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New insights into structural and stratigraphic aspects of central Northern Switzerland from the Nagra 2D reflection seismic campaign 2011/12

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Key words: Tectonics, Kinematics, Seismic Stratigraphy, Mandach Thrust, Permo-Carboniferous Trough, Dogger

Abstract
In this article, some findings resulting from the interpretation of reprocessed and newly acquired 2D seismic data in central Northern Switzerland are presented. The seismic examples illustrate the relationship between basement and cover tectonics and offer a closer look at seismic-stratigraphic characteristics which can be observed in the Middle Jurassic sequence.
The new 2D seismic data have closed important data gaps between the Nagra siting regions ‹Jura Ost› and ‹Nördlich Lägern› proposed for radioactive waste disposal and allow clarification of the general structural framework and internal composition of the Permo-Carboniferous Trough. Furthermore, the kinematic relationships between the basement and cover structures can be studied and the newly acquired seismic data have allowed detailed depositional structures and seismic facies changes within the Mid-Upper Dogger sequence to be recognized, particularly east and west of the lower Aare valley.

Zusammenfassung
Anhand von seismischen Beispielen werden einige Ergebnisse präsentiert, die aus der Interpretation der reprozessierten und neu akquirierten 2D Seismik in der zentralen Nordschweiz gewonnen wurden. Sie illustrieren exemplarisch die Beziehung zwischen Grund- und Deckgebirgstektonik und ermöglichen einen Einblick in seismofazielle Besonderheiten und laterale seismische Fazieswechsel im Mittleren Jura.
Die neu akquirierte 2D Seismik konnte wichtige Datenlücken zwischen den Standortgebieten für geologische Tiefenlager ‹Jura Ost› und ‹Nördlich Lägern› schliessen. Die Auswertung der Daten ermöglichte eine breiter abgestützte Darstellung des regionalen Strukturrahmens sowie des internen Aufbaus des Permokarbontroges und konnte Hinweise für die kinematischen Zusammenhänge zwischen dem Grund- und dem Deckgebirge liefern. Die neu akquirierten seismischen Daten ermöglichten zudem die Erkennung von Ablagerungsstrukturen und lateralen seismischen Fazieswechseln im Mittleren und Oberen Dogger, besonders östlich und westlich des unteren Aaretales.

1 Introduction

In this extended abstract, a few examples have been picked out from the numerous findings gained from interpreting the reprocessed and newly acquired 2D seismic data in central Northern Switzerland (Madritsch et al. 2013). These examples illustrate the relationship between basement and cover tectonics and provide a closer look at seismic-stratigraphic characteristics which can be observed in the higher resolution 2D seismic data recently acquired (Meier & Deplazes 2014).
This article is based on an oral presentation

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given by the author at the 82nd SASEG annual convention in Baden on 20th June 2015. It is intended to document some key topics of the seismic exploration campaign for a suitable site for radioactive waste disposal which were introduced by the previous speaker Dr. H. Madritsch by giving an overview of the geological evolution of the region (Madritsch 2015, this volume).

The present article gives a brief overview of

- some general aspects concerning the processing and interpretation of the seismic data,
- the geometry of the Permo-Carboniferous Trough in central Northern Switzerland and its relationship to the Mandach Thrust at the front of the Alpine deformation front, as well as
- depositional geometries and seismic facies characteristics concerning the Middle Jurassic, overall basinal sequence of the ‹Brauner Dogger› in the Nagra siting region ‹Nördlich Lägern› and possible seismic facies transitions towards the west into the Nagra siting region ‹Jura Ost› (locally known as the Bözberg, Fig. 1).

2 General aspects

The seismic data acquired in 2011/12 consist of twenty new 2D seismic lines with a total

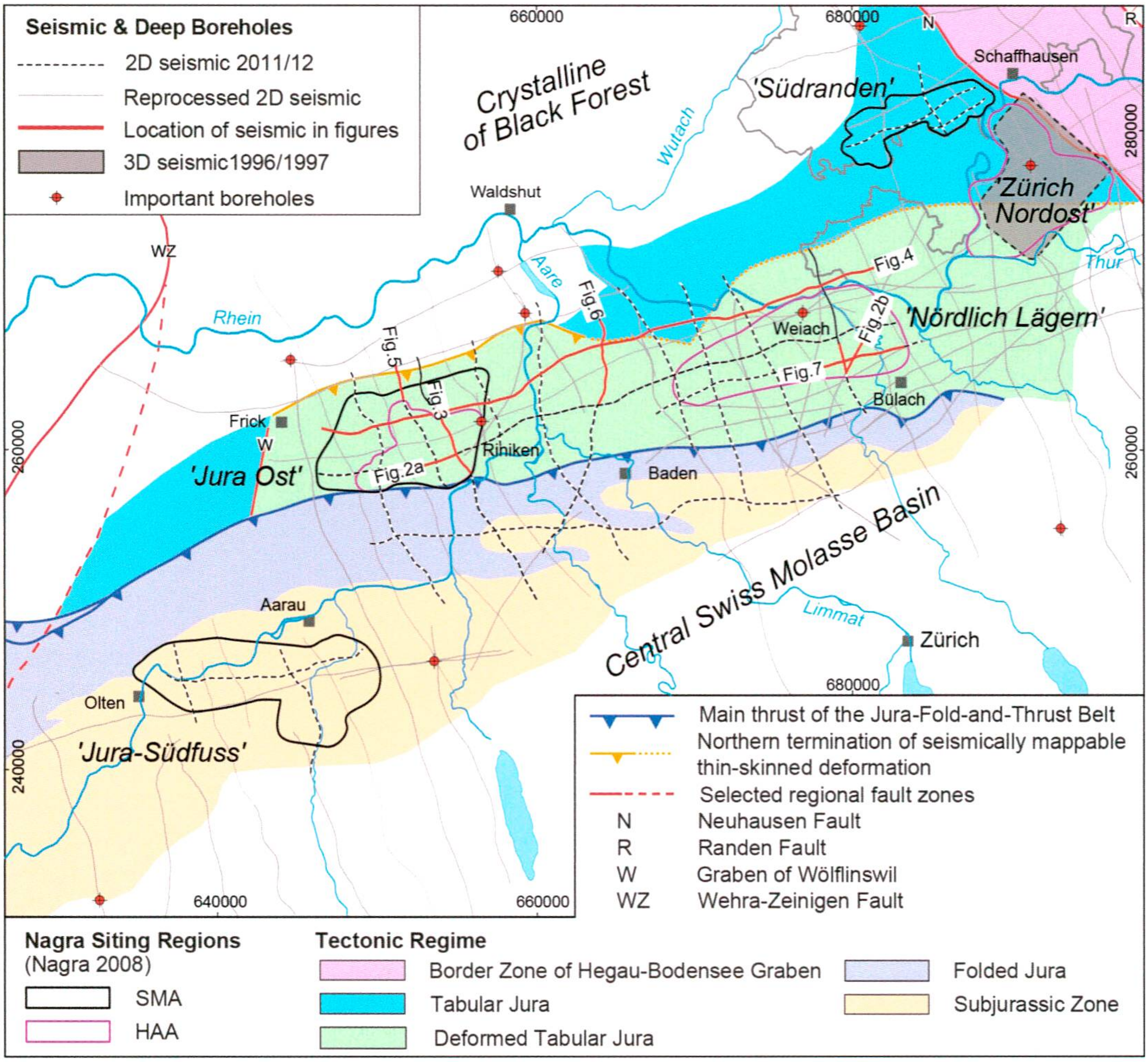

Fig. 1: Seismic and well location map with location of the seismic sections shown in the figures.

length of about 300 km. These lines form an infill grid of existing 2D and 3D seismic data which were originally acquired in the 80s and 90s and were recently reprocessed (Fig. 1). The goal of the new data acquisition was to further detail the structural pattern previously established (Nagra 2008) and eventually to improve the understanding of the relationships between the regional tectonic structures.
Processing of the newly acquired seismic data (Rybarczyk 2013) provided a further improvement of the data quality, with a generally more coherent imaging of the subsurface and reflection data containing higher frequencies. Furthermore, signal-to-noise ratios were noticeably improved and the seismic lines revealed higher reflection continuities at the shallow and at the deeper levels (Fig. 2).
The Pre-Stack Depth Migration (PSDM) is the end-product of the seismic data processing (Rybarczyk 2014). The PSDM has been calculated with a depthing velocity model for each seismic line. These velocity data were initially developed during reprocessing of the existing seismic data and later refined by tying-in the newly acquired seismic data. At first, the seismic interpretation was carried out in the time domain on a Pre-Stack Time Migration (PSTM) of the seismic profiles. The final interpretation was then carried out on seismic data converted back from the depth into the time domain (DTconv). Depth information was then obtained by converting the horizon and fault interpretation from time (DTconv) into depth (PSDM); interpretations in time and depth are thus directly linked through the depthing velocity model.
For the semi-quantitative estimation of the vertical and lateral resolution of the new seismic data, spectral analyses were carried out in four Nagra siting regions for specific CMP ranges and at the depth levels of the Opalinus Clay target formation (Madritsch et al. 2013). Applying the Rayleigh criteria for the calculation of the vertical seismic resolution (Sheriff 1991) yields a vertical seismic resolution ranging between 13 to 18 m. This means that an individual layer of about 15 m thickness can be imaged with separate seismic reflections from the top and base of the unit. Compared to the reprocessed seismic data, a general

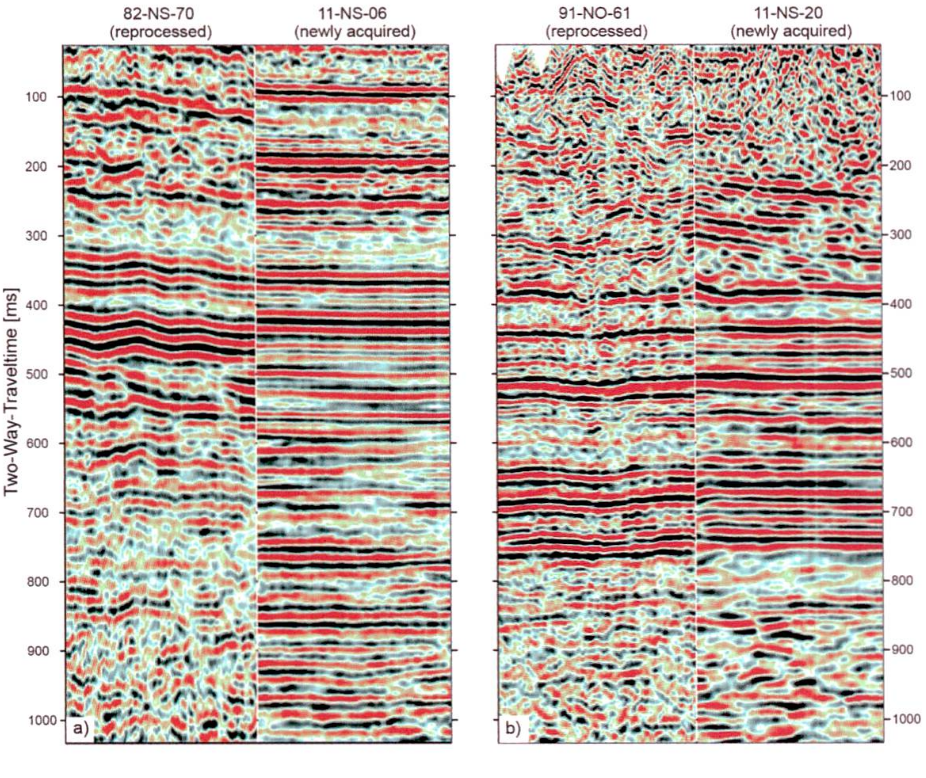

Fig. 2: Comparison of the data quality between reprocessed seismic data of the campaigns 1982/91 and the newly acquired seismic data 2011/12. For location of the sections see Fig. 1.

improvement of the seismic resolution could be achieved for the new 2D data by the seismic acquisition and processing parameters optimized for the depth ranges of potential host rocks for radioactive waste disposal (Fig. 2, Madritsch et al. 2013).

At the level of the Mesozoic, five seismic marker horizons were interpreted to obtain the structural framework for the seismic and stratigraphic analyses (Fig. 3). These marker horizons were calibrated by nine synthetic seismograms (Madritsch et al. 2013). The synthetic seismograms were constructed with the help of adequate well log data and displayed with appropriate filtering such that the modelled seismic signals can be compared with the actual seismic data. Depending on the impedance contrasts at the corresponding stratigraphic levels, the reflection signal (on SEG reverse display) may be a peak, such as for the Base Tertiary and the Top of the Liassic/Base Opalinus Clay, a zero-crossing, as for the Base Malm, or a trough, such as for the Top Muschelkalk and for the Base Mesozoic. These reflection characteristics may however vary laterally and between the siting regions, depending on the lateral facies changes and different depth levels. At a later stage of interpretation, the Near-Top Opalinus Clay horizon was also picked (Meier et al. 2014). Because of the differing data qualities for various seismic vintages with varying reflection imaging, it is often not possible to determine

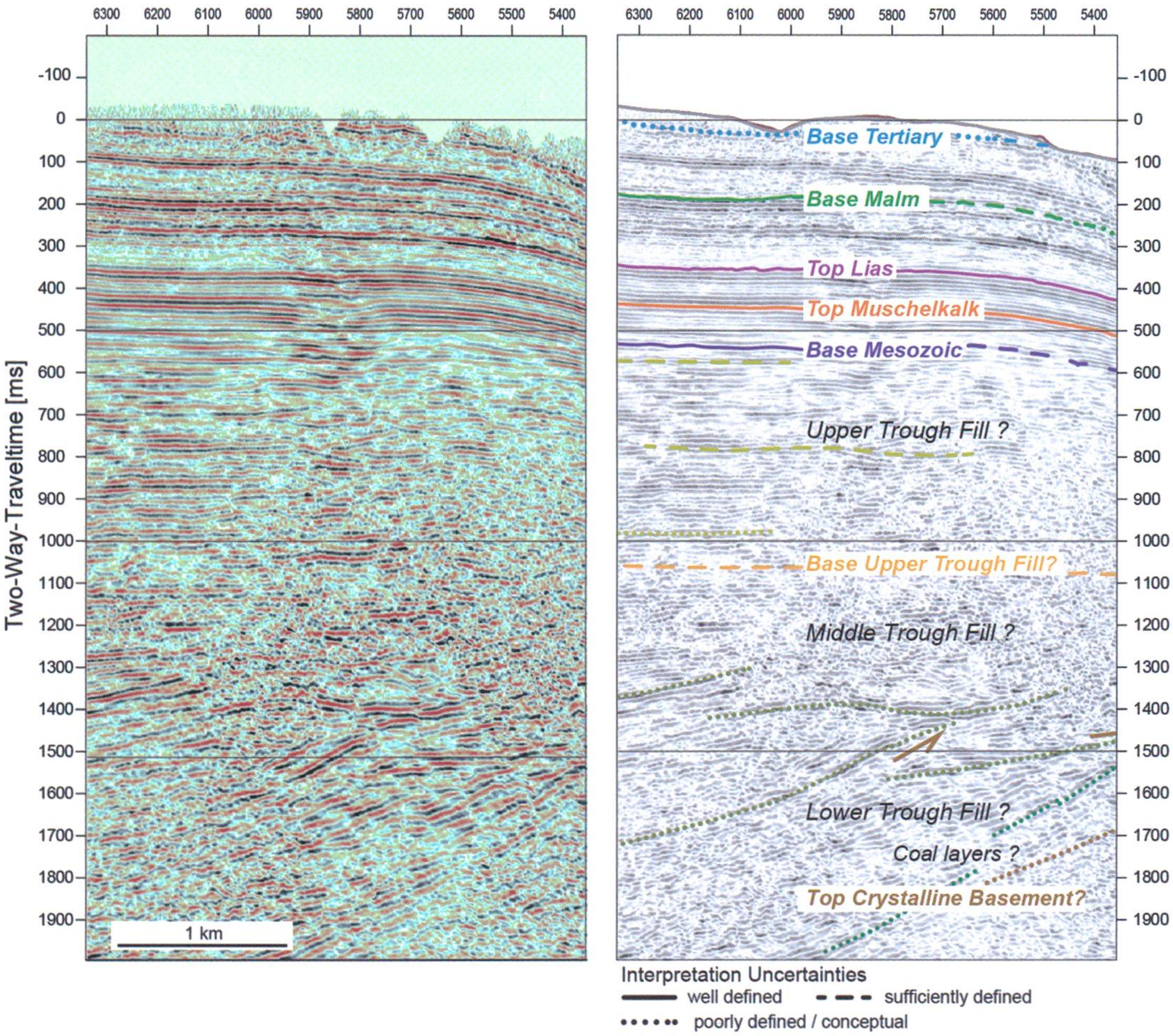

Fig. 3: Regional marker horizons picked and classification of interpretation uncertainties.

a continuously mappable seismic event at the corresponding stratigraphic level. The Near-Top Opalinus Clay is therefore merely regarded as an auxiliary seismic horizon because its mapping may be associated with larger picking uncertainties.

For the marker horizons and for the identified faults, a qualitative, three-level classification of interpretation uncertainties was introduced and indicated on the seismic sections with the corresponding signatures (Fig. 3). Based on this, the interpretation of the marker horizons is classified as ‹well defined›, ‹sufficiently defined› or ‹poorly defined/conceptual›. Fault interpretation is accordingly regarded as ‹robust›, ‹uncertain› or ‹conceptual›.

At the Mesozoic level, the available grid of 2D seismic data allows a detailed and broadly based horizon and fault interpretation. However, at the sub-Mesozoic level, interpretation of the Permo-Carboniferous Trough and its fill (Naef & Madritsch 2014) must still be regarded as largely conceptual, because the reflection seismic signals at depth are often weak and the seismic image is more often affected by artefacts from seismic acquisition and processing. Similarly, in the area of the Jura Fold-and-Thrust Belt, seismic imaging is often very poor and strongly limited and interpretation can therefore be only hypothetical and schematic.

3 Structural aspects

3.1 Permo-Carboniferous Trough

As outlined by Madritsch (2015), the new 2D seismic data acquired in 2011/12, combined with newly processed gravity maps (Green et al. 2013), filled some important data gaps in the area of the lower Aare valley and yielded additional information on the Trough geometry and possible kinematics of its formation.

The WSW-ENE oriented seismic section 11-NS-37 (Fig. 4), together with other dip- and strike-lines, forms the backbone of the interpretation of the Permo-Carboniferous Trough. It clearly shows a separation of the Trough into a deep western part and an apparently shallower eastern part. The Trough is interpreted to be filled by three units with varying thicknesses (Diebold et al. 1991, Naef & Madritsch 2014). The western Trough contains a thick middle fill observed to onlap onto the basal lower fill and an upper fill with an unconformity at its base (Fig. 4). The eastern Trough appears to form a kind of shoulder zone (‹Trograndzone Nord› in Naef & Madritsch 2014) with a much thinner middle fill above the basal lower fill with high amplitude reflection packages. According to the Weiach borehole, this lower fill contains coal layers (Matter 1987). The upper fill appears to wedge out towards the west and disappear below the unconformably overlying Mesozoic.

The western Trough has a thickness of possibly more than 5 km (Meier et al. 2014, Naef & Madritsch 2014) and is separated from the eastern Trough by a large normal fault flattening out at depth towards the west and displacing the Base Mesozoic where the so-called Unterendingen Fault has been mapped (Madritsch et al. 2013).

Beneath the Nagra siting region ‹Jura Ost› (Fig. 1), the reprocessed and new seismic dip-lines confirm a steep northern boundary fault coinciding with the Mandach Flexure and the overlying Mandach Thrust (Diebold et al. 1991, Madritsch et al. 2013). The southern flank dips much more gently towards the north. Overall, a half graben geometry is apparent. The middle fill of the Trough shows partially divergent reflections and drag geometries along the northern boundary fault, thus indicating a syntectonic deposition. The upper fill follows unconformably above the middle fill. The southern boundary of the Trough – as a concept – is assumed to be located below the main thrust of the Jura-Fold-and-Thrust Belt. In these areas and depth ranges, the seismic data quality is however often limited or poor. South of the presumed southern boundary fault of the main Trough, the presence of Permo-Carboniferous sediments is less evident. However, there are isolated but clear indications for the existence of Permo-Carboniferous sediments in this area on several seismic lines.

Beneath the Nagra siting region ‹Nördlich Lägern›, the Permo-Carboniferous Trough, on the other side, appears to be more compartmentalized by internal faults. The seismic units of the northern boundary zone, separated as ‹Trograndzone Nord› (see above), dip towards the south with a steep southern boundary fault inferred along the Baden-Irchel-Herdern Lineament (Madritsch et al. 2013, Naef & Madritsch 2014). Again, a half graben geometry, with a central deep trough, is suggested, but now reverse to the geometry in the west. South of the Baden-Irchel-Herdern Lineament, the presence of Permo-Carboniferous sediments is not well established from seismic data and a positive Bouguer anomaly in gravity data may suggest their absence (Green et al. 2013, Nagra 2014).

Based on the most recent 2D seismic interpretation (Madritsch et al. 2013) and general considerations about Permo-Carboniferous graben formation and kinematics, the tectonic model of the Trough could be updated, underlining the importance of NW-SE striking transfer faults that enabled the formation of deep pull-apart style basins along the Trough's strike. This is illustrated by the synoptic tectonic map of Naef & Madritsch (2014), which summarizes the main elements of the Permo-Carboniferous Trough. The apparent reversal of the Trough's half graben geometry from west to east outlined above may have resulted from dextral pull-apart tectonics, with a releasing bend below the Unterendingen Fault and an interfering transfer zone in the prolongation of the NW-SE oriented dextral Vorwald Fault from the Black Forest (Naef & Madritsch 2014).

3.2 Mandach Thrust

The Mandach Thrust is an important regional fault zone forming the boundary between the Deformed Tabular Jura and the Tabular Jura to the north (Nagra 2014, Madritsch 2015 this volume). In this area it is also considered as the northern boundary of ‹Fernschub› or ‹distant push› tectonics, i. e. the

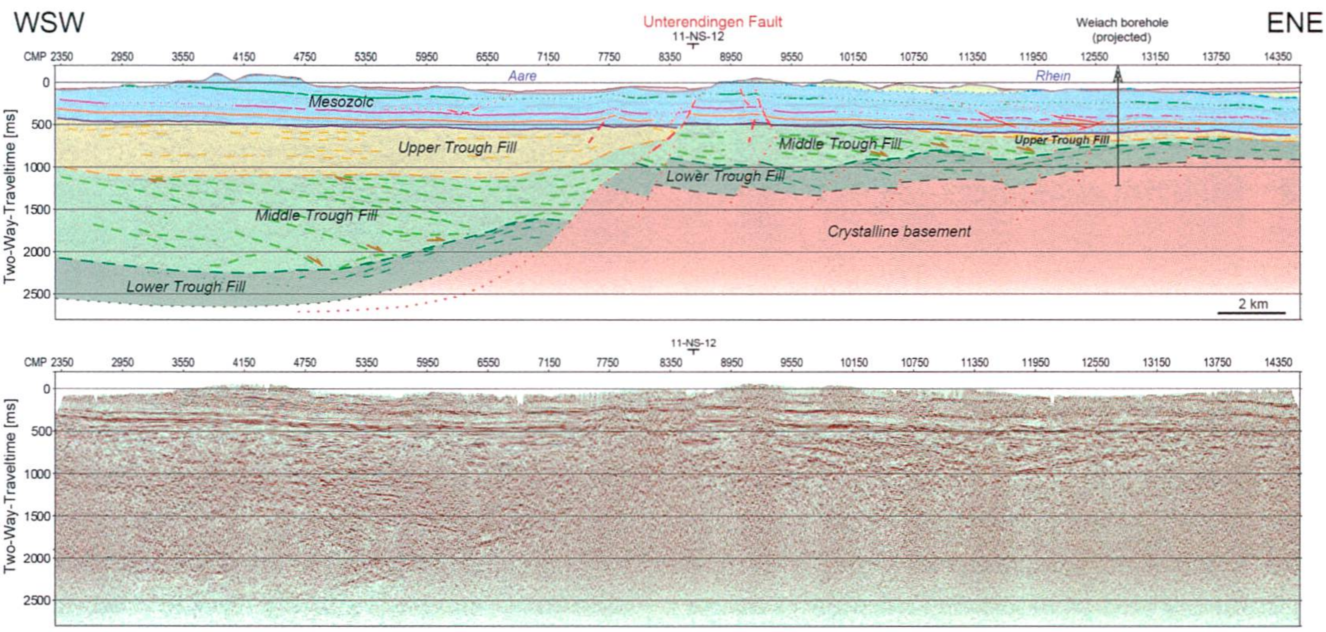

Fig. 4: Key seismic section along the Permo-Carboniferous Trough and interpretation of the Trough fills (adapted from Naef & Madritsch 2014). For location see Fig. 1 and for seismic marker horizons and classification of interpretation uncertainties see Fig. 5.

thin-skinned Alpine deformation front which propagated to the north along a décollement horizon in the Middle to Upper Triassic evaporites (e. g. Buxtorf 1916, Laubscher 1961, Burkhard 1990, Jordan et al. 1990).

Seismic imaging of the Mandach Thrust is often poor but there are also seismic profiles showing very clear imaging and indicating a thin-skinned tectonic style of the structure (Fig. 5). North of the Nagra siting region

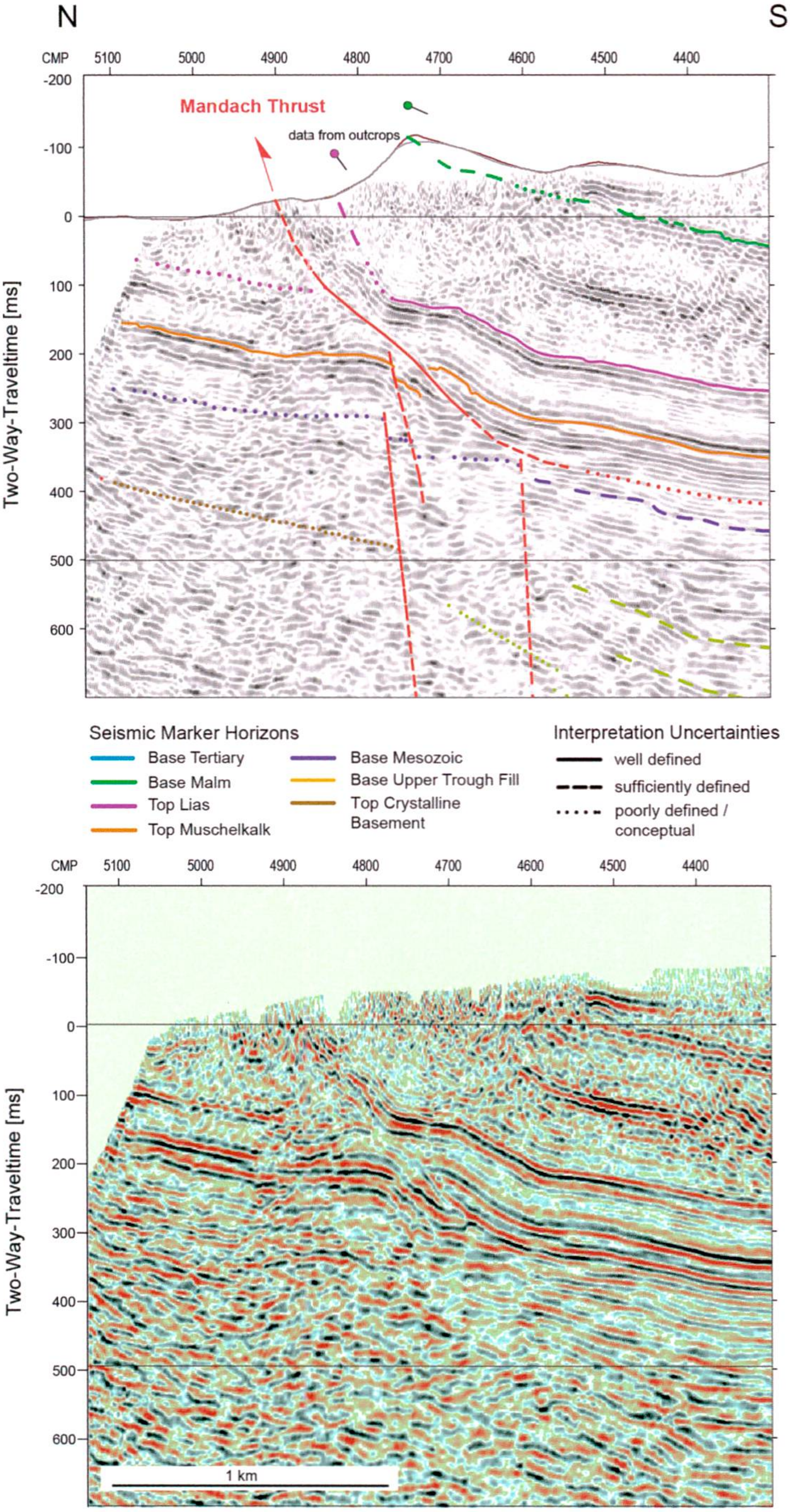

Fig. 5: Mandach Thrust above the northern boundary of the Permo-Carboniferous Trough on seismic section 11-NS-04. For location see Fig. 1.

‹Jura Ost›, the seismic data strongly suggest a direct kinematic relationship of the Mandach Thrust with the underlying northern boundary of the Permo-Carboniferous Trough (Laubscher 1986, Madritsch et al. 2013); it appears that the thrust – with a basal décollement in the Triassic – has been triggered by normal faults displacing the Base Mesozoic and Triassic sediments (Fig. 5). A thick-skinned tectonic style of the Mandach Thrust taken into account by some authors (e. g. Ustaszewski & Schmid 2007) is

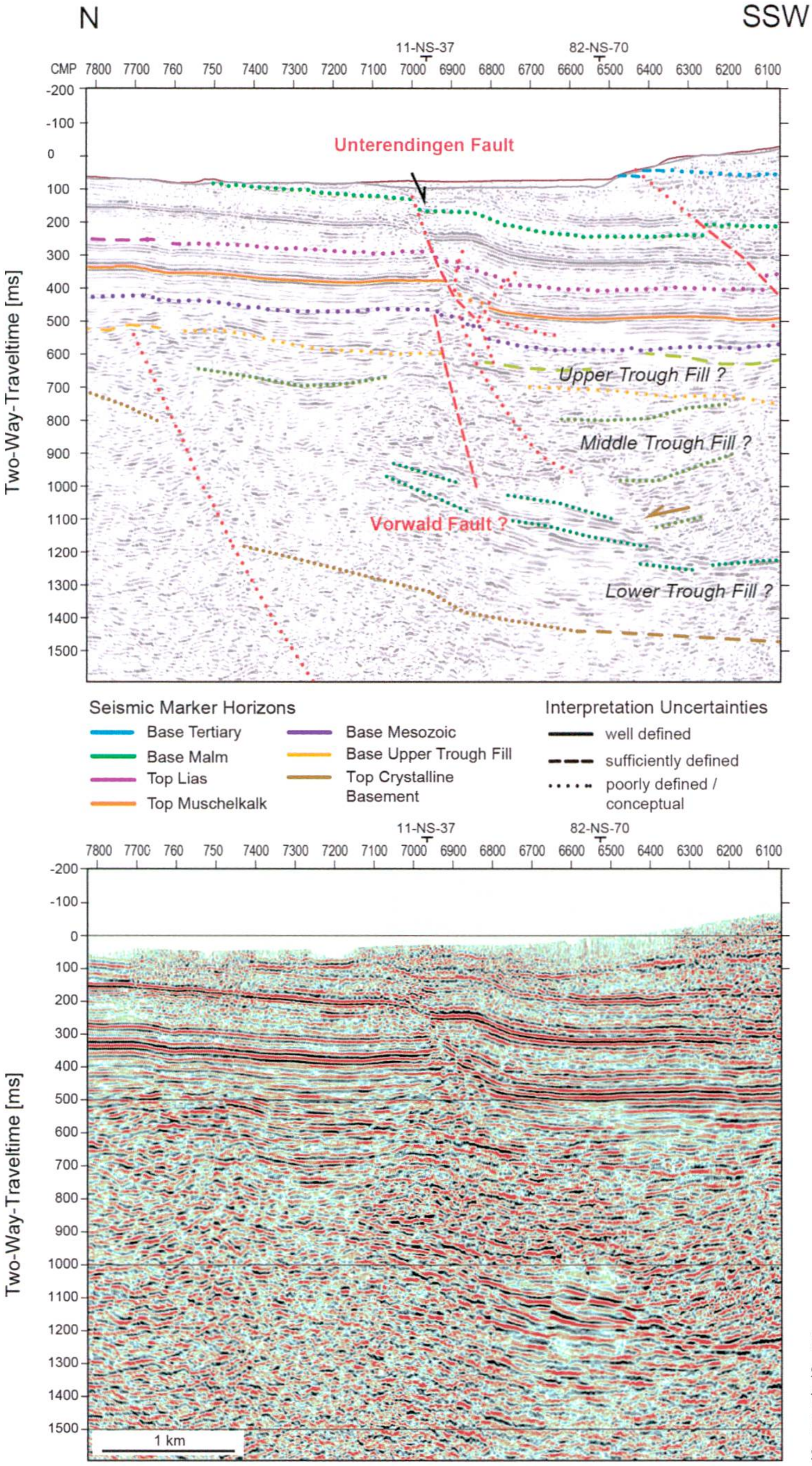

Fig. 6: Unterendingen Fault on seismic section 11-NS-12 at the eastern extension of the Mandach Thrust. For location see Fig. 1.

only clearly inferable on one seismic line (décollement at the Keuper level with underlying normal faulting in the Triassic and a weak inversion of the northern boundary of the Permo-Carboniferous Trough, compare Madritsch et al. 2013). This scenario, however, could not be observed consistently on other seismic lines.

The new seismic data acquired in the lower Aare valley provided surprising but clear evidence for normal faulting in the eastern extension of the Mandach Thrust. As documented by seismic section 11-NS-12 (Fig. 6), a complex south-dipping normal fault and flexure zone is found where the Mandach Thrust would have been expected. In the hanging wall, between Top Liassic and Base Malm, an embryonic anticlinal structure is developed and further indications for compressive to transpressive reactivation can be seen at the Triassic level below. The normal fault geometry is confirmed by intersecting seismic sections (Madritsch et al. 2013). In view of the magnitude of the vertical fault displacement and of the correlatability of the structure on neighbouring dip and strike lines to the east, this newly found structure designated the Unterendingen Fault by Madritsch et al. (2013) is considered to be of regional importance.

The kinematic interpretation of the structural pattern in the lower Aare valley can be summarized as follows (Madritsch et al. 2013):

1. The Mandach Thrust, with detachment at the level of the Triassic and normal faulting at the Base Mesozoic, appears to stop at the Unterendingen Fault, which is assumed to form the south-eastward extension of the Vorwald Fault from the Black Forest.
2. The Unterendingen Fault, with parallel structures, may have been reactivated during later deformation phases by extensive-transtensive movements and later acted as an inclined oblique ramp with dextral displacements during the formation of the Jura Fold-and-Thrust Belt.
3. Although locally an alternative interpretation may suggest that the Mandach Thrust could also represent an inversion structure rooting in the basement, this perception cannot be consistently seen on the seismic lines. Seismic interpretation rather supports the classical view with a basal detachment of the Mandach Thrust at the level of the Triassic (Muschelkalk or alternatively Keuper) and normal fault displacement at the base Mesozoic along the northern boundary fault of the Permo-Carboniferous Trough.

4 Sedimentological aspects

For the deposition of the Middle Jurassic sediments above the Opalinus Clay, two facies domains are distinguished in Northern Switzerland. The transition between these two facies domains is located approximately in the area of the lower Aare valley (Madritsch 2015, this volume). To the east, the ‹Brauner Dogger› claystone sequence (see Fig. 6 in Madritsch 2015, this volume) is developed in an overall ‹basin facies› (Bläsi et al. 2013; Nagra 2014). To the west, above the Passwang Formation with complex internal facies changes, thick oolithic limestones of the Hauptrogenstein Formation were deposited in an overall ‹platform facies› (Gonzalez & Wetzel 1996). The Klingnau Formation represents the transition facies, but, in view of the mainly clay-prone nature of its sediments, the depositional realm is already considered as being overall basinal (Gonzalez & Wetzel 1996, Bläsi et al. 2013).

Particularly within the Nagra siting region ‹Nördlich Lägern›, the newly acquired, higher resolution 2D seismic data have enabled a more detailed insight into depositional aspects of the Middle Jurassic sediments. Reflection geometries and seismic facies characteristics suggest the occurrence of possible lateral facies changes above the Opalinus Clay.

In the eastern part of the ‹Nördlich Lägern› siting region, the new seismic lines have revealed clear depositional geometries at the level of the Mid-Upper Dogger, with inclined, westward-dipping reflections above the seismically ‹transparent› Opalinus Clay (Fig. 7). Downlap of reflections onto the seismic horizon Near-Top Opalinus Clay may also be inferred. The foresetting reflections are laterally associated with high-amplitude, continuous reflections, whereas

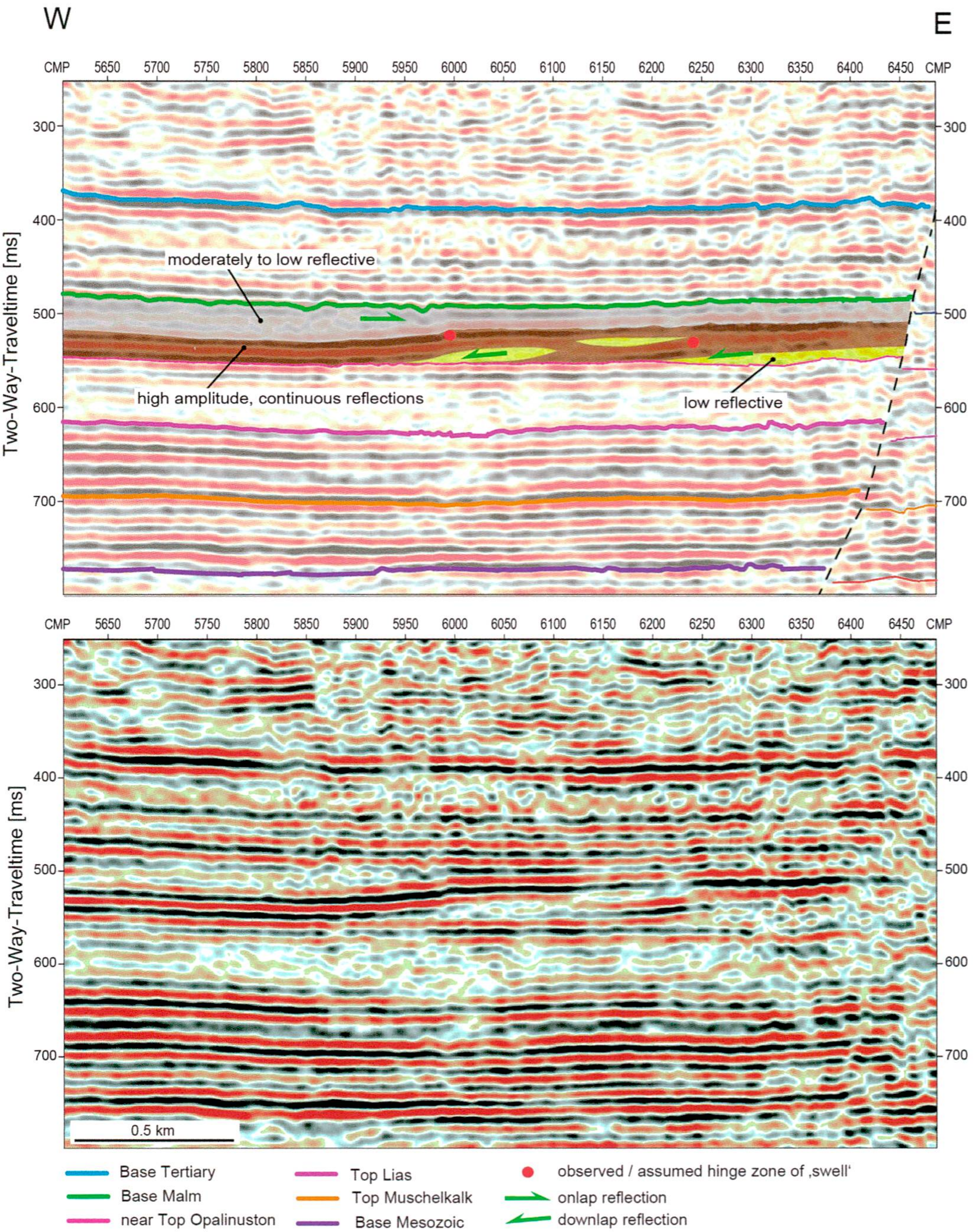

Fig. 7: Reflection geometries and seismic facies changes within the Mid-Upper Dogger sequence outlining a ‹swell area› in the Nagra siting region ‹Nördlich Lägern›. For location see Fig. 1.

internally less reflective domains can be observed. Above the strongly reflective, high-amplitude seismic facies unit outlining a ‹swell area›, onlap geometries are developed that are associated with a mostly moderately to low reflective seismic facies unit.
Reassessing some of the reprocessed seismic lines supports the possible presence of a ‹swell›, and mapping the reflection geometries and seismic facies in the lower part of the Mid-Upper Dogger sequence suggests a roughly north-south trending depositional structure. The sedimentological nature of this newly found ‹swell area› is unknown. Meier & Deplazes (2014) suggested that it is possibly constituted by accumulated quartz or calcarenitic sandbars which are intercalated with more clay-rich intervals created in shallower depositional environments as they are known from other areas (Geyer et al. 2011) and other formations (Burkhalter et al. 1997).
Stratigraphic and well log data from the Weiach borehole drilled west of the ‹swell area› suggest that the strongly reflective seismic facies unit represents approximately the Murchisonae-Oolith, Wedelsandstein and Humphriesioolith Formations. The overlying, mostly low reflective seismic facies unit in the upper part of the Mid-Upper Dogger sequence mainly corresponds to the marls and clays of the Parkinsoni-Württembergica strata (Meier & Deplazes 2014).
From the siting region ‹Nördlich Lägern›, a high-amplitude, continuous reflection package can be traced above the Opalinus Clay into the area of the western facies domain. This reflection package in the lower part of the Mid-Upper Dogger sequence mostly corresponds to the Passwang Formation with a more distinct interlayering of limestone and marl units (Meier & Deplazes 2014). On the other hand, the above-mentioned, low reflective seismic facies corresponding to the Parkinsoni-Württembergica strata in the upper part of the Mid-Upper Dogger sequence can be followed into the area of the lower Aare valley. Further to the west, this seismic facies appears to change into a slightly more reflective seismic facies with continuous reflections. This seismic facies unit is interpreted to reflect the transition facies of the Klingnau Formation (Meier & Deplazes 2014). Tentative mapping of the seismic facies distribution in the upper part of the Mid-Upper Dogger shows that this transitional seismic facies almost reaches the area of the Riniken borehole, where it seems to be laterally replaced by a less continuous seismic facies type. The Riniken borehole data (Meier & Deplazes 2014) suggest that this less continuous seismic facies type still corresponds to the Klingnau Formation. However, the Klingnau Formation here contains more oolithic and marly limestones than further to the east. The stratigraphic sequence corresponding to the less continuous seismic facies type contains thicker intercalations of the Hauptrogenstein ‹platform› facies type from the west.
In the upper part of the Mid-Upper Dogger sequence, seismic facies changes can be inferred from laterally varying reflection characteristics within the regional framework of a ‹platform› with thick oolithic limestones of the Hauptrogenstein Formation in the west and a ‹basinal› depositional realm for the ‹Brauner Dogger› east of the Lower Aare valley. The area of the Riniken borehole is considered to be located in a transitional zone, containing sediments from both the ‹platform› as well as ‹basinal› domains.

5 Conclusions

The new 2D seismic data acquired in 2011/12 have closed important data gaps between the Nagra siting regions ‹Jura Ost› and ‹Nördlich Lägern›. The high resolution seismic data have enabled a clarification of the general structural framework of the Permo-Carboniferous Trough of Northern Switzerland. Furthermore, regional and local fault zones could be outlined in more detail and a broader understanding of the kinematic relationships between the basement and cover structures could be achieved. In addition, the new seismic lines together with the reprocessed data have allowed the recognition of detailed depositional structures and seismic facies characteristics within the Mid-Late Dogger sequence, particularly east and west of the lower Aare valley.

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