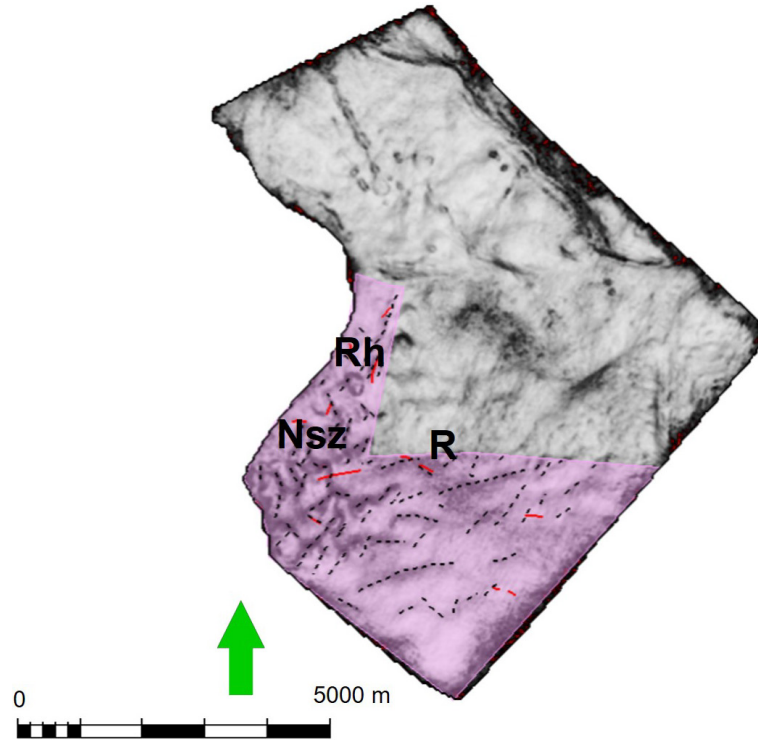


Fig. 5-37: Overview of the fault systems in the Niderholz-Marthalen Structural Domain

237 Lad 200 - Intra Bänkerjoch variance horizon slice with the Niderholz-Marthalen Structural Domain highlighted in pink. Black dashed lines are fault traces at 237 Lad 200 - Intra Bänkerjoch with superimposed in red (solid) fault traces at 170.9 Aal 300 - Top Opalinus.

Key structural features: Niderholz Structure Zone (Nsz), Rafz-Marthalen Flexure (R) and the Rheinau Fault (Rh).

The Niderholz Structure Zone was already described by Birkhäuser et al. (2001), by Marchant et al. (2005) and in NAB 18-36 (Nagra 2019) as a complex structural zone formed by NNE- to NE-trending faults representing reverse (inverted) faults (Fig. 5-38).

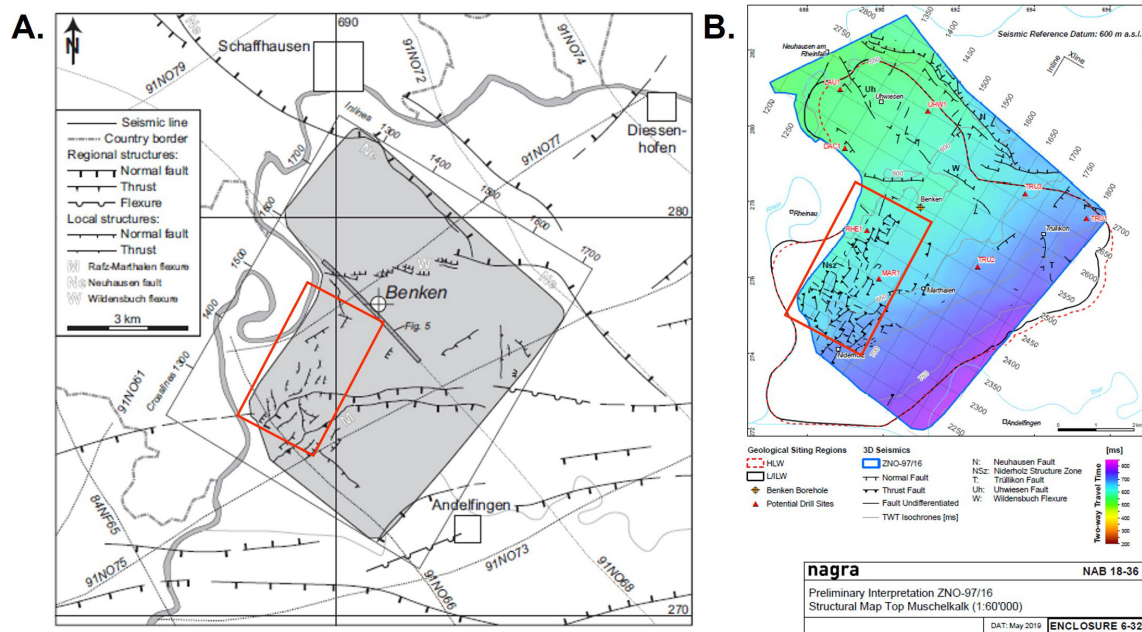


Fig. 5-38: Maps showing existing previous interpretations for the Niderholz Structure Zone (red polygon)

A. Interpretation proposed by Marchant et al. 2005 and B. interpretation proposed by Nagra 2019

Geometrically, seismic-scale deformation within this structural zone appears to be characterised by the presence of NNE- to NE- striking and NW-striking high-angle faults (and associated folds), which predominantly tip at the Top Lias (174.7 Toa 100 – Top Lias) and rarely affect the Opalinus Clay interval (Fig. 5-29, Fig. 5-39).

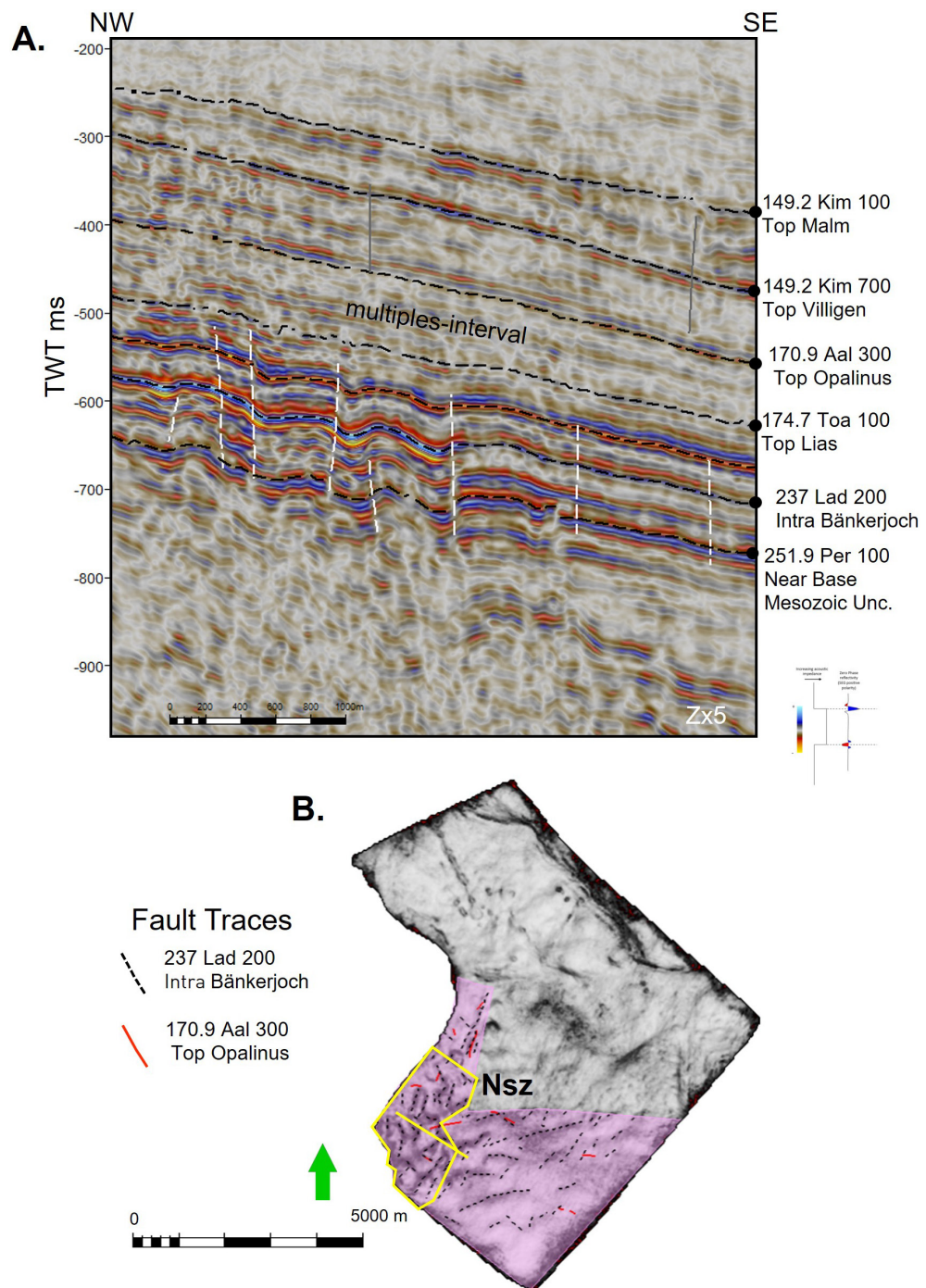


Fig. 5-39: Part of crossline 2320 showing the high-angle faults and associated folds particularly well-developed in the Niderholz Structure Zone (yellow polygon, B.)

A. Crossline 2320. Faults are shown as white dashed lines; only a few low-confidence faults were recognised above the Opalinus Clay (grey thin solid lines) not related to the deeper lineaments. B. Line location (yellow line) shown over 237 Lad 200 - Intra Bänkerjoch variance horizon slice with the perimeter of the Niderholz-Marthalen Structural Domain (NMSD) highlighted in pink. Fault traces are for 237 Lad 200 - Intra Bänkerjoch and 170.9 Aal 300 - Top Opalinus, showing that the NNE- and NE-striking faults belonging to this structural zone rarely affect the Opalinus Clay interval. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Folds also de-amplify upwards and do not propagate into the incompetent Opalinus Clay. Therefore, it is inferred that the deformation within the Opalinus Clay is accommodated in a more diffuse fashion (roughly homogeneous strain), as occurring in buckling (Fig. 5-40). The shortening produced by the folds is very minor, as reflected by the slight thickening observed in the Opalinus Clay interval and in an interval just below the Top Lias horizon (upper part of the Staffelegg Formation).

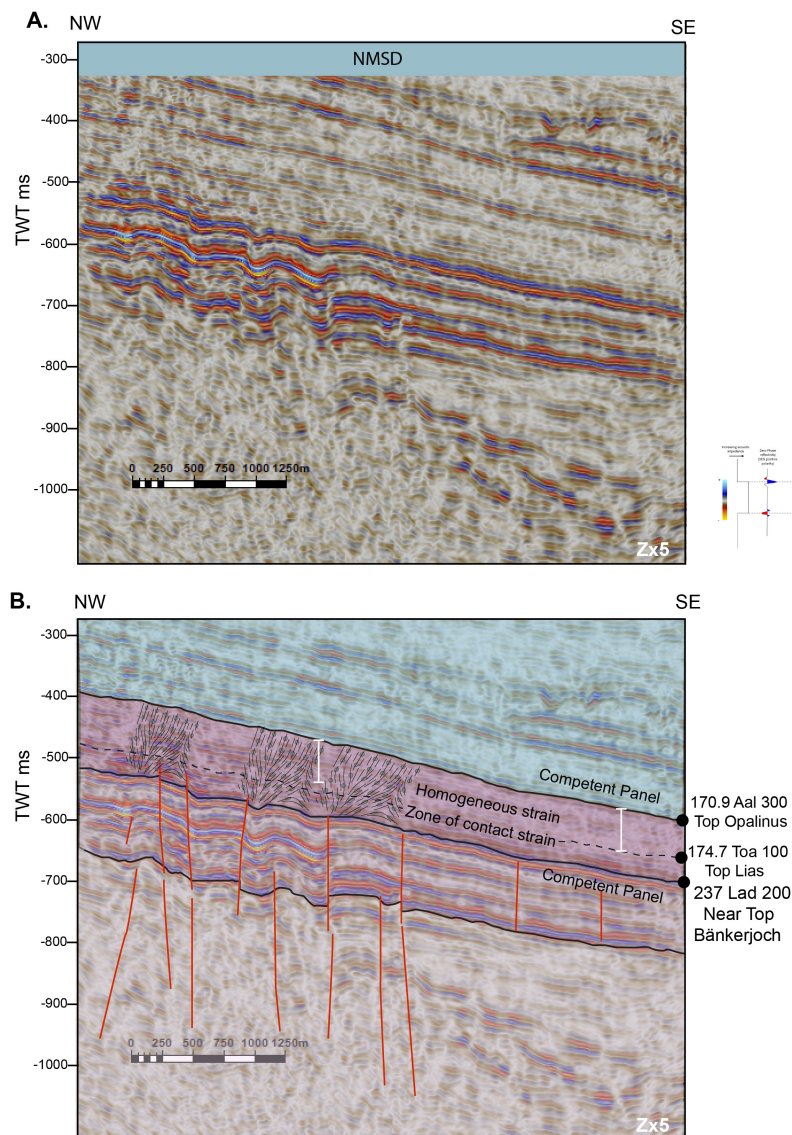


Fig. 5-40: Crossline 2320 showing the inferred deformation within the Opalinus Clay interval

A. Uninterpreted and B. interpreted seismic line across the Niderholz-Marthalen Structural Domain (NMSD). Faults (red lines) and folds de-amplify above the lower competent unit (Near Top Bänkerjoch) and the strain associated with the minor folding is accommodated roughly homogeneously with a slight thickening of the Opalinus Clay (see white bar) and in the interval just below 174.7 Toa 100 – Top Lias. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

As folds in this sector are mostly associated with high-angle faults, characterised by a relatively short length (few hundred metres; Fig. 5-37) and showing two dominant strikes (NNE-SSW to NE-SW and NW-SE), the development of the Niderholz Structure Zone may be interpreted as resulting from dominant strike-slip motion.

The Niderholz Structure Zone extends towards the north, forming a narrow deformation zone formed by predominantly NNE- to NE-striking en-echelon segments, referred to here as the Rheinau Fault (Fig. 5-37, Rh), since the Rheinau-1 deviated well was planned and drilled with the purpose of characterising the deformation associated with high-angle faults within the Opalinus Clay (Fig. 5-41, Nagra 2023).

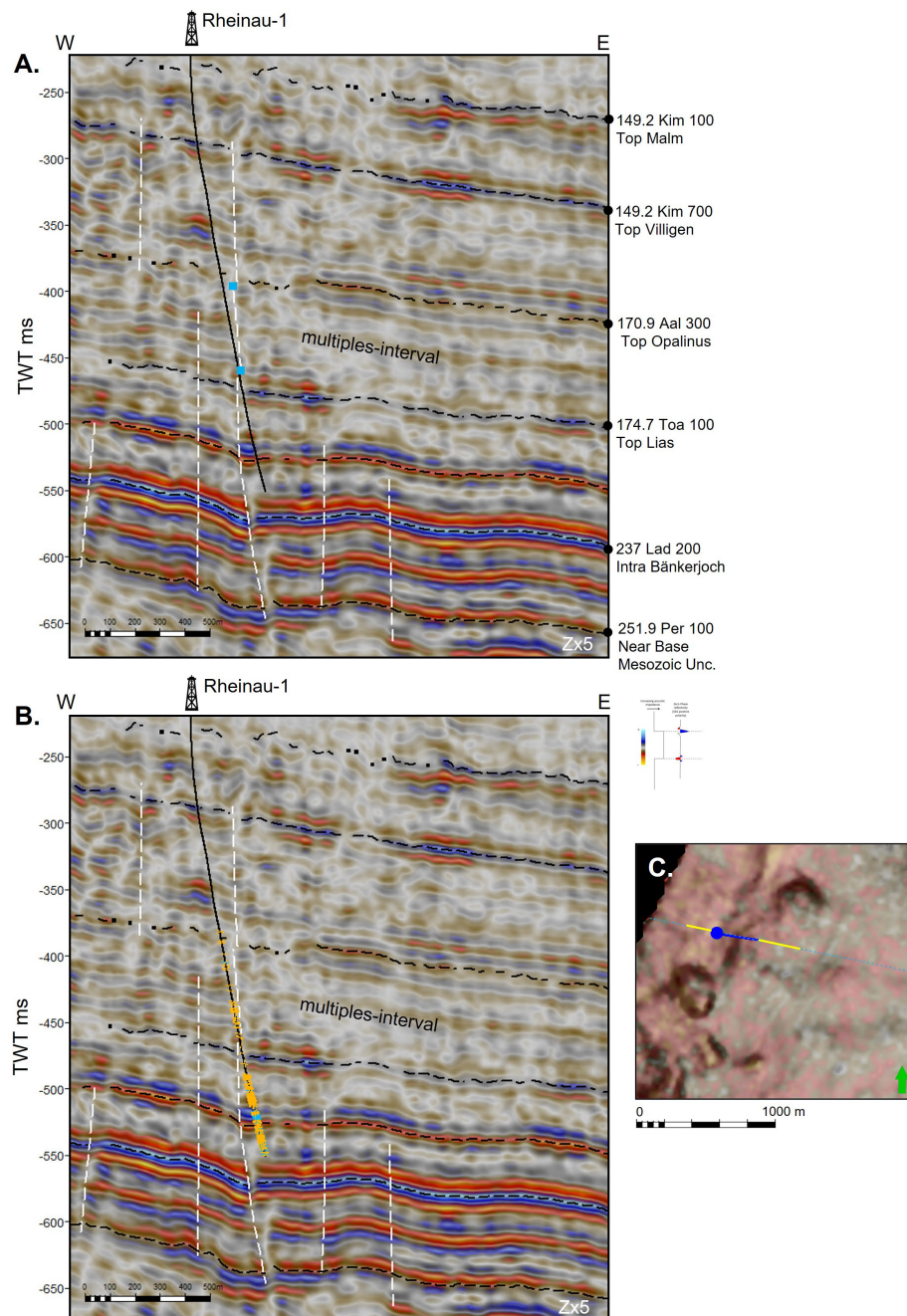


Fig. 5-41: Random seismic section along the Rheinau-1 deviated well trajectory

A. Interpretation of the Rheinau Fault. Note that consistently with the proposed approach, the fault was subdivided into three segments defining the upper and lower competent layers and the Opalinus Clay (fault stick with light blue squares). B. Same displays as for A., but with core structures plotted along the well (orange sticks are (micro-) fault planes and light blue are (micro-) mirror-like fault planes, Nagra 2023). Note the clustering of core structures within the Opalinus Clay interval near the seismic (inferred) fault plane. Fault interpretation in seismic was performed independently from core structural analysis and only compared at a later stage. Consistently with the concept proposed for the Niderholz Structure Zone, the deformation within the Opalinus Clay interval is inferred to be accommodated by diffuse deformation. C. Rheinau-1 well trajectory (blue) and line location (yellow) are shown over 237 Lad 200 - Intra Bänkerjoch variance and RMS horizon slice. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Seismic interpretation of the Rheinau Fault on PreSTM-ref dataset was performed independently from the well results and the fault sticks were mapped prior to the availability of the core structural inventory. Considering the two different scales of the observation, the seismic interpretation and the well structural inventory offer a consistent image of the Rheinau Fault. The highly segmented nature of this structure (laterally and vertically) indicates a strong control of mechanical layering on its development, whereas the inferred strike-slip kinematics is consistent with the vertical articulated fault throw profile (Fig. 5-42).

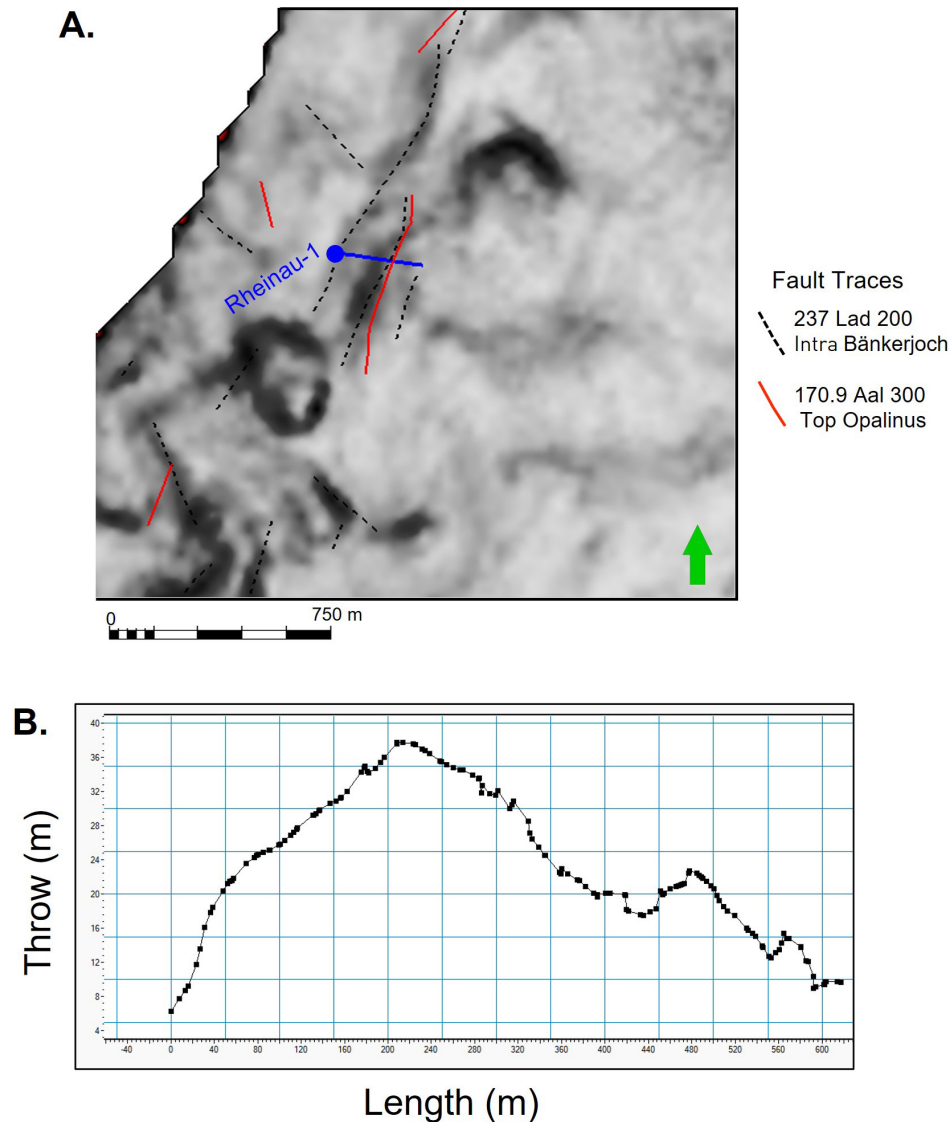


Fig. 5-42: Structural dimensions of the Rheinau Fault

A. Zoomed-in display of 237 Lad 200 - Intra Bänkerjoch variance horizon slice showing the lateral segmentation of the structure and B. Throw/length profile calculated for the main segment at 237 Lad 200 - Intra Bänkerjoch stratigraphic level and automatically converted into depth using an interval velocity of 3800 m/s. The articulated throw trend may suggest amalgamation of fault segments, typically observed in an incipient transtensional system.

The Rheinau Fault can be consistently mapped in 3D, where the linkage with the deep-seated (basement) structural grain can be inferred by seismic data (Fig. 5-43).

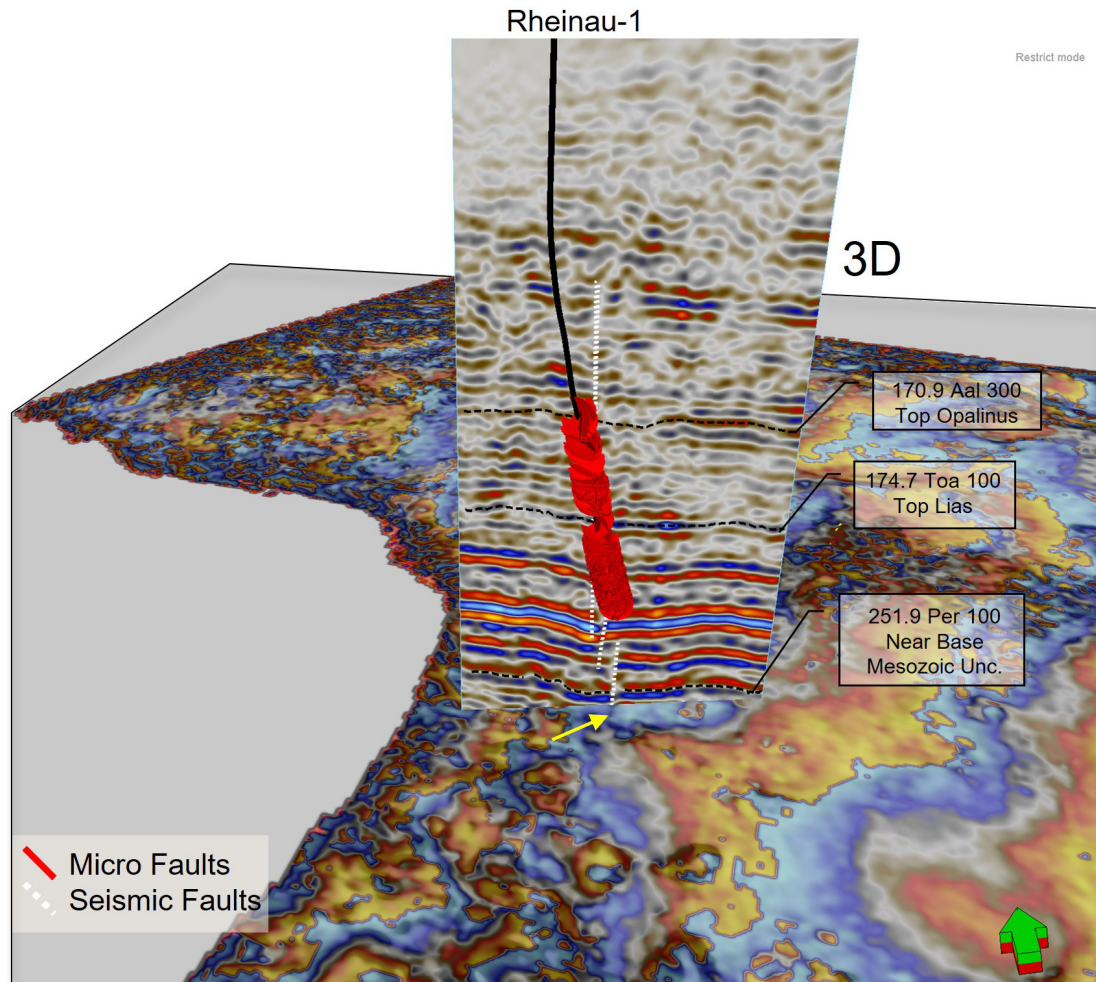


Fig. 5-43: 3D composite seismic display (in TWT) of the Rheinau Fault

Amplitude seismic section along the Rheinau-1 well displaying the interpreted fault segments (white lines) and the recognised major microstructure in the core (Nagra 2023) plotted with combined instantaneous phase and variance time slice at -650 ms TWT (below 251.9 Perm 100 – Near Base Mesozoic Unconformity), showing the relationship between the Rheinau Fault and deeper (Basement) structure. Green arrow points towards the north.

The Rafz-Marthalen Flexure (indicated with R, Fig. 5-37) was previously described by Birkhäuser et al. (2001) and NAB 18-36 (Nagra 2019) and interpreted to represent an E-W-striking monocline draping a reactivated basement fault marking the southern boundary of a horst structure in the crystalline basement.

The presence of a high-angle fault near the Marthalen-1 well, showing an ~E-W-strike related to a deeper (basement) structure, is nicely imaged in the PreSTM-ref dataset (Fig. 5-44). Consistently with previous observations, this fault appears to tip below the 171.7 Toa 100 - Top Lias reflector. However, the presence of a Quaternary valley, and its associated seismic noise, impairs the seismic signal. Therefore, despite the presence of some dimmed amplitudes, faults were not interpreted above the Opalinus Clay (Fig. 5-44).

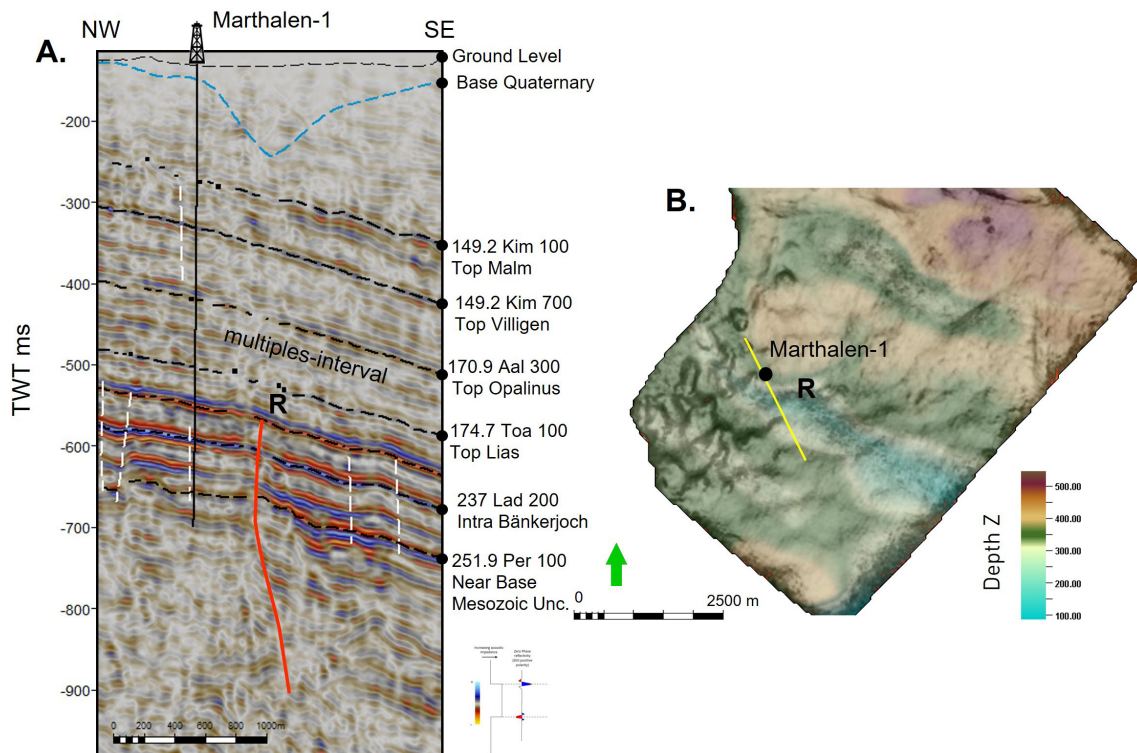


Fig. 5-44: Random seismic line showing the seismic expression of the Rafz-Marthalen Flexure

A. In section display, the fault (red line, R) in the lower Mesozoic interval can be connected to a deeper (basement) structural lineament. Despite some seismic disturbance observed in the upper Mesozoic interval (above the Opalinus Clay), faults were not mapped since the concomitant occurrence of a Quaternary valley strongly impairs the seismic imaging quality. B. Base Quaternary morphology displayed over 237 Lad 200 - Intra Bänkerjoch variance horizon slice highlighting the presence of the incised valley at the fault location. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.3.1.3 Central Panel

The Central Panel (Fig. 5-45) is the area bounded by the Wildensbuch Flexure to the north, by the Rafz-Marthalen Flexure to the south, by the Rheinau Fault to the west and by the continuation of the Neuhausen Fault to the east; the latter is outside the ZNO-97/16 merged seismic survey (Nagra 2014).

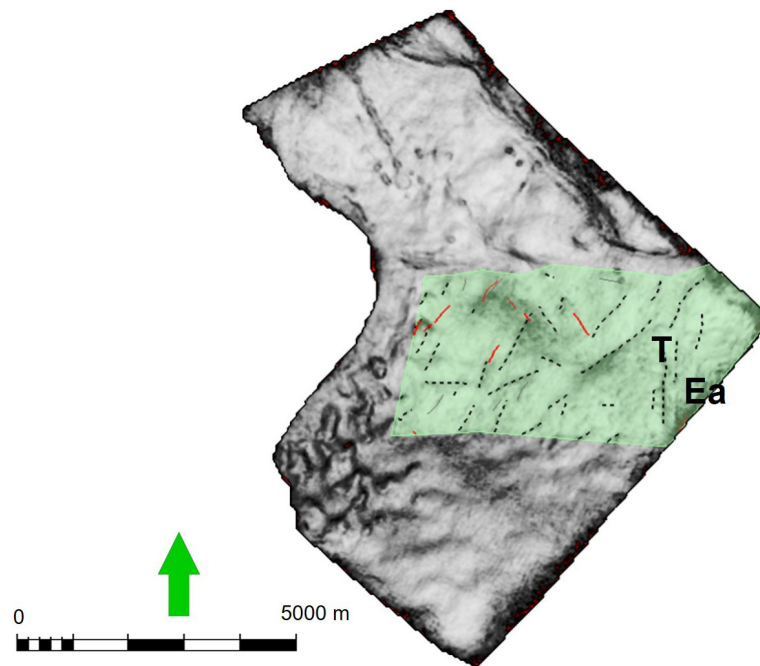


Fig. 5-45: Overview of the fault systems in the Central Panel

237 Lad 200 - Intra Bänkerjoch variance horizon slice with the Central Panel highlighted in green. Black dashed lines are fault traces at 237 Lad 200 - Intra Bänkerjoch, with low-confidence faults indicated as thin, solid grey lines. Superimposed in red solid lines are fault traces at 170.9 Aal 300 - Top Opalinus, with thin red lines for low confidence.

T is the Trüllikon Anticline and Ea represents an area affected by a seismic survey edge artefact where fault interpretation was not performed.

Seismic-scale deformation is associated with predominantly NNE- to NE-striking and rarely ~WNW- striking high-angle faults, which mainly affect the lower part of the Mesozoic succession (i.e. the succession underlying the Opalinus Clay interval; Fig. 5-45, Fig. 5-46). Despite being seismically subtle faults, these trends coincide remarkably well with the main Palaeozoic structural trends known from the Jura Mountains (Schori et al. 2021), which include NNE-SSW (“Rhenish”, N010°-N020°) and NW-SE (“Hercynian”, N120°-N130°) striking faults. This suggests that some of the faults observed in the Mesozoic succession may be controlled by inherited basement structures. The presence of seismic multiples is suspected below the Base Mesozoic Unconformity, which reduces the confidence in the fault interpretation of deeper structures.

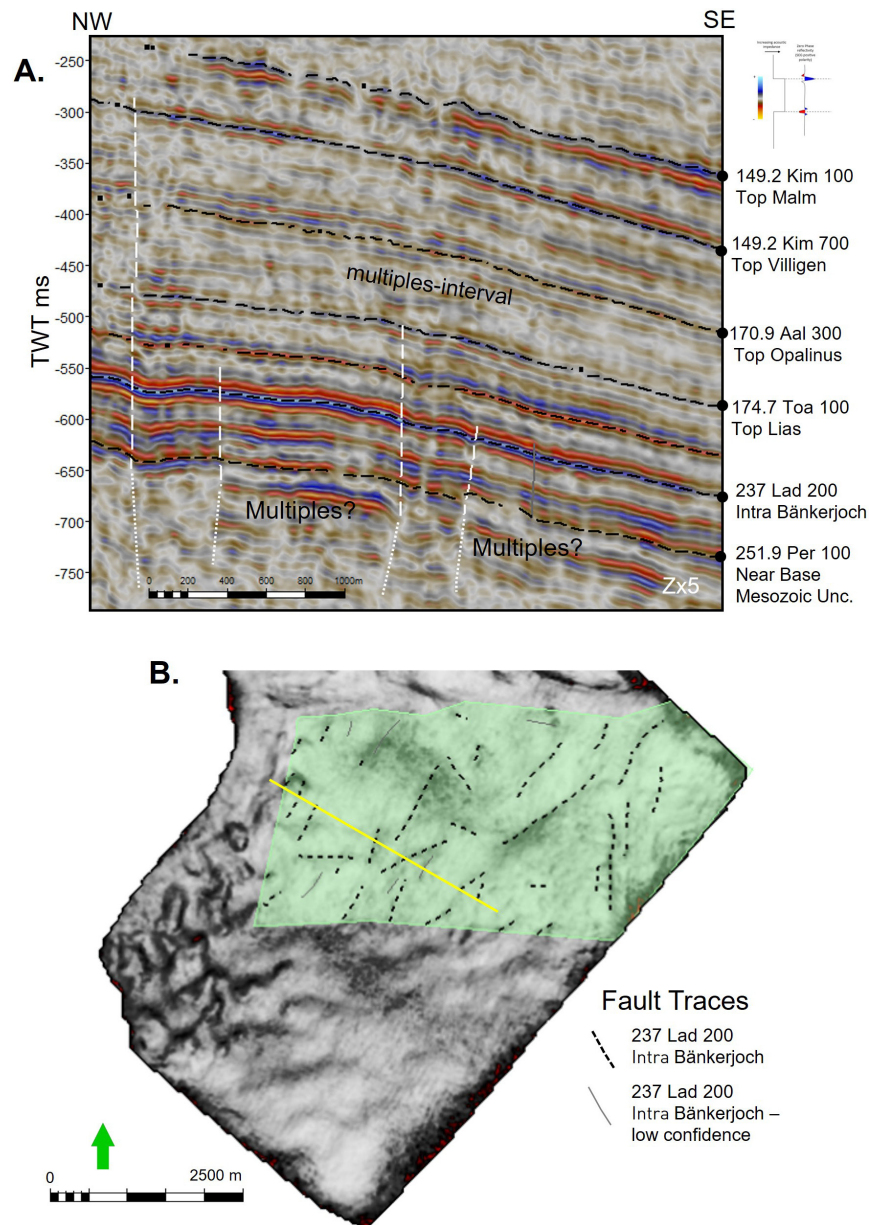


Fig. 5-46: Crossline 2491 across the Central Panel, showing the high-angle faults

The recognition and interpretation of such subtle faults are strongly driven by the attribute response and detailed evaluation of the amplitude response in a 3D integrated manner. Some of the faults (A., white dashed lines) observed in the Mesozoic succession can be related to inherited structures (white dotted dashed lines). However, the presence of seismic multiples below the Base Mesozoic Unconformity might impair the interpretation confidence for deeper structures. B. 237 Lad 200 - Intra Bänkerjoch variance horizon slice with line location (yellow solid line) and the Central Panel area (green polygon). Black dashed lines are fault traces at 237 Lad 200 - Intra Bänkerjoch. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Within the Central Panel, the Trüllikon Anticline was first described by Birkhäuser et al. (2001) and, consistent with the interpretation proposed in NAB 18-36 (Nagra 2019), represents a N-striking fault (Fig. 5-47) with a length of about 1.2 km at Lower Mesozoic levels. The fault does not affect the 174.7 Toa 100 - Top Lias horizon, vertically developing into a fault-tip monocline. A seismic discontinuity with similar strike is observed, located ~ 150 m to the east of the Trüllikon Anticline. This discontinuity is only partly interpreted as a fault, since it laterally extends into an area where the seismic imaging cannot be trusted because it is impacted by significant artefacts (disturbances) related to edge effects of the seismic survey (Fig. 5-1, area indicated by Ea in Fig. 5-47 B.).

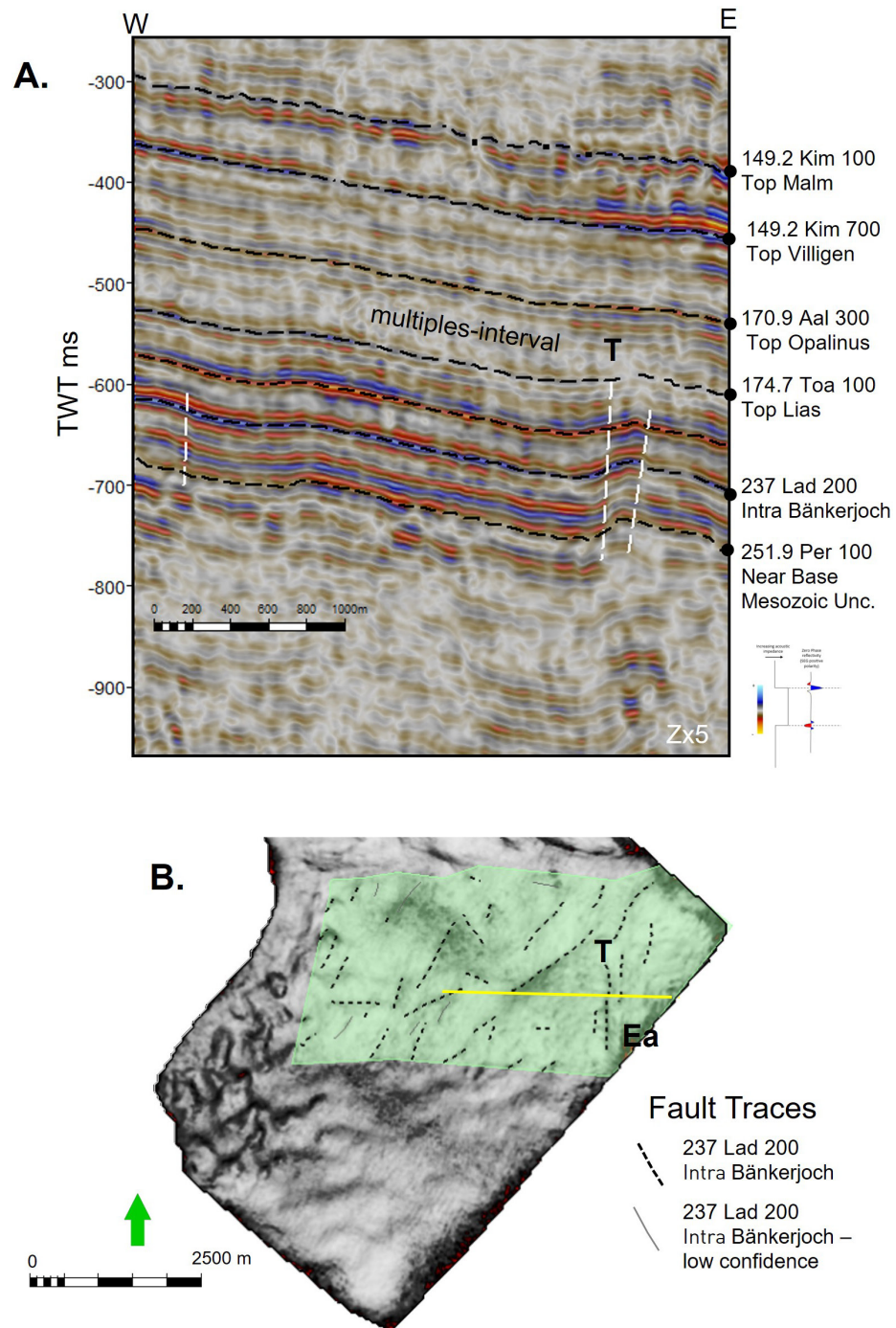


Fig. 5-47: Seismic display of the Trüllikon Anticline

The recognition and interpretation of such subtle faults are strongly driven by the seismic attribute response and detailed evaluation of the amplitude response in a 3D integrated manner. A. seismic section and B. 237 Lad 200 - Intra Bänkerjoch variance horizon slice with line location (yellow solid line) and the Central Panel area (green polygon). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

Despite a consistent seismic imaging of the discontinuity attributes of the several seismic processing vintages (Fig. 5-48), the resulting fault interpretation for the Central Panel differs from the previously proposed interpretations (Fig. 5-26, Fig. 5-23, Fig. 5-31, Birkhäuser et al. 2001, Nagra 2019). This indicates that the observed differences are likely to be related to the interpretation approach and/or to the human bias (interpreter). Since the fault distribution and its variability directly impact the definition of an undisturbed area, this critical point further investigated and elaborated in Chapter 6.

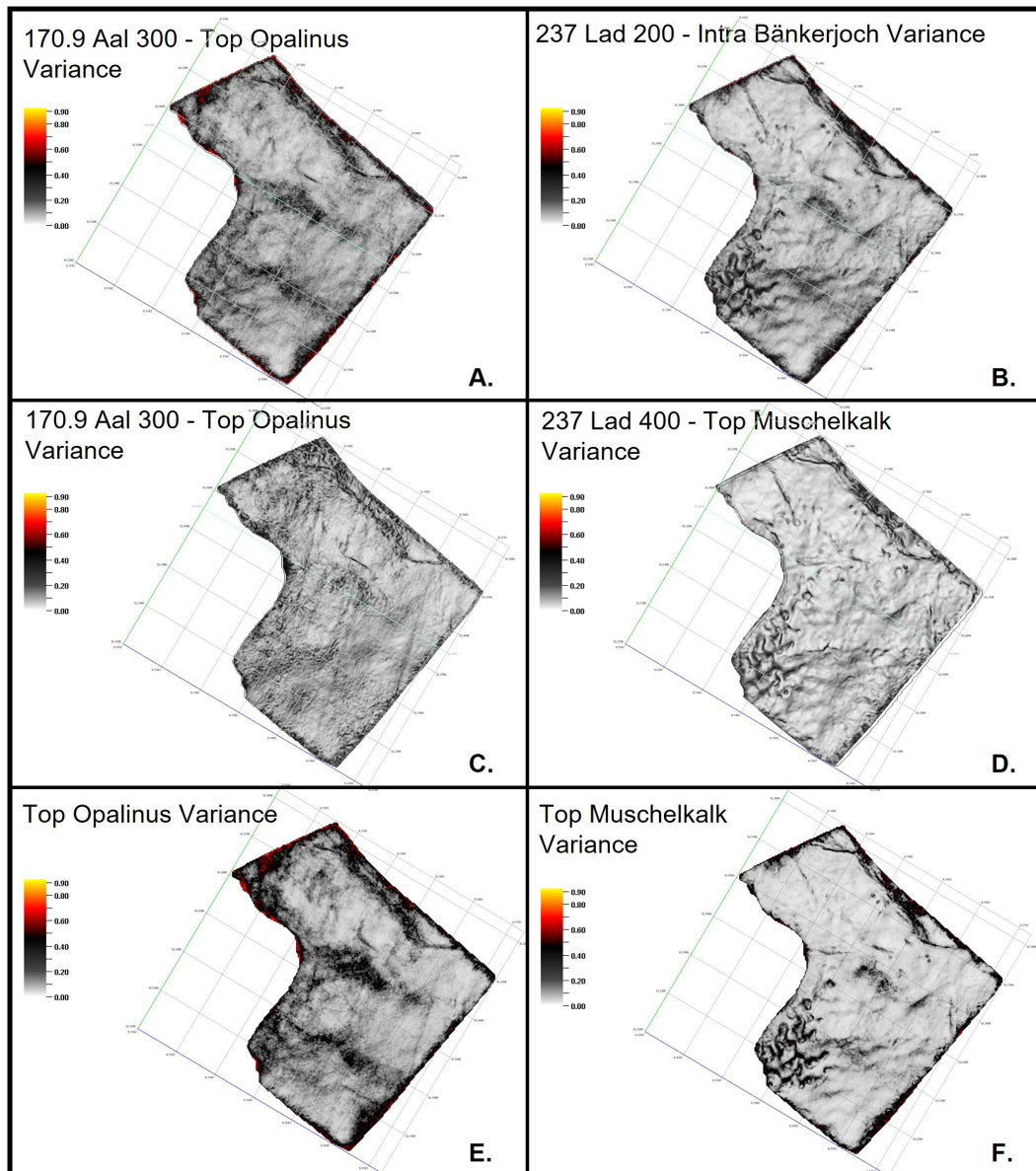


Fig. 5-48: Comparison of two key variance horizon slices for the three seismic vintages
237 Lad 400 - Top Muschelkalk or 237 Lad 200 - Intra Bänkerjoch and 170.9 Aal 300 - Top Opalinus horizon

A. and B. PreSTM-ref zero-phase; C. and D. QLP; and E. and F. PreSDM. Note the consistent seismic response and the presence of discontinuities in the central area of the seismic survey (Central Panel) in all the seismic vintages.

Subseismic deformation (cm- to mm-scale shear planes) is documented at core scale in the Marthalen-1, Rheinau-1 and Trüllikon-1 wells (Fig. 5-49; Nagra 2024d) located in the Niderholz-Marthalen Structural Domain and in the Central Panel, respectively. Reverse faulting recorded by core analysis may be interpreted as the result of subseismic deformation accommodating bulk coaxial strain (roughly homogeneous shortening) associated with the easternmost propagation of the Jura shortening by localised non-coaxial deformation zones (i.e. shear planes) at meso- and microscales (i.e. at core scale). On the other hand, the dominant normal faulting recorded by core analysis could be associated with the Neogene regional extensional phase. Strike-slip faulting recorded by core analysis could be associated with both Jura-related crustal shortening (i.e., accommodating deformation in an area of inhibited detachment-dominated thrusting due to the reduced thickness of the Triassic evaporites) and the mentioned Neogene regional extensional phase. To note that vertical wells have a natural bias to sample high angle (i.e. strike-slip) faults, since the lower likelihood to intersect them.

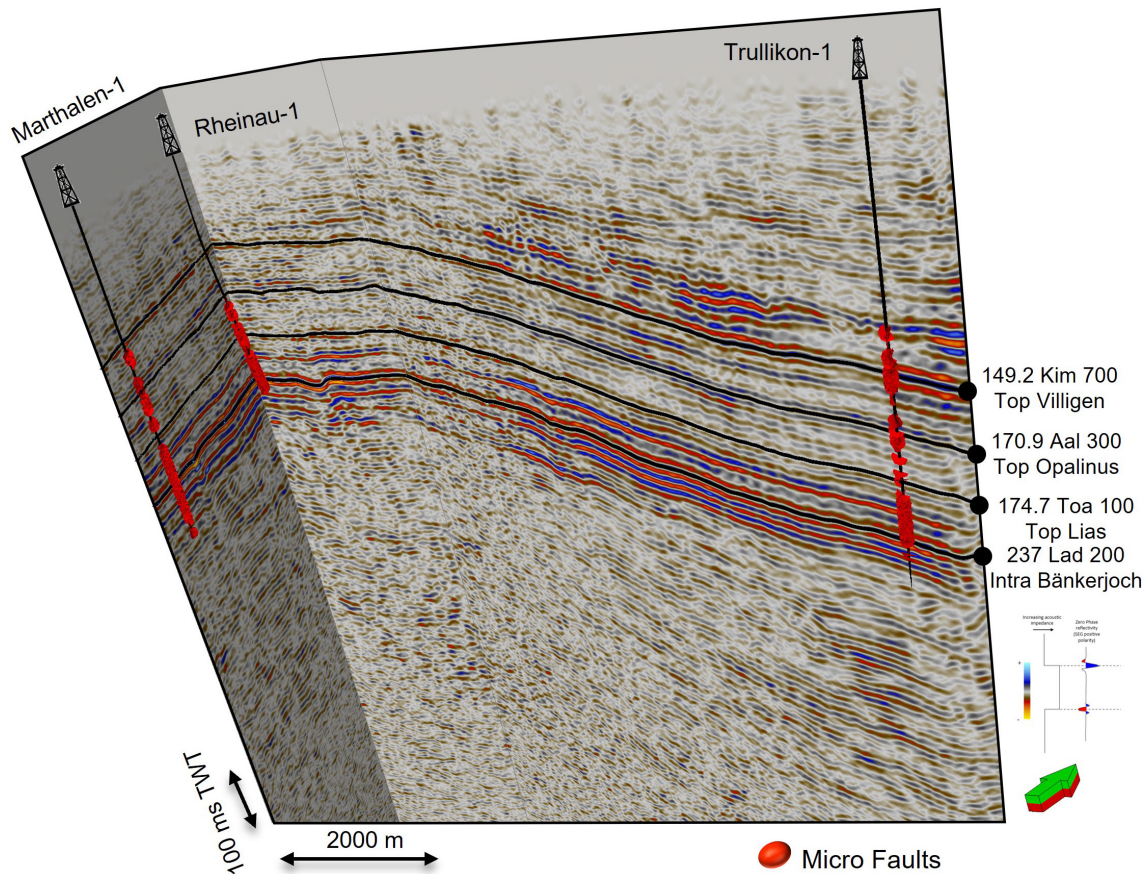


Fig. 5-49: 3D display of seismic and wells with core microstructure interpretation

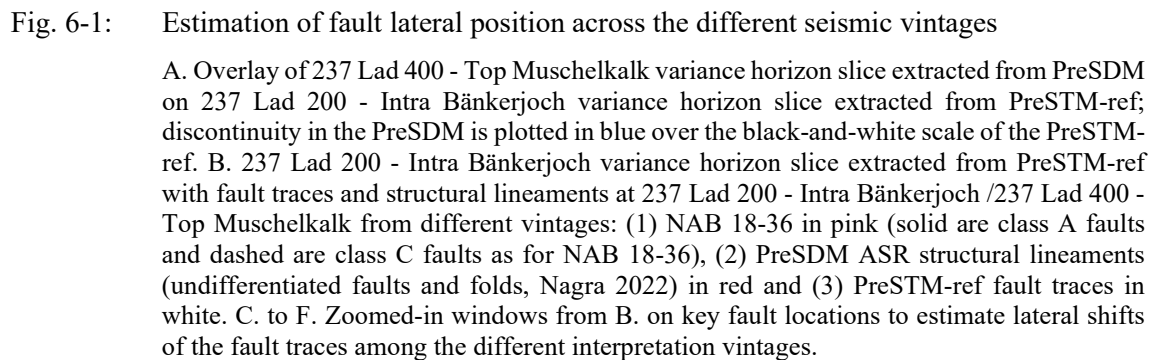
The seismic random line (PreSTM-ref reflectivity) with well microstructures from core description across Marthalen-1, Rheinau-1 and Trüllikon-1 wells located in the Niderholz-Marthalen Structural Domain and in the Central Panel, respectively. Green arrow points towards north.

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 the damage zones in 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 allows larger faults to be identified more easily than smaller faults due to 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 or other seismic features, higher weight was given to the pre-stack depth migration cube (PreSDM). Since ray bending was taken into account, PreSDM should result in a corrected lateral position of 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 slices (Fig. 6-1, Fig. 6-2), with measured lateral shifts generally lower than 50 m. Few cases were observed where the lateral distance between the same mapped faults on different seismic vintages reaches values up to 80 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.



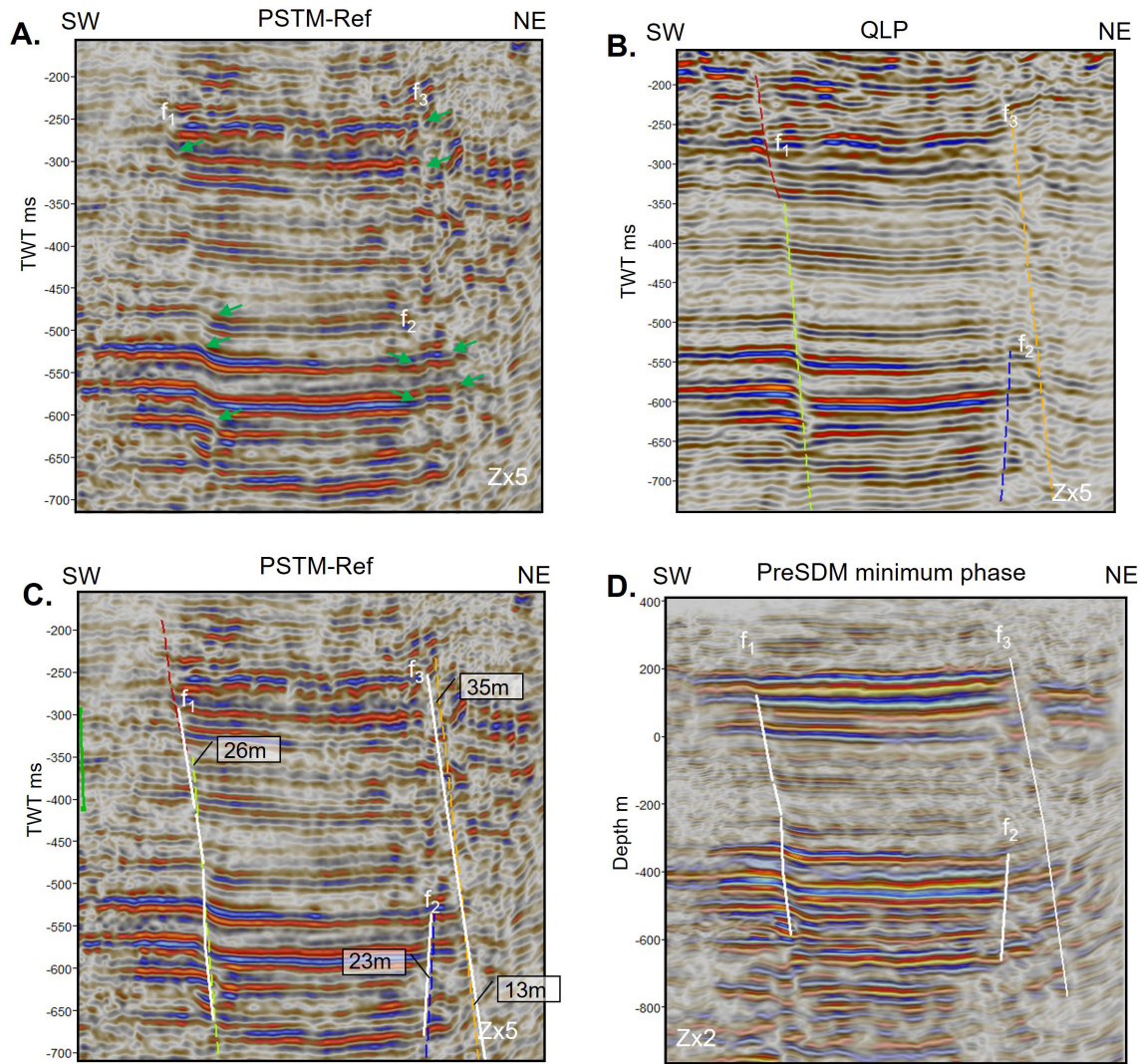


Fig. 6-2: Estimation of fault lateral position uncertainty across the different seismic vintages by comparing seismic fault signature across the different seismic cubes

A. Part of inline 1548 PreSTM-ref showing fault seismic indicators for three interpreted faults (green arrows, f_1 , f_2 and f_3) and B. same inline but QLP vintage with NAB 18-36 interpretation (same three faults - coloured dashed lines). C. Overlaying NAB 18-36 (coloured dashed lines) and 2023 fault interpretation (white solid lines) over PreSTM-ref seismic data. Lateral shifts (uncertainty) are ~28 m for f_1 , 23 m for f_2 . For f_3 , a lateral shift of 13 m was measured at the lower Mesozoic interval with lateral shift increasing to 35 m at shallow level, likely to be associated with degraded seismic imaging. When plotting the depth converted (2023) fault sticks on the PreSDM dataset (D.), f_1 and f_2 seem to nicely match the seismic data. Positioning and associated uncertainty for f_3 becomes challenging to evaluate due to the very poor image of the PreSDM dataset in this area.

6.2 Comparison with Previous Interpretations

Since the first seismic processing product (2018), Nagra has dedicated a continuous effort to seismic interpretation, with a strong focus on fault mapping. Several interpretation products covering different seismic vintages from different interpreters have been produced (Fig. 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. 5-31, NAB 18-36) 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 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 (NAB 18--36). 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 have been considered less robust since the structures have been 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 (NAB 18-36, Nagra 2019).

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

Interpretation Vintage	Seismic Data	Workflow	Products	Interpreter
NAB 18-36	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 23-19	PreSTM-ref zero-phase	3D interpretation → sections and attribute horizon slices	3D fault sticks/planes Fault traces at key horizons	Nagra + 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 Tab. 6-1) in the fault interpretation carried out on the PreSTM-ref minimum-phase seismic vintage (Fig. 6-3). In this interpretation vintage, however, only A-class faults were mapped. However, the number and density of faults decreased if compared to the NAB 18-36 interpretation, specifically in major structures such as the Wildensbuch Flexure, the Niederholz Structure Zone and the Rheinau Fault.

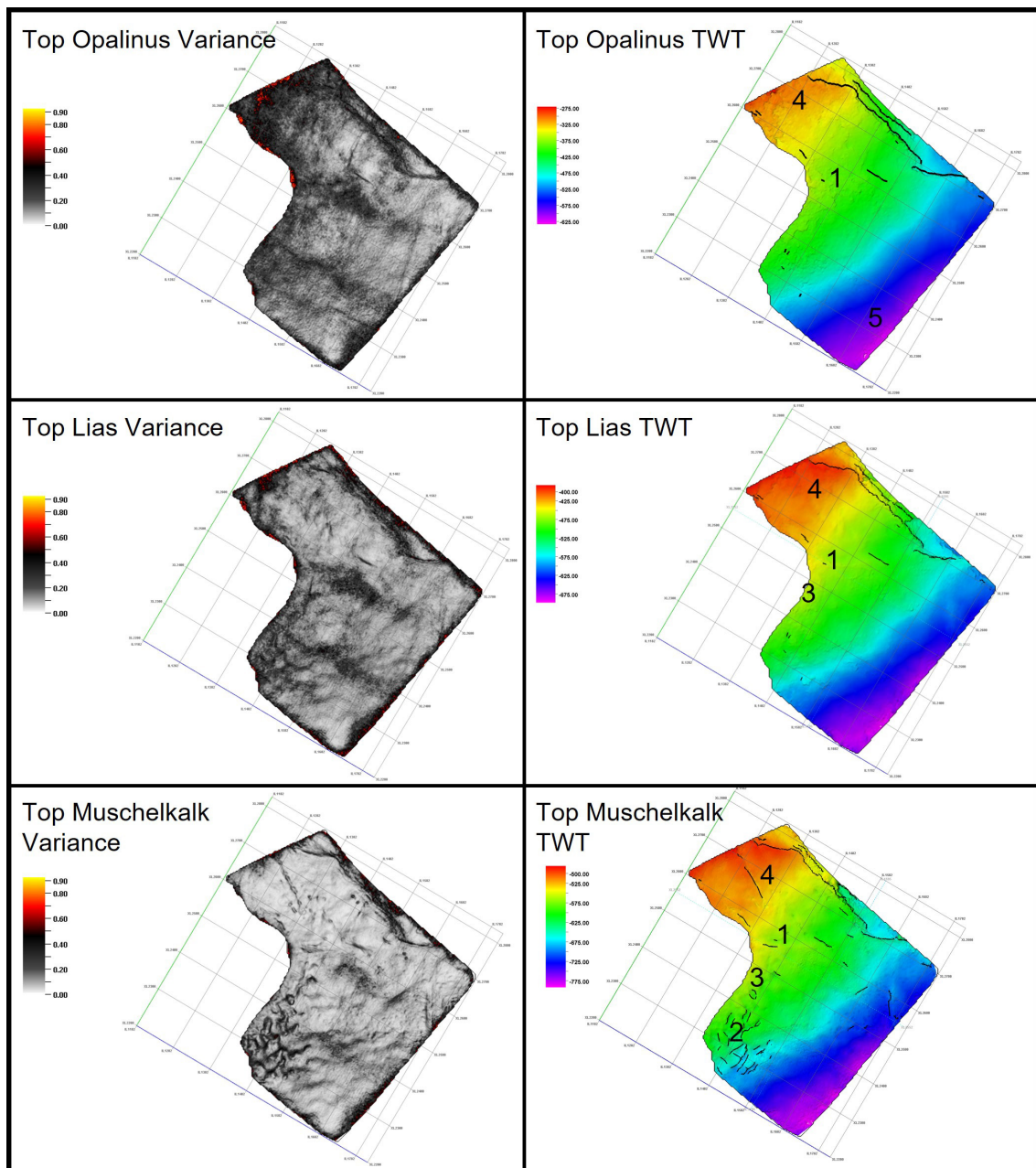


Fig. 6-3: Fault interpretation matrix - PreSTM-ref minimum-phase (interpreter A contractor 2022 evaluation)

Similar matrix to Fig. 5-23, Fig. 5-24, Fig. 5-26 and Fig. 5-31 (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. 5-31), note: 1: the fault segments forming the Wildensbuch Flexure are shortened at Top Muschelkalk level and hardly interpreted at Top Lias and Top Opalinus; 2: the fault segments characterising the complex Niederholz Structure Zone at Muschelkalk level are notably decreased in density; 3: the fault segments forming the Rheinau Fault are no longer interpreted and 4: small NE-striking faults in the northern sector of the seismic survey are also no longer considered as class A faults.

As input for the ASR evaluation (Nagra, 2022), a structural interpretation was carried out based both on a PreSDM, PreSTM-ref minimum-phase seismic vintages (Fig. 5-23, Fig. 5-24). The 3D screening approach has been described in the methodology section (Fig. 4-8, Fig. 4-9) and allowed the 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 deformation zones were mapped and displayed in a 2D map view of three key stratigraphic horizons. Such lineaments include indistinctive seismic faults and fault-tip monoclines (drape-folds on top of blind normal or reverse faults; Fig. 5-25).

Fault maps for all the available interpretations (Tab. 6-1) were captured in a graphic matrix (Fig. 5-23, Fig. 5-24, Fig. 5-26, Fig. 5-31 and Fig. 6-3).

Interpretations from different interpreters and/or different seismic processing vintages are displayed over the interpretation proposed in this 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, for the known regional structural elements (Neuhausen Fault, Wildensbuch Flexure, Uhriesen Fault, Rafz-Marthalen Flexure), the main difference is related to fault distribution and orientation, but the definition and dimension of the “deformation zones” associated with these tectonic elements is consistent. Nevertheless, despite the different spatial distribution and density, a consistent trend can be inferred, with a net decrease in the amount of deformation towards the shallow stratigraphic levels, specifically from the Base Opalinus Clay interval upwards.

When looking at the Phase 1 (ASR, Nagra 2022) interpretation results (Fig. 6-5, Fig. 6-6, Fig. 6-8) with “fault interpretation” products, the apparent interpretation divergence is related to the “definition/terminology” used for the interpreted mapped discontinuities. As previously mentioned, the ASR (Nagra 2022) deformation zones include faults and folds, and only seismic discontinuities which fit the proposed criteria (Fig. 4-8, Fig. 4-12) were “filtered” as faults.

The critical difference between the ASR (Nagra 2022) and 2023 interpretation products versus the interpretation products from Interpreter A Contractor (NAB 18-36, Nagra 2019 and 2022 Pre-STM ref interpretation) is the fault distribution in the Central Panel Structural Domain. In NAB 18-36, the Central Panel appears as a relatively undisturbed area, with few class C faults (Fig. 5-31, Fig. 6-4) bounding a central perimeter free of seismic-scale faults. In contrast, the proposed the 2023 interpretation identified the presence of small faults distributed within the entire domain boundary of the Central Panel.

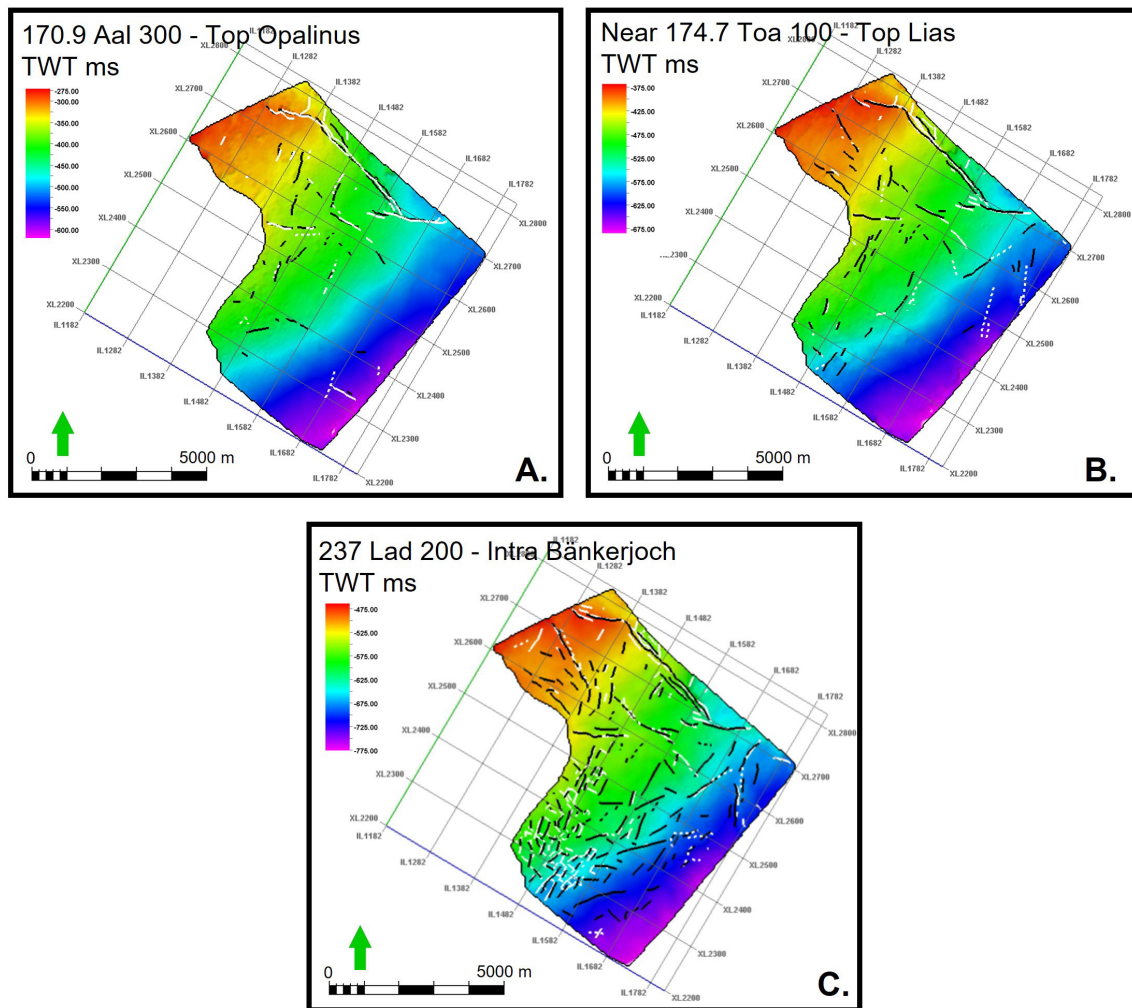


Fig. 6-4: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2018 QLP (NAB 18-36)

Overlay of 2023 fault traces (black lines = this report) and NAB 18-36 (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. Note that in NAB 18-36 only class A faults were shown for Top Muschelkalk, but maps with class A and class C faults were reproduced in this report from the original database.

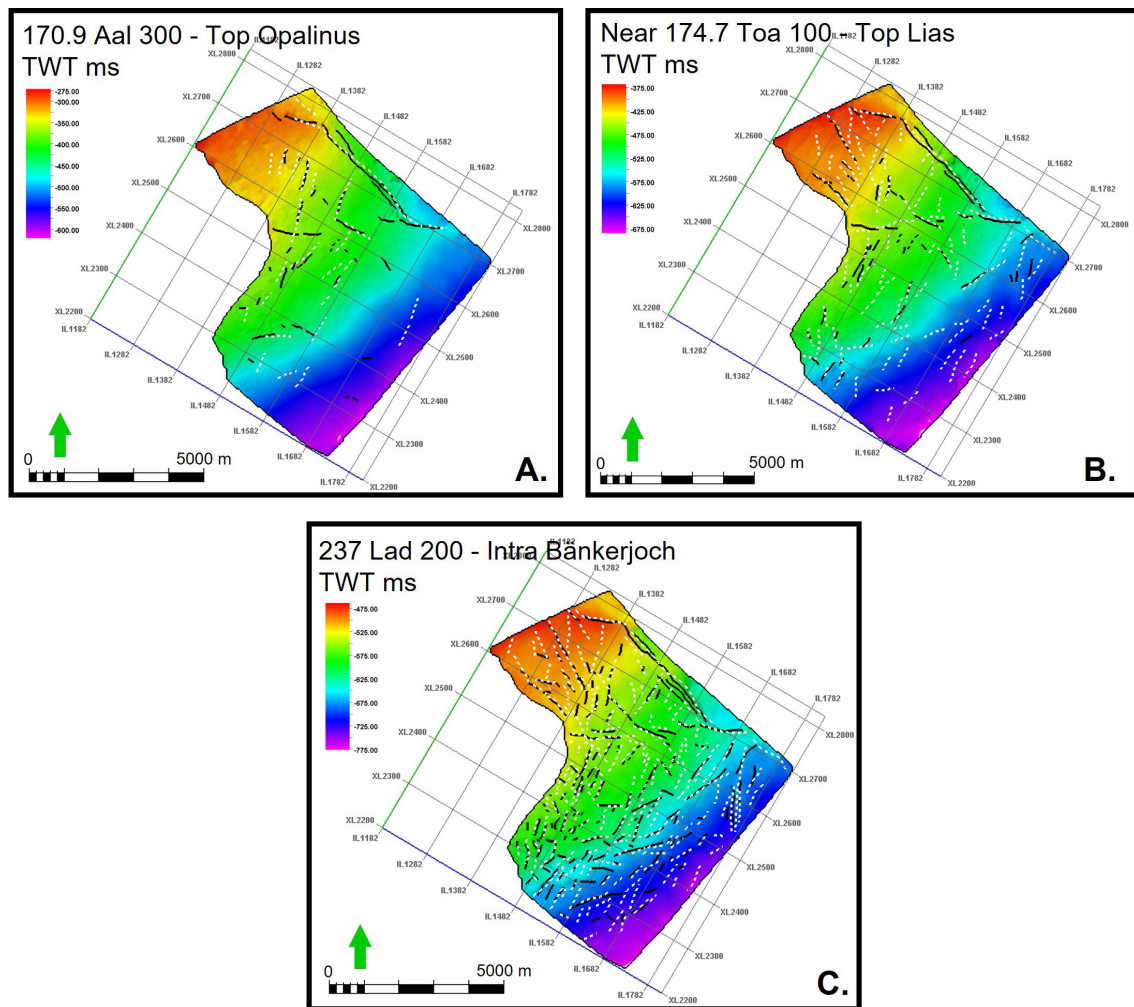


Fig. 6-5: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (ASR)

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 structural lineaments faults and folds. Refer to Tab. 6-1 for seismic vintage and interpreter details.

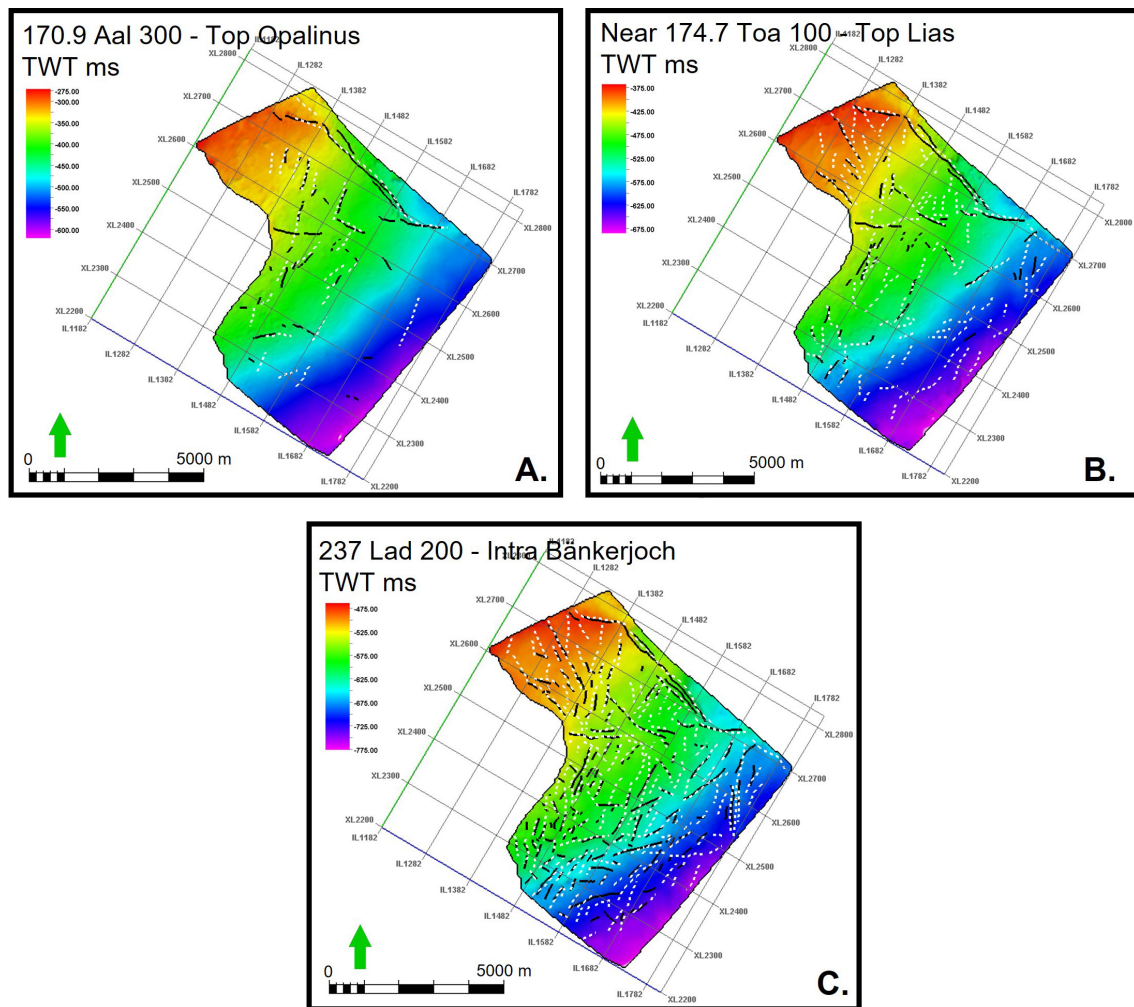


Fig. 6-6: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2021 PreSDM (Pre-ASR)

Overlay of 2023 fault traces (black lines = this report) and ASR structural lineaments (white dashed lines = PreSDM) 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 structural lineaments faults and folds. This might result in the difference at near 174.7 Toa 100 - Top Lias horizon, where the presence of structural lineaments could be associated with folding at fault tips. Refer to Tab. 6-1 for seismic vintage and interpreter details.

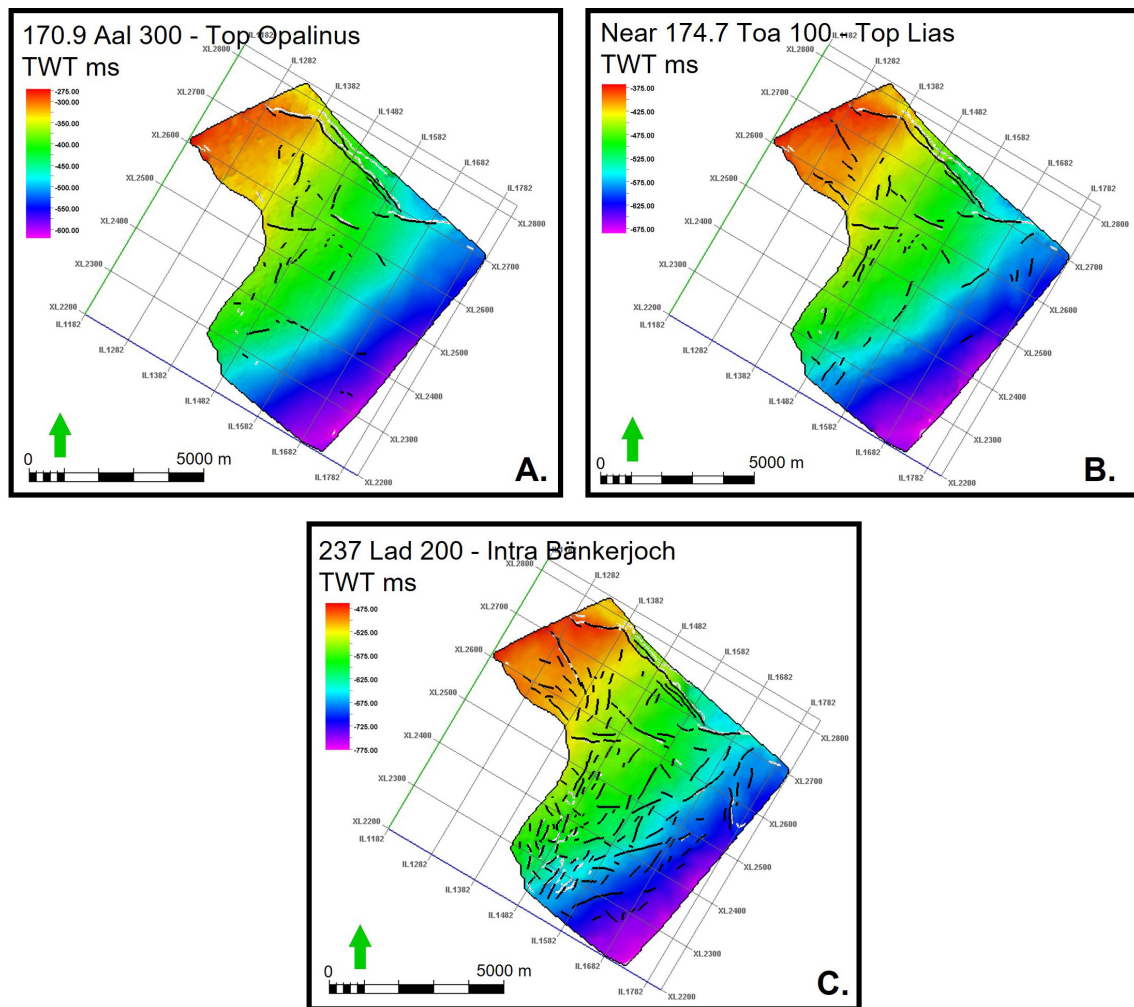


Fig. 6-7: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (interpreter A contractor)

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 - 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.

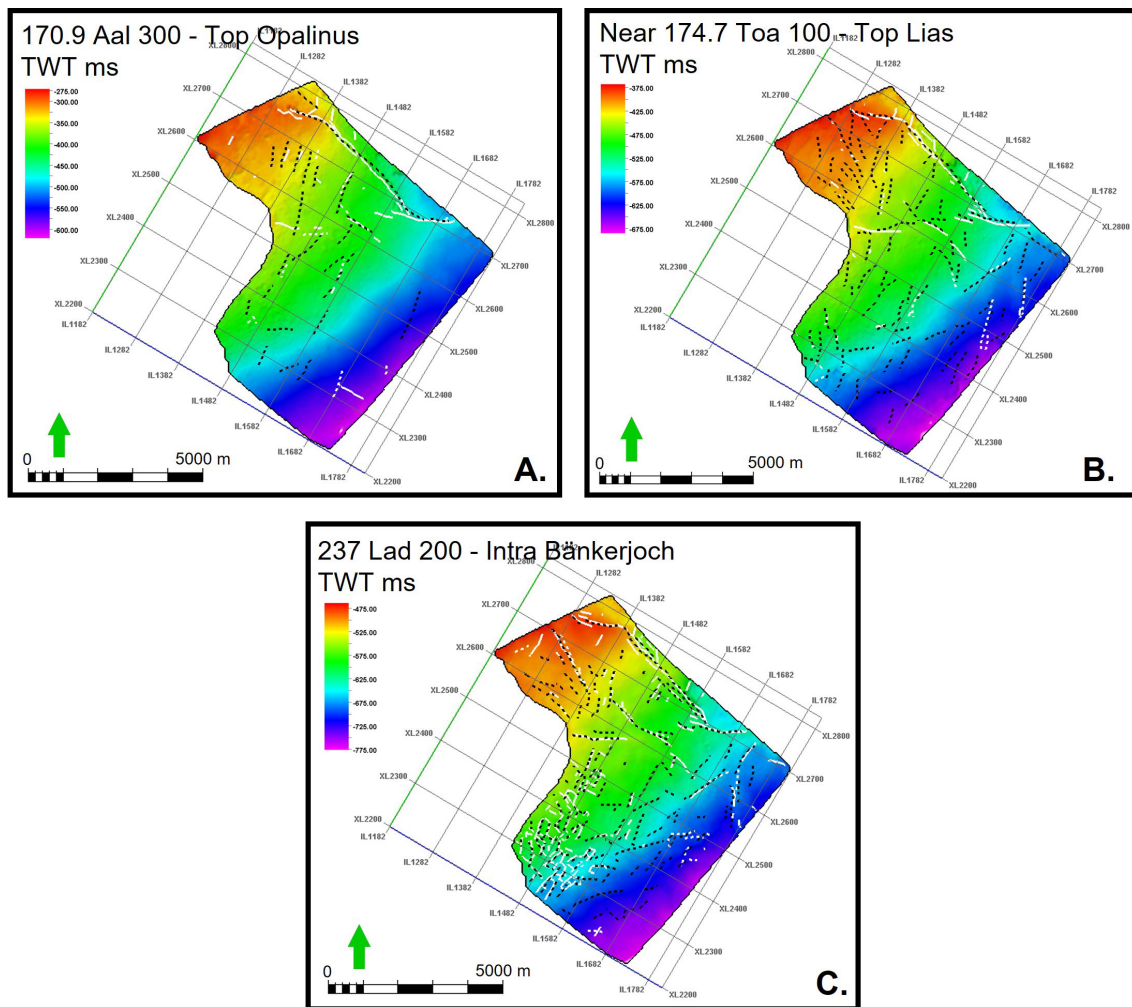


Fig. 6-8: Fault interpretation vintage comparison: 2022 PreSTM-ref minimum-phase (ASR) versus 2018 QLP (NAB 18-36)

Overlay of ASR structural lineaments (black dashed lines) and NAB 18-34 faults (white line = A faults, white dashed lines = C faults) for the three key stratigraphic levels. A. 170.9 Aal 300 - Top Opalinus; B. 174.7 Toa 100 - Top Lias; C. 237 Lad 200 - Intra Bänkerjoch. For the ASR no distinction was made between structural lineaments faults and folds. This might result in the difference at Near 174.7 Toa 100 - Top Lias horizon, where presence of structural lineaments could be associated with folding at fault tips. Refer to Tab. 6-1 for seismic vintage and interpreter details. Note that in NAB 18-36 only class A faults were shown for Top Muschelkalk, but maps with class A and class C faults were reproduced in this report from the original database.

Despite the fact that among the different seismic vintages no major discrepancies in seismic imaging have been recognised in the seismic attributes, clear differences were observed between the 2023 and the 2018 fault interpretations, which were carried out on different seismic datasets and with different methodologies (Fig. 5-48).

A detailed evaluation of the 2018 QLP dataset was performed, with the intent to gain confidence in the seismic response, which led to the 2023 interpretation, and consequently investigating the causes for the interpretation discrepancies.

Fig. 6-9 shows variance and curvature attributes for Top Muschelkalk reproduced on the QLP dataset to recreate the 2018 interpretation results from NAB 18-36. Whereas class A faults are defined by reflection offset or flexure in vertical amplitude sections, definition of the lower confidence class C faults requires these to be recognisable as seismic discontinuities in at least two seismic attributes. A revised interpretation (this work) of the QLP dataset revealed three examples from the Central Panel where seismic discontinuities were detected in two seismic attributes, namely variance and curvature (Fig. 6-9 A' and B'). These three seismic discontinuities were not considered class C faults in the 2018 QLP interpretation (Nagra 2019).

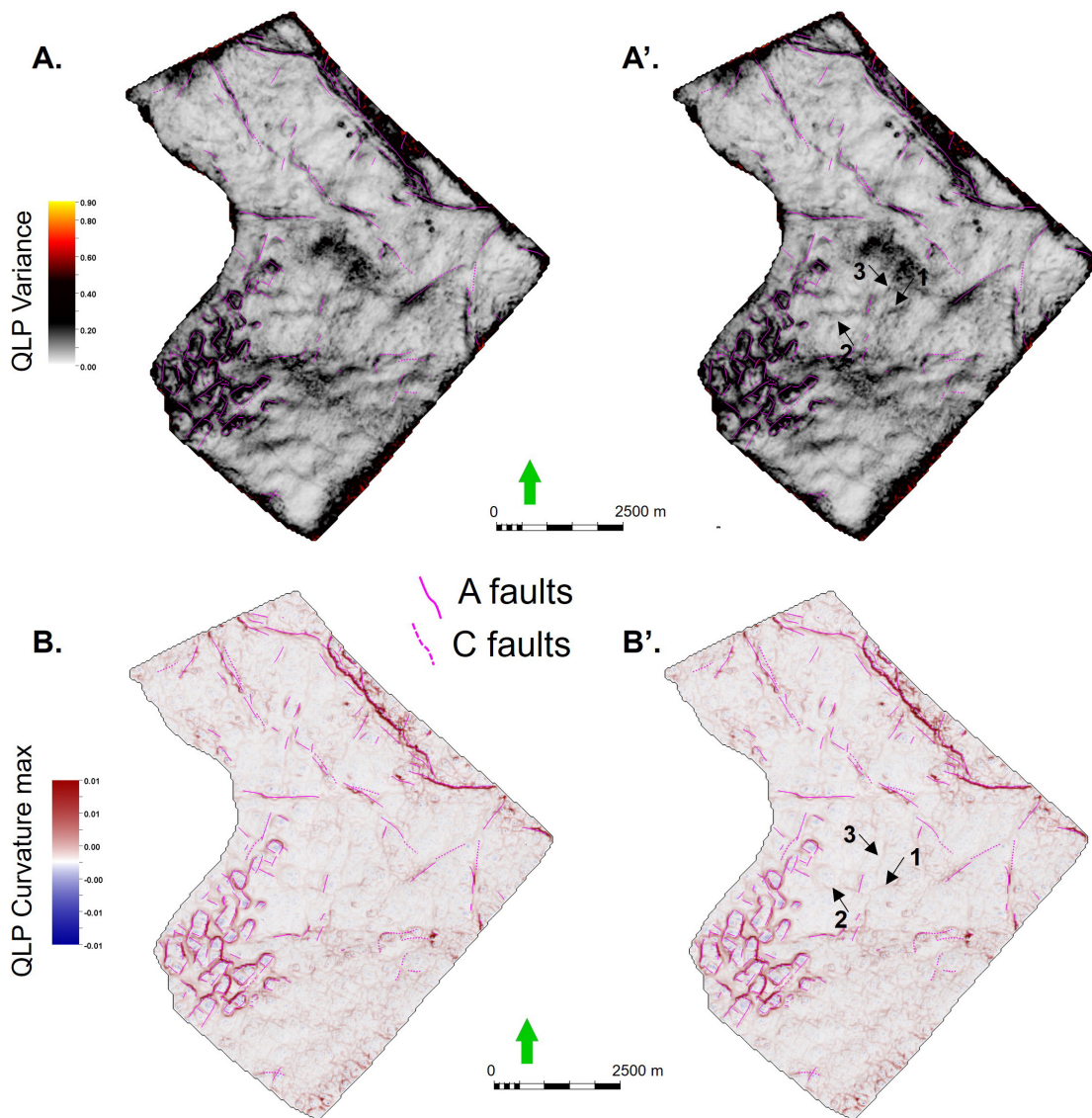


Fig. 6-9: NAB 18-36 QLP seismic attribute analysis

A. QLP Top Muschelkalk Variance and B. QLP Top Muschelkalk Curvature reproduced as originally in 2018 QLP interpretation from NAB 18-36. In pink are plotted NAB 18-36 class A faults (solid line) and class C faults (dashed line). Class C faults mapping required a seismic discontinuity to be visible in at least two seismic attribute displays. A' and B' show three examples (indicated by arrows 1, 2 and 3) of discontinuities which in NAB 18-36 were not considered to represent faults, although the discontinuities are visible in both displays (variance and curvature attributes).

Since these lineaments (seismic discontinuities) were interpreted as faults in the 2023 interpretation, they should, according to the proposed workflow, also show, even in a subtle way, seismic fault signatures in amplitude sections in at least two of the available seismic datasets. Seismic sections across these three lineament examples confirm the presence of diagnostic signatures, i.e. very subtle throws visible at zero-crossing, dimming, but predominantly flexure with dip-change (Fig. 6-10, Fig. 6-11, Fig. 6-12). These diagnostic signatures for the three examples are actually also visible in the QLP dataset, especially when comparing with seismic

discontinuities mapped in 2018 as faults (both class A and C) in the same area (Fig. 6-13, Fig. 6-14). These observations suggest that the fault distribution proposed by 2018 fault interpretation (Nagra 2019) might underestimate the amount of deformation in the ZNO siting region, and particularly in the Central Panel.

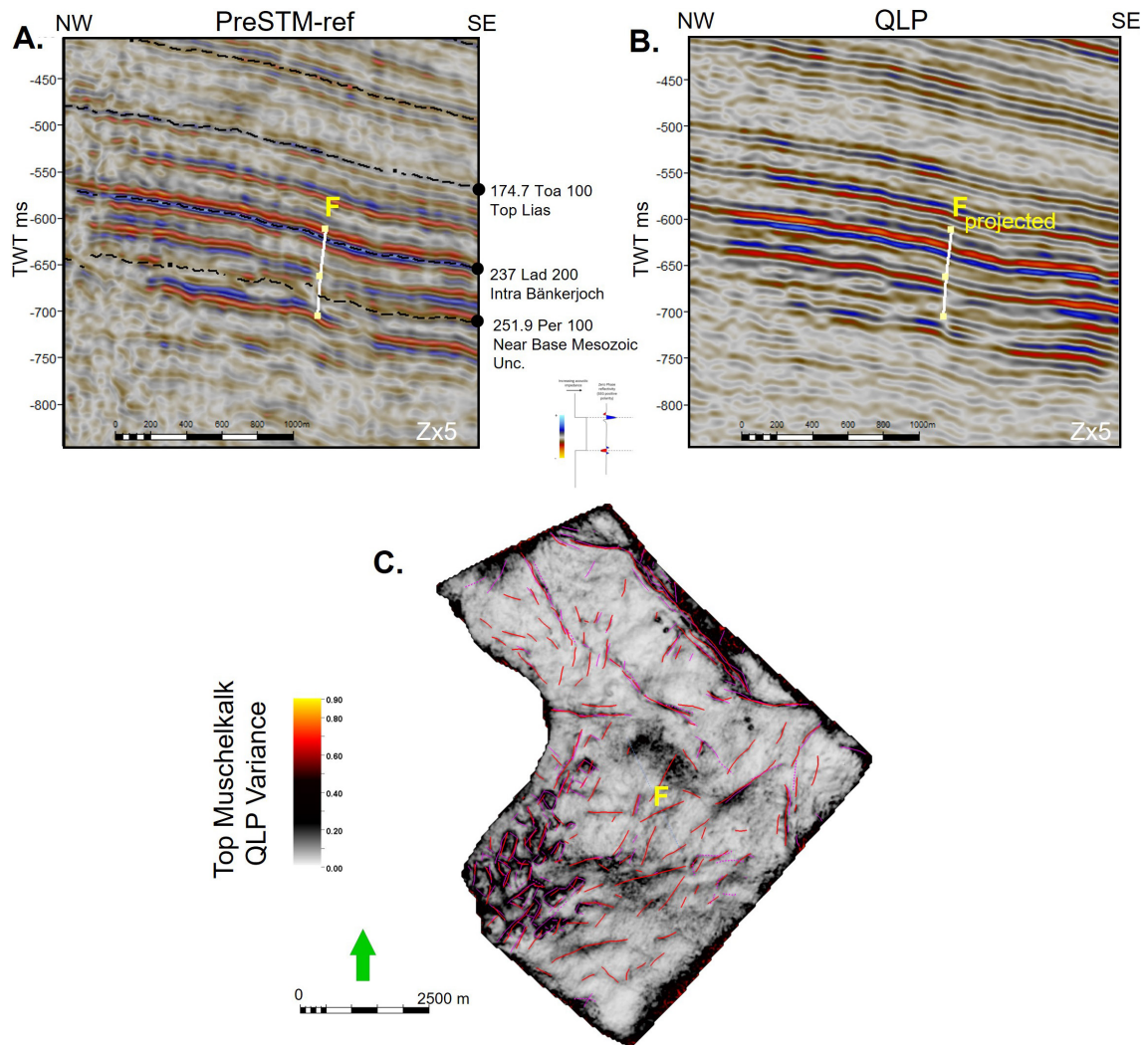


Fig. 6-10: Random line across seismic discontinuity (F) (example 1 of Fig. 6-9 A' and B')

A. PreSTM-ref random line with 2023 fault interpretation (F). The observed discontinuity on variance attribute (C.) was interpreted as fault (F). B. Same random line as A. but displaying QLP seismic vintage with 2023 fault stick projected (F). Note that, in both seismic datasets, the fault stick correlates with the presence of a narrow flexure, dimmed amplitudes and reflection displacement at deeper stratigraphic level. C. QLP Top Muschelkalk variance horizon slice with 2023 faults (red), and QLP class A faults (pink solid) and class C faults (pink dashed). Fault F was not interpreted in NAB 18-36 (Nagra 2019).

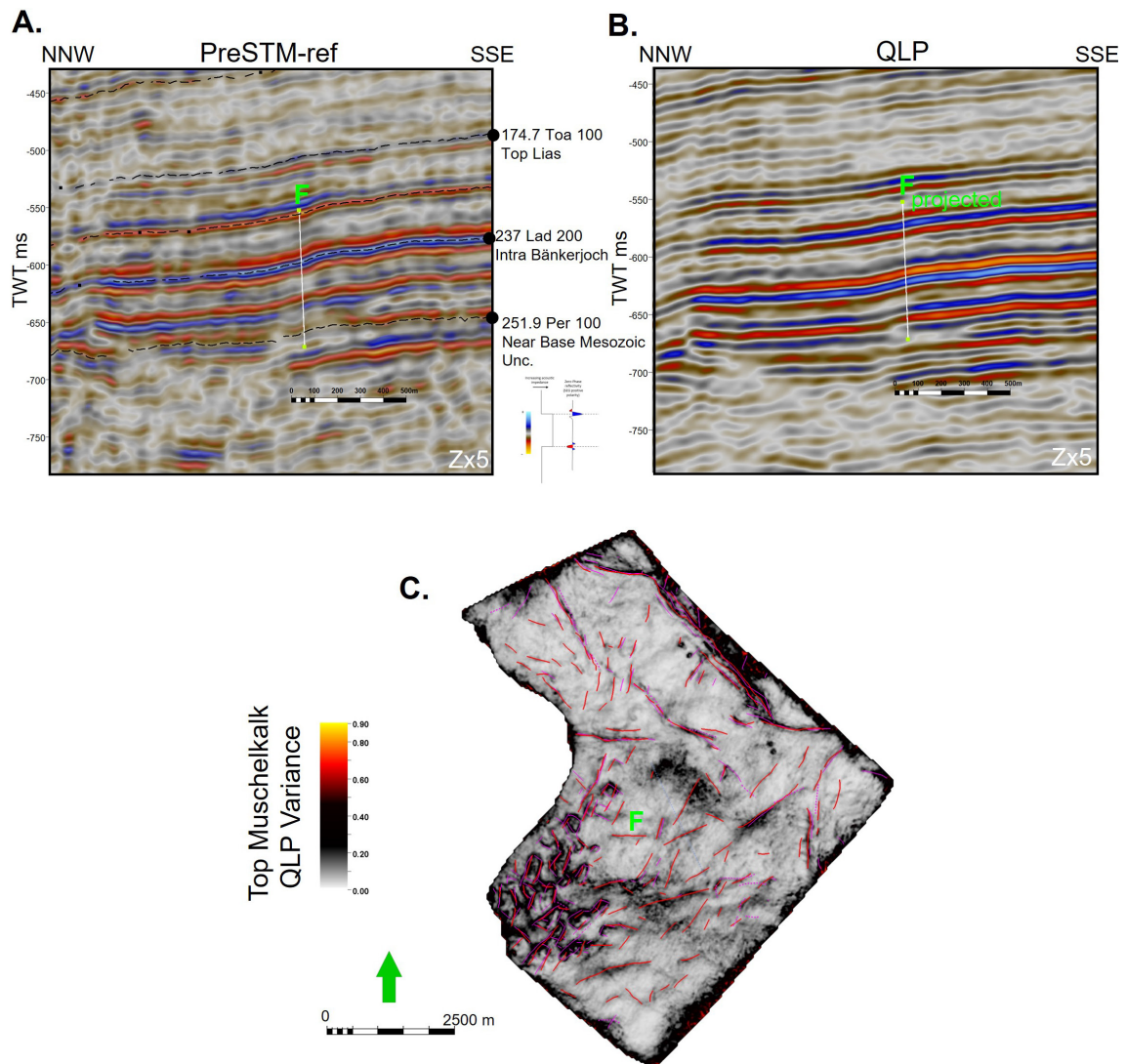


Fig. 6-11 Random line across seismic discontinuity (F) (example 2 of Fig. 6-9 A' and B')

A. PreSTM-ref random line with 2023 fault interpretation (F). The observed discontinuity on variance attribute (C.) was interpreted as faults (F). B. Same random line as A. but displaying QLP seismic vintage with 2023 fault stick projected (F). Note that, in both seismic datasets, the fault stick correlates with the presence of a narrow flexure and dimmed amplitudes. C. QLP Top Muschelkalk variance horizon slice with 2023 faults (red), and QLP class A faults (pink solid) and class C faults (pink dashed). Fault F was not interpreted in NAB 18-36 (Nagra 2019).

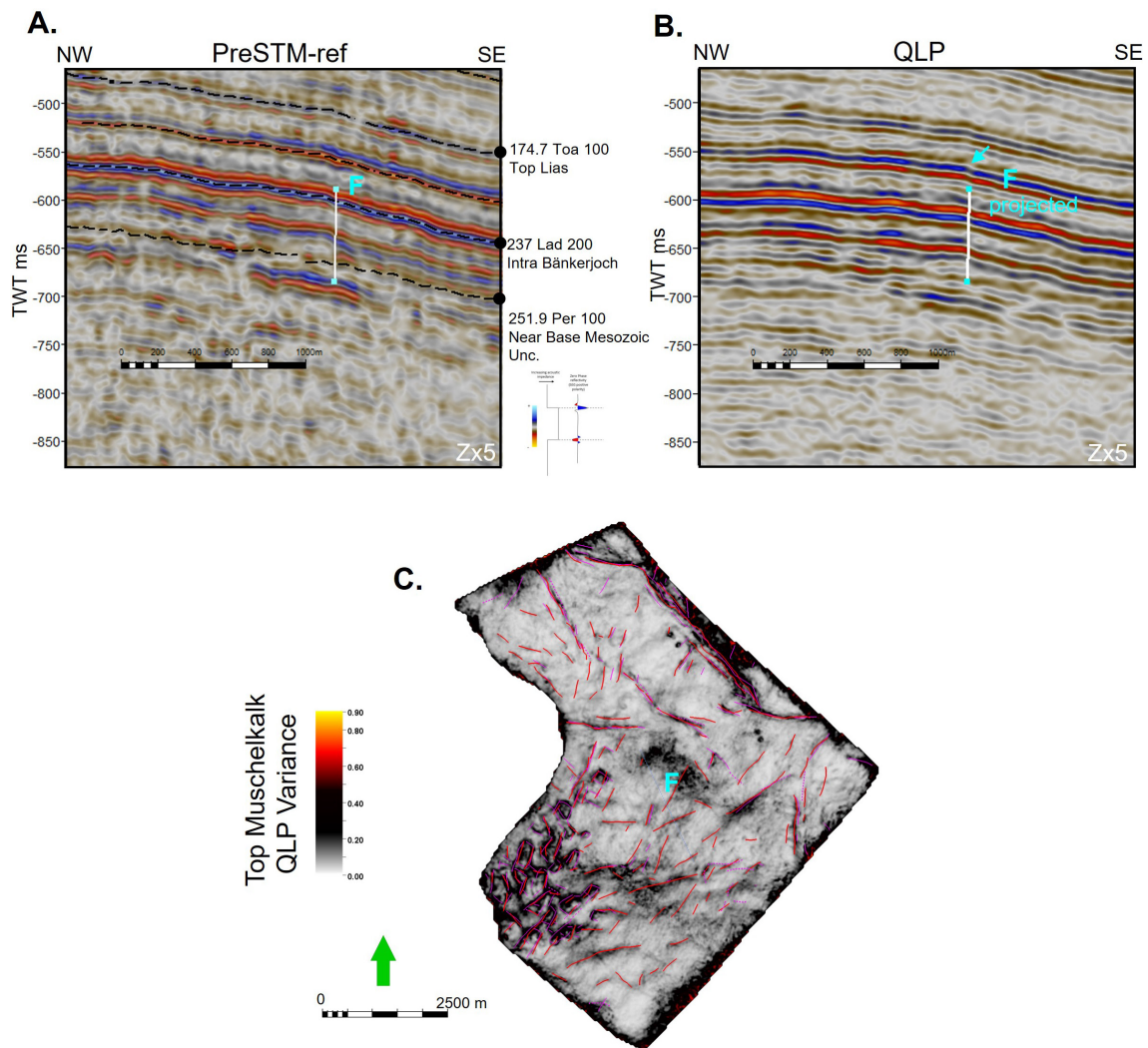


Fig. 6-12: Crossline 2526 across seismic discontinuity (F) (example 3 of Fig. 6-9 A' and B')

A. PreSTM-ref random line with 2023 fault interpretation (F). The observed discontinuity on variance attribute (C.) was interpreted as fault (F). B. Same random line as A. but displaying QLP seismic vintage with 2023 fault stick projected (F). Note that, in both seismic datasets, the fault stick correlates with the presence of a narrow flexure and reflection displacement. C. QLP Top Muschelkalk variance horizon slice with 2023 faults (red), and QLP class A faults (pink solid) and class C faults (pink dashed). Fault F was not interpreted in NAB 18-36 (Nagra 2019).

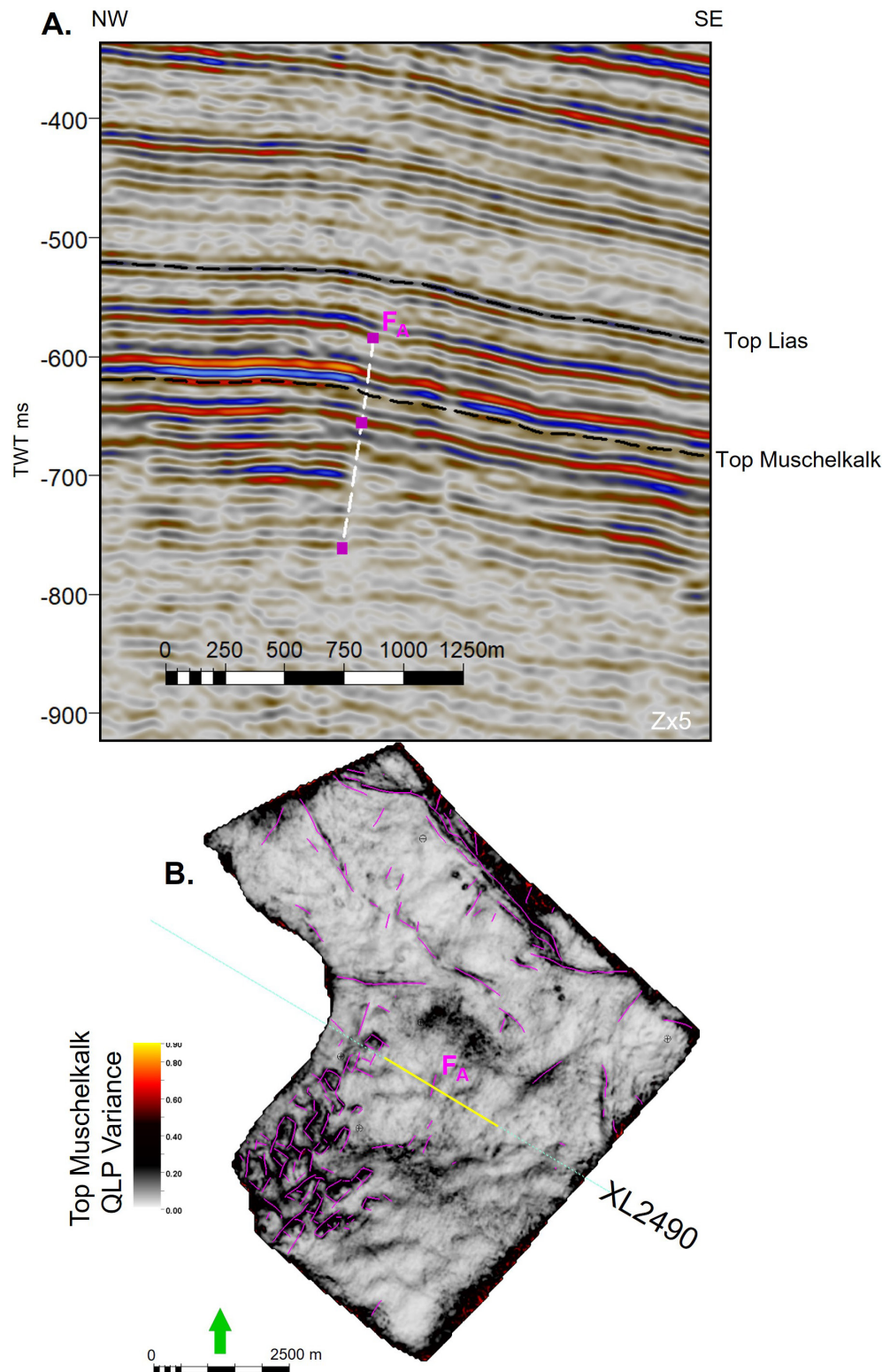


Fig. 6-13: Example of class A fault (Nagra 2019) interpreted in the Central Panel

A. Crossline 2490 (QLP vintage) showing a class A fault interpreted at Top Muschelkalk. B. Top Muschelkalk variance (QLP vintage) with class A fault traces (pink solid lines) reproduced from NAB 18-36 (Nagra 2019). Seismic signature is similar to the imaging shown in Fig. 6-10 and Fig. 6-12.

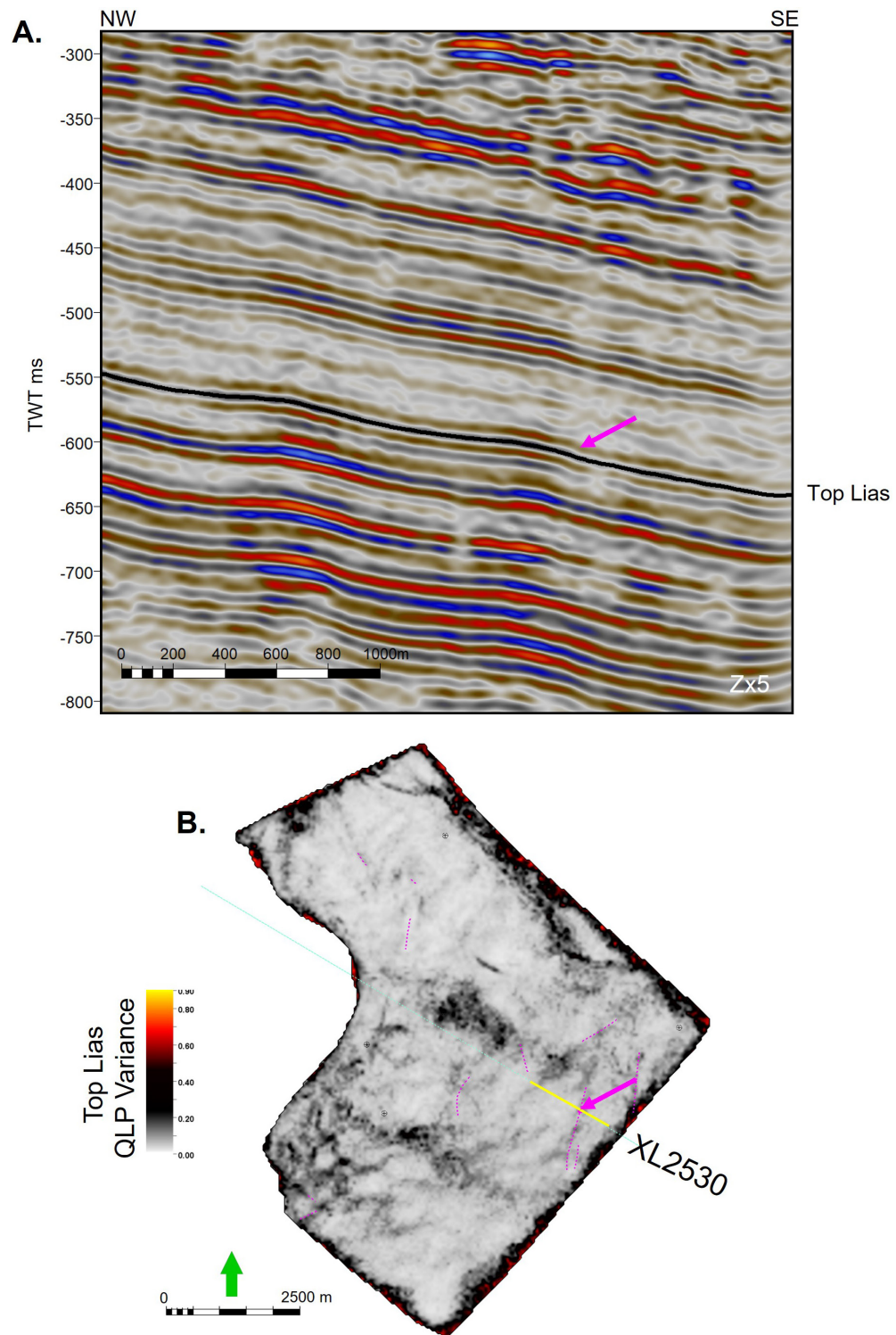


Fig. 6-14: Example of class C fault (Nagra 2019) interpreted in the Central Panel

A. Crossline 2530 (QLP vintage) showing the location (pink arrow) of the class C fault interpreted at Top Lias. Class C faults were interpreted based on seismic attribute response only. B. Top Lias variance (QLP vintage) with class C fault traces (pink dashed lines) reproduced from NAB 18-36 (Nagra 2019). Seismic signature is similar to the imaging shown in Fig. 6-11.

When dealing with subtle faults, particularly incipient strike-slip faults having displacements close to the deductibility limit, the identification and interpretation of these structures is considered extremely challenging. Examples from hydrocarbon fields in the Middle East, where seismic imaging is tied and calibrated with a large number of wells, many of them being long horizontal, indicate that these faults can be detected and interpreted with high degree of reliability by means of seismic attributes and detailed evaluation of the amplitude changes, facilitated by a large vertical stretch (> 7) of the seismic section images (Fig. 6-15, Zampetti et al. 2014, Alqahtani & Al-Shuhail 2012, Kein et al. 2009, Johnson et al. 2005).

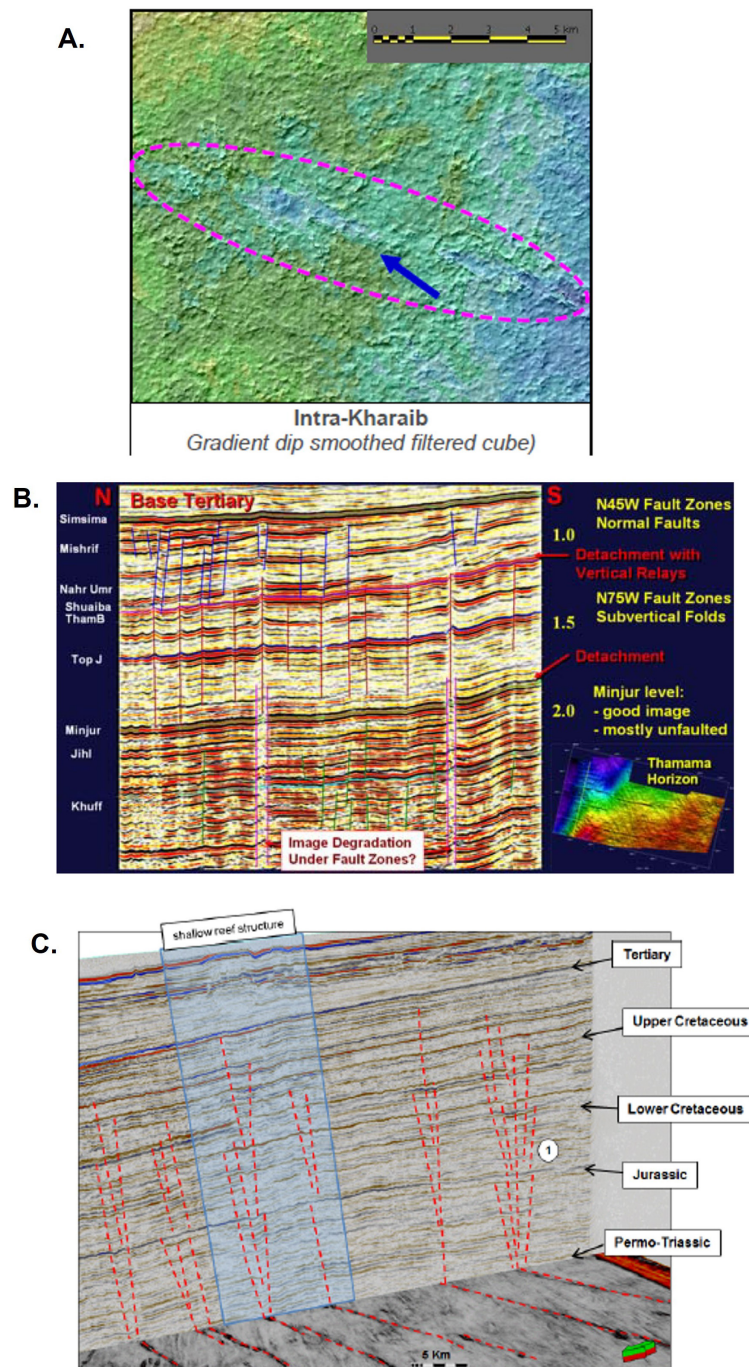


Fig. 6-15: Analogues of seismic expression of subtle strike-slip faults

Incipient strike-slip faults are characterised by subtle seismic expression, and despite being of key importance in hydrocarbon production, their interpretation is still challenging and is mainly guided by seismic attribute displays. Three examples from hydrocarbon fields in the Middle East are shown as seismic expression analogues for the subtle faults observed in the ZNO-97/16 merged seismic survey, particularly in the Central Panel. Faults in the three examples are mainly characterised by very small amplitude offsets, visible at exaggerated vertical stretch, and their interpretation is guided by seismic attribute displays (horizon and time slices) and constrained by well data (static and dynamic). A. Al Khaliq Field, Qatar (Kein et al. 2009), B. Abu Dhabi (Johnson et al. 2005), C. Al Shaheen Field, Qatar (Zampetti et al. 2014).

The different appearance of the seismic-scale structures observed in the ZNO siting region, compared to Jura Ost (JO) and Nördlich Lägern (NL), is simply the mirror of a very different tectonic configuration. In contrast to JO and NL siting regions, the location of the ZNO siting region, with respect to the Permo-Carboniferous Kostanz - Frick Trough (Madritsch et al. 2018, Fig. 2-3), implies more intense influence of basement faulting on the Mesozoic succession due to the limited occurrence of Upper Palaeozoic sediments as well as an observed reduced thickness of the Triassic evaporites (particularly in the central area of the ZNO-97/16 merged seismic survey, Benken well). The major regional tectonic events (Fig. 2-3) are translated in ZNO into both extensional and (dominant) strike-slip high-angle faulting. The normal faulting along the Neuhausen Fault Zone and oblique extensional reactivation of basement faults giving rise to the Wildensbuch Flexure (Fault Zone) are ascribed to the Early to Middle Miocene extension in the Hegau-Bodensee - Lake Constance. On the other hand, Middle Miocene to Pliocene shortening resulted in dominant strike-slip and associated deformation related with high-angle faulting/fault reactivation (e.g., Niederholz Structure Zone).

In such a strike-slip dominated environment, the presence of widely distributed subtle faults, with orientation consistent with regional trends, is not unexpected.

7 Conclusions

A dedicated seismic evaluation matching the requirements at the scale of the site selection process and ensuring comparability among the three siting regions was carried out for the ZNO 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).

Using all the seismic datasets (Tab. 3-1), the interpretation results were captured in the PreSTM-ref seismic data. Their 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 similar seismic imaging.

A critical difference between the 2022 (ASR) and 2023 interpretation products versus the 2018 QLP interpretation products (NAB 18-36, Nagra 2019) corresponds to the observed fault density in the central area of the ZNO-97/16 merged seismic survey. In the 2018 QLP interpretation, this central area appears tectonically as relatively undisturbed, with an absence of seismic-scale faults. However, in the 2023 interpretation the widely distributed presence of small faults within this central area was identified. Differences arise from the recognised challenge of interpreting seismically subtle faults. Detailed analysis and comparison indicated that the 2018 QLP seismic mapping (NAB 18-36, Nagra 2019) might have underrepresented the amount of seismic-scale deformation in this important area of the ZNO siting region.

The performed evaluation shows that the ZNO siting region can be subdivided into three main structural domains: (i) Neuhausen-Wildensbuch Structural Domain (NWSD) (ii) Niederholz-Marthalen Structural Domain (NMSD), and (iii) the Central Panel (CP, including the Trüllikon Anticline).

The different appearance of the seismic-scale structures observed in the ZNO siting region, compared to Jura Ost (JO) and Nördlich Lägern (NL), is simply the reflection of a rather different tectonic configuration. The location of the ZNO siting region with respect to Carboniferous Kostanz - Frick Trough, implies more intense effects of basement faulting on the Mesozoic succession compared to JO and NL siting regions. Major regional tectonic events are translated into the re-activation and/or generation of high-angle faults, predominantly in a strike-slip mode.

In contrast to the other two siting regions, in the ZNO siting region no tectonically undisturbed area for the host rock could be identified, discounting two small areas (each ~ half square kilometre large; Fig. 7-1 U). Yet, because of the relatively wide spacing and the nature of the interpreted subtle faults (expected to be highly segmented vertically, at key mechanical breaks), the Central Panel is proposed to be considered as the (most) undisturbed area in the ZNO seismic survey, which has a total surface of 16.5 km² (Fig. 7-1).

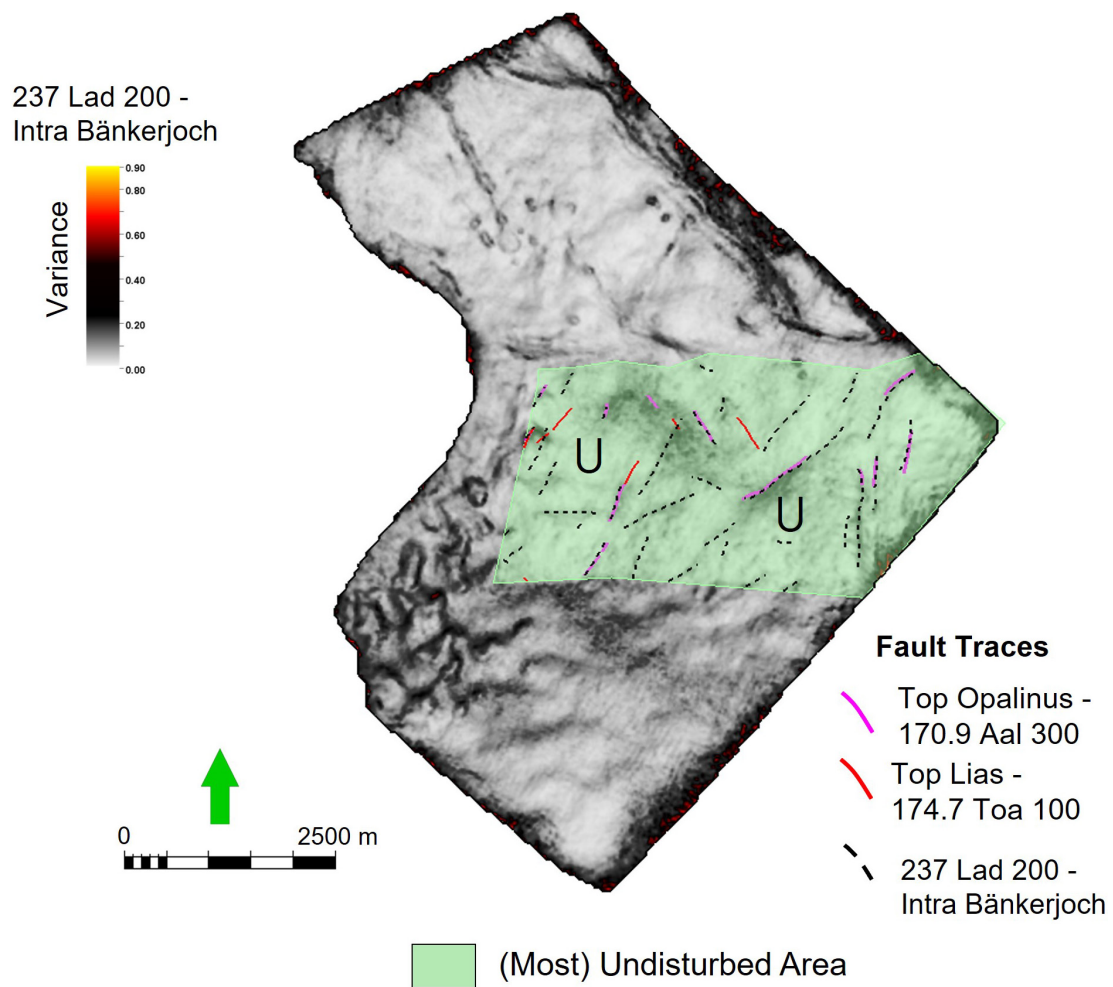


Fig. 7-1: Identification of a seismically undisturbed area

Based on a detailed seismic analysis, only two $\sim 0.5 \text{ km}^2$ undisturbed (seismic-scale fault free) areas (U) could be identified in the ZNO siting region; however, a (relative) undisturbed area was proposed coinciding with the Central Panel.

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