



ARBEITSBERICHT NAB 23-18

3D Seismic Interpretation of Stratigraphic
Horizons and Structures in Time Domain
Nördlich Lägern

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, NL, Nördlich Lägern

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

Abstract

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

While 3D seismic data greatly improve the imaging of the subsurface, the challenge of separating seismic reflections associated with geological features and seismic artefacts represents the key pitfall in the interpretation results, especially for onshore data with complex and heterogeneous shallow geology. Therefore, interpreting 3D seismic data 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 the final 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 the seismic data reprocessing designed such that all the processing input parameters and workflows were consistent across the three seismic surveys, but also an interpretation approach with rigorous criteria was established and implemented in the interpretation of the three seismic surveys covering the three siting regions. Consequently, importance was given to the methodology section, which is repeated in the three seismic interpretation reports for the respective siting regions (NAB 23-17, NAB 23-18, NAB 23-19), where the applied workflow is illustrated based on site-specific examples.

The resulting horizon-fault framework in the NL siting region included the interpretation of six key horizon markers:

- (i) 149.2 Kim 100 – Top Malm
- (ii) 149.2 Kim 700 – Top Villigen
- (iii) 168.2 Baj 400 – Top Clay Unit
- (iv) 201.4 Rha 100 – Top Klettgau
- (v) 237 Lad 400 – Top Muschelkalk
- (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 subsurface image of the three investigated siting regions.

The evaluation performed shows that the NL siting region can be subdivided into four main structural domains, from south to north: (i) the Southern Fold-and-Thrust Zone (SFTZ, i.e. Baden-Irchel-Herdern Lineament), (ii) the Undisturbed Central Panel (UCP), (iii) the Weiach-Glattfelden-Eglisau Structure (WGE) and (iv) the Northern Fold-and-Thrust Zone (NFTZ, i.e. Siglistorf Anticline). The Undisturbed Central Panel (UPC) represents a $\sim 25 \text{ km}^2$ seismically undisturbed area between the deformation zones. In this area, the Opalinus Clay is consistently interpreted not to act as detachment level but rather as a decoupling layer between the structures in the lower and the upper competent panels and to accommodate deformation by localised non-coaxial deformation zones (i.e. shear planes) at meso- and microscales (i.e. at core scale) without reactivation / formation of seismic-scale structures.

Within a regional tectonic framework, several structural evolution scenarios for the NL siting region were proposed by several authors (Diebold et al. 1991, Naef et al. 1995, Madritsch et al. 2013, Malz et al. 2016, Bond et al. 2023, Schöpfer et al. 2023, Zambrano et al. 2024, Bond et al. 2023). The main discussion points focus on the relative timing of the major deformation zones (SFTZ, NFTZ and WGE), their kinematics and the role and interaction of the Mesozoic faults with deep-seated grains (thin- vs thick-skinned models).

While the alternative scenarios describe different tectonic evolutions of the NL siting region and the larger area of Northern Switzerland as discussed in NTB 24-17 (Nagra 2024d), none of those evolutionary tectonic scenarios propose either a different structural configuration or a different areal definition for the UCP in the NL siting region.

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List of Acronyms

AGC	Automatic Gain Control
AOI	Area of Interest
ASR	Auswahl der Standorte für die Vorbereitung der Rahmenbewilligungsgesuche Site Selection in Preparation for General Licence Application
BIH	Baden-Irchel-Herdern Lineament
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
NL-16	Nördlich Lägern Seismic Survey acquired in 2016
NFTZ	Northern Fold-and-Thrust Zone
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 Move-out
SFTZ	Southern Fold-and-Thrust Zone
SIA	Siglistorf Anticline
SRD	Seismic Reference Datum
TDR	Time-Depth Relationship
TWT	Two Way-Travel Time
UCP	Undisturbed Central Panel
VSP	Vertical Seismic Profile measured in a well
WGE	Weiach-Glattfelden-Eglisau Structure
ZNO	Zürich Nordost
ZOVSP	Zero-offset vertical seismic profile

1 Introduction

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

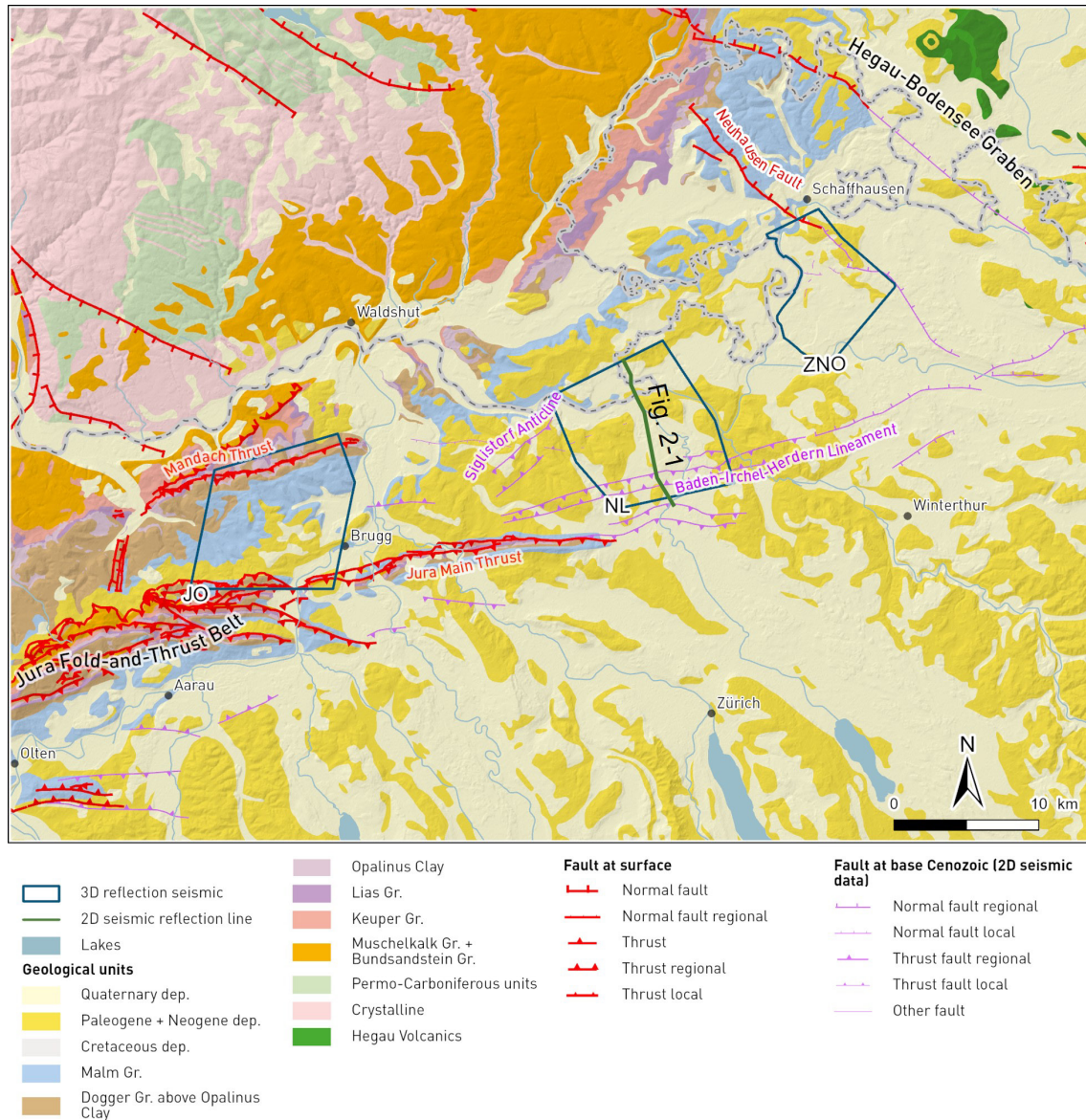


Fig. 1-1: Regional geological map showing the location of the three siting regions: JO, NL and ZNO

Modified after Nagra (2024d)

Green line is the 2D 11-NS-20 regional seismic line shown in Fig. 2-1.

This report will elaborate on the work carried out to seismically characterise the subsurface in the area covered by the NL-16 seismic survey. A critical challenge in the investigation of the three siting regions is meeting 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 still remain. Similarly, for the strategy followed within the framework of seismic reprocessing (Pre-Stack Time Migration Reference: PreSTM-ref, Nagra 2024a), a critical requirement for the interpretation methodology is the comparability of its application among the three siting regions. Therefore, a standard workflow (Fig. 1-2) with a rigorously structured approach was established showing that the challenges associated with the data were recognised and understood and that the criteria for stratigraphic and fault interpretation were defined, explained and rigorously implemented.

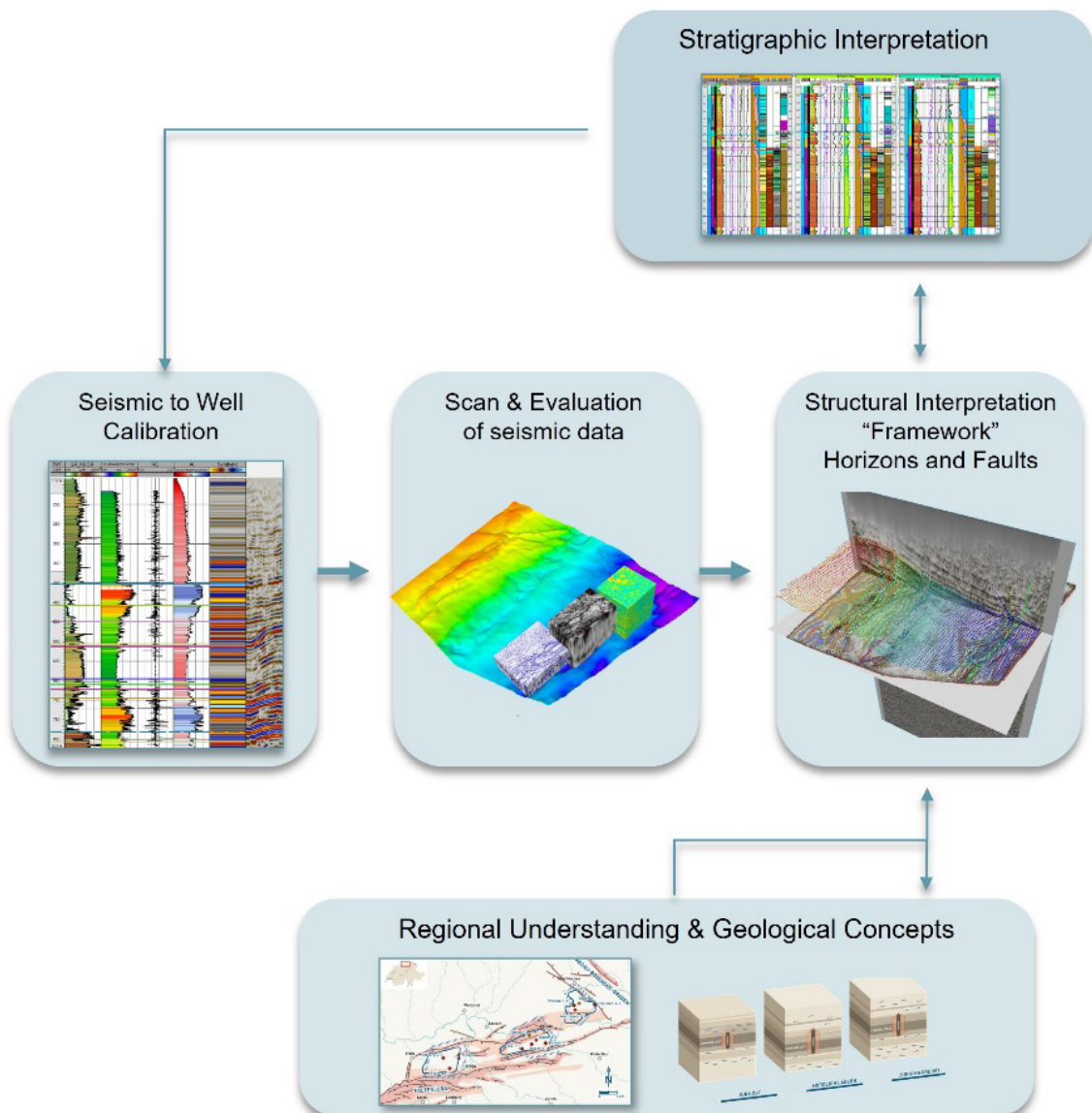


Fig. 1-2: Diagram showing the proposed integrated workflow

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

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

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

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

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

2 Geological setting

The Nördlich Lägern siting region is located in Northern Switzerland, north of the Lägern Anticline, which is the easternmost thrust-related fold of the Jura Fold-and-Thrust Belt and is classically associated with the Jura Main Thrust (Fig. 1-1). The Jura Fold-and-Thrust Belt is part of the detached Alpine foreland. The Molasse Basin, located south of it, is a flexural foreland basin formed as a result of the building-up of the Alps (Nagra 2024d).

The area covered by the NL-16 seismic survey is located at the easternmost tip of the Jura Fold-and-Thrust Belt (Fig. 1-1), immediately north of the Lägern Anticline, where the Stadel-Irchel Anticline occurs at the surface. This gentle antiform was characterised as a complex fish-tail structure in the subsurface (Baden-Irchel-Herden triangle zone in Malz et al. 2016).

The major fault underlying the Lägern Anticline beneath the main décollement level represents an inherited ENE-striking (N-dipping) basement feature (fault step with basement topography) that was interpreted as a key structure concentrating the deformation and influencing the structural style of the overriding Jura Fold-and-Thrust Belt (Caer et al. 2018). In addition to its main ENE-striking graben edge faults, major NW-striking basement faults are well documented and extend beyond the graben system into the outcropping pre-Mesozoic basement in the Black Forest area. To the north, the Siglistorf Anticline forms the outermost deformation feature of the external Jura in the area of interest (Fig. 1-1, Fig. 2-1).

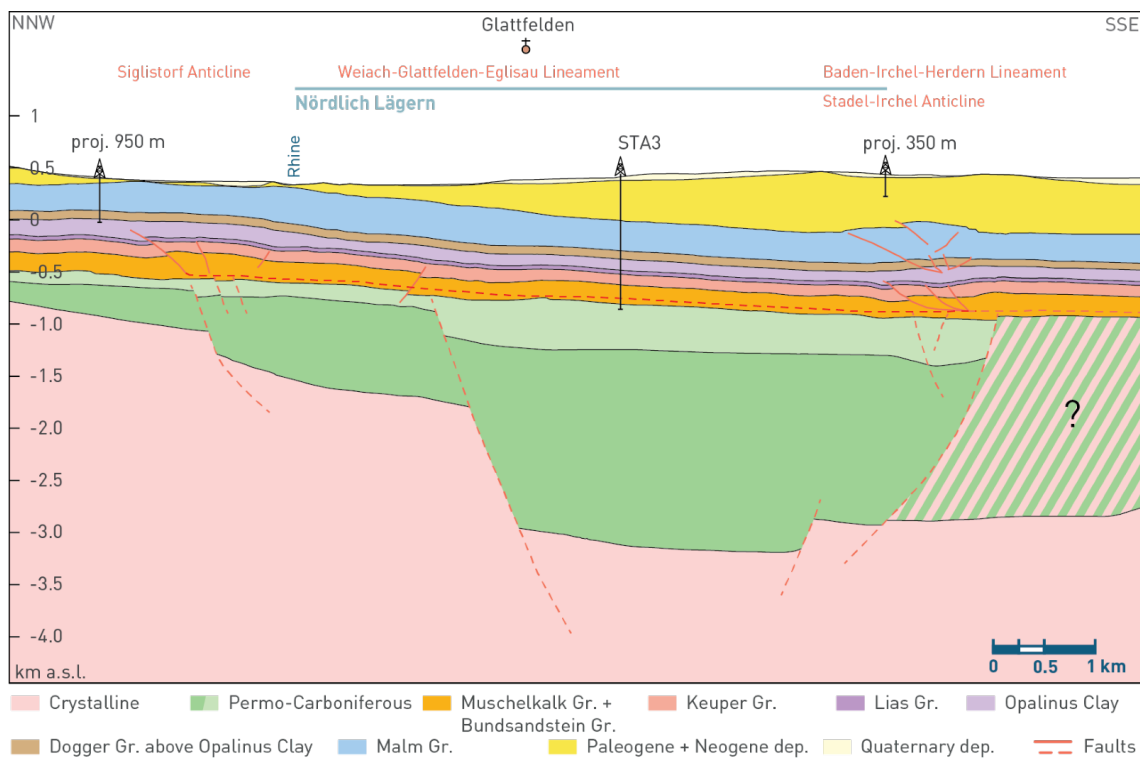


Fig. 2-1: Large-scale geological cross-section through Nördlich Lägern siting region

The geological section is drawn along the 2D seismic reflection line 11-NS-20. The section is based on Meier et al. (2014) and Jordan et al. (2015). Results from 3D seismic reflection interpretation were integrated within the seismic perimeter (Nagra 2024d). Gr.: Group, Dep.: deposits NTB 24-17 (Nagra 2024d). Line location shown in Fig. 1-1.

In addition to the inherited basement topography, deformation of the Mesozoic-Cenozoic sedimentary cover is strongly controlled by the presence and distribution (thickness) of salt in the Muschelkalk Group evaporites (Sommaruga et al. 2017). The large-scale Pre-Mesozoic structure in the area of interest is the Permo-Carboniferous Konstanz – Frick Trough (Diebold et al. 1991, McCann et al. 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- and NNE-SSW-striking faults as important segmenting elements (Madritsch et al. 2018, Nagra 2024d), while the very low well penetration does not provide a good calibration and estimation of the variability in facies and thickness of the sedimentary fill.

In the study area, the Mesozoic sedimentary sequence 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). This time period has long been considered to be characterised by relative tectonic quiescence (Naef et al. 1995). Several authors, however, have questioned this view and infer synsedimentary 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 sedimentary rocks 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 in 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.

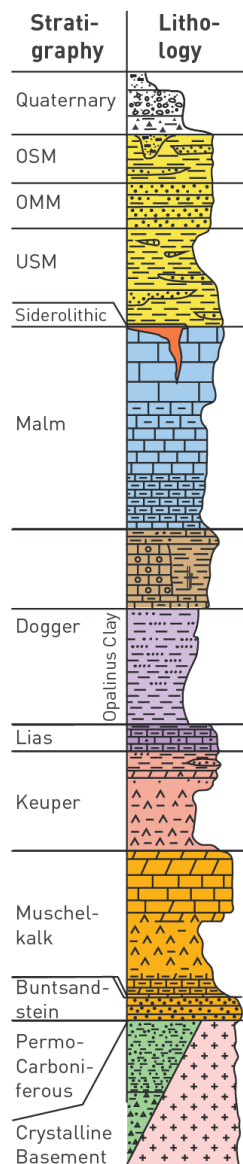


Fig. 2-2: Simplified lithological column of Northern Switzerland

Detailed description of the litho- and stratigraphic units is captured in NTB 24-17 (Nagra 2024d).

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

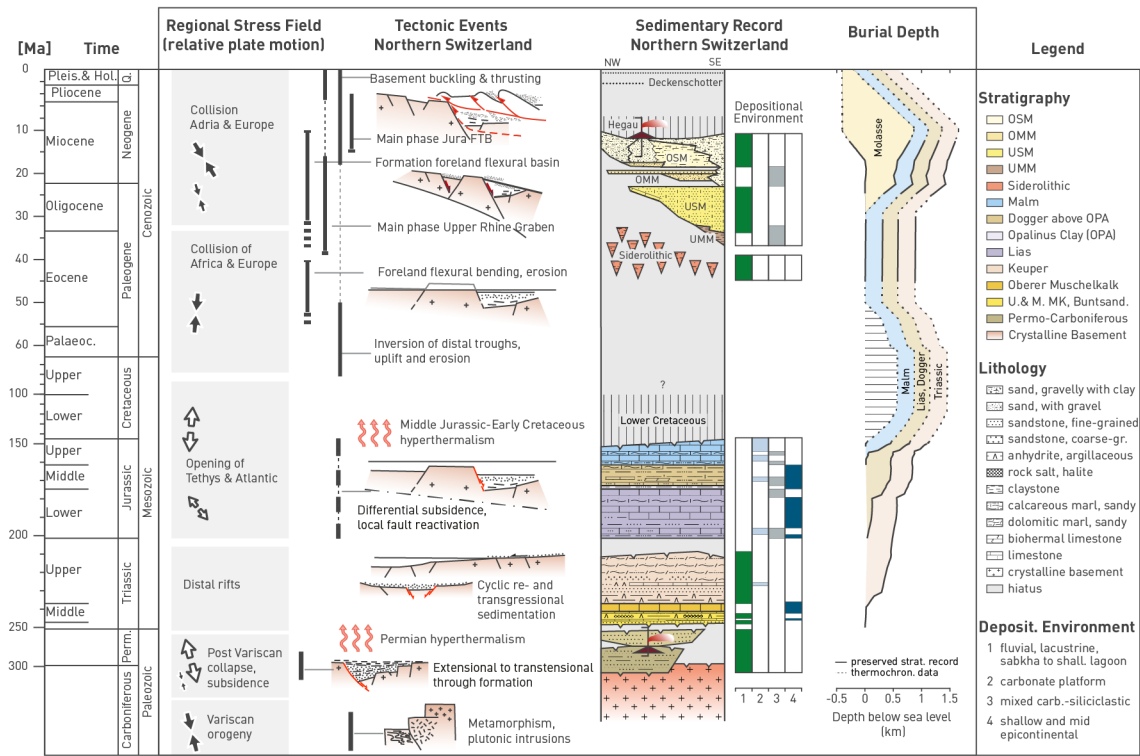


Fig. 2-3: Timeline summarising the geological evolution of Northern Switzerland
Nagra (2024d)

3 Dataset

The seismic interpretation performed in this study relied on the integration of 3D seismic data originating from different seismic processing vintages and the integration with key wells drilled during Nagra's deep borehole campaign (Fig. 3-1). While six wells were drilled within the seismic survey perimeter (Weiach-1 and -2, Stadel-2, Stadel-3, Bülach-1 and Bachs-1), only the four most recent wells (Stadel-2, Stadel-3, Bülach-1 and Bachs-1; Nagra 2021, 2022a, 2022b, 2023) were used in this study, together with comparable wireline log data and vertical seismic profile surveys (VSP).

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

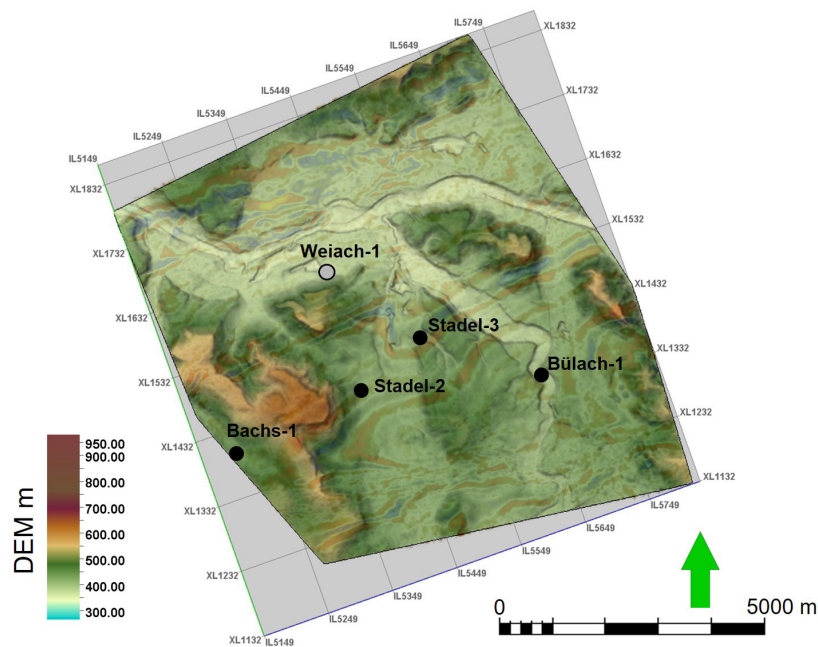


Fig. 3-1: Seismic data and well locations on digital elevation model (DEM)

Six wells are available within the perimeter covered by the NL-16 seismic survey; however, only the four most recent wells (black dots) were used for seismic interpretation. Note that well Weiach-2 is not displayed as it is too close to Weiach-1 (grey dot).

The integrated dataset was loaded into Petrel software for interactive interpretation. The Petrel project was set up using a seismic reference datum of 650 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 was acquired in 2016. The survey covered an area of $\sim 91 \text{ km}^2$ and contains 679 NNE-SSW-trending inlines and 731 WSW-ENE-trending crosslines with a line spacing of 15 m (Fig. 3-2).

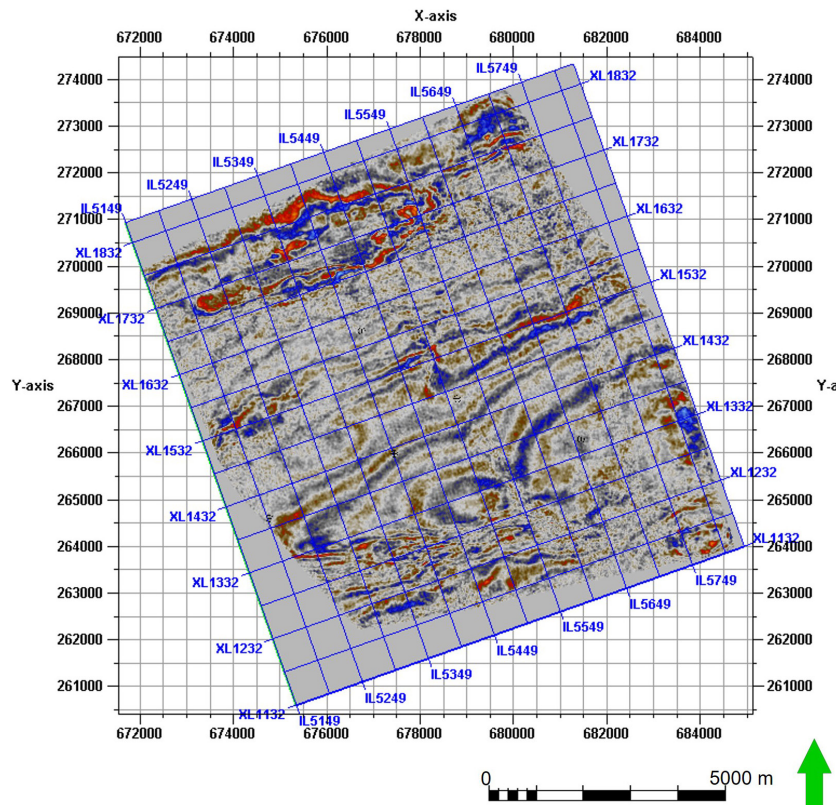


Fig. 3-2: NL-16 seismic survey (with grid coordinates)

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

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

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

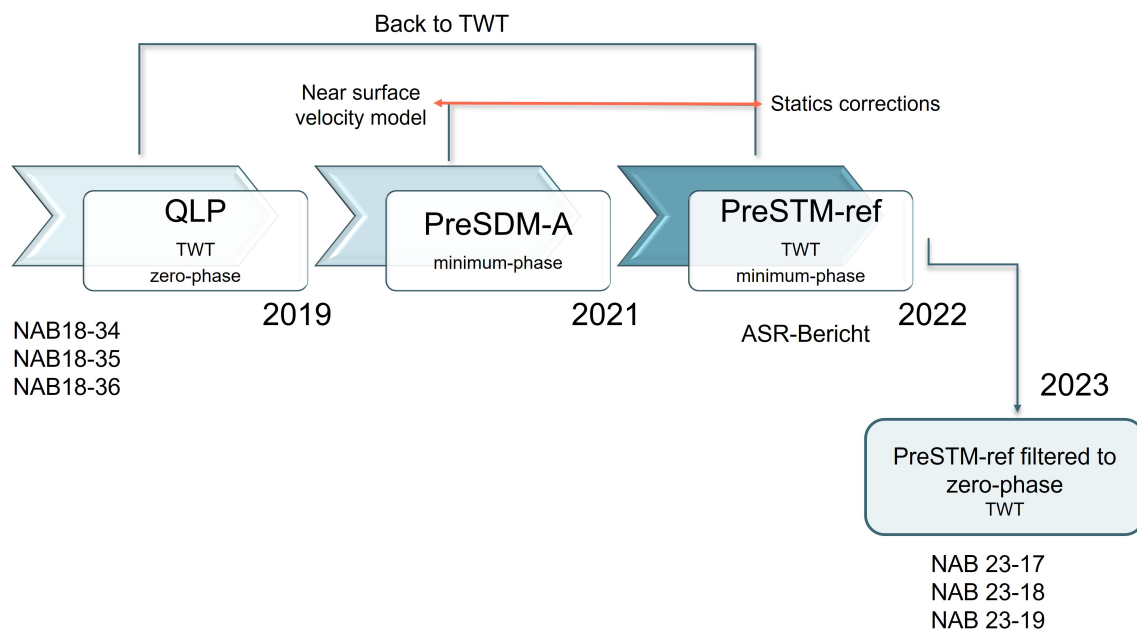


Fig. 3-3: Seismic processing simplified roadmap

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

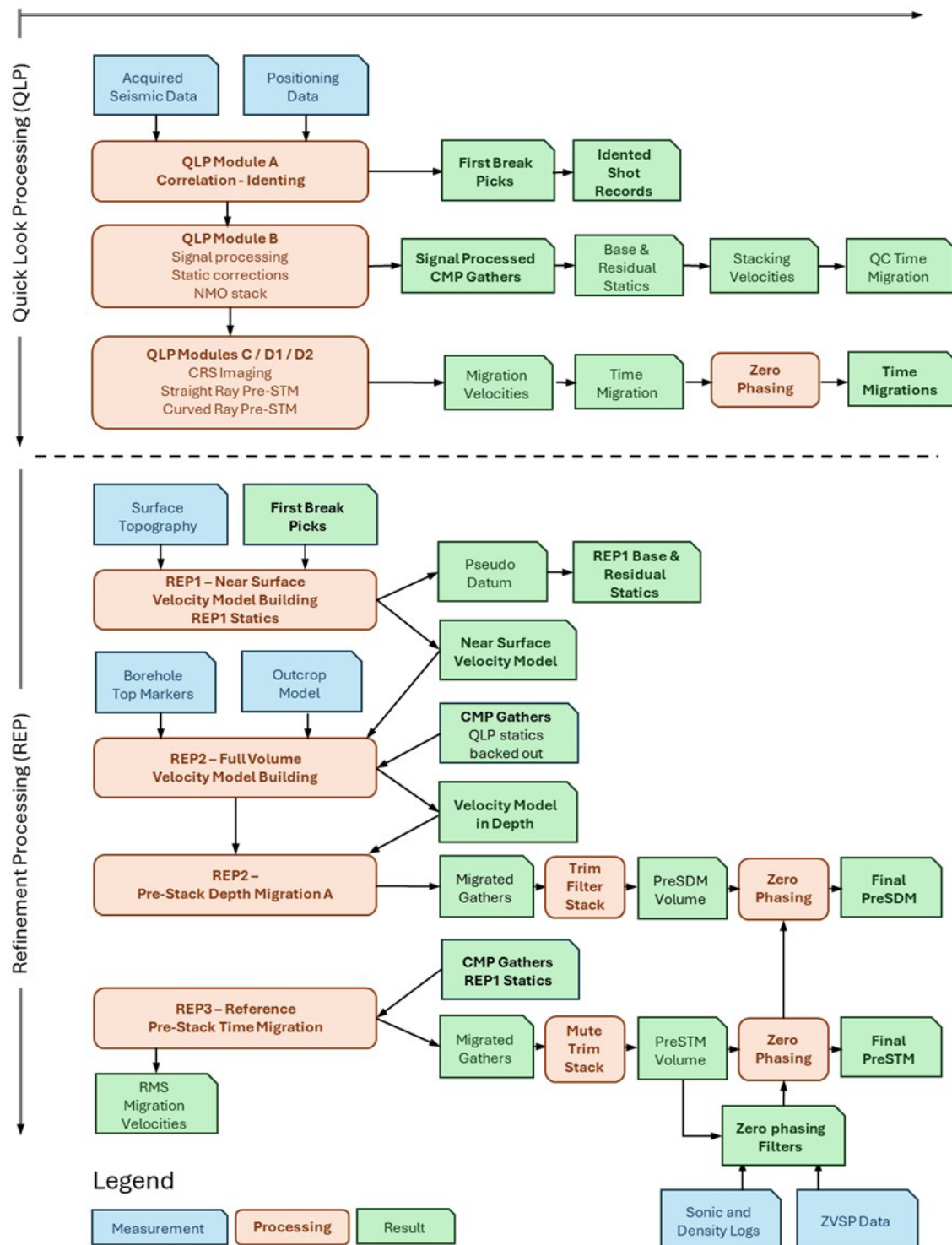


Fig. 3-4: Flowchart summarising the processing steps applied in 2017 and 2020/21
Nagra (2024a)

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 several seismic processing products. A number of different seismic imaging products were screened as a result of quick-look processing, and processing vintage D16 was selected since it showed very coherent reflectors compared with the other processing products (Nagra 2019). The data were stacked with residual moveout (RMO) correction followed by post-stack processing, and PreSTM imaging was carried out using geometry-regularised data after a common reflection surface (CRS; Nagra 2019). The original 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 convolution of 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-A (minimum-phase)

Following the Quick Look Processing, 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-A2 volume was generated and selected (here referred simply as PreSDM-A) and finally, a Pre-Stack Time Migration creating the PreSTM-ref volume (Sections 3.1.3, 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 laterally considerably varying 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 the removal of earlier statics (elevation, refraction, residual) from the shot-processed seismic refraction tomography using an Eikonal solver, a spatially varying pseudo datum, the calculation of corresponding refraction static- and station-consistent residuals (based on first-break picks), and 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-A velocity models, which are not supported by well data and regional geological understanding. Such velocity anomalies aligned with observed local variations of top structure morphologies but they do not coincide with geological bodies (Fig. 3-5), impairing the confidence in depth-migrated seismic imaging results (Fig. 3-5 A). Several attempts demonstrated that the realisation of a reliable Pre-Stack Depth Migration (PreSDM) cannot be easily achieved due to the large variability in shallow geology-associated parameters (statics) and overburden heterogeneities. Such geological variability is even stronger among the three siting regions (Fig. 3-6). Taking into account that the seismic data should provide critical input for the site selection (i.e. presence, position and density of structural lineaments and the host rock geometry), comparability of the data among the three siting regions becomes the key parameter to ensure the same level of resolution and uncertainty in the data quality and associated interpretation. Therefore, a reference Pre-Stack Time Migration (PreSTM-ref) imaging step was designed and executed such that the processing parameters and applied workflow were similar across the three seismic surveys.

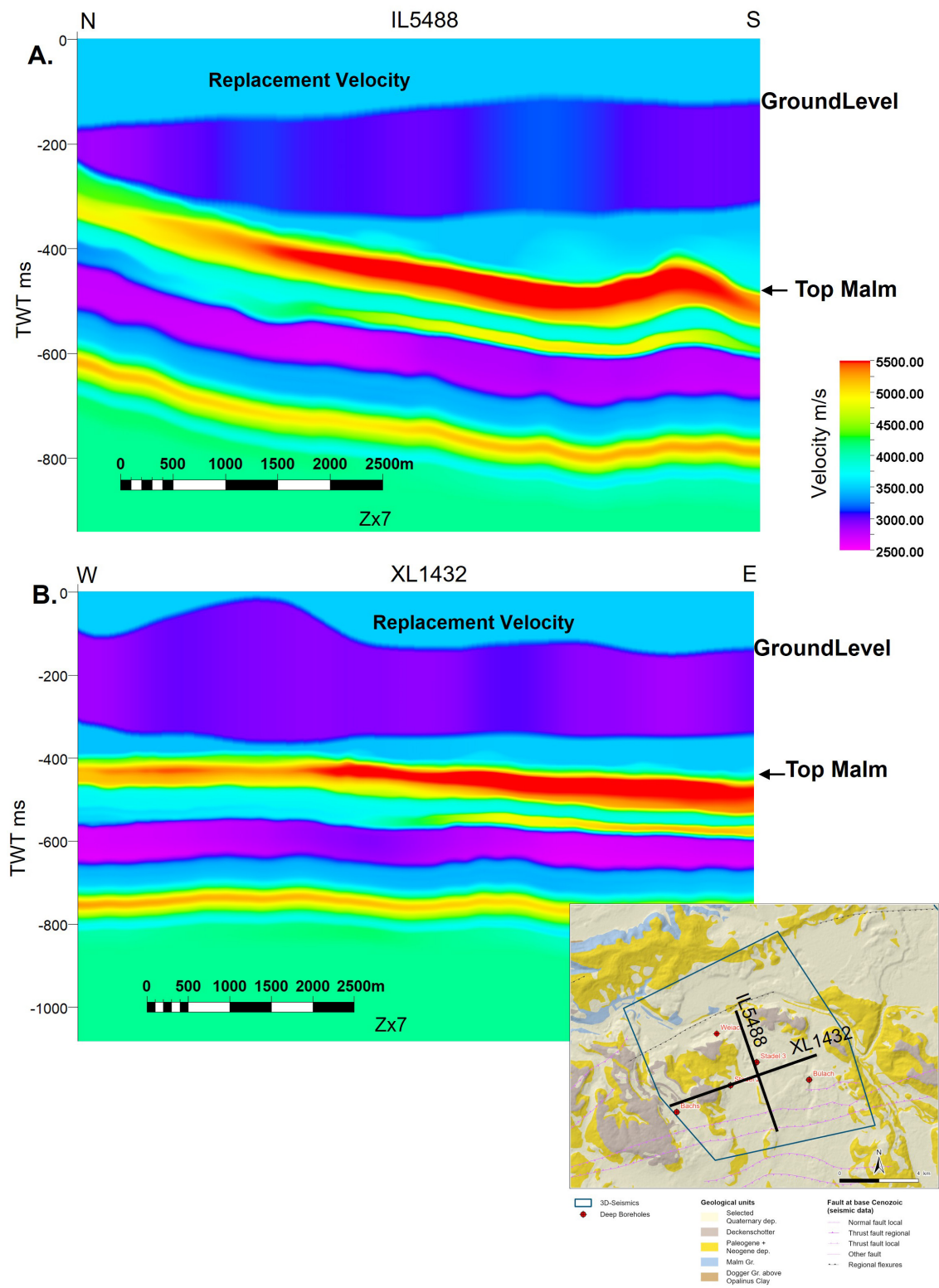


Fig. 3-5: PreSDM-A velocity model

A. Inline 5488 and B. Crossline 1432 displaying the (smoothed) velocity (model from PreSDM-A showing major velocity anomalies in the shallow levels (above the Top Malm).

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

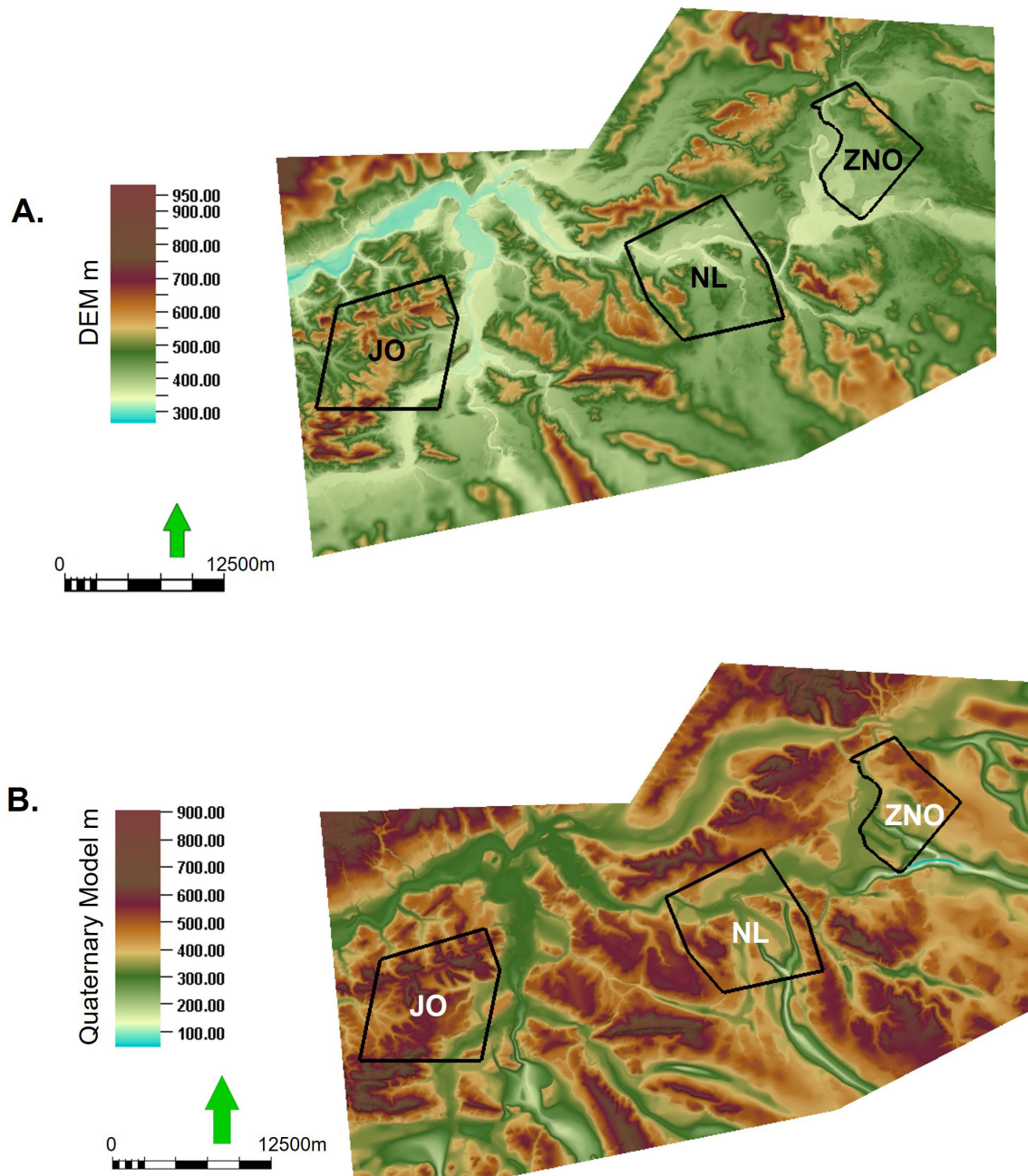


Fig. 3-6: Morphological complexity of the shallow geology has a direct impact on the seismic imaging

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

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

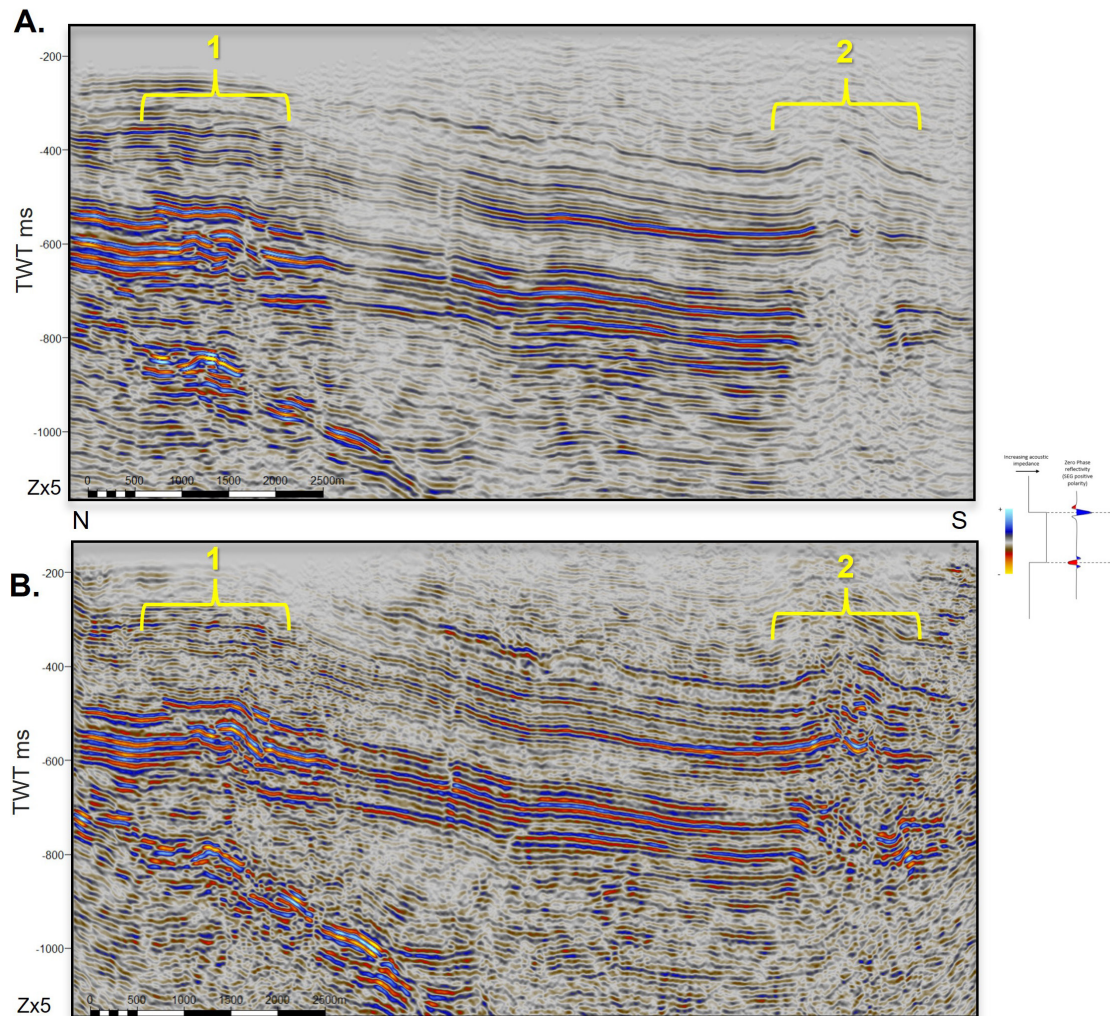


Fig. 3-7: Seismic section showing processing vintage comparison

Inline 5420 from A. QLP and B. PreSTM-ref. Note the improved seismic imaging in the northern (1) and southern (2) structurally complex zones of the PreSTM-ref data.

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 objective of this conversion was: (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 vs VSPs comparison to verify log quality, generating a zero-phase synthetic matching the VSP corridor stack.
- Generate minimum-phase synthetics 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 supertraces by combining the zero-phase and the minimum-phase synthetics of individual wells.
- Calculate a shaping filter between the two synthetic supertraces.
- Apply the shaping filter to the minimum-phase data to obtain the zero-phase data.

Despite the use of a single seismic volume by the interpreter is not an uncommon practice, the use of different processing vintages helps to understand how the seismic signatures, diagnostic for geological features, can be differently imaged. Given that each imaging 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 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 in the text that PreSTM-ref zero-phase is always referred to as PreSTM-ref.

3.1.5 Seismic resolution

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

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

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

For the QLP dataset, based on its dominant frequency and velocity, a theoretical vertical resolution of around $\lambda/4$ was estimated, i.e. around 12.5 m for the Opalinus Clay interval and 28 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.)	$\lambda/4$	$\lambda/10$
168.2 Baj 400	Top Clay	50	3058 m/s	15 m	6 m
		70		10 m	4.3 m
237 Lad 400	Top Muschelkalk (near)	45	3600 m/s	20 m	8 m
		65		13 m	5.5 m
Below 237 Lad 500	Within Muschelkalk Fm	42	5000 m/s	29 m	11 m
		64		20 m	8 m

3.2 Well dataset

The available wireline logs include typical log suites (e.g. gamma ray, density, porosity, sonic, neutron and caliper from the four vertical wells Stadel-2, Stadel-3, Bülach-1 and Bachs-1 (Nagra 2021, Nagra 2022a, Nagra 2022b, Nagra 2023) and were complemented by edited and quality-controlled density and sonic logs using zero-offset VSP (ZOVSP) results.

Within the NL siting region, ZOVSP data were acquired for four wells (i.e. Bachs-1, Stadel-2, Stadel-3 and Bülach-1). VSPs are useful in the well 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 may have been applied.

4 Methodology

Seismic interpretation is the extraction of subsurface information from seismic data. The danger in seismic interpretation is in assuming that everything that it is imaged is geology (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, therefore, is 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 siting region investigations, the analysis and interpretation of the available 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 the stratigraphic framework and on how to interpret the seismic data, (iii) a seismic data interpretation framework resulting in a stratigraphic-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 and depositional architecture up to lithology and fluid content.

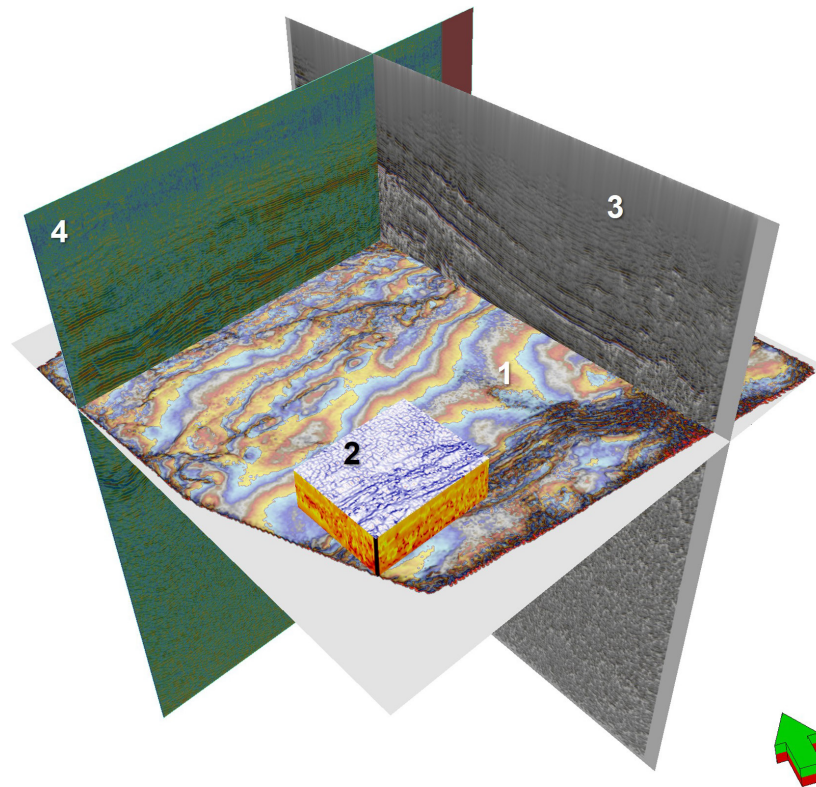
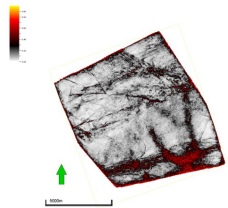
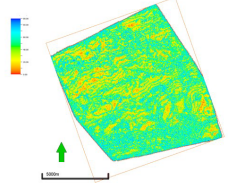
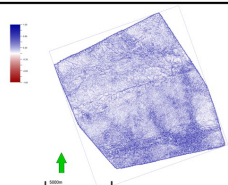
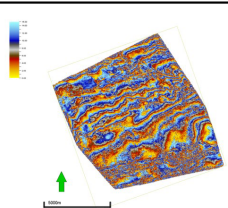
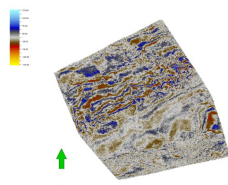
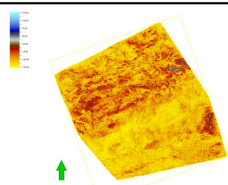
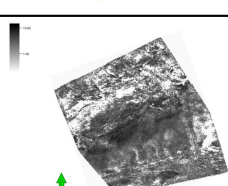


Fig. 4-1: Example of 3D visualisation and screening of attributes

Several attributes are combined or interrogated to gain confidence in the seismic imaging: 1. time slice combination of instantaneous phases and variance; 2. cropped cube of 3D curvature as well as inline and crossline displaying frequency; 3. inline with outcrop look; 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 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 – 640 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

A subset of four wells (Stadel-2, Stadel-3, Bülach-1 and Bachs-1) was used for a detailed seismic-to-well tie. The goal for this correlation is to be able to locate the key well markers in the time domain with the highest interpretation confidence (i.e. highest traceability) and to guide their interpretation in order to assess the relationship between the seismic signal and well data. This can be achieved by generating synthetic seismograms. Synthetic seismograms allow to: (i) tie geological markers to seismic horizons, (ii) understand the seismic response to seismic markers (stratigraphy) and define whether these events are single, doublets, or more complex reflections and determine how to pick them, (iii) understand phase and frequency characteristics of seismic data and (iv) generate accurate time-depth relationships (as part of the overall process). A critical and fundamental step, before starting the seismic-to-well tie workflow (or any seismic interpretation), is to define and fully establish (freeze) a complete set of geologically sound stratigraphic markers. Since the 1970s (Sheriff 1977, Vail et al. 1977, van Wagoner et al. 1990, Tipper 1993, Nielsen & Van Weering 1998), it has been well recognised that the most ideal marker types to be used in seismic interpretation are those that subdivide geological time intervals into “genetically related” stratigraphic units and thus identify “time-evolving” depositional sequences. A sequence stratigraphic framework was therefore developed, applying a cross-discipline and multi-scale approach (Fig. 4-2) integrating depositional facies characterisation, vertical stacking pattern, key stratal boundaries identification (core data) with biostratigraphic calibration (i.e. chronostratigraphy and associated timelines) and log calibration (i.e. physical properties).



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 deployment of standardised well logs to define formation tops from petrophysical analysis, and incorporated 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).

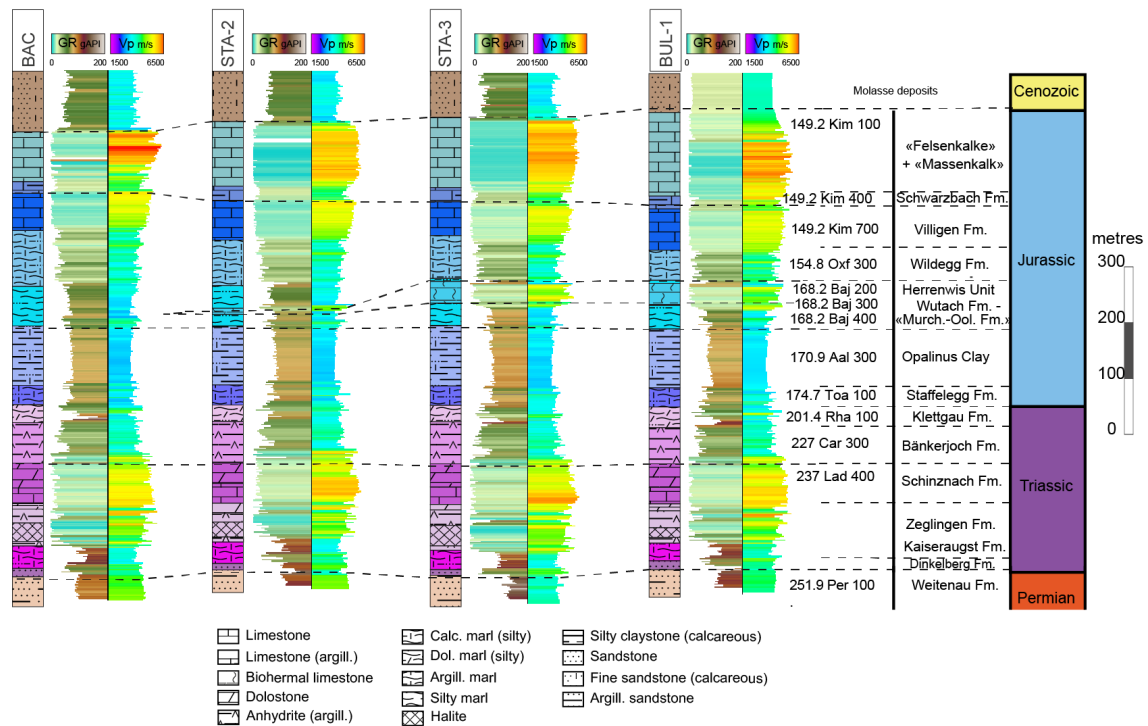


Fig. 4-3: Sequence stratigraphic scheme referenced to lithological formation and petrophysical signature

Well correlation panel flattened at 170.9 Aal 300 – Top Opalinus. Well location shown in Fig. 3-1.

Once the stratigraphic framework had been established, synthetic seismograms were generated in Petrel 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.
- The wavelet was extracted from the seismic data at well location using a statistical approach. The wavelet amplitude spectrum is derived from scanning of seismic traces at intervals of interest. Phase is assumed to be constant and equal to zero.

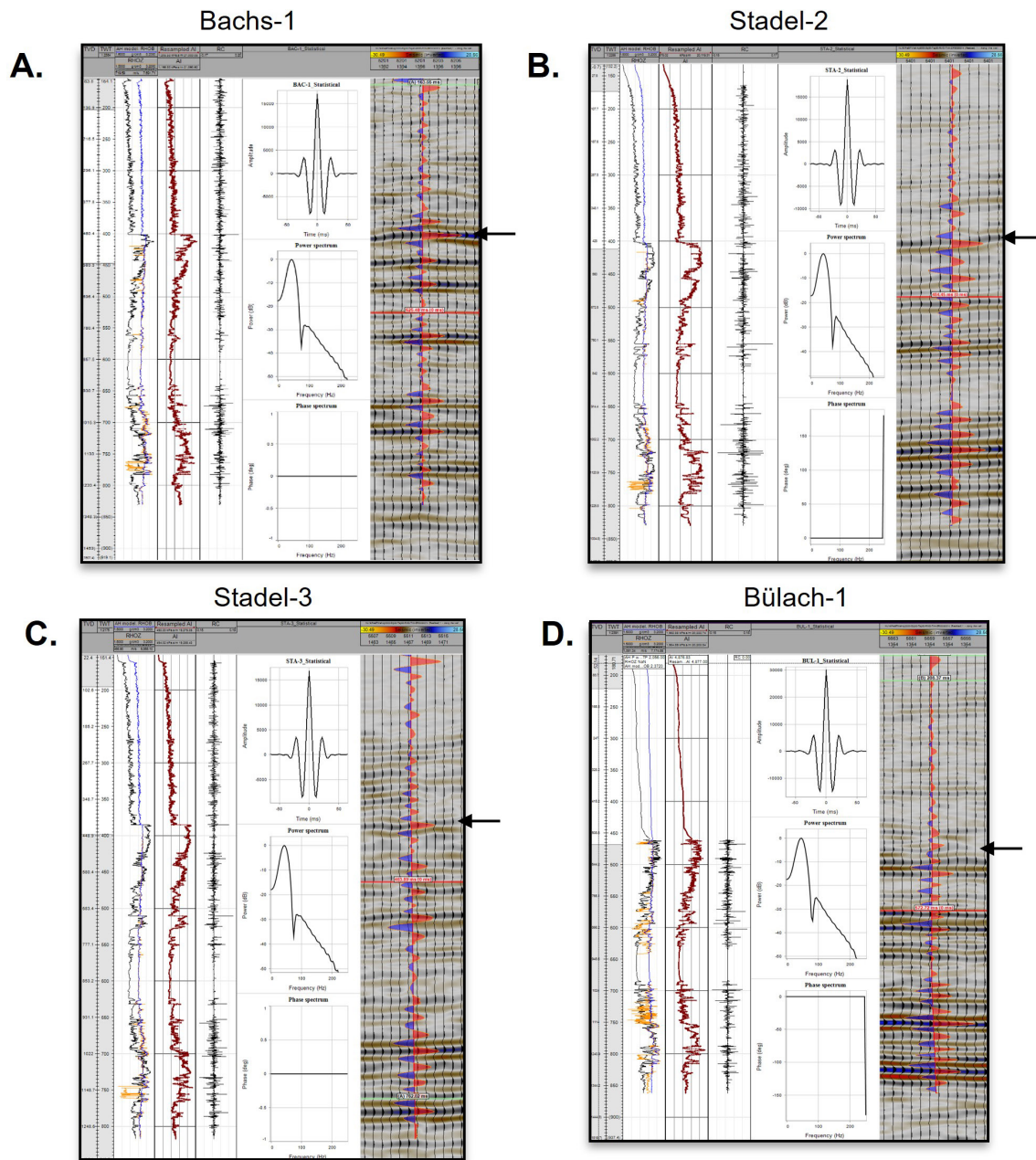


Fig. 4-4: Synthetic panels for the four wells

A. Bachs-1, B. Stadel-2, C. Stadel-3 and D. Bülach-1.

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

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 has not a complete zero-phase characteristic. Key stratigraphic markers horizons do not, therefore, always perfectly tie to a seismic loop in the seismic data and zero-crossing is in cases preferred to perform the interpretation.

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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 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.

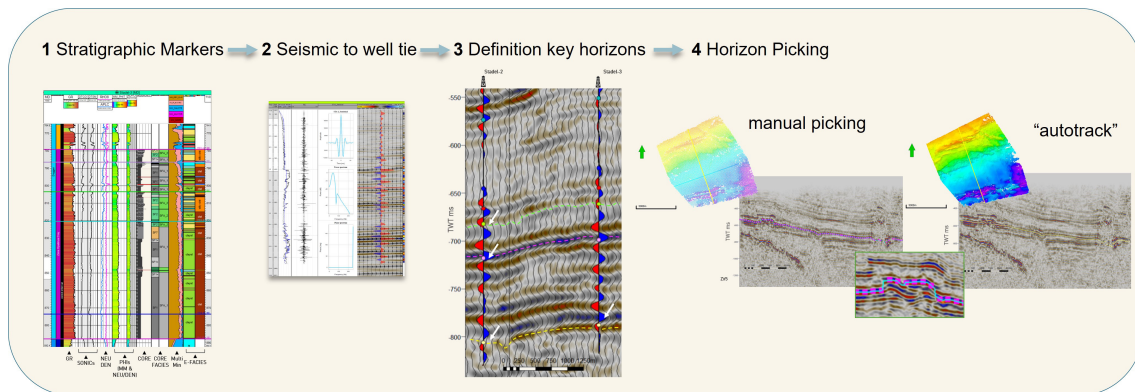


Fig. 4-5: Horizon interpretation workflow

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 lineaments. Limitation of the traditional fault-picking algorithm becomes critical across the major deformation zones (specifically in the case of reverse faults), where the horizon multi-z (i.e. multi-depth values) at the hanging wall and footwall across the fault are not tolerated.

4.3.1 Horizon interpretation strategy

After identifying the continuous seismic events, the reflector was interpreted in areas where it is coherent and clear, and then infilled in areas with moderate noise and finally interpolated / manually pushed across patches of poor data. 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 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 Stadel-2 and Stadel-3 wells (Fig. 4-6 A, B) and closed the “square” at the Bülach-1 and Bachs-1 wells (Fig. 4-6 D). The latter wells were used as blind quality checks for horizon interpretation. The seedlines were manually picked using both Petrel manual and 2D autotrack options.

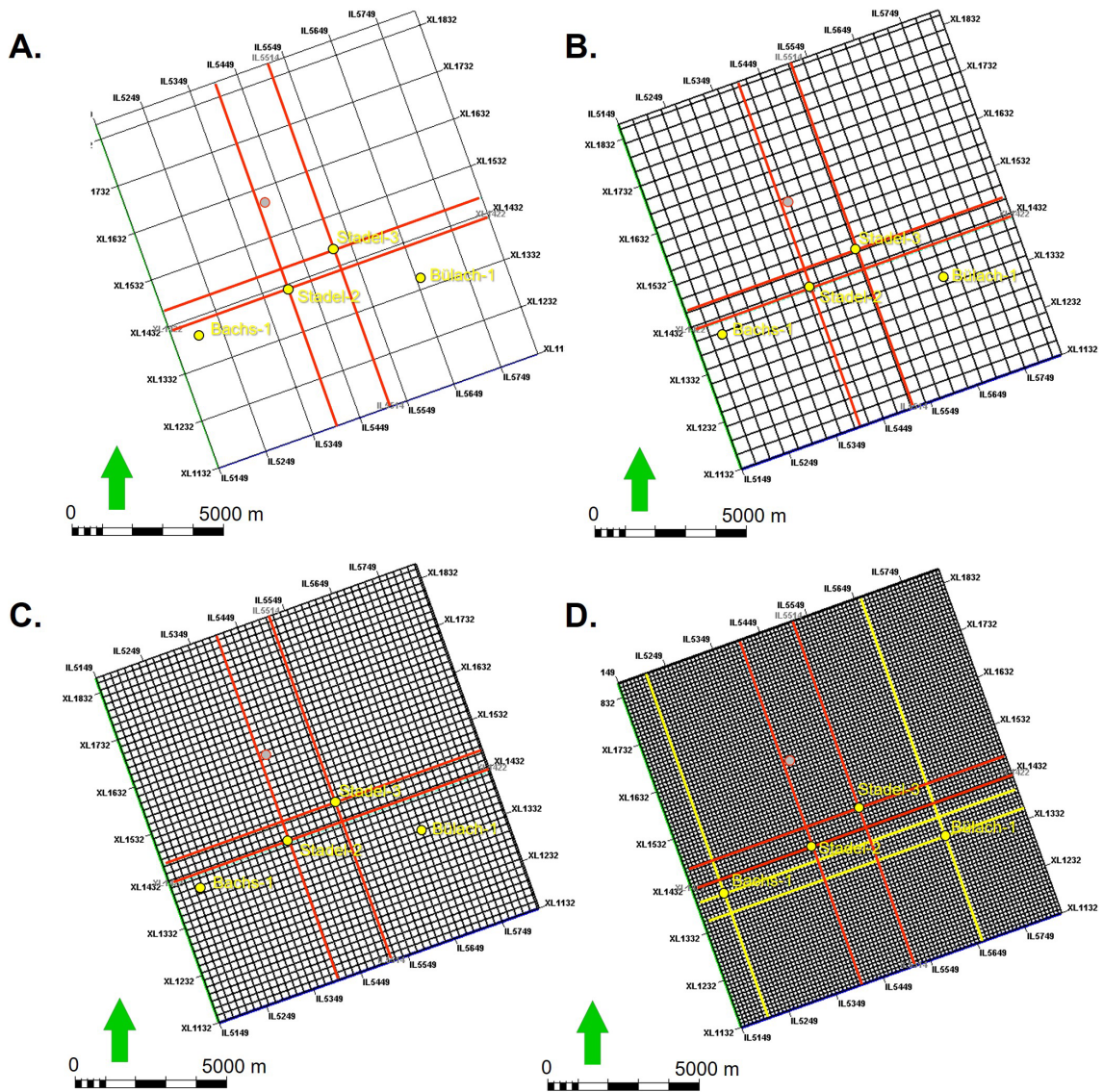


Fig. 4-6: Interpretation seedline methodology and grid building

A. Horizon interpretation is calibrated at in- and crosslines (red lines) crossing the Stadel-2 and Stadel-3 wells; B. interpretation is then performed with the initial line-grid of 32×32 ; C. decreasing to 16×16 and finally to 8×8 (D.) and finally checked along the in- and crosslines crossing the Bachs-1 and Bülach-1 wells (yellow lines in D).

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

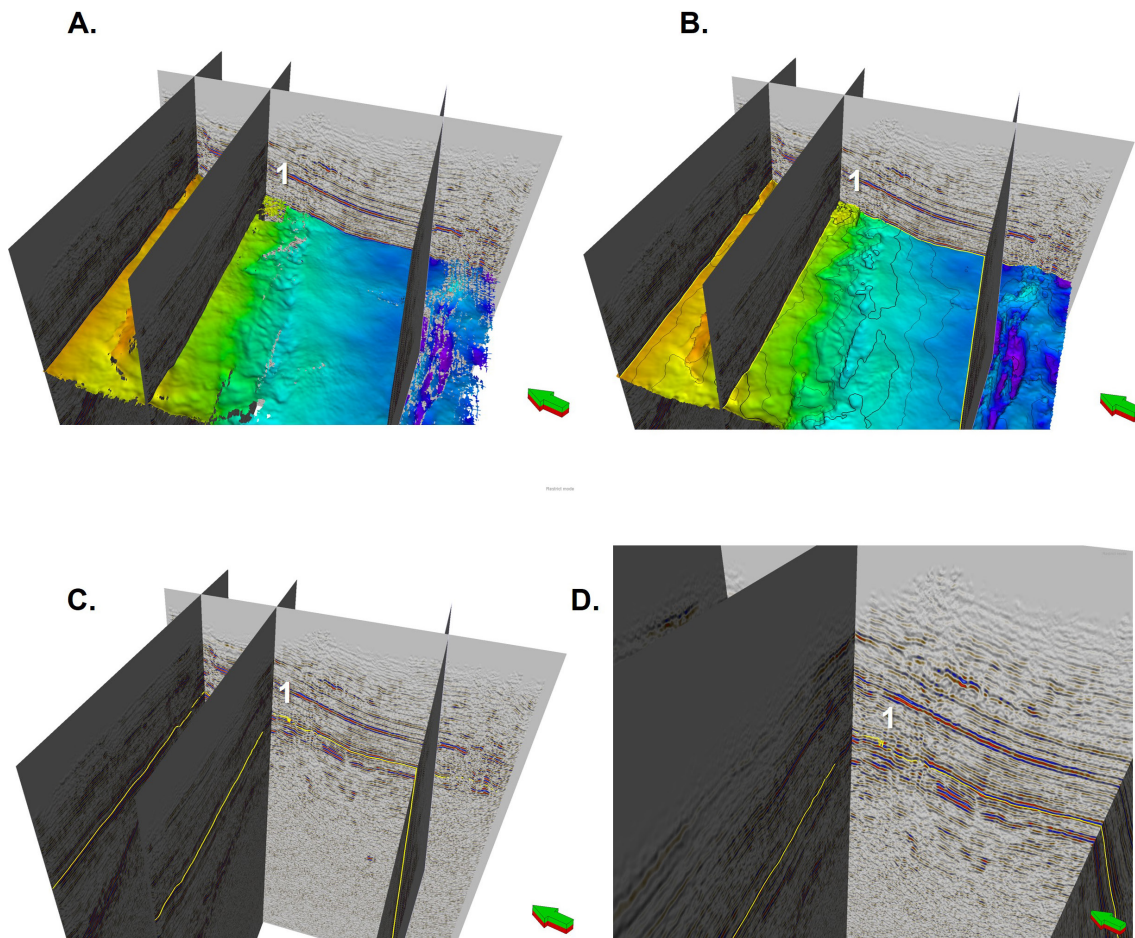


Fig. 4-7: Quality control of autotracked horizon in 3D viewer

A. 3D autotracked horizon screening and identification of problematic areas using the horizon as well as in- and crosslines (1); B. Screening of gridded surfaces for 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 (deformation zones); Nagra 2022c).

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.

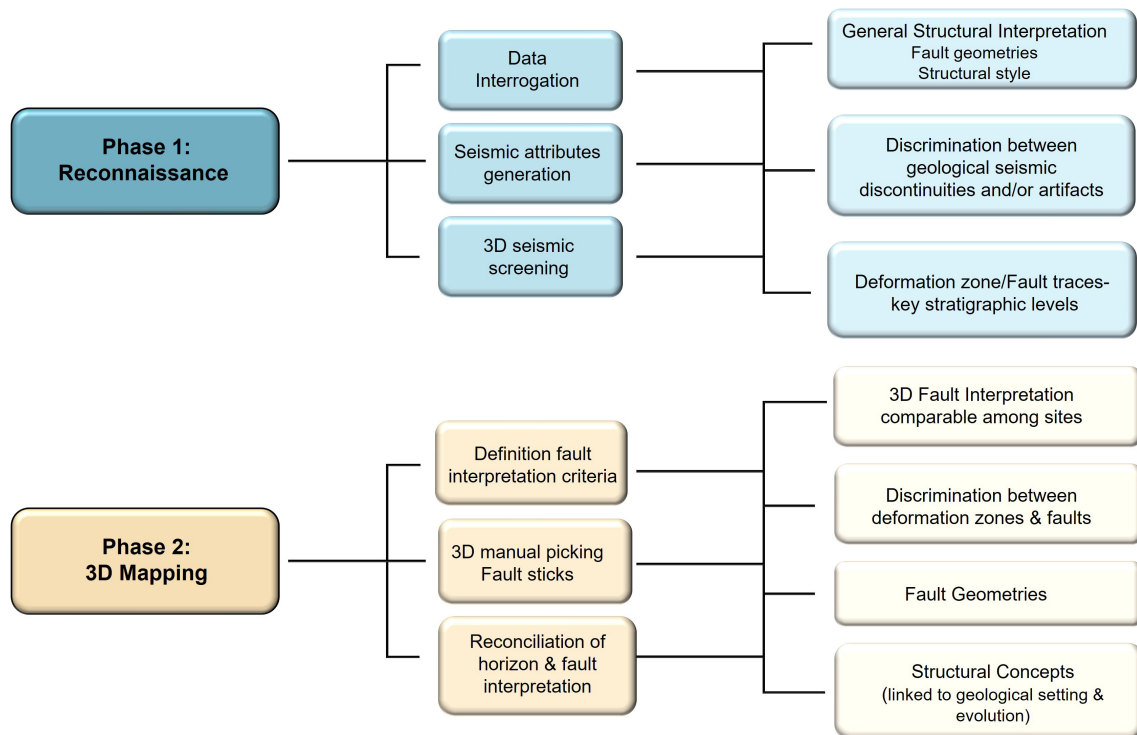


Fig. 4-8: Fault interpretation carried out using a two-phase approach

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 2022c), sedimentological features and artefacts. 3D fault mapping was then performed (Phase 2), which involved picking fault sticks / planes based on the defined criteria and allowing the separation of the deformation zones into faults and folds.

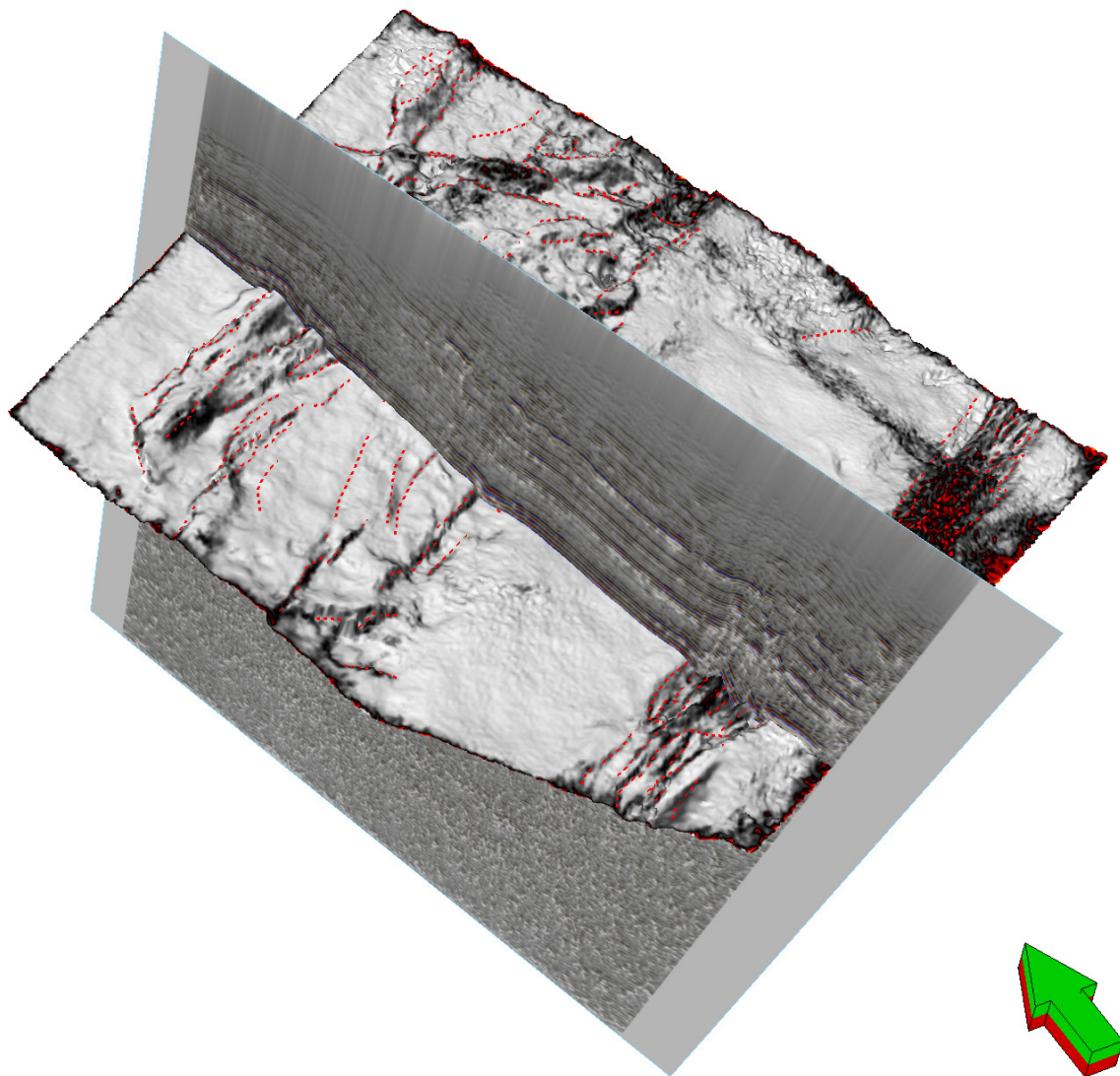


Fig. 4-9: 3D display for Phase 1 fault interpretation workflow

237 Lad 400 – Top Muschelkalk 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.

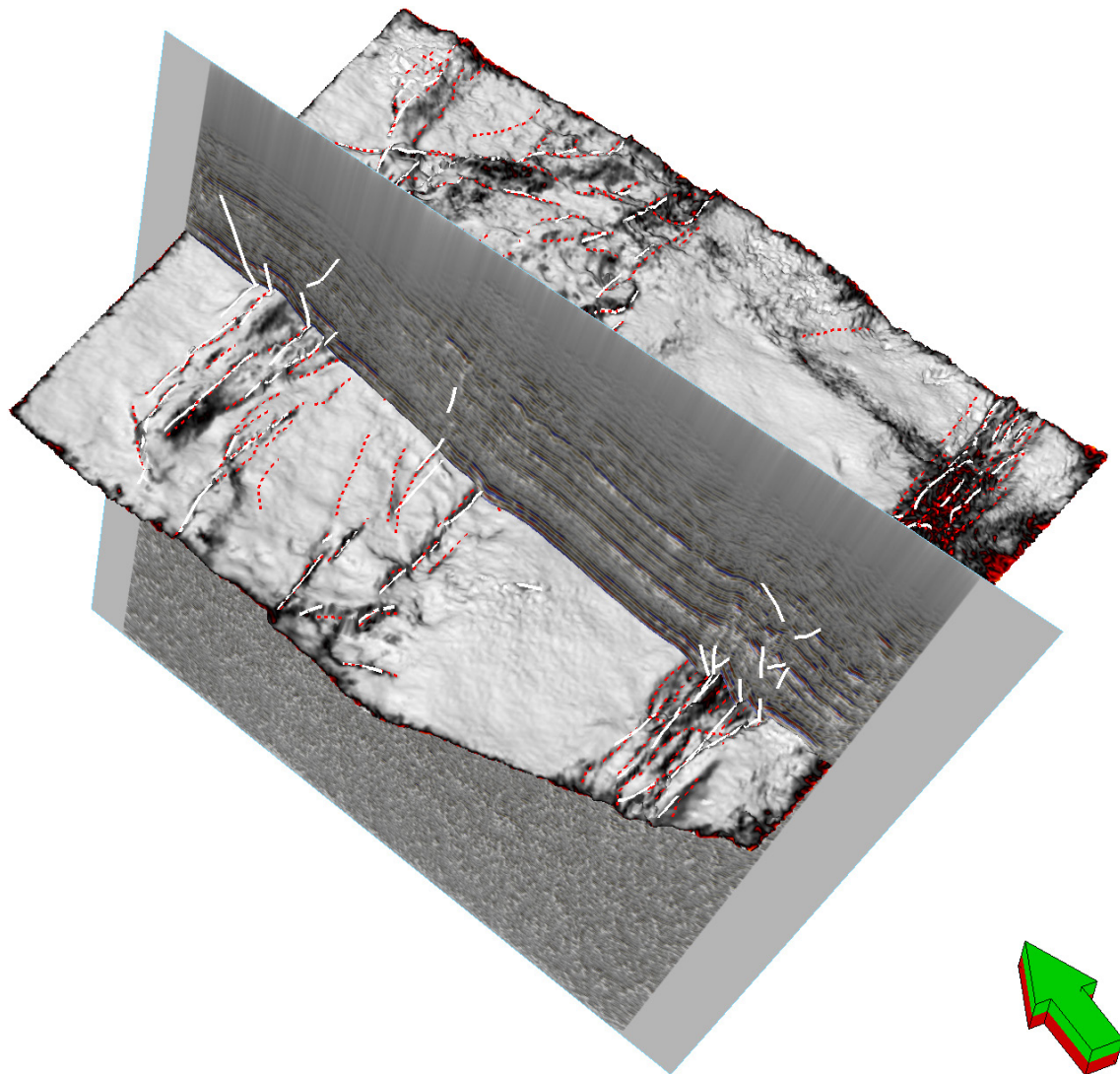


Fig. 4-10: 3D display for Phase 2 fault interpretation workflow

237 Lad 400 – Top Muschelkalk variance horizon and inline outcrop view, showing the fault interpretation 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 folds within 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 within the seismic data by a number of diagnostic signatures. Faults can be loosely subdivided into those large enough to offset the two-way-time arrivals of reflections (loops), enabling them to be identified on traditional section-and-time-slice data displays, and those with smaller throws close to the detection limits of the seismic survey, which can only be imaged by data “attribute” variations. Depending upon the geology, the seismic data 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 processing vintages, increasing the confidence in the fault pick and the fault lineament position by using the Pre-Stack Depth Migration (PreSDM) cube. This 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 throw diminishes to approach the resolution limits of the 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.

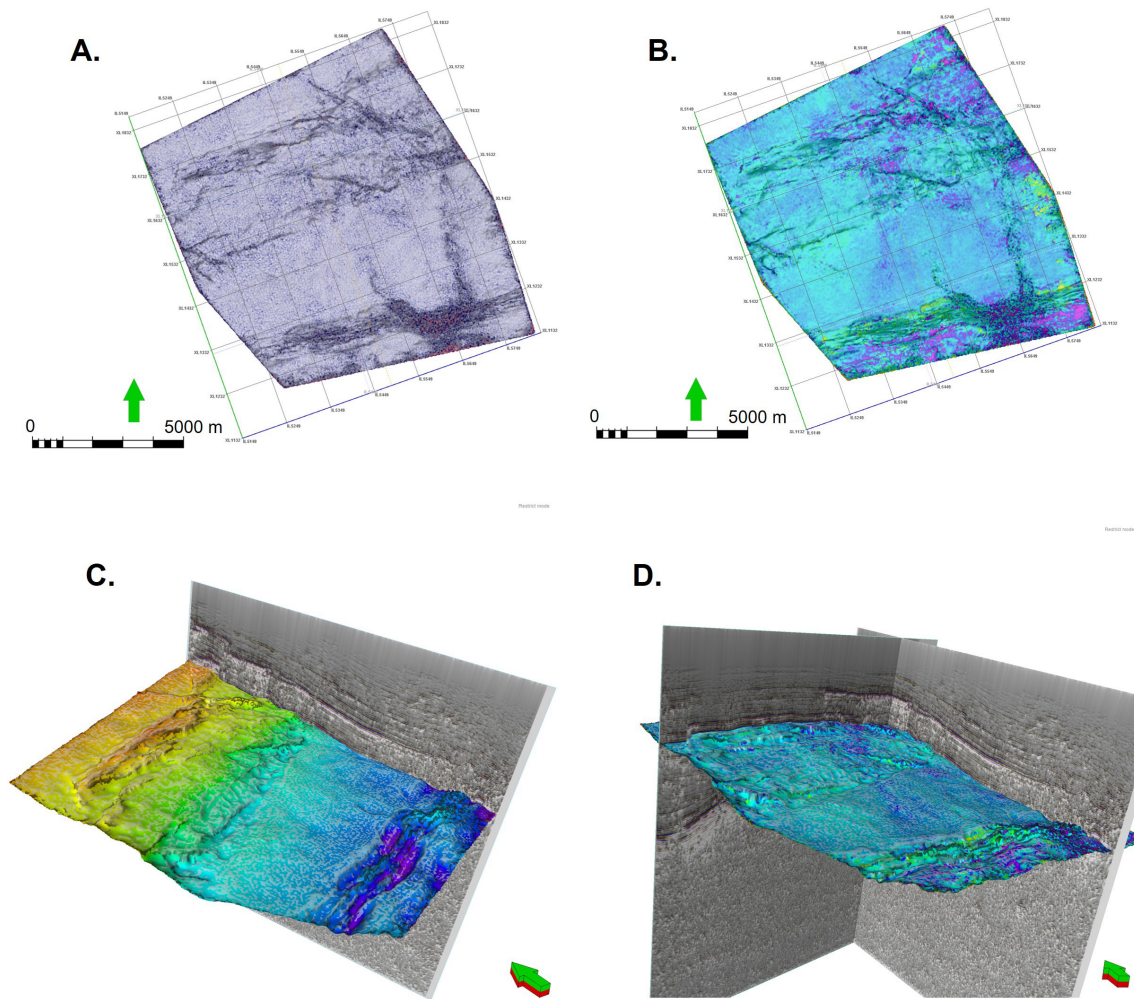


Fig. 4-11: Displays showing the multi-attribute approach in 2D and 3D views

The combination of several seismic attributes and 3D correlation with section and top structure trend increases the level of confidence in the fault pick. A. 237 Lad 400 – Top Muschelkalk horizon variance and 3D curvature; B. Top Muschelkalk horizon variance and frequency; C. Top Muschelkalk horizon combining top structure and variance with vertical inline in outcrop view; D. Top Muschelkalk 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 of the fault.
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 seismic 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 of reflection multiples and diffraction patterns and, in some cases, igneous intrusives (dykes) that can produce similar responses.

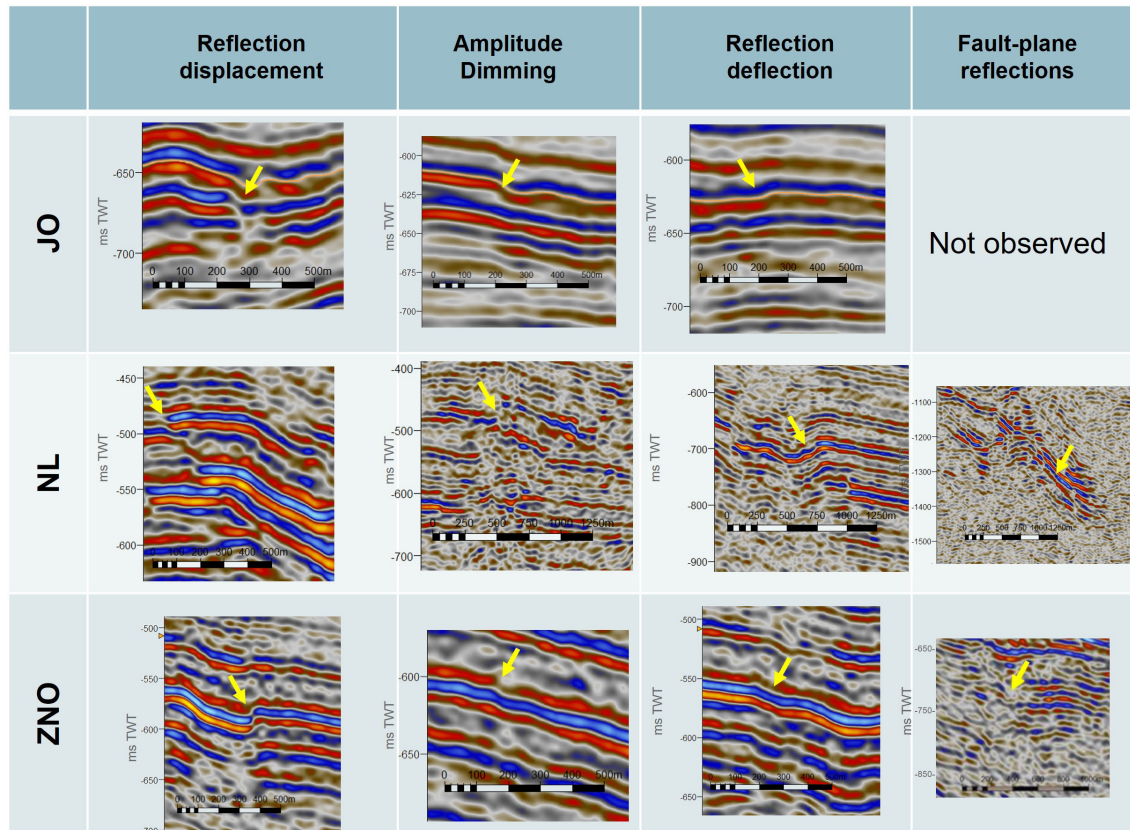


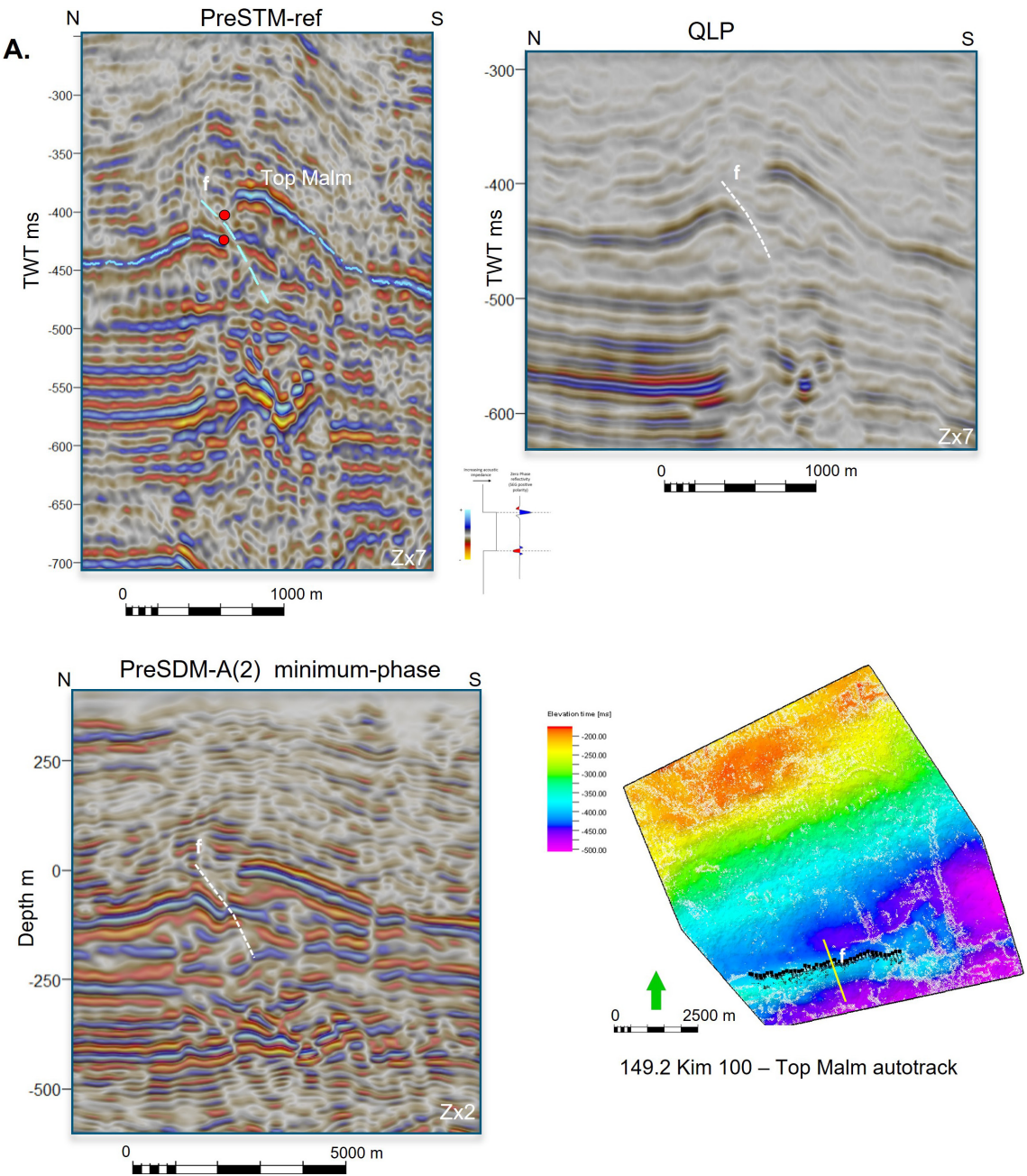
Fig. 4-12: Examples of the most common fault signatures in seismic sections for the three siting regions

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) linear features and edges in the time / horizon slices. Fault signatures were used in a similar manner for JO, NL and ZNO seismic data in order to facilitate comparability in the interpretation. Seismic display is PreSTM-ref.

4.4.2 Fault interpretation strategy

Following reconnaissance work, 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 Per 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).



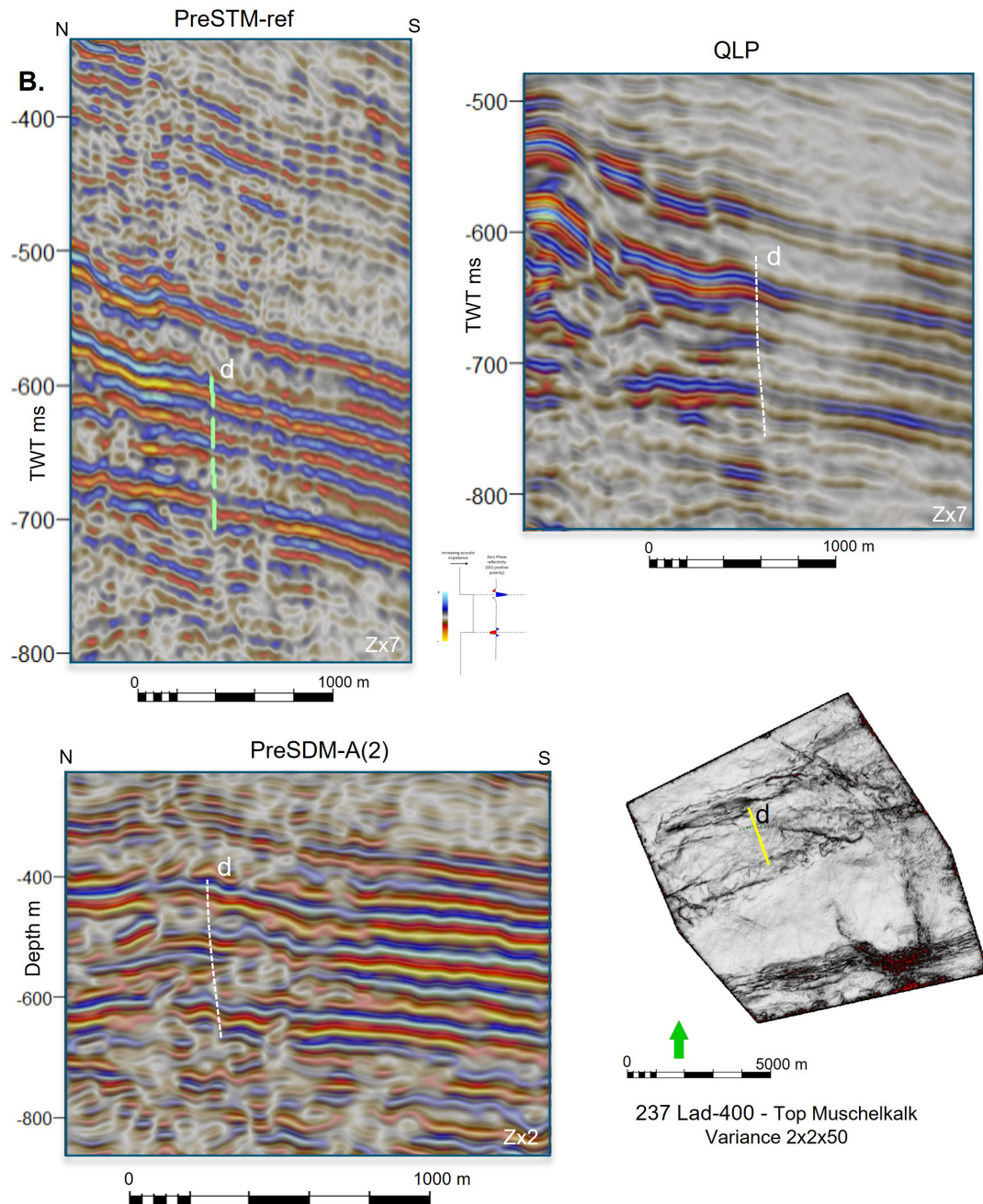


Fig. 4-13: Fault interpretation by comparing fault signatures in available seismic vintages

The recognised fault signatures were compared in all the available seismic vintages, increasing the interpretation confidence. The fault sticks interpreted in the PreSTM-ref were projected in the QLP and (after depth conversion) in the PreSDM-A data. A. Example from inline 5440. In this example, the seismic fault (f) is recognised based on reflection offset (red dots) and dimming, which is also clearly captured in the 149.2 Kim 100 – Top Malm structure. B. Example from inline 5415, where the seismic fault is interpreted based on reflection deflection (d) and dimming associated with a linear edge in the variance extraction.

Fault stick picking was manually performed predominantly along inlines and crosslines (8×8 line-grid) since the acquisition orientation in the NL-16 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. 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 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).

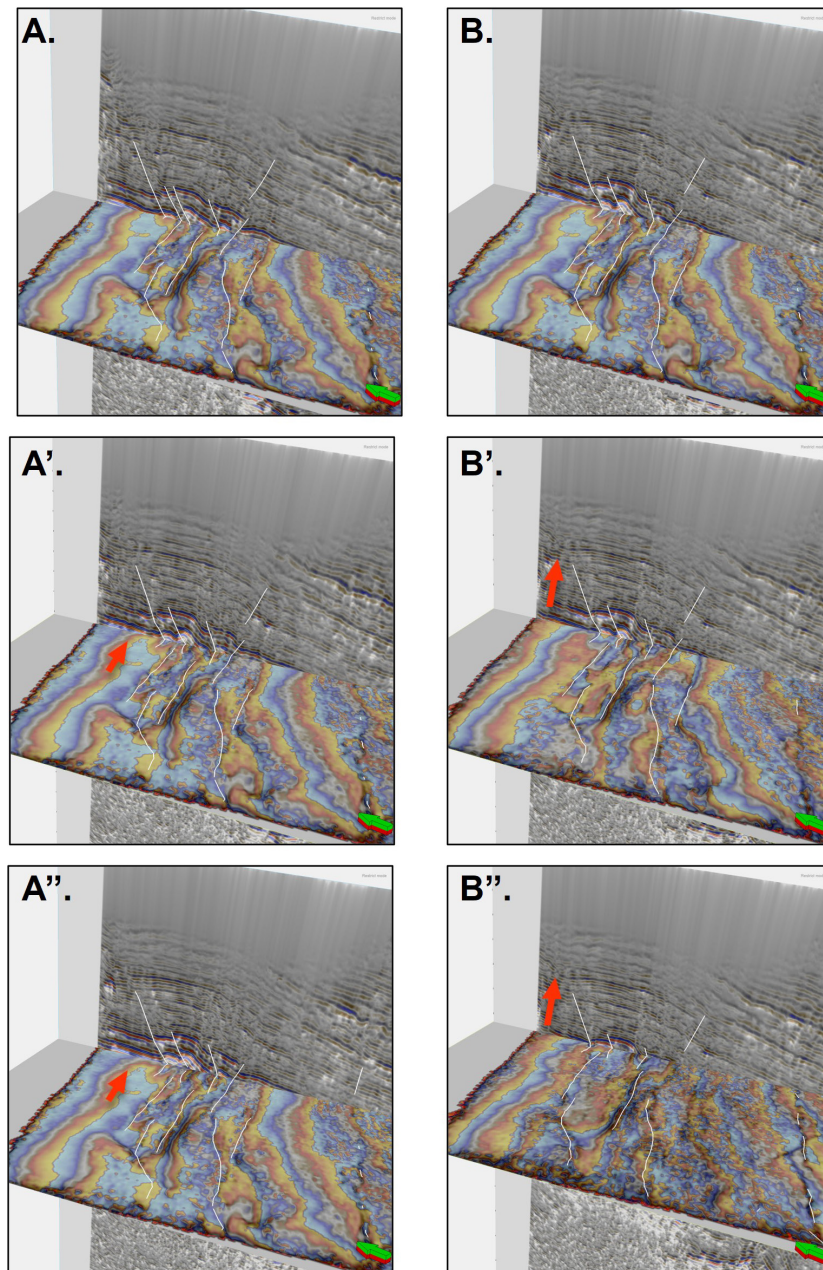


Fig. 4-14: Sets of 3D displays showing the 3D QC performed for fault interpretation

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 5343; A'. Inline 5353; A''. Inline 5363; B. Time slice 572 ms TWT; B'. Time slice 558 ms TWT and B''. Time slice 506 ms TWT. Seismic display is PreSTM-ref. red arrows indicate the sliding direction of seismic section (A', A'') and time slice (B', B'') relatively to A. and B. Green arrow points towards north.

A scaled-down approach was applied for the 3D fault interpretation. First, the larger faults were mapped to create a structural framework of primary kinematic family, followed by a second phase of interpretation where smaller structures infill the details of 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) and 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 sticks) were not 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 interval (e.g. Opalinus Clay) despite the implemented vertical simplification approach. The Opalinus Clay interval is characterised by the presence of seismic multiples (see Section 5.1). Therefore, the fault plane cannot be traced with confidence. In addition, due to the rheological behaviour of the clay, deformation is expected to be accommodated without evident fault displacement at seismic scale. However, to capture the fault presence across the entire sequence, sticks representing the segments were singularly mapped and referred to by a progressive naming convention. Exceptions are thrust faults, where the structural style implies the propagation across weak mechanical layers.

Faults are usually picked as two-dimensional lines and discrete (simplified) planes, which do not capture the complexity of fault architecture as observed in outcrop (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 site comparison purposes, fault segmentation was simplified. Such simplification comes with some limitations in the interpretation products.

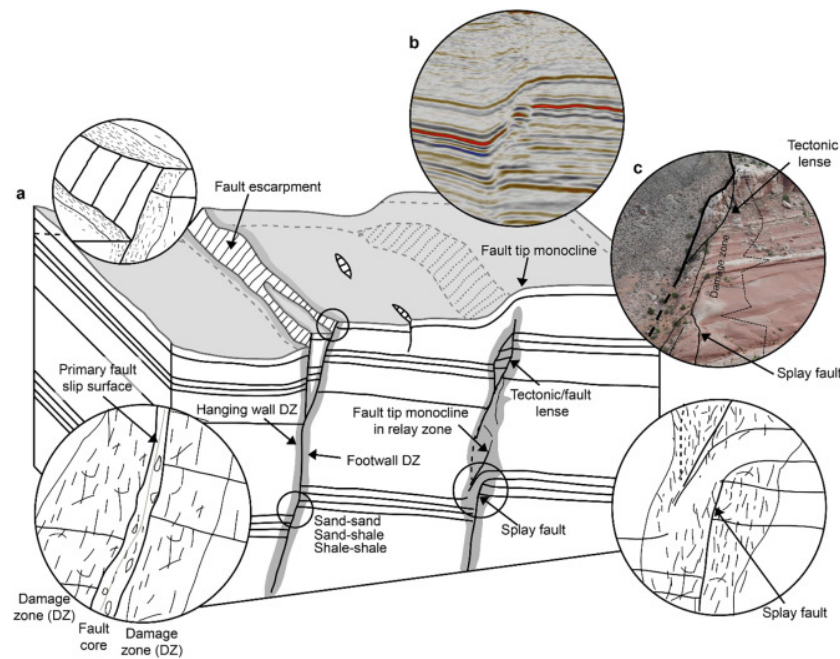


Fig. 4-15: Schematic 3D fault block model showing the complex architecture of a fault zone comparing the scale of details between b. (fault in seismic) and c. (fault in outcrop)

After 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 121 matches of the stick in the seismic in-between sections. Further segmentation and complexity of the interpreted fault zones are expected within stratigraphic levels and associated with lithological changes (Childs et al. 1996, Roche et al. 2021). Nevertheless, while compromising on “fault architecture”, the applied simplification still captures the key characteristics, complexity and distribution of the deformation zones.

5 Results

5.1 Seismic data quality

A first step to weight the confidence level in the resulting interpretation is to understand the seismic signal quality. The 3D seismic data were therefore qualitatively screened based on overall event continuity and amplitude fidelity (signal / noise, clarity of reflections, internal depositional / structural features, bandwidth / seismic character preservation, remnant multiples and noise trains). Since 1997, it was established that using a 3D approach to evaluate reflectivity continuity and geometry allows discrimination of discontinuities, which represent geological features, from those 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).

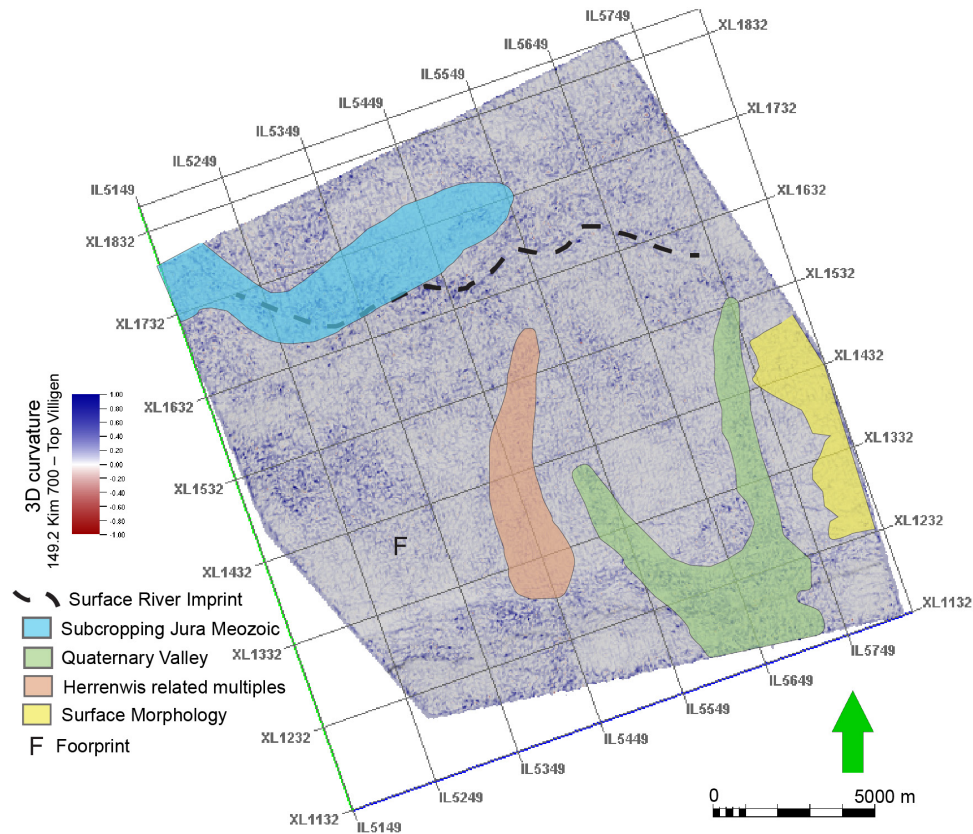


Fig. 5-1: Areas impacted by seismic signal disturbance (artefacts) were recognised and mapped

The observed seismic artefacts are mainly driven by the complex surface morphology and the Quaternary geology (i.e. outcropping / subcropping of the Malm carbonate, surface rivers and morphology, deep Quaternary valley).

Areas where interpretation can be impaired due to lack of signal and/or noise masking geological features are predominantly associated with:

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 (1997b) and Hesthammer et al. (2001) indicate that noise-interference lineaments interfere at high angles with real reflections and cause disruption of the weaker signal (Fig. 5-2A; Hesthammer et al. 2001). These dipping features may, in part, be a result of imperfect migration of the seismic data. Within the NL-16 seismic survey, such vertically dimming stripes coincide with complex zones at shallow level (Fig. 5-2B.) and could represent dipping noise. While those dipping noises were not captured as an artefact polygon (confined within specific shallow stratigraphic intervals), awareness of the presence of such discontinuities is critical when interpreting faults.

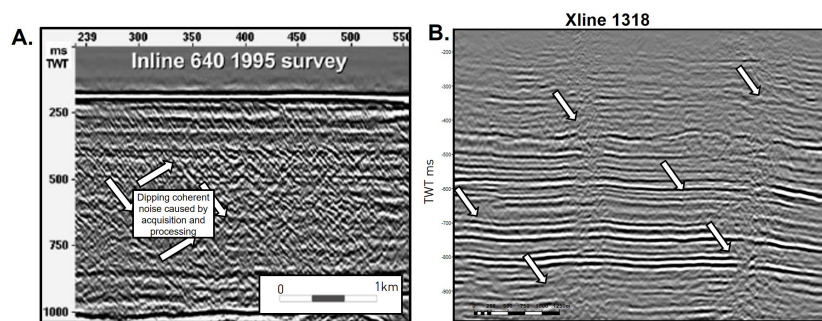


Fig. 5-2: Example of seismic processing artefacts, which can directly impair fault recognition and interpretation

A. North Sea seismic section example 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) and B. example from NL-16 PreSTM-ref dataset. Whereas the use of a colour palette is useful to recognise disruptions of reflections, a grey scale is best suited for the identification of the dipping noise.

Multiples are reflections created by acoustic waves that travel several times between two strong reflectors before being intercepted by a geophone. Multiples are mostly treated as artefacts that need to be removed during data processing (Backus 1959) and were therefore included here 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 re-processing exercise). This is partly supported by the VSP dataset (Fig. 5-3B.). The VSP response suggests that primary reflections could still be present in the upper part of the clay interval, but they do not correspond to the seismic pattern imaged by the seismic data. At seismic data scale, however, the morphology of those reflections mirrors the Top Herrenwis carbonate architecture, and they repeat themselves across the entire thickness of the clay interval (Fig. 5-4). Separation between primary and secondary patterns is therefore extremely challenging, hampering stratigraphic interpretation also in the upper section of the clay interval.

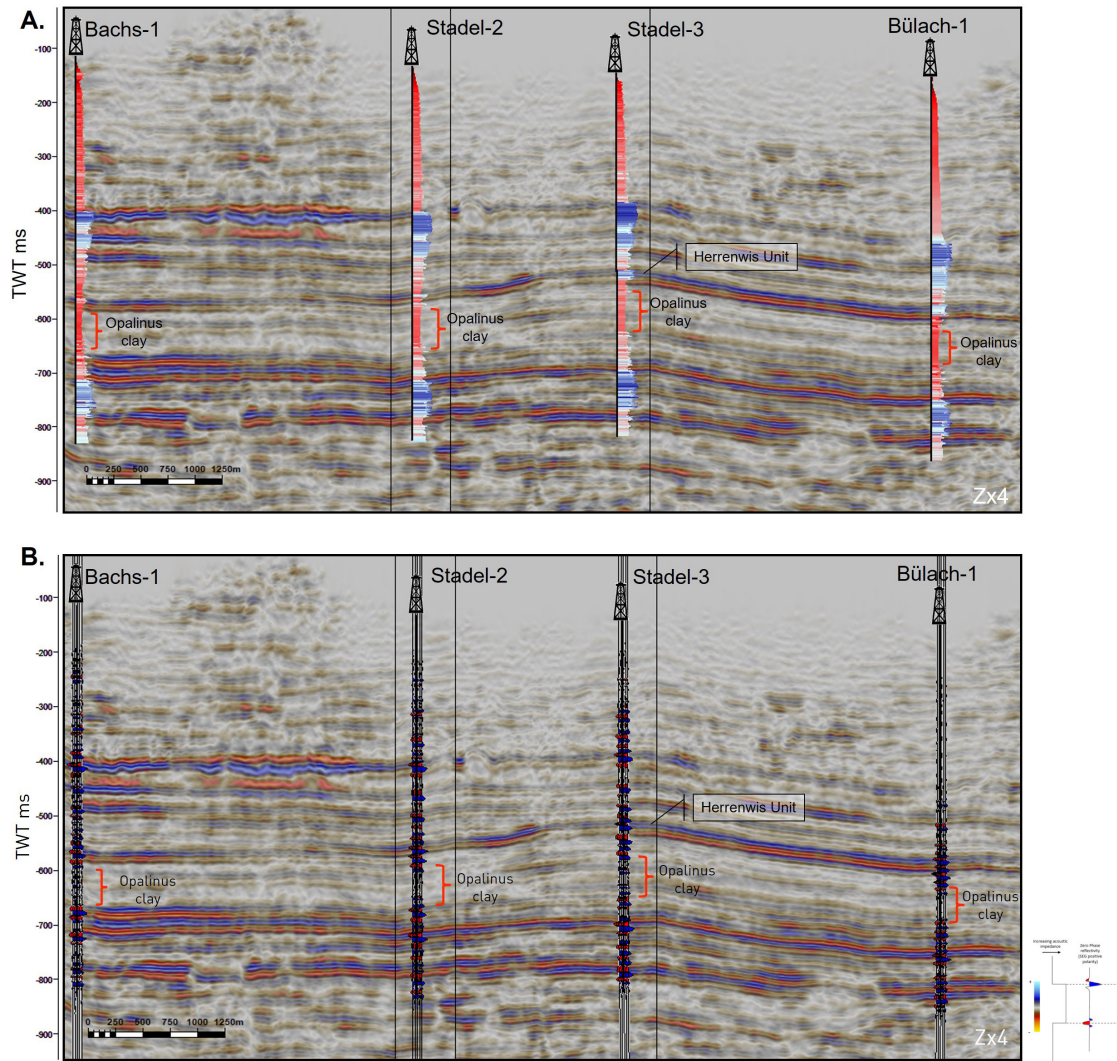


Fig. 5-3: Seismic section (reflectivity and relative acoustic impedance) across the four wells

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

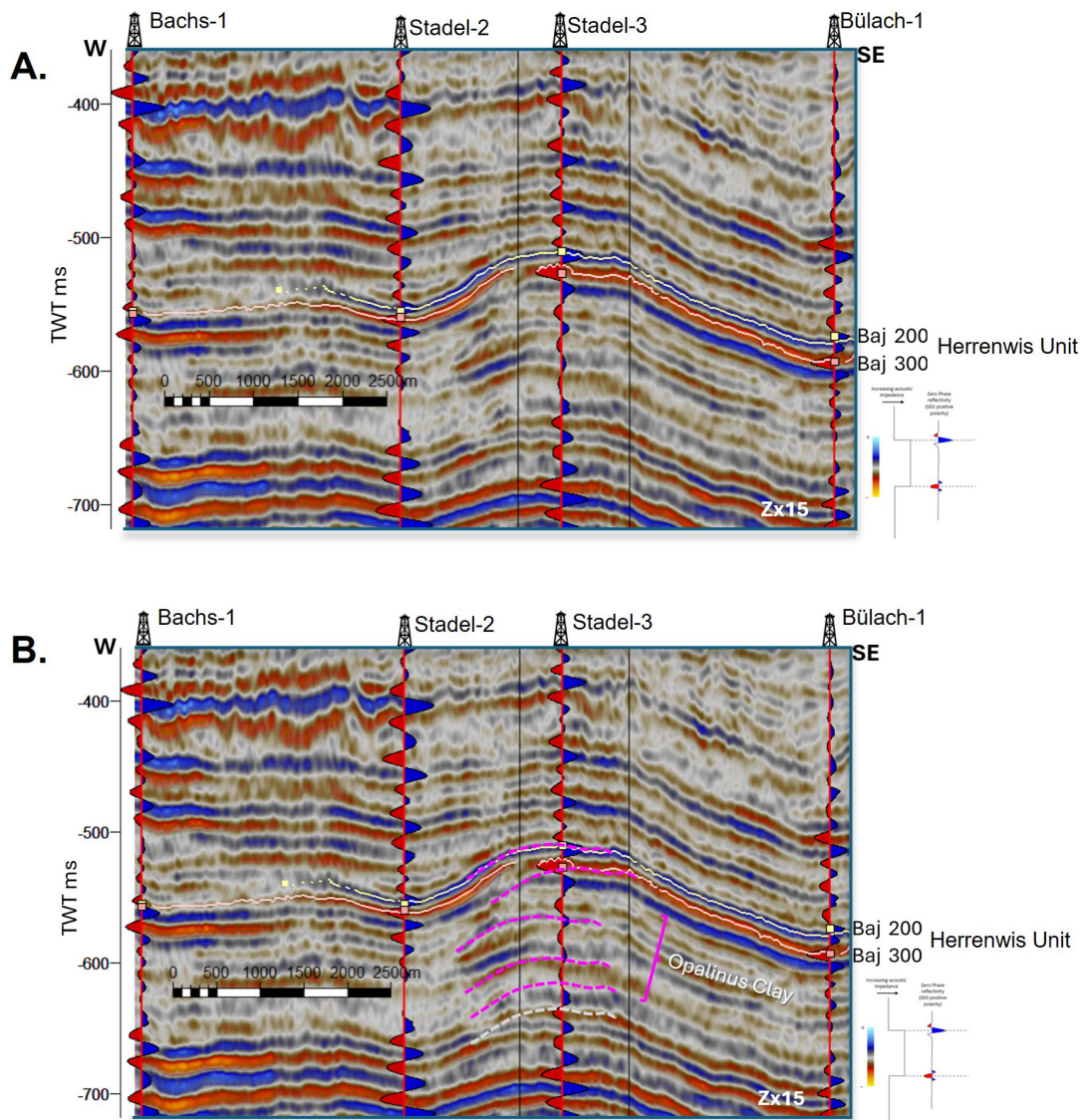


Fig. 5-4: Seismic section showing the Herrenwis Unit sourced seismic multiples

A. Seismic section (reflectivity and structural smoothing) across the 4 wells showing the Herrenwis carbonate platform architecture with top carbonate marked by a hard kick (synthetics). Less than 2 m shaly carbonate bed was observed in the Bachs-1 well. This change is consistent with the synthetic seismogram (non-hard kick at 168.2 Baj 200 – Top Herrenwis) and seismic imaging, suggesting the transition towards a clastics-dominated system. B. The acoustically strong top carbonate reflection generates a set of seismic multiples in the acoustically transparent Opalinus Clay (dashed fuchsia lines) which are not observed at the next good acoustic contrast layer (grey dashed line; ~ horizon 201.4 Rha 100 – Top Klettgau). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

In the southeastern corner of the survey, a square-shaped depression with sharp edges is visible in all the seismic vintages (Fig. 5-5; Nagra 2019). The shape and the character of this area is controlled by the presence of the amplitude wash-out zones associated with the easternmost Quaternary valley and the interaction with surface topography. The interpretation and the top structural morphology in this area are of lower confidence due to the impact of shallow topography and do not appear to be correctly processed (Fig. 5-5).

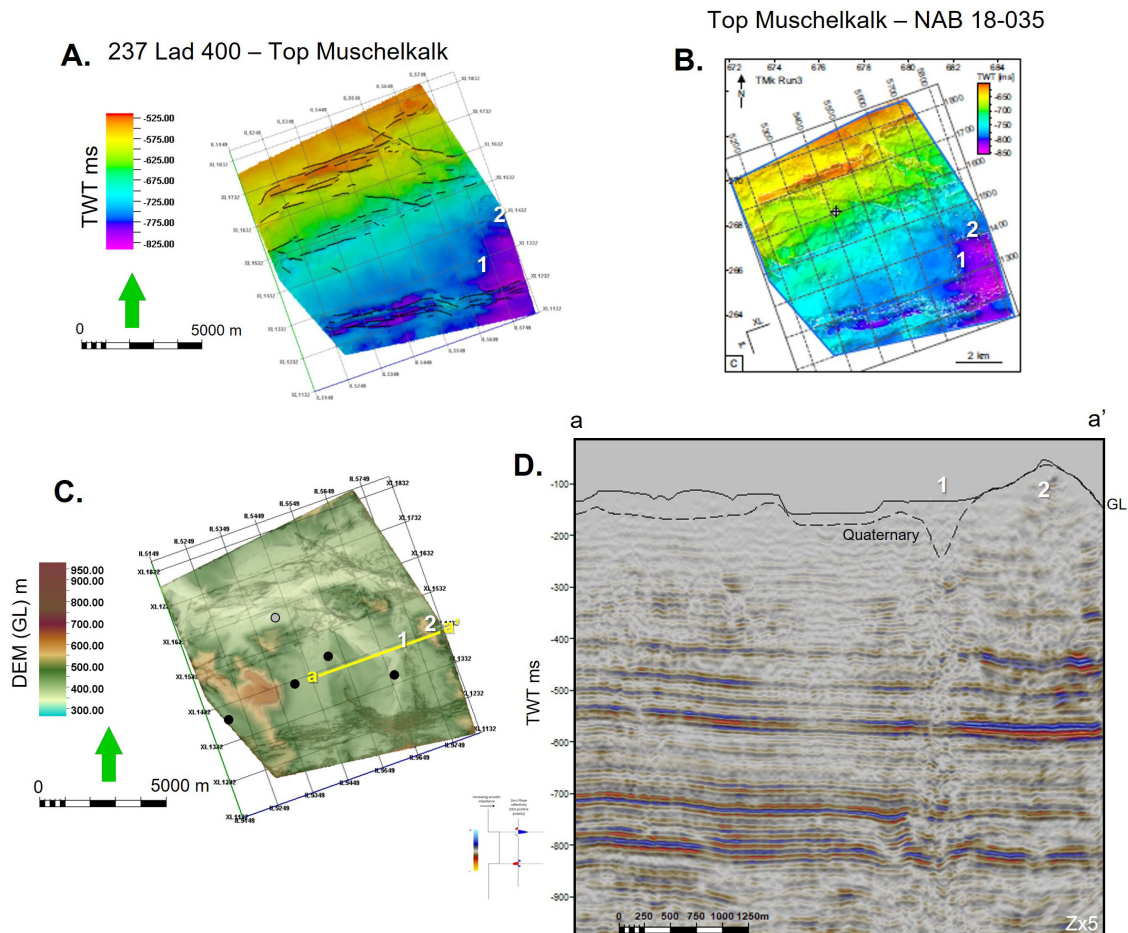


Fig. 5-5: In the southeastern corner of the survey, a square-shaped depression with sharp edges is consistently visible in the different seismic vintages at different stratigraphic levels

A. Examples of 237 Lad 400 – Top Muschelkalk horizon for A. PreSTM-ref and B. QLP NAB 18-35 (Nagra 2019). The shape of this feature appears to be controlled by imprints associated with Quaternary valleys (1) and with a topographically articulated surface relief (C.; 2). These shallow features degrade the seismic imaging, reducing the confidence in the geological interpretation of reflection patterns below (D.). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

2 – Imprints are amplitude morphologies that appear in sections, time slices or horizon slices produced by geological features in overlying intervals. In the NL-16 seismic datasets, imprints are represented by zones of amplitude wash-outs. Degraded seismic imaging showing vanished reflection events coincides with major Quaternary valleys (Fig. 5-6). Degraded seismic signals were widely observed in association with the presence of channels (Callow et al. 2021, Connolly et al. 2015). However, they have also been observed in connection with other features such as shallow reefs or gas chimneys. Gas chimneys imply a working petroleum system with “leakage” of gas along faults or “thief” pathways. They are often associated with pockmark geometries in time slices, amplitude anomalies and shallow gas accumulation (bright amplitude push-down effects). When they occur together with other geological features that could generate signal degradation (i.e. presence of channels), a high probability gas chimney should not coincide with them. Those diagnostic features were not observed in the NL-16 amplitude wash-out zones. In addition, for comparison, a similar amplitude degraded seismic pattern is also visible in ZNO, and again in concomitance with the presence of Quaternary valleys (Nagra 2024c). Furthermore, petrophysical analysis (gas show evaluation) of TBO wells within the NL-16 perimeter does not support the presence of an active petroleum system in the Mesozoic succession.

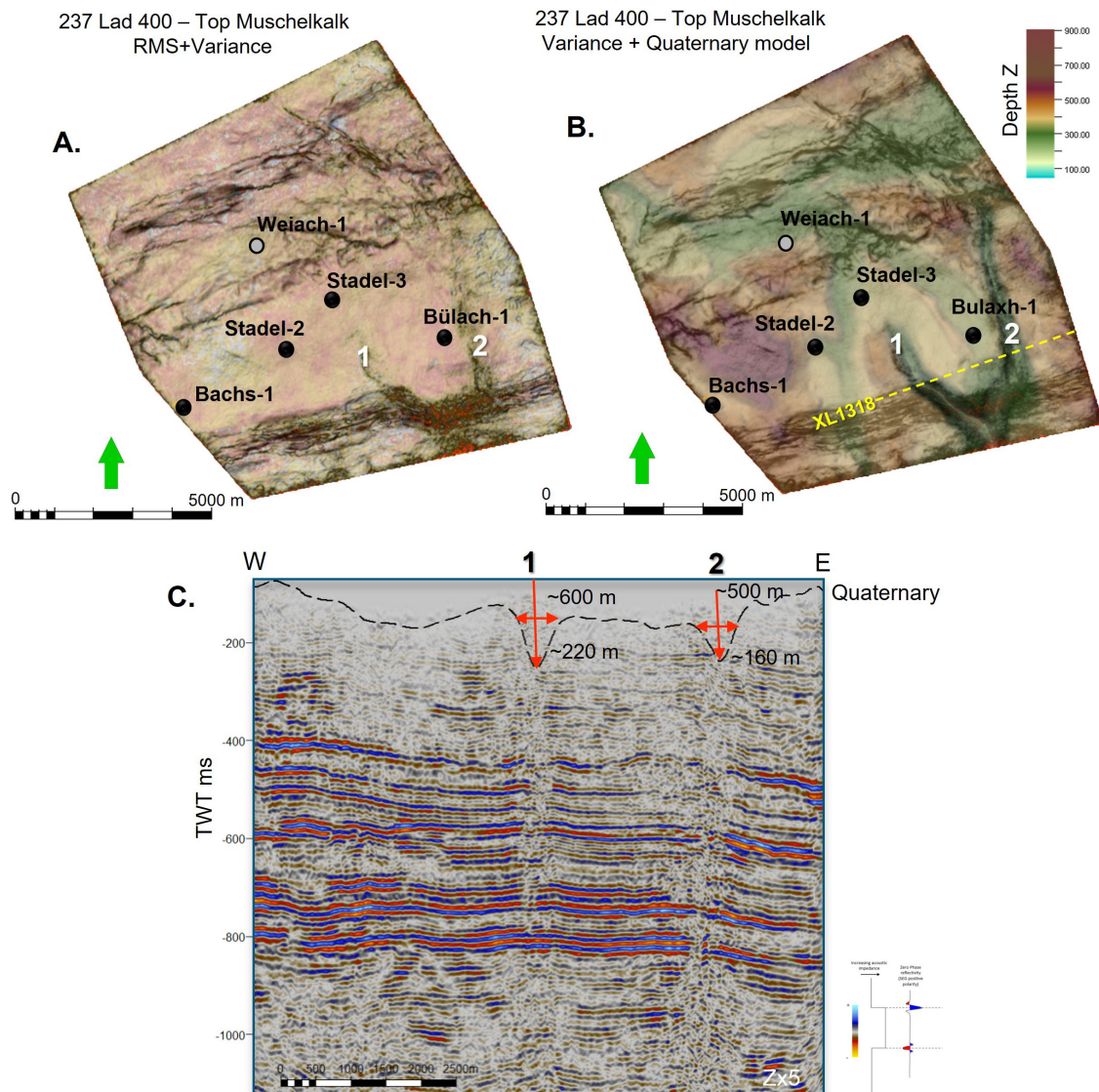


Fig. 5-6: Degraded seismic areas coincide with the main Quaternary valleys (1. Strassberg Trough and 2. parallel valley) with an estimated width >500 m and depth >150 m

Note the superimposition of incoherent seismic signals in map view and amplitude wash-out zones in the section display down to deep stratigraphic levels (i.e. 237 Lad 400 – Top Muschelkalk). A. 237 Lad 400-Near Top Muschelkalk RMS and variance horizon slice; B. Identical to A. but with overlaying Quaternary model morphology; C. PreSTM-ref seismic crossline 1318 cutting two Quaternary valleys. Seismic display is PreSTM-ref reflectivity.

One of the observed anomaly zones overlaps with the Strassberg Trough (Buechi et al. 2018, Fig. 5-6), an overdeepened Quaternary valley which was previously interpreted as an NNW-SSE-striking structural lineament (Fig. 5-7; Nagra 2019), traceable for approximately 1.5 km (Fig. 5-6, Nagra 2019).

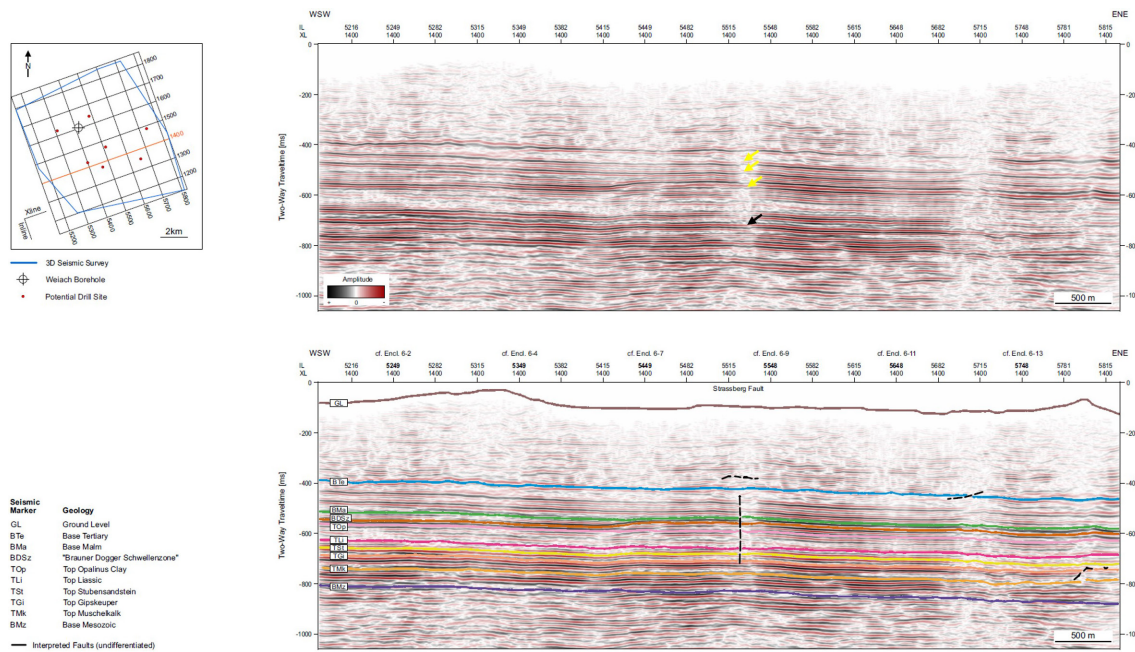
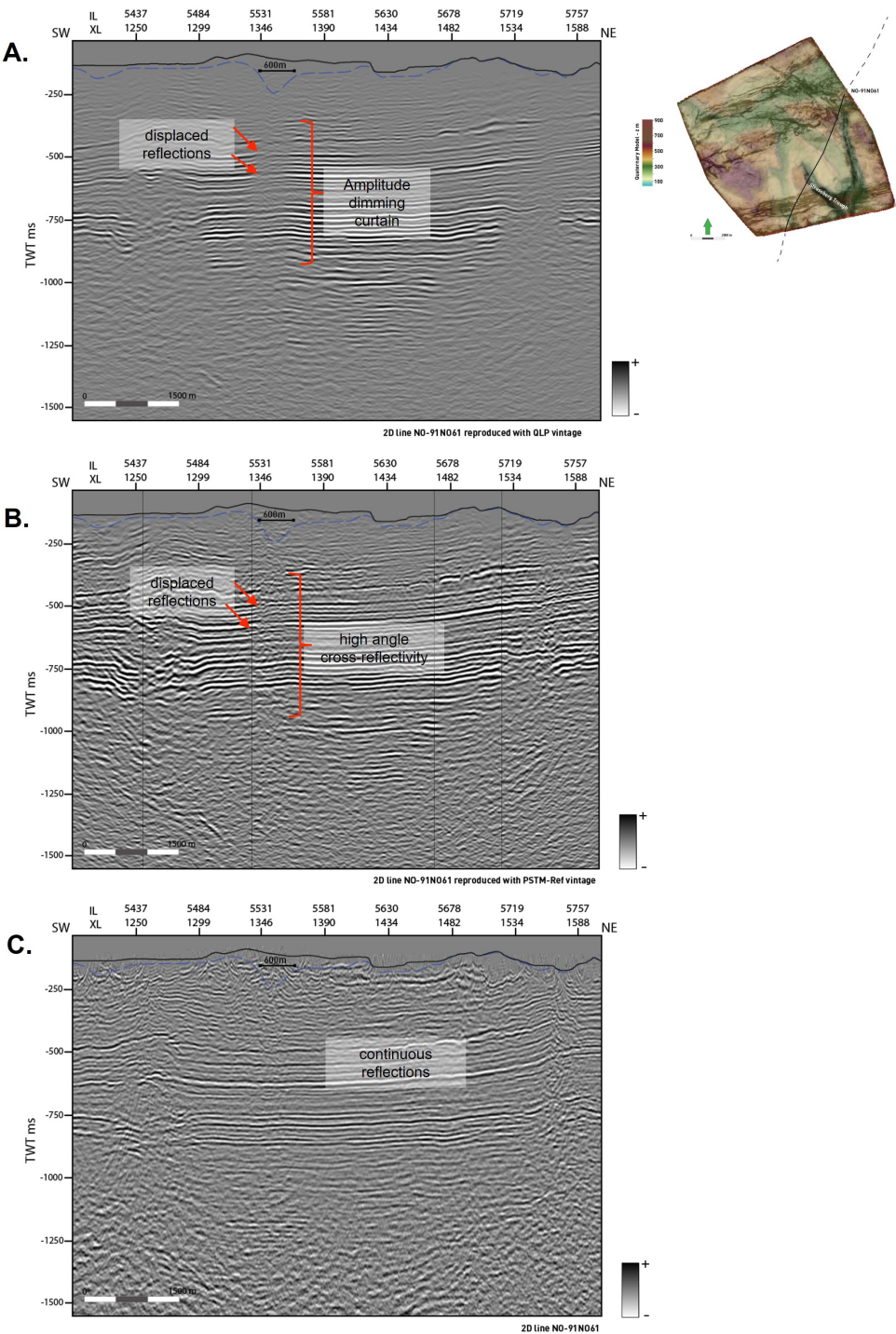


Fig. 5-7: Seismic section showing the Strassberg Lineament interpreted as a fault

QLP seismic vintage; NAB 18-35, Enclosure 6-19. Note some inconsistency in the fault-throws (yellow arrows) and the absence of fault seismic signature below the Top Gipskeuper (black arrow fault interpretation).

Comparison among the 3D seismic processing vintages and 2D seismic lines over the Strassberg Trough provides strong evidence that the anomalous wash-out zone represents an artefact associated with the presence of a Quaternary valley (~600 m wide and ~200 m deep, Fig. 5-8). The degraded amplitude and the horizon displacements are not visible in one of the two 2D seismic lines (i.e. NO-91NO61-PSTM STK, Fig. 5-8 A), while in the 2011 2D seismic vintage 11-12-12-33-PSTM STK, it appears to be characterised by an X shape (Fig. 5-8 B).



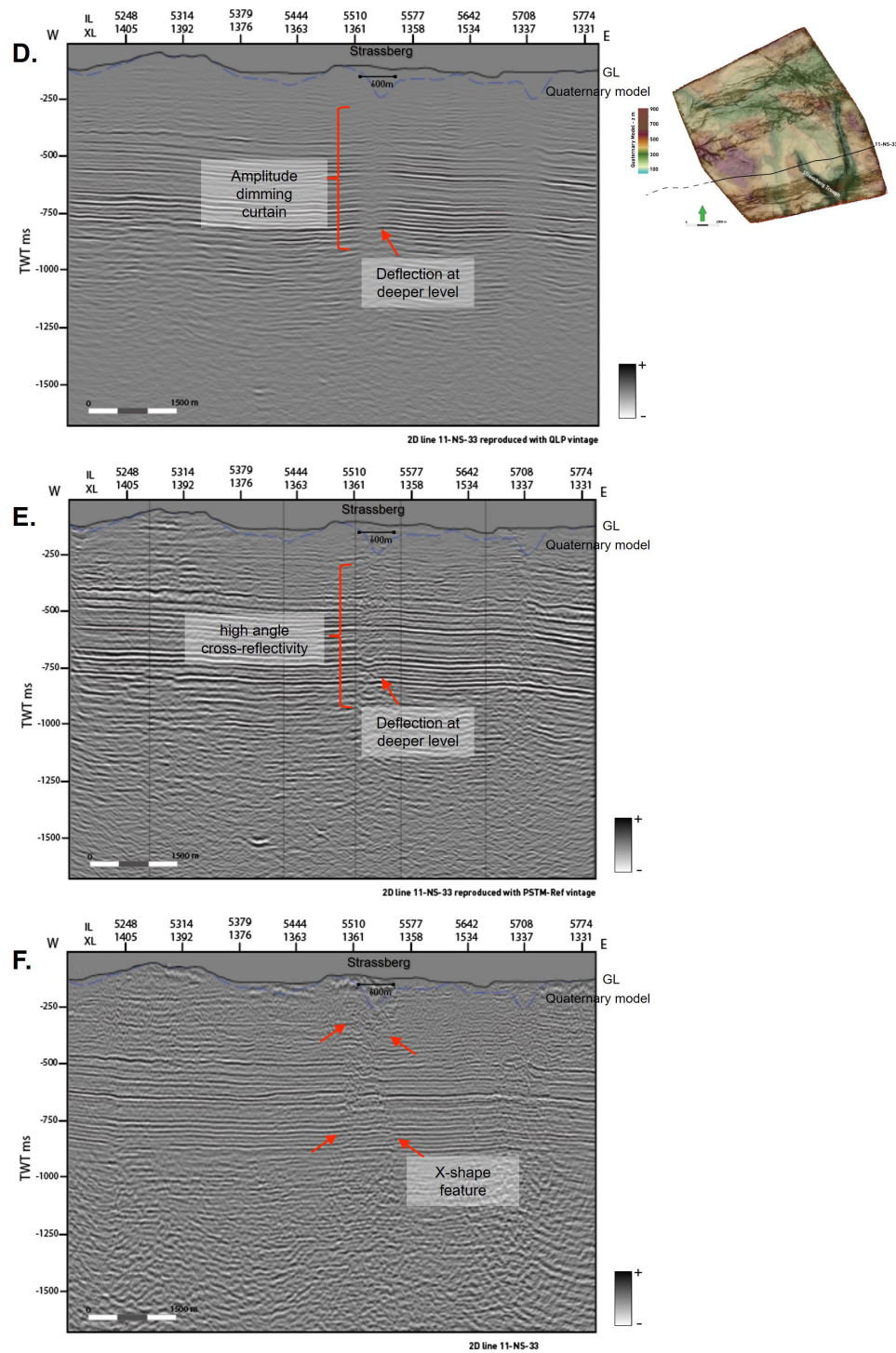


Fig. 5-8: 3D vs. 2D seismic lines across the Strassberg Trough

91-NO-61 (A. to C.) Strassberg Trough comparison. 2D line 91-NO-61 (C.) was reproduced in the QLP (A.) and PreSTM-ref (B.). Note the displaced reflections associated with dimming in the QLP (A.) and with high-angle cross-reflectivity in PreSTM-ref (B.), while continuous reflections are imaged in the original 2D line (C.). D. to F.: 11-NS-33 Strassberg Trough comparison. 2D line 11-NS-33 (G.) was reproduced in the QLP (D.) and PreSTM-ref (F.). Note the deflected reflections at deeper stratigraphic levels associated with dimming in the QLP (D.) and with high-angle cross-reflectivity in the PreSTM-ref. (E.), while in the original 2D line (F.), an X-shaped feature can be observed.

This X-shape was interpreted as a complex trapezoid-shaped fault in NAB 13-10 (Fig. 5-9, Madritsch et al., 2013). This geometry, however, can also represent a typical pattern originating from near-surface statics.

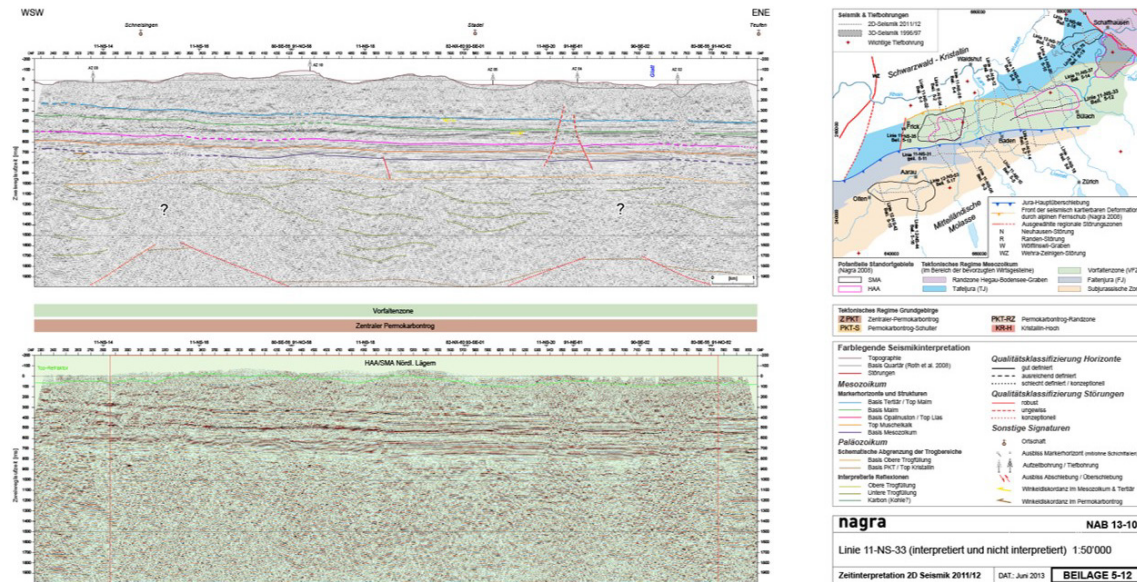


Fig. 5-9: 2D seismic line 11NS33 as in NAB 13-10 interpretation

Madritsch et al. (2013)

Note that the Strassberg wash-out zone was interpreted as a structural lineament bounded by opposite dipping faults. The fault to the west shows a reverse sense of displacement while the eastern fault shows a normal one.

The effect of the near-surface anomaly is typically an anomalous zone demarcation that is as wide as the anomaly itself and with the cross-point of the X-shaped feature coinciding with the depocentre of the valley itself. Initial blanking in combination with the channel boundaries can result in a cross-type pattern in the data, depicting where the shot and receiver positions go into the channel zone (Fig. 5-10, Cox 1999, Ylmez 2001).

3 – Footprints are not clearly visible in the NL-16 dataset. Some indications of acquisition-related noise are slightly detectable only on 3D curvature attributes (Fig. 5-1). Therefore, the subtlety of the artefact does not hamper interpretation confidence.

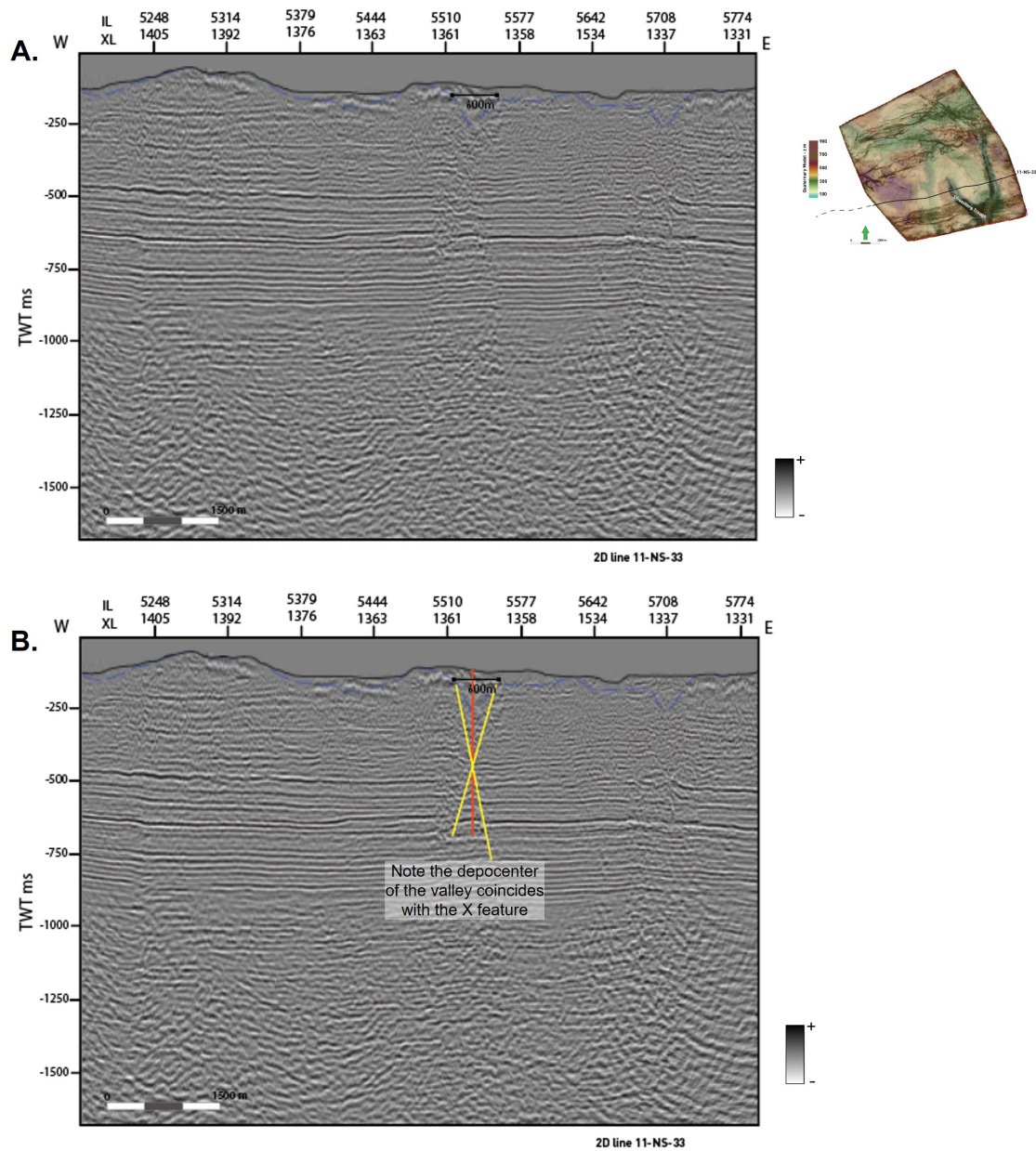


Fig. 5-10: 2D seismic line 11NS33 across the Strassberg Trough

A. Uninterpreted and, B. showing how the initial blanking-in of the geometry in combination with the channel boundaries can result in a cross-type pattern in the data depicting where the shot and receiver positions go into the channel zone. The depocentre of the valley (red line) should coincide with the cross-point of the X-shaped feature (yellow lines).

5.2 Stratigraphic interpretation

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

Within the framework of the site selection process, seismic interpretation was performed solely for the Mesozoic succession (Top Malm - Base Mesozoic Unconformity), since it contains the three major units (upper confining units, host rock and lower confining unit (Nagra 2024d). Six regional markers comprising and marking the above units were mapped across the entire survey (Fig. 5-11, Tab. 5-1). 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.

Due to their discontinuous / transparent seismic characteristics, the Top Opalinus Clay and the Top Liassic (upper and lower boundaries of the host rock) could not be mapped across the entire area of the seismic survey. Instead, the nearest confidence picks were selected (168.2 Baj 400 – Top Clay Unit, and 201.4 Rha 100 – Top Klettgau, respectively, Fig. 4-3).

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. 5-11 B).

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	
168.2 Baj 400	Top Clay unit	 peak	
201.4 Rha 100	Top Klettgau	 S-crossing	
237 Lad 400	Top Muschelkalk	 Z-crossing	
251.9 Per 100	Near Base Mesozoic Unc.	 Z-crossing	

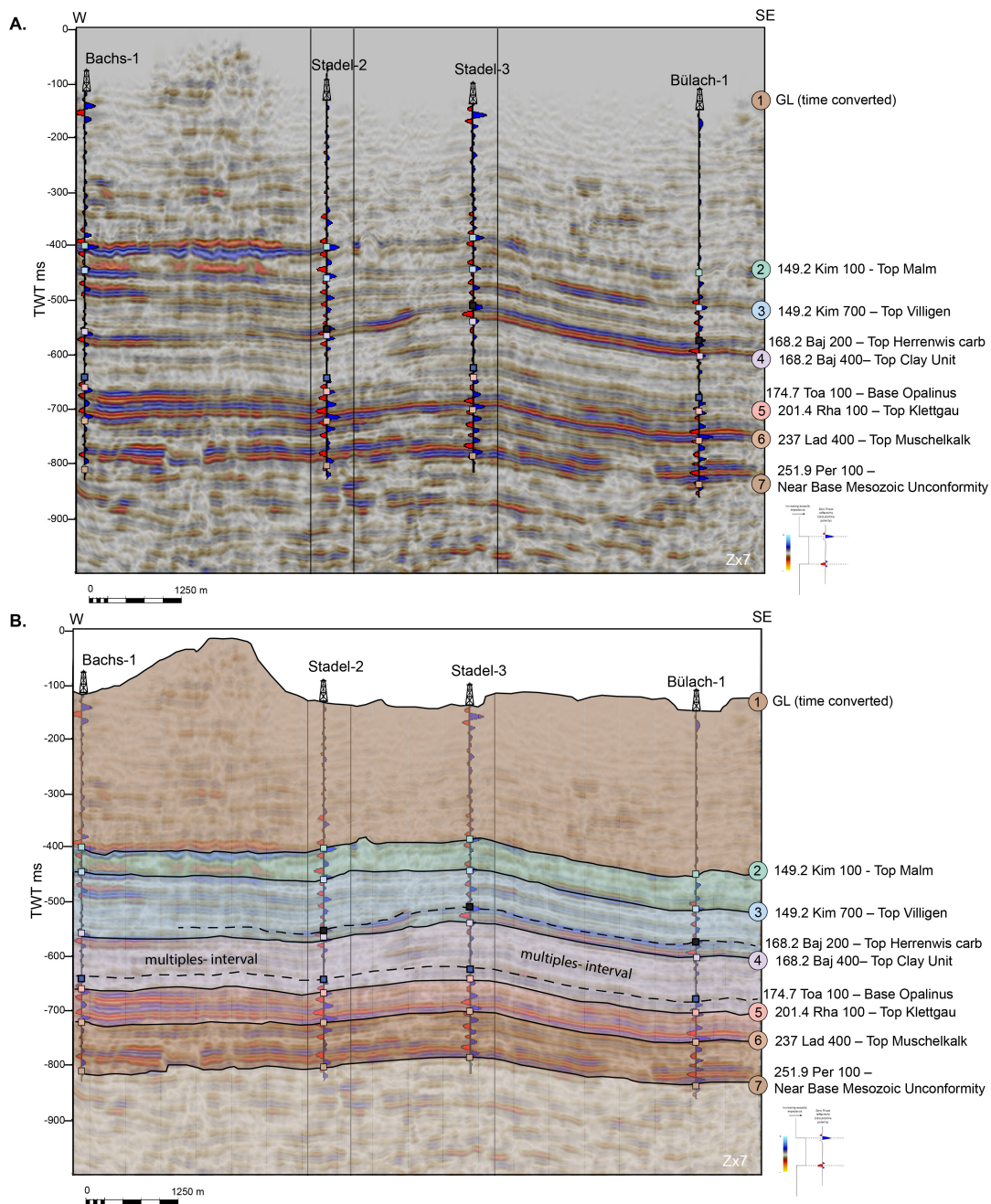


Fig. 5-11: Seismic section across the wells with key stratigraphic horizons

A. Uninterpreted and, B. Interpreted showing the seismic-to-well tie and the six key stratigraphic horizons interpreted across the entire NL-16 seismic survey. The two dashed horizons represent (1) 168.2 Baj 200 – Top Herrenwis carbonate, with the acoustically strong reflection responsible for multiple generation within the clay interval and (2) 174.7 Toa 100 – Top Lias, the weak acoustic response with the overlaying Opalinus Clay. Here, the presence of seismic multiples makes this horizon very low confidence and challenging to interpret, particularly in structurally complex areas. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.1 149.2 Kim 100 – Top Malm

The Top Malm (149.2 Kim100) appears as a comparatively strong positive amplitude (Fig. 5-12, Tab. 5-1).

Such good impedance contrast can be related to the geological contact between the overlaying Molasse unit characterised by alluvial sand- and siltstones, variegated marls and claystones of terrestrial or lacustrine origin as well as the Malm Siderolithic claystone above the calcareous Malm units (Fig. 5-11 - Felsenkalke and Massenkalk Members, Nagra 2024d, Nagra 2022a, Nagra 2022b, Nagra 2023). The “Massenkalk” 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 consists 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 carbonatic 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. 5-12). Towards the north, the carbonate portion of the Malm suboutcrops with a Quaternary cover of thickness up to few decametres (Fig. 1-1, Fig. 5-1).

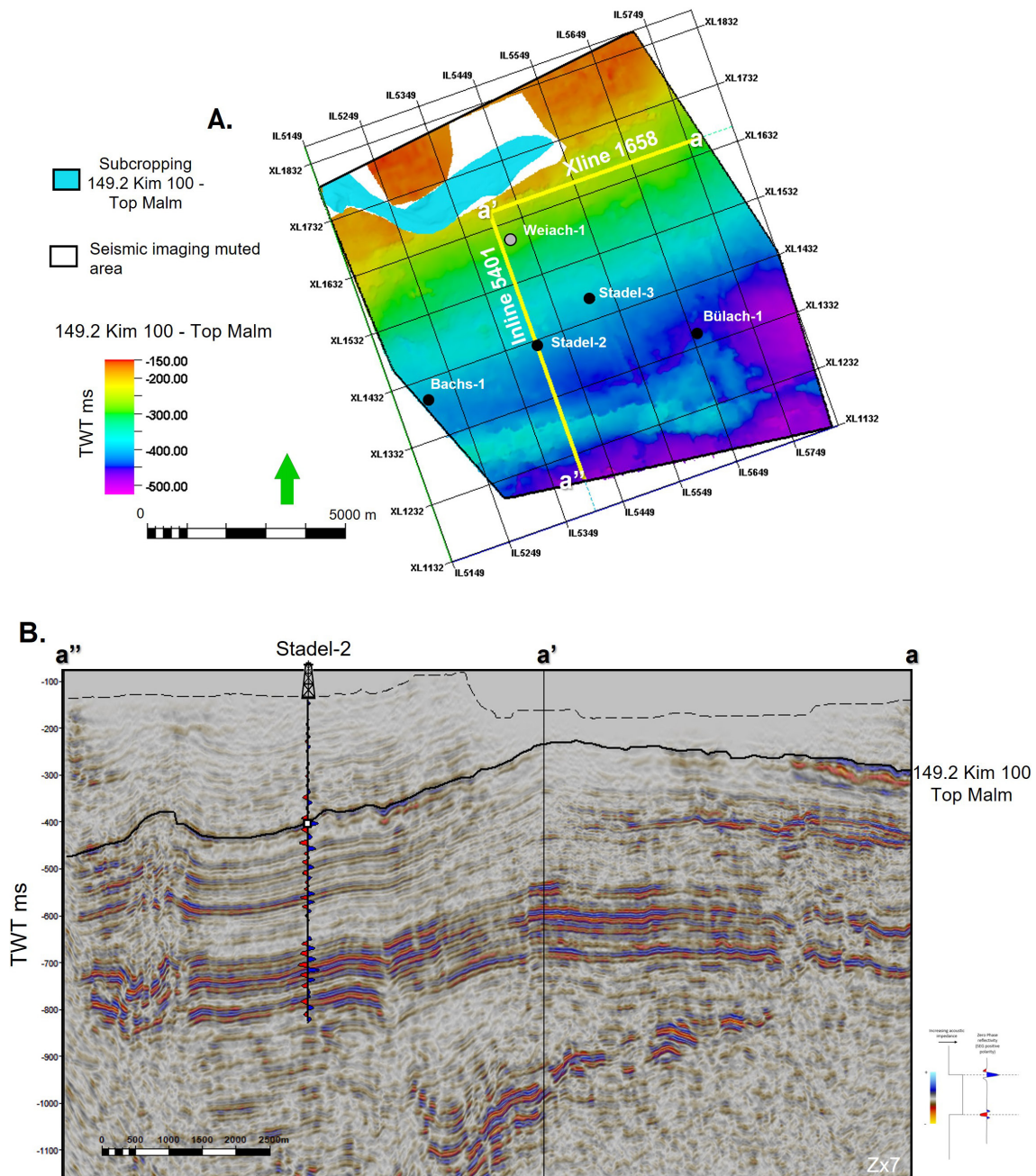


Fig. 5-12: 149.2 Kim 100 – Top Malm horizon interpretation

A. TWT top structure of horizon 149.2 Kim 100 – Top Malm; B. Inline-crossline composite across the Stadel-2 well. Horizon 149.2 Kim 100 – Top Malm is a strong and relatively continuous peak, associated with the clear acoustic boundary generated by the Molasse-Malm Carbonate contact. Amplitude strength decreases around the area where 149.2 Kim 100 – Top Malm is subcropping. Note the complex seismic facies below the horizon. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The suboutcrop extension cannot be geometrically correlated with the seismic reflections since the subcropping portion is surrounded by a ring of muted data, and reflection dips potentially result from false migration (Fig. 5-13). Consequently, the uninterpreted Top Malm perimeter is larger than the estimated subcropping area (Fig. 5-13 B.).

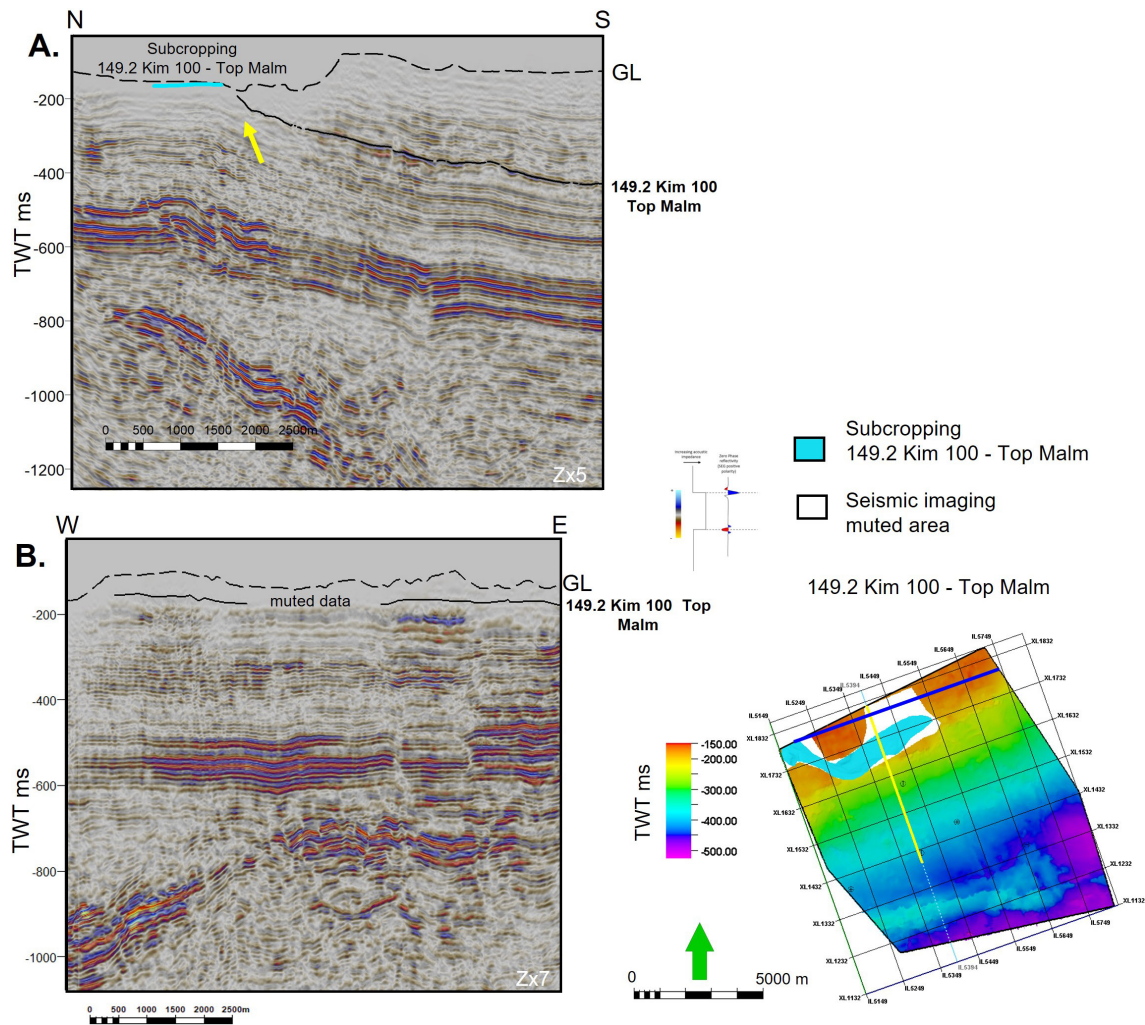


Fig. 5-13: Area with subcropping horizon 149.2 Kim 100 – Top Malm

A. Inline 5394 and B. Crossline 1795 across showing where the 149.2 Kim 100 – Top Malm horizon is subcropping and the associated ring of muted seismic data does not allow the picking of the horizon. Note that near the subcropping area, the horizon has to be pushed upwards, cross-cutting the reflection, in order to match the outcropping portion (A. yellow arrow). Seismic display is PreSTM ref reflectivity with an overlay of relative acoustic impedance.

In the NL-16 seismic data, just below the strong acoustic boundary of the Top Malm, where continuous reflection should be expected (well-bedded and sponge-free «Felsenkalke» carbonates), seismic horizons display chaotic seismic facies with truncated, hummocky to irregular reflections, short-discontinuous, high-amplitude events within transparent reflections associated with dish-shaped concave-upwards features (Fig. 5-14).

Several authors (Moldovanyi et al. 1995, Wagner et al. 1995, 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, suggesting 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. Sedimentological evaluation and evidence from core data within an established regional framework (Nagra 2024d) indicate that this interval underwent diagenetic alteration associated with subaerial exposure. For the NL siting region, the

A. N S
IL5403 Stadel-2
TWT ms
149.2 Kim 100 - Top Malm
Isochored down 149.2 Kim 100 - Top Malm
Top and Base karstified interval @core
Zx4

B. W E
XL1423 Stadel-2
TWT ms
Zx4

C. 3045 m line
Stadel-2
Bachs-1
Stadel-3
Xline 1423
Büsch-1
5000 m
0

D. 3D
XL1423
1 2 3
TS -426 ms

Fig. 5-14: Seismic imaging of the Malm carbonates

A. Inline 5403 and B. Crossline 1423 showing the variability of the seismic response within the Malm carbonates, where transparent and chaotic seismic facies appear to correspond to the karstified carbonate interval observed in the Stadel-2 well. Such irregular reflections are reflected in the horizon and time slices by chaotic seismic response (C., B.). C. Variance horizon slice of 149.2 Kim 100 – Top Malm isochroned down by 15 ms TWT, and D. 3D display of outcrop look crossline 1423 and a combined time slice (-426 ms TWT) of variance and instantaneous phase. Notes 1 and 2 represent chaotic seismic facies associated with the amplitude wash-out zones of the Quaternary valleys, which can, in some cases, mask the Malm discontinuous seismic pattern.

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, Fig. 5-11, Fig. 5-15) that can be consistently observed throughout the entire survey. However, when the overlying Top Malm outcrops or is extremely shallow, the Top Villigen reflector appears dimmed. This might indicate that the reflection positions could have erroneously migrated, forming geometric artefacts as a result (Fig. 5-13). Nevertheless, because of the continuity and stability of the reflection pattern, Top Villigen 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.

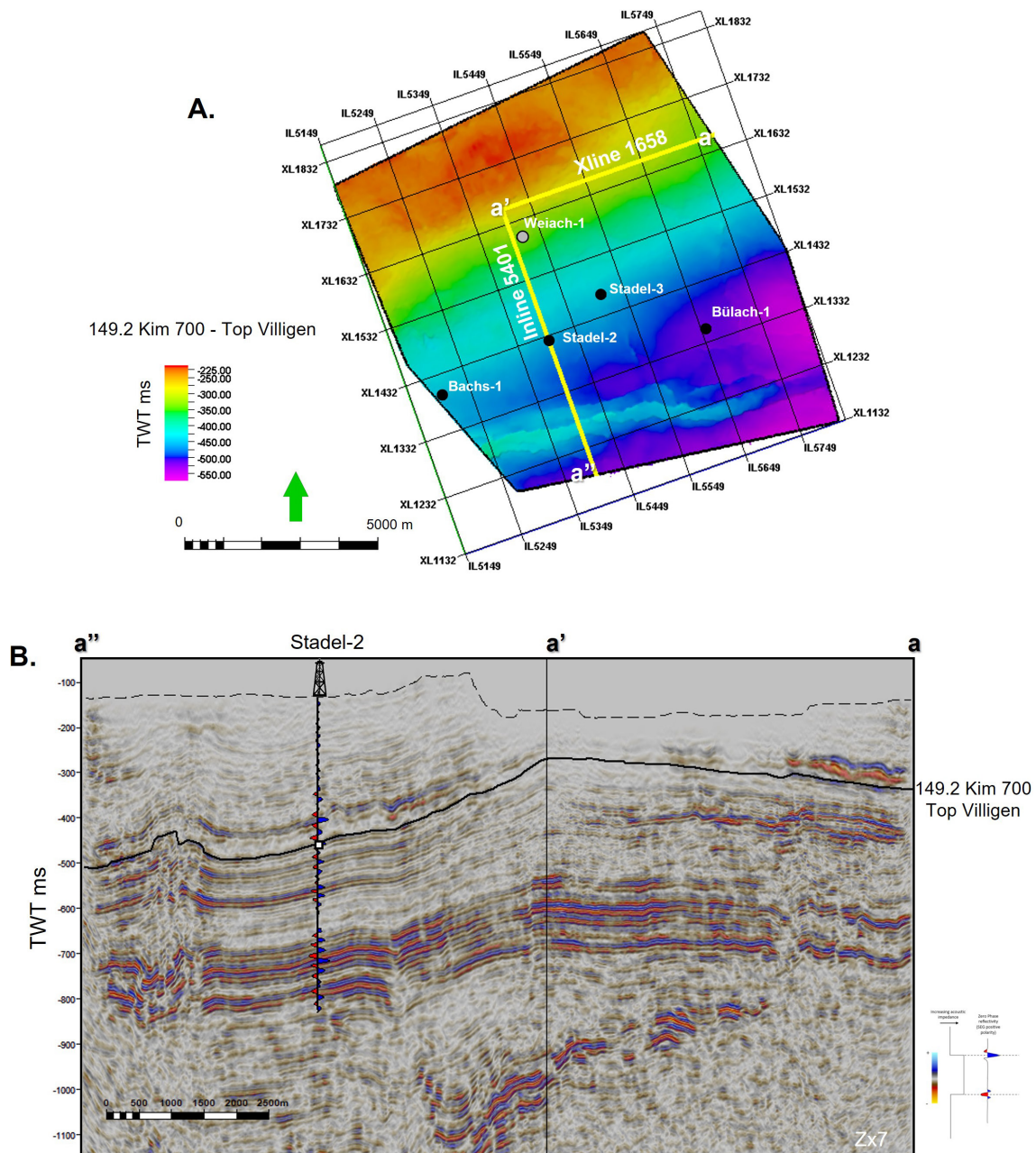


Fig. 5-15: 149.2 Kim 700 – Top Villigen horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Stadel-2 well. 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. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.3 168.2 Baj 400 – Top Clay Unit (as proxy for Top Opalinus)

Top Opalinus (170.9 Aal 300 well marker Tab. 5-1, Fig. 4-3, Fig. 5-3) is located within the transparent acoustic impedance zone where seismic multiples interfere with primary reflectivity and, therefore, the interpretation of this critical interval is of extremely low confidence. Between the Stadel-3 and Stadel-2 wells, the interpretation is further hampered by the presence of Herren-wis carbonate multiples (Fig. 5-4). Despite VSPs seemingly suggesting that some primary reflections could still be recognised below the level of 170.9 Aal 300 (Top Opalinus; Fig. 5-16), this horizon cannot be consistently mapped in-between the wells (Fig. 5-16) and even less so in areas at a distance from well control and with increased structural complexity. This issue was already demonstrated by previous interpretation (Nagra 2019, Fig. 5-17), where the Top Opalinus horizon is forced to jump loops in order to maintain the continuity of the interpretation.

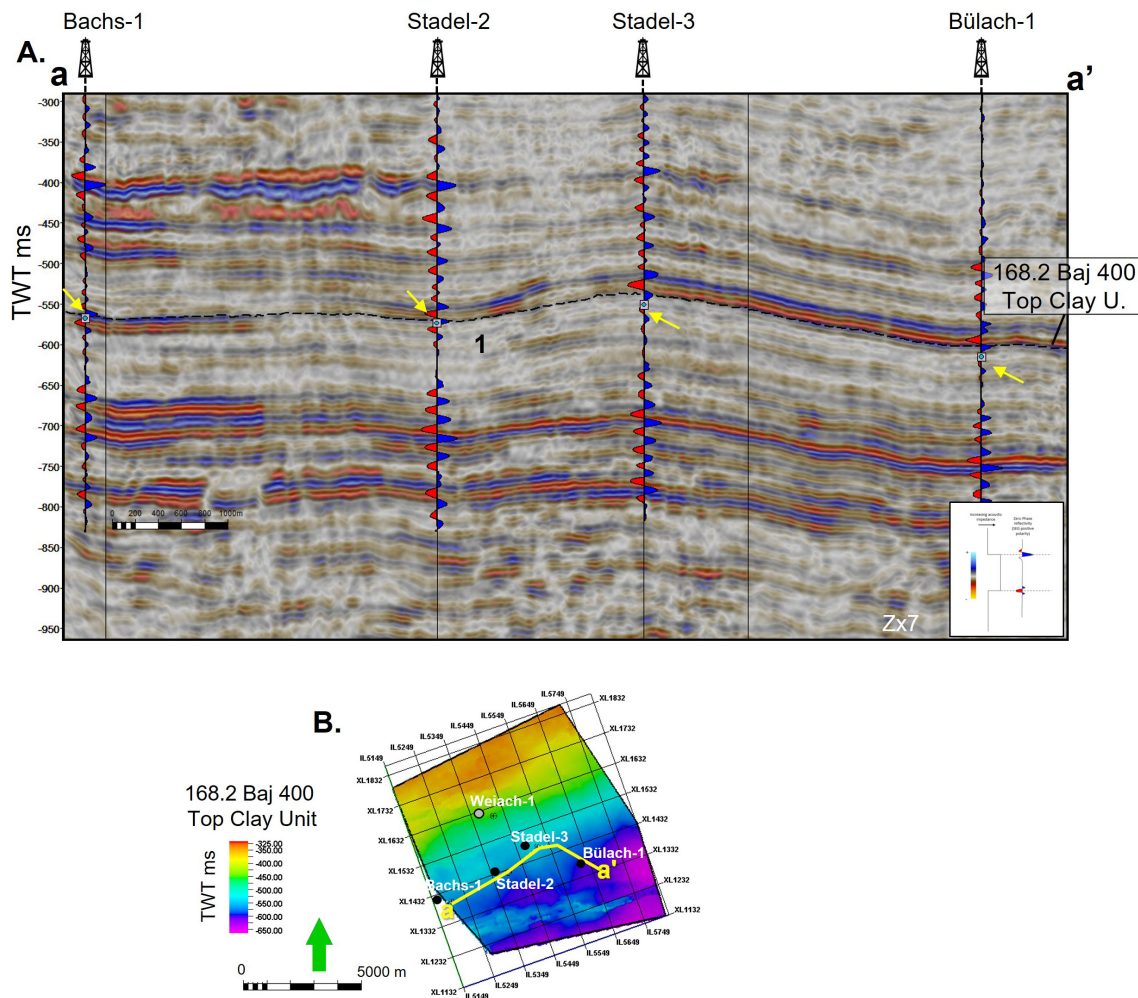


Fig. 5-16: Seismic section across the four wells (A.) showing seismic-to-well ties (synthetics) and the correlation of 170.9 Aal 300 (minute green circles in the pink square of the Top Opalinus) well tops

Reflection jumps are required to connect the well tops across the four wells. This stratigraphic marker is located within the acoustic impedance transparent zone where seismic multiples interfere with primary reflectivity. Due to the extremely low confidence, this horizon was not interpreted, even in the most undisturbed central area. The continuous and strong acoustic contrast above is therefore selected as reference horizon for the seismic definition of the host rock (black-dashed line - 168.2 Baj 400 Near Top Clay Unit-Fig. 5-18). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. B. Line location plotted on 168.2 Baj 400-Near Top Clay Unit TWT structure.

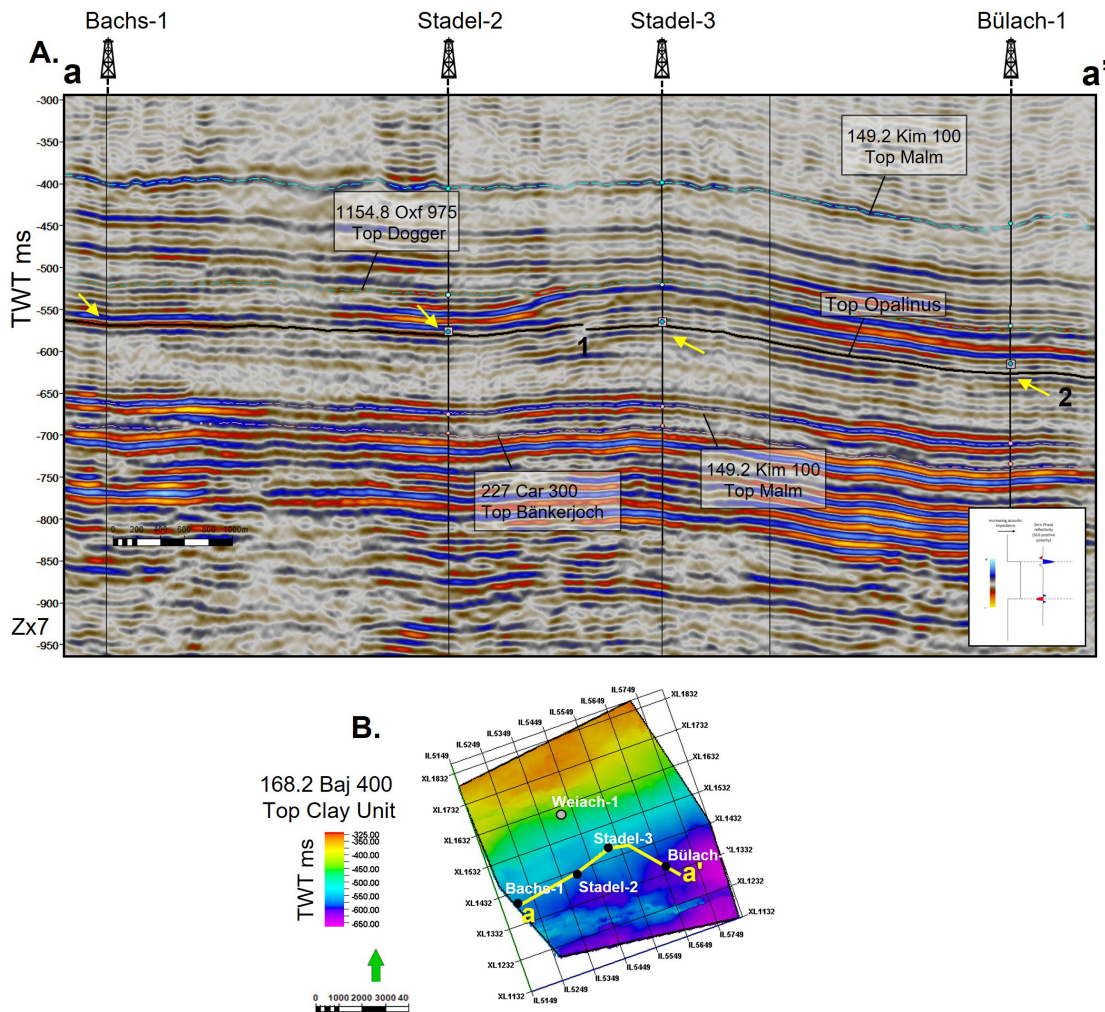


Fig. 5-17: Seismic section across the four wells showing seismic-to-well ties (A., minute pink square top is Top Opalinus and green circle represents 170.9 Aal 300) and the Top Opalinus (black line) interpretation with clear challenges already identified in NAB 18-35 (Nagra 2019)

Good well calibration is demonstrated by the over- and underburden horizons displayed as dashed lines. To consistently follow a reflection calibrated at the Stadel-2 well and roughly at Stadel-3, a loop jump (1) is required between Stadel-3 and Stadel-2 and a considerable mismatch (2) can be observed at the Bülach-1 well. Seismic dataset is QLP reflectivity. B. Line location plotted on 168.2 Baj 400 – Near Top Clay Unit TWT top structure.

The stratigraphic marker 168.2 Baj 400 was therefore selected to represent the key reflection positioned near the top of a clay-rich interval, which includes the Opalinus Clay, sensu stricto (Nagra 2024a); Fig. 5-11). The horizon corresponds to a very prominent hard kick below the acoustic contrast, marking the base of the Herrenwis carbonates. It can be continuously traced across the entire seismic cube (Fig. 5-18). Seismically, the 168.2 Baj 400 horizon is referred to as Top Clay (-rich) Unit, indicating the main rheological boundary between the host rock and the upper confining unit.

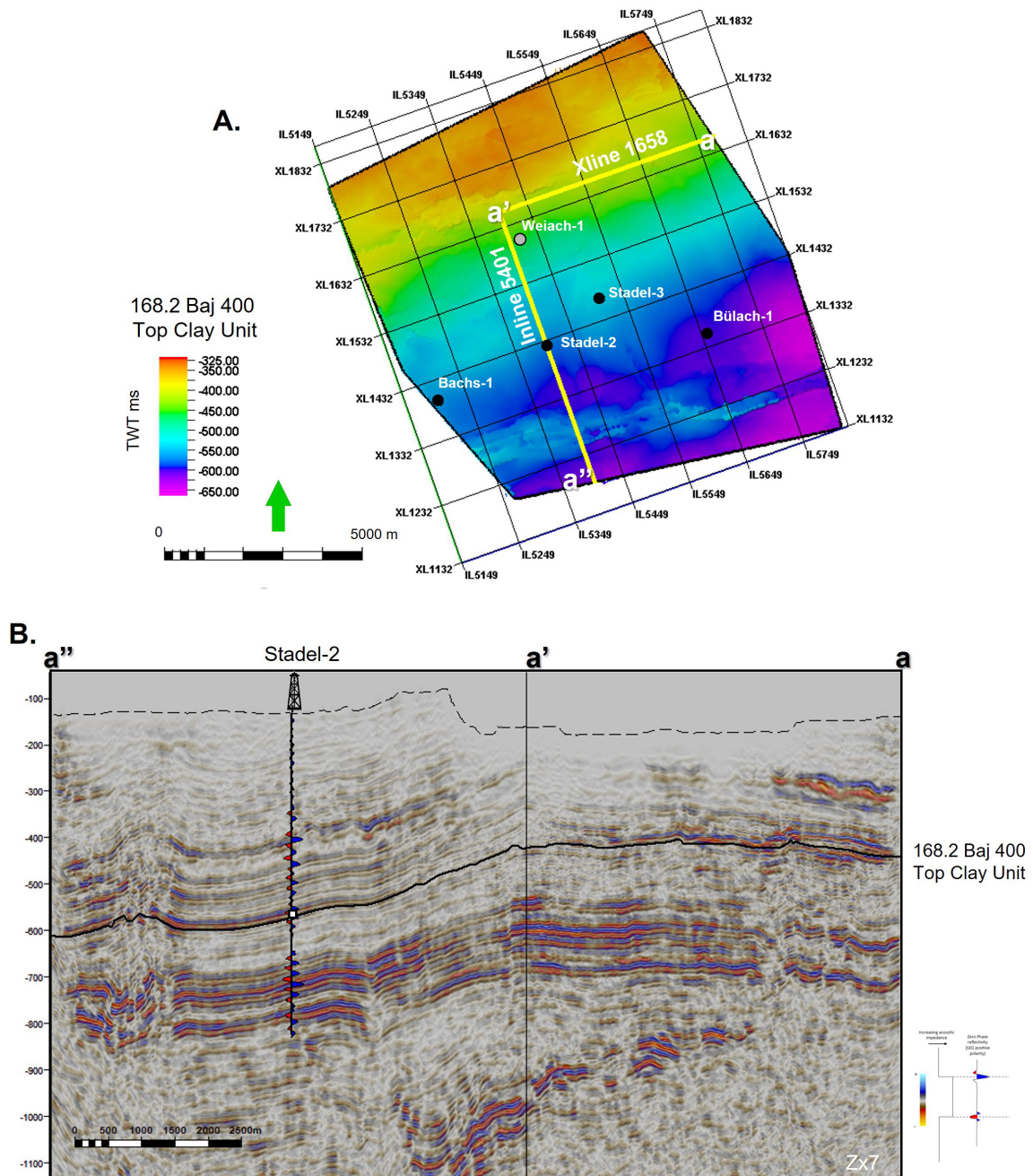


Fig. 5-18: 168.2 Baj 400 – Top Clay Unit horizon interpretation

A. TWT top structure B. Inline-crossline composite across the Stadel-2 well. The Top Opalinus and Near Opalinus are located within the transparent acoustic impedance zone where seismic multiples interfere with primary reflectivity. 168.2 Baj 400 has therefore been selected to represent a key reflection positioned near the top of a clay-rich interval, which, sensu stricto, includes the Opalinus Clay. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.4 201.4 Rha 100 – Top Klettgau (as proxy for 174.7 Toa 100 – Top Lias)

Clear challenges were identified in the interpretation of the Top Lias (174.7 Toa 100) even in the undisturbed central area (Fig. 5-19). In this area, the Top Lias seismic event shows a strong lateral variability in amplitude strength and reflection shape, which is not consistent with the described homogeneous rock properties (Nagra 2024d, Nagra 2022a, Nagra 2022b, Nagra 2023).

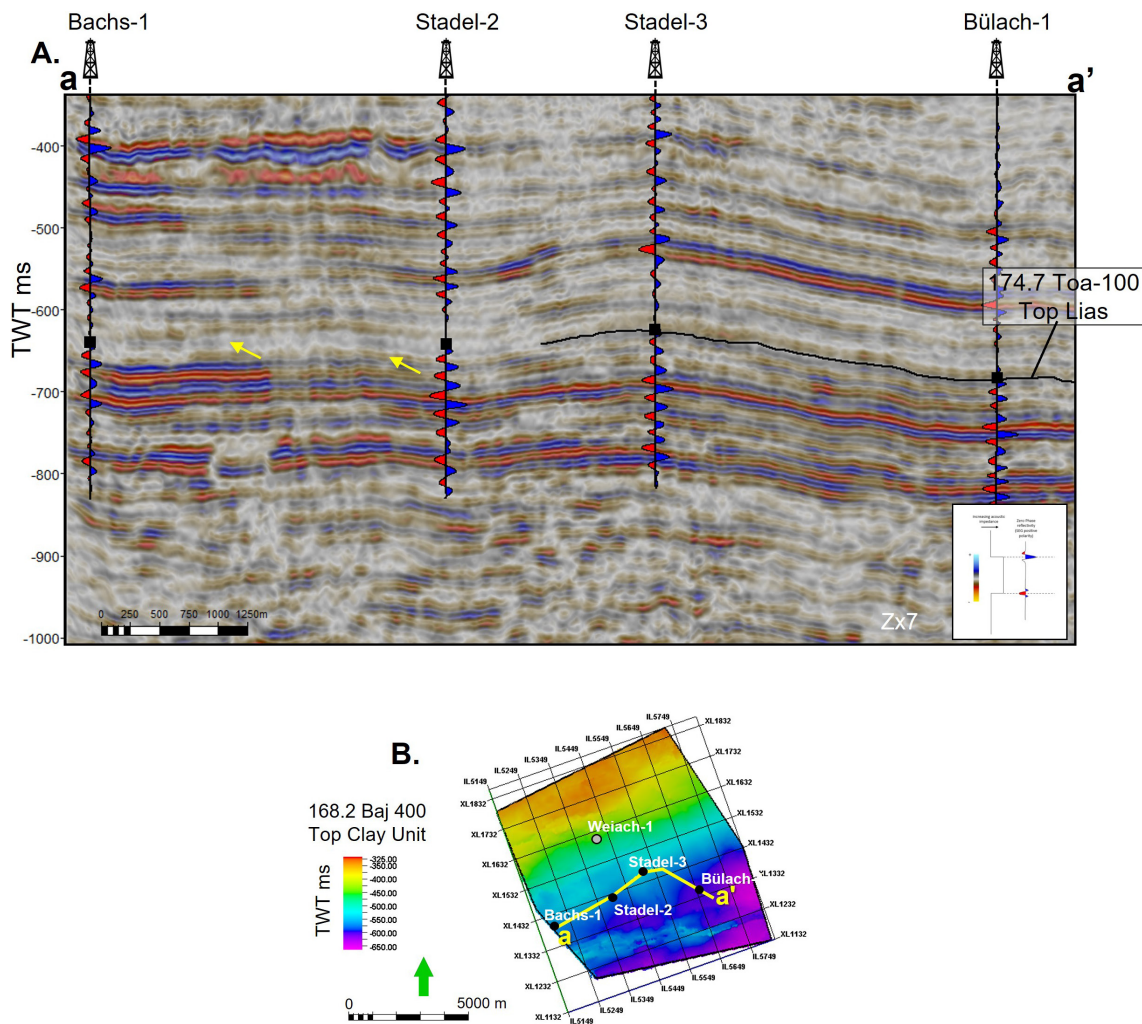


Fig. 5-19: Seismic section across the four wells (A.) showing seismic-to-well ties (synthetics) and the correlation of 174.7 Toa 100 – Top Lias (Base Opalinus) well tops

Clear challenges were recognised in the interpretation of this horizon even in the most undisturbed central area. A strong lateral variability in amplitude strength and width (yellow arrow) is observed apart from a high-amplitude reflection segment, which coincides with the area where seismic multiples from Top Herrenwis carbonate were recognised within the Opalinus Clay interval (black line). Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. B. Line location plotted on 168.2 Baj 400 – Near Top Clay Unit TWT top structure.

Furthermore, the high-amplitude reflection segment coincides with the area where seismic multiples from the Top Herrenwis carbonate were recognised within the Opalinus Clay interval. Away from this “multiples” zone, 174.7 Toa 100 – Top Lias appears discontinuous and almost transparent with loop doublets (Fig. 5-19). The lateral variability of the 174.7 Toa 100 – Top Lias reflection seems to mirror the presence of Herrenwis carbonate multiples more than intrinsic (and unexpected) geological complexity. At this specific stratigraphic level, confidence (mappability) in the horizon picking is a critical factor to establish the vertical upward propagation of the faults affecting the deeper Mesozoic succession (i.e. lower confining unit) and their impact on host rock integrity. Consequently, the 201.4 Rha 100 (Top Klettgau) marker was selected as it represents the most continuous horizon below the Top Lias (Fig. 5-19, Fig. 5-11). The Klettgau Formation, together with the underlying Bänkerjoch Formation, forms the Keuper Group. It is a heterogeneous succession dominated by dolomitic and argillaceous marls with intercalations of dolostones and sandstones. Seismically, such heterogeneity is revealed by the lateral variability of the amplitude strength and thickness of the seismic event. To maximise the effectiveness and confidence of the event continuity for the autotrack algorithm, and to be as close as possible to the base of the host rock, 201.4 Rha 100 was mapped as a zero-crossing horizon (Fig. 5-20).

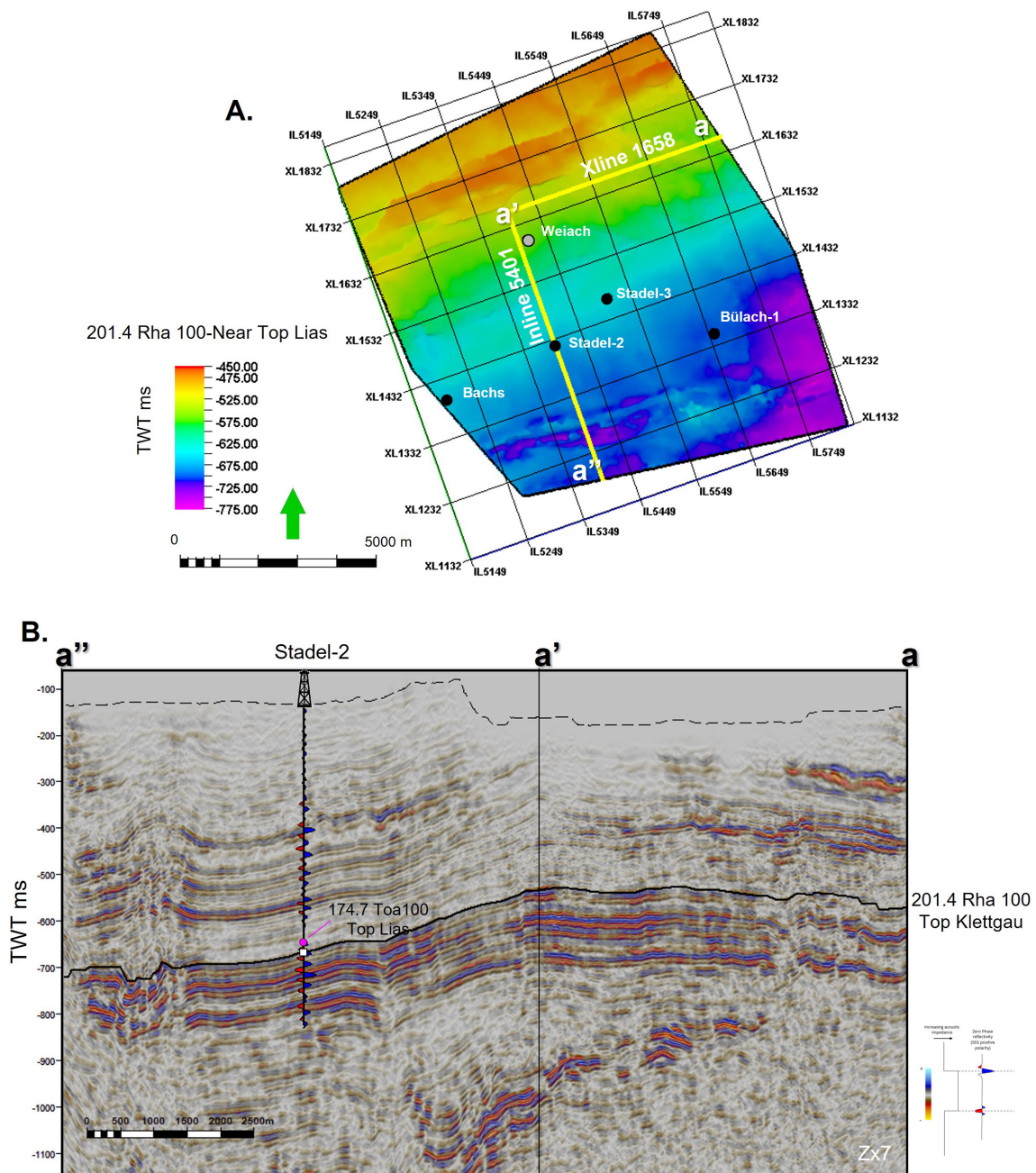


Fig. 5-20: 201.4 Rha 100 – Near Top Lias (Top Klettgau) horizon interpretation

A. TWT top structure of horizon B. Inline-crossline composite across the Stadel-2 well. Clear challenges were identified in the interpretation of the 174.7 Toa 100 – Top Lias which represents the base of the Opalinus Clay interval. Therefore 201.4 Rha 100 – Top Klettgau was selected as it represents the most continuous horizon below it. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.2.5 237 Lad 400 – Top Muschelkalk

The stratigraphic marker 237 Lad 400 correlates with the top of the Muschelkalk Group (Tab. 5-1, Fig. 5-11, Fig. 5-21, Jordan, 2015).

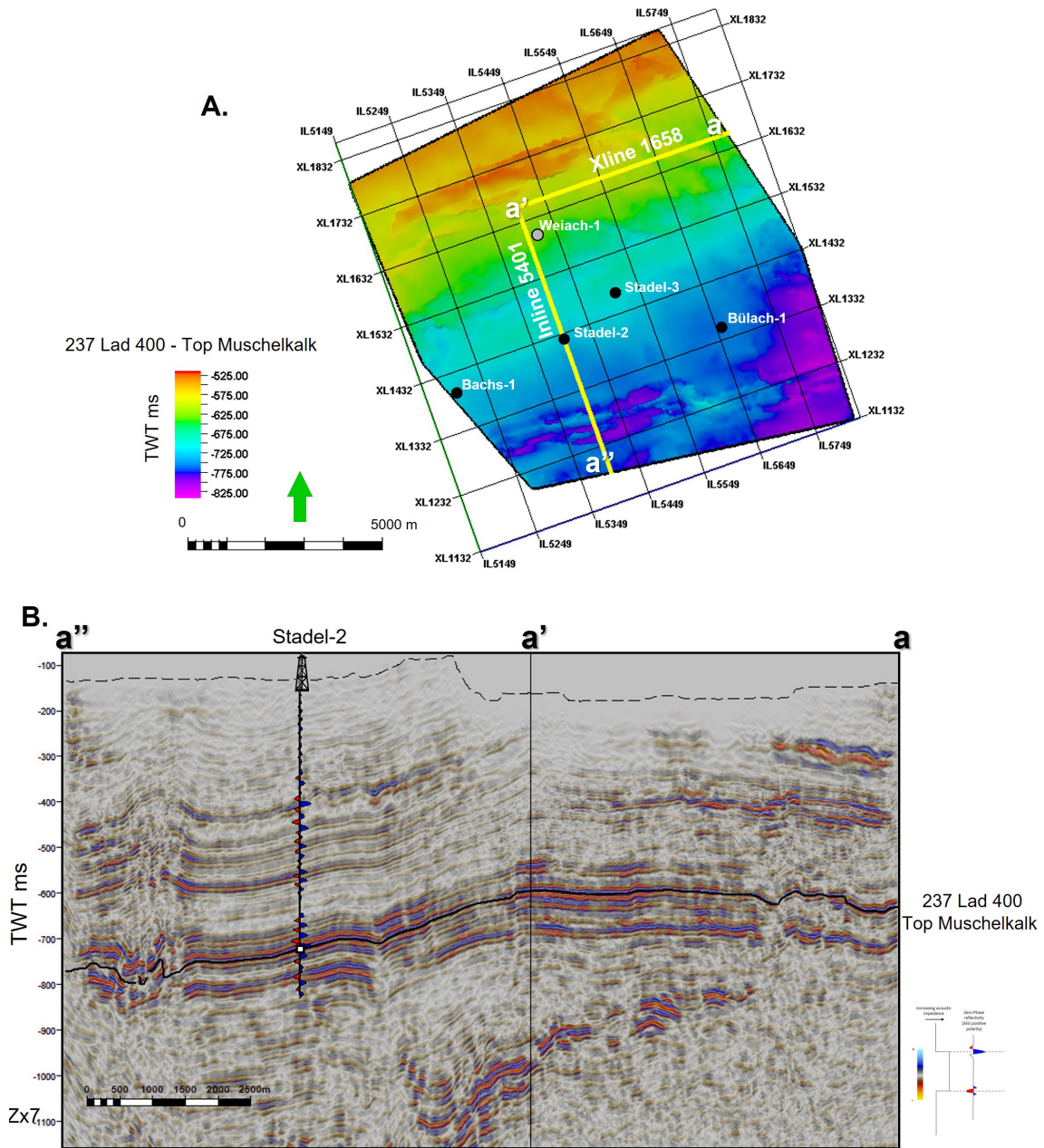


Fig. 5-21: 237 Lad 400 – Top Muschelkalk horizon interpretation

A. TWT top structure of. B. Inline-crossline composite across the Stadel-2 well. This horizon is seismically imaged by soft acoustic contrast with the overlying Bänkerjoch Formation and represents the reference horizon for identifying faults in the stratigraphic interval below the Opalinus Clay. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The three phases distinguished in the Muschelkalk Group record 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 and some halite were recorded in the wells; correspondingly, a lateral variation in seismic facies was observed in the seismic data (Fig. 5-22), to (iii) a marine transgression and regression phase where shallow marine micrite and intermittent bioclastic beds (transgression) underlie oolitic micrite locally deposited during the regressive phase (Nagra 2024d). The top of the Muschelkalk group is thus marked by fossiliferous claystone and dolomite, indicating a subsequent transgressive phase. This marker is seismically imaged by the soft acoustic contrast with the overlying Bänkerjoch Formation (Fig. 5-11) and represents the reference horizon for identifying discontinuities and unlocking their complexity in the lower confining unit (Fig. 5-21).

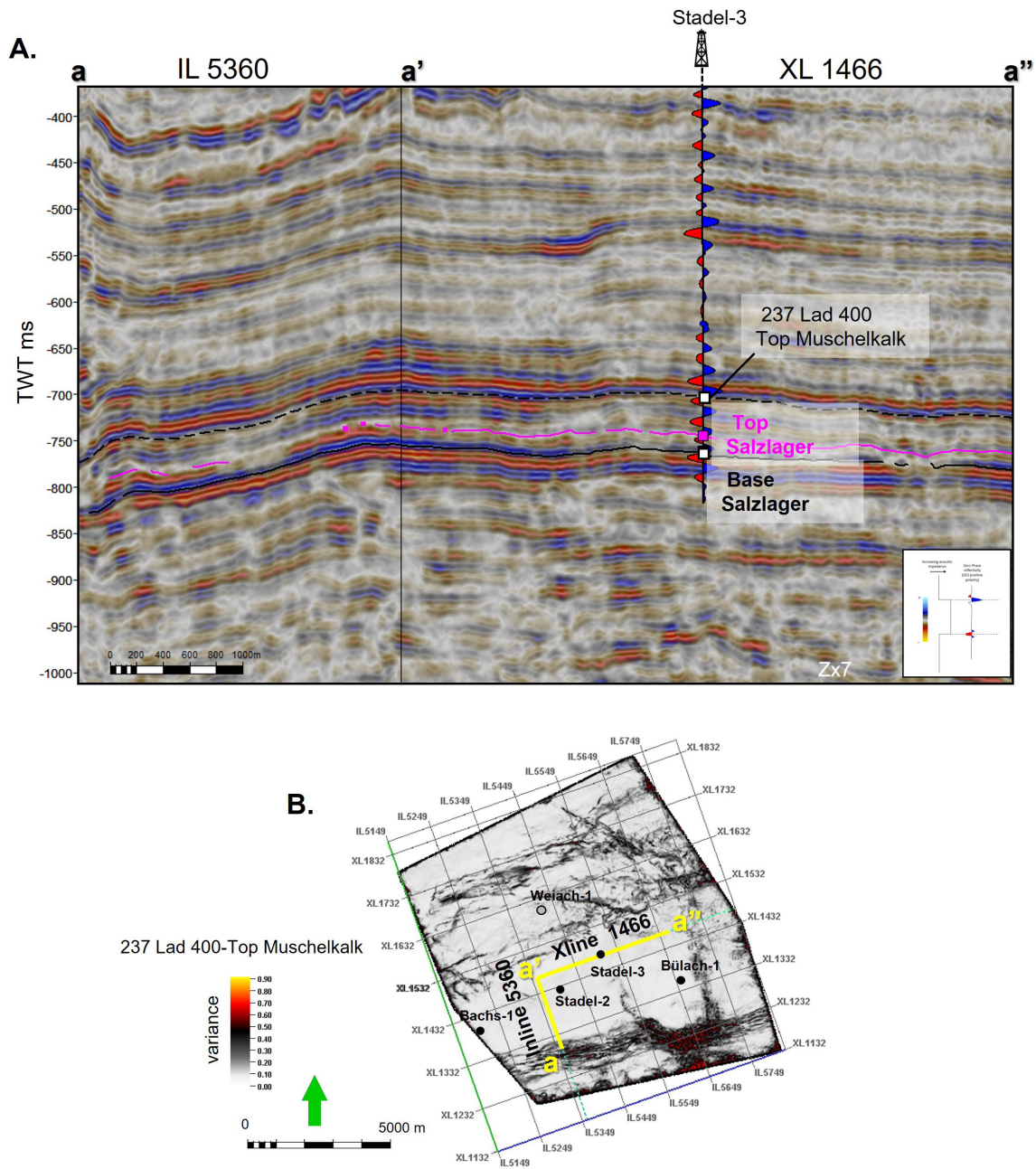


Fig. 5-22: Composite inlines and crosslines across the Stadel-3 well showing amplitude variations within the Muschelkalk Formation

Amplitude variations within the Muschelkalk sequence might reflect its depositional complexity. Specifically, variability in thickness and seismic imaging is observed for the evaporitic member (Salzlager) that corresponds to the Triassic regional detachment level. B. Line location shown above the 237 Lad 400 – Top Muschelkalk variance horizon slice.

Seismic attribute extractions highlighted the presence of clusters of circular to ellipsoidal features (Fig. 5-23) already recognised in NAB 18-35 and interpreted to represent dissolution features of the Muschelkalk evaporitic interval.

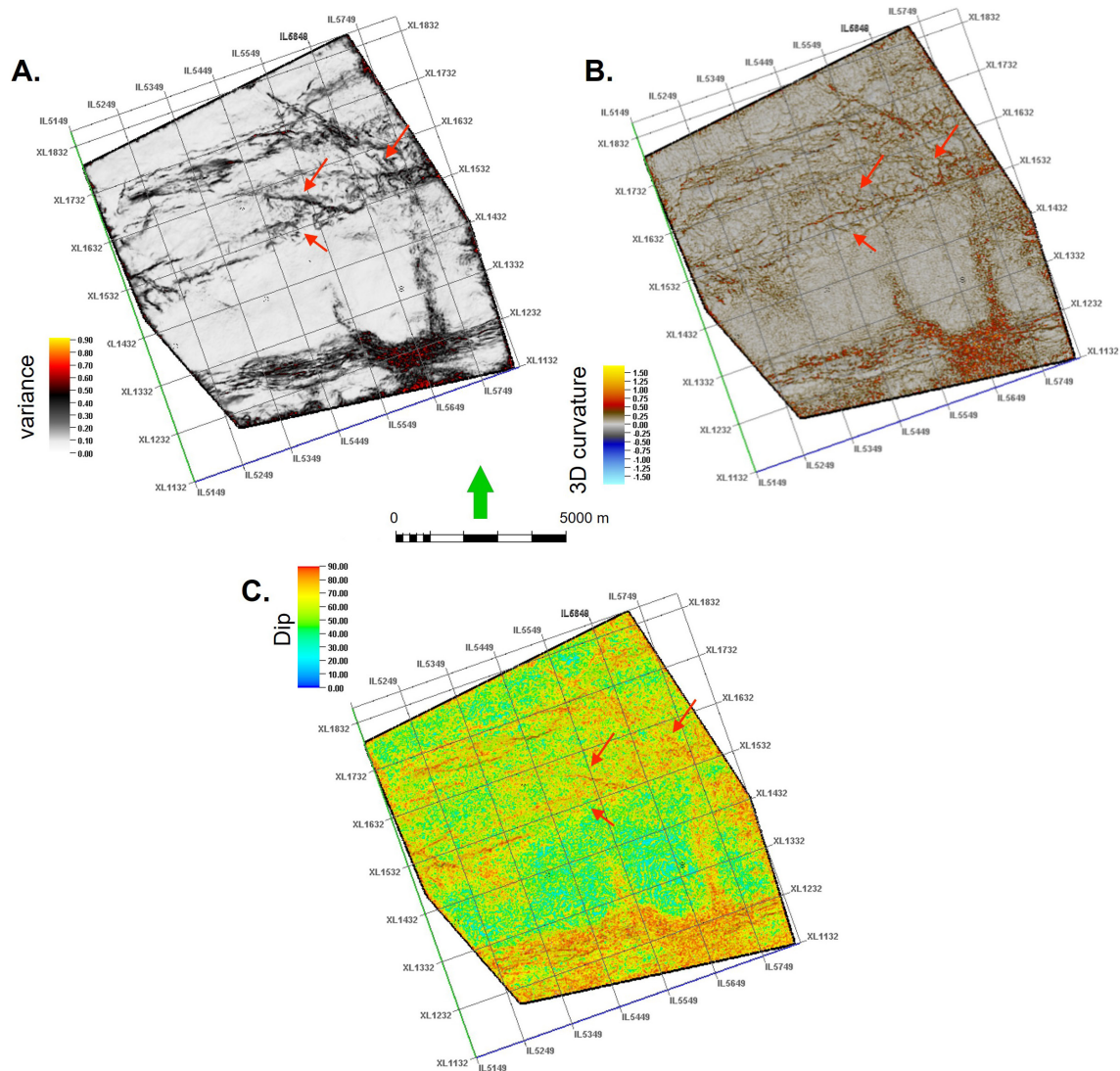


Fig. 5-23: 2018 interpretation (Nagra, 2019) highlighted the presence of Triassic marker horizons, circular structural depressions and polygonal fault patterns

These features, interpreted as potentially related to dissolution process, are recognised along the WSW-ENE-striking Weiach-Glattfelden-Eglisau Structure (WGE). Attribute extractions of 237 Lad 400 – Top Muschelkalk on PreSTM-ref support the presence of circular to ellipsoidal features (red arrow) clustered along major WGE fault segments. A. 237 Lad 400 – Top Muschelkalk variance; B. 237 Lad 400 – Top Muschelkalk 3D curvature and C. 237 Lad 400 – Top Muschelkalk dip.

In cross-sections (Fig. 5-24), those features, however, can correspond to extremely coherent and continuous Muschelkalk reflections. The overlying Bänkerjoch Formation, on the other hand, is characterised by disrupted and transparent seismic facies (Fig. 5-25), which potentially reveal the articulated depositional architecture of this formation (chicken-wire anhydrite, dolomitic claystone with thin anhydrite layers and claystone (Nagra 2024d). Based on a comparison between attribute extractions (Top Muschelkalk vs. autotracked Top Bänkerjoch; Fig. 5-25) and section displays (Fig. 5-24), those features are inferred to represent mostly imprints from the Bänkerjoch features on Top Muschelkalk level. When present, the transparent seismic facies observed at the Top Muschelkalk level could indicate a multi-phase exposure-related dissolution with an older phase occurring at Muschelkalk time.

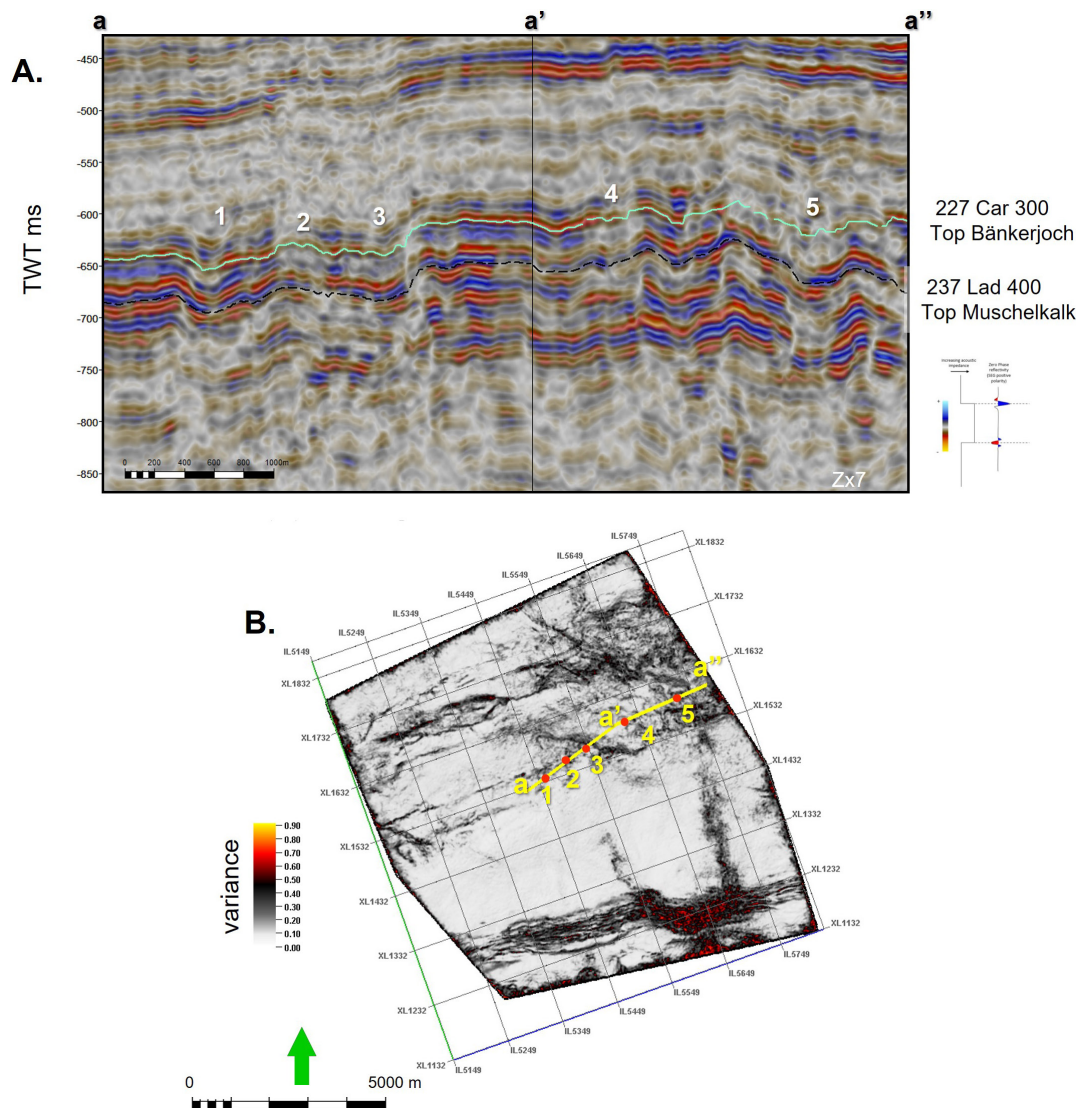


Fig. 5-24: 3D integrated analysis indicates that the negative structures recognised along the WSW-ENE-striking Weiach-Glattfelden-Eglisau Structure (WGE) are associated with amplitude dimming at the 227 Car 300 – Top Bänkerjoch interval

These features do not always coincide with comparable seismic response at a deeper level, i.e. 237 Lad 400 – Top Muschelkalk. A. Random section across the circular / ellipsoidal features (1 to 5) along the WGE. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance. B. 227 Car 300 – Top Bänkerjoch variance horizon slice showing the line location and circular features.

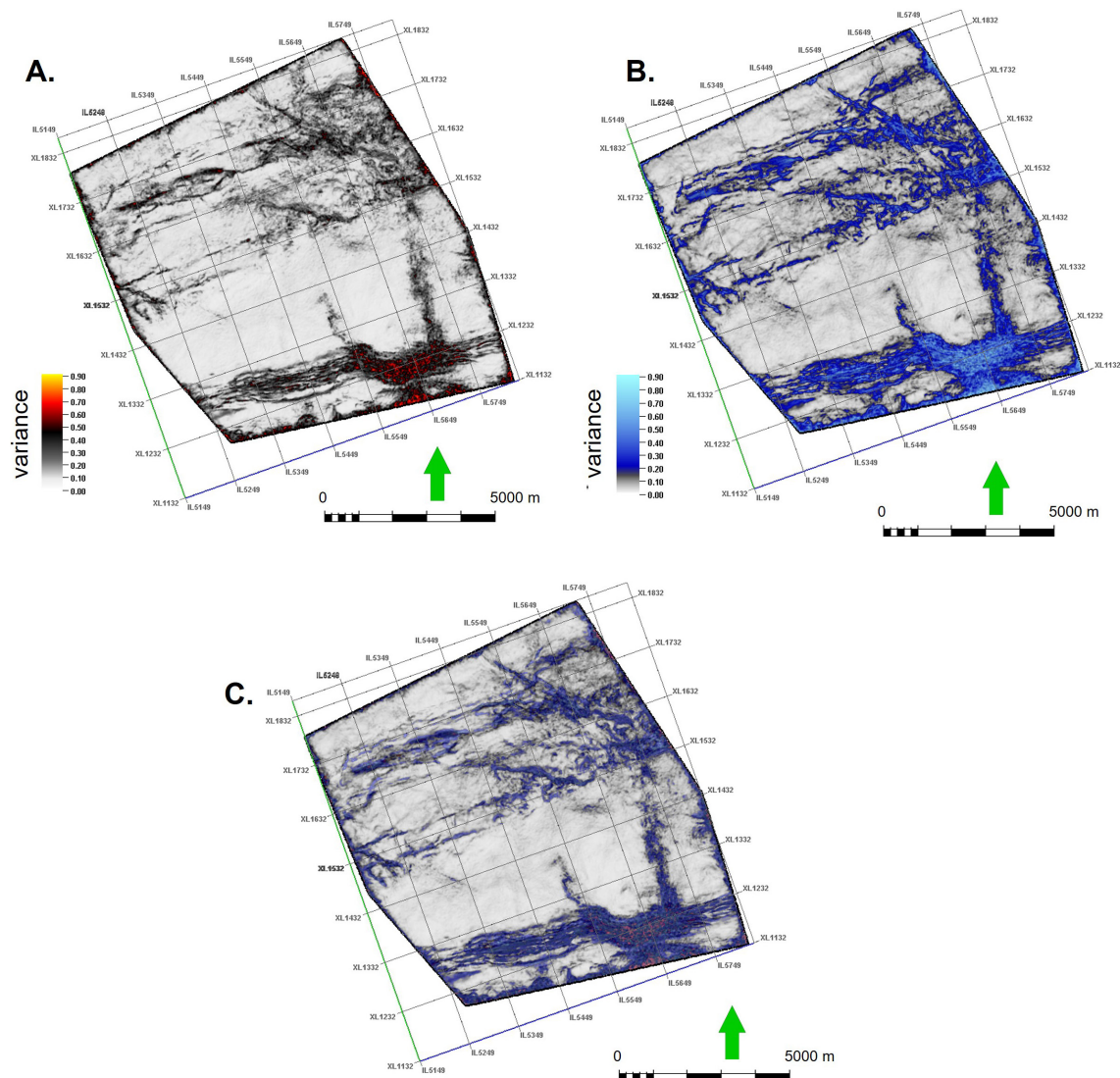


Fig. 5-25: Comparison of variance horizon slices showing the overlapping occurrence of the circular / ellipsoidal features along the WSW-ENE-striking Weiach-Glattfelden-Eglisau Structure (WGE)

This suggests that these features could represent imprints of 227 Car 300 – Top Bänkerjoch anhydritic dissolution features. Alternatively, several overlaying dissolution events could potentially affect both the 227 Car 300 – Top Bänkerjoch and 237 Lad 400 – Top Muschelkalk. A. 227 Car 300 – Top Bänkerjoch variance horizon slice; B. 237 Lad 400 – Top Muschelkalk variance horizon slice and C. combined display of 227 Car 300 – Top Bänkerjoch (black) and 237 Lad 400 – Top Muschelkalk variance (blue) horizon slices.

5.2.6 251.9 Per 100 – Near Base Mesozoic Unconformity

Horizon 251.9 Per 100 has the lowest confidence among the interpreted surfaces, since it represents a major unconformity (Tab. 5-1, Fig. 5-26). The seismic response to an unconformity depends on the nature of the contact between pre-unconformity and post-unconformity sections.

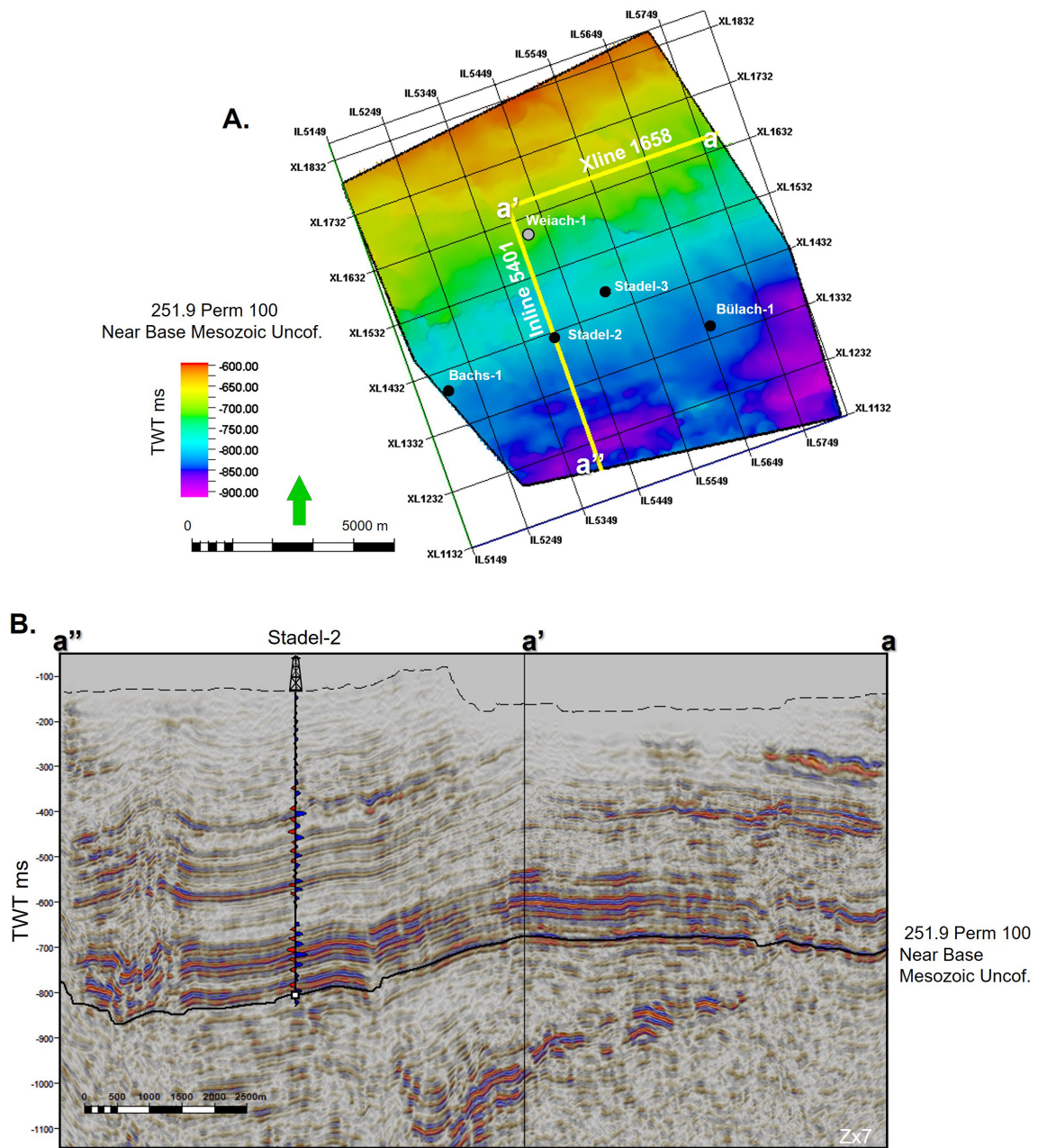


Fig. 5-26: 251.9 Perm 100 – Near Base Mesozoic Unconformity horizon interpretation

A. TWT top structure; B. Inline-crossline composite across the Stadel-2 well. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

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 (Fig. 5-27). Due to the property variability of pre-unconformity and post-unconformity deposits, a change in reflection polarity can be expected.

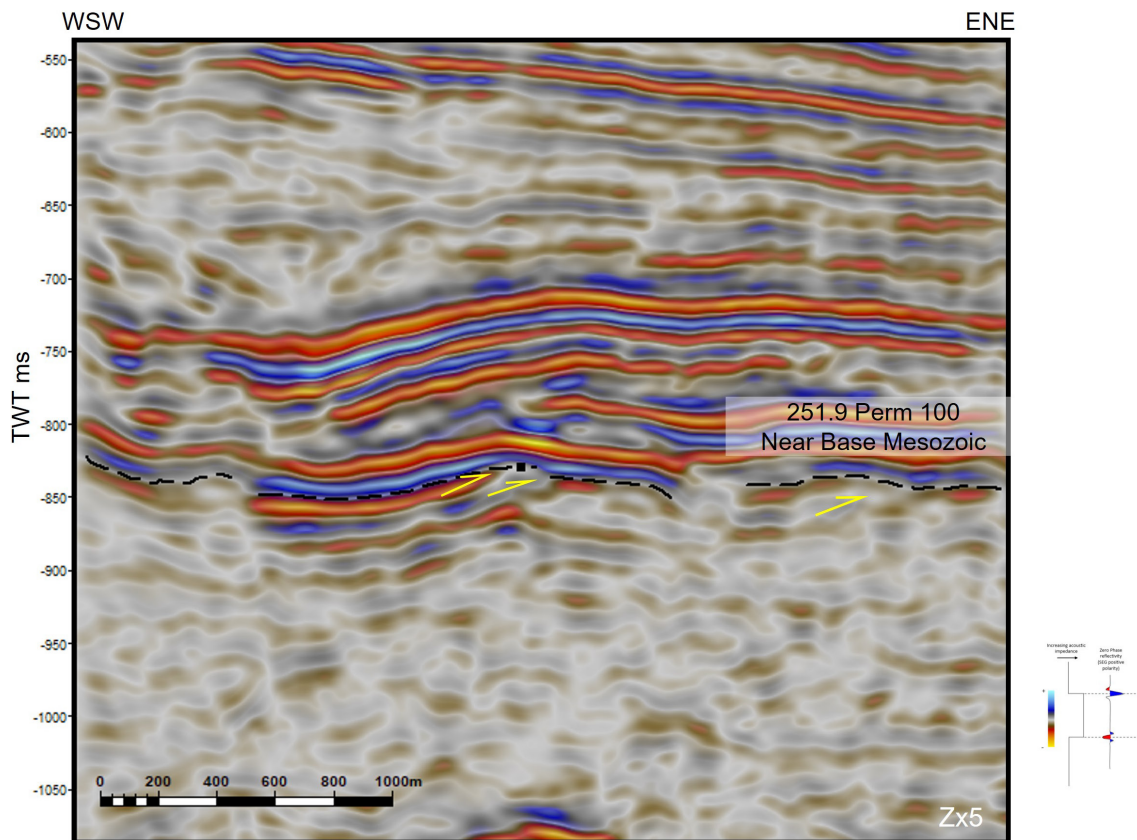


Fig. 5-27: Evidence of strata truncation at 251.9 Per 100 – Near Base Mesozoic Unconformity

The Base Mesozoic Unconformity was interpreted with challenges recognised by previous interpretation attempts (Nagra 2019, Diebold et al. 1991, Naef et al. 1995, Birkhäuser et al. 2001, Madritsch et al. 2013). To mitigate the picking uncertainty, despite considering the limitation of this approach, this horizon was traced following a zero-crossing (Z-crossing; Fig. 5-11, Fig. 5-26, Tab. 5-1). At the well locations, this Z-crossing correlated consistently with the stratigraphic marker 251.9 Per 100. Not representing the unconformable boundary, but rather the nearest continuous event, the resulting interpreted horizon was referred to, therefore, as the Near Base Mesozoic Unconformity. Despite the interpretation uncertainty, the Near Base Mesozoic Unconformity is a key marker since it plays a fundamental role in unlocking the interaction and influence of the deeper structural grains (basement and Permo-Carboniferous faults) on Mesozoic deformation (Nagra 2024e, Zambrano et al. 2024, Schöpfer et al. 2023).

5.3 Fault interpretation

Fault interpretation was carried out using a 3D multi-phase approach (Fig. 4-8). The screening phase resulted in structural maps where structural lineaments (faults and folds; ASR deformation zones, Nagra, 2022c) were discriminated from other geological features and seismic artefacts and captured as traces for the four main stratigraphic horizons (Fig. 5-28, Fig. 5-29).

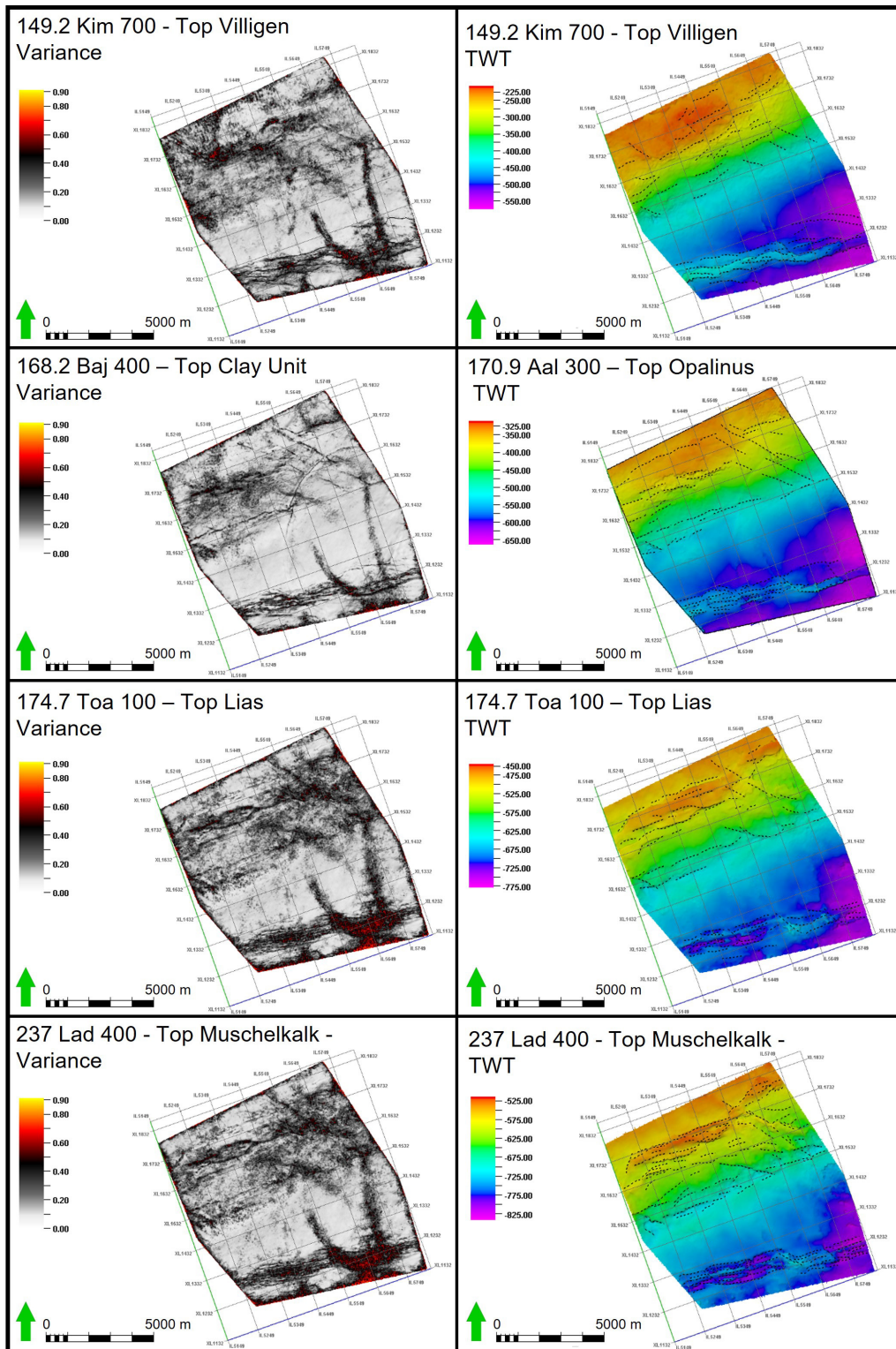


Fig. 5-28: ASR structural interpretation matrix based on PreSTM-ref minimum-phase Nagra (2022)

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.

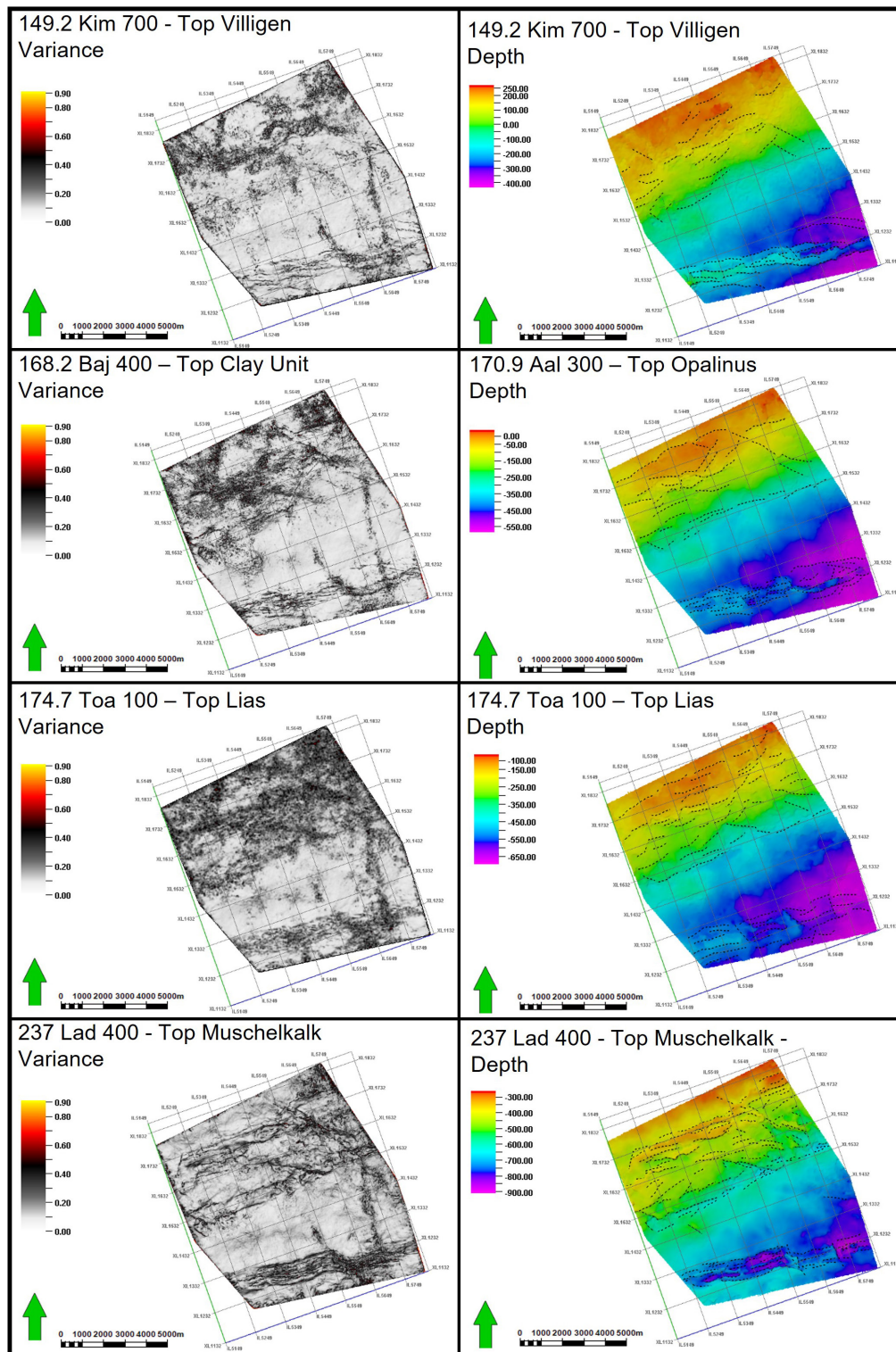


Fig. 5-29: Pre-ASR 2021 structural interpretation matrix based on PreSDM-ref minimum-phase

Displays of the variance attribute horizon slices and the deformation zones on top of TWT structural maps in the four main stratigraphic horizons (dashed black lines represent fault interpretation of Phase 1 workflow; interpreted seismic discontinuities represent deformation zones: faults and folds). Definition of structural lineament as in Fig. 5-33. Seismic data is PreSDM-A minimum-phase.

At this stage of the interpretation workflow (Phase 1 - reconnaissance), the interpreted structural lineaments are considered (structurally) as undifferentiated deformation zones (Nagra 2022c) that can be attributed indiscriminately to faults or fault-related folds (i.e. fault-tip monoclines; Fig. 5-30). Since, on attribute maps, the identified seismic discontinuities appear to have similar seismic expression that make them indistinguishable from fold and fault traces (Fig. 5-28 and Fig. 5-29), the recognition and separation of seismic faults from 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.

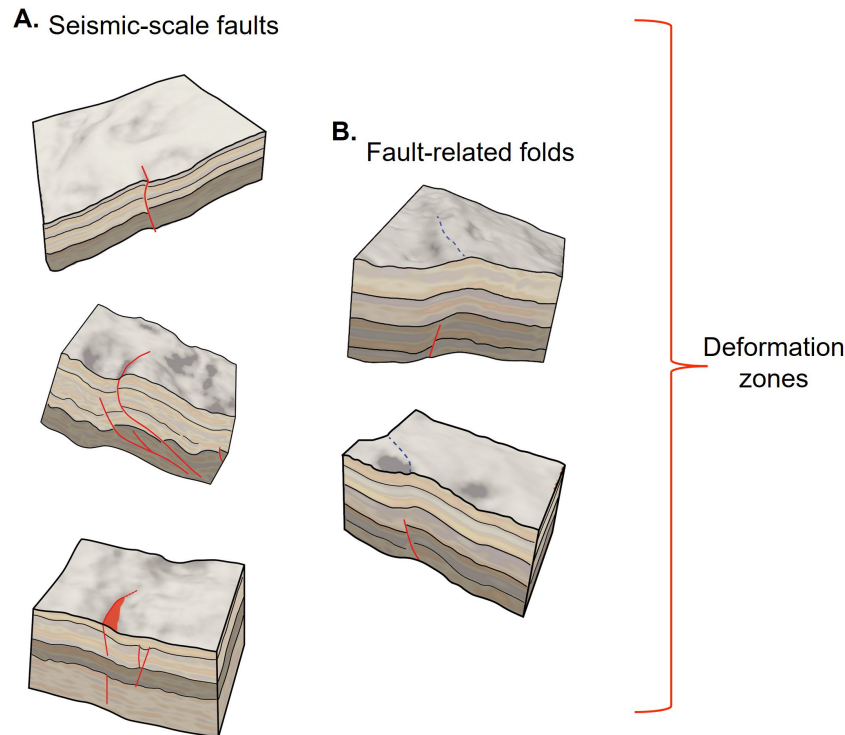


Fig. 5-30: Conceptual diagrams of the structural lineaments as for the Phase 1 (reconnaissance) interpretation

The seismic structural lineaments mapping does not differentiate between faults and fault-related folds (i.e. drape-folds / fault-tip monoclines) and they are generally referred to as deformation zones. Definition of seismic fault signatures and 3D fault stick interpretation allow the distinction 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).

The resulting fault mapping of Phase 2 is a filtered image of the seismic deformation zones of Phase 1 (Fig. 5-31) where solely fault traces are displayed with some of the lineament trends adjusted to fully honour the vertical (section) criteria.

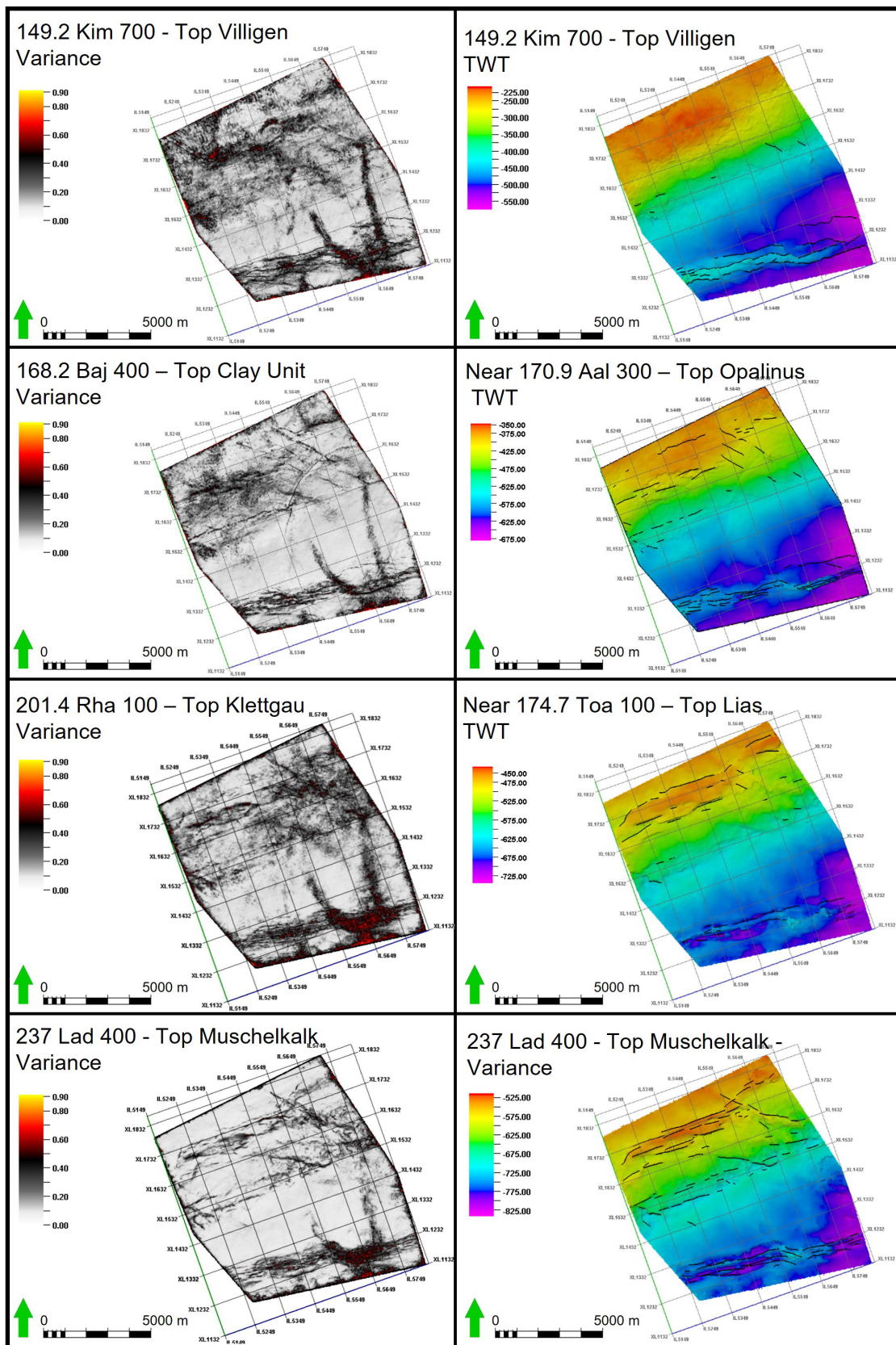


Fig. 5-31: 2023 (this report) fault interpretation matrix

For caption see next page.

Displays of the variance attribute horizon slices and fault traces on top of TWT structural maps for the four main stratigraphic horizons (black lines represent fault interpretation of Phase 2 workflow). Compared to the ASR deformation zones (Nagra 2022), only lineaments interpreted in 3D as faults were selected. Note that the fault traces are referred to as Near 170.9 Aal 300 – Top Opalinus Clay. They are derived by the intersection of the interpreted 3D fault sticks and the interpreted horizon 168.2 Baj 400 – Top Clay Unit - isochroned down to mimic Top Opalinus Clay, therefore representing faulting at near Top Opalinus level. The same approach was adopted for the Top Lias fault traces where 201.4 Rha 100 – Top Klettgau was isochroned up to match the 174.7 Toa 100 – Top Lias well top, here referred to as Near 174.7 Toa 100 – Top Lias. Seismic data is PreSTM-ref.

Note that horizon 170.9 Aal 300 – Top Opalinus and the 174.7 Toa 100 – Top Lias are referred to as Near 170.9 Aal 300 – Top Opalinus and Near 174.7 Toa 100 – Top Lias since they are “calculated” horizons derived from the isochroned down of the 168.2 Baj 400 – Top Clay Unit and the isochroned up of the 201.4 Rha 100 – Top Klettgau horizons, respectively.

Fault traces were obtained by the intersection of the 3D fault planes with the two isochroned horizons to represent faults at 170.9 Aal 300 – Top Opalinus and 174.7 Toa 100 -Top Lias levels.

The distribution and style of the interpreted seismic faults are also captured in key cross-sections (Fig. 5-32, Fig. 5-33, Fig. 5-34 and Fig. 5-35). Seismic-scale faults appear to be systematically identifiable through the different vintages of seismic data and interpretations.

While single fault segments could show alternative length and/or orientation, their spatial distribution, geometry and density are consistent with structural grains documented in previous studies (Nagra 2019), Fig. 5-36, Schöpfer et al. 2023, Zambrano et al. 2024, Bond et al. 2023; Section 6.2). Two previously identified major faults (H and S; Fig. 5-36, NAB 18-35) are interpreted in this evaluation as not representing structural lineaments, but rather imprints associated with overlaying sedimentological features, i.e. the Herrenwis carbonate platform margin (H) and Quaternary valley (S), respectively.

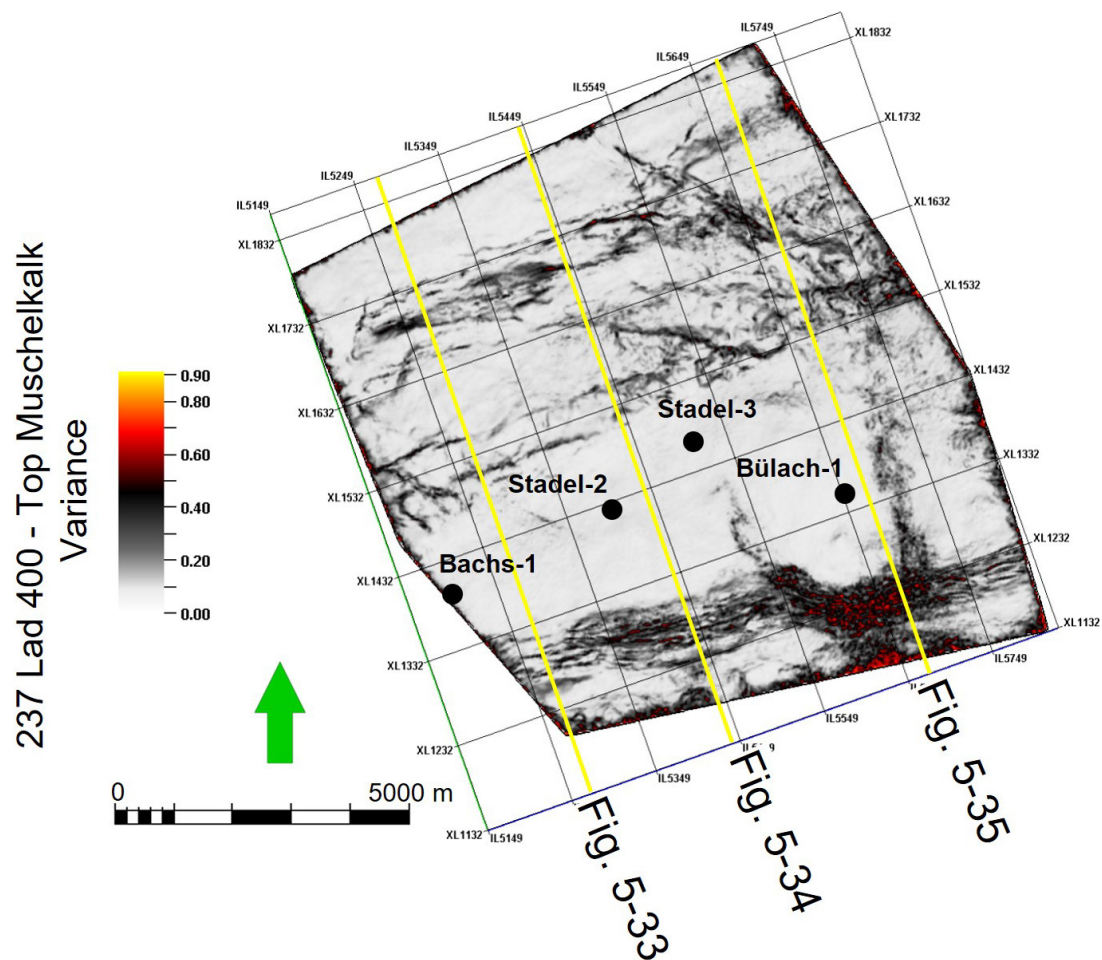


Fig. 5-32: 237 Lad 400 – Top Muschelkalk Variance showing the position of the four wells and the three key seismic sections as for Fig. 5-33, Fig. 5-34 and Fig. 5-35

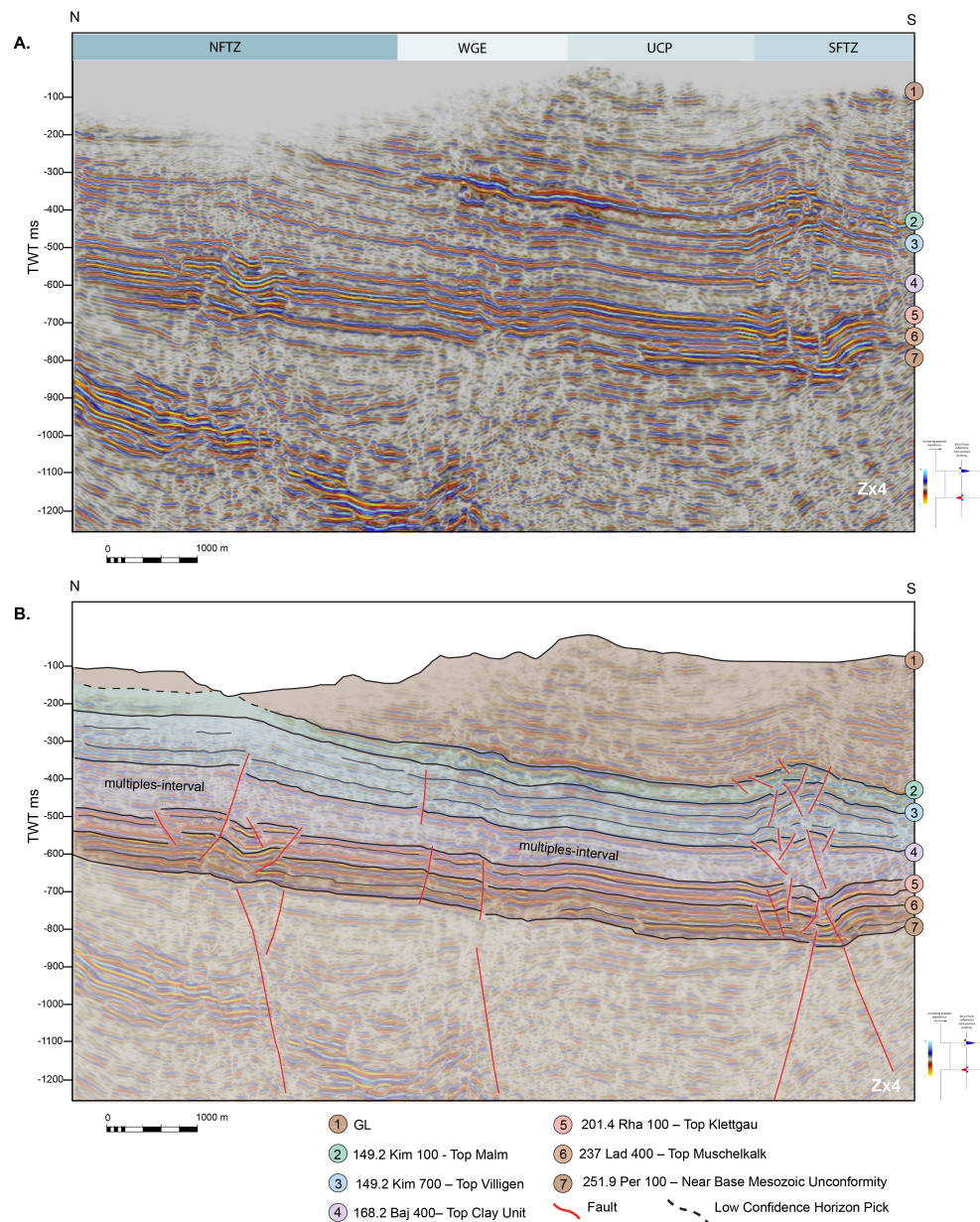


Fig. 5-33: Inline 5269 showing the fault interpretation and structural geometry and complexity across the NL siting region

A. Uninterpreted. B. Interpreted. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by the presence of seismic multiples. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Line location is shown in Fig. 5-32. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

NFTZ: Northern Fold-and-Thrust Zone, WGE: Weiach-Glattfelden-Eglisau Structure, UCP: Undisturbed Central Panel, SFTZ: Southern Fold-and-Thrust Zone.

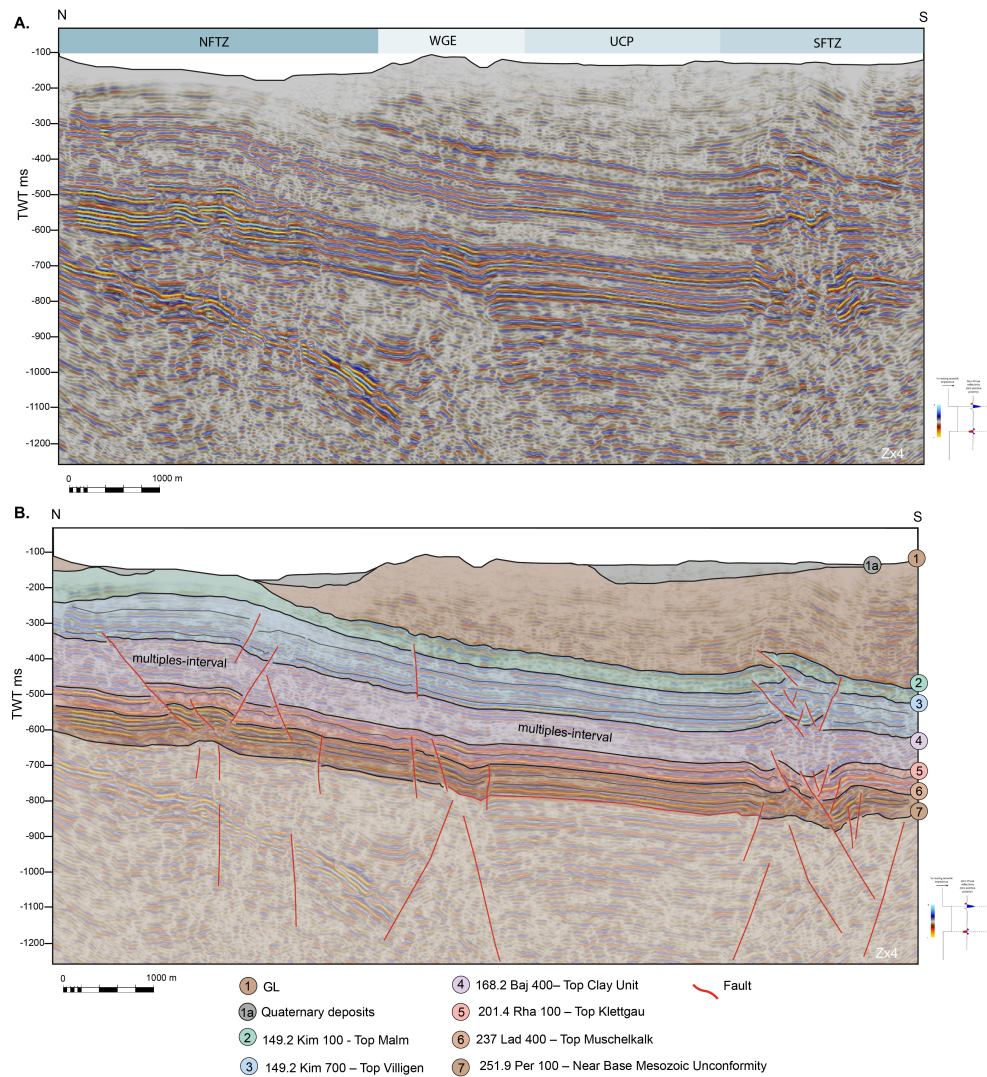


Fig. 5-34: Inline 5440 showing the fault interpretation and structural geometry and complexity across the NL siting region

A. Uninterpreted. B. Interpreted. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by the presence of seismic multiples. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Line location is shown in Fig. 5-32. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

NFTZ: Northern Fold-and-Thrust Zone, WGE: Weiach-Glattfelden-Eglisau Structure, UCP: Undisturbed Central Panel, SFTZ: Southern Fold-and-Thrust Zone.

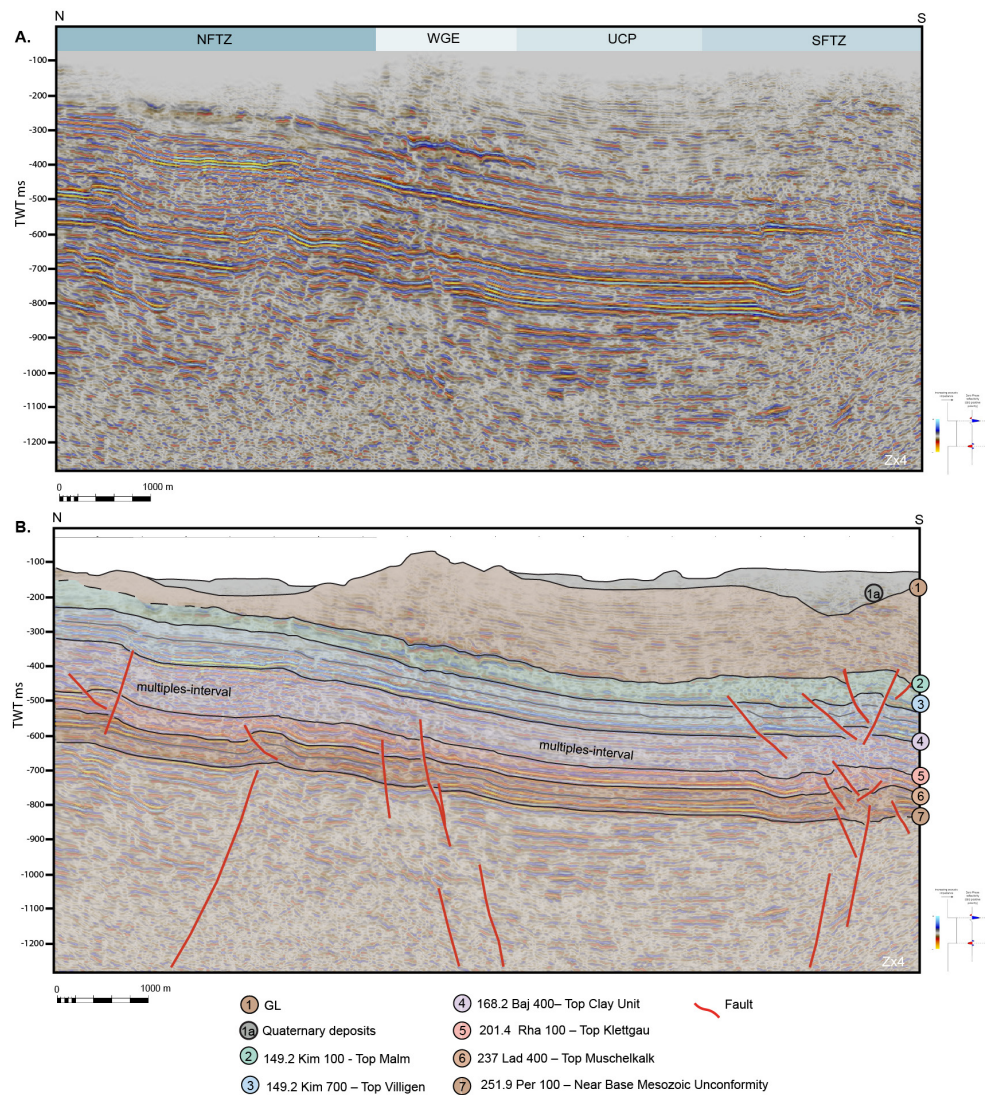


Fig. 5-35: Inline 5671 showing the fault interpretation and structural geometry and complexity across the NL siting region

A. Uninterpreted. B. Interpreted. Note that the recognition of fault signatures within the Opalinus Clay interval is strongly impaired by the presence of seismic multiples. Only major basement faults were drawn to show the structural link between deep-seated grains and Mesozoic faults. Line location is shown in Fig. 5-32. GL is ground level. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

NFTZ: Northern Fold-and-Thrust Zone, WGE: Weiach-Glattfelden-Eglisau Structure, UCP: Undisturbed Central Panel, SFTZ: Southern Fold-and-Thrust Zone.

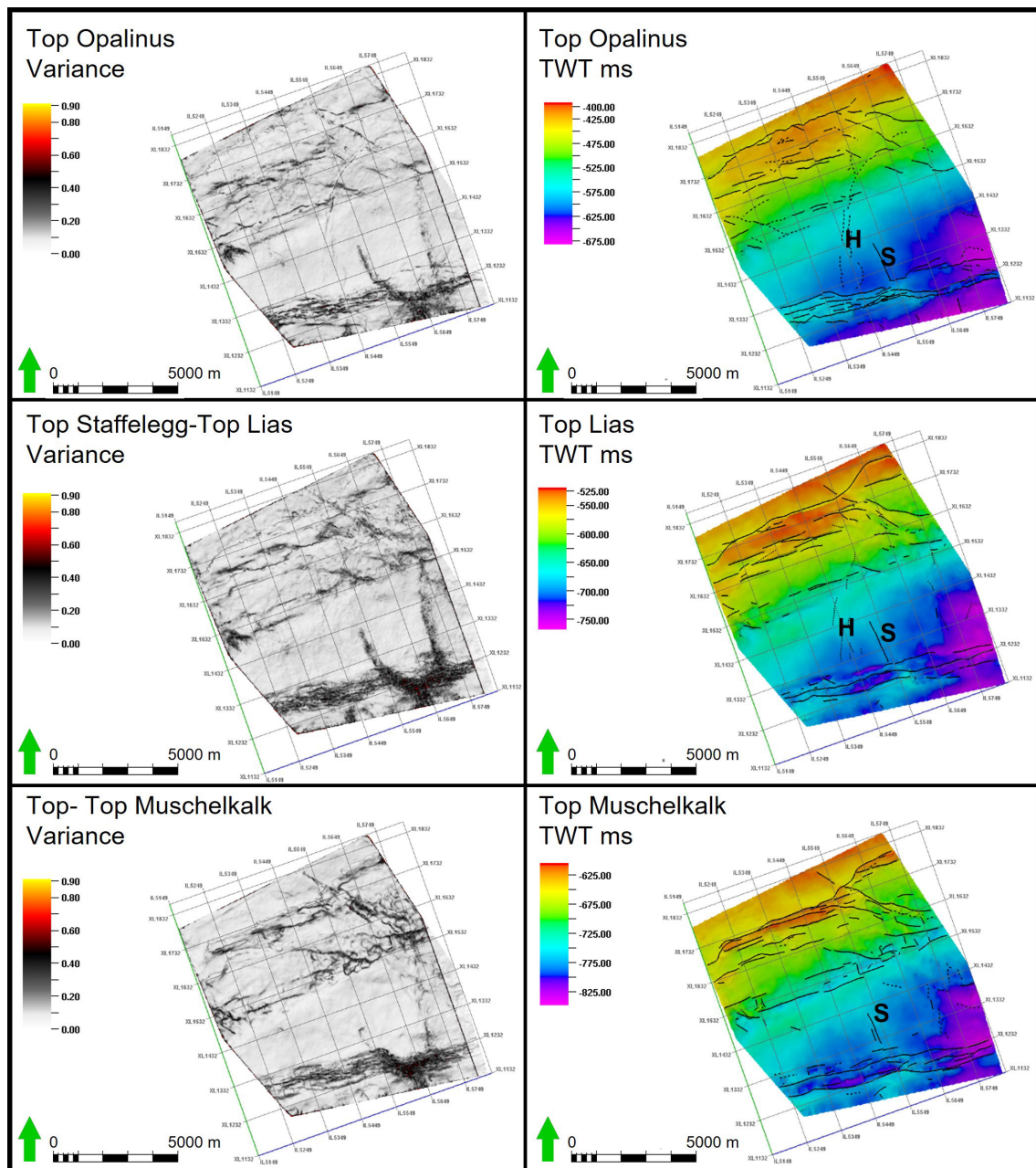


Fig. 5-36: Fault interpretation matrix from the 2018 evaluation (Nagra 2019)

Similar fault interpretation matrix as Fig. 5-28, Fig. 5-29, and Fig. 5-31 (variance horizon slices and TWT top structure), reproducing the 2018 fault interpretation (black lines) on a QLP dataset from NAB 18-35 (Nagra 2019). Black solid lines are class A faults and dashed lines are class C (lower confidence) as for the definition in NAB 18-35 (Nagra 2019). The dashed lines in the Undisturbed Central Panel coincides with imprints associated with the Herrenwis carbonate platform margin (H). The Strassberg Trough (S) is alternatively interpreted as an artefact related to a Quaternary valley.

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 NL siting region can be subdivided into four main structural domains (Fig. 5-37, see also Fig. 5-32, Fig. 5-33, Fig. 5-34, and Fig. 5-35):

1. Southern Fold-and-Thrust Zone (SFTZ)
2. Northern Fold-and-Thrust Zone (NFTZ)
3. Weiach-Glattfelden-Eglisau Structure (WGE)
4. Undisturbed Central Panel (UCP)

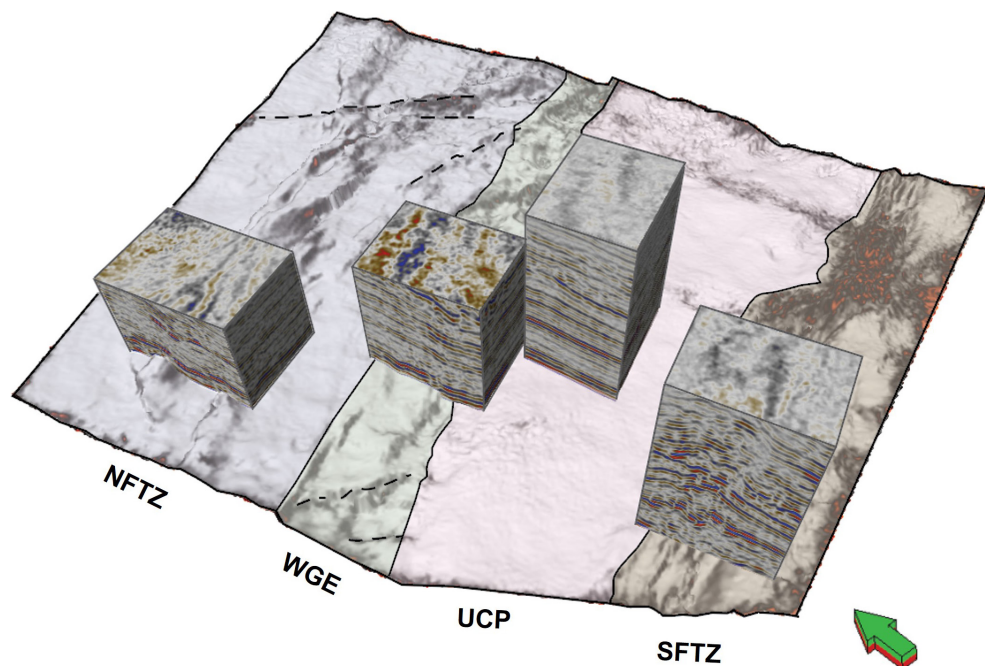


Fig. 5-37: Four structural domains defined for the NL siting region

Structural domains overlain on 3D view of 237 Lad 400 – Top Muschelkalk variance map (north direction indicated by green arrow). NFTZ: Northern Fold-and-Thrust Zone (blue), WGE: Weiach-Glattfelden-Eglisau Structure (green), UCP: Undisturbed Central Panel (pink), SFTZ: Southern Fold-and-Thrust Zone (yellow). Note that dashed lines capture NW-SE-trending faults, which create internal compartmentalisation both in the NFTZ and the WGE. Green arrow points toward north.

5.3.1.1 Southern Fold-and-Thrust Zone

The Southern Fold-and-Thrust Zone (Fig. 5-37, see also Fig. 5-32, Fig. 5-33, Fig. 5-34 and Fig. 5-35) coincides with the Baden-Irchel-Herdern (BIH) Lineament, a regional fault zone that was already identified by structural interpretations of 2D seismic lines (Diebold et al. 1991, Naef et al. 1995, Madritsch et al. 2013, Malz et al. 2016, Fig. 1-1). It consists of multiple ENE-WSW thrusts and back-thrusts, forming a series of fish-tail structures arranged in a narrow, steep belt involving the Triassic-Jurassic series (Zambrano et al. 2024). Seismic discontinuities are consistently clustered along strikes in this narrow vertical belt, but they are characterised by seismic-scale lateral segmentation (Fig. 5-38). Furthermore, the lateral continuity of the ENE-WSW fold-and-thrust zone is interrupted by NW-SE-striking lateral ramps (Fig. 5-38). The presence of these ramps appears to be associated with the presence of high-angle faults, which propagate from the underlying Palaeozoic units offsetting the Mesozoic succession.

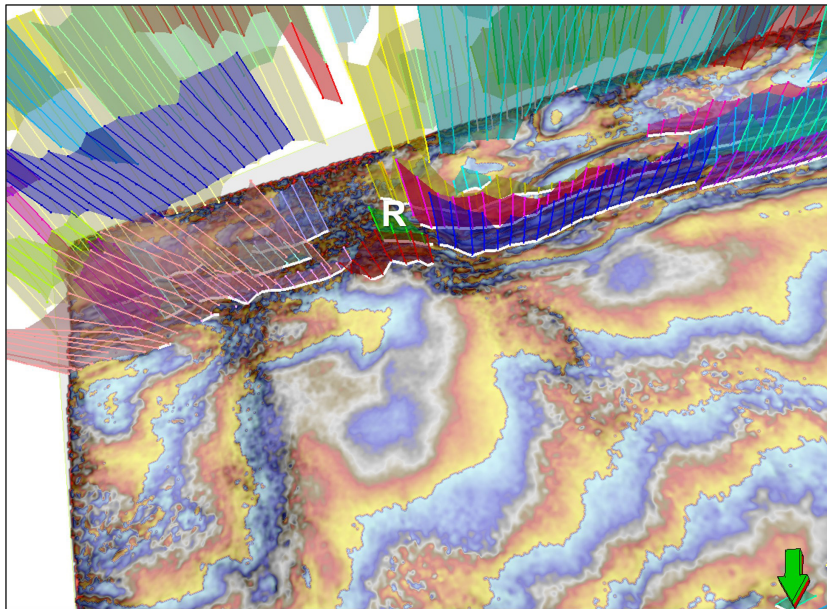


Fig. 5-38: 3D zoomed-in display showing the presence of NW-SE-trending lateral ramp (R) segmenting the continuity of the SFTZ structure along the strike

PreSTM-ref time slice is -750 ms TWT (within Muschelkalk interval). Vertical exaggeration is 10. Green arrow points toward north.

A significant change in deformation geometries was observed above and below the clay-rich unit incorporating the Opalinus Clay (i.e. between the underlying Triassic-Lower Jurassic formations and the overlying post-Aalenian succession), suggesting decoupling of the deformation controlled by the thick shales (Fig. 5-32, Fig. 5-33, Fig. 5-34 and Fig. 5-35). The upper competent panel (from 149.2 Kim 100 – Top Malm down to 168.2 Baj 400 – Top Clay Unit) is antiformally folded, while the lower competent panel (from 201.4 Rha 100 – Top Klettgau down to 251.9 Per 100 – Near Base Mesozoic Unconformity) is synformally folded, explaining the thickened Opalinus Clay observed in the core of both folds. According to Zambrano et al. (2024), this indicates that the thickness of the incompetent Opalinus Clay (and adjacent incompetent units) is sufficient to allow disharmonic folding of the two competent rock panels, and that the zone of contact strain of the two competent beams above and below the Opalinus Clay does not overlap during buckling (Fig. 5-39; Zambrano et al. 2024).

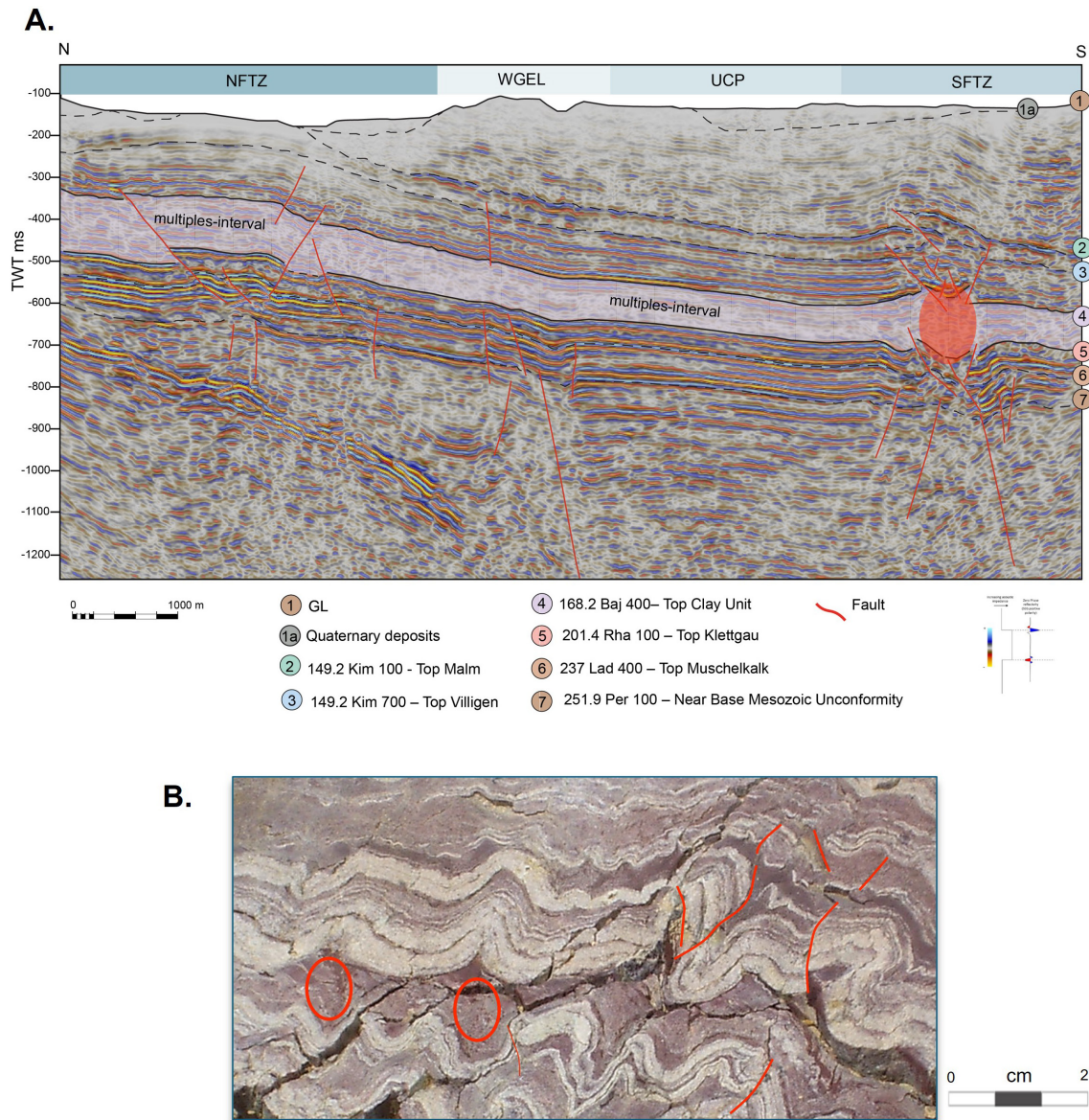


Fig. 5-39: Opalinus Clay thickening observed in the SFTZ

A. Inline 5440 across the structural domain showing in the SFTZ, with the upper competent panel (between horizons 149.2 Kim 100 – Top Malm and 168.2 Baj 400 – Top Clay Unit) antiformally folded, while the lower competent panel (between horizons 201.4 Rha 100 -Top Klettgau and 251.9 Per 100 – Near Base Mesozoic Unconformity) is synformally folded. This can explain the observed thickening of the Opalinus Clay. B. Outcrop example in the Variscan belt of SW Sardinia of polyharmonic, and locally disharmonic, folding produced by buckling of Cambrian interbedded thin shales (less competent) and siltites (more competent). Ellipses show zones of thickening of incompetent material at sites of disharmonic folding. Note that the deformation style is consistent regarding the difference in scale between outcrop (cm scale) and seismic section (km scale).

Furthermore, the thickness of the Triassic evaporites appears to be reduced below the syncline (Fig. 5-40). Salt weld development at this position may have been associated with the reactivation of the underlying Late Palaeozoic faults, enhancing the “downfolding” of the lower competent panel underlying the Opalinus Clay (Fig. 5-40, Zambrano et al. 2024).

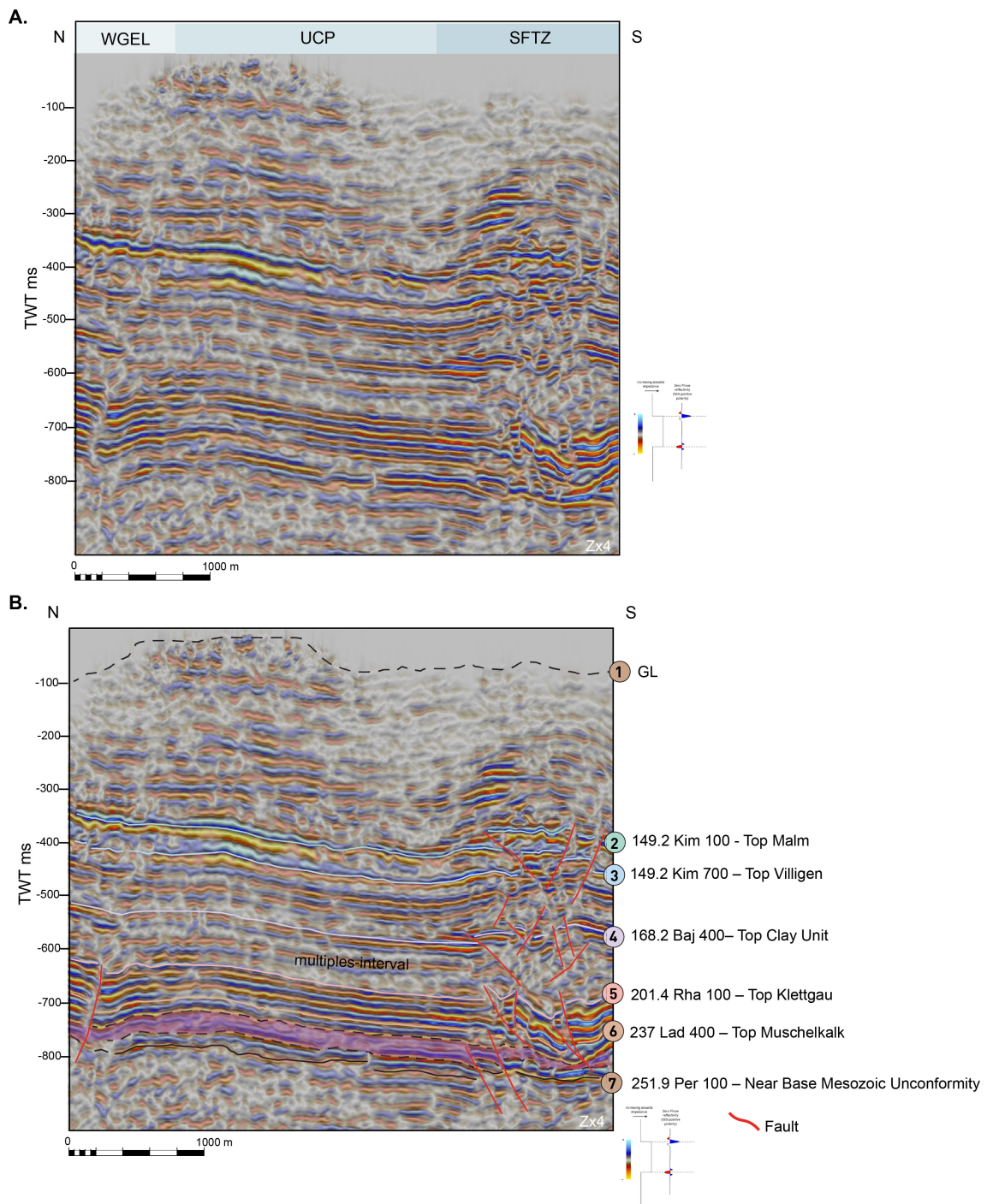


Fig. 5-40: Inline 5403 showing the thickness of the Triassic evaporites (Salzlayer: pink polygon), which appears to be reduced below the syncline

Salt weld development at this position may have been associated with the reactivation of the underlying Late Palaeozoic faults, enhancing the “downfolding” of the lower competent panel underlying the Opalinus Clay (Zambrano et al. 2024). A. Uninterpreted and B. Interpreted. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

5.3.1.2 Northern Fold-and-Thrust Zone

The Northern Fold-and-Thrust Zone is manifested at the surface by the Siglistorf Anticline and consists of an up to ~2-km-wide composite pop-up including highly segmented thrust and back-thrust splays (Fig. 5-32, Zambrano et al. 2024). The major thrusts and back-thrusts forming the pop-up structures do not continuously propagate across the Opalinus Clay (Fig. 5-32, Fig. 5-33, Fig. 5-34, Fig. 5-35). Deformation in the upper competent panels appears to be accommodated more by folding than faulting (Fig. 5-32, Fig. 5-33, Fig. 5-34, Fig. 5-35). Along the major pop-up structures, typical “box-fold” geometry can be observed (Fig. 5-41). In the lower competent panel, the geometry of the thrusts and back-thrusts appears to gently dip within the chaotic seismic interval associated with the Triassic evaporite, which also appears to thicken in the fold core (Fig. 5-41). This indicates that the pop-up structure might not be directly hard-linked to the S-dipping fault observed in the underlying Permo-Carboniferous Trough as proposed by Schöpfer et al. 2023 (Fig. 5-42).

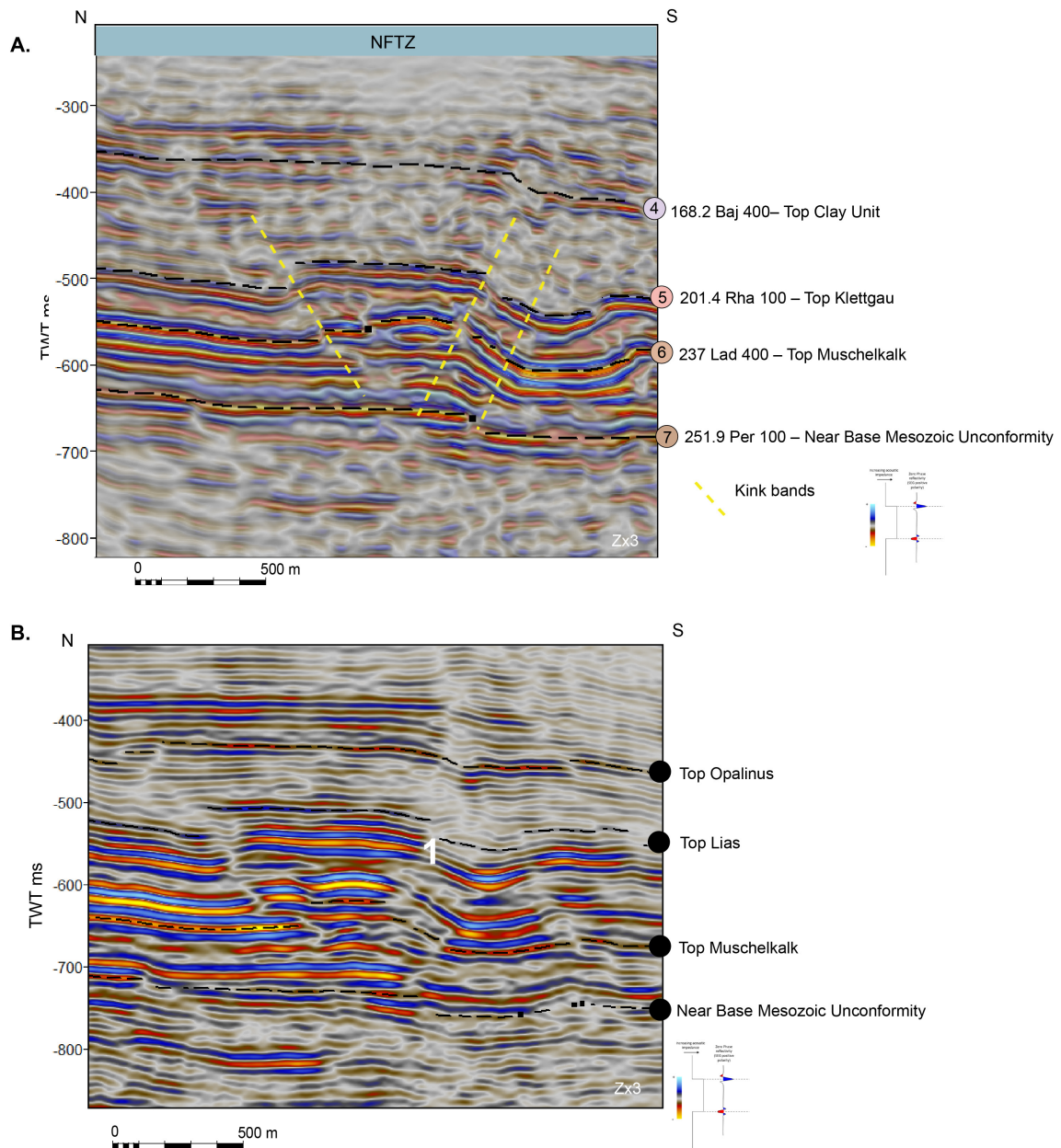


Fig. 5-41: Part of inline 5244 across the NFTZ showing box-fold structure

A. PreSTM-ref seismic data and B. QLP seismic data showing a geometry resembling a box-fold structure. The oppositely dipping, conjugate axial surfaces of the kink bands imaged by seismic data define a shallow depth to detachment that is clearly incompatible with deeply rooted faulting. Structures closely resembling the geometry of the Northern Fold-and-Thrust Zone were produced by sandbox analogue modelling (Schori et al. 2021). This modelling also suggests that viscosity contrasts within the multi-layered Mesozoic sequence played a minor role in the development of the NFTZ. Note that in the QLP seismic data, at back-thrust position (1), the reflections are more continuous, suggesting just folding and no faulting (offset at Top Lias appears to be related to horizon mispick).

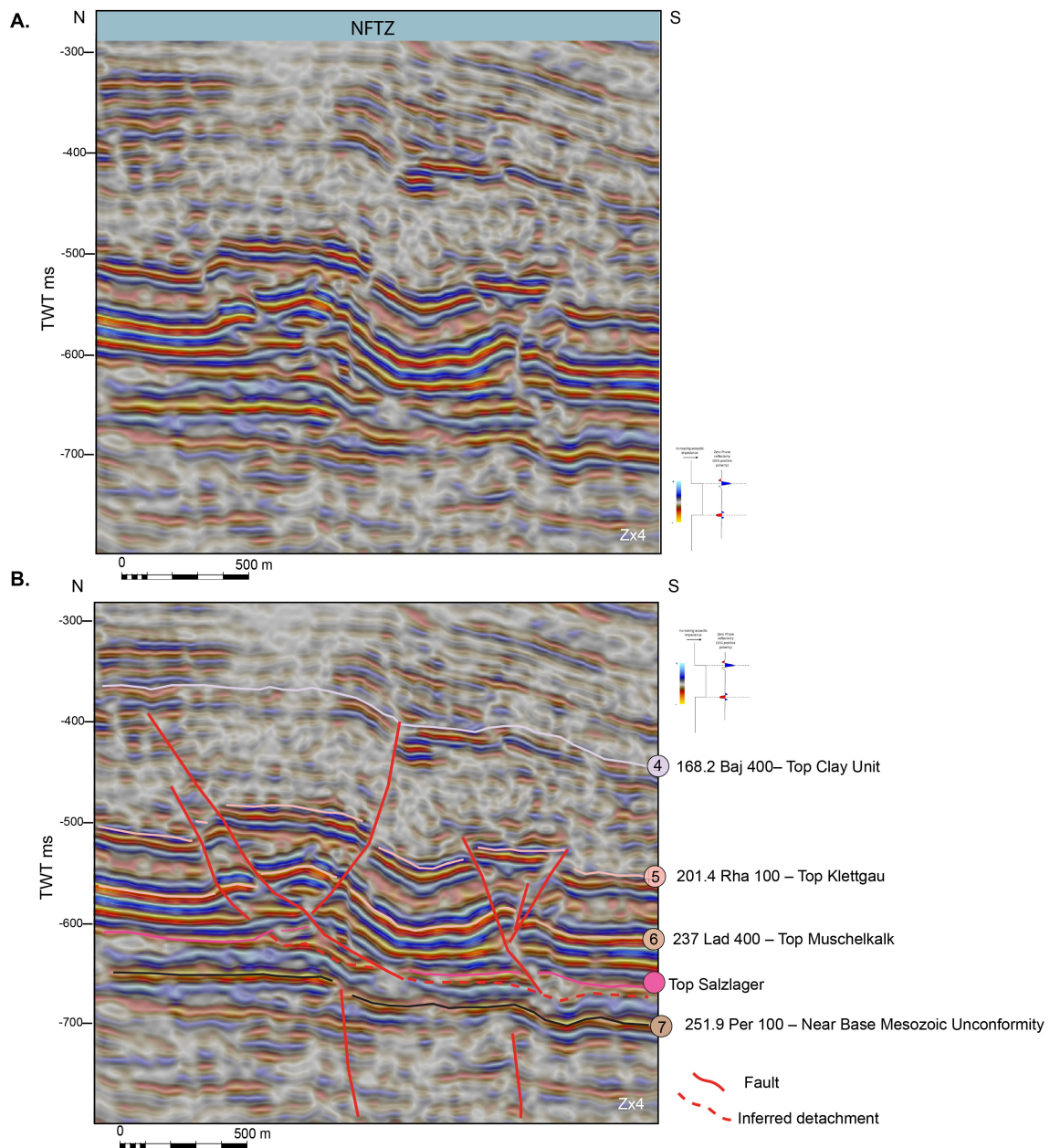


Fig. 5-42: Part of inline 5239 showing the relationship of thrusting and deeper fault

The thrust affecting the Mesozoic sequence (red dashed line) appears to flatten within the Triassic evaporite interval (Salzlager) with no obvious direct linkage with the S-dipping fault observed in the underlying Permo-Carboniferous Trough (below horizon 251.9 Per 100) A. Uninterpreted and B. Interpreted. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The WSW-ENE elongated highly non-cylindrical structures and intense fault segmentation are further compartmentalised in subdomains by NW-SE-trending high-angle faults (i.e. Eglisau Fault and Zweidlen Fault; Fig. 5-43, Nagra 2019, Zambrano et al. 2024). Their geometric complexity is displayed by vertical and lateral segmentation patterns, which show no consistent offset along strikes and above and below the Opalinus Clay. In the Mesozoic succession, these faults display a reverse sense of displacement and appear to be rooted in deeper grains offsetting the Permian and Carboniferous strata, suggesting a reactivation (inversion) of pre-existing normal faults (Fig. 5-43, Fig. 5-44, Schöpfer et al. 2023, Zambrano et al. 2024).

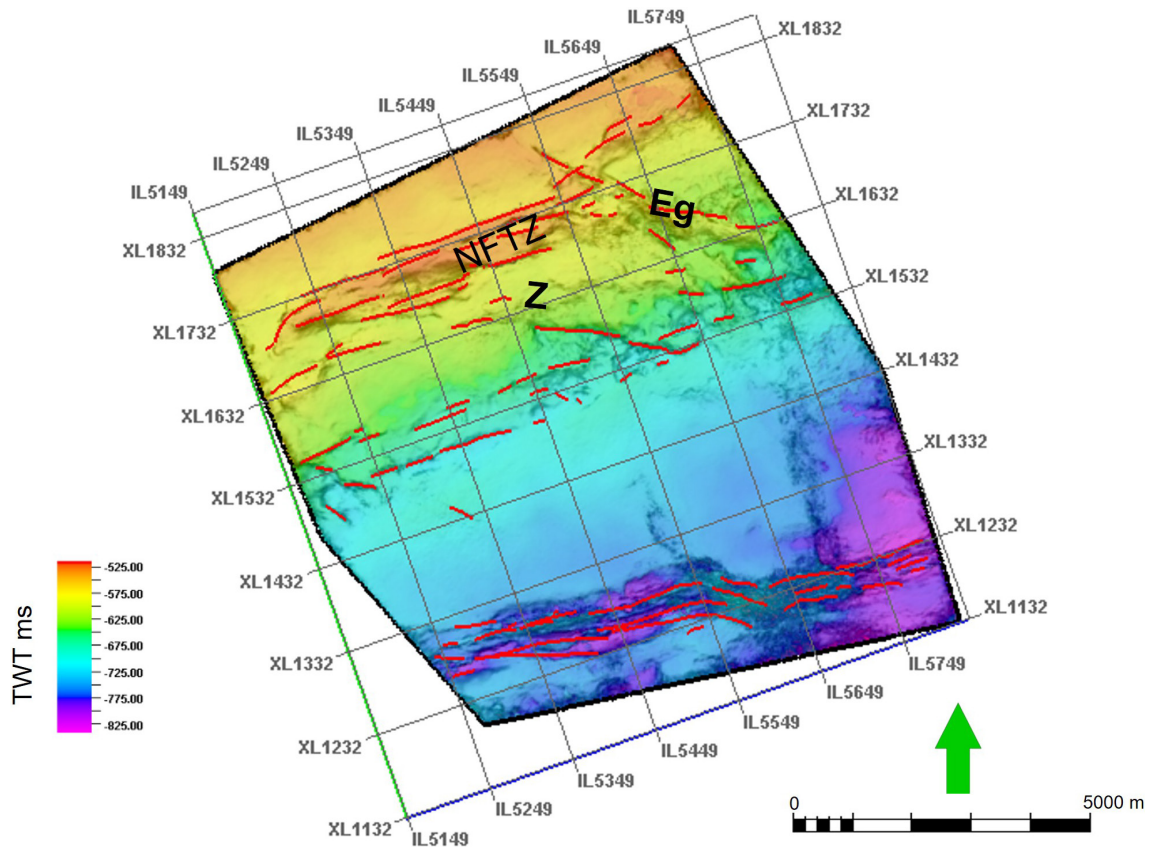


Fig. 5-43: The NFTZ is characterised by WSW-ENE elongated, highly non-cylindrical structures and intense fault segmentation

NFTZ subdomains originate by compartmentalisation through the NW-SE-trending high-angle Eglisau Fault (Eg) and Zweidlen Fault (Z).

237 Lad 400 – Top Muschelkalk TWT Top Structure map overlaying variance horizon slice. Fault traces at Top Muschelkalk shown as red lines.

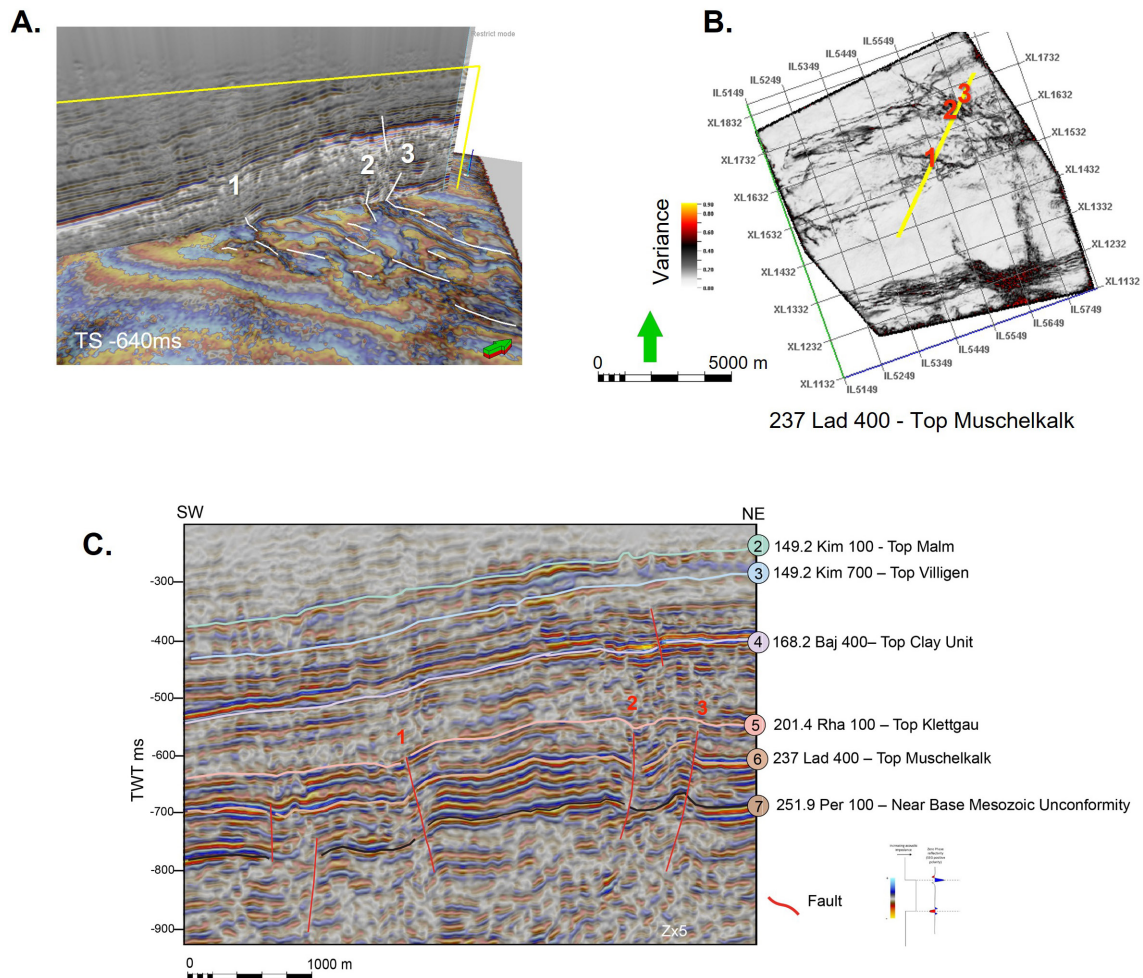


Fig. 5-44: Seismic display of the Eglisau and Zweidlen faults

A. 3D display of a random line (PreSTM-ref zero-phase reflectivity + outcrop look) and time slice -640 ms TWT (PreSTM-ref zero-phase, instantaneous phase + variance) with fault sticks / traces; B. 237 Lad 400 – Top Muschelkalk variance showing random line location and C. Random line (PreSTM-ref reflectivity + relative acoustic impedance) perpendicular to the NW-SE fault system showing NW-SE faults (i.e. Eglisau (2 and 3) and Zweidlen (1)), which display a reverse sense of displacement and appear to be rooted in deeper grains offsetting the Permian and Carboniferous strata, suggesting a reactivation (inversion) of pre-existing normal faults. Green arrow points toward north.

5.3.1.3 Weiach-Glattfelden-Eglisau Structure

The transition zone between the gently dipping panel of the Northern Fold-and-Thrust Zone and the subhorizontal to gently folded Mesozoic rock panel to the south corresponds with the Weiach-Glattfelden-Eglisau Structure (WGE) (Fig. 5-32, Fig. 5-33, Fig. 5-34, Fig. 5-35, Fig. 5-37), a predominantly WNW- and ENE-striking, high-angle structural element interpreted in NAB 18-35 (Nagra 2019) as a fault zone of regional relevance. In accordance with NAB 18-35 (Nagra 2019), the segmented nature of the WGE is clearly imaged by discontinuity attributes in map view (Fig. 5-43). At the Muschelkalk level, from west to east, arrays of fault segments can be seismically identified with segment lengths ranging from 300 m to 1 km (Fig. 5-43), and circular to oval features can be observed. These circular depressions (Fig. 5-23, Fig. 5-24) were previously interpreted as features associated with polygonal faults and possibly related to dissolution NAB 18-35 (Nagra 2019). These features were discussed in Section 5.2.5 (Fig. 5-15) and are interpreted to represent, at Top Muschelkalk, imprints associated with the complex depositional architecture of the overlying Bänkerjoch anhydrites (Fig. 5-23, Fig. 5-24). Vertically, the relatively high-angle faults mostly terminate below the 174.7 Toa 100 – Top Lias (i.e. Base Opalinus Clay; Fig. 5-32, Fig. 5-33, Fig. 5-34, Fig. 5-35). Only a few major segments affect the upper confining units, but they appear to be soft linked through the Opalinus Clay (Fig. 5-34). As observed for the Northern Fold-and-Thrust Zone, the WGE can also be subdivided into subdomains at intersections with NW-SE faults (Fig. 5-43, Fig. 5-44). Specifically, the Zweidlen Fault (Fig. 5-45) represents a key structural boundary in the stratigraphic interval above the Opalinus Clay, which separates a western compartment, where faults preserve the WGE WNW-ENE direction, from an eastern compartment dominated by NW-SE-trending faults, subparallel to the Zweidlen and Eglisau faults. This NW-SE fault trend is proposed to propagate across the upper Mesozoic interval as also proposed by Schöpfer et al. 2023 (Fig. 5-46).

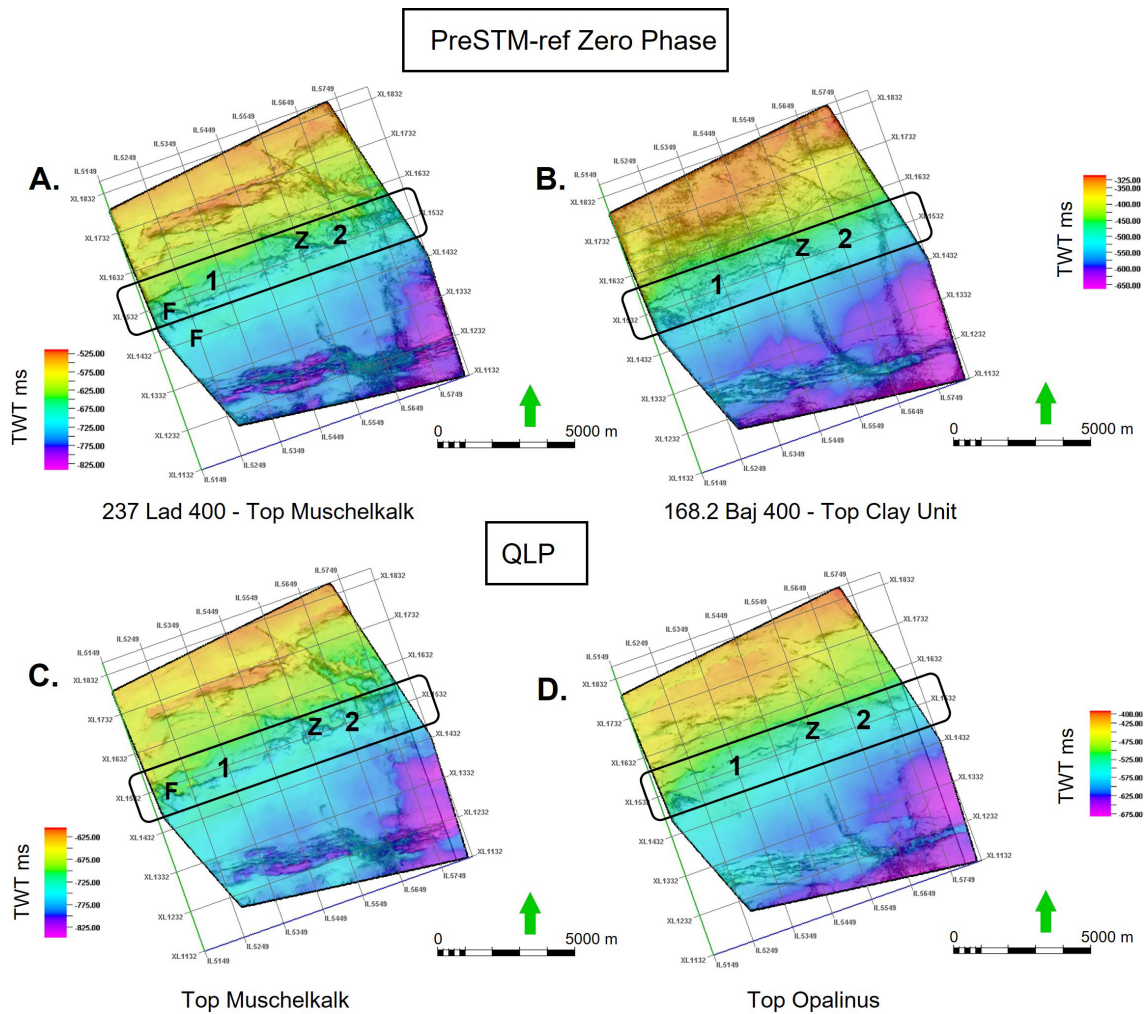


Fig. 5-45: Segmentation of the Weiach-Glattfelden-Eglisau Structure (WGE)

The WGE is not a continuous WSW-ENE structure even at deeper stratigraphic levels (i.e. at Top Muschelkalk): A. PreSTM-ref zero-phase, and C. QLP where NW-SE-trending faults play a key role in structure segmentation. Even more, the WGE can be subdivided by the Zweidlen fault (Z) into a western compartment (1) dominated by WSW-ENE segments and an eastern compartment (2) dominated by NW-SE-trending faults (subparallel to the Zweidlen and Eglisau faults). Such a trend is also observed at the easternmost corner of the WGE structure (F), suggesting a more articulated architecture along the strike. A. TWT Top Structure map of 237 Lad 400 – Top Muschelkalk overlaying variance horizon extraction (PreSTM-ref); B. TWT Top Structure Map of 168.2 Baj 400 – Top Clay Unit overlaying variance horizon extraction (PreSTM-ref); C. TWT Structure map of Top Muschelkalk structure overlaying variance horizon extraction (QLP; interpretation, Nagra 2019); D. TWT Structure map of Top Opalinus overlaying variance horizon extraction (QLP; interpretation, Nagra 2019).

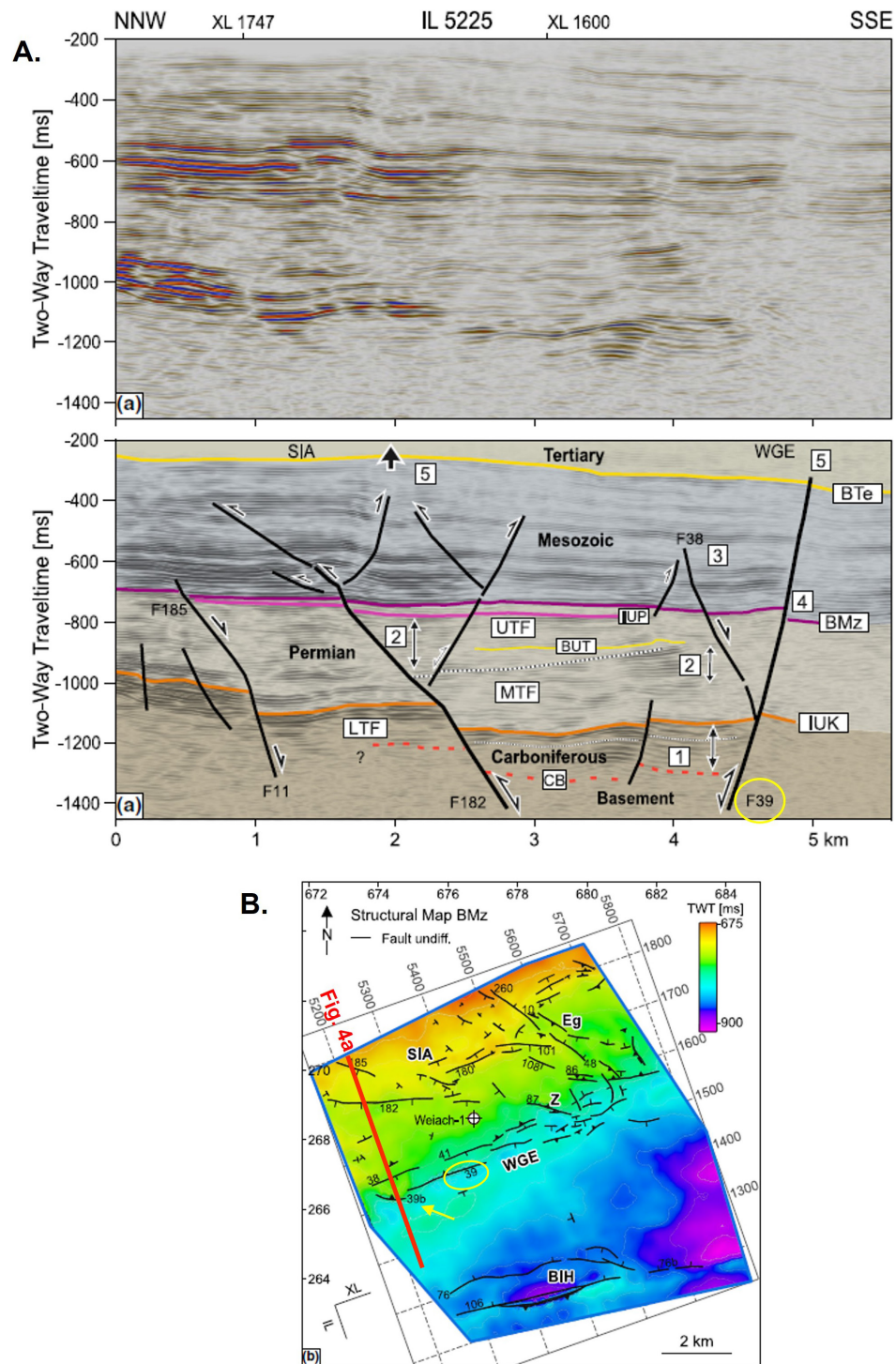


Fig. 5-46: Fault segment mislabelled by Schöpfer et al. 2023 along the Weiach-Glattfelden-Eglisau Structure (WGE)

Seismic section (A.) from Fig 4a of Schöpfer et al. 2023 (inline 5225) suggesting that fault 39 (yellow oval on seismic section and on map view) is affecting the upper interval of the Mesozoic succession. The reproduced structural map (B.) from Schöpfer et al.2023 (their Fig. 6b) clearly shows that the inline 5225 is not crossing the fault coded 39 (yellow oval), but a NW-SE-striking fault segment (39b, yellow arrow). The fault labelled as 39 in the seismic inline corresponds to fault 39b. Mislabelled fault code (39 in the section) would imply a different fault orientation (WSW- ENE).

5.3.1.4 Undisturbed Central Panel

The Undisturbed Central Panel (UCP) is bounded to the south by the most external (northern) thrust front of the SFTZ (Top Villigen level) and to the north by the flexure associated with the southern extension of the WGE (Fig. 5-32, Fig. 5-33, Fig. 5-34, Fig. 5-35, Fig. 5-37). On the seismic discontinuity attribute maps, the UCP is characterised by a very continuous response disrupted only by the presence of wash-out zones associated with Quaternary valley imprints and the processing anomaly to the southeastern corner (Fig. 5-1, Fig. 5-6). No seismic-scale faults were observed and mapped within this area, apart from the NW-SE-striking fault in the Stadlerberg region (Fig. 5-47). This NW-SE-trending minor fault does not propagate into the Liassic interval. At the 237 Lad 400 – Top Muschelkalk horizon, it can be seismically traced for a length of ~500 m. Consistently with the other NW-SE-trending faults observed in other structural domains (i.e. Eglisau and Zweidlen faults as well as the identified lateral ramps), this fault is interpreted to be related to an inversion of pre-existing Permian and Carboniferous normal faults (Fig. 5-46, Zambrano et al. 2024). Nevertheless, this short fault segment did not propagate upsection and remains vertically constrained within the Lower Mesozoic interval.

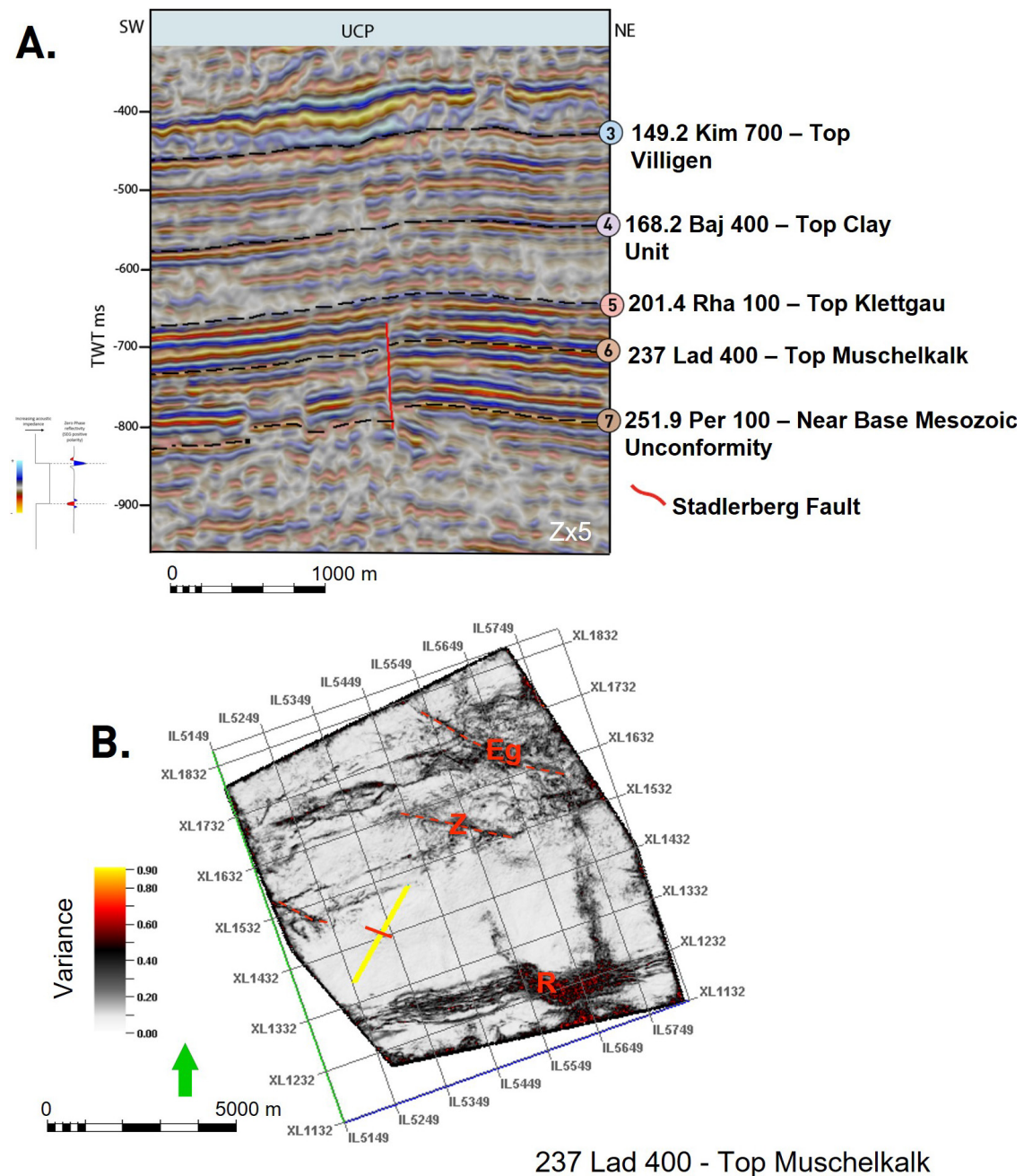


Fig. 5-47: Within the Undisturbed Central Panel (UCP), only one clear seismic discontinuity matches the seismic criteria and can be interpreted as a fault

A. Random line striking perpendicular to the Stadlerberg Fault (PreSTM-ref reflectivity + relative acoustic impedance) showing the vertical propagation of the seismic discontinuity, which does not affect the Liassic interval. B. 237 Lad 400 – Top Muschelkalk variance with the major NW-SE-trending fault polygons including the minor Stadlerberg Fault. Yellow line is the random section shown in A. Eg represents the Eglisau Fault, Z represents the Zweidlen Fault, R represents the SFTZ lateral ramp illustrated in Fig. 5-38.

The continuous seismic response is characteristic for this area in all the seismic vintages (Fig. 5-48). Some chaotic clusters of discontinuities are observed in the PreSDM-A horizon extractions, which correlate to velocity anomalies associated with Quaternary morphologies that were not properly corrected (Fig. 3-5).

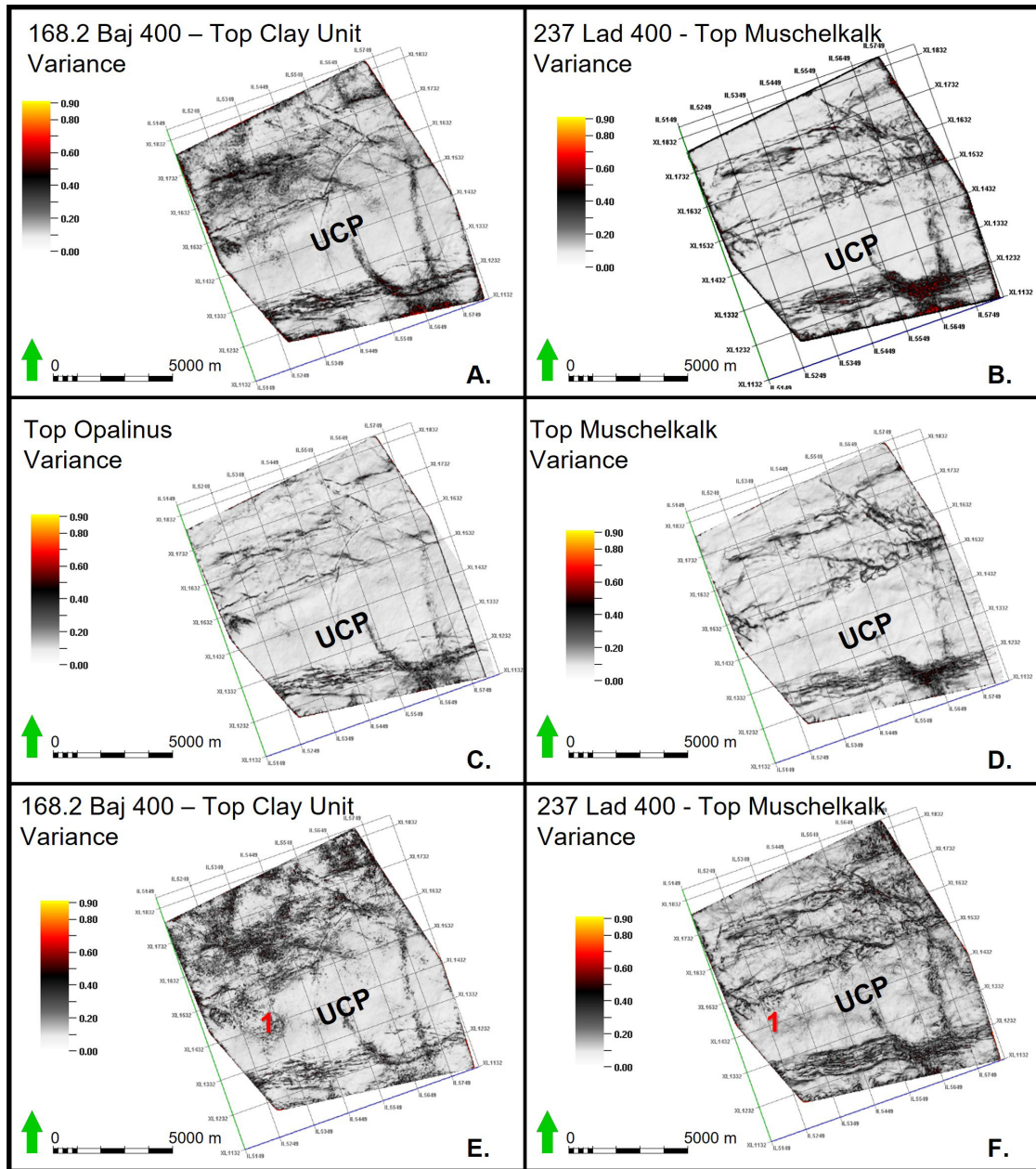


Fig. 5-48: Comparison of two key variance horizon slices for the three seismic vintages 237 Lad 400 – Top Muschelkalk and 168.2 Baj 400 – Top Clay Unit (Top Muschelkalk and Top Opalinus, respectively for QLP vintage).

A. and B. PreSTM-ref zero-phase; C. and D. QLP; E. and F. Pre-SDM-A. Note the consistent seismic response and the lack of major discontinuities (apart from the wash-out zones associated with Quaternary valley imprints) within the UCP. Only in the PreSDM-A is a round, mound-shaped feature visible. This is interpreted to represent an artefact associated with erroneous seismic velocity (low velocity anomalies) in the Stadlerberg area.

The observed absence of seismic-scale deformation can be structurally explained by the presence of the bounding Permo-Carboniferous faults, which act as a buttress and pin the Miocene (Jura-related) deformation. Nevertheless, subseismic deformation (cm-to-mm-scale shear planes) was documented at core scale in the wells within the UPC (Fig. 5-49, NTB 24-17 (Nagra 2024d)). In the investigated area, the Opalinus Clay did not act as a detachment level (Bond et al. 2023, Nagra 2024d), but rather as a decoupling layer between the structures in the lower competent panel and the upper competent panel. The bulk coaxial strain (homogeneous shortening) associated with the main Jura shortening phase may therefore be accommodated by localised non-coaxial deformation zones (i.e. shear planes) at meso- and microscales (i.e. at core scale) and does not result in the reactivation / formation of seismic-scale structures.

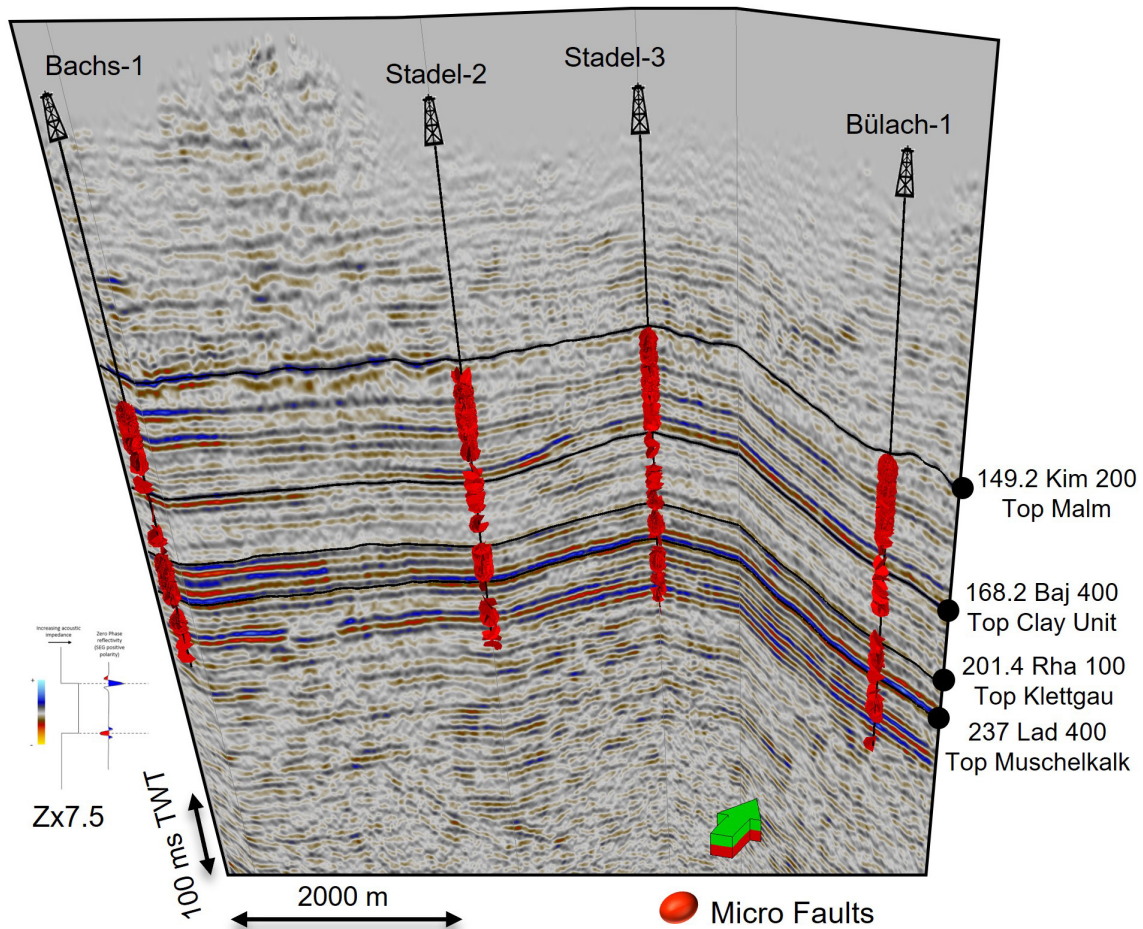


Fig. 5-49: 3D display of seismic and wells with core microstructure interpretation across the UPC

Seismic display is PreSTM-ref reflectivity. Note the consistent density of the microstructure across the wells with vertical intensity driven by mechanical, but consistently distributed above and below the host rock, suggesting that the Opalinus Clay did not act as a detachment level but rather as a decoupling layer between the structures in the lower competent panel and the upper competent panel. The bulk coaxial strain (homogeneous shortening) associated with the main Jura shortening phase could therefore be accommodated by localised non-coaxial deformation zones (i.e. shear planes) at meso- and microscales (i.e. at core scale) and does not result in the reactivation / formation of seismic-scale structures.

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 Fig. 4-15; Faleide et al. 2021) and 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 derives directly from the actual seismic data, e.g. resolution (i.e. depth interval where the faults are picked) and from fault imaging itself that makes it easier to identify larger faults 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, Alcalde 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 2015a, 2015b, Alcalde et al. 2019, Schaaf & Bond 2019). Specifically, considering that the reference seismic data are time-migrated data and therefore do not fully take into account ray bending in the overburden, the seismic events could be laterally mispositioned. Subjective uncertainties or human biases 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 2015a, 2015b, 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 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. For a small critical area in the central part of the seismic coverage, this qualitative approach was complemented by a 3D image ray tracing calculation where estimation of Δ -Easting and Δ -Northing error / positioning was determined by means of ray bending. The distance between fault seismic signatures was manually calculated among the different vintages, both in vertical sections and in variance key horizon slices. Mispositioning ranges are ~35 m (for steep faults) when comparing the PreSTM-ref with PreSDM (Fig. 6-1 and Fig. 6-2). The image ray bending in the NL-16 3D PreSTM images (central area seismic coverage) was not analysed / modelled explicitly for lateral positioning NAB 24-09 (Nagra 2024f) since it is based on a velocity model. While this simplifies the velocity complexity within the near surface (Quaternary and Tertiary), it can still provide a quantitative indication of the lateral positioning of seismic features. Values of estimated errors for key structural elements associated with the Weiach-Glattfelden-Eglisau Structure (WGE) are shown in Fig. 6-3. Note that higher uncertainty values coincide with areas below and near glacial channels, where the degraded seismic amplitudes result in a blurred image of the subsurface (Fig. 3-6). 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 the fault position by around 30 m to a maximum of 100 m relative to the PreSTM image. Calibration of a time-migrated seismic dataset with long horizontal and deviated wells from examples in the Middle East indicate that, even with complex overburden, the position of the faults versus fault cut-offs at the well generally do not exceed 50 m (Li et al. 2009, Hoch et al. 2010, Lorenzen et al. 2014, Zampetti et al. 2014b).

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

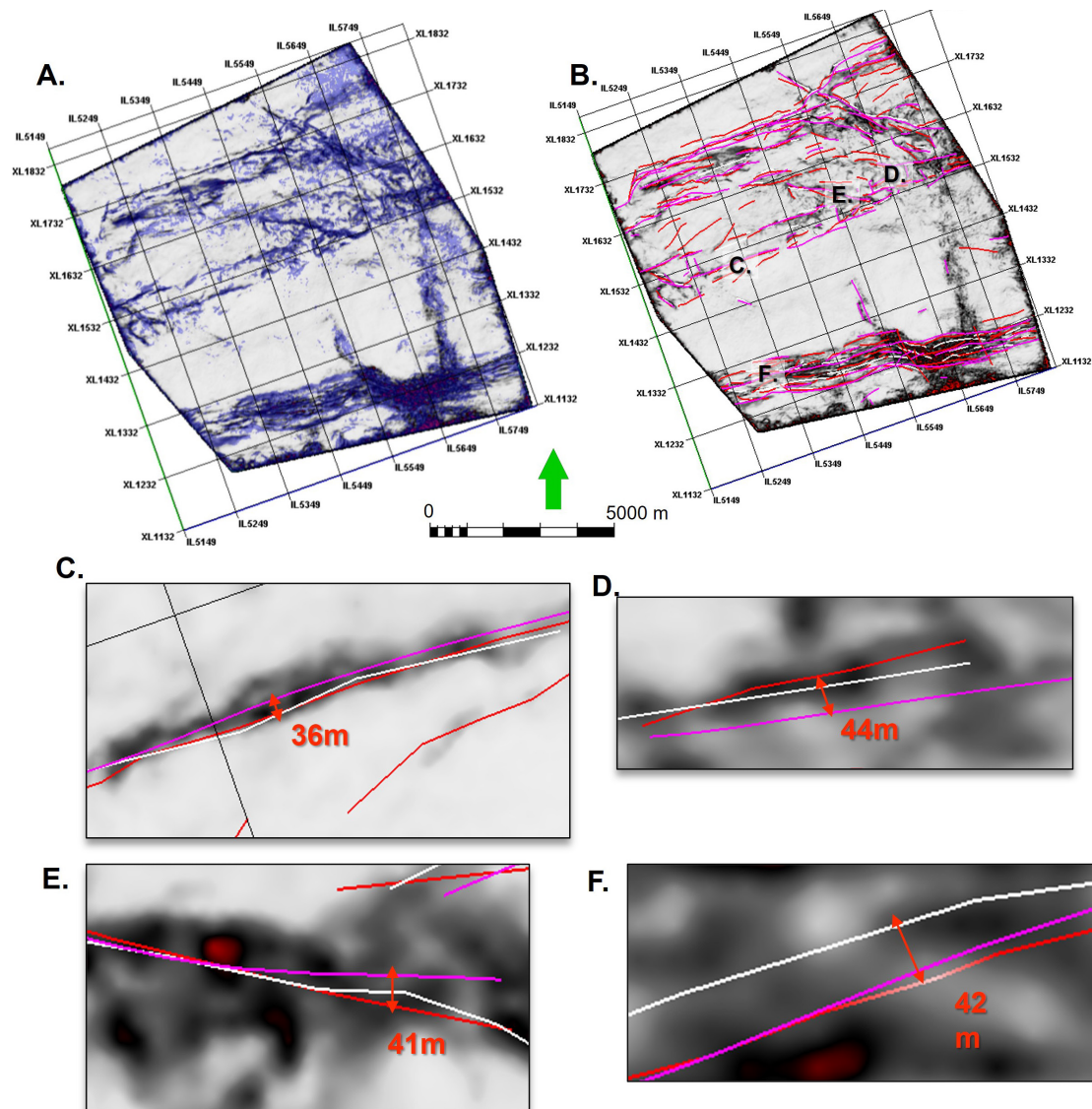


Fig. 6-1: Estimation of fault lateral position across the different seismic vintages

A. Overlying Top Muschelkalk (Lad 400) variance horizon slices extracted from PreSDM-A and PreSTM-ref, discontinuity in the PreSDM-A is plotted in blue over the black-and-white scale of the PreSTM-ref. B. PreSTM-ref Top Muschelkalk variance horizon slice with fault traces and structural lineaments at Top Muschelkalk (Lad 400) from different vintages: (1) NAB 18-35 in pink, (2) PreSDM-A ASR structural lineaments (undifferentiated faults and folds) in red and (3) PreSTM-ref fault traces in white. C. to F. Zoomed-in windows from B. at key fault locations to estimate lateral shifts of the fault traces among the different interpretation vintages. Zoomed-in window positions are shown in B. Note that zoomed-in windows do not have the same zoom-in scale.

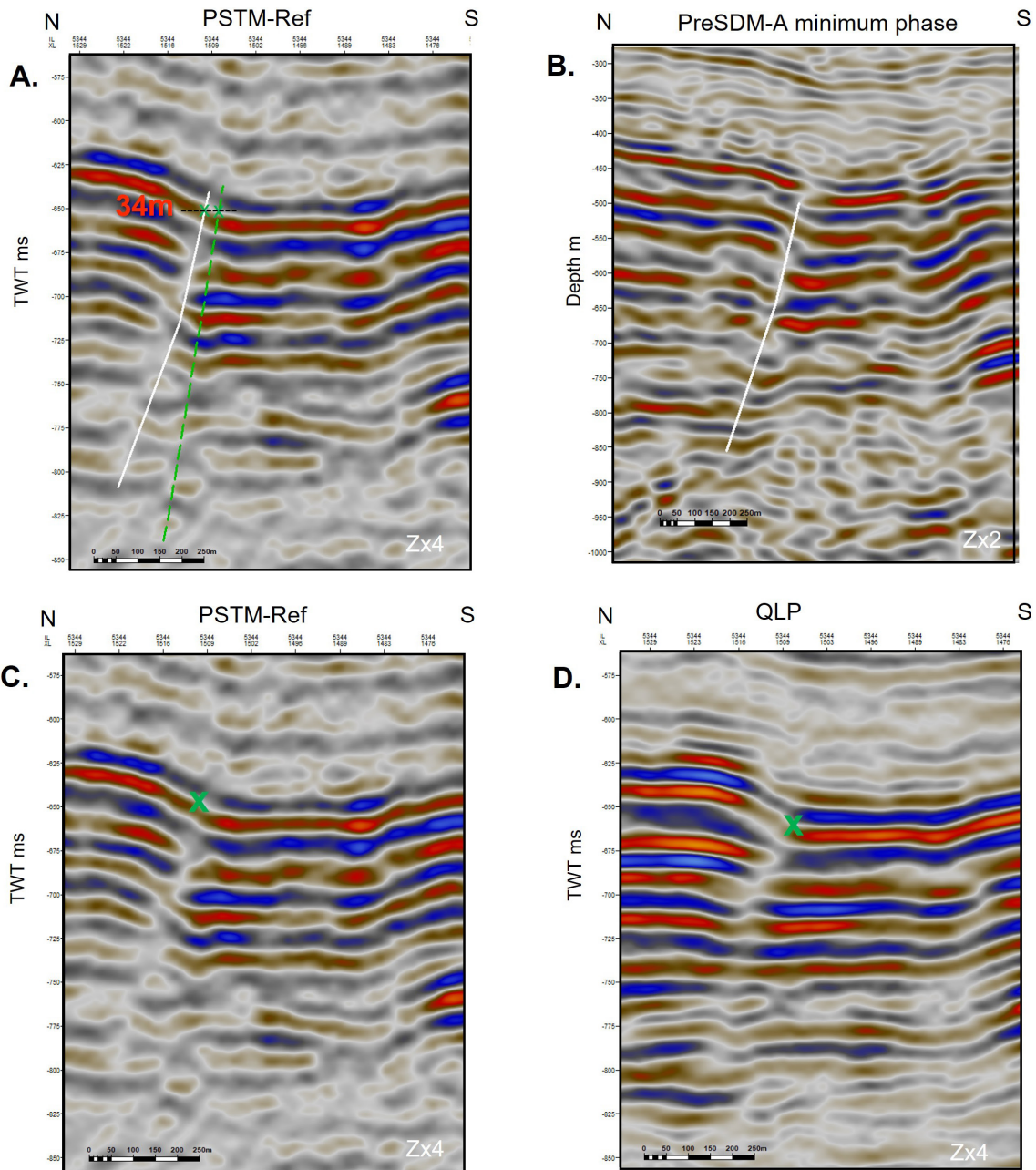


Fig. 6-2: Estimation of fault lateral position uncertainty across the different seismic vintages by comparing seismic fault signature across the different seismic data cubes

Example across the WGE, inline 5344. A. Comparison between fault interpretations from PreSTM-ref (white line) and NAB 18-35 QLP (green dashed line); B. Depth-converted fault from PreSTM-ref to PreSDM-A minimum-phase diagnostic (note a slight vertical shift due to both a different velocity model and a phase shift); C. and D. display QC of fault cut-offs (green cross) associated with fault signature. Note that the fault cut-offs (green arrow) are not positioned on the same side of the “dimmed displaced feature”. The estimated lateral uncertainty between the two TWT cubes is ~34 m (A.) because of the position of the fault cut-offs (C. and D.) and such value seems to account also for the “human component” of the uncertainty.

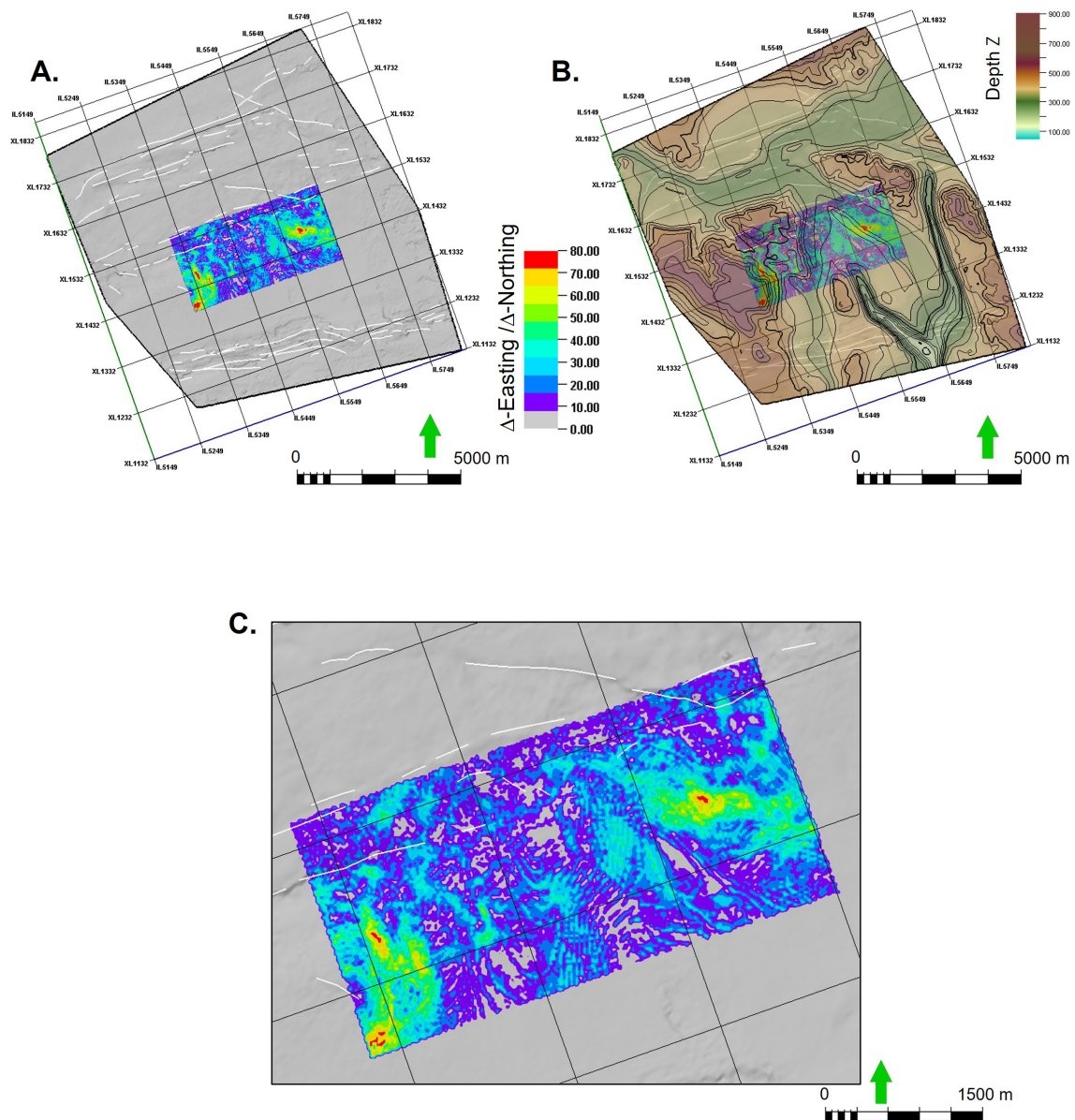


Fig. 6-3: 3D image ray tracing calculation generated for the central area of the NL-16 seismic survey, covering the central part of the WGE

Δ -Easting and Δ -Northing error / positioning estimation is calculated by ray bending, based on which a quantitative indication of the lateral positioning of seismic features can be deduced. A. 237 Lad 400 – Top Muschelkalk horizon extraction shows a general bulk distribution of Δ -Easting and Δ -Northing <50 m, but areas coincide with more complex Quaternary morphology (B.), where the error can reach 80 m. Zoomed-in images of 237 Lad 400 – Top Muschelkalk showing the interpreted faults (white lines) within the WGE are in areas with error values <30 m.

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 were produced (Tab. 6-1).

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

The fault interpretation in 2018 on the QLP seismic vintage (Fig. 5-36, Nagra 2019) was performed along a 5×5 interpretation seedline grid, and followed two interpretation criteria, resulting in the identification of two classes of faults, namely class A and class C faults. The identification of class A faults relied on a first-order criterion of reflection discontinuity in the seismic sections, i.e. (i) as a reflection displacement or (ii) as the presence of a narrow flexure, solely, for at least one of the mapped horizons and on a minimum of two neighbouring seedlines (Nagra 2019). The traces of the faults identified during the manual seedline interpretation were subsequently also mapped on relevant time slices of seismic amplitude cubes, as well as on horizon extracts of seismic attribute volumes. The class C faults were considered as less robust since the structures were solely mapped based on seismic attribute response. These structures showed hardly any fault throw and narrow flexure in the seismic amplitude sections but a consistent expression in seismic attribute maps (Nagra 2019).

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

Interpretation Vintage	Seismic Data	Workflow	Products	Interpreter
NAB 18-35	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-A 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 23-18	PreSTM-ref zero-phase	3D interpretation → sections and attribute horizon slices	3D fault sticks/planes Fault traces at key horizons	Interpreter B Contractor

In 2022, the same fault interpretation criteria, as defined for the 2018 interpretation of the QLP seismic vintage (Nagra 2019), were used by the same interpreter contractor (see Tab. 6-1) in the fault interpretation carried out on the PreSTM-ref minimum-phase seismic vintage (Fig. 6-4). 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 within the Undisturbed Central Panel.

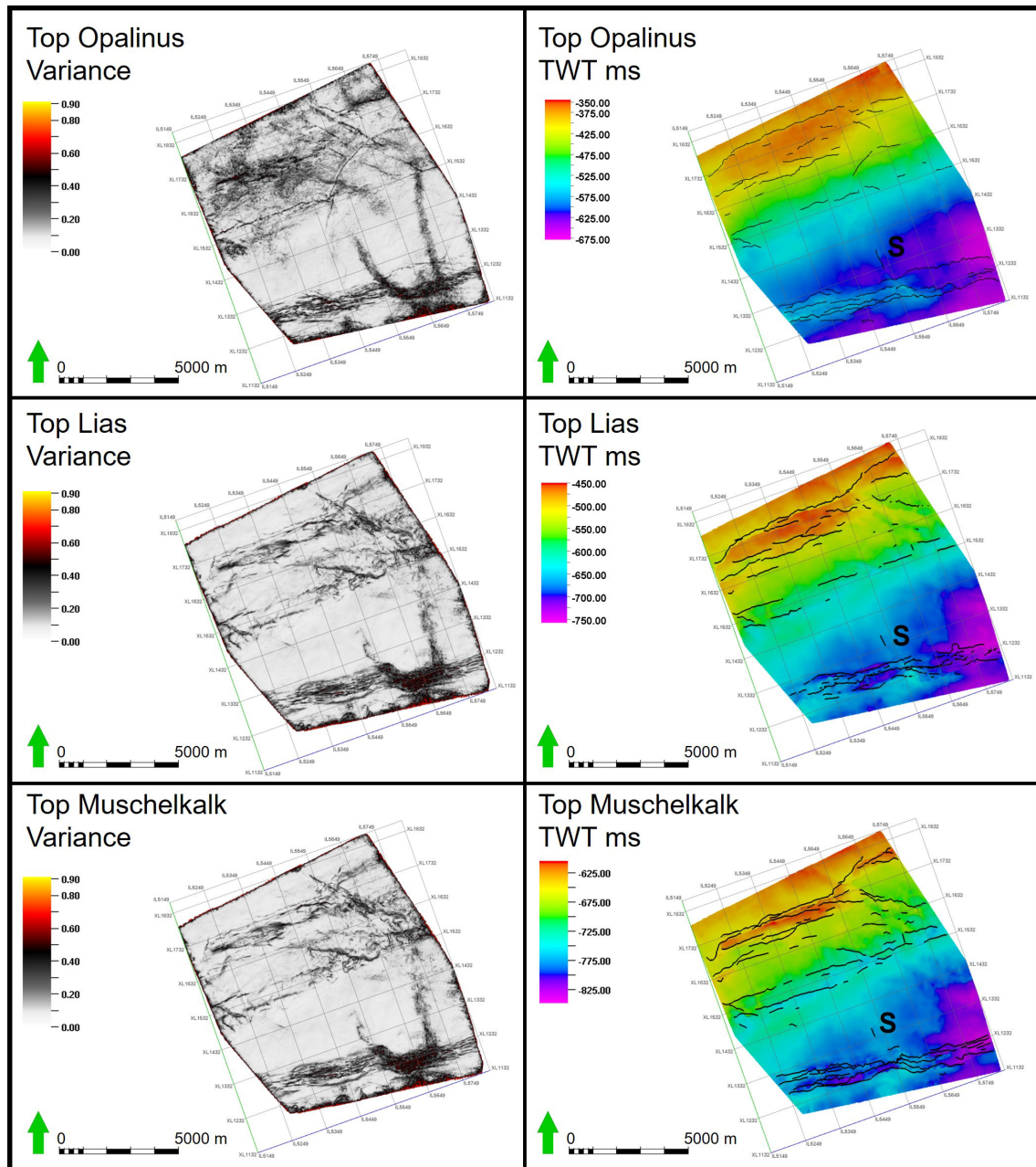


Fig. 6-4: Fault interpretation matrix - PreSTM-ref minimum-phase (interpreter A - only fault class A)

Similar figure matrix to Fig. 5-28, Fig. 5-29 and Fig. 5-31 (variance horizon slices and TWT top structure). Black lines are fault polygons.

Note how the Strassberg Lineament (S) is reduced in length and shows a different shape at the Top Muschelkalk level compared to Fig. 5-36 (same interpreter as for QLP).

As input for the ASR evaluation (Nagra 2022c), a structural interpretation was carried out based both on a PreSDM-A and PreSTM-ref minimum-phase seismic vintages (Fig. 5-28 and Fig. 5-29). The 3D screening approach was described in the methodology section (Fig. 4-8 and Fig. 4-9) and allowed the discrimination between (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 folds associated with fault-tip monoclines (drape-folds on top of blind normal or reverse faults; Fig. 5-30).

Fault maps for all the available interpretations (Tab. 6-1) were captured in a graphic matrix (Fig. 5-28, Fig. 5-29, Fig. 5-31, Fig. 5-36, Fig. 6-4). Interpretations from different interpreters and from different seismic processing vintages are displayed over the final interpretation proposed in this report (referred to as 2023) for easy comparison. When comparing all the interpretation results (Fig. 6-5, Fig. 6-6, Fig. 6-7, Fig. 6-8), it becomes clear that, despite uncertainties associated with seismic imaging (processing solutions) and human biases (different interpreters), the structural skeleton remains consistent and the lateral positioning shift of critical faults does not exceed 50 m (Fig. 6-1, Fig. 6-2, Fig. 6-3).

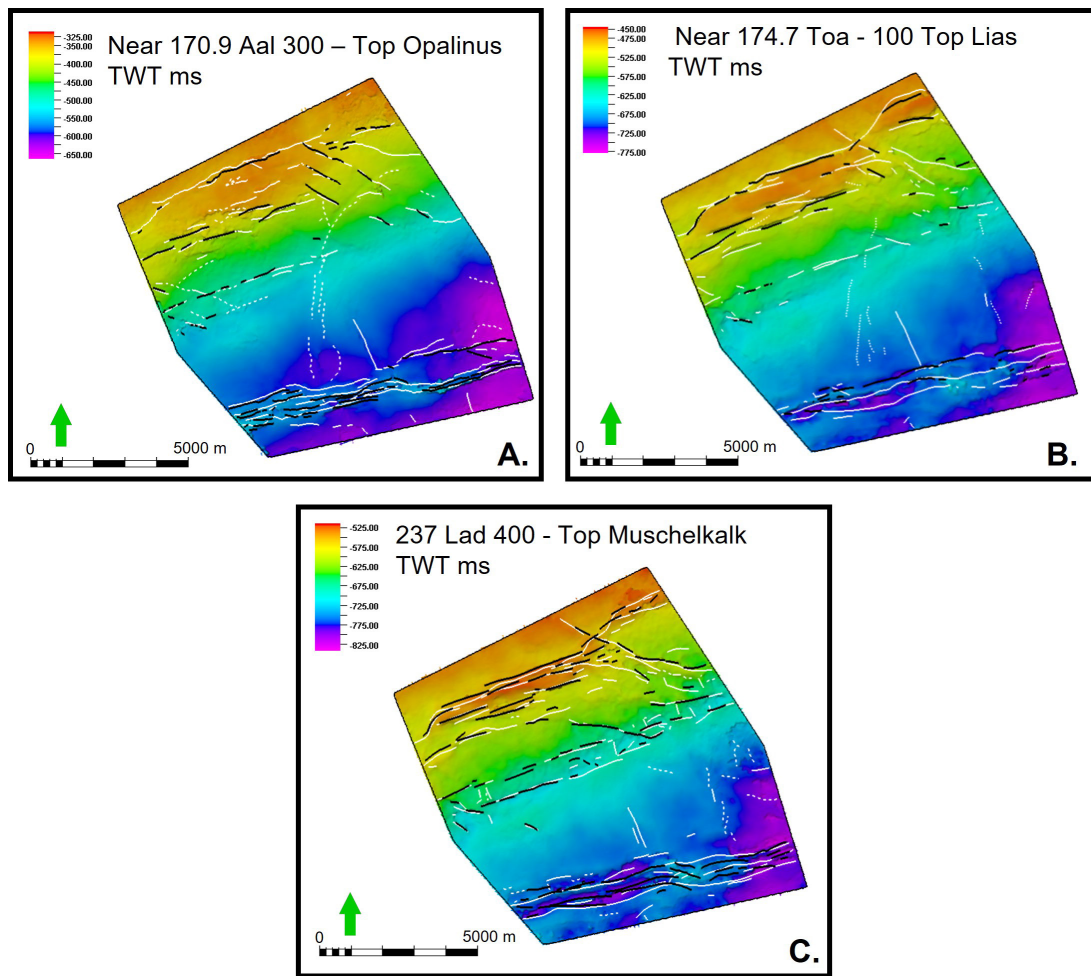


Fig. 6-5: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2018 QLP (NAB 18-35)

Overlay of 2023 fault traces (black lines = this report) and NAB 18-35 (white solid lines = fault class A, and white dashed lines = fault class C) for the three key stratigraphic levels A. 168.2 Baj 400 – Near Top Clay unit; B. 174.7 Toa 100 – Near Top Lias and C. 237 Lad 400 – Top Muschelkalk. Refer to Tab. 6-1 for seismic vintage and interpreter details.

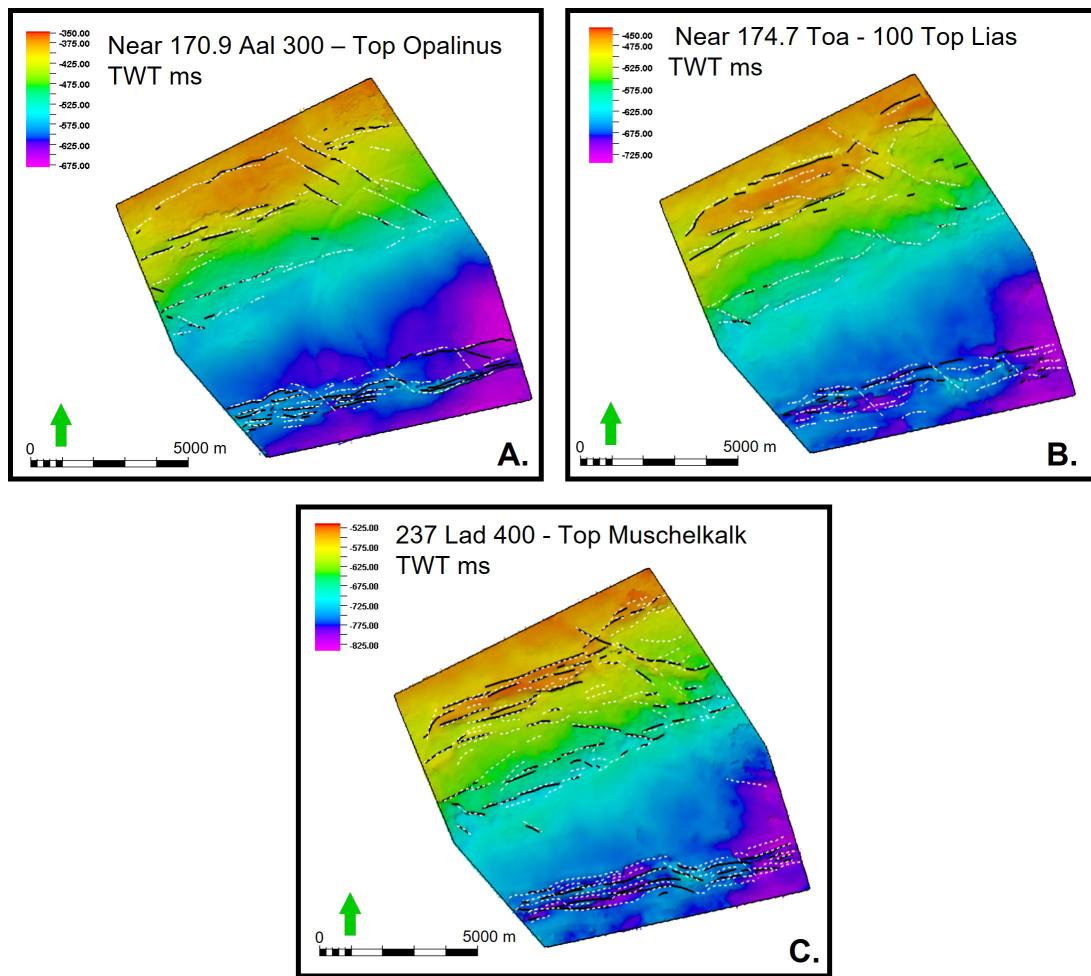


Fig. 6-6: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (ASR)

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. 168.2 Baj 400 – Near Top Clay unit; B. 174.7 Toa 100 – Near Top Lias and C. 237 Lad 400 -Top Muschelkalk. For the ASR, no distinction was made between structural lineaments faults and folds. Refer to Tab. 6-1 for seismic vintage and interpreter details.

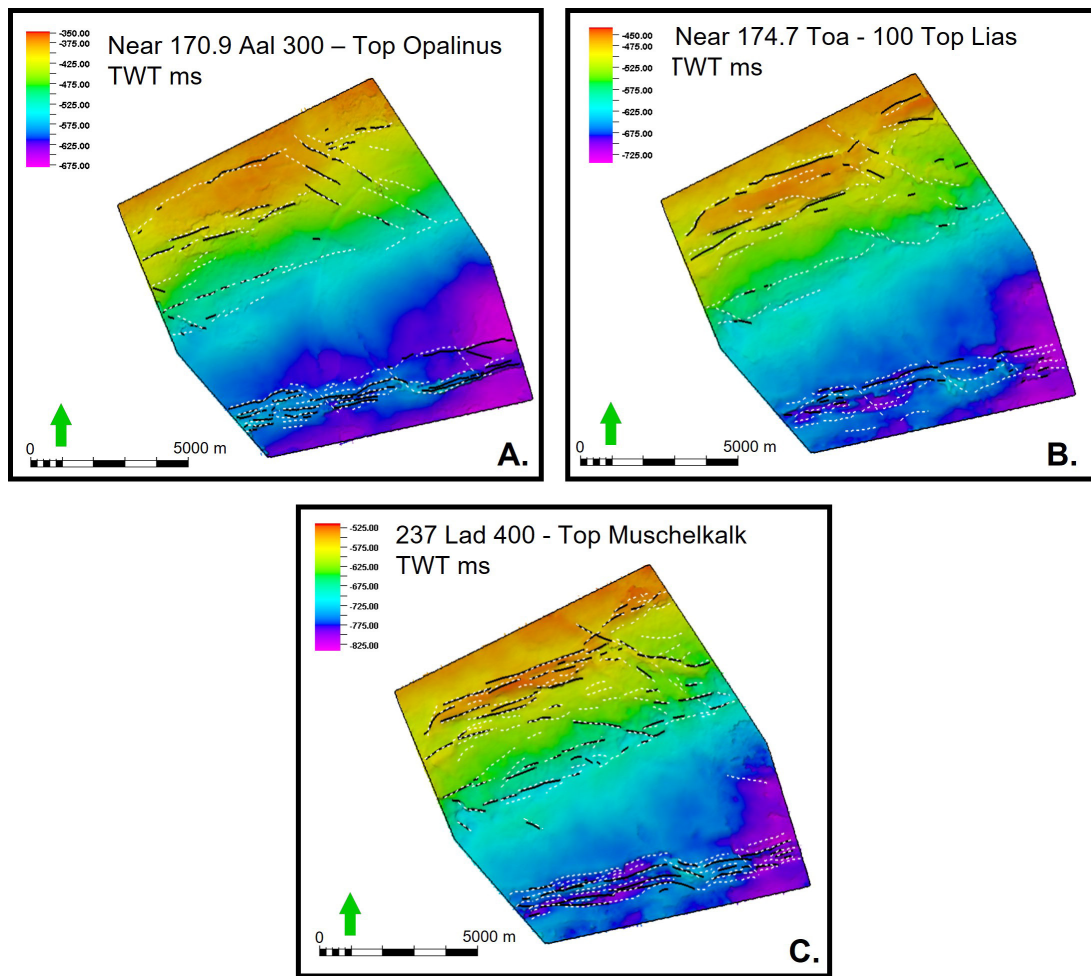


Fig. 6-7: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2021 PreSDM-A (Pre-ASR)

Overlay of 2023 fault traces (black lines = this report) and ASR structural lineaments (white dashed lines = PreSDM-A) for the three key stratigraphic levels. A. 168.2 Baj 400 -Near Top Clay unit; B. 174.7 Toa 100 – Near Top Lias and C. 237 Lad 400 – Top Muschelkalk. For the ASR, no distinction was made between structural lineaments faults and folds. Refer to Tab. 6-1 for seismic vintage and interpreter details.

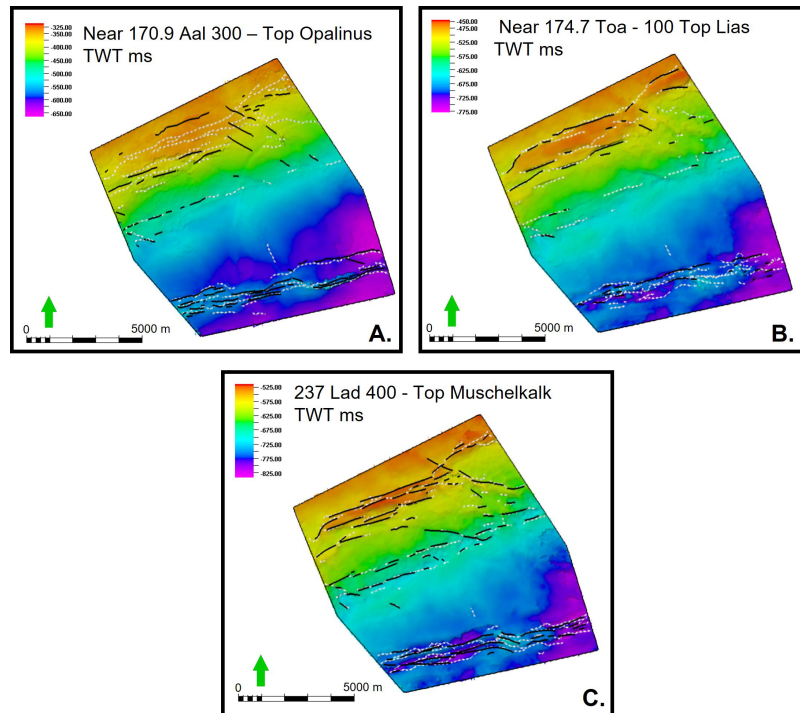


Fig. 6-8: Fault interpretation vintage comparison: 2023 PreSTM-ref zero-phase (this report) versus 2022 PreSTM-ref minimum-phase (interpreter A contractor)

Overlay of 2023 fault traces (black lines = this report) and 2022 (white dashed lines = PreSTM-ref minimum-phase class A faults only) for the three key stratigraphic levels. A. 168.2 Baj 400 – Near Top Clay unit; B. 174.7 Toa 100 – Near Top Lias and C. 237 Lad 400 – Top Muschelkalk. Different interpreters on PreSTM-ref data. Refer to Tab. 6-1 for seismic vintage and interpreter details.

Differences in the interpretation are mainly related to length and orientation of the single fault segments, but spatial distribution, density and patterns are comparable, as is the definition of the four structural domains provided in this report. In the undisturbed central area (UCP), the Stadlerberg fault is consistently interpreted as a feature within the lower confining unit, and it is consistently tipped up into the Liassic sequence (below Top Liassic; Fig. 6-9). Due to the low-quality seismic imaging, different scenarios were proposed for the seismic discontinuities underneath the two main Quaternary valleys. While for the easternmost washed-out zone, the interpretation as a fault was advocated only in the 2018 QLP interpretation and with very low confidence, the Strassberg Lineament was also mapped as a high-confidence lineament in the 2019 PreSTM-ref interpretation (Fig. 6-4). This lineament was described as a steeply dipping reflection discontinuity cutting through the marker horizons Top Gipskeuper to Base Tertiary but is not traceable down to the Base Mesozoic NAB 18-35 (Nagra 2019).

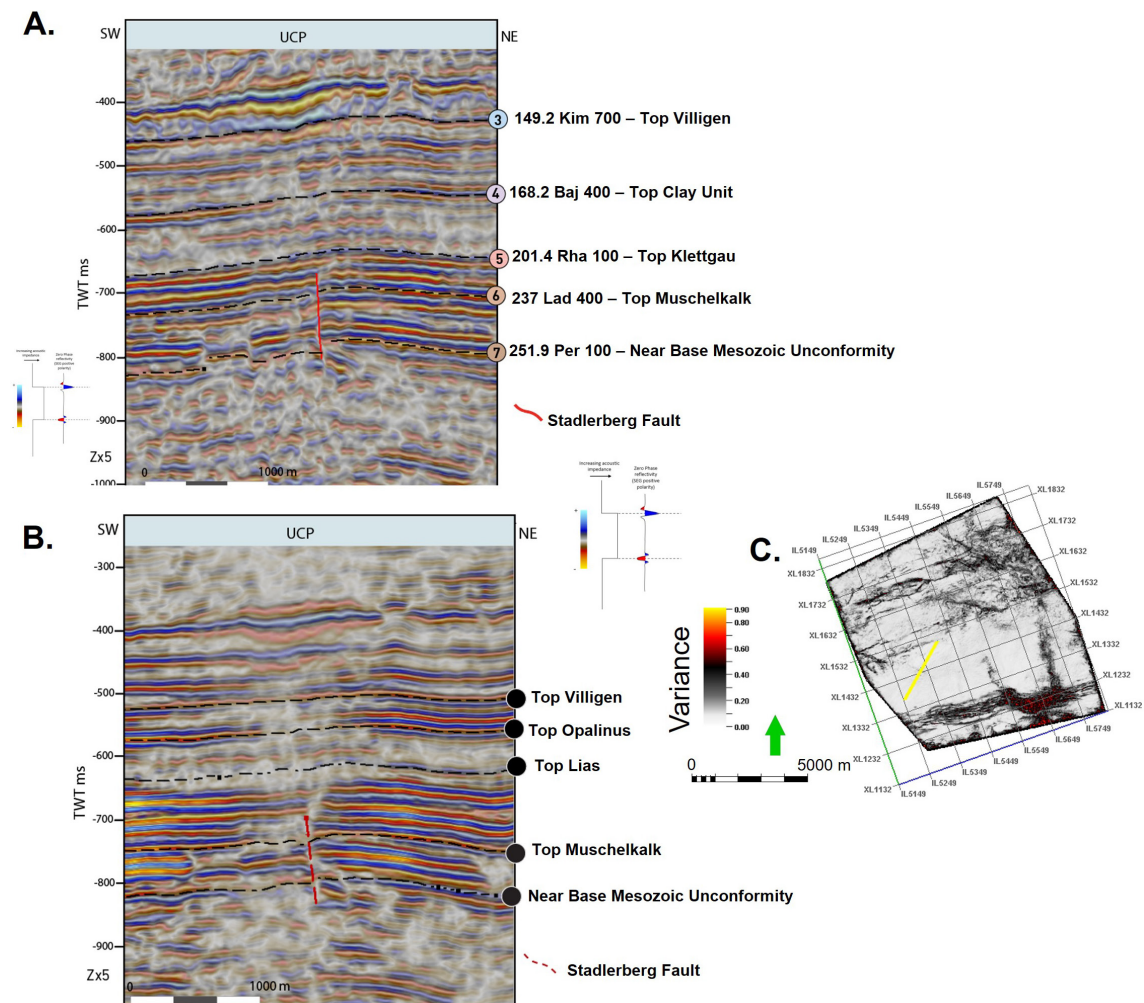


Fig. 6-9: “Stadlerberg fault”: comparison between 2023 and NAB 18-35 interpretations

A. Random line PreSTM-ref (reflectivity + RAI); B. Same line reproduced with NAB 18-35 (Nagra 2019) interpretation on QLP seismic cube (display reflectivity + RAI) and C. 237 Lad 400 -Top Muschelkalk variance horizon slice (PreSTM-ref) with the random line location. The seismic line was generated perpendicular to the lineament strike. Note that both interpretations vertically terminate the fault sticks below 201.4 Rha 100 – Top Liassic.

Alternatively, Schöpfer et al. (2023) propose a conflicting interpretation of the Strassberg Trough representing a deeper structural grain that does not affect the Mesozoic succession (Fig. 6-10). This further demonstrates the ambiguity of this feature. A detailed investigation was conducted during this study to reduce the uncertainty regarding the Strassberg Lineament. Evaluation of two 2D seismic lines cutting across the Strassberg Trough with different orientations (Fig. 5-9, Fig. 5-10, Section 5.1) provided evidence that the washed-out zone is most likely associated with a near-surface anomaly (i.e. Quaternary valley; Fig. 5-13). The southernmost segment of the Strassberg Trough seems to align with the interpreted NW-SE-trending ramp of the Southern Fold-and-Thrust Zone (Fig. 5-38, Fig. 5-8). The prolongation of this lineament into the undisturbed central domain (Strassberg Fault, NAB 18-35) implied, however, a forced change in the lineament direction from NW-SE to NNW-SSE, Fig. 6-10). Furthermore, considering that in the

NL siting region all the available fault interpretations (Fig. 5-28, Fig. 5-29, Fig. 5-31, Fig. 5-36, Fig. 5-44) have recognised two major fault trends (WNW-ESE and NW-SE) and that no other NNW-SSE-trending (even secondary) structures were imaged or documented, it could be concluded that the interpretation of the Strassberg Lineament as a fault seems quite unlikely.

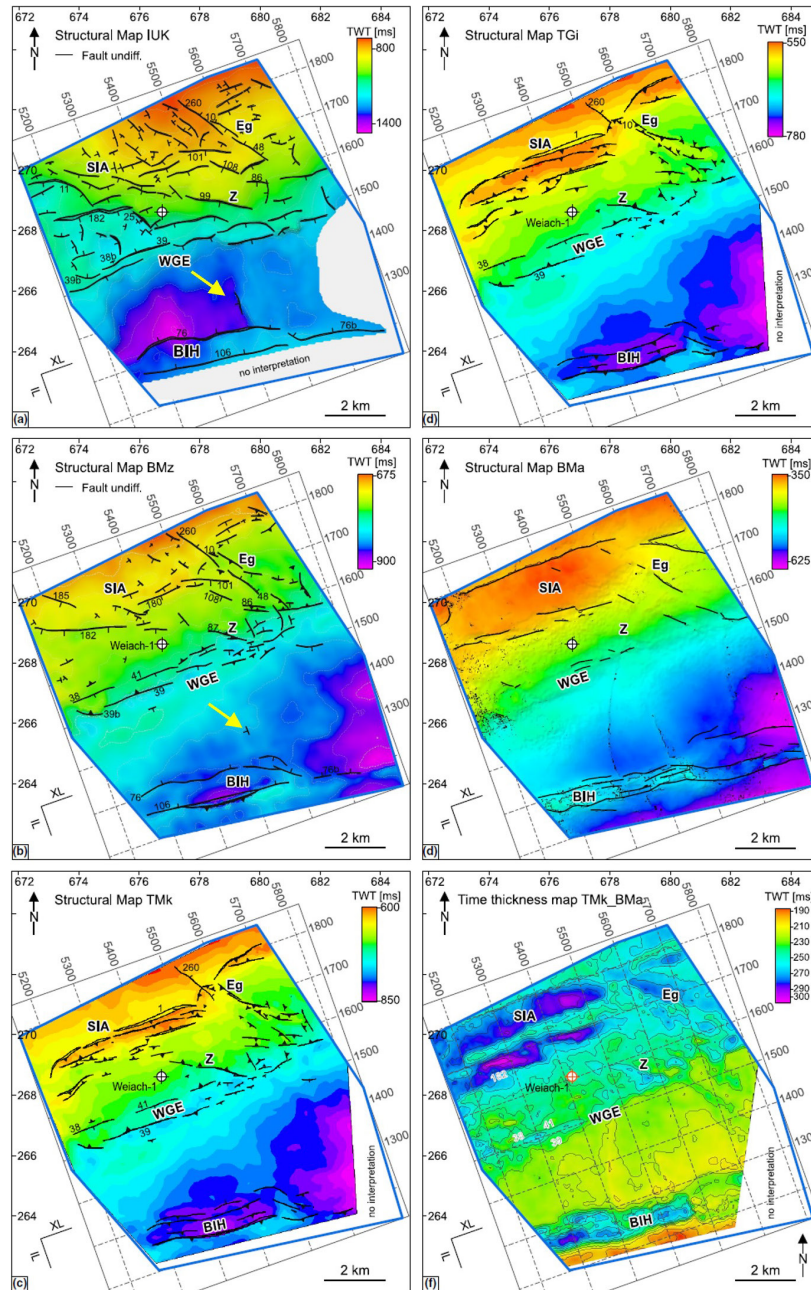


Fig. 6-10: The “Strassberg fault” as shown in Fig. 6 from Schöpfer et al. 2023

The lineament is seismically interpreted only at the deepest stratigraphic units (yellow arrows) and barely affects the Base Mesozoic unconformity. Horizon maps: (A) IUK (intra Upper Carboniferous), (B) Base Mesozoic (BMz), (C) Top Muschelkalk (TMk, top Middle Triassic), (D) Top Gipskeuper (TGi, Upper Triassic) and (E) Base Malm (BMa, Upper Jurassic), (F) Time-thickness map constructed for the interval between Base Upper Triassic (TMk) and Top Middle Jurassic (BMa) seismic horizons.

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 NL siting region. For this seismic evaluation, all the available seismic processing datasets were considered 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 for the evaluations (Tab. 3-1), the interpretation results were captured in the PreSTM-ref seismic dataset. The processing of the seismic datasets was designed such that all the processing input parameters and workflows were consistent across the three seismic surveys of the three siting regions. While this might not have resulted in the best processing approach for each of the individual seismic surveys, it best served the scope and objective of comparing the three siting regions through the availability of uniform seismic imaging.

A robust horizon-fault framework was established for the NL siting region which is comparable to the other siting regions. Confidence in the resulting subsurface image was bolstered by a detailed evaluation of the uncertainties associated with the interpretation of seismic data. Uncertainties and pitfalls associated with data quality were mitigated by the use and comparison of all the seismic processing vintages (Tab. 3-1), while the impact of human bias was assessed by the superimposition of all the available interpretations (Tab. 6-1). While length and orientation of the individually interpreted fault segments or tectonic lineaments might vary across the different interpretation products (Fig. 5-28, Fig. 5-29, Fig. 5-31, Fig. 5-36, Fig. 6-4), the distribution and density of the seismic-scale structural lineaments is consistent. A critical divergence in fault interpretation corresponds with the Strassberg Lineament (Nagra 2019). The challenge in the interpretation of this lineament lies in its position within an area of degraded seismic amplitudes associated with the presence of the Quaternary Strassberg Trough (Buechi et al. 2018). Variability in imaging across the seismic datasets (including 2D regional lines; Fig. 5-9, Fig. 5-10, Fig. 5-13) and structural geology considerations (e.g. change in Strassberg Lineament orientation from NW-SE to NNW-SSE; Fig. 6-9) indicates that the lineament interpreted in 2018 NAB 18-35 (Nagra 2019) is unlikely to represent a seismic-scale fault but is highly likely the result of a near-surface anomaly (seismic artefact).

The detailed seismic analysis showed that the NL region can be subdivided into four main structural domains: (i) the Southern Fold-and-Thrust Zone (SFTZ), (ii) the Northern Fold-and-Thrust Zone (NFTZ), (iii) the Weiach-Glattfelden-Eglisau Structure (WGE) and (iv) the Undisturbed Central Panel (UCP) and that the Opalinus Clay did not act as a detachment level (Bond et al. 2023, Nagra 2024d, Bond et al. 2024), but rather as a decoupling layer between the structures in the lower competent panel and the upper competent panel.

Such structural configuration resulted in the identification of a large seismically undisturbed area of 25 km² (Fig. 7-1). In this central area, within the Opalinus Clay interval, the bulk coaxial strain (homogeneous shortening) associated with the main Jura shortening phase is interpreted to be accommodated by localised non-coaxial deformation zones (i.e. shear planes) at meso- and microscales (i.e. at core scale) and does not result in the reactivation/formation of seismic-scale structures.

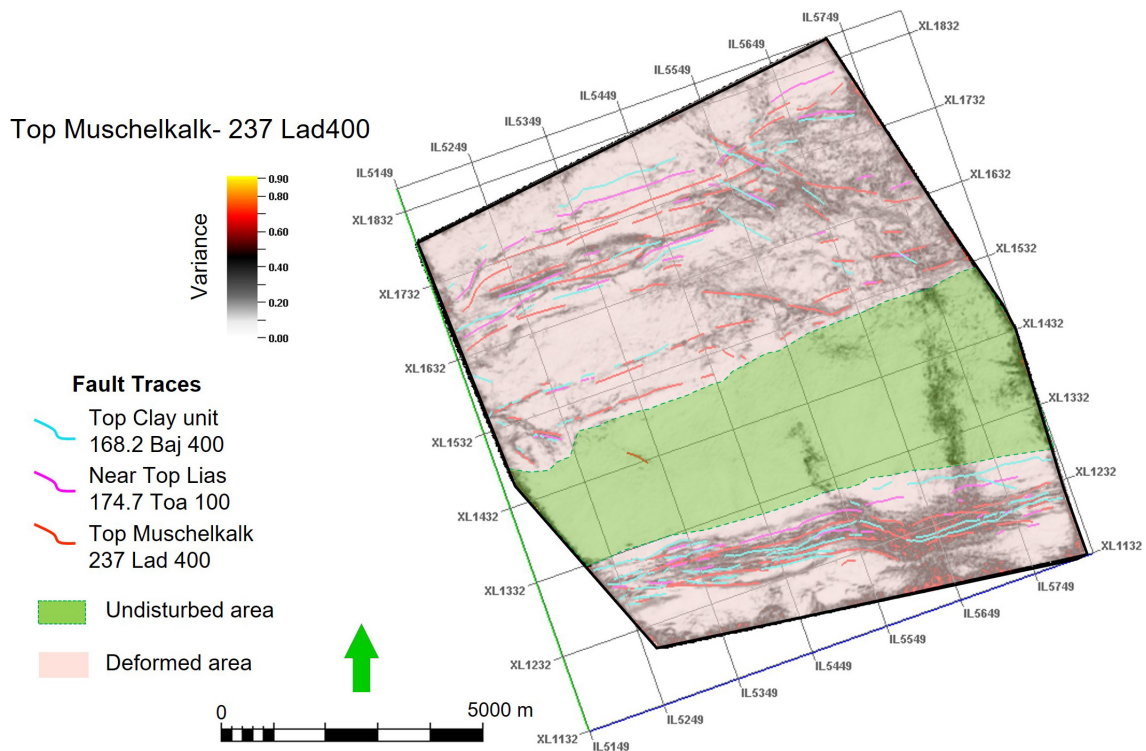


Fig. 7-1: Identification of a seismically undisturbed area

Based on a detailed seismic analysis, the NL siting region can be subdivided into four structural domains, which allowed the identification of a large seismically undisturbed area of ~25 km², named the Undisturbed Central Panel (UCP).

Within a regional tectonic framework, several structural evolution scenarios for the NL siting region were proposed by several authors (Diebold et al. 1991, Naef et al. 1995, Madritsch et al. 2013, Malz et al. 2016, Bond et al. 2023, Schöpfer et al. 2023, Zambrano et al. 2024, Bond et al. 2023). Main discussion points focus on the relative timing of the major deformation zones (SFTZ, NFTZ and WGE), their kinematics and the role and interaction of the Mesozoic faults with deep-seated grains (thin- versus thick-skinned models). While the alternative scenarios describe different tectonic evolutions of the NL siting region and the larger area of Northern Switzerland as discussed in NTB 24-17 (Nagra 2024d), none of those evolutionary tectonic scenarios propose either a different structural configuration or a different definition of the undisturbed area for the NL siting region.

8 References

- Alcalde, J., Bond, C. E., Johnson, G., Kloppenburg, A., Ferrer, O., Bell, R. & Ayarza, P. (2019): Fault interpretation in seismic reflection data: an experiment analysing the impact of conceptual model anchoring and vertical exaggeration. *Solid earth*, 10(5), 1651-1662.
- Allenbach, R.P. (2001): Synsedimentary tectonics in an epicontinental sea: a new interpretation of the Oxfordian basins of northern Switzerland *Eclogae Geologicae Helvetiae*, 94, 265-287.
- Backus, M.M. (1959): Water reverberations—their nature and elimination. *Geophysics*, 24(2), 233-261.
- Becker, A. (2000): Der Faltenjura: geologischer Rahmen, Bau und Entwicklung seit dem Miozän. *Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins. Neue Folge* 82, 317-336.
- Birkhäuser, P., Roth, P., Meier, B. & Naef, H. (2001): 3-D Seismik: Räumliche Erkundung des mesozoischen Sedimentschichten im Zürcher Weinland. *Nagra Technischer Bericht NTB 00-03*.
- Bond, C., Robledo, F. & Butler, R. (2023): The Jura Fold-Thrust Belt, Switzerland—a contractional deformation setting for nuclear waste disposal. *EGU General Assembly Conference Abstracts*, EGU23-9905.
- Bond, C.E., Gibbs, A.D., Shipton, Z.K. & Jones, S. (2007): What do you think this is? “Conceptual uncertainty” in geoscience interpretation. *GSA today*, 17(11), 4-10.
- Bond, C.E., Johnson, G. & Ellis, J.F. (2015a): Structural model creation: the impact of data type and creative space on geological reasoning and interpretation. *Geological Society of London, Special Publications*, 421(1), 83-97.
- Bond, C.E. (2015b): Uncertainty in structural interpretation: Lessons to be learnt. *Journal of Structural Geology*, 74, 185-200.
- Braathen, A., Tveranger, J., Fossen, H., Skar, T., Cardozo, N., Semshaug, S.E., Bastesen, E. & Sverdrup, E. (2009): Fault facies and its application to sandstone reservoirs. *AAPG bulletin*, 93(7), 891-917.
- Brown, A.R. (1996): Seismic attributes and their classification. *The leading edge*, 15(10), 1090-1090.
- Brown, A.R. (2011): Interpretation of three-dimensional seismic data. *Society of Exploration Geophysicists and American Association of Petroleum Geologists. AAPG Memoirs*, 42 / SEG Investigations in Geophysics, No. 9.
- Buechi, M.W., Graf, H.R., Haldimann, P., Lowick, S.E. & Anselmetti, F.S. (2018): Multiple Quaternary erosion and infill cycles in overdeepened basins of the northern Alpine foreland. *Swiss Journal of Geosciences*, 111, 133-167.
- Caër, T., Souloumiac, P., Maillot, B., Leturmy, P. & Nussbaum, C. (2018): Propagation of a fold-and-thrust belt over a basement graben. *Journal of Structural Geology*, 115, 121-131.

- Callow, B., Bull, J.M., Provenzano, G., Böttner, C., Birinci, H., Robinson, A.H., Henstock, T.J., Minshull, T.A., Bayrakci, G., Lichtschlag, A., Roche, B., Yilo, N., Gehrmann, R., Karstens, J., Falcon-Suarez, I.H. & Berndt, C. (2021): Seismic chimney characterisation in the North Sea-implications for pockmark formation and shallow gas migration. *Marine and Petroleum Geology*, 133, 105301.
- Campbell, A., Fryer, A., Isaacson, L. & Wendt, B. (2005): Successful imaging in a structurally complex environment, using a Look-Ahead VSP. SEG Technical Program Expanded Abstracts 2005
- Childs, C., Nicol, A., Walsh, J.J. & Watterson, J. (1996): Growth of vertically segmented normal faults. *Journal of Structural Geology*, 18(12), 1389-1397.
- Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A. & Schöpfer, M.P. (2009): A geometric model of fault zone and fault rock thickness variations. *Journal of Structural Geology*, 31(2), 117-127.
- Connolly, D.L. (2015): Visualization of vertical hydrocarbon migration in seismic data: Case studies from the Dutch North Sea. *Interpretation*, 3(3), SX21-SX27.
- Cox, M. (1999): Static corrections for seismic reflection surveys. Society of Exploration Geophysicists.
- Diebold, P., Naef, H. & Amman, M. (1991): Zur Tektonik der Zentralen Nordschweiz: Interpretation aufgrund regionaler Seismik, Oberflächengeologie und Tiefbohrungen. Textband. Nagra Technischer Bericht NTB 90-04.
- El Awawdeh, R., Khouri, N., Al Neyadi, A., Shevchek, Z.J., Shebl, H., Edwards, H.E., Gombos, A. & Johns, M. (2008) 3-D Seismic Evidence of Tertiary-Cretaceous Karsts & Collapse Disturbances from Offshore Oil Field in Abu Dhabi and Outcrop Analogs from Jebel Hafit, United Arab Emirates. Abu Dhabi International Petroleum Exhibition and Conference, SPE-118006-MS.
- Eruteya, O.E., Crinière, A. & Moscariello, A. (2024): Seismic expression of paleokarst morphologies and associated Siderolithic infill in the Geneva Basin, Switzerland: Implications for geothermal exploration. *Geothermics*, 117, 102868.
- Evans, E., Papouin, M., Abedi, S., Gauer, M., Smith, P. & Jones, I.F. (2005): Southern North Sea PreSDM imaging using hybrid gridded tomography. SEG Technical Program Expanded Abstracts 2005.
- Faleide, T.S., Braathen, A., Lecomte, I., Mulrooney, M.J., Midtkandal, I., Bugge, A.J. & Planke, S. (2021): Impacts of seismic resolution on fault interpretation: Insights from seismic modelling. *Tectonophysics*, 816, 229008.
- Geyer, O.F. & Gwinner, M.P. (1991): *Geologie von Baden-Württemberg*. 4., neubearb. Aufl. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
- Herron, D.A. (2011): First steps in seismic interpretation. Society of Exploration Geophysicists.
- Hesthammer, J. & Fossen, H. (1997a): The influence of seismic noise in structural interpretation of seismic attribute maps. *First Break*, 15(6).

- Hesthammer, J. & Fossen, H. (1997b): Seismic attribute analysis in structural interpretation of the Gullfaks Field, northern North Sea. *Petroleum Geoscience*, 3(1), 13-26.
- Hesthammer, J. Landrø, M. & Fossen, H. (2001): Use and abuse of seismic data in reservoir characterisation. *Marine and Petroleum Geology*, 18(5), 635-655.
- Heubeck, C., Story, K., Peng, P., Sullivan, C. & Duff, S. (2004): An integrated reservoir study of the Liuhua 11-1 field using a high-resolution three-dimensional seismic data set. *Seismic Imaging of Carbonate Reservoirs and Systems*. G.P. Eberli, J.L. Masaferro & J.F.R. Sarg. AAPG Memoirs, 81, 149-168.
- Hoch, E., Ohrt, H.B., Brink, D.I., Flikkema, J. & Noman, R. (2010): Pushing the limits for field development. Abu Dhabi International Petroleum Exhibition and Conference SPE-138301-MS.
- Jordan, P., Malz, A., Heuberger, S., Pietsch, J., Kley, J. & Madritsch, H. (2015): Regionale geologische Profile durch die Nordschweiz und 2D-Bilanzierung der Fernschubdeformation im östlichen Faltenjura: Arbeitsbericht zu SGT Etappe 2. Nagra Arbeitsbericht NAB 14-105.
- Hölker, A. & Birkhäuser, P. (2018): 3D Seismik Datenbearbeitung 2016-2017: Jura Ost, JO-15: Nördlich Lägern, NL-16: Zürich Nordost, ZNO-97 /16-4 Nagra Arbeitsbericht NAB 17-36.
- Laubscher, H. (1986): The eastern Jura – Relations between thin-skinned and basement tectonics, local and regional. *Geologische Rundschau* 75/3, 535-553.
- Li, B., Al-Awadi, M., Perrin, C., Al-Khabbaz, M., Al-Ashwak, S. & Al-Qadeeri, B. (2009): Fracture and Sub-Seismic Fault Characterization for Tight Carbonates in Challenging Oil-Based Mud Environment-Case Study from North Kuwait Jurassic Reservoirs. Middle East Oil and Gas Show and Conference SPE Middle East Oil and Gas Show and Conference, SPE-120424-MS.
- Lorenzen, R., Madsen, L., Huegen, C., Ting, T., Henderson, J. R., Raborn, C. B., Uldall, A., Cromie, H., Zampetti, V. & Emang, M.I. (2014): Applications of Geophysics to the Al Shaheen Field, Qatar, for Reservoir Characterisation and Field Development. IPTC 2014: International Petroleum Technology Conference (Abstract).
- Madritsch, H., Meier, B., Kuhn, P., Roth, P., Zingg, O., Heuberger, S., Naef, H. & Birkhäuser, P. (2013): Regionale strukturgeologische Zeitinterpretation der Nagra 2D-Seismik 2011/12. Nagra Arbeitsbericht NAB 13-10.
- Madritsch, H., Naef, H., Meier, B., Franzke, H.J. & Schreurs, G. (2018): Architecture and Kinematics of the Constance-Frick Trough (Northern Switzerland): Implications for the Formation of Post-Variscan Basins in the Foreland of the Alps and Scenarios of their Neogene Reactivation. *Tectonics*, 37(7), 2197-2220.
- Malz, A., Madritsch, H., Meier, B. & Kley, J. (2016): An unusual triangle zone in the external northern Alpine foreland (Switzerland): Structural inheritance, kinematics and implications for the development of the adjacent Jura fold-and-thrust belt. *Tectonophysics*, 670, 127-143.

- McCann, T., Kiersnowski, H., Krainer, K. Vozárová, A., Peryt, T.M., Opluštil, S., Stollhofen H., Schneider, J., Wetzel, A., Boulvain, F., Duser, M., Török, Á., Haas, J., Tait, J. & Körner, F. (2008): Permian, In McCann T. (Ed.). The geology of Central Europe, 1, 531-595.
- Meier, B., Kuhn, P., Muff, S., Roth, P. & Madritsch, H. (2014): Tiefenkonvertierung der regionalen Strukturinterpretation der Nagra 2D-Seismik 2011-12. Nagra Arbeitsbericht NAB 14-34.
- Michie, E.A., Alaei, B. & Braathen, A. (2022): Assessing the accuracy of fault interpretation using machine-learning techniques when risking faults for CO₂ storage site assessment. Interpretation, 10(1), T73-T93.
- Misra, A.A. & Mukherjee, S. (2018): Atlas of structural geological interpretation from seismic images. John Wiley & Sons.
- Moldovanyi, E. P., Wall, F. M. & Yan, Z. J. (1995): Regional exposure events and platform evolution of Zhujiang Formation carbonates, Pearl River Mouth Basin: evidence from primary and diagenetic seismic facies. Unconformities and porosity in carbonate strata. D.A. Budd, A.H. Saller & P.M. Harris (eds.). AAPG Memoirs, 63, 125-14.
- Nagra (2019): Preliminary horizon and structure mapping of the Nagra 3D seismics NL-16 (Nördlich Lägern) in time domain. Nagra Arbeitsbericht NAB 18-35.
- Nagra (2021): TBO Bülach-1-1: Data Report. Nagra Arbeitsbericht NAB 20-08.
- Nagra (2022a): TBO Stadel-3-1: Data Report. Nagra Arbeitsbericht NAB 22-01.
- Nagra (2022b): TBO Stadel-2-1: Data Report. Nagra Arbeitsbericht NAB 22-02.
- Nagra (2022c): Der Standort für das Tiefenlager: Der Vorschlag der Nagra. ASR Bericht.
- Nagra (2023): TBO Bachs-1-1: Data Report. Nagra Arbeitsbericht NAB 22-04.
- Nagra (2024a): Processing 3D Seismic Surveys Jura Ost, Nördlich Lägern and Zürich Nordost. Nagra Arbeitsbericht NAB 23-16.
- Nagra (2024b): 3D Seismic Interpretation of Stratigraphic Horizons and Structures in Time Domain Jura Ost. Nagra Arbeitsbericht NAB 23-17.
- Nagra (2024c): 3D Seismic Interpretation of Stratigraphic Horizons and Structures in Time Domain Zürich Nordost. Nagra Arbeitsbericht NAB 23-19.
- Nagra (2024d): Geosynthesis of Northern Switzerland. Nagra Technical Report. NTB 24-17.
- Nagra (2024e): Becker Jens, Marnat S. (2024): Petrophysical Data and Core-Calibrated Multi-mineral Interpretation. Nagra Arbeitsbericht. NAB 24-17.
- Nagra (2024f): NagraFuture human actions report. Nagra Arbeitsbericht. NAB 24-09.
- Naef, H., Birkhäuser, P. & Roth, P. (1995): Interpretation der Reflexionsseismik im Gebiet nördlich Lägeren-Zürcher Weinland. Nagra Technischer Bericht NTB 94-14.

- Nielsen, T. & Van Weering, T.C.E. (1998): Seismic stratigraphy and sedimentary processes at the Norwegian Sea margin northeast of the Faeroe Islands. *Marine Geology*, 152(1-3), 141-157.
- Roche, V., Camanni, G., Childs, C., Manzocchi, T., Walsh, J., Conneally, J., Saqab, M.M. & Delogkos, E. (2021): Variability in the three-dimensional geometry of segmented normal fault surfaces. *Earth-Science Reviews*, 216, 103523.
- Richard, P., Bazalgette, L. & Al-Kindi, M. (2014): North Oman fault geometries in outcrops, analogues and subsurface. *Geological Society, London, Special Publications*, 392(1), 447-460.
- Sayago, J., Di Lucia, M., Mutti, M., Cotti, A., Sitta, A., Broberg, K., Przybylo, A., Buonaguro R. & Zimina, O. (2012): Characterization of a deeply buried paleokarst terrain in the Loppa High using core data and multiattribute seismic facies classification. *AAPG bulletin*, 96(10), 1843-1866-4
- Schaaf, A. & Bond, C.E. (2019): Quantification of uncertainty in 3-D seismic interpretation: implications for deterministic and stochastic geomodeling and machine learning. *Solid earth*, 10(4), 1049-1061.
- Schöpfer, K., Decker, K., Nazari, F. & Madritsch, H. (2023): 3D-seismic evidence for thick-skinned tectonics in a ‘classic’ thin skinned tectonics region (external Alpine foreland, Switzerland). *Terra Nova*, 00, 1 -13.
- Schori, M., Zwaan, F., Schreurs, G. & Mosar, J. (2021): Pre-existing Basement Faults Controlling Deformation in the Jura Mountains Fold-and-Thrust Belt: Insights from Analogue Models, *Tectonophysics*, 814, 228980.
- Sheriff, R.E. (1977): Limitations on resolution of seismic reflections and geologic detail derivable from them. *Seismic stratigraphy-applications to hydrocarbons exploration*. C. E. Payton. *AAPG Memoirs*, 26, 3-14.
- Sheriff, R.E. (1985): Aspects of seismic resolution: Chapter 1. *Seismic stratigraphy II - applications to hydrocarbons exploration*. O.R. Berg & D.G. Woolverton. *AAPG Memoirs*, 39, 1-12.
- Sheriff, R.E. & Geldart, L.P. (1995): *Exploration seismology*. Cambridge University Press.
- Sheriff, R.E. (1997): Seismic resolution a key element. *AAPG Explorer*, 18(10), 44-51.
- Simm, R. & Bacon, M. (2014): *Seismic amplitude: An interpreter's handbook*. Cambridge University Press.
- Sommaruga, A., Mosar, J., Schori, M. & Gruber, M. (2017): The role of the Triassic evaporites underneath the North Alpine Foreland. In *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, Elsevier, 447-466-4.
- Tannert, C., Elvers, H.D. & Jandrig, B. (2007): The ethics of uncertainty: In the light of possible dangers, research becomes a moral duty. *EMBO reports*, 8(10), 892-896.
- Tipper, J.C. (1993): Do seismic reflections necessarily have chronostratigraphic significance?. *Geological Magazine*, 130(1), 47-55.

- Vail, P.R., Mitchum Jr, R.M. & Thompson III, S. (1977): Seismic stratigraphy and global changes of sea level: Part 3. Relative changes of sea level from Coastal Onlap: section 2. Application of seismic reflection Configuration to Stratigraphic Interpretation. Seismic stratigraphy-applications to hydrocarbons exploration. C. E. Payton. AAPG Memoirs, 26, 62-82.
- van der Velde, J.J. (2006): Applied Geophysics in Shell Europe's Mature Asset. 68th EAGE Conference and Exhibition (Abstract).
- Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. & Rahmanian, V.D. (1990): Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. AAPG Methods in Exploration Series, 7.
- Wagner, P.D., Tasker, D.R. & Wahlman, G.P. (1995): Reservoir degradation and compartmentalization below subaerial unconformities: Limestone examples from west Texas, China, and Oman, in D. A. Budd, A. H. Saller, and P. M. Harris, eds., Unconformities and porosity in carbonate strata. D. A. Budd, A. H. Saller & P. M. Harris (eds.). AAPG Memoirs, 63, 177 -19
- Wibberley, C.A., Yielding, G. & Di Toro, G. (2008): Recent advances in the understanding of fault zone internal structure: a review. Geological Society, London, Special Publications, 299(1), 5-33.
- Yilmaz, Ö. (2001). Seismic data analysis. Society of exploration geophysicists.
- Zambrano, M., Mazzoli, S. & Mosar, J. (2024). Influence of Inherited Structures on Deformation Patterns in the Eastern Jura Fold and Thrust Belt: Insights from 3D Seismic Data, EGU General Assembly EGU24-13025.
- Zampetti, V., Marquez, X., Mukund, S., Bach, S. & Emang, M. (2014a): 3D seismic characterization of UER karst, offshore Qatar. IPTC 2014: International Petroleum Technology Conference, IPTC-17638-M.
- Zampetti, V., Madsen, L., Cromie, H., Durance, G., Emang, M., Bounoua, N. & Gagigi, T. (2014b): The role of regional basement fabric on Cretaceous structural deformation; a case study from Al Shaheen Field, offshore Qatar. IPTC 2014: International Petroleum Technology Conference, IPTC-17612-MS.