



ARBEITSBERICHT NAB 23-16

Processing 3D Seismic Surveys Jura Ost,
Nördlich Lägern and Zürich Nordost

October 2024

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

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KEYWORDS

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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.

Executive summary

The sectoral plan for deep geological repositories for nuclear waste requires supplementary site-specific investigations in the proposed siting regions Jura Ost, Nördlich Lägern, and Zürich Nordost. Earth scientific investigations such as seismic surveying contribute to the site comparison and selection. In combination with information from deep boreholes, the seismic data allows to estimate the depth trends, thickness, and spatial continuity of the Opalinus Clay host rock formation and of the confining geological units, as well as the identification of major deformation structures.

For that purpose, mixed-source 3D land seismic surveys were acquired in the three proposed siting regions in the years 2015 – 2016. In the Zürich Nordost siting region, the existing 3D survey of 1997 was merged in for larger areal coverage and processed together with the 2016 survey.

The processing of the seismic field data was optimized to support the comparison of the three siting regions for the purpose of the site selection. The work was essentially done in two stages: Quick Look Processing and Refinement Processing. The Quick Look Processing delivered seismic field records merged with geometry, picked first-break travel times as well as conditioned common midpoint seismic gathers. The conditioned gathers served as a basis for Quick Look time-domain imaged products and also as the input for the Refinement Processing. The Quick Look Processing took place in the year 2016 – 2017 and was reported in detail in Hölker & Birkhäuser (2018).

The purpose of the report at hand is primarily to document the Refinement Processing which took place in 2019 – 2021. The purpose of the Refinement Processing was to obtain higher quality and more detailed seismic images, as well as velocity information for depth imaging and depth conversion purposes. The construction of near surface and full volume velocity models in 3D was an essential component of this stage. All shot and signal processing of the field data was done in the Quick Look Processing stage and the resulting data was reused in the Refinement Processing.

Driven by laterally highly variable acoustic near surface conditions, three separate near surface velocity models were derived for all three siting regions through seismic refraction tomography. Differences in geology and data acquisition mandated region-specific procedures in near surface model building and statics evaluation.

These near surface models were used as the starting point for building full-volume velocity models by seismic reflection tomography for each of the areas. In these models the strong vertical and lateral velocity variations in the subsurface were represented. Using these three individually optimized velocity models, imaging was performed by Pre-stack depth migration, a technology which honours the lateral velocity variations and produces a result in the depth domain. The Pre-stack depth migration provided detailed results with locally improved fault imaging, which are however limited in comparability to each other due to the different modelling and processing parameter choices used per siting region.

To constrain interpretation uncertainties and to maximise the comparability of the three siting regions, a uniform Pre-stack time migration processing scheme was also carried out with -as much as possible- equal parameters and regularised geometry for all three sites. This so-called Reference Pre-stack time migration was used as the primary product for subsequent comparative interpretation as an input for the site selection.

A confident interpretation of geological horizons and identification of faults was possible for the areas of primary interest in all three siting regions by using these seismic volumes and combinations thereof (see Nagra 2024a, 2024b, 2024c). Hence, the Refinement Processing results have contributed to the selection of the Nördlich Lägern siting region as the preferred location for constructing the repository.

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List of Acronyms

AGC	Automatic Gain Control
AI	Acoustic impedance
AOI	Area Of Interest
CMP	Common Mid-Point
CRS	Common Reflection Surface
FD	Floating Datum
IL	In-line direction of the seismic grid
JO	Jura Ost
LVL	Low Velocity Layer
NAB	Nagra Arbeitsbericht
Nagra	National Cooperative for the Disposal of Radioactive Waste
NIP	Normal Incidence Point
NL	Nördlich Lägern
NMO	Normal Move-Out
MSL	Mean Sea Level
PD	Pseudo Datum (also known as ‘Intermediate Datum’)
PostSDM	Post-Stack Depth Migration
PreSDM	Pre-Stack Depth Migration
PreSTM	Pre-Stack Time Migration
QC	Quality Control
QLP	Quick Look Processing
REP	REfinement Processing
RMO	Residual Move-Out
S/N	Signal to Noise
SPS	Shell Processing Support Format for 3D Surveys
SRD	Seismic Reference Datum
VSP	Vertical Seismic Profile (obtained in a borehole)
XL	Cross-line direction of the seismic grid
ZNO	Zürich Nordost

1 Introduction

1.1 Background and setting

This report documents the processing of the 3D seismic data, which was acquired in the context of the sectoral plan / general license application for a deep geological repository in Switzerland.

The three proposed siting regions Jura-Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) were characterised earlier by Nagra: Nagra (2014a) and Nagra (2014b). Their locations are shown below on the map of Fig. 1-1. Over these three areas, 2D and 3D seismic data has been acquired in various vintages. The 3D data was processed and interpreted to compare the three siting regions within the framework given by the sectoral plan deep geological repository (BFE 2008). Drilling of new deep exploratory boreholes happened in parallel with the seismic data processing, thus borehole information contributed piecewise and as and when it became available to the seismic processing and interpretation.

This report builds on the Quick Look Processing (QLP), which is already documented in an existing report (Hölker & Birkhäuser 2018). The QLP provided time domain products which were interpreted in terms of horizon and structural mapping (Nagra 2019a, Nagra 2019b, Nagra 2019c). This report documents the follow up Refinement Processing (REP) stage resulting in additional seismic imaging products provided to the seismic interpretation project. The workflow and the results of this interpretation are documented in Nagra (2024a) (JO), Nagra (2024b) (NL), and Nagra (2024c) (ZNO). A synthesis of the geological investigations can be found in Nagra (2024d).

1.2 Structure of the report

This report starts with an introduction of the geology and the associated seismic data processing objectives and challenges in this Chapter 1. Relevant details of the seismic data acquisition over the three siting regions are summarized in Chapter 2.

The phasing of the seismic processing activities into QLP and REP is introduced in the Processing Strategy description of Chapter 3. The main purpose of this report is to describe the REP. For the sake of completeness however, the QLP which was described in detail by Hölker & Birkhäuser (2018) is still summarized in Chapter 4.

Details on the building of the near surface velocity models for the three siting regions are provided in Chapter 5. The subsequent building of three full-volume velocity models and the associated pre-stack depth migration imaging efforts are covered in Chapter 6. The reference pre-stack time migration which was executed for optimized comparability of the three siting regions is detailed in Chapter 7.

Zero-phasing of all seismic volumes was applied after the imaging stage. Derivation of the zero phasing filters with the help of borehole data is the subject of Chapter 8.

Discussion of the results and conclusions are presented in Chapter 9.

1.3 Geological setting

1.3.1 Overview

The three siting regions are situated in the external northern Alpine Foreland Basin with the Mesozoic units widely covered by Paleogene-Neogene sedimentary rocks (Fig. 1-1). Regional structures belonging to the Jura Fold-and-Thrust-Belt, which roughly strikes east-west, affect mainly the JO and NL siting regions and the southwestern corner of ZNO. The easternmost site ZNO is located next to the NNW-ESE trending Hegau-Bodensee Graben (Diehl et al., 2024). Underneath the Cenozoic and Mesozoic units, a buried Permo-Carboniferous graben (Konstanz – Frick Trough) crosses the entire study area in ENE-WSW direction, and related structures are observed below the JO and NL siting regions (Fig. 1-2 and Fig. 1-3). The majority of the ZNO siting region is located on a crystalline high north of the Konstanz – Frick Trough (Fig. 1-4).

The geological synthesis (Nagra 2024d) provides further details on the geology in Northern Switzerland. The following sections briefly summarise geological aspects that are relevant in the context of the seismic data processing.

1.3.2 Bedrock outcrops

In JO most bedrock outcrops and sub-crops (bedrock below Quaternary) are formed by Mesozoic units and comparably thin Paleogene-Neogene deposits (i.e. Molasse) occur in the central area (Fig. 1-2). In the central and southern parts of the NL and ZNO siting regions, a relatively thick Molasse wedge covers the Mesozoic units (Fig. 1-3 and Fig. 1-4). Only in small windows in the very north of the 3D-seismic perimeters of the NL and ZNO regions, the Mesozoic units are outcropping or sub-cropping. Mesozoic outcrops often occur along the morphological imprint of the river Rhine.

In general, in JO the outcropping units get younger from north to south reflecting the overall inclination of the Mesozoic units to the SSE. In ZNO and NL, mainly Molasse units are outcropping, Malm outcrops are more frequent in JO.

1.3.3 Near surface geology

Repeated Quaternary glaciation periods had a strong impact on the landforms and on the shallow geology in those areas. The following landscape elements are of particular relevance:

- The most prominent features are up to ~300 m deep glacial valleys. Such valleys occur in the 3D seismic perimeter of NL and ZNO (Fig. 1-3 and Fig. 1-4). These valleys are cut into Molasse bedrock, and the sedimentary structure is often inherited from multistage glaciation periods. The heterogeneous infill of these valleys consists of unconsolidated fine grained lake sediments, glacial tills, gravels and moraine material. Valley geometry in these two siting regions was investigated with 2D reflection seismic techniques in an independent project (Nagra 2018). A glacially overdeepened valley also occurs below the Aare river (Gegg et al. 2021) but east of the JO perimeter (Fig. 1-2). Glacially overdeepened valleys are characterised by low seismic propagation velocities and significant acoustic scattering.
- The upper part of the valleys is mostly infilled with up to a few decametres thick glacio-fluvial gravels and internally complex tills. The gravels are typically deposited as flat or terraced bodies. They often host deep active or refilled gravel pits causing challenges for seismic acquisition and processing. The lower part of the valleys contain interchanging fillings of moraine gravels and sands, clay-rich sediments, and partly saturated gravels (Buechi et al. 2018). Above the tills the surface topography is often more irregular.

- Between the valleys, hills with flat tops reaching up to a few hundred meters above the valley surface occur in all three siting regions. In NL and ZNO the hills typically consist of Molasse bedrock covered by up to a few decametre thick Quaternary gravel units (glaciofluvial gravel; Deckenschotter; Fig. 1-3, Fig. 1-4, Fig. 1-5:), partly overlain by moraine. Due to their elevated topographic position, they often show a variable degree of saturation and cementation, both of which may negatively affect seismic coupling and lead to high acoustic attenuation.
- In the JO central plateau, the Quaternary cover is comparably thin, and Deckenschotter gravel deposits are absent (Diebold et al. 2006). Hillslope deposits are occasionally present at the edge of the steep slopes. These deposits are often thin but can complicate shothole drilling. Furthermore, local anomalies in propagation velocities and significant attenuation may occur.

1.3.4 Structural setting

The three siting regions are located in the external northern Alpine Foreland (Fig. 1-1), for which a detailed overview of the tectonic setting is given in Nagra (2024d). Selected aspects are mentioned here to provide the necessary tectonic background for the geological cross sections shown in Fig. 1-2 to Fig. 1-4. The most prominent structures covered in the 3D reflection seismic data of the respective siting regions are in:

- JO: The Jura Main Thrust to the south and the Mandach Thrust to the north (Diebold et al. 2006).
- NL: The Baden-Irchel-Herdern Lineament to the south and the Siglistorf Anticline to the north (Bitterli-Dreher et al. 2007).
- ZNO: The Neuhausen Fault to the northeast (Hofmann 1981).

Folding and thrusting related to the formation of the Jura mountains resulted in the Jura Main Thrust representing the topographic southern expression of the siting region JO and its eastern expression, the Lägern Anticline south of NL. Associated with the Jura Fold-and-Thrust Belt are also the more distal structures encountered in JO (Mandach Thrust) and NL (Baden – Irchel – Herdern Lineament and Siglistorf Anticline). The amount of N-S contraction related to the Jura Fold-and-Thrust Belt is known to decrease eastwards until termination in the southwestern corner of ZNO (Nagra 2024d). The majority of ZNO locates in an autochthonous position (i.e. not affected by contraction related to the Alpine orogeny).

All these structures show evidence for contractional deformation but also precursor normal faulting related to the formation of the Konstanz – Frick trough and the Paleogene normal faulting related to the northward migration of the flexural forebulge (Nagra 2024d). The transtensional formation of the Hegau-Bodensee Graben resulted in the formation of the Neuhausen Fault and high-angle faults encountered in ZNO.

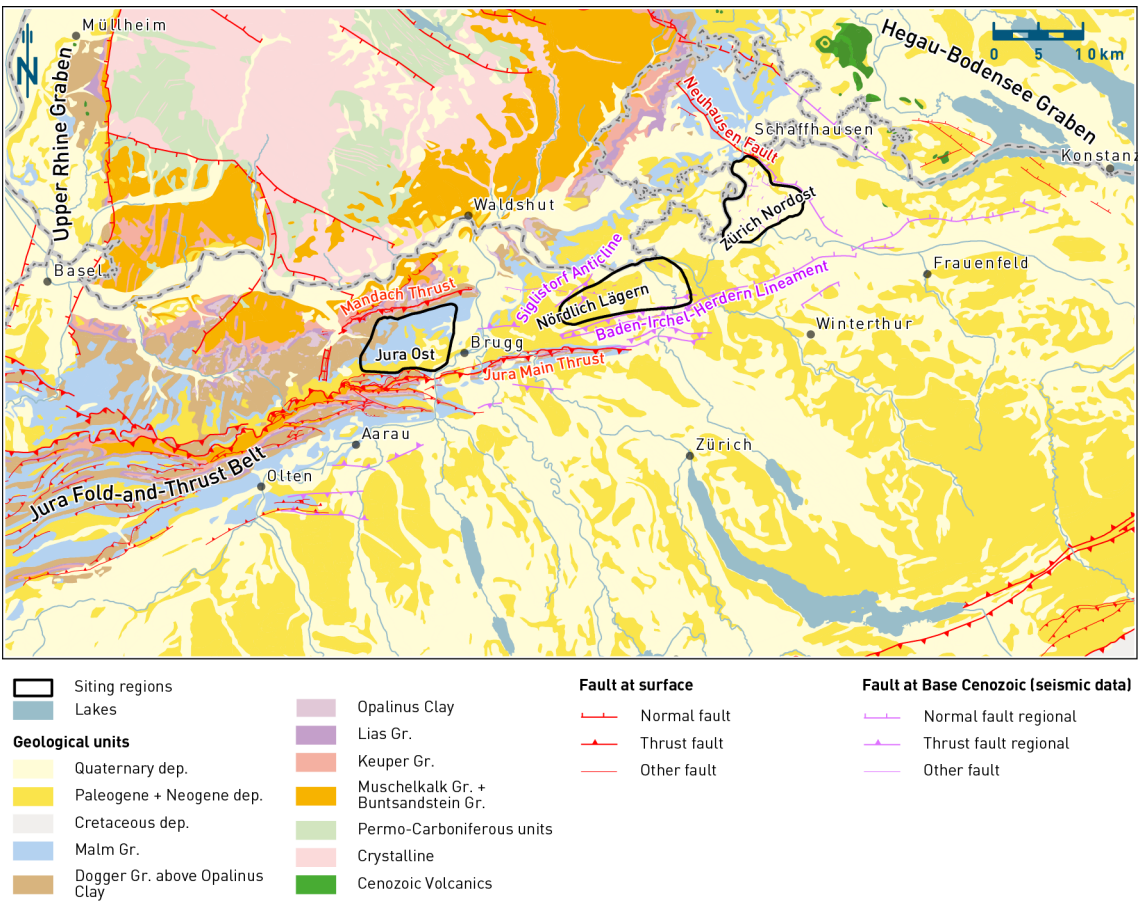


Fig. 1-1: Position of the three siting regions on a geological map of Northern Switzerland

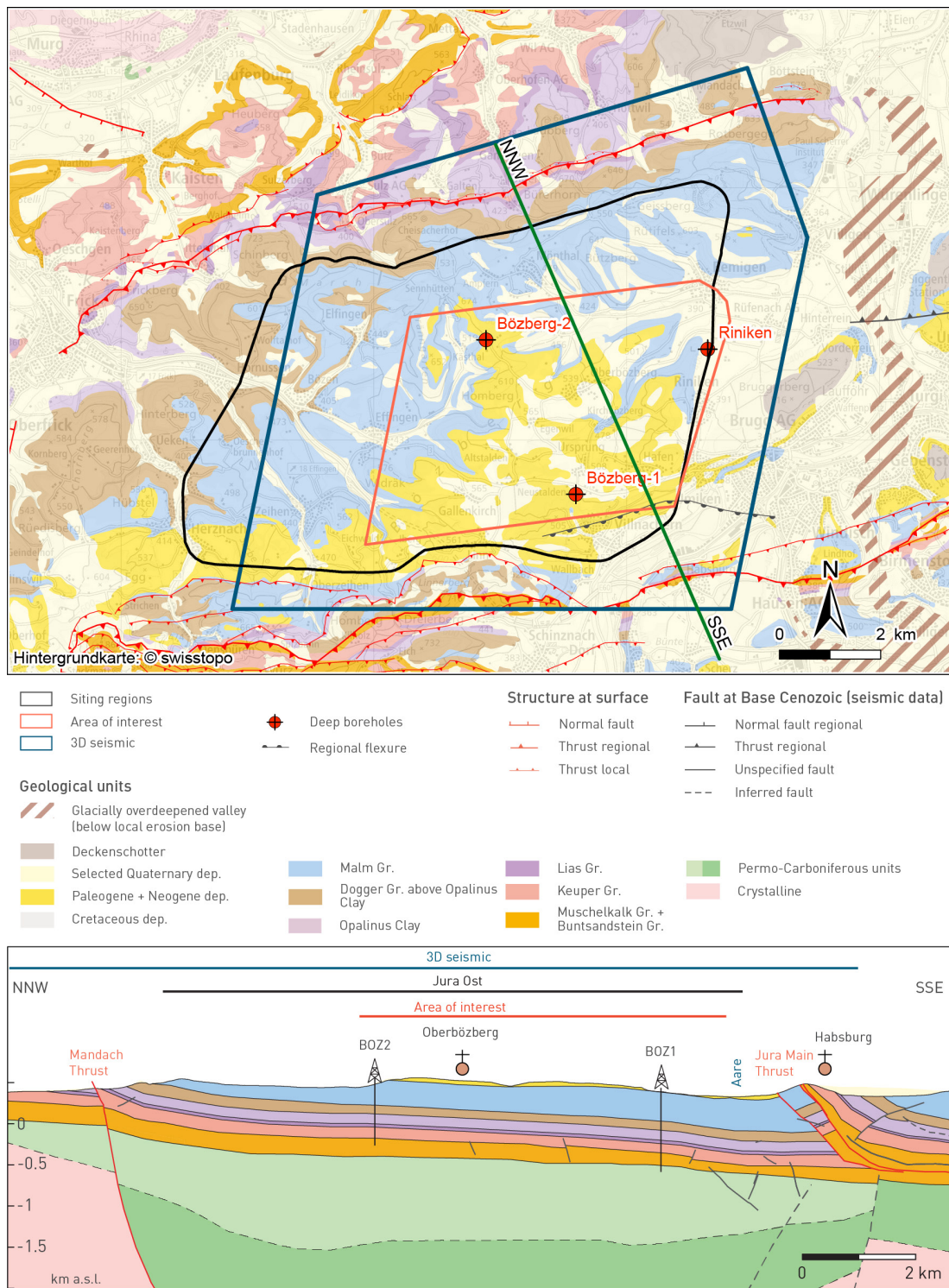


Fig. 1-2: (a) Geological overview map and (b) cross section of the JO siting region

The JO siting region is shown in black, the 3D seismic perimeter in blue, and the area of interest in red. Note the pronounced topography with a rather shallow and thin molasse cover in the centre of the area.

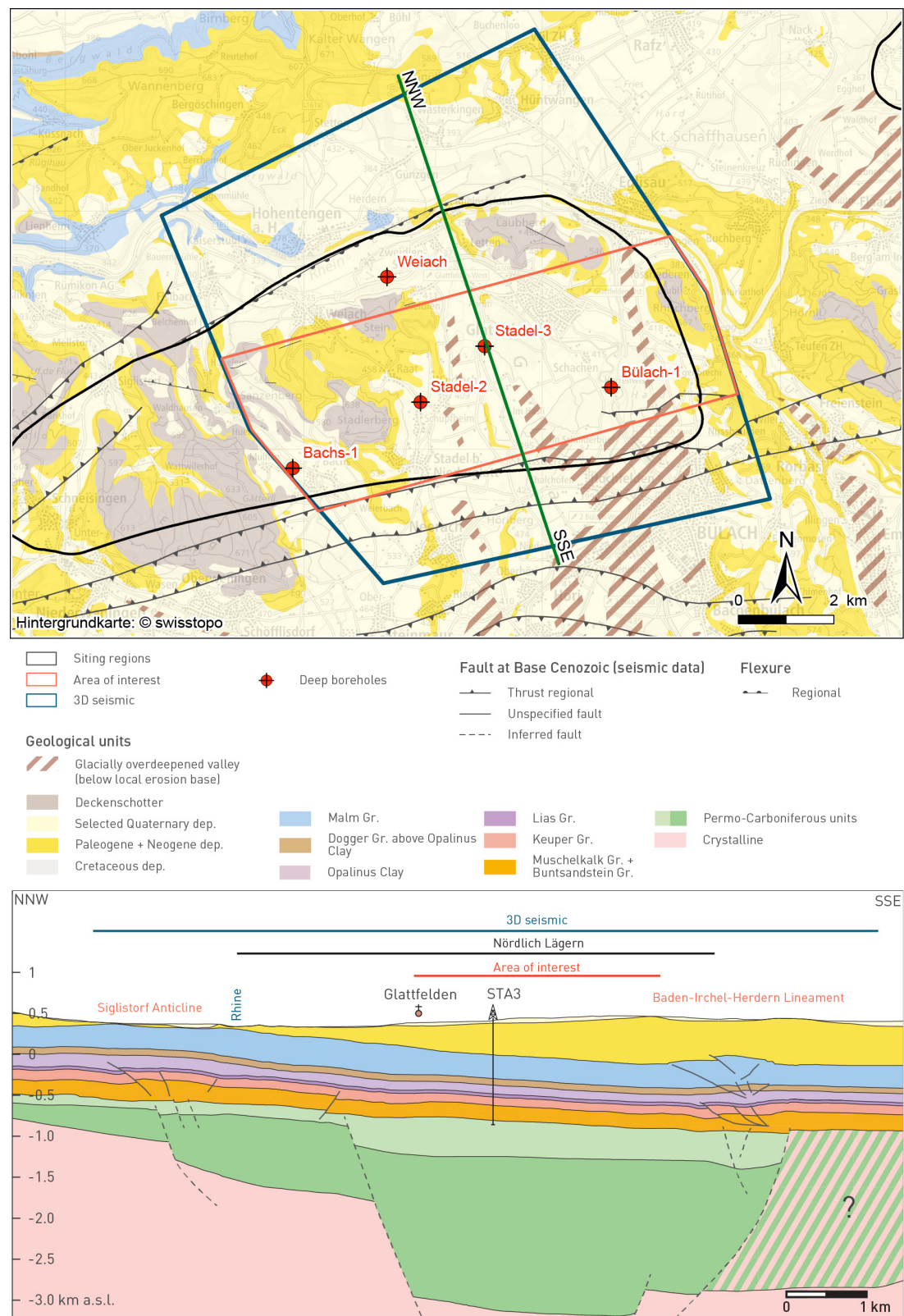
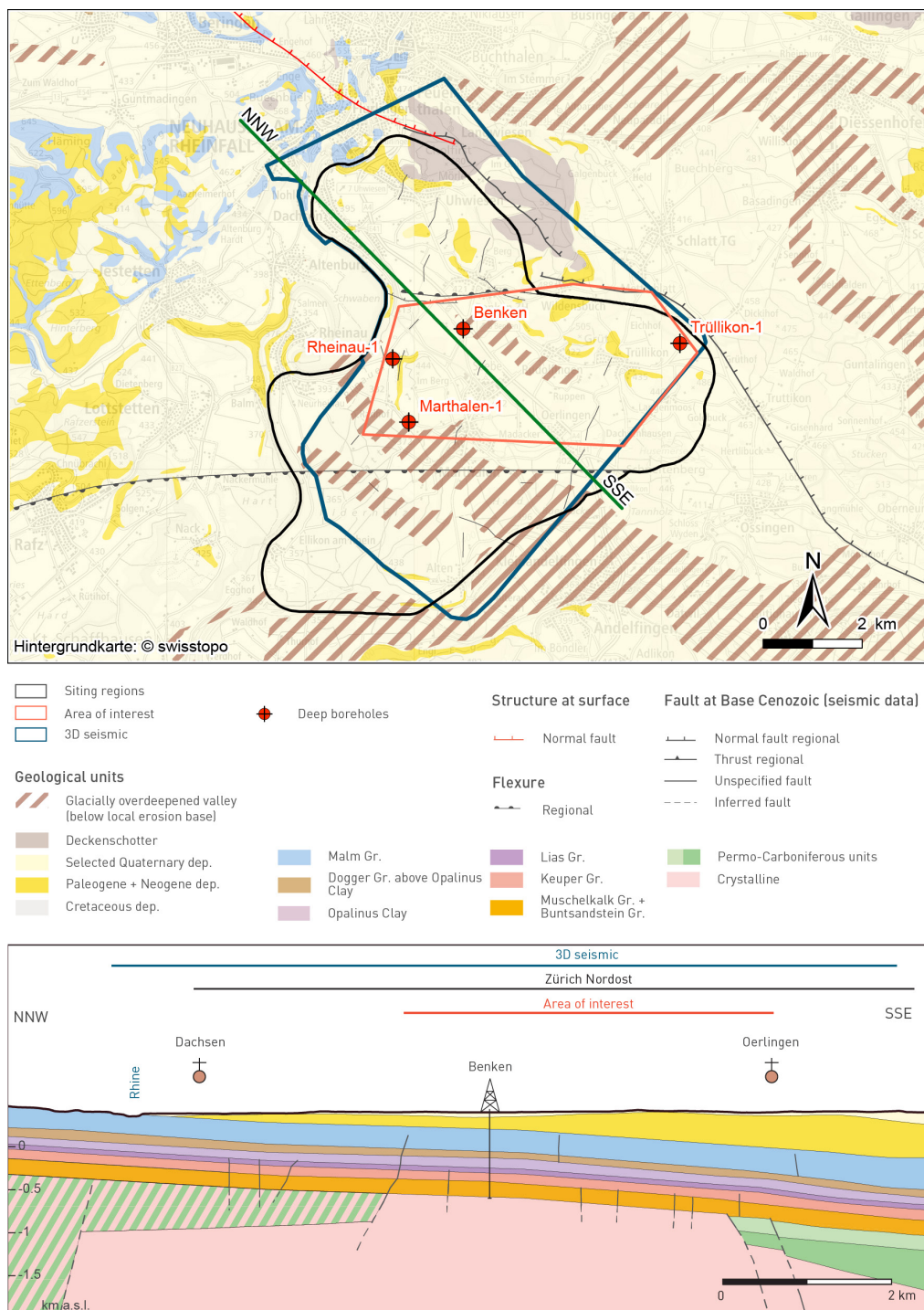


Fig. 1-3: (a) Geological overview map and (b) cross section of the NL siting region

The NL siting region is shown in black, the 3D seismic perimeter in blue, and the area of interest in red. Note the SSE-directed dip of the Mesozoic units and the up to ~450 m-thick Molasse deposit in the central and southern part of the siting region.



1.3.5 Generic acoustic velocity regime

While the near surface geology considerably differs between the three siting regions (Section 1.3.3), the Mesozoic sedimentary structure beneath is comparable. This is highlighted in Fig. 1-5 with the idealised acoustic impedance and P-wave velocities for representative borehole measurements per siting region.

Generic acoustic characteristics, relevant for seismic imaging, of the three siting regions are:

- Small scale lateral velocity variations occur in the Quaternary deposits. The Quaternary deposits exhibit thickness variation between 0 to approximately 40 percent of the target (Opalinus Clay) overburden thickness, hence leading to significant lateral velocity variations.
- Velocity is gradually increasing with depth in the Cenozoic sequence.
- Relatively high velocities prevail in the competent Malm Group with intra-unit lows. Extending partially over ZNO, relicts of the “Plattenkalk” create a distinctive velocity contrast with the Molasse deposits and Felsenkalk unit.
- Significant impedance contrasts occur within the Malm Group.
- Stepped or gradual velocity decrease (velocity inversions) occur towards the Dogger Group.
- In NL, the “Herrenwis unit” within the Dogger Group above Opalinus Clay represents an isolated carbonate platform with strong acoustic impedance contrasts at its top and bottom.
- Relatively low and homogeneous velocities as well as insignificant impedance contrasts occur in the Opalinus Clay target layer.
- Generally increasing but strongly varying velocities occur in the Lias and Trias Groups.
- A laterally varying contrast to the basement, depending on the presence or absence of Permo-Carboniferous sequences (PK-Trough) occur above the crystalline basement.

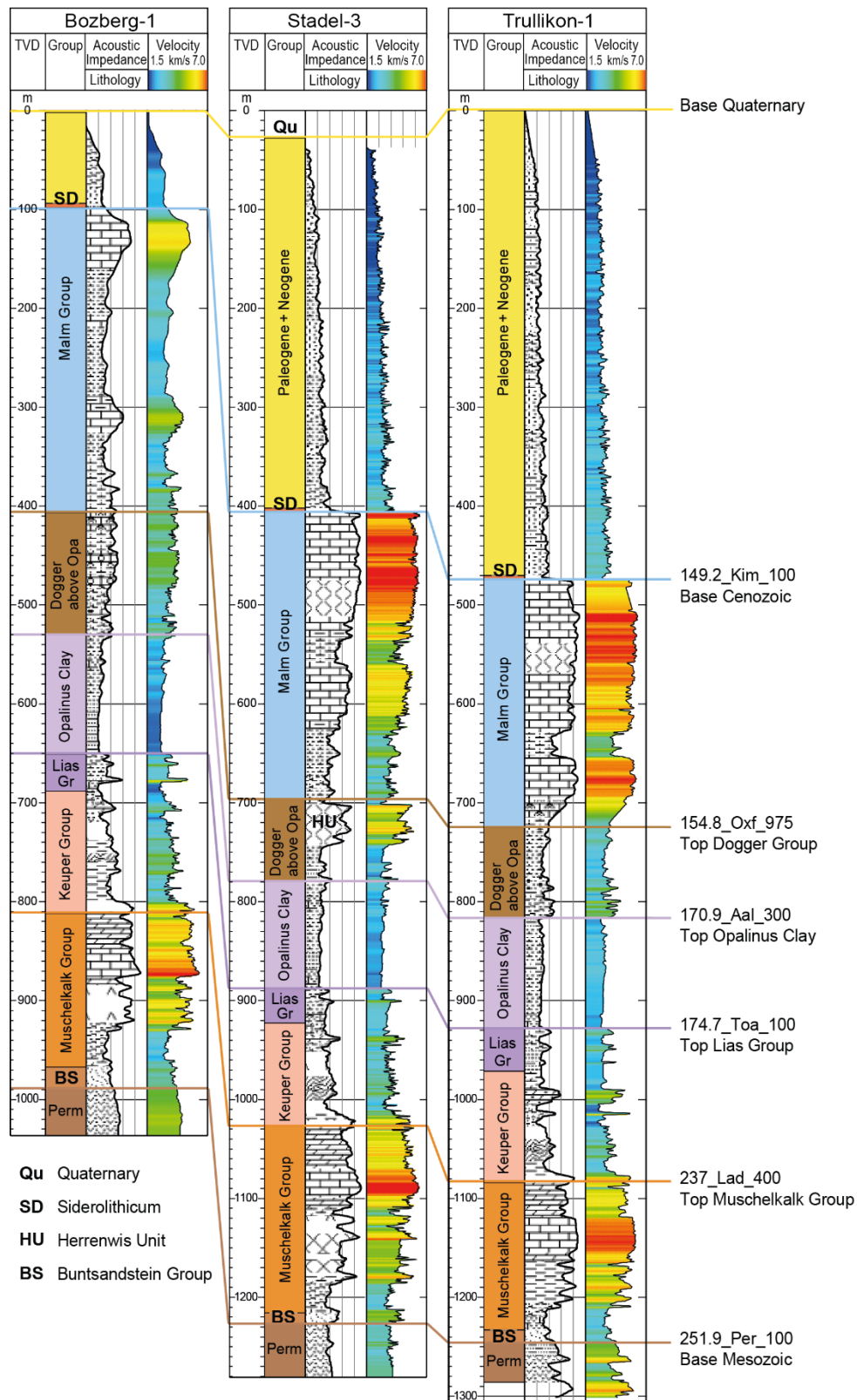


Fig. 1-5: Stratigraphy, idealised acoustic impedance and selected formation tops at three representative boreholes in the JO, NL and ZNO regions (left to right)

Note the strong positive impedance contrast at the base of the Cenozoic Molasse unit and its reduction in the Dogger units below the Malm Group.

1.4 Objectives of the seismic investigations

1.4.1 Requirements

One of the objectives of Sectoral plan stage 3 is to deepen the understanding of the site specific geology using geological investigations such as seismic surveys and boreholes (BFE 2008). Specific requirements on such investigations were formulated in the regulator's document ENSI (2018). Relating to seismic investigations in stage 3 the regulator required that:

- The two 3D seismic datasets acquired in the ZNO region are compatible and allow for a robust site comparison.
- Deep exploration boreholes are drilled and logged to calibrate the 3D data sets in all three siting regions.
- "Tectonic dissection" will be clarified using results from 3D seismic data and boreholes.

1.4.2 Seismic investigation strategy

The requirements as listed above were translated into the following strategy for the seismic investigation. More details on the related processing strategy are provided in Section 3.

1. Do 3D seismic data acquisition with main illumination focus on the host rock at depths between 300 m and 700 m (JO), 450 m and 550 m (ZNO-16), and 500 m and 1000 m (NL). The ZNO-97 vintage 3D survey was considered appropriate for the illumination focus in that area.
2. Perform a robust and conservative Quick Look Processing in the time domain with subsequent interpretation.
3. Perform a detailed Refinement Processing including calibration with geological data from the boreholes drilled during the processing and subsequent interpretation in primary areas of interest (AOI).

1.4.3 Technical objectives for seismic imaging

To fulfil the requirements outlined above, the following technical objectives of the processing were defined as:

- Confident delineation of the Mesozoic sequence, specifically the Opalinus Clay target.
- Consistent imaging of seismically detectable faults and lineaments such that fault pattern across the three siting regions can be compared.
- Optimisation of fault resolution is targeted, within the constraints posed by the seismic data, such as available bandwidth and noise level.
- A reliable and borehole-calibrated depth conversion of time-domain image products for each siting region.

1.4.4 Geology related seismic data processing challenges

While the geology of the Mesozoic sequence is relatively simple, the geology of the overburden (Paleogene / Neogene deposits and Quaternary deposits) poses significant challenges for accurate seismic processing and imaging. The most important of these challenges are:

- Considerable variations in elevation, with differences of up to 400 m, and laterally varying near surface geology occur. This results in considerable short- and long-wavelength statics as well as variable near surface scattering and absorption. The laterally varying near-surface properties also contribute significantly to the uncertainties in depth.

Velocity modelling from surface and imaging in the depth domain aimed to address this challenge.

- In the Quaternary, deep incisive glacial valleys (processing-wise a near surface feature), making up to 40% of the target overburden, lead to relevant heterogeneity of wave propagation velocities and attenuation in the near-surface subsurface.

Near-surface velocity model building included the typically lower velocities in such Quaternary valleys.

- In the Mesozoic units, the high-velocity Malm Group (4,200 – 4,600 m/s) may not only be a source of (interbed and surface) multiples but may also limit the accuracy of velocity picking in the underlying Opalinus Clay, which has significantly lower velocities (3,000 – 3,200 m/s).

Velocity accuracy was improved by including borehole information as it became available during the refinement processing.

- In order to map in detail relevant geological features such as the reef observed during the seismic processing in borehole Bülach-1, a high vertical and lateral seismic resolution is required.

The balance between noise and resolution was shifted towards resolution and a slightly higher noise level was accepted.

- Outcropping complex structures, such as the Mandach Thrust, are very challenging in a Prestack depth migration project.

This was addressed in the JO siting region by defining and focusing on an area of interest (Fig. 1-2) away from the complex structures.

2 The 3D seismic data acquisition

2.1 Introduction

The 3D seismic data acquisition over the three siting regions JO, NL and ZNO required significant field efforts as it was often difficult to ensure unrestricted surface access for receiver and source positioning in these populated areas. In many places, compromises were required between the desired notional and actual source and receiver positions.

The surveys began with a design stage to determine the notional survey parameters and field layout. Subsequent field work involved a roll-over process including permitting with landowners, surveying and stake out of positions, receiver placement, shothole drilling for dynamite sources, shooting/vibrating at the source points, receiver pick-up and culture / cleaning of the site.

This chapter outlines survey design, field parameters and site-specific survey details which are important to understand the data processing, for each of the three siting regions.

2.2 Survey design and field parameters

For each of the three potential siting regions, 3D land seismic acquisition was performed first in the ZNO region (1997 by CGG), and next in JO-15 (2015 – 2016 by DMT), in ZNO (2016 by DMT) and in NL (2016 – 2017 by DMT).

An overview of the parameters of the four surveys is given in Tab. 2-1. The surveys used a mix of dynamite and vibroseis sources. Acquisition parameters were chosen to optimise effective fold on the target formation depth as well as the required field efforts. Differences for the ZNO-97 parameters reflect the state of technology at the time of that acquisition (1997).

Refinement processing was applied to all three siting regions. For the ZNO area both the 1997 and 2015 surveys were jointly processed for the purpose of site selection. The combined survey is referred to as ZNO-97/16.

Tab. 2-1: 3D seismic survey parameters

Survey	JO-15	NL-16	ZNO-16	ZNO-97
<i>Acquisition</i>	2015/10 – 2016/02	2016/10 – 2017/02	2016/03	1997/01 – 1997/03
<i>Survey layout</i>				
Survey type	3D	3D	3D	3D
Survey geometry	Irregular cross-spread	Irregular cross-spread	Irregular cross-spread	Cross-spread
Survey size	92.6 km ²	91.2 km ²	18.3 km ²	48.3 km ²
<i>Source layout</i>				
Nr vibroseis points	16,376	15,000	3,345	2,024
Nr Dynamite points	3,418	2,400	407	6,931
Shot line direction	SWW to NEE	SWW to NNE	NW to SE	NW to SE
Shot line spacing	150 m	150 m (northern part) 180 m (southern part)	150	180
Source spacing	30 m	30 m	30 m	30 m

Tab. 2-1: Cont.

Survey	JO-15	NL-16	ZNO-16	ZNO-97
<i>Receiver layout</i>				
Nr Geophone points	25,947	20,250	5,055	9,036
Rec-line direction	NNW to SSE	SSE to NNW	SW to NE	SW to NE
Rec-line spacing	120 m	150 m	120 m	180 m
Geophone spacing	30 m	30 m	30 m	30 m
Active geophones	16 rec lines 90 per line Split spread	16 rec lines 90 per line Split spread	16 rec lines 70 per line Split spread	8 rec lines 60 per line Split spread
<i>Bin layout</i>				
Bin size	15 m × 15 m	15 m × 15 m	15 m × 15 m	15 m × 15 m
Notional fold	58 (8 il x 7 xl)	56 (8 il x 7 xl)	56 (8 il x 7 xl)	20
<i>Vibroseis parameters</i>				
Vibroseis pattern	2 Vibrators	1 – 2 Vibrators	2 Vibrators	3 Vibrators
Sweeps per VP	2 – 3	2 – 4	2 – 3 (and 4 – 6)	6
Sweep type	Linear	Linear	Linear	Non-Linear +3dB/ Flat spectrum
Sweep range	10 – 120 Hz	10 – 120 Hz	10 – 120 Hz	10 – 100 Hz
Sweep length	18 sec	18 sec	18 sec	12/24 sec
<i>Dynamite pattern</i>				
Nr of holes	3	3	3	1-3
Distance	3 m	3 m	3 m	-
Depth	8 m	8 m	8 m	6 – 12 m
<i>Receiver parameters</i>				
Receiver pattern	12 per group Inline array 25 m or bunched	12 per group Inline array 30 m or bunched	12 per group Inline array 25 m or bunched	18 per group (2 × 9) Inline array 30 m or bunched
Geophone type	Sercel JF-20DX	Sercel JF-20DX	Sercel JF-20DX	Sensor SM4U mB
Polarity	Standard SEG Y	Standard SEG Y	Standard SEG Y	Standard SEG Y
<i>Data parameters</i>				
Trace sampling	2 ms	2 ms	2 ms	2 ms
Trace length	4 s	4 s	4 s	4 s
Polarity	SEG	SEG	SEG	SEG
Low cut filter	Out	Out	Out	Out
High cut filter	200 Hz Anti Alias	200 Hz Anti Alias	200 Hz Anti Alias	200 Hz Anti Alias

2.3 Specifics of the Jura Ost JO-15 survey

The Jura Ost survey JO-15 is located in the Bözberg area in Northern Switzerland. Survey design is a combination of orthogonal and irregular field layouts (e.g. Cordsen et al. 2000). The receiver or in-lines (IL) paralleled the dip direction of the Mesozoic strata in NNW-SSE direction. The notional cross-spread layout with cross-lines (XL) was approximated with actual source locations allowed to deviate using the existing network of roads. This facilitated an efficient and maximal use of vibroseis acquisition even on challenging topography. Essential survey parameters are given in Tab. 2-1, the resulting survey layout is shown in Fig. 2-1.

Three boreholes were drilled within the survey perimeter, one in 1983 – 1984 (Matter et al. 1987), and the two others recently as part of the recent exploration campaign: BOZ-1 (Nagra 2022a) and BOZ-2 (Nagra 2022b).

In Fig. 2-2 the surface elevation, which varies between 340 m and 720 m, is plotted, illustrating the pronounced topography within the survey areas. Receiver and source positioning is shown in Fig. 2-1 together with labels of the notional in-line / cross-line grid. Receiver positioning (in green) is generally quite close to the notional one. Vibroseis source locations meanders around the notional location. In some places infill with explosive sources was required. The resulting effective fold map is shown in Fig. 2-2. The local high fold block (yellow box in Fig. 2-2) resulted from access limitations due to a quarry in the area.

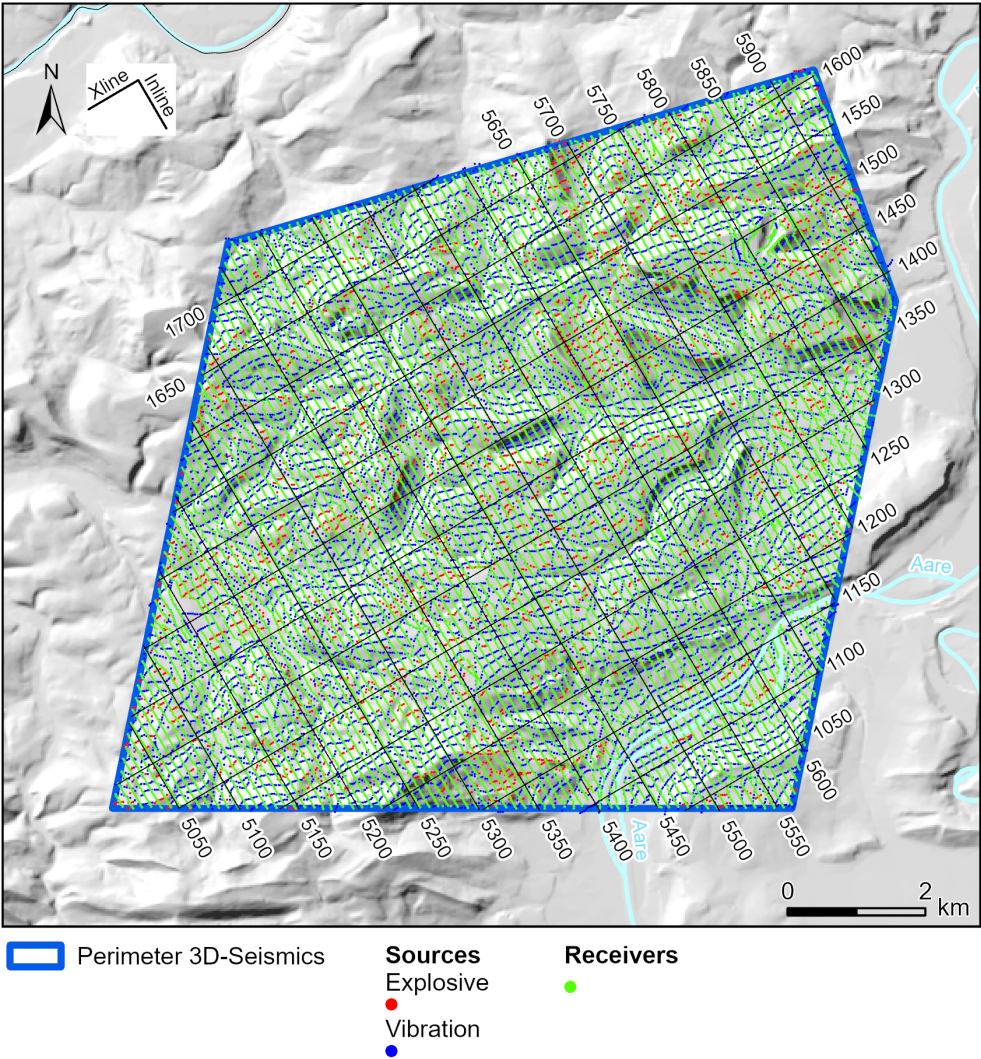


Fig. 2-1: Outline and layout of the JO-15 seismic survey

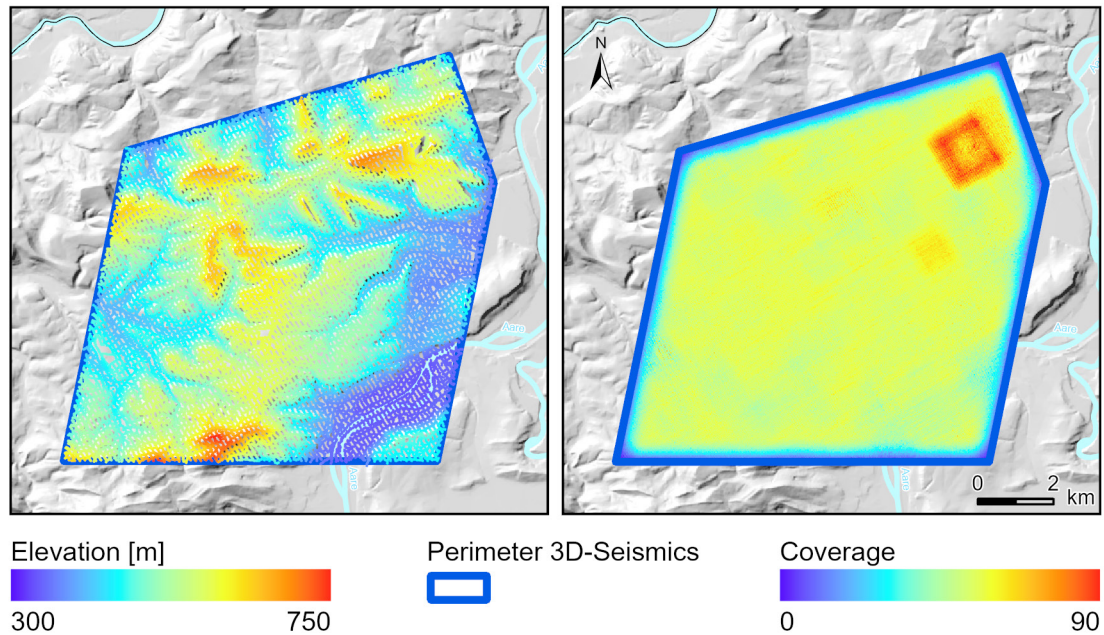


Fig. 2-2: JO-15 elevation (left) and effective fold of coverage on Top Lias Group (right)

2.4 Specifics of the Nördlich Lägern NL-2016 survey

The NL-16 survey was located in the northern part of Kanton Zürich and also covers the eastern part of Kanton Aargau and an area in Germany north of the Rhine river. The same combination of orthogonal and irregular survey layout as in JO-15 was used in NL. Essential survey parameters are given in Tab. 2-1, the resulting survey layout is shown in Fig. 2-3. Receiver line (Inline) was directed NNW-SSE, with receivers close to the notional position. The notional source line direction (cross-line) was WSW-ENE. Since the use of vibroseis on agricultural land was not permitted, the vibroseis pattern varied to make use of the existing network of roads and tracks. Infill explosive sources filled gaps in areas not accessible for Vibroseis.

The northern part of the survey, beyond the area of main interest, crossed the Rhine and was located on German territory. Two separate recording systems and two vibroseis fleets were used north and south of the Rhine. Combination of the two recordings was part of the data conditioning (Hölker & Birkhäuser 2018).

Data from five boreholes was partly available: Weiach (drilled in 1983, Nagra 1989), Bülach-1 (Nagra 2021a), Stadel-2 (Nagra 2022c), Stadel-3 (Nagra 2022d) and Bachs-1 (Nagra 2023a) which were drilled in the course of the 3D seismic refinement processing project.

The elevation and maximum fold of the NL-16 survey are shown in Fig. 2-4. Maximum fold considers all acquired data and is higher in the north than in the south due to the narrower notional source line spacing there (150 m vs 180 m, see Tab. 2-1)

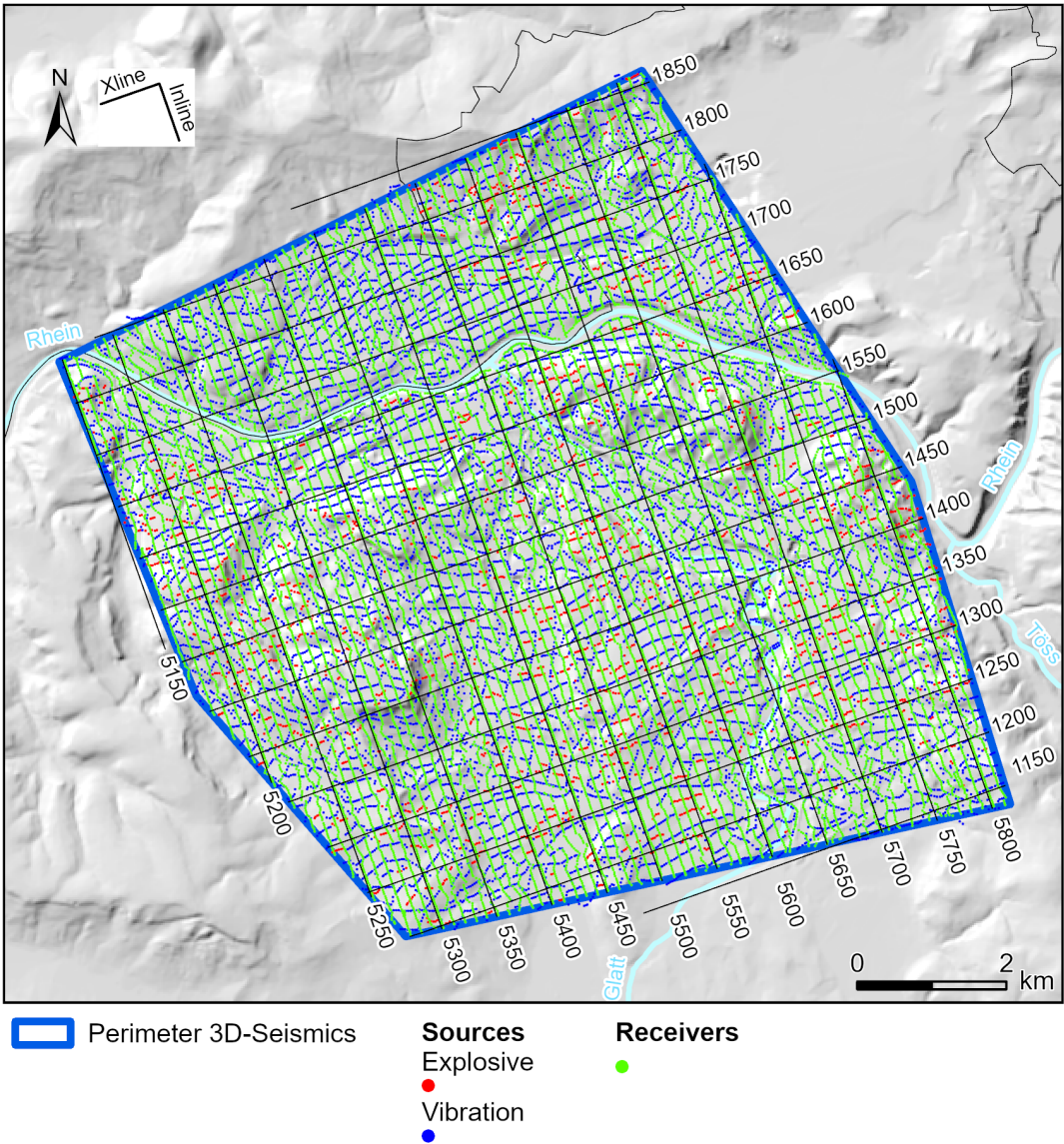


Fig. 2-3: Outline and survey layout of the NL-16 3D seismic survey

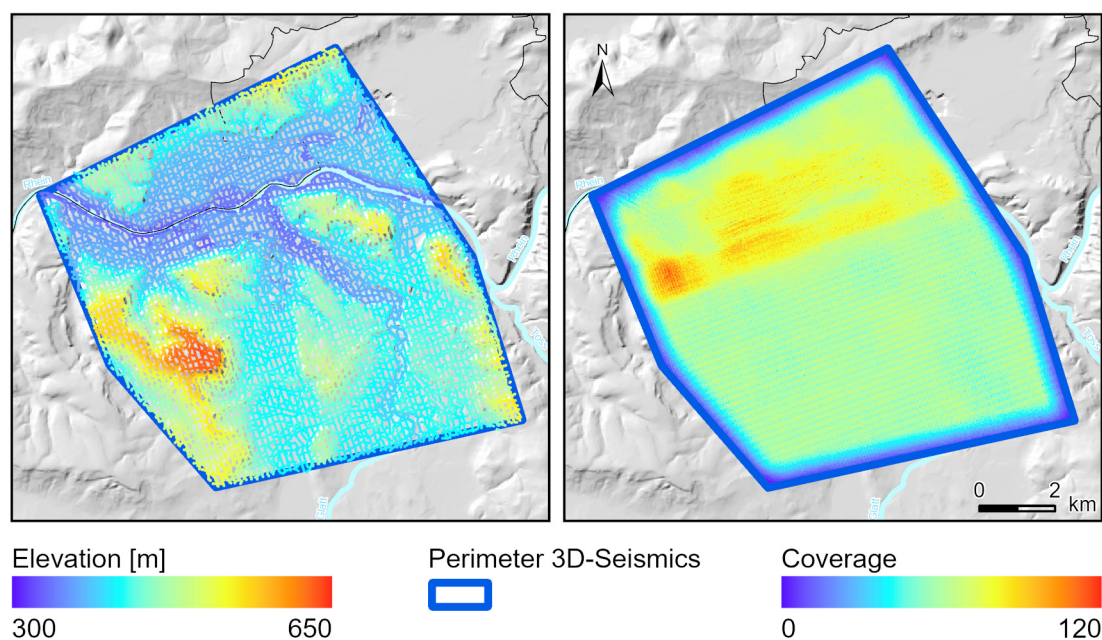


Fig. 2-4: NL-16 survey elevation (left) and effective fold of coverage at Top Lias Group (right)

2.5 Specifics of the Zürich Nordost ZNO-2016 and ZNO-1997 surveys

The ZNO surveys are located in the Zürcher Weinland area of northeastern Switzerland. The larger of the two, the ZNO-1997 was acquired in 1997 by CGG using a traditional cross-spread layout. In 2015 a smaller but denser survey was acquired in the northwestern part of the 1997 survey by DMT using the orthogonal and irregular layout. Both receiver and source line distances were reduced in the modern survey (Tab. 2-1) to (i) enhance fold over the northern survey area with shallower strata, and (ii) extend the survey perimeter slightly to the north. As can be seen in Fig. 2-5 the two surveys mostly overlap.

Data from four exploration boreholes was becoming available during the project corresponding to the drilling progress: Benken (drilled 1998 – 1999, Nagra 2001), Trüllikon-1 (Nagra 2021c), Marthalen-1 (Nagra 2021b) and Rheinau-1 (Nagra 2023b), drilled 2019 – 2021.

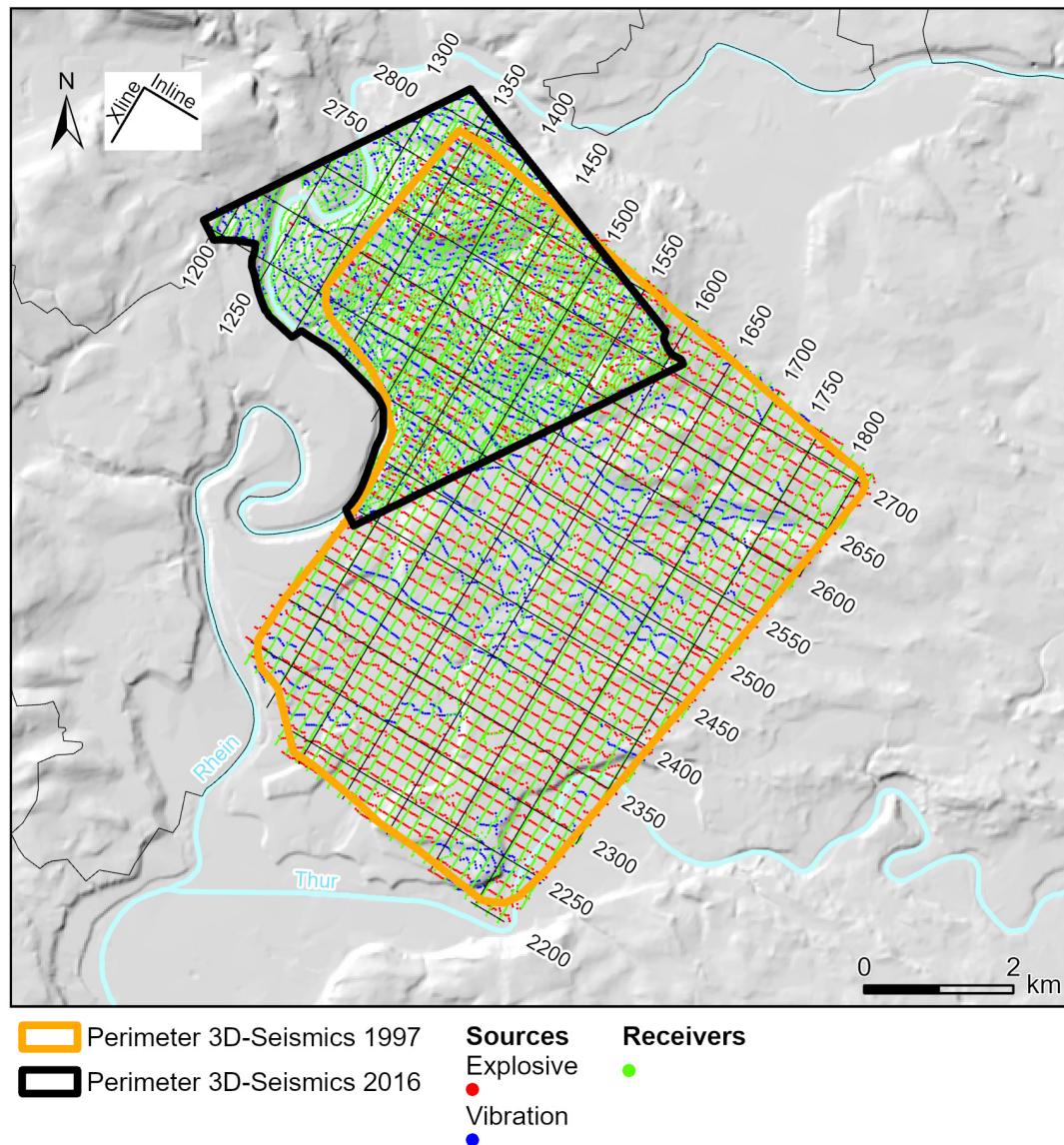


Fig. 2-5: Outline and survey layout of the combined ZNO-97/16 3D seismic survey

The vibroseis pattern was varied a bit where required by local conditions. In some areas the receivers were bunched. In general, as can be seen in Fig. 2-5, actual receiver positions (lines running SW-NE) were mostly close to the notional position. For most part of the ZNO-97 survey, the actual source positions are also reasonably close to the notional position. In the North-west they are, however, more irregular as dictated by local circumstances.

The left plot of Fig. 2-6 shows the elevation at shot and receiver positions varying from about 350 m (blue) in the south to 570 m (red) in the North. The effective fold of coverage of the combined surveys is shown in Fig. 2-6 (right). The fold map of the combined surveys illustrates the resulting high fold area in the northern part, where both surveys spatially overlap.

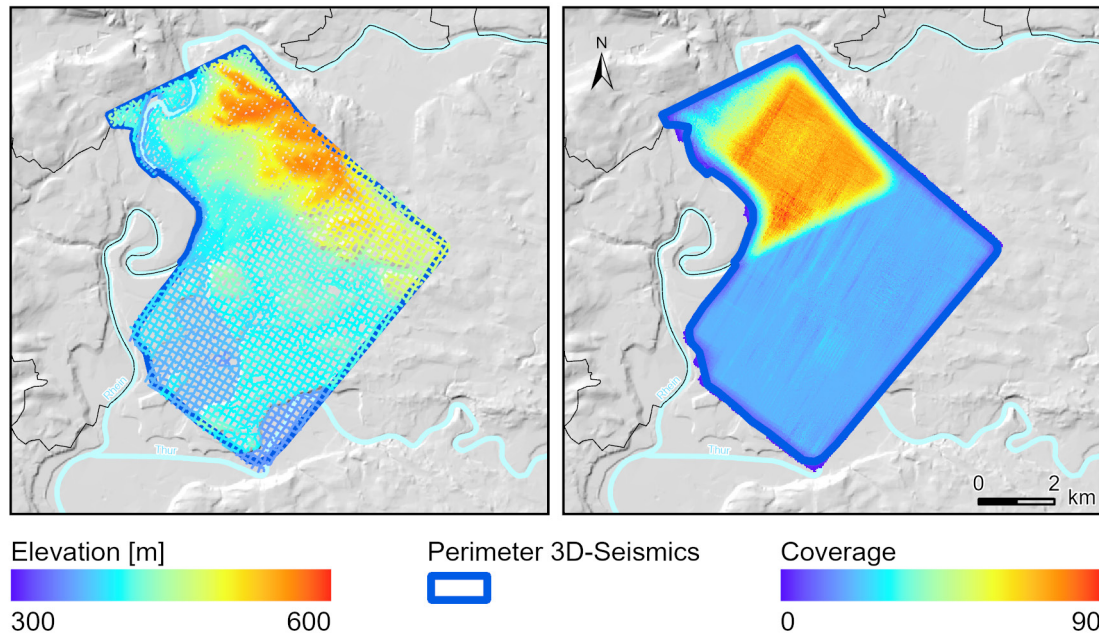


Fig. 2-6: ZNO-97/16 survey elevation (left), and effective fold of coverage on Top Lias Group (right)

2.6 Processing challenges posed by the seismic acquisition

The acquisition parameters chosen for the surveys create some limitations for the processing, notably:

Acquisition bandwidth: The vibroseis sweep for all surveys (10 – 100/120Hz) already limits the bandwidth on the low side to 10 Hz. Moreover, in practice the usable bandwidth at the low side is, especially at the near offsets, is further restricted by the low frequent noise dominating the spectrum up to about 20 Hz. At the high end of the spectrum, near-surface absorption and scattering significantly further limit the bandwidth of the data and thereby the resolution.

Sweep taper: The linear vibroseis sweep also has a relatively short taper, which yields a waveform with significant side lobes after correlation (non-causal energy). This e.g. reduces accuracy of (automatic) first arrival time picking.

Acquisition layout: The acquisition layout that was achieved in practice does not allow direct signal processing in the cross-spread domain. This makes it difficult to apply the standard ground roll attenuation methods such as 3D FK and 3D Radon filters.

Resolution of the LVL surveys: the Low Velocity Layer (LVL) surveys carried out as an additional characterisation of the near surface (weathering layer), provide only local information and do not have the resolution to sample the rapid lateral velocity variations.

3 Processing strategy

The seismic data processing of the three surveys was conducted into two stages, first the Quick Look Processing (QLP), which was followed by Refinement Processing (REP). Fig. 3-1 depicts simplified workflows for the two processing stages.

The QLP stage included several modules on:

- i. Data preparation and conditioning, including first break picking.
- ii. Basic and conservative signal processing – also used as input for the REP.
- iii. Pre-stack imaging in the time domain.
- iv. Followed by post-stack imaging in the depth domain.

The REP stage included:

- i. Detailed velocity model building in the depth domain aiming at obtaining a high spatial fidelity and improved imaging quality.
- ii. Producing an imaging result in the depth domain.
- iii. Followed by refined imaging in the time domain, leveraging improved velocity analysis.

3.1 Objectives and execution of the Quick Look Processing

The QLP was the first data processing of the 3D seismic data that was acquired in 2015-2017. It included a reprocessing of the existing survey ZNO-97 by merging it with the newly acquired ZNO-16. The merged survey is referred to as ZNO-97/16. The QLP products formed the basis for a first geological interpretation of JO-15, NL-16, and the merged ZNO-97/16 area (the ZNO-97 area was reinterpreted).

The QLP was separated into Modules A (geometry assignment, first break picking), B (signal processing, statics), C (stacking and migration) and D1 (pre-stack time migration 1), D2 (pre-stack time migration 2) as summarized below in Chapter 4 and detailed in Hölker & Birkhäuser (2018). The upper part of Fig. 3-1 provides a graphical representation of the modularized QLP workflow and resulting products, a summary of which is given in Chapter 4.

Modules A, B and D1 were carried out by Geofizyka Toruń S.A. TEEC GmbH carried out modules C and shared work on modules D1b and D2 with DMT Petrologic GmbH. Geophytex GmbH was assigned the technical project management and quality control.

3.2 Objectives and execution of the Refinement Processing

To deliver a higher quality result needed for comparative interpretation in the siting areas, the refinement processing (REP) was carried out as detailed in Chapters 5, 6, and 7 of this report.

The REP objectives included the creation of detailed and accurate seismic images in the depth domain, referred to as Pre-stack depth migration (PreSDM) images. This method required site-specific representation of the velocity structure in great detail. Hence, subsurface velocity models for each of the siting regions were constructed to be used for the Pre-stack depth migration.

It was decided to use established technologies during this stage of the processing. This was first of all to minimise technical risks. In addition, results had to be available within a reasonable timeframe. For the purpose of site comparison and selection, good structural imaging and interpretation was considered key and other aspects, such as amplitude preservation, were considered to be of secondary importance.

The lower part of Fig. 3-1 provides a simplified graphical representation of the REP tasks and results. Development of the velocity models was separated into two stages. In the first stage, carried out by Augeos, a near surface velocity model was constructed using the first break picks as delivered by Module A of the QLP. In the second stage, carried out by TEEC, the near surface velocity model was extended to deeper levels, leading to a Pre-stack depth migration of the full volumes.

In the third stage a Pre-stack time migration (PreSTM) was carried out by TEEC to obtain migrated volumes for the three areas that enabled direct comparison.

To maximise comparability between the three sites and minimise imaging artefacts, pre-stack time migrations were also delivered with the parameter choices as similar as possible for the three sites. Being less prone to artefacts and providing better continuity, these PreSTM-ref products served as the key product for interpretation. The PreSTM-ref processing task was carried out by TEEC.

The improved velocity models obtained in the REP also provided input to the time to depth conversion of time products and a good match to the seismic velocities observed in the borehole logs and VSP measurements. At a later stage, following initial interpretation, zero phasing filters were derived and applied for the three areas to enable direct matching of the seismic to well synthetics.

The resulting seismic volumes, notably the PreSTM-ref supported by the PreSDM volumes, were used for comparative interpretation (Nagra 2024a, Nagra 2024b, Nagra 2024c)(Nagra 2024a, Nagra 2024b, Nagra 2024c).

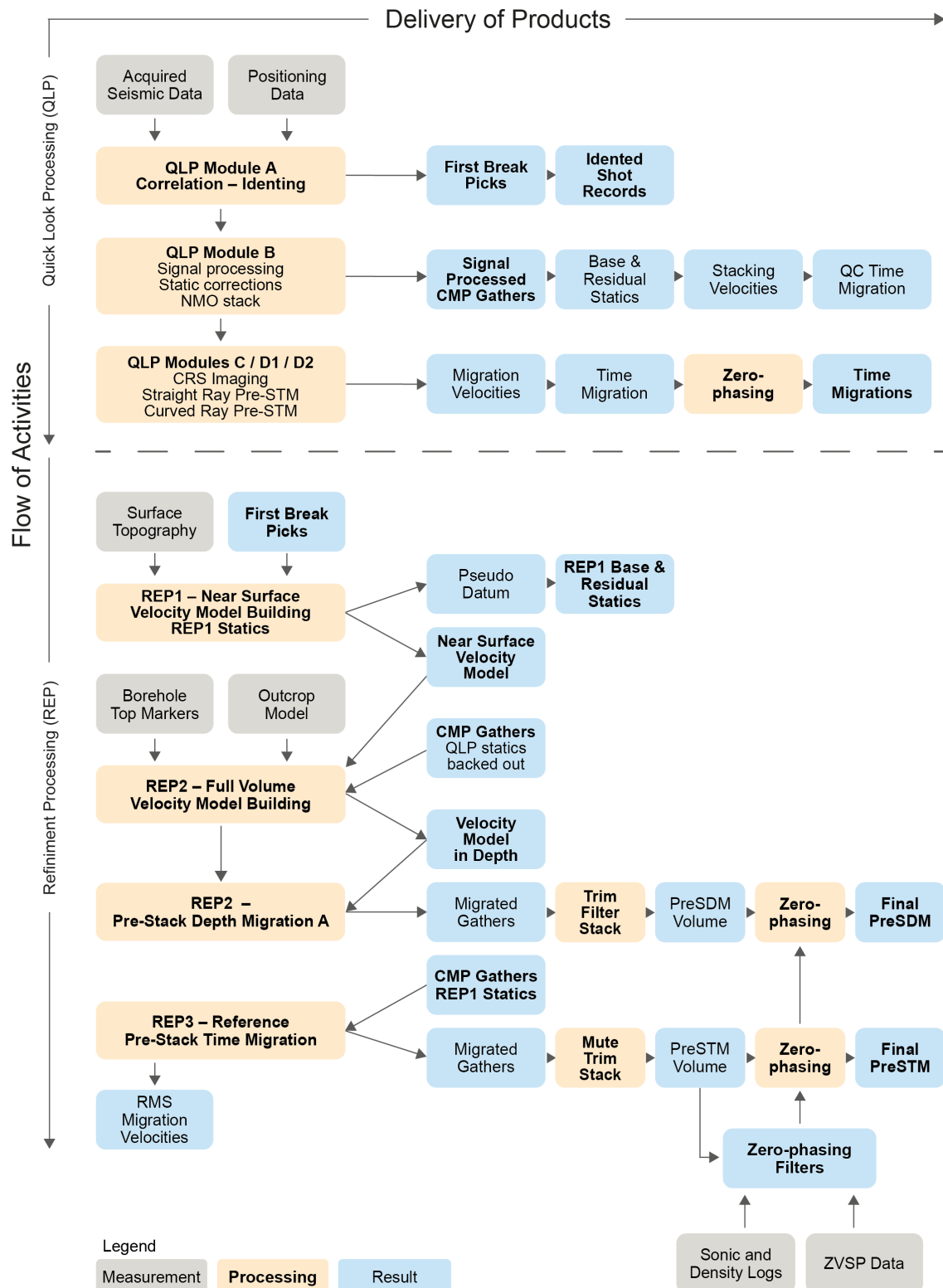


Fig. 3-1: Simplified summary of the full project processing flow; QLP applied in 2016 – 2017 and REP in 2019 – 2021

4 Summary of the quick look processing

This chapter provides a summary of the quick look processing (QLP) applied. Fully detailed reporting can be found in Hölker & Birkhäuser (2018). It clarifies the interface between QLP signal processing products used as input for the REP as well as the QLP imaging products and REP imaging products reported in Chapter 5. Finally, essential outcomes of the QLP and motivations for the REP are discussed.

4.1 Signal processing sequence (Module A)

All signal processing was done as part of the QLP stage – no new signal processing happened in the REP stage. The main signal processing steps which have been applied and the data used and produced are summarized in the workflow chart of Fig. 4-1 below. The identified CMP domain signal processed gathers produced in Module B are the main deliverable used for further imaging.

Minimum phase identified shot records in SEG-Y format (with first break times in headers) with and without diversity stacking were produced as an intermediate product in Module A. These gathers have been archived to enable a quick start in potential further processing.

4.1.1 Conversion to minimum phase

For all surveys the vibroseis data was converted from zero phase to minimum phase and matched to the dynamite data. In all cases the conversion filter was calculated from the sweep parameters. For the NL-16 and the JO-15 surveys, only a single filter was required. For the ZNO-97 survey two filters had to be calculated, one for the linear sweep and one for the flat-spectrum sweep. Additionally, the ZNO-15 required the filter for the standard 10 – 100 Hz sweep. Furthermore, the polarity of the vibroseis records was reversed to match the polarity of the dynamite data. The amplitude of the first arrival was now negative for all records.

4.1.2 First break picking

Using the minimum phase data, first break picking was done in Module A for all surveys. In principle, as the data is minimum phase, the zero crossing prior to the first arrival should be picked as correct first-break time. In practise, as the onset was not always clear, picking was done on the first through (ZNO, JO-15) or peak (NL-16) and then shifted by -9, -10 or -20 ms respectively to align with the first break. Depending on the survey different approaches were followed.

The JO-15 survey first arrival times were 28% hand-picked; the rest was auto-picked. To account for the different quality of the picks (where automatic picks are expected to be less reliable), the two different types of picks were weighted during the inversion (manual picks = full weight, automatic picks = 0.5 weight). Picking was done on the first through and shifted 10 ms upwards.

For the NL-16 survey first arrival times were 40% hand-picked; the rest was auto-picked. To account for the different quality of the picks (automatic picks are expected to be less reliable), the two different types of picks were weighted during the inversion (manual picks = full weight, automatic picks = 0.5 weight). There was an efficient and functional prediction of first arrival times based on the hand-picked subset to guide and control the auto-picking. Hand- and auto-picked times were reviewed systematically and are considered good and fit for purpose. First arrival times were picked on the first peak (not onset) and subsequently shifted 20 ms upwards.

For the ZNO surveys first arrival times were 100% manually picked on the first through and then shifted 9 ms upwards. Pick quality was good here as most of the data was acquired with dynamite sources.

4.1.3 Merge of datasets (ZNO only)

For the ZNO surveys, merging of the two datasets was an additional step as compared to the NL-16 and the JO-15 surveys. Technically, the two surveys ZNO-97 and ZNO-16 were treated independently in Modules A and B, and merged to ZNO-97-16 in the imaging module D. Both the bin-size and the orientation of the ZNO-16 had been chosen such that this was relatively easy. Merging required some renumbering of shot and receiver points to avoid duplication. As the acquisition parameters (sweep, dynamite settings, instrument etc.) for the surveys were different, the parameters tests for signal processing and noise attenuation were done separately.

QLP A+B: Signal Processing Sequence

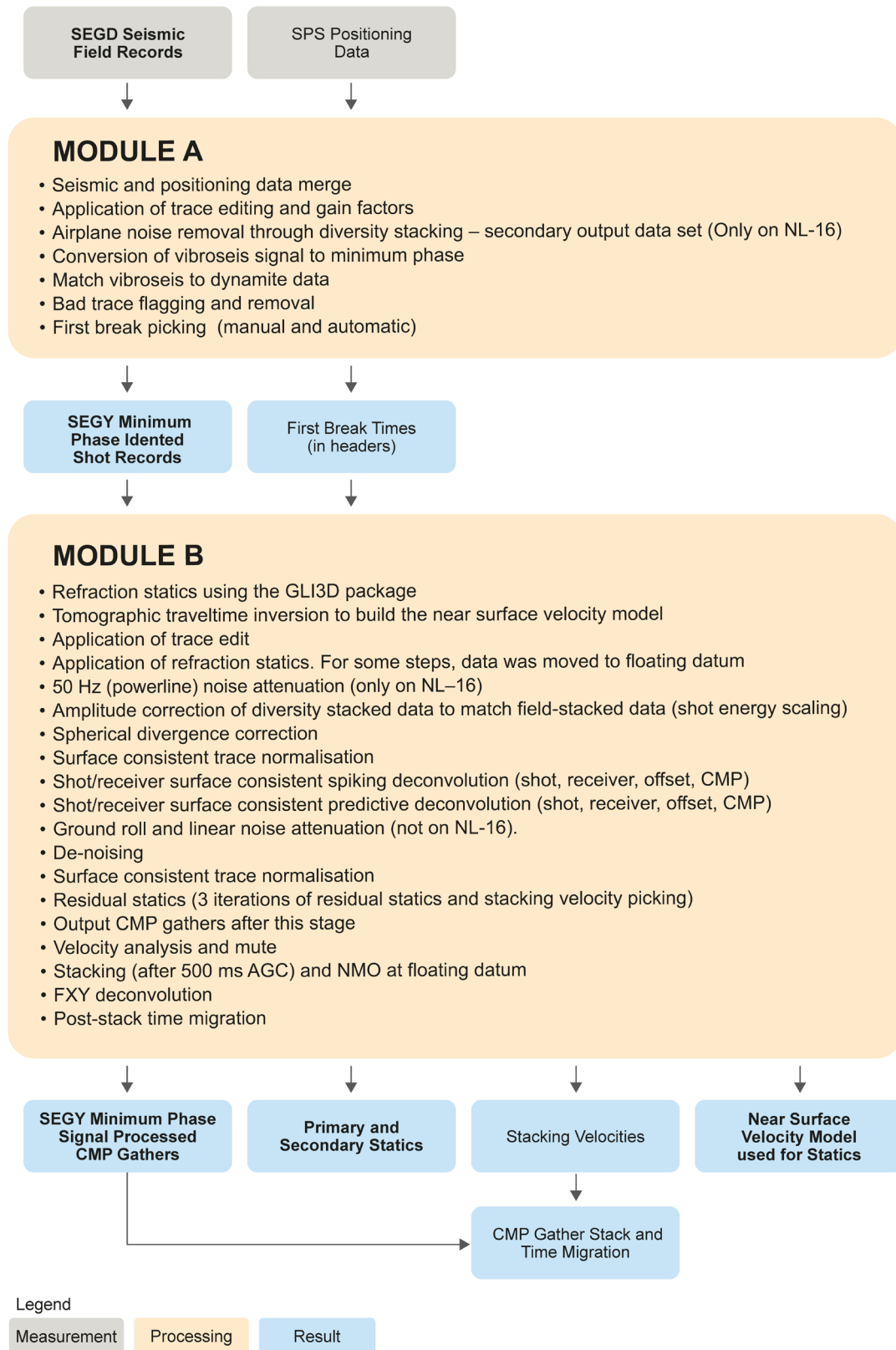


Fig. 4-1: Workflow of the QLP Modules A and B (Signal Processing)

4.2 Main signal processing steps and statics corrections (QLP Module B)

4.2.1 Refraction statics

In order to remove the effect of topography and shift the survey to a flat Seismic Reference Datum (SRD), the primary statics are applied. Using the first break picks as obtained in module A, refraction statics determination was run for the three surveys. The principle of this is sketched in Fig. 4-2. Refraction statics computes travel-times t_{down} from the acquisition surface down to the pseudo datum. This travel-time is replaced by the theoretical t_{up} that is based on the replacement velocity. The combined effect of these two travel-times shifts the survey to the flat (SRD).

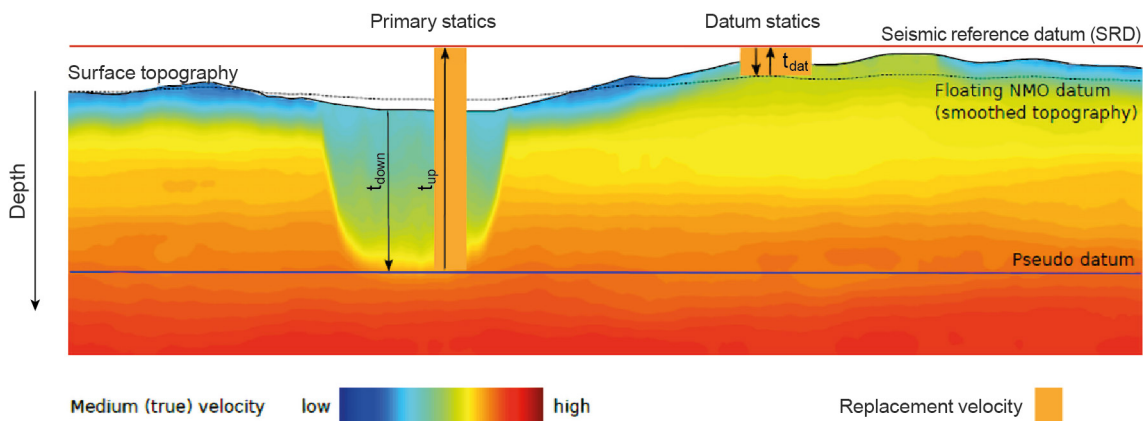


Fig. 4-2: Refraction and datum statics model

Low-velocity incision indicates existence of a Quaternary valley. t_{down} : travel-time from topography to PD using medium velocity, t_{up} : travel-time from PD to SRD using replacement velocity.

The choice of the replacement velocity is generally governed by the velocities between the surface and the pseudo datum which was at 100 m above sea level for all surveys. The elevations of the Seismic Reference Datums and the replacement velocities for each of the surveys are summarised in Tab. 4-1.

Tab. 4-1: QLP seismic reference datum and replacement velocity

Survey	Seismic reference datum	Replacement velocity
JO-15	750 m	3,800 m/s
NL-16	650 m	3,500 m/s
ZNO-97 and ZNO-16	600 m	3,500 m/s

4.2.2 Spherical divergence correction

For JO-15 the spherical divergence correction was multiplication with $t^{1.8}$. For NL-16 the exponent was 2.0 and for ZNO the exponent was 2.2. The optimal factor depends on local sub-surface velocities as the drop in amplitude is distance rather than time related.

4.2.3 Surface consistent amplitude normalisation

For all surveys surface consistent amplitude normalisation was applied twice. First after the spherical divergence correction and a second time after the deconvolution, linear noise attenuation (if applicable), time/frequency denoising and air blast attenuation. The second application was done in three iterations, and after each iteration, data was run through a noise attenuation process in which noise burst and spikes were identified through sliding window amplitude comparison and scaled down.

4.2.4 Deconvolution and ground roll attenuation

In order to determine deconvolution parameters and the potential for removal of linear noise a similar testing procedure was carried out for all three areas.

Typically for data acquired with a cross-spread layout, 3D Radon filtering or 3D FK filtering is applied in the cross-spread panels for linear noise removal. Due to the irregular survey layout the cross-spread domain was too randomly sampled for either of these to be effective. 2D Radon filtering was tested on shot/halve-receiver-line records.

For both the JO-15 and the ZNO-97/16 surveys, 2D Radon filtering proved beneficial, so it was applied. For the NL-16 survey 2D Radon filtering was tested but appeared not to be beneficial and no Radon filtering was applied. On all surveys air blast attenuation and a (low frequency) noise adaptive filter was applied.

Surface consistent whitening deconvolution followed by surface consistent gapped deconvolution was applied. As can be seen in Fig. 4-3 the whitening acted as a low-frequency attenuation filter, suppressing the ground roll and the signal below the ground roll in the same amount. The offsets inside the ground roll cone therefore remained unusable at low frequencies.

Air blast removal was done on all surveys. Additionally, the data was passed through a time-frequency domain noise rejection process.

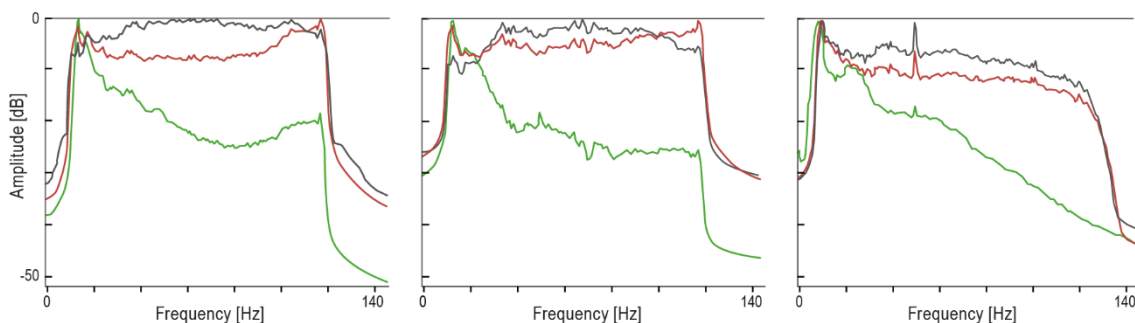


Fig. 4-3: Normalised spectra before (green) and after spiking deconvolution (red) and after subsequent gapped deconvolution (black).

Left: JO-15, centre: NL-16, right: ZNO-97/16

4.2.5 Statics

First of all, a combined elevation and refraction statics correction (further referred to as base statics) was applied to the data. The base statics are dominated by near surface geology and topography. For illustration purpose the elevation statics has been subtracted in Fig. 4-4.

Moderate and symmetrically distributed static corrections were derived for JO-15. Larger corrections with multi-modal distributions resulted for NL-16 and ZNO-15/97. Competent and high velocity Malm layers in the near surface were the likely cause for the positive static anomalies observed in the north of NL and ZNO¹.

For the derivation of the residual statics, data was brought back from SRD to floating datum (FD). Residual statics were determined in four iterations of automatic residual statics and intermediate refinement of stacking velocities. With the finally accepted range of shot and receiver residual statics between -14 ms and 14 ms, a clear improvement of stacking velocities was achieved for all three areas.

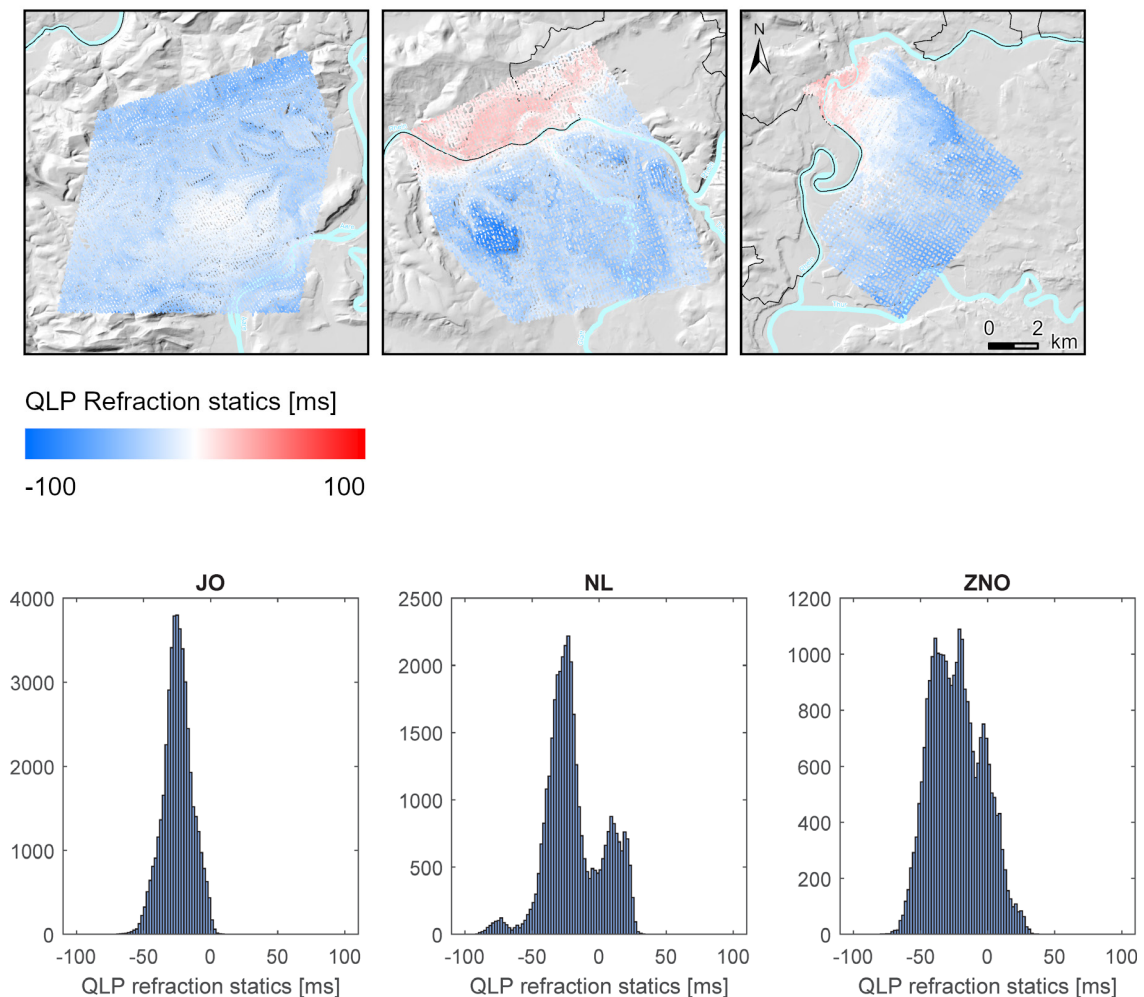


Fig. 4-4: Combined refraction static corrections for shots and receivers

Left: JO-15, centre: NL-16, right: ZNO

¹ Negative refraction static corrections ($t_{up} - t_{down}$) shift the data upwards in travel-time, positive downwards

4.2.6 Products

The main products of Module B were the conditioned CMP gathers including acquisition and processing geometry and statics corrections. To assess the parameterisation in Module B, velocity picking and, after definition of an appropriate mute function, stacking was applied.

4.3 Imaging in the time domain (Modules C, D1 and D2)

A variety of imaging algorithms were applied in QLP Modules C, D1 and D2 as depicted in the workflow chart of Fig. 4-5. Some more details on the algorithms applied are given below in this Section.

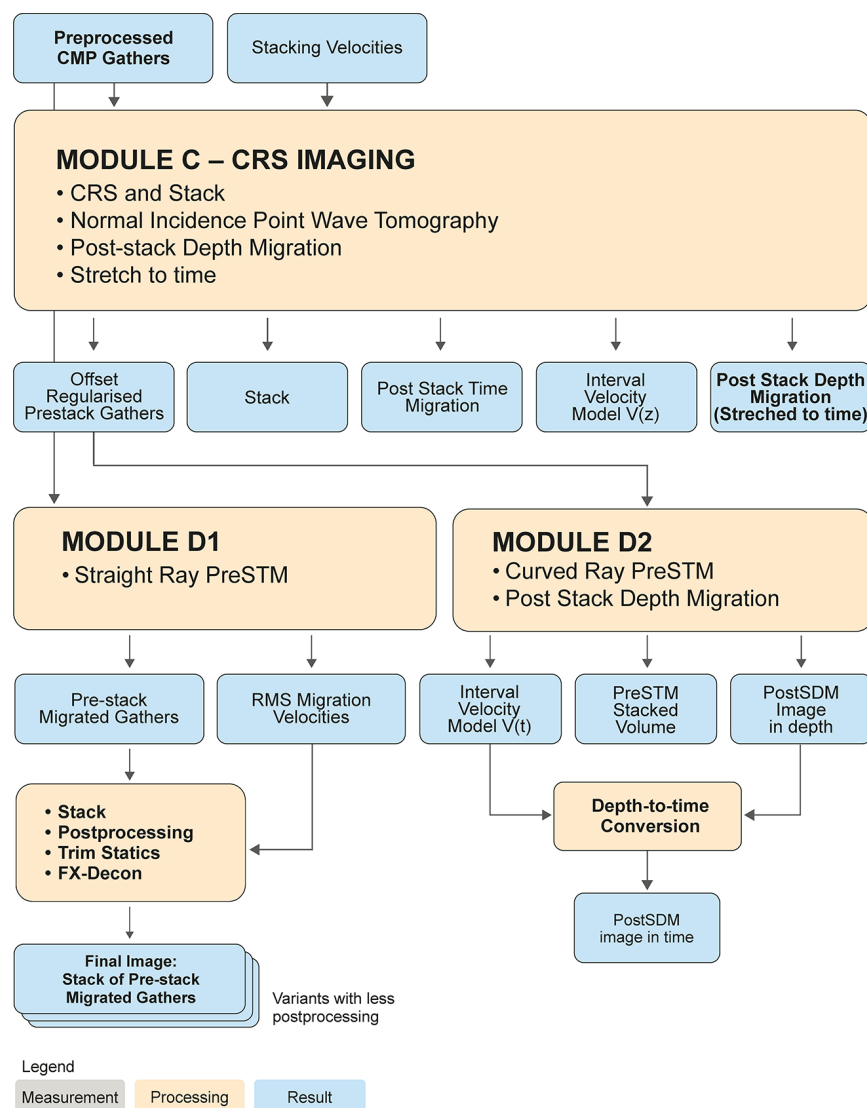


Fig. 4-5: Workflow of the imaging steps in QLP Modules C, D1 and D2

4.3.1 Module C

CRS

Common Reflection Surface stacking (CRS) stacks the data along a curved wavefront. For every data-point in 3D characterised by X-midpoint, Y-midpoint, time, offset and possibly receiver-source direction, eight parameters are in principle required to define the operator. These are the two emergence angles, three normal wave curvature radii and three normal incidence point curvature radii. In practice it is often assumed that the normal wave radii are infinite – so the reflector is locally flat. As long as a small mid-point aperture is used this is generally a good approximation (complexities, such as faulting may violate this assumption).

The output data of this process can be slotted in various ways. For the QLP, both a CRS stack and a partial CRS stack (basically offset regularised pre-stack data) were produced.

Normal Incidence Point Wave Tomography

Using the CRS attributes (the kinematic wavefield attributes) a velocity model was generated using Normal Incidence Point (NIP)-wave tomography. The principle is that normal incident point waves have to focus at a point at zero time if propagated back through the subsurface.

An example (for JO-15) of an interval velocity field that was derived using NIP-wave tomography is shown in Fig. 4-6.

Imaging

The CRS stack was post-stack depth migrated. After migration the depth-domain image was converted back to time to allow direct comparison with the time migration result.

4.3.2 Module D1

The conditioned non-regularised CMP gathers from module B were run through a PreSTM. Actual coordinates were used and acquisition deviation related gaps in the data were filled up using neighbouring traces. The velocities from module B were iteratively updated through RMO measurements. Post migration processing included RMO and various stacked volumes (with and without RMO application) were delivered. The migration operators in Module D1 were calculated using effective migration velocities only (straight-ray assumption) which are constant laterally for each image point.

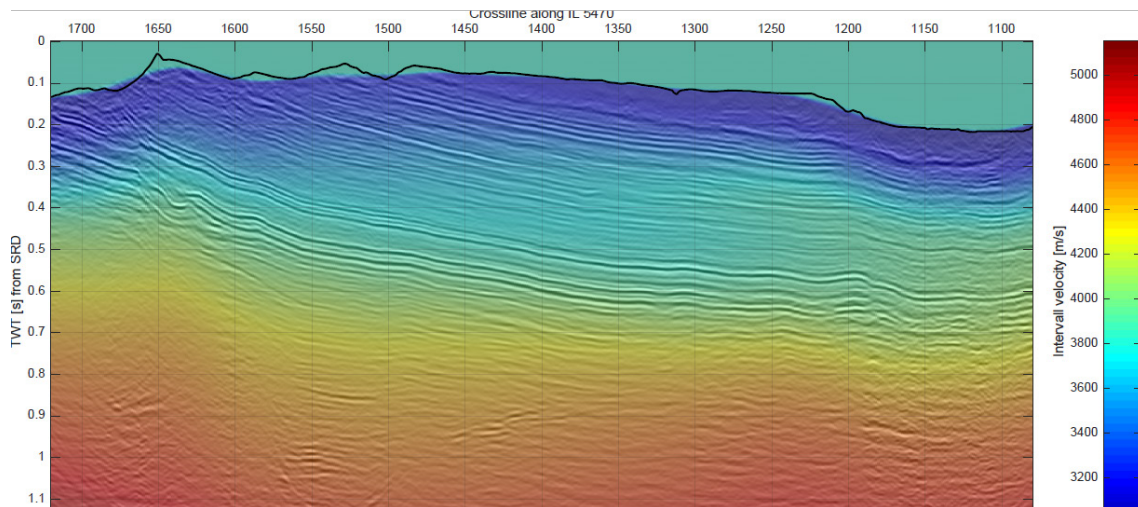


Fig. 4-6: Interval velocity model from NIP-wave tomography (background PostSDM seismic)

4.3.3 Module D2

Module D2 used the offset-regularised CRS data from module C as input. The imaging was done from floating datum. Like in D1, migration velocities were iteratively updated by RMO measurements on PreSTM gathers. Using an interval velocity model, this implementation applied a ray curvature correction. The operators were calculated from floating datum. A comparison of results using the two PreSTM implementations is shown in Section 4.4.

In addition to various output stacks, a Post stack depth migration (PostSDM) was executed after converting the velocities to interval velocities, as an alternative for the depth migration created in module C using the NIP-Wave derived velocities. In this module also a migration of non-regularised data was run as a comparison.

4.4 Quick look processing results and conclusions

Following the signal processing, the various imaging products were compared to each other, see Fig. 4-7 for an example. Comparison of the products, especially looking at the top row with the non-regularised data migrations in Fig. 4-7, indicates that the D3a migration -output of Model D1- implementation and parameterisations are quite different from the D13b – output of Module D2. The straight ray implementation (D3a) appears crispier than the ray curvature corrected result (D13b). Differences in migration operator length and blanking and/or anti-alias and stretch handling would further explain the smoother appearance of the D13b. The bottom pictures show a comparable effect though here the differences in CRS parameterisation will also play a role. Hölker & Birkhäuser (2018) provide a more complete comparison of imaging products for all three surveys.

The main benefit of the quick look processing was that it yielded quick results which provided an insight into the characteristics and challenges of the three areas. The impact of processing parameterisation on the images as shown above, also indicates that very similar processing flows have to be applied to each of the surveys in order to maintain comparability of the three areas.

However, as the near surface geology of the three areas varies significantly, it was realised that equalising processing parameters did not necessarily provide an unbiased comparison. Dipping layers and deep Quaternary valleys, both leading to lateral velocity changes, implied that the use of a fixed pseudo datum level of 100 m above sea level (e.g. ~300 – 700 below topography) did not make it possible to optimize imaging below all near surface conditions.

Despite the above, the QLP provided a good starting point for further work, a description of which is the main purpose of this report.

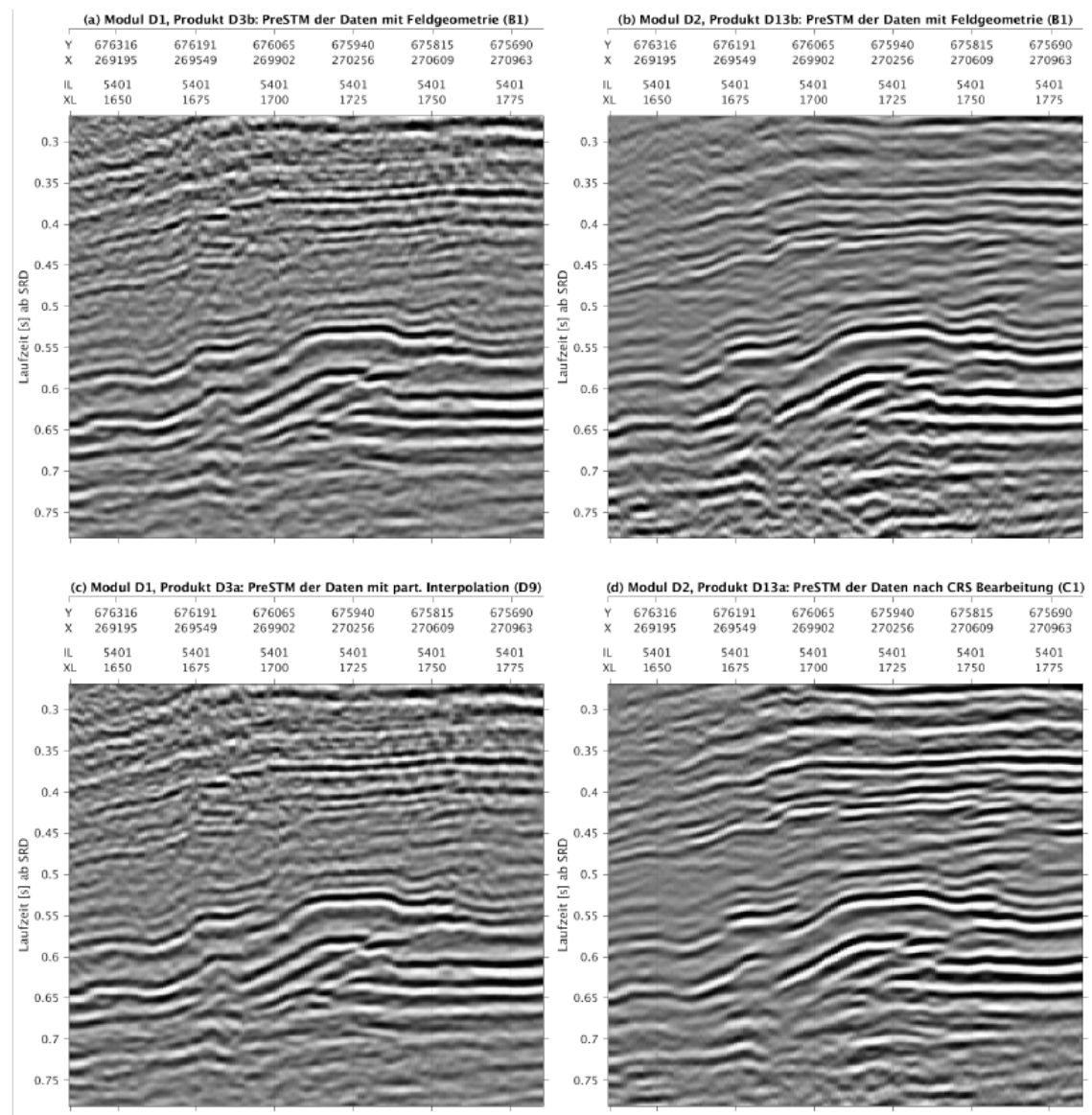


Fig. 4-7: Raw PreSTM stacks (NL-16 IL 5401, reproduced from Hölker & Birkhäuser (2018))

Top row: non-regularised input, left: product D3a, and right: product D13b

Bottom: CRS regularised data input, left: product D3a, and right: product D13a

5 Refinement processing – near surface velocity model building and static corrections

5.1 Introduction

The first stage of the refinement processing was to build a near surface velocity model for each of the three siting regions. It is well understood that the near surface properties have a strong effect on the imaging of deeper layers.

The near surface velocity model is intended to accurately represent the geological layering and the seismic wave propagation velocities by making use of the available near surface velocity information, such as present in first breaks and seismic refractions, up-hole measurements and low velocity layer measurements.

Such a model provides the basis for picking a structured pseudo datum, base statics for the subsequent refinement PreSTM, and a good near-surface velocity model for the subsequent PreSDM model building and imaging. The latter should help to avoid imprints of the near surface velocities in the full velocity model, therewith improving imaging quality and leading to more accurate depth conversion.

The near surface is understood to encompass the Quaternary and Paleogene-Neogene deposits down to approximately 400 m below surface. The geological features causing static anomalies at that level include dry slope debris and gravel terrasses, erosive glacial channels, and the top of the Mesozoic sequence.

5.2 Description of workflow

The workflow, consisting of (1) inverting the first break times to obtain the near surface velocity model, and (2) computations to establish the associated statics corrections, is summarized in Fig. 5-1. The 3D travel time inversion for (1) was done by Augeos GmbH, and followed by interpolation, re-gridding and base statics computations, which were all performed by Geophyttec GmbH.

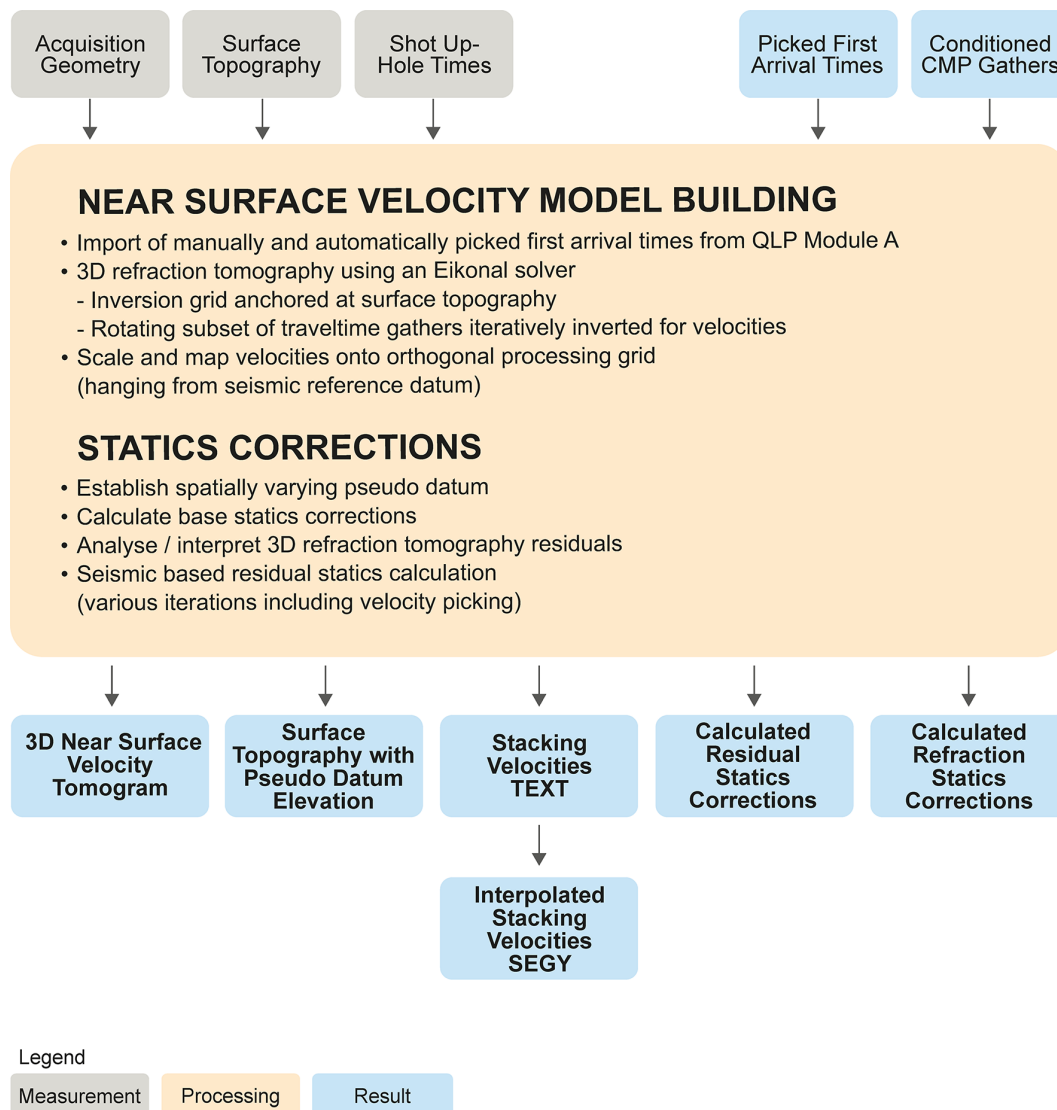


Fig. 5-1: Workflows for near surface velocity model building and static corrections

3D refraction tomography

Using the first arrival picks obtained in Module A of the QLP (see Section 4.1.2), travel times were inverted for a 3D P-wave velocity model. The full offset range was used in the tomography in order to maximise the illumination depth for the available data.

To strike a balance between the numerical accuracy and the number of cells, forward modelling was carried out on a grid with a mesh size of $5 \times 5 \times 5$ m. This is considerably smaller than the mesh size used in the QLP inversion which was $30 \times 30 \times 11$ m. Though the nominal source and receiver spacing are (also) 30 m, it should be realised that, due to terrain restrictions, actual receiver spacings might have been smaller in places. An Eikonal solver was used for the forward modelling. Computational limitations were overcome by limiting the forward modelling to the area covered by the receivers. In depth the forward modelling grid was quite extensive. E.g. for the NL-16 the model extended from 600 m above sea level to 540 m below sea level.

Following the forward modelling, editing was carried out by calculating the differences between the travel times found by the Eikonal solver and the time sum over the ray path segments and rejecting outliers (>20 ms). Subsequently the differences between the modelled and the picked travel times were calculated after which all data points with data residuals (observed minus predicted travel times) of more than 50 ms were removed. In total less than 0.6% of the data was removed by these editing steps.

The inversion was done on layers of control points hanging from topography. The distance between the control points increased with increasing depth to compensate for the decreasing ray density with depth. At the surface the control point grid was 30 m by 30 m but at 5 m below surface this became 33 m by 33 m. For subsequent layers both the horizontal and the vertical control point spacing were increased for each layer. In the test stage the increase was 10% per layer but in the production stage only 3%. Per control point there was one inversion parameter (velocity).

The matrix to be inverted was in principle of size (number of first break picks) * (number of control points). Stabilisation of the inversion was achieved by appropriate damping and smoothing operators, for which the related equations were added to the matrix to be inverted. To limit the required computer time, a rotating subset of shot records (typically 10% of all shots) per iteration were used.

After each inversion iteration the updated velocities of the control points had to be mapped (assigned) to the forward modelling grid to prepare for the next iteration.

A significant amount of computer time was required for each iteration. To speed convergence an initial inversion with a decimated dataset was carried out. The production runs for the whole area comprised 20 iterations.

Analysis of the results

Using the final velocity model residuals were calculated. Source and receiver consistent components, so-called supplementary statics, were subsequently determined. These were however found to explain only 10 – 20% of the residuals. The remaining 80% could partly be explained by picking noise, but other numerical effects e.g. related to the different definitions of the forward modelling grid and the inversion grid or matrix inversion properties could also play a role in addition to the constraints imposed by the smoothing operators.

Where possible, velocities were compared with borehole information down to base Quaternary and base Cenozoic (NL-16 and ZNO only).

Resampling onto orthogonal grid

The velocity cube as output from the inversion was sampled onto the inversion grid hanging from topography. To enable the use of this cube in further processing, the velocity cubes were resampled onto the orthogonal IL/XL/Z grid at depth sampling of 3 m. For the later PreSDM model a further resampling to a depth interval of 15 m was done. After mapping onto the orthogonal grid, travel-time residuals were determined by raytracing through the orthogonal grid. The shot and receiver consistent parts of these residuals were calculated and output to be used as additional static correction. As illustrated by Fig. 5-2, smoothing was applied after the mapping to take out the resulting artefacts.

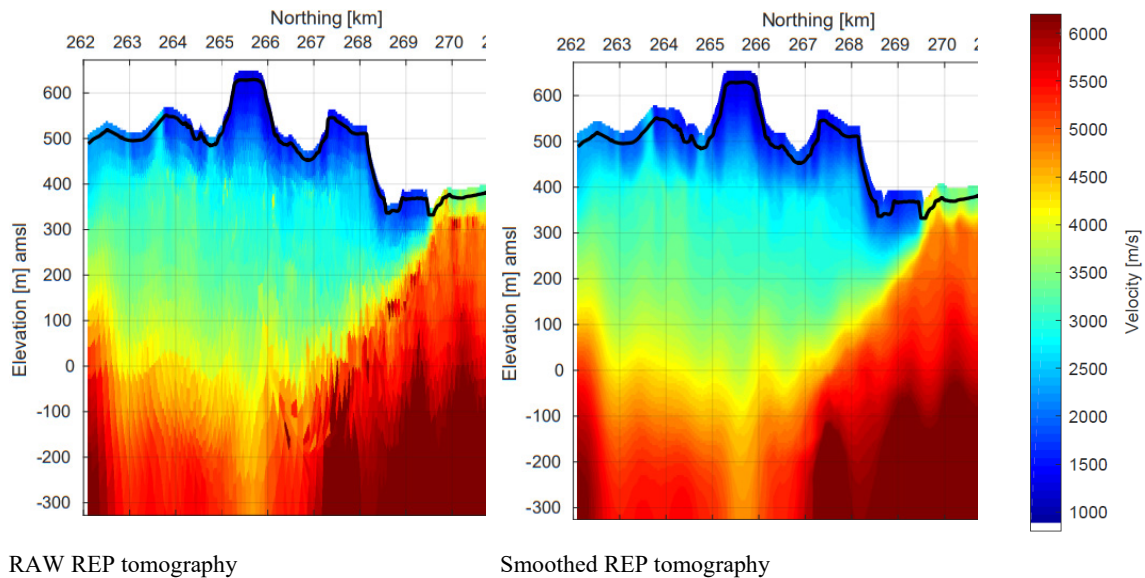


Fig. 5-2: Near surface velocity section before (left) and after (right) smoothing
(10x vertically exaggerated)

Calculation of the static corrections

The obtained near surface velocity model was used to calculate refraction statics. This served multiple purposes.

Firstly the refraction statics, or at least the part between smoothed elevation and the pseudo datum, were computed and applied to the data to be imaged with time migration. Secondly, residual statics were calculated in a number of NMO analysis / residual statics determination loops. The derived residual static represents the part of the total static that is not incorporated in the near surface velocity model.

To calculate refraction statics, a replacement velocity and a pseudo datum (PD) had to be defined. For the earlier refraction tomography carried out in QLP module B, a flat pseudo datum at 100 m above mean sea level (MSL) had been used, above which the derived velocities were replaced by the replacement velocity as used for each survey. With the strong lateral variations in geology this approach was in many places not appropriate. In some areas, the depth of the PD was deeper than the illumination depth of the first-break picks. The non-properly updated velocities at this level resulted in incorrect statics shifts. In addition, in some areas high velocity formations were replaced with a lower replacement velocity violating the “vertical ray” assumption of the statics. It was therefore decided to use a smoothly spatially variant pseudo datum, roughly following the iso-velocity plane in the near surface velocity cubes corresponding to the replacement velocity.

A number of these pseudo-datum / replacement-velocity combinations were tested for NL and ZNO: a shallow PD at base Quaternary with a corresponding replacement velocity of around 2,200 m/s and a deeper PD at roughly Top Malm Group with a replacement velocity of 3,500 m/s. Based on the consideration that the shallow PD would leave too much lateral variability for the PreSTM, the deeper version was chosen for the production processing. For the JO-15 area the PD was at the base of the weathering layer and velocities were rapidly increasing below that level. Selected PDs and replacement velocities were checked against the refracted wave density at the PD level.

Following these analyses the replacement velocity for the JO area was therefore set at 3,600 m/s, and the SRD was set at 800 m. Tab. 5-1 lists the seismic reference datum and replacement velocities as defined for the REP.

Tab. 5-1: REP seismic reference datum and replacement velocity

Survey	Seismic reference datum	Replacement velocity
JO-15	800 m	3,600 m/s
NL-16	650 m	3,500 m/s
ZNO-97 and ZNO-16	600 m	3,500 m/s

Residual statics

For the residual statics calculation, data was first moved to floating datum (by taking out the elevation part of the statics) and supplementary statics were applied for NL-16 and JO-15. Preliminary tests indicated no improvement for ZNO, so supplementary statics were not applied there. This was followed by NMO analysis on a grid of positions. Using the method of (Ronen & Claerbout 1985), residual statics were calculated. The same process (NMO analysis / statics calculation) was repeated two times. With the coherency of the data improved in this way, two more iterations were conducted with the panel cross-correlation / travel-time decomposition approach which is in theory more accurate but is also less robust on noisy data.

An example of the effect of residual statics is shown in Fig. 5-12.

Application of the statics for further processing

The PreSTM used the total of the primary statics, supplementary statics (only in JO and NL) and the residual statics with migration operators calculated from FD elevation at CMP positions (Chapter 7).

The PreSDM used only the total residual statics and operated from original source/receiver X/Y/Z positions (Chapter 6).

5.3 Jura Ost

Cross sections through the near surface velocity model in Fig. 5-3 show significant differences between the QLP and the refinement processing, especially at depths below the mainly shallow (in JO) Malm refractor (Fig. 5-3 top). The QLP model picks essentially the very low velocities (1,500 – 1,700 m/s) at the near surface and extends them to deeper, non-illuminated areas. The REP has deeper illumination down to the higher velocity zone and the derived model could serve as basis for definition of the REP pseudo datum. The REP pseudo datum was manually modelled, essentially following the expected geological layering.

The slices through the velocity models at surface (Fig. 5-4) illustrate differences in the shallow part. The QLP model has more prominent low velocity zones and appears to have some more detail near surface. Despite showing less near-surface variability, the REP model proved more practical in the PreSDM model building approach.

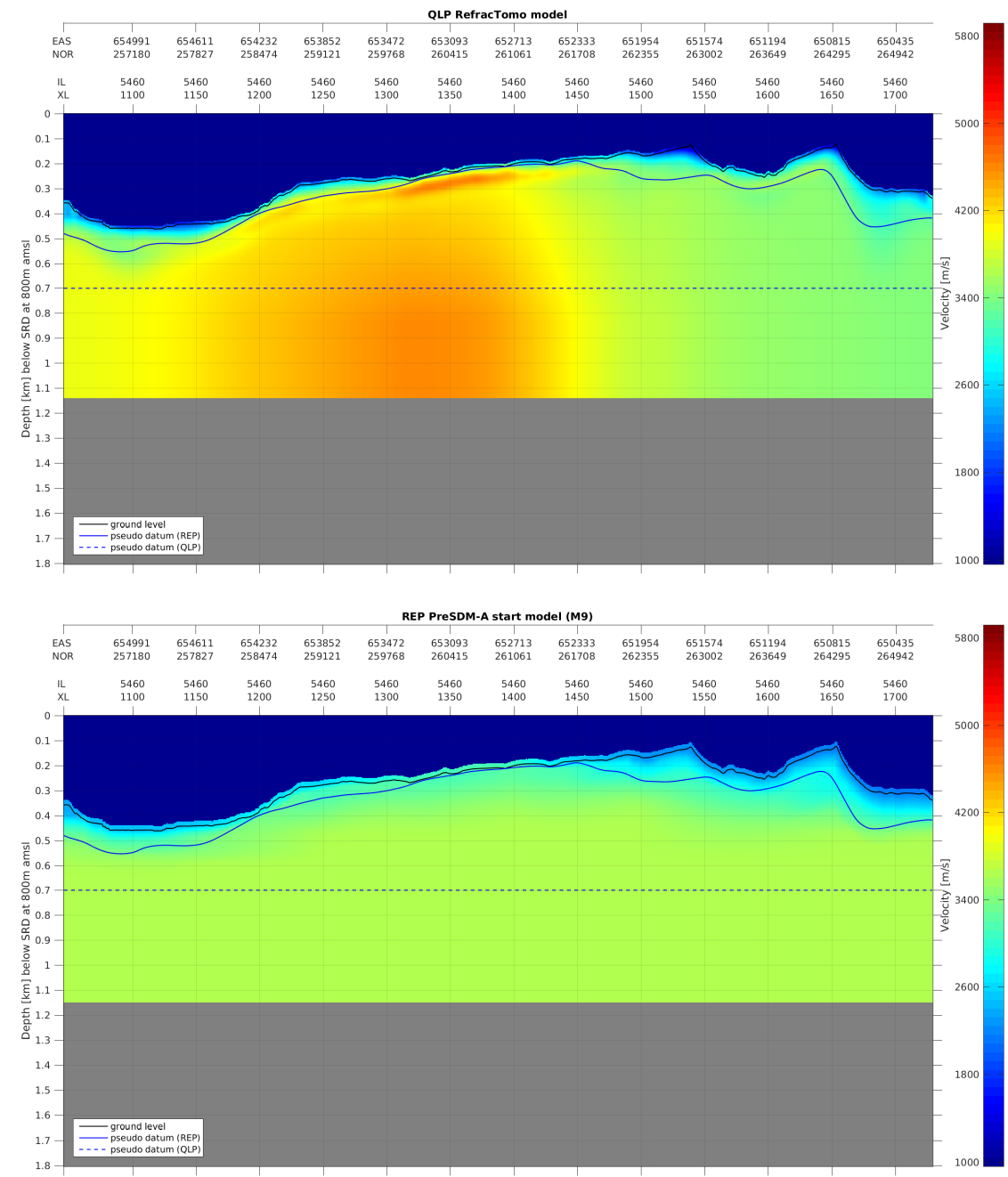


Fig. 5-3: Near surface velocity model section at JO-15 IL 5462
Top: QLP, bottom: REP. The straight blue/dotted lines indicate the pseudo datum in QLP and REP, respectively.

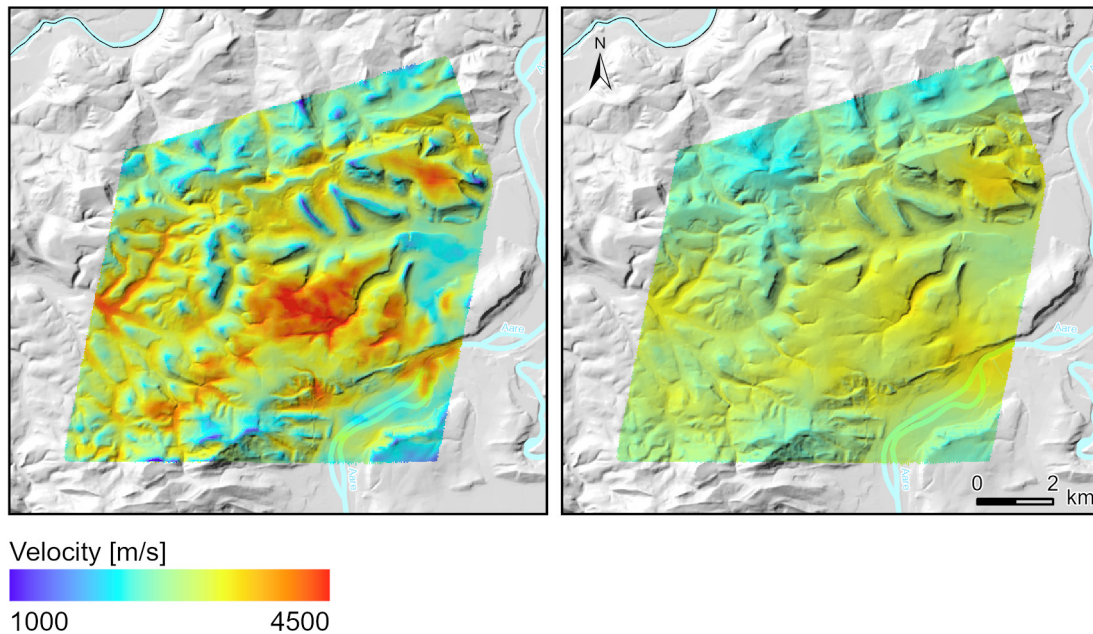


Fig. 5-4: JO-15 near surface velocity model slice for QLP (left) and REP (right)

Map shows mean velocity in an interval 15 – 24 m below ground level.

The refraction statics corrections (without elevation part) of the QLP and the REP are compared in Fig. 5-5. The bottom part of the figure also compares the residual statics component. Histograms for refraction and residual statics for QLP and REP are shown in Fig. 5-6. The two sets of refraction statics mainly reflect the large differences in pseudo datum level and velocities (also see Fig. 5-3). The shallow and structured pseudo datum minimised refraction static corrections in the REP as illustrated in Fig. 5-6.

The residual statics as derived in JO-15 as illustrated in Fig. 5-5 reflect a dependency on the refraction model (compare with Fig. 5-4). Significantly negative residuals are seen in the areas in which the QLP model had low velocities and the REP less so. The histograms in Fig. 5-6 illustrate the slightly wider distribution for REP residuals.

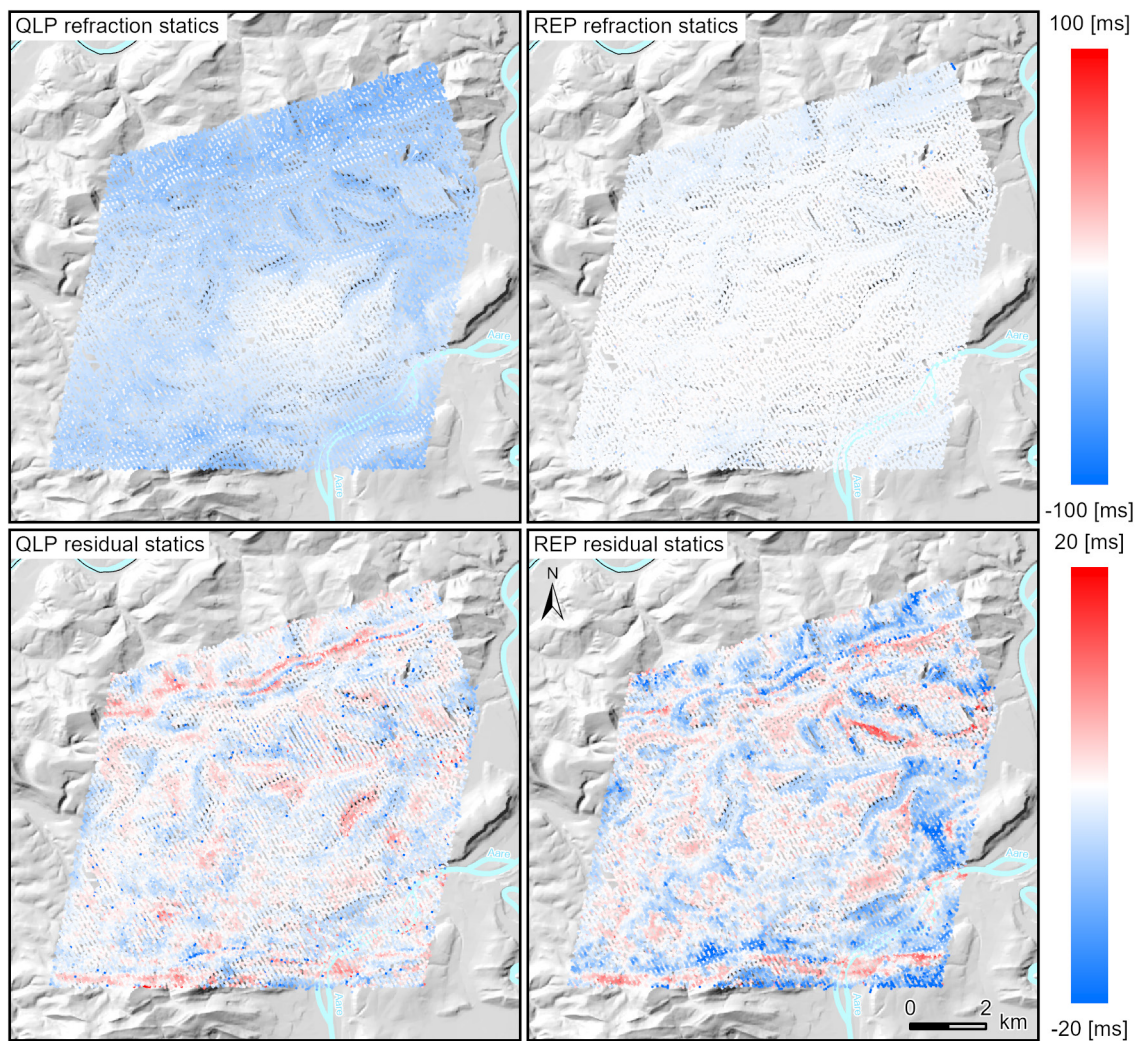


Fig. 5-5: Comparison of refraction statics (top) and residual statics (bottom) for JO-QLP (left column) and REP (right column)

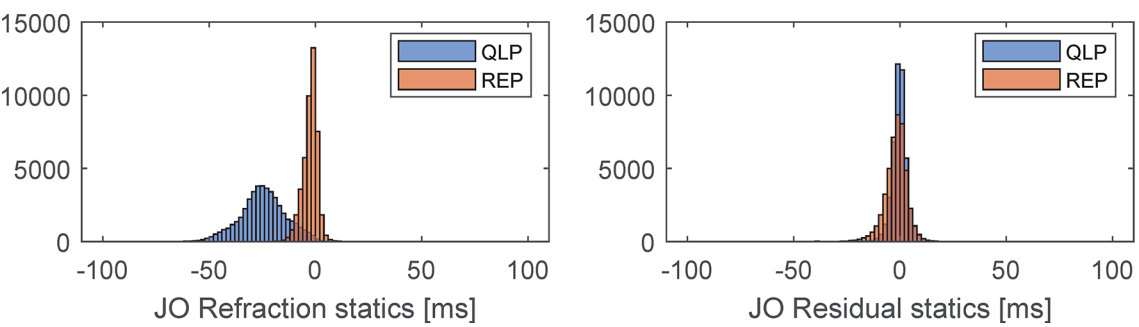


Fig. 5-6: Distribution of refraction statics (left) and residual statics (right) for QLP and REP in JO-15

5.4 Nördlich Lägern

In Fig. 5-7 cross-sections through the QLP velocity model and the REP velocity model are compared. Limited depth resolution of the QLP statics resulted in underestimated velocities in the northern part of the site. The REP velocity model images the up-dipping Malm and outcrops at the river Rhine. This model was used to establish the varying-depth pseudo datum in the REP (Fig. 5-7 bottom).

Note the shallow pseudo datum in the north (right-hand side) of the section. For comparison, in the QLP processing the fixed pseudo-datum was at 100 m above sea level, so 550 m below Seismic Reference Datum (SRD) for this survey. This implies that high velocities there are replaced by the lower replacement velocity, in a resulting push-down (positive refraction statics).

In the South, the pseudo datum in the REP is at comparable depth as the fixed pseudo datum for the QLP.

Another difference is that for QLP only offsets up to 1,000 m were used, which only resolved the subsurface velocities to roughly 200 m below surface (Fig. 5-7), which is above the level of the pseudo datum. For the REP all offsets were used, which extended the (maximum) illumination to more than 400 m below the surface, and was appropriate to define the structured PD surface.

In the North, the near surface velocity gradient is significantly higher, thereby limiting the resolution of refraction analyses down to the top of the Malm Group.

In Fig. 5-8 a comparison is made between the QLP, and the REP tomography showing mean velocities from a layer 14 – 24 m below the topography. Though the REP result has some short-wavelength artefacts, it shows less extrema than the QLP model. The near surface Malm layer in the north is clearly depicted. The glacial channels in the southeast are expressed in both models but stand out slightly better in the REP model (Fig. 5-8 right).

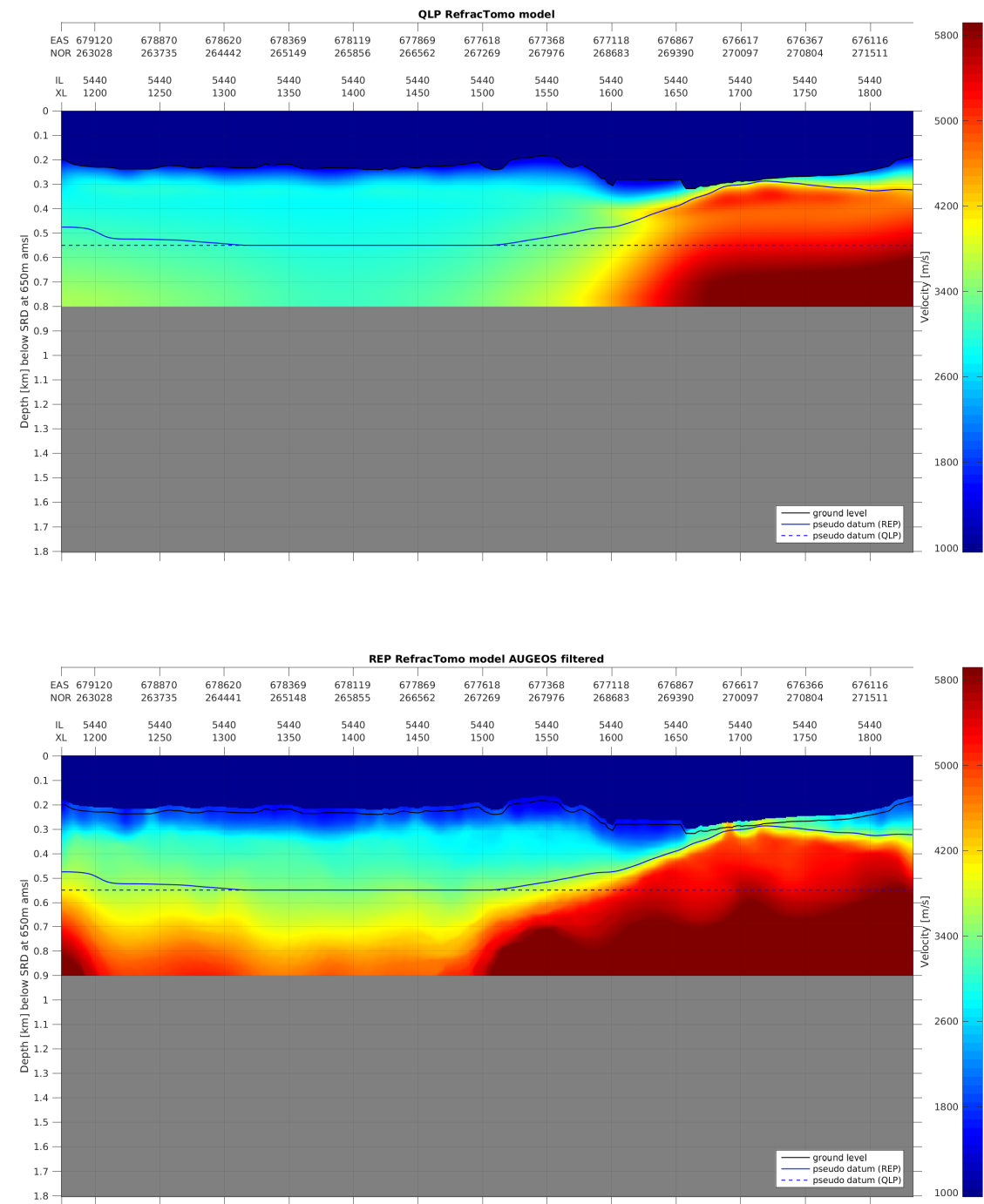


Fig. 5-7: Cross section of near surface velocity models in NL
Top: QLP, bottom: REP

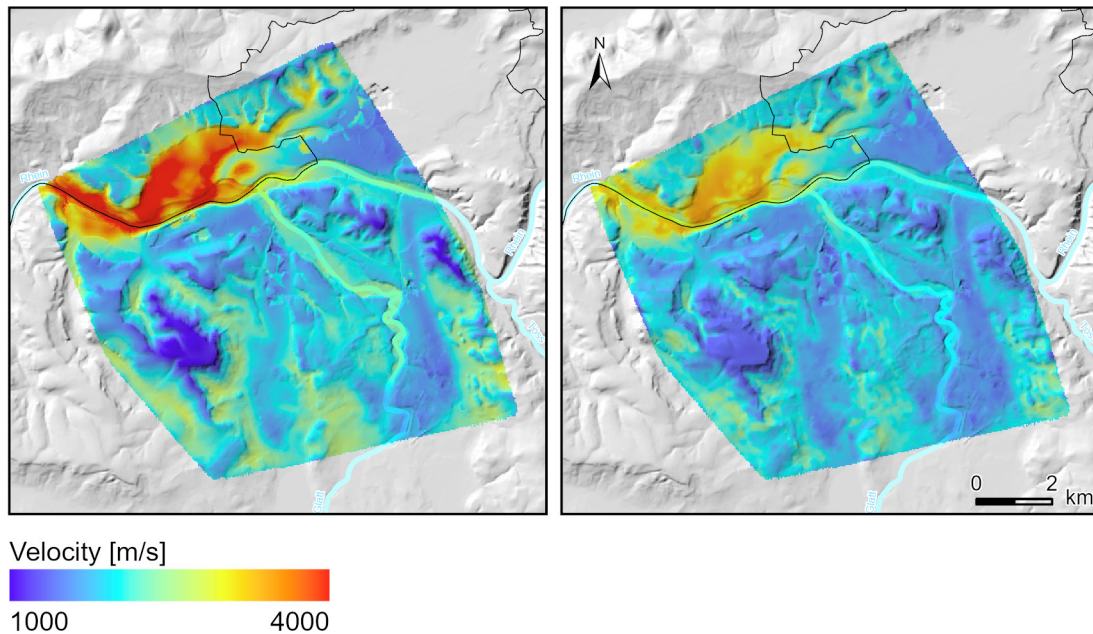


Fig. 5-8: NL-16 near surface velocity model slice for QLP (left) and REP (right)
Map shows mean velocity in an interval 15 – 24 m below ground level.

The base and residual statics corrections of the QLP and the REP related to these models are compared in Fig. 5-9. The distribution of refraction statics values shows a reduction in spread for the REP, seen more clearly in the histograms (Fig. 5-10). Residual statics distribution remained similar with slightly less outliers in REP (compare histograms in Fig. 5-10 right).

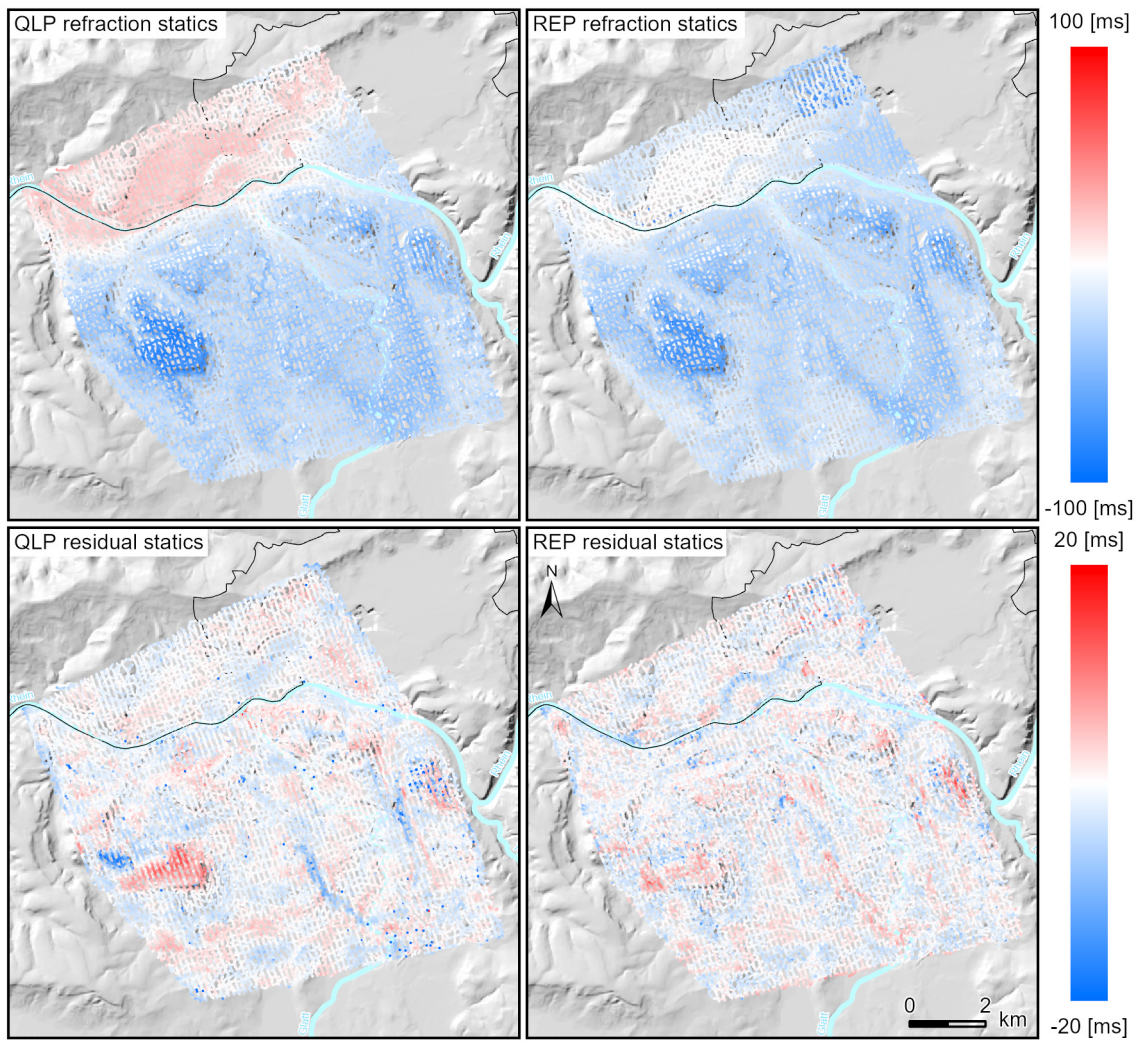


Fig. 5-9: Comparison of refraction statics (top) and residual statics (bottom) for NL-16 QLP (left column) and REP (right column) data is shown.

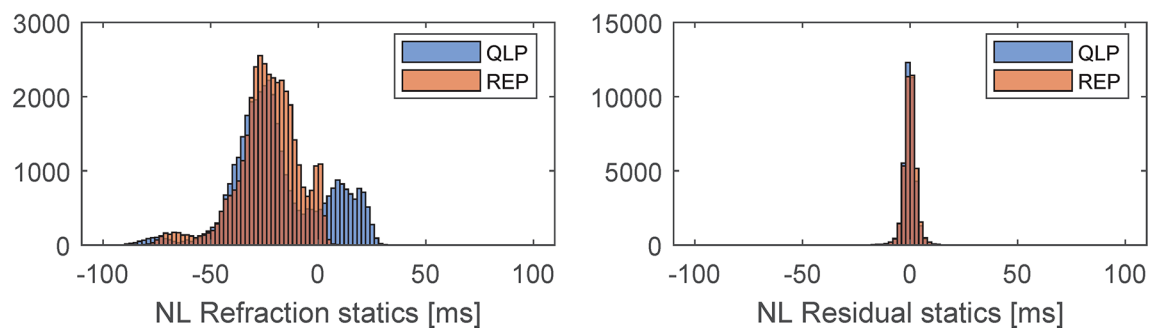


Fig. 5-10: Distribution of refraction statics (left) and residual statics (right) for QLP and REP in NL-16

The results show that, especially in the north, the REP statics are smaller than the QLP statics. This implies that in the north the REP seismic, after application of refraction statics, is pulled up in time compared to the QLP seismic (Fig. 5-11). In the north the REP pseudo datum gets very close to the surface, so the applied statics consist almost entirely of elevation statics. In the QLP the part between the surface and the pseudo datum contributes significant (positive) statics. Results on a stack with only refraction statics also look a bit smoother on the QLP stack than on the REP stack. Using a different grid for the forward modelling than for the inversion, mapping of control point velocities onto the orthogonal grid and the required model smoothing have very likely caused short-wavelength disturbances.

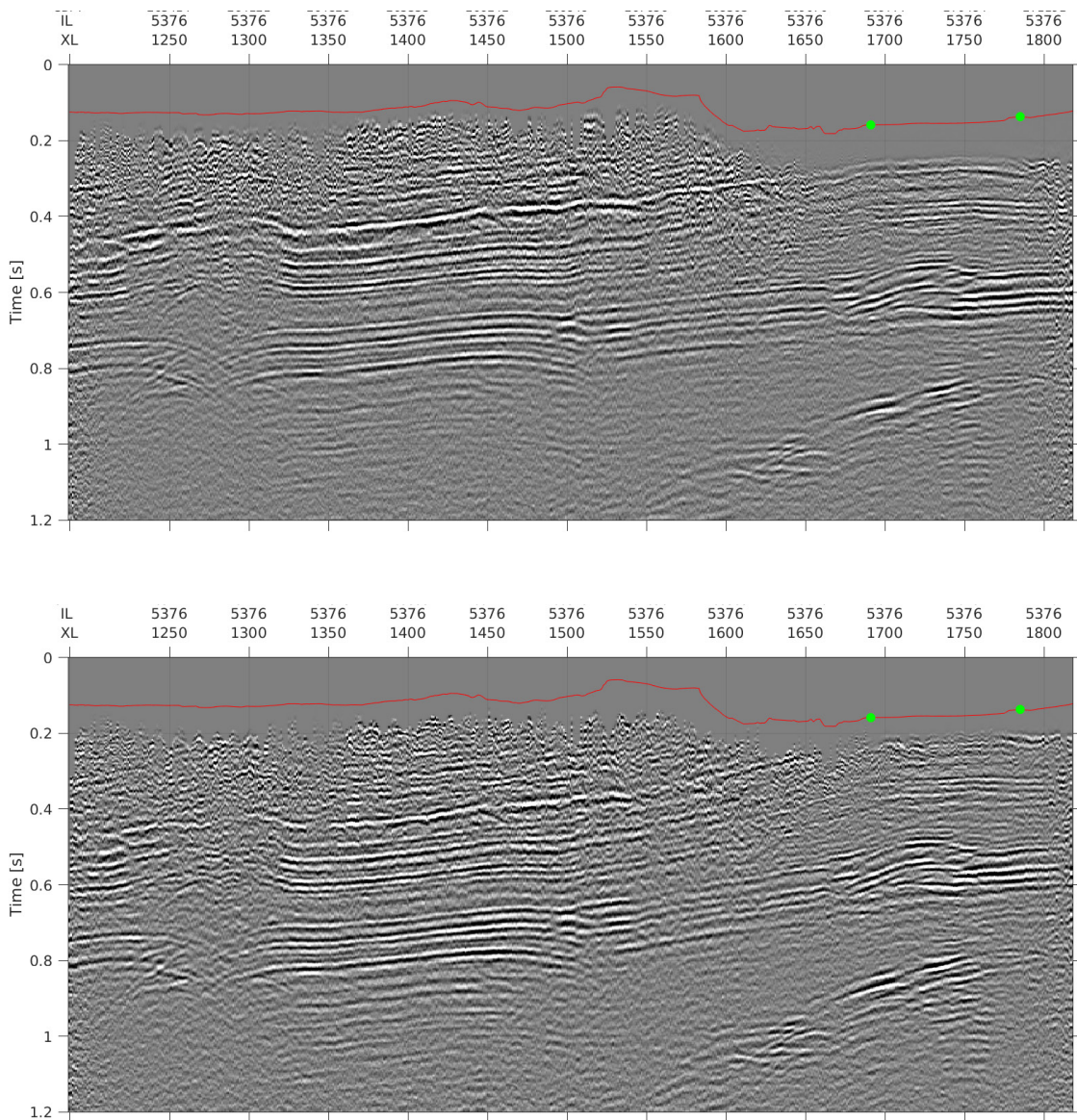


Fig. 5-11: NL-16 IL 5376 Refractions statics only

Top: QLP statics, bottom: REP statics. Red line: topography, green dots: Malm outcrops

As refraction tomography is not able to accurately map the low velocities very near to the surface for a survey with no (very) near offset coverage and limited spatial sampling, reliable residual statics are essential. The refraction statics derivation was therefore followed by four rounds of residual statics derivation as described earlier. Results of these, demonstrating a clear improvement in imaging, are shown in Fig. 5-12.

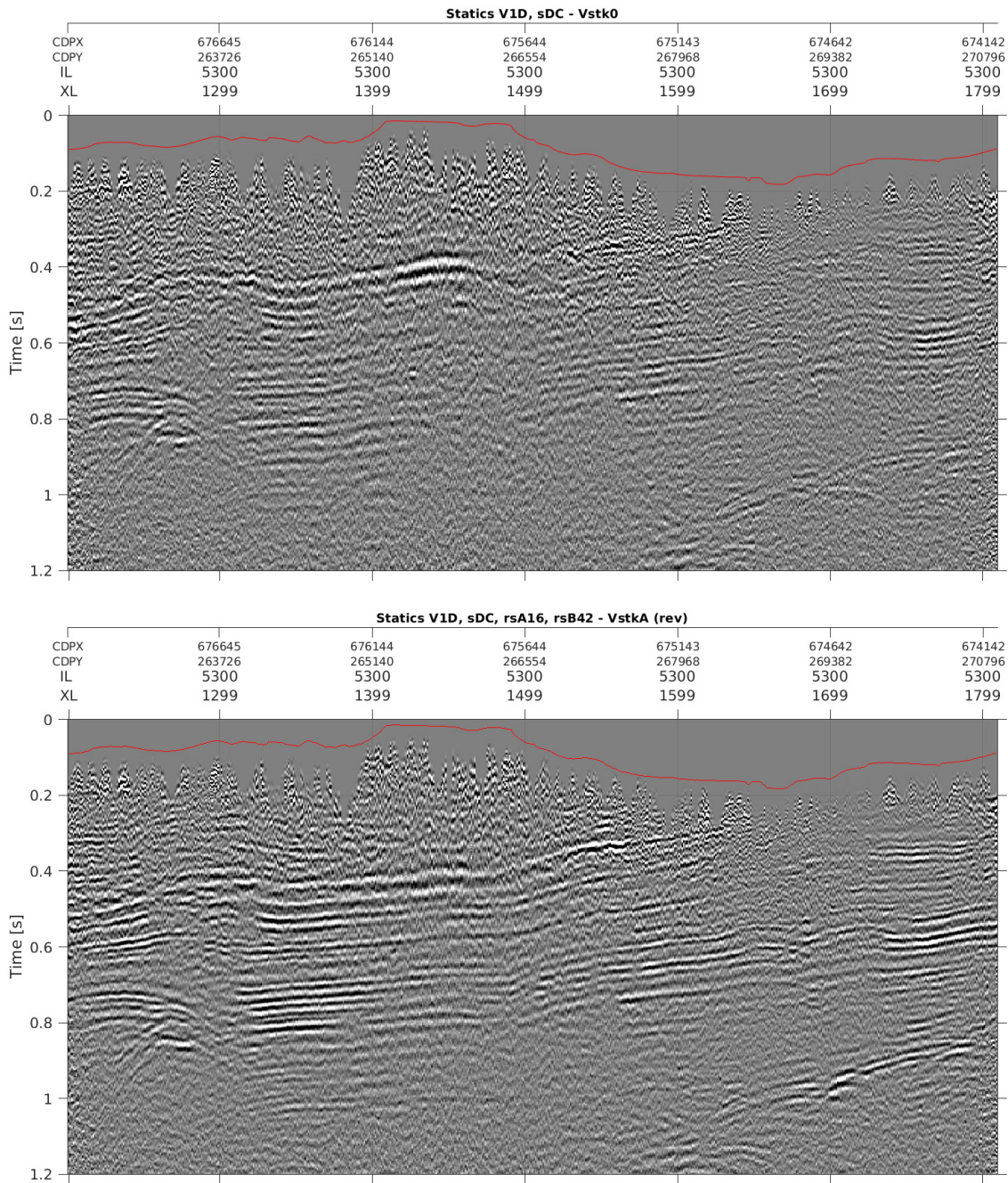


Fig. 5-12: Refinement processing in-line 5300 before (top) and after (bottom) application of residual statics

Red line: topography

5.5 Zürich Nordost

Fig. 5-13 compares the QLP and REP near surface velocity models and pseudo datum for ZNO. Similar to NL, thanks to the longer offsets and related deeper illumination available in the REP, the Top Malm is well captured, whereas the QLP reverts to almost constant velocity at that level.

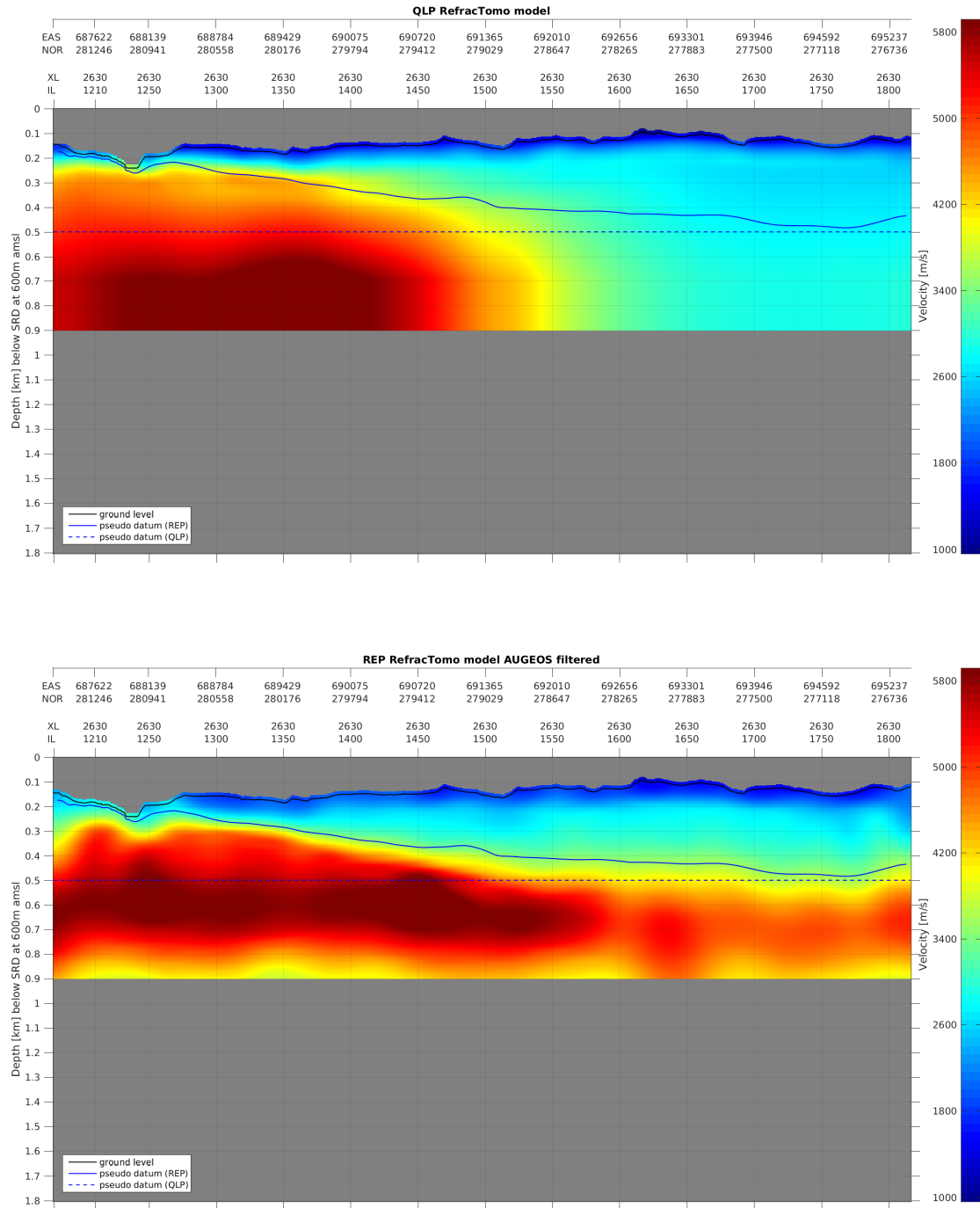


Fig. 5-13: Cross sections through the ZNO near surface velocity model

Top: QLP, bottom: REP tomography filtered version

Fig. 5-13 also illustrates the variable depth of the pseudo datum as used in the refinement processing. Note the shallow pseudo datum in the northwest (left-hand side) of the section. For comparison, in the QLP processing the fixed pseudo-datum was at 100 m, so 500 m below SRD for this survey. This implies that high velocities there are replaced by lower velocities, with a resulting push-down of the reflection image in time. In the southeast the relative effect is reversed and much smaller as the pseudo datum approaches the 500 m sub-SRD level and near surface model velocities are lower.

In Fig. 5-14 a comparison between the QLP and the REP tomography velocity results is presented as velocity average of a depth slice 15 – 24 m below surface.

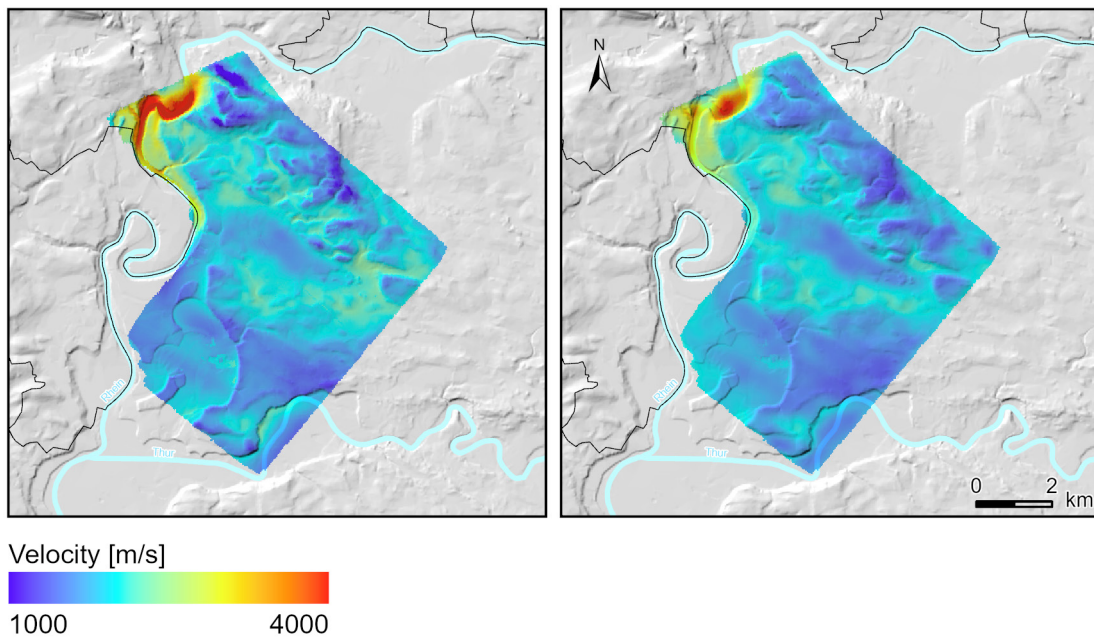


Fig. 5-14: Depth slice through near surface velocity model

Map shows mean velocity in an interval 15 – 24 m below ground level.

The ZNO-97/16 refraction statics corrections of the QLP and the REP in Fig. 5-15, top row, show strong similarities, with the QLP solution moving to positive values in the northwestern part of the survey. Similarities are also observed for the two residual statics solutions, where the REP model further reduced a spatially correlated component in the residual statics (Fig. 5-15 bottom row). Histograms in Fig. 5-16 essentially confirm the similarities and bias discussed above.

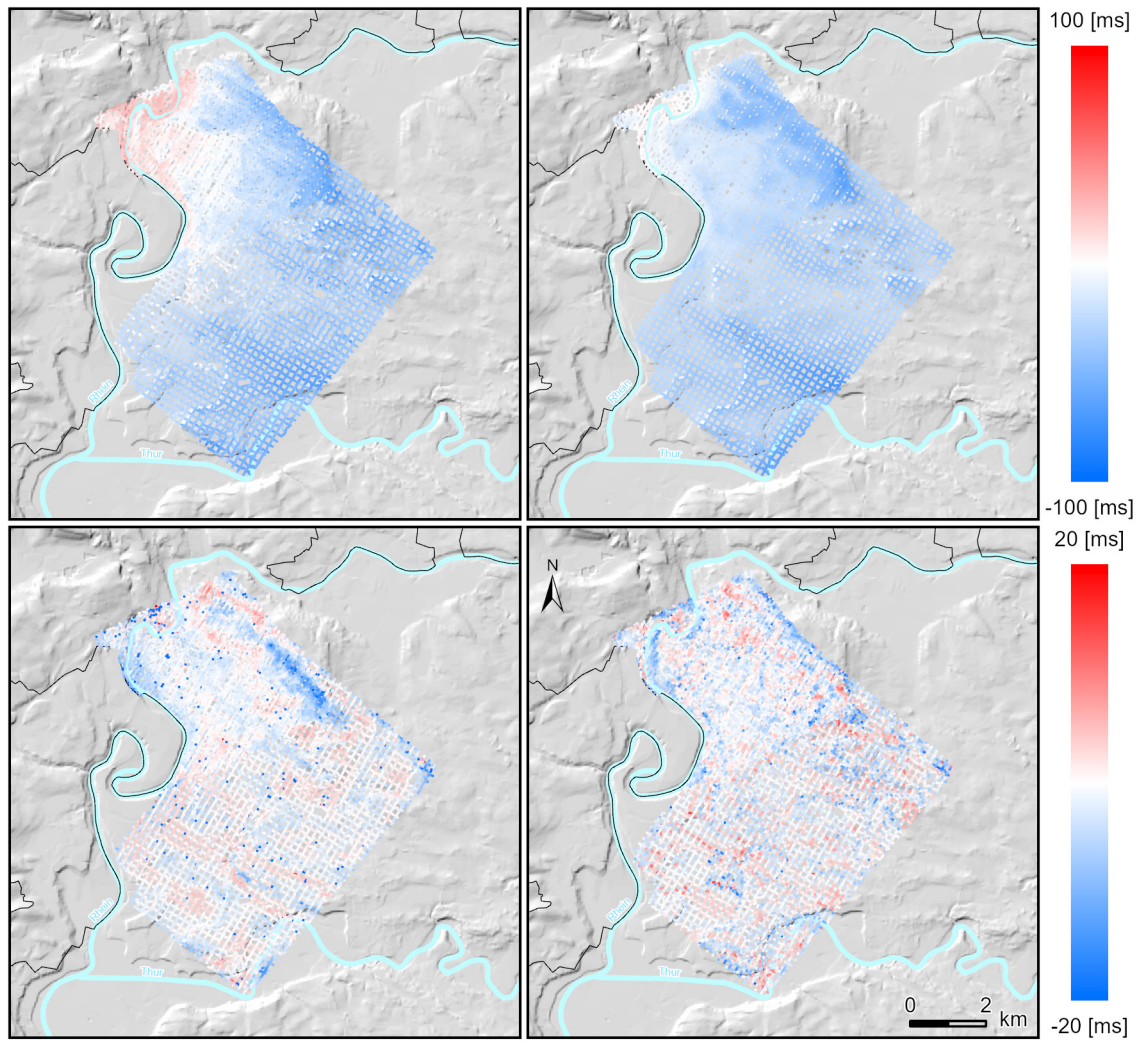


Fig. 5-15: Comparison of refraction statics (top) and residual statics (bottom) for ZNO-97-16
Left column: QLP, right column: REP

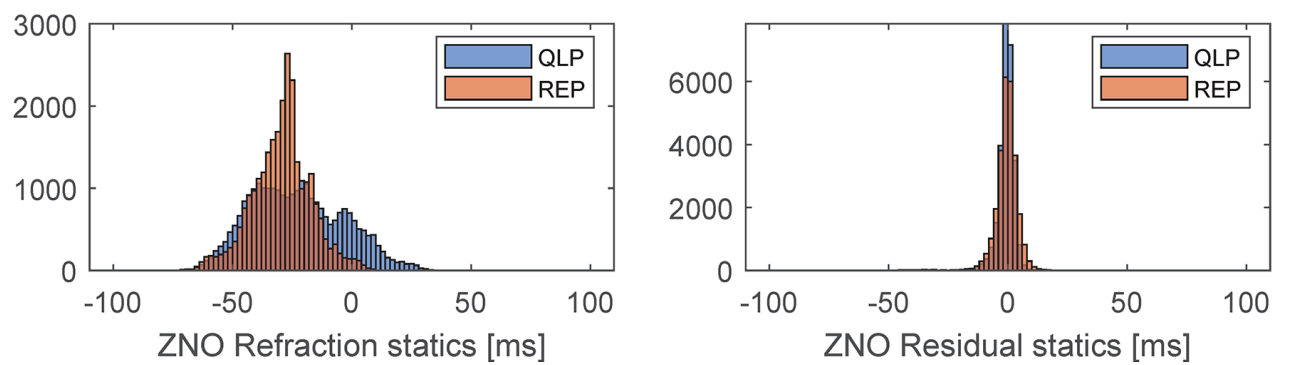


Fig. 5-16: Distribution of refraction statics (left) and residual statics (right) for QLP and REP in ZNO-97/16

In Fig. 5-16 the results of the QLP and the REP are compared on a stack with only refraction statics applied. The green dots on the time-domain plot indicates the position of a Malm outcrop and an approximate Top Malm Group guideline in black. As can be seen, the timing of this event corresponds nicely with the strong loop on the seismic in case of the REP. The QLP result has been pushed down more than the refinement result.

As shown in Fig. 5-18, application of the residual statics in combination with better stacking velocities improved the stacked seismic image significantly.

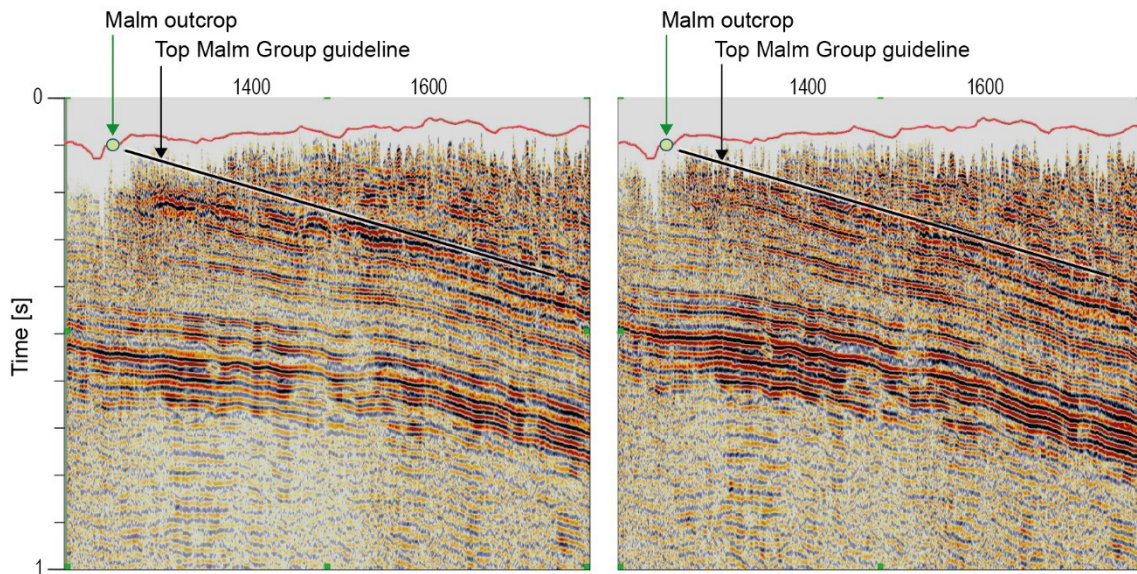


Fig. 5-17: ZNO-97/16 cross line example after refraction statics for QLP (left) and REP (right)
Exemplary data display for XL 2630 in time domain. Red line: topography.

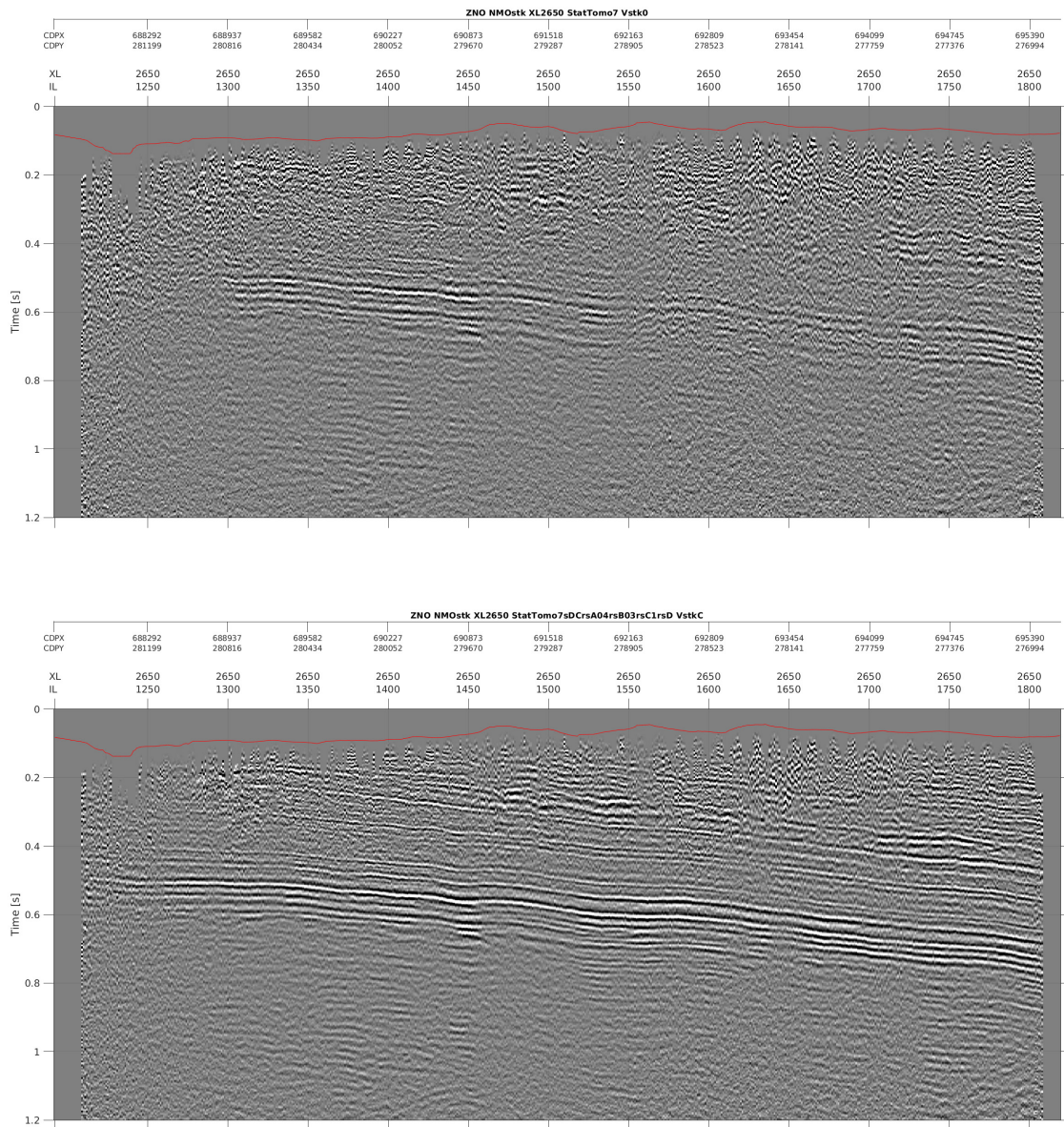


Fig. 5-18: Stack of cross line XL2650 before (top) and after (bottom) REP residual statics
Red line: topography

5.6 Discussion of the results

The results of the near surface velocity model building of the Refinement Processing are in general an improvement over the results from the QLP. Main gains of the REP compared to the QLP are improved resolution and deeper illumination of the subsurface in areas where the Malm Group is not close to the surface. Closing this gap is an essential step towards the PreSDM work from surface topography.

As a consequence, the refraction statics as derived from the REP velocity model are generally smaller than the statics calculated using the QLP velocity model. The variable-depth pseudo datum used in the REP also contributed to this. Velocity model improvements from feedback of long-wavelength components of residual statics solutions into the velocity model were modest. In some areas the short-wavelength solution of the REP appears even less successful as judged from visually poorer NMO stacks than those from the QLP. This is, however, resolved by the subsequently derived residual statics.

The choice of pseudo datum and replacement velocity aimed to optimise the follow-on reference PreSTM. In choosing relatively high replacement velocities and a corresponding locally deep pseudo datum, a compromise was sought, balancing the requirement to incorporate near surface velocity variations as much as possible prior to time migration, with the “statics” assumption that rays are vertical in the replacement depth interval. The latter plays more of a role in the near-surface imaging than in the deeper imaging as the high-velocity Malm Group acts as a high-cut filter for the ray parameter.

For the PreSDM, the deeper illumination of the REP inversion is quite significant to provide a reliable near surface starting model down to a level where model extension using RMO based reflection tomography becomes feasible.

6 Refinement processing – velocity model building and PreSDM

6.1 Introduction

The near surface complexity was already in an early stage of the processing recognised to be one of the key challenges for proper imaging of the various datasets. In addition, borehole information down to the intended repository level was sparse before the exploration drilling campaign in all areas. The velocity model at and between the borehole positions has to reflect geological reality to avoid significant errors in time to depth conversion and artefacts in depth domain imaging. Moreover, the definition of an undisturbed area, away from structurally complex zones and major faults is a key site selection criterium, so optimal imaging of faults is essential.

The initial processing strategy (Hölker & Birkhäuser 2018) planned for a PreSDM including anisotropic velocity model building and borehole calibration. In practice, and after a pilot study in the NL region, the so-called PreSDM-A was extended to include important anisotropic layers in the Paleogene-Neogene units as well as depth constraints as they became available during the processing from the results of the drilling campaign. A fully anisotropic and depth calibrated PreSDM has not been implemented and the Reference PreSTM (PreSTM-ref) was considered to be more useful for the purpose of site comparability.

In the PreSDM-A², the near surface model as derived earlier in the refinement processing was consolidated and, where required, modified using amongst others independent near surface data such as up-hole data and LVL data. Starting from this near surface model, an isotropic velocity model was developed to image the Mesozoic sequence using residual moveout inversion (reflection tomography) in a number of iterations.

For JO-15 and ZNO-97/16 one PreSDM processing project (PreSDM-A, see Tab. 6-1) was planned and executed. The PreSDM for NL-16 was undertaken twice. Firstly as a purely data-driven process at the beginning of the project as PreSDM-A1; and secondly after the JO-15 and ZNO-97/16 PreSTMs had been done, repeated with an adjusted workflow, similar to the one used for JO-15 and ZNO-97/16, as PreSDM-A2. The PreSDM-A2 was the version eventually used and will be the only one for NL-16 further discussed in this report. The chronological sequence of the PreSDM and PreSTM projects is given in Tab. 6-1.

The project used contributions from various parties that worked together in an integrative manner. TEEC did most of the work related to CRS processing, model updating and final imaging. Geo5 did horizon interpretation and Geophytex worked on the velocity scaling, starting model preparation, and some post-processing.

² The PreSDM-A label is part of product names and mentioned for completeness. This report uses PreSDM as a synonym for PreSDM-A products.

Tab. 6-1: Sequence of the refinement processing projects

Survey	Project	Time period
NL-16	PreSDM-A1*	July 2019 – January 2020
ZNO-97/16	PreSDM-A	April 2020 – October 2020
JO-15	PreSDM-A	October 2020 – March 2021
NL-16	PreSDM-A2	June 2021 – November 2021
All	PreSTM-ref	August 2021 – January 2022

* The PreSDM-A1 pilot study in NL-16 is mentioned for completeness and not further discussed in this report.

6.2 Description of the workflow

The workflows applied for building the full depth velocity model, and producing pre-stack depth migrated output volumes, are summarized below in Fig. 6-1. More details on the workflow steps are provided in the following sections.

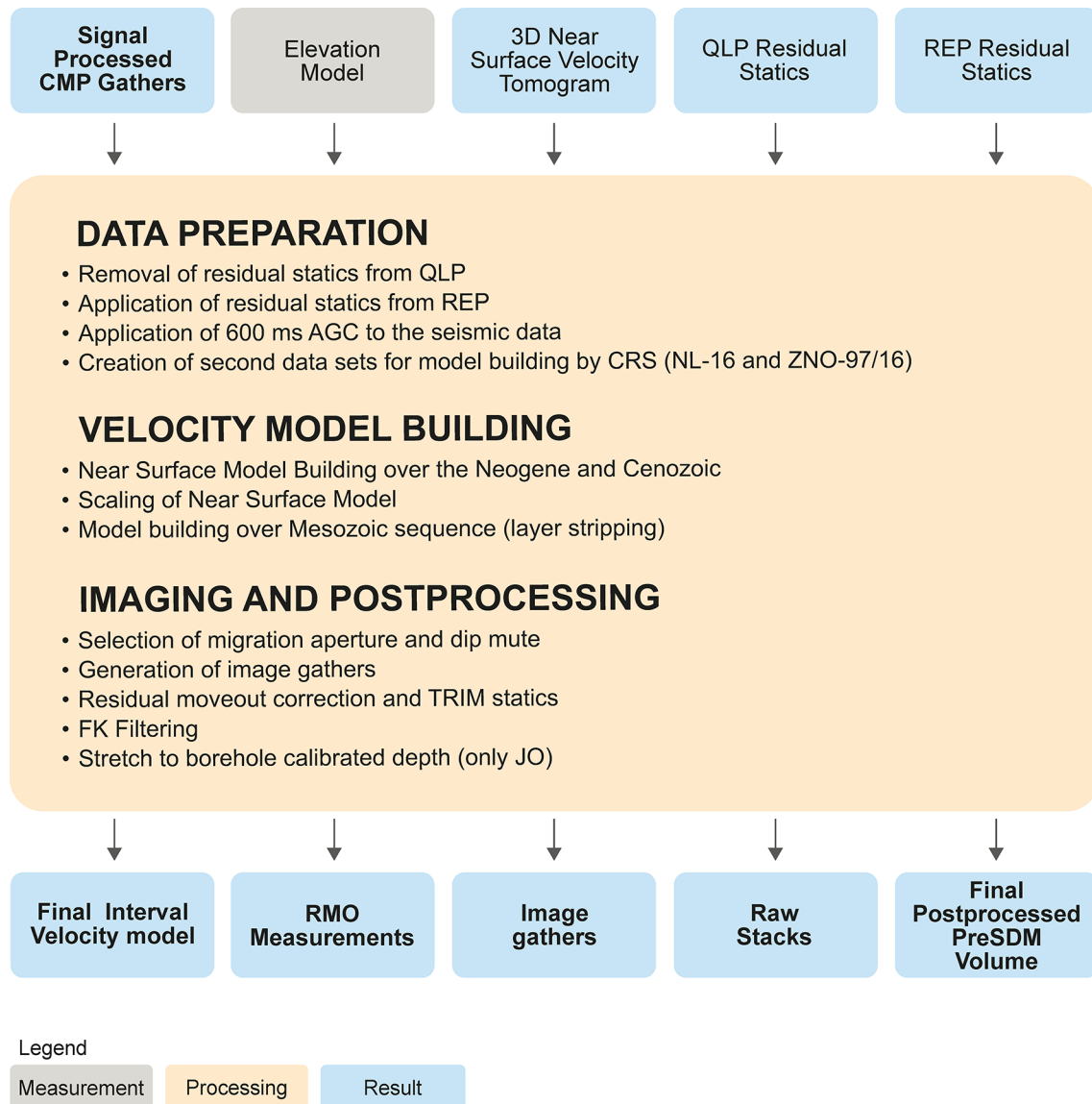


Fig. 6-1: Workflows applied for velocity model building and depth imaging

Removal of residual statics from QLP – Application of residual statics from REP

The near surface velocity model from the refinement processing was absorbed into the initial velocity model for the PreSDM. As the residual statics derived in the refinement processing are consistent with this model, they were the ones applied. In addition, the up-hole times from the dynamite data were corrected.

Creation of a second dataset for model building (CRS)

A geometry conserving CRS dataset was created for model building purposes. Objective of the partial stacking was to achieve an improvement of the signal/noise ratio for preliminary PreSDM products. After application of NMO, with velocities taken from the latest residual statics iteration in the earlier REP, plane wave dip scans were run on stacked data. Due to the small midpoint aperture, curvature modelling could be neglected. Azimuth binning using 6 bins of 30 degree and offset binning was done at 30 m slot width and interval. The midpoint aperture varied in time from 5 midpoints at the surface to 1 midpoint at about 300 ms below surface. As can be seen in Fig. 6-2, the CRS slightly reduced the noise level but had very little impact on the stack. For PreSDM purposes the acquisition geometry was preserved in this process by defining the midpoint positions, offset and azimuth of the original traces as stacking targets. CRS processing was not necessary for the JO-15 dataset as the S/N ratio of this survey is considerably higher than the S/N ration of the other two surveys.

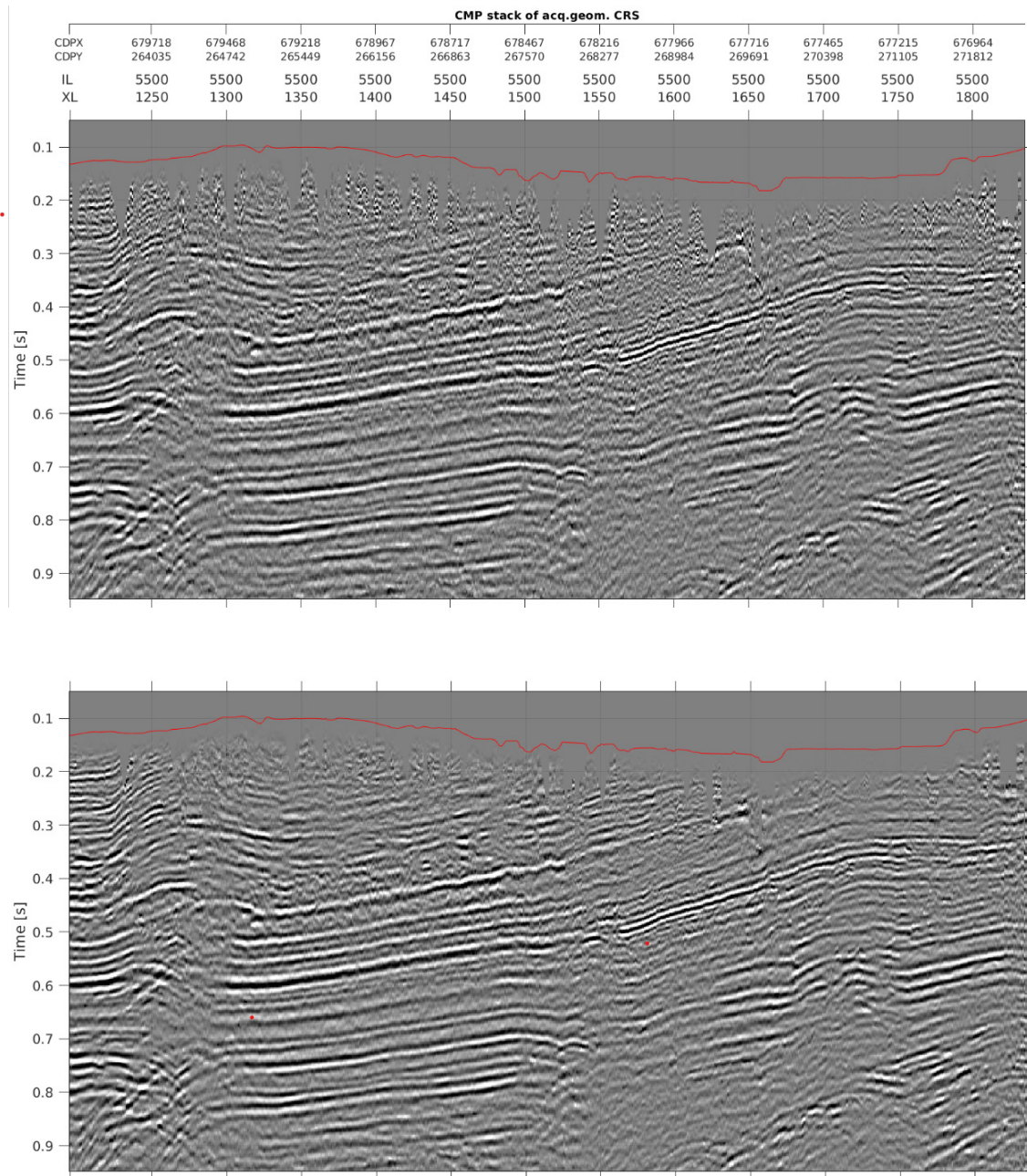


Fig. 6-2: Representative stack before CRS (top) and after CRS (NL-16)
Red line: topography

Initial velocity model building

For the PreSDM, a velocity grid was used with a cell size of 15 m by 15 m (in-line, cross-line) and a depth increment of 3 m. Using the smoothed elevation model as generated earlier for the refraction tomography, the near surface velocities were taken from the final refinement processing refraction tomography outcome as described in the previous chapter.

Starting with this model, the near surface velocities in the upper 200 m were scaled to reduce the RMO on the image gathers at and below that level. The refraction velocities were observed to be too high, probably due to anisotropy as refracted waves travel mainly horizontally along the fastest layers in the bedding. Scaling functions were derived on a grid of suitable locations with high near-offset CMP coverage, reasonable data quality and identifiable near-surface reflections – and subsequently interpolated. The scaling of the near surface velocities was done for all relevant PreSDM projects.

Fig. 6-3 shows an example of such a velocity scan on JO-15. A scaling factor of about 0.88 was deemed appropriate here at a depth of 500 meter.

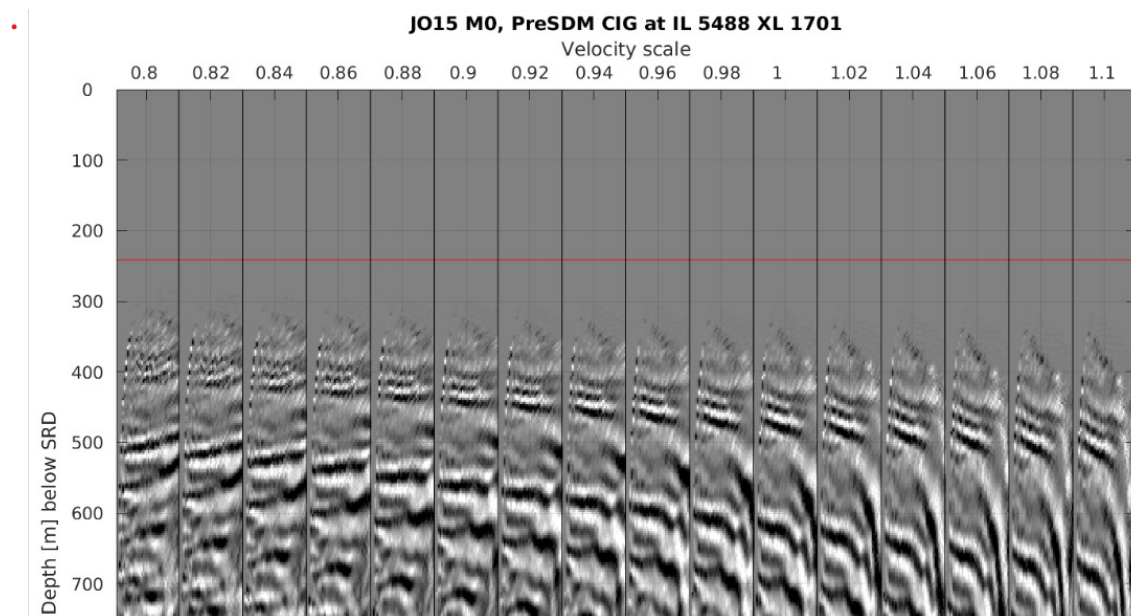


Fig. 6-3: JO-15 Near surface velocity scans

Red line: ground level

Model updating

For the subsequent model updating the iterative procedure was:

- Identification and picking of reflections corresponding to the target horizons;
- Picking of locally continuous reflection elements in the overburden of the objective formation;
- Computation of PreSDM image gathers using the previous model version;
- RMO analysis along above identified reflections;
- Inversion of (filtered) RMO picks to derive an isotropic velocity model update.

Travel times were calculated using the Eikonal equation.

Following the scaling of the near surface velocities, the first layer for which the velocities were updated was down to the first mappable horizon in the area of interest. This was the top Gerstenhübel bed (intra Malm Group) for JO-15 and the Top Malm Group for NL-16 and ZNO.

Having followed the process as outlined above, a single (Thomsen) δ value was derived to match the Top Malm Group in depth using the relevant borehole marker.

Anisotropy after Alkhalifa & Tsvankin (1995) was implemented in the near surface models for NL-16, JO-15 and ZNO-97/16. Misties of the preliminary Top Malm Group horizon at shallow boreholes were converted to a constant δ and the near surface velocities were scaled accordingly. An ε field was derived and interpolated from an image panel scan analysis.

In a similar fashion, the velocity model was updated for a number of layers down from the Top Malm Group horizon (or intra-Malm Group for JO-15) to the base Mesozoic unconformity (for JO-15 and ZNO) or top Muschelkalk Group (for NL-16). Velocities above the top of each interval to be updated were frozen and from the available logs and VSPs a suitable initial velocity for the layer was established. Subsequently a number of iterations of the tomographic updating procedure were run until convergence was achieved. Detailed lists of the various horizons used in this stage of the model building are provided in the sections below for the three areas. Bedrock velocity was extrapolated without further refinement.

RMO picking

A data driven workflow, such as the one adopted here, is largely based on RMO analysis, the principle of which is show in Fig. 6-4. Due to mute and stretch effects, as well as poor coverage shallow, RMO measurement becomes quite difficult at shallow depths and in high velocity formations. In the high velocity area, above the lower velocity zone, semblance clouds tend to spread out, making accurate RMO determination very challenging. Further below the high velocity zone, picking becomes gradually more accurate.

RMO was analysed on a grid of 40 by 40 in-lines/cross-lines and inverted for an updated velocity model. Repeat application of the process was initiated if visual quality control indicated velocity deviations of more than 5%.

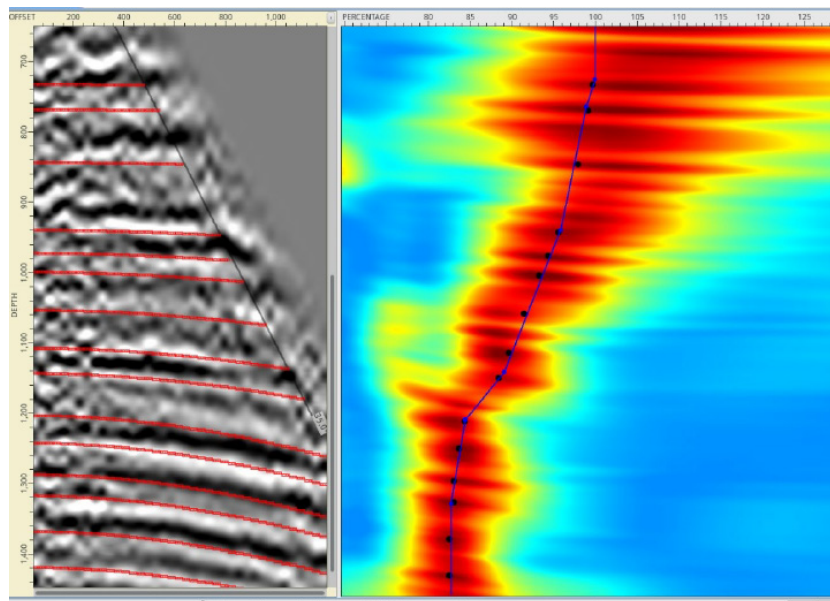


Fig. 6-4: Illustration of RMO analysis in ZNO

Left: common Image Gathers with mute applied (black line) and analysed horizons (red curves) indicating residual moveout. Right: Semblance maxima indicate the expected velocity correction.

Imaging

A reduced migration aperture of 300 m was consistently used for gather generation for model building. Migration aperture and dip mute were tested for each survey to find the optimum balance between (fault) resolution and migration noise. The final image products resulted from applying the optimal test results.

Tab. 6-2 lists the migration test and final product parameters per area. First test series with the ZNO-97-16 dataset indicated limited benefit of apertures >500 m. Dip mute angles were independently tested. An aperture of 500 m and dip mute of 15/25° was selected for the final ZNO image product.

The presence of regional tectonic features and a permo-carboniferous trough system in JO motivated migration tests with longer apertures and wider, independently tested dip mute angles than realised in the ZNO tests (Tab. 6-2). The final products include two 500 m aperture migrations that are optimised on imaging the Mesozoic sedimentary rocks. A wide-aperture product was optimised on imaging the deeper structures.

Benefiting from the test series in the previously processed data sets, the NL-16 test series focused on specific aperture / dip mute combinations, the evaluation of which led to production of two final image products (Tab. 6-2). Similar to JO, a 500 m aperture image focusing on the Mesozoic units, and a 1,200 m aperture image enhancing the deeper structures resulted as final products.

Tab. 6-2: PreSDM migration parameters

Area	Apertures [m]	Dip mute [min/max °]	Product
JO-15	300 500 700 900 1,100	20/30	Aperture tests
	500	20/30 25/35 30/40 35/45 40/50 45/55 50/60	Dip mute tests
	500 500 1,200	20/30 35/45 35/45	Final products
NL-16	300 500 800 1,200 1,200	20/30 25/35 30/40 35/45 25/35	Aperture and dip mute tests
	500 1,200	25/35 25/35	Final products
ZNO-97-16	300 400 500 600 700 900 1,100	20/30	Aperture tests
	500	10/20 15/25 20/30	Dip mute tests
	500	15/25	Final product

Post-processing

Final RMO was picked on the PreSDM gathers stacked over all azimuths into offset classes and interpolated over the area. Following an RMO correction, trim statics were applied to the gathers up to 4 samples which is 12 m as 12.5 m was assumed to be the shortest possible $\frac{1}{4}$ wavelength in the data (at 60 Hz, 3000 m/s).

A Cadzow filter (FK-domain type of principle component analysis and matrix rank reduction) was applied to the JO stacks and a standard 2D FK filter was applied to offset volumes of NL-16. No FK type of filter was applied in ZNO.

At a later stage a delta-Z stretching (borehole depth marker calibration) was derived and applied on JO and NL-16. For this purpose, selected horizons were matched to borehole tops and the depth difference between the horizons and the boreholes was measured. Following a 2D inter- and extrapolation along horizons, a 1D interpolation was carried out per in-line / cross-line position, a velocity volume was calculated representing the delta-Z and the seismic data (stacks and gathers) was accordingly stretched. For ZNO delta-Z was near zero so it was not applied.

6.3 Jura Ost

The horizons used for model building in the Jura Ost area are listed in Tab. 6-3

Tab. 6-3: Tentatively interpreted horizons for model building in JO-15

Horizon
Near Top Gerstenhübel bed, tied to outcrop*
Top Dogger Group, tied to outcrop
Top Opalinus Clay, tied to outcrop
Top Keuper Group*
Intra Bänkerjoch Formation*
Base Mesozoic

* No reference in Fig. 1-5. Temporary pick for model building

To concentrate model building efforts to the area of highest interest, the PreSDM project for JO concentrated on an inner perimeter (see Fig. 1-2 for the extent of the AOI). The model was extrapolated and refined with a reduced density of analysis points in the outer area to include offsets from the outer area as well. The geologically more complex outer area, however, was fully processed and imaged in the subsequent PreSTM-ref project.

For the processing of the AOI as described in this report, the modelling was limited to the isotropic part of the model, as there were no thick Tertiary deposits in the area of the AOI that would have made anisotropic modelling necessary.

As can be seen in Fig. 6-5, the Mesozoic sequence outcrops in the central and northern JO-15 area. This yields a difficulty for the model building insofar as there is a transition from a deep-subsurface domain where velocity is controlled by lithology to a shallow-subsurface domain where velocity is controlled by disaggregation. Formation top outcrop data were used to steer the model building (Fig. 6-5).

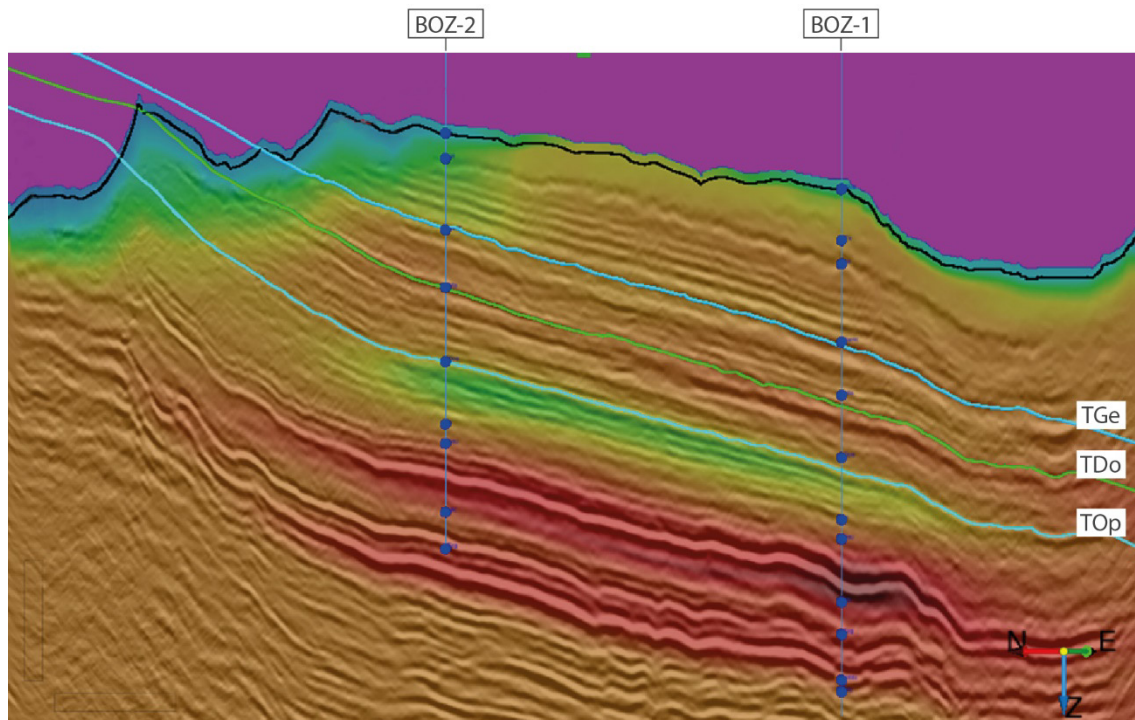


Fig. 6-5: JO-15 Intermediate velocity model and geologically controlled horizons

Horizons from bottom to top: light blue: top Opalinus Clay (Top), green: Base Malm Group (TDo), Navy: top Gerstenhübel bed (TGe). Preliminary borehole tops in blue.
Note that display extends beyond the AOI.

In addition to checking the geological plausibility, considerable effort was spent on optimisation of the initial model as the near surface velocities from refraction tomography appeared too high in the upper 200 m, resulting in residual moveout. Clipping ($v_{max} \leq 3,600 \text{ m/s}$) and scaling of the near surface velocities lead to the desired and plausible result as shown in Fig. 6-6.

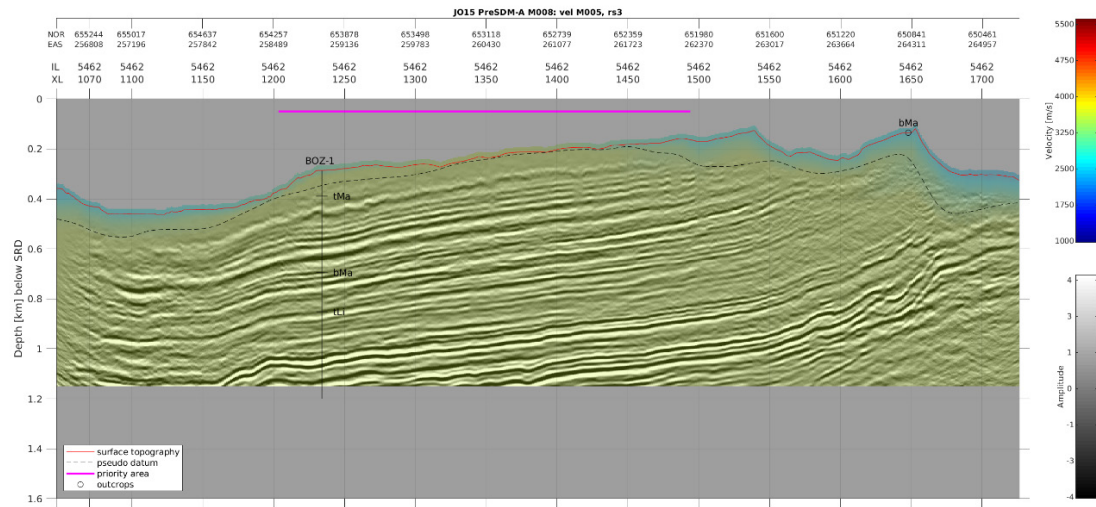


Fig. 6-6: JO-15 interim image with adjusted near surface velocity model

Red line on top indicates extend AOI, BOZ-1 indicates Bözberg-1 borehole with a selection of preliminary interpreted horizons (tMa: top Malm; bMa: base Malm, tLi: top Lias). Note bMa outcrop near XL 1650.

Model building continued with the typical RMO analysis and reflection tomography workflow (Section 6.2). In Fig. 6-7 the final result on in-line (IL) 5460 is shown. Note that from the SE (left) towards the NW (right) velocities gradually decrease, also in the Malm Group. Please also note the red line at top of the section which indicates the extend of the area where the velocity model was updated for this survey.

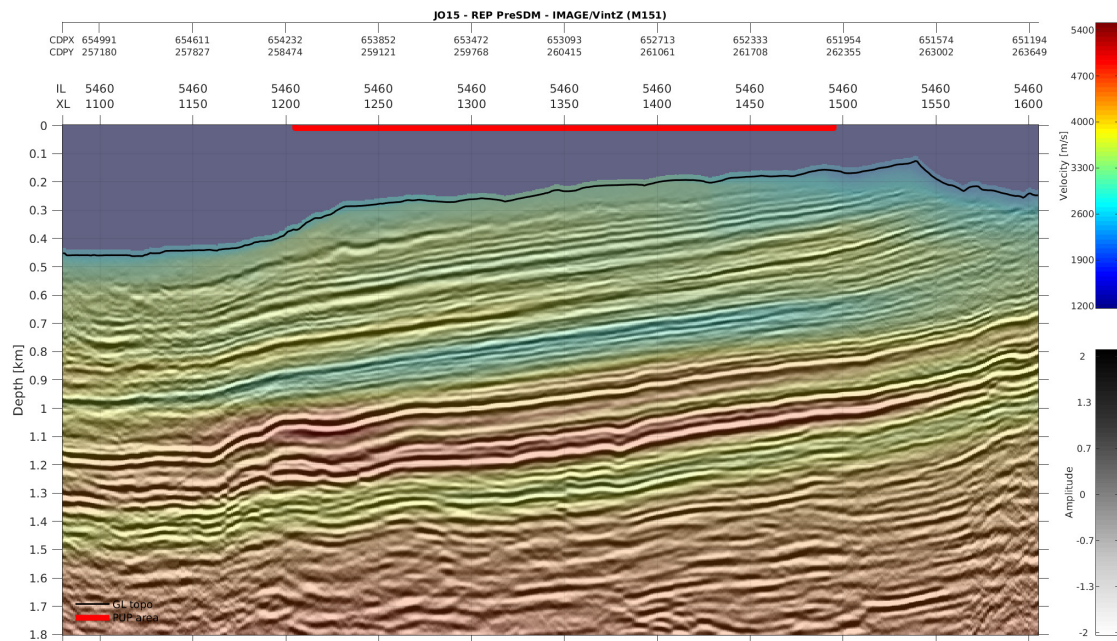
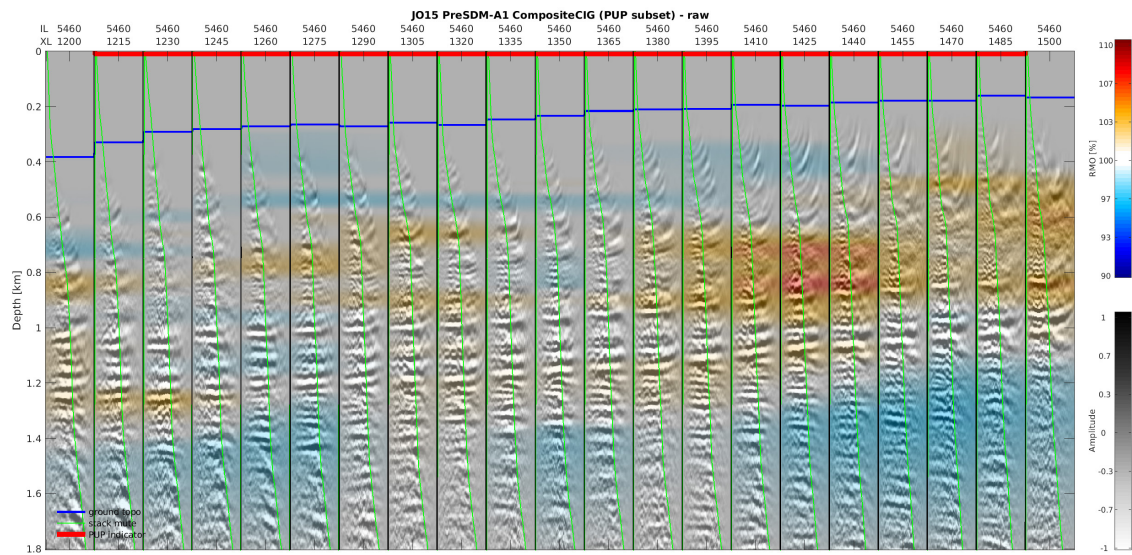


Fig. 6-7: JO-15 IL 5460 Overlay display of final PreSDM stack and velocity model

Red line on top: extent of the AOI, black line: topography.

Fig. 6-8: JO-15 IL 5560 Common Image Gathers final model

Green lines: mute, blue: topography. RMO in background colour. Red line on top indicates AOI.



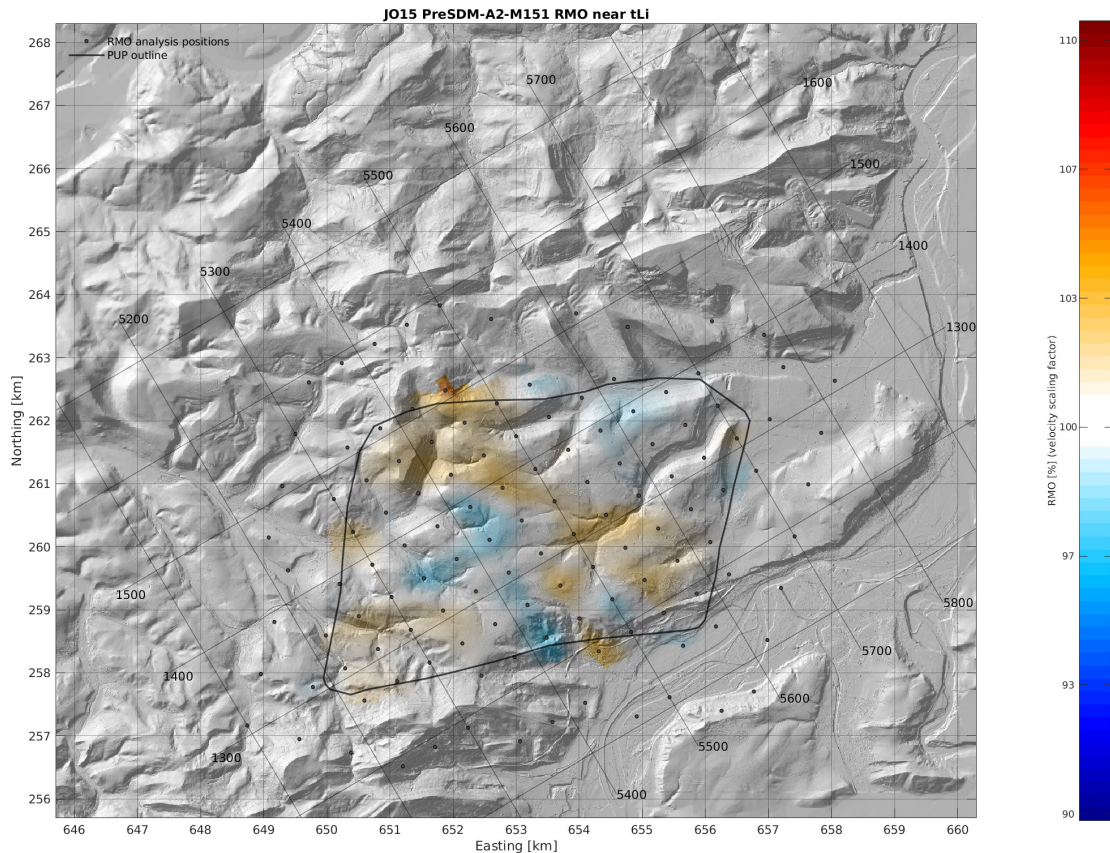


Fig. 6-9: JO-15 Map of RMO near top Lias Group (final model)

Black dots: RMO picking locations, black line: AOI.

In the QC comparison of the depth of the horizons with the borehole markers, significant differences were obtained. Typically, velocities derived from moveout tend to be too high resulting in a too deep imaging of horizons. As seen in Fig. 6-10 the differences gradually build up deeper, up to about 40 m. Also note the lateral variability of the differences keeping in mind that there are only a few boreholes at which the exact difference values are known. So, although using the Thomson delta parameter would have resolved the depth differences at the well positions, further away from the borehole control areas depth uncertainties would still be present.

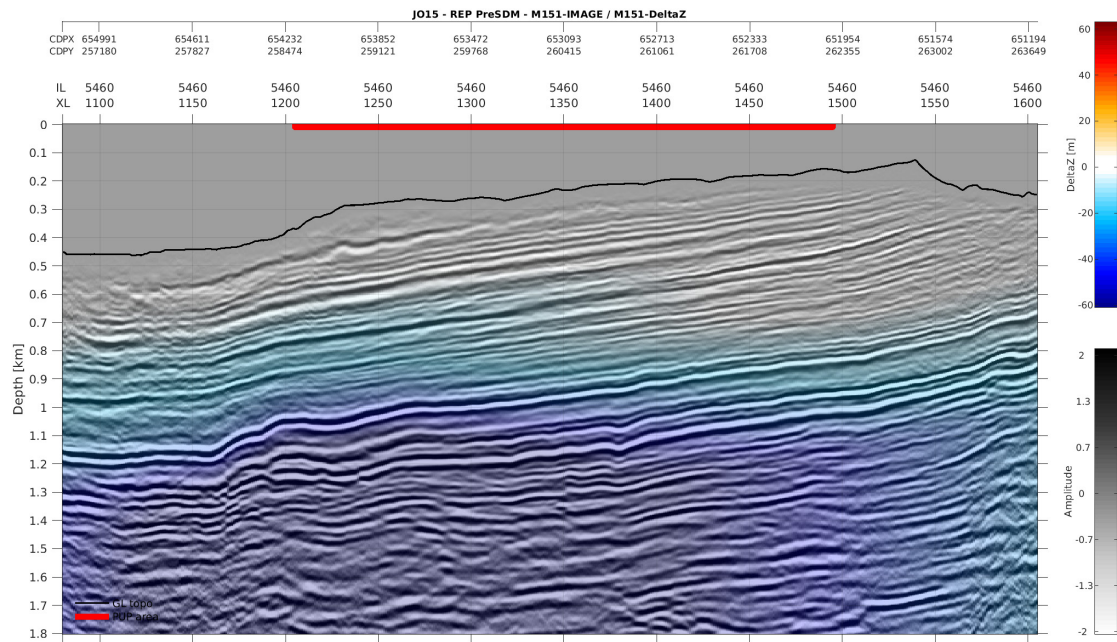


Fig. 6-10: Depth difference between PreSDM horizons and borehole formation top markers (interpolated)

Red line on top indicates the extent of the AOI.

6.4 Nördlich Lägern

The horizons used for model building in the NL-16 area were

Tab. 6-4: Tentatively interpreted horizons for model building in NL-16

Horizon
Base Cenozoic
Near Top Wildegg Formation (Malm internal)*
Top Dogger Group
Top Herrenwis unit*
Base Herrenwis unit with separation of basin and lagoon facies*
Top Opalinus Clay
Top Lias Group
Base Mesozoic

* No reference in Fig. 1-5. Temporary pick for model building.

The full volume of the NL-16 survey was processed using the starting model (Section 5.4) and according to the PreSDM workflow (Section 6.2). Fig. 6-11 shows an overlay of the final PreSDM stack with the velocity field. The high velocity Malm Group, going towards the surface in the north, clearly stands out. The Opalinus Clay is observed as the blueish low velocity section dipping upwards from about 1,150 m depth in the south to ~700 m in the north (depth values relative to SRD in Fig. 6-11). The Herrenwis Unit is recognised as a thin high-velocity zone with limited extent above the Opalinus Clay.

A number of factors limit the quality of the deeper image. The velocity inversion below the Malm Group implies that the incidence angle range will be smaller there, which can impact both the imaging and the velocity error. Velocities were observed to be fairly stable and generally following the geology, indicating a reasonable balance between applying smoothing and allowing lateral variation. Towards the north, the imaging of the Malm Group deteriorates, partly caused by the Malm Group outcropping and/or sub-cropping.

While in the refinement processing a more realistic near surface model was derived than in the QLP (see Fig. 5-7 for a comparison), it should be realised that fold is very low for the near surface making the velocity uncertainties of any RMO-based updates in the upper 200 – 300 m relatively high.

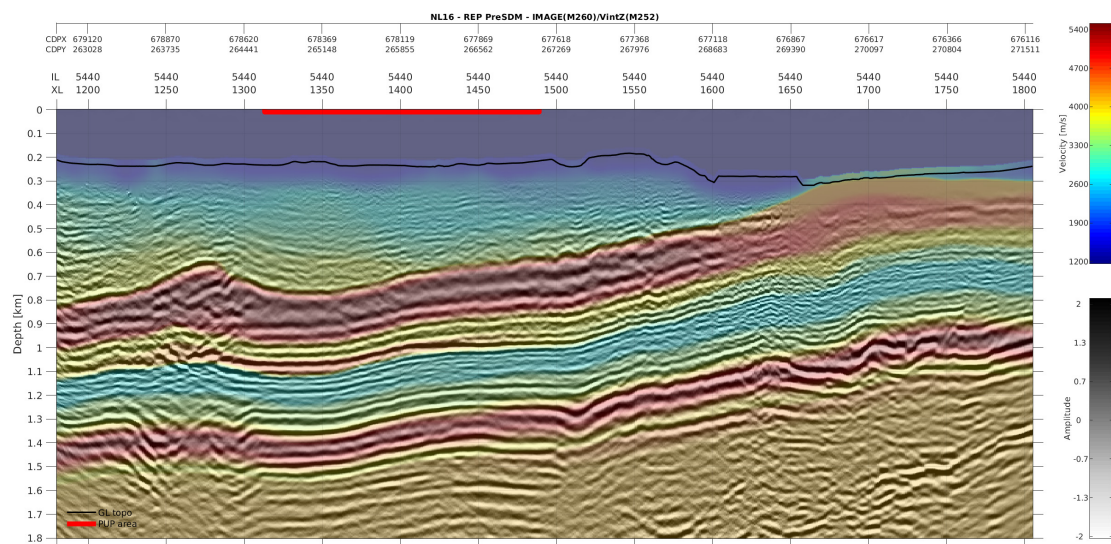


Fig. 6-11: NL-16 IL 5440 Overlay display of final PreSDM stack and velocity model

Red line on top: extent of the AOI, black line: topography.

In Fig. 6-12 common image gathers of the depth migration with the final velocity model are shown. Reflections appear to be contaminated by source generated noise. Note the significant stretch effect at the Top Malm Group and the mute functions applied to exclude stretched data from the stack. RMO appears to be small (less than 3%) down to approximately Top Lias Group (1,100 – 1,200 m depth below SRD in Fig. 6-12). Below that level RMO quickly increases as the effort on deeper updates was limited.

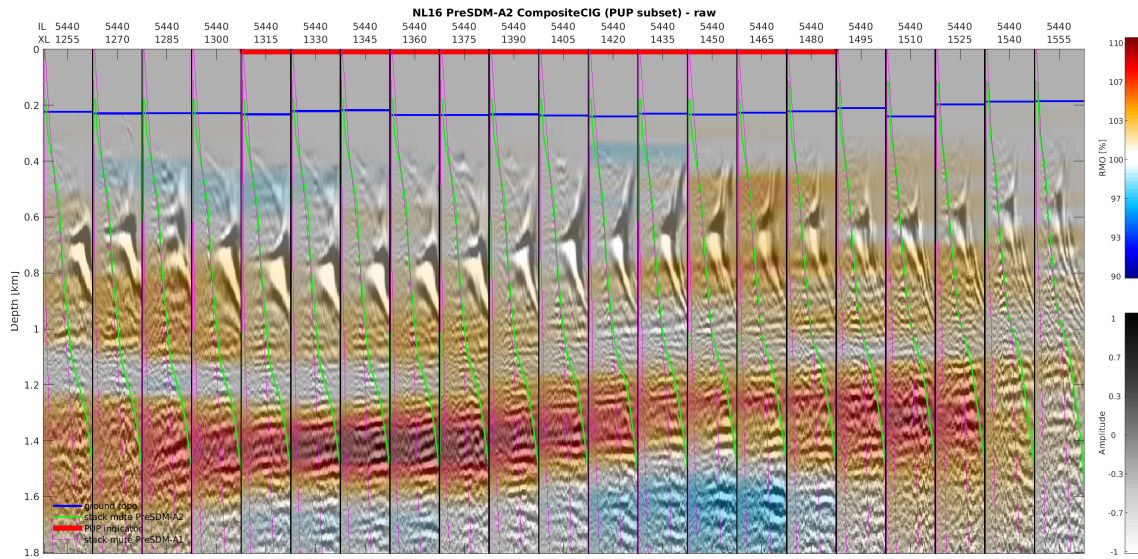


Fig. 6-12: NL-16 IL 5440 Common Image Gathers final model and RMO

Mute: green lines, blue: topography, RMO in background colour, red line on top: AOI

The RMO at the top Lias Group horizon is shown spatially in Fig. 6-13. There appears to be some imprint of topography on the RMO map (elevation is plotted as shaded elevation map in Fig. 6-13), with higher areas having slightly lower (<100%) RMO and depressions have higher RMO.

A comparison of the depth difference between the finally imaged horizons (preliminary interpretation) and the matching borehole formation tops is shown in Fig. 6-14. Relatively small differences of ~-5 m at top Malm Group (near XL 1400 at 700 m) to ~+10 m at top Muschelkalk Group (near XL 1,350 at 1,250 m) are observed.

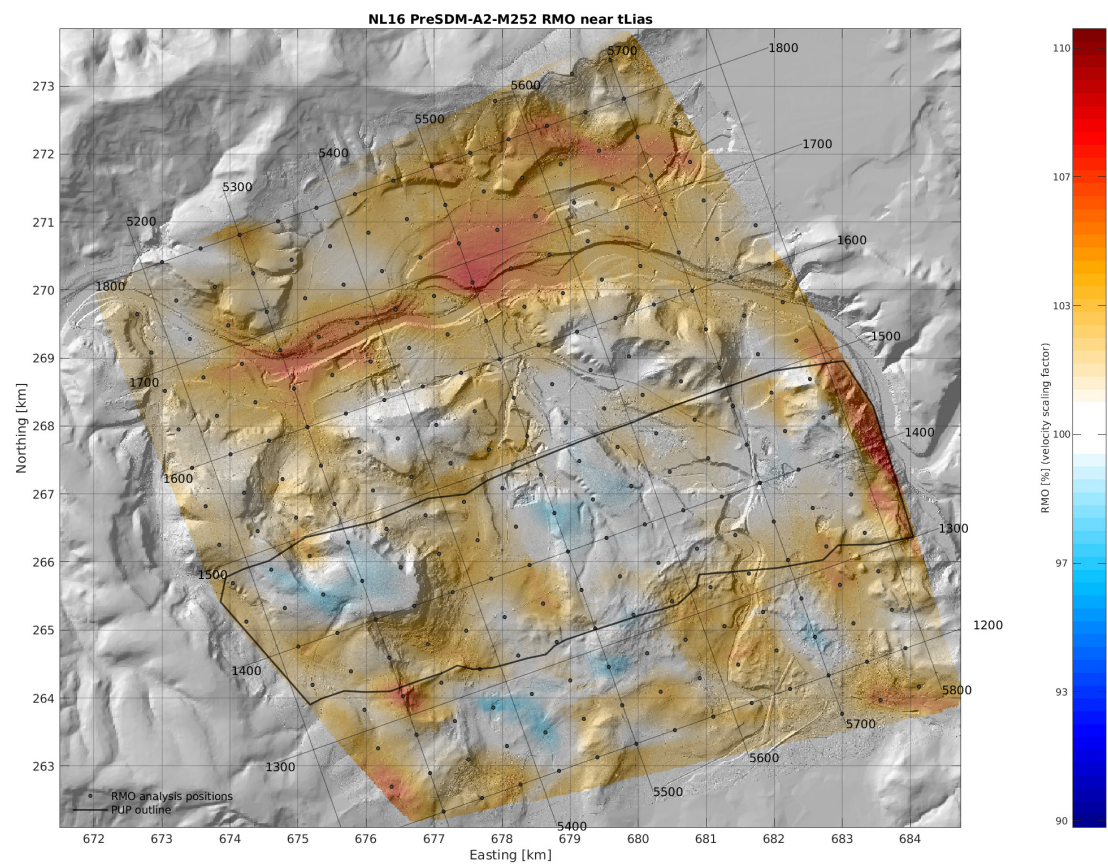


Fig. 6-13: NL-16 RMO map overlaying shaded elevation map
Black dots: RMO picking locations, black line: AOI.

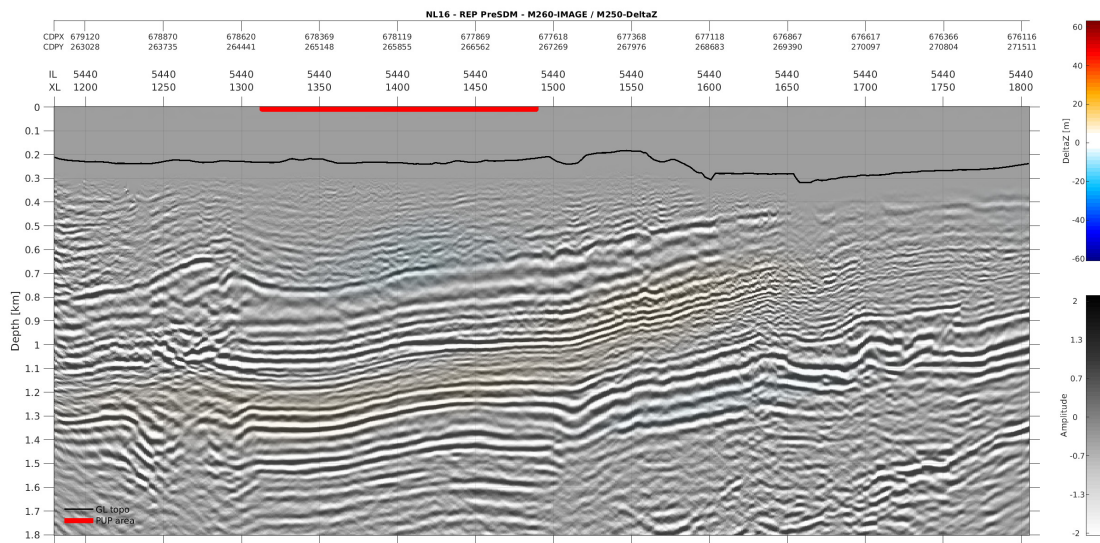


Fig. 6-14: NL-16 final amplitude image overlain by interpolated depth differences between PreSDM horizons and borehole formation tops

Black: topography; red line on top: AOI. Note use of the identical colour scale in Fig. 6-10.

6.5 Zürich Nordost

The horizons used for model building in the ZNO area were:

Tab. 6-5: Tentatively interpreted horizons for PreSDM model building in ZNO-97/16

Horizon
Base Cenozoic
Top Felsenkalke (Malm internal)*
Near Top Villigen Formation (Malm internal)*
Top Dogger Group
Top Opalinus Clay
Top Lias Group
Top Seebi Member*
Base Mesozoic

* No reference in Fig. 1-5. Temporary pick for model building.

The ZNO-97/16 volume integrated the data from the two surveys ZNO-97 and ZNO-16. Fig. 6-15 shows a cross-line after PreSDM using the final model, which is plotted in the background. Paleogene-Neogene velocities are observed to be fairly consistent laterally whilst velocities in the Malm Group decrease somewhat towards the north-west where the Malm Group gets closer to the surface. Using indications from the Benken and Trüllikon boreholes and unique for the ZNO area, a thin layer of “Plattenkalke” (equal to Base Cenozoic) was interpreted and modelled above the massive “Massenkalke”.

Below the Malm Group, a high velocity zone is identified with a northward velocity trend and the typical velocity inversion associated with the Opalinus Clay can be recognised. Again, no significant lateral variation of the velocities is observed in the Opalinus Clay interval, but it should be noted that measurable RMO and imaging are not very sensitive to changes in (local) interval velocity as the reflection angle range has been limited by the velocity inversion. The Lower Mesozoic zones were guided by the observed reflections, and a constant velocity was extrapolated to the depths below the Base Mesozoic unconformity.

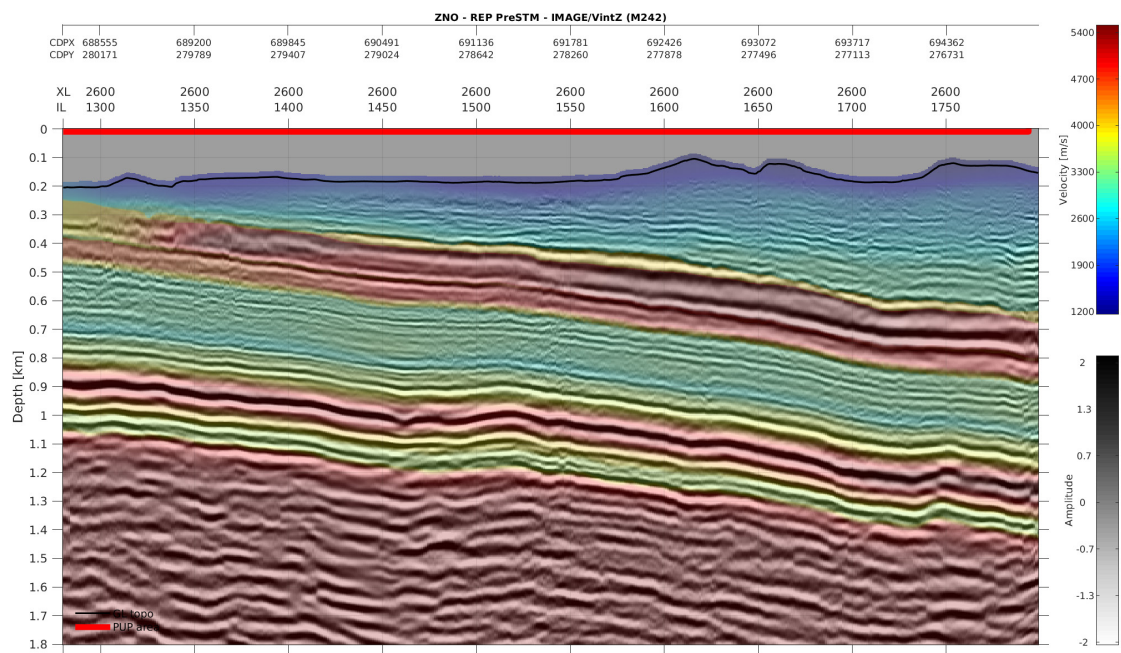


Fig. 6-15: ZNO XL 2600 Final PreSDM stack with overlain final PreSDM velocity model
Display with equals the extent of the AOI, black line: topography.

Fig. 6-16 shows some image gathers migrated with the final velocity model. Generally, the RMO is modest, except for locally more pronounced variations just below the Top Malm Group. Here, due to stretch effects, RMO measurement becomes quite difficult and may result in significant velocity uncertainties (see Fig. 6-4 for explanations).

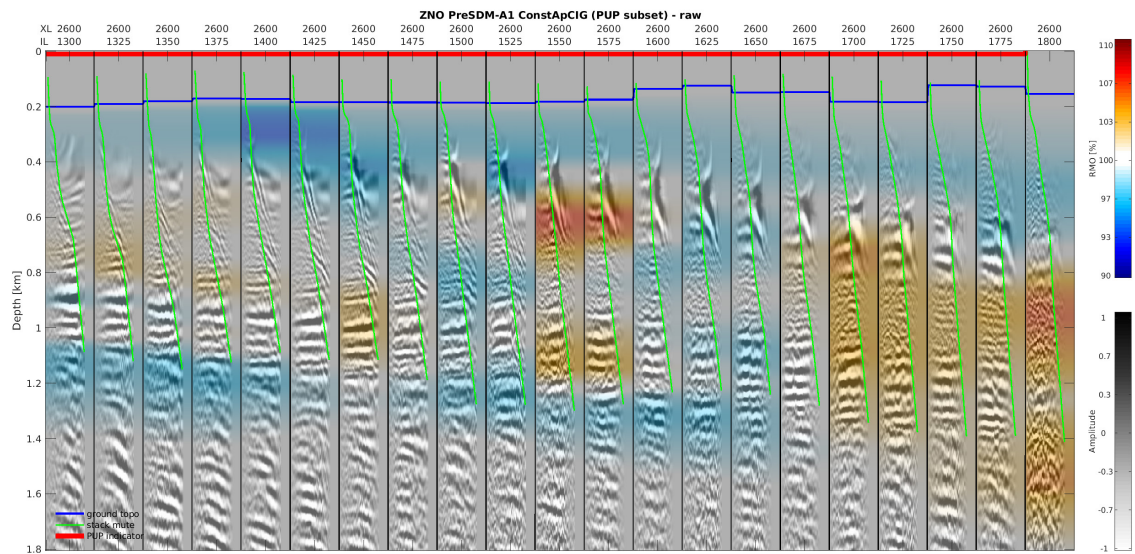


Fig. 6-16: ZNO XL 2600 Common PreSDM image gathers with overlay of the final RMO correction

Green lines: mute; blue: ground level; RMO in background colour; red line on top: AOI

Fig. 6-17 shows the areal distribution of RMO near the Top Lias Group horizon. Apart from a few points close to the edge of the survey in the northeast and southwest, RMO is observed to be reasonable.

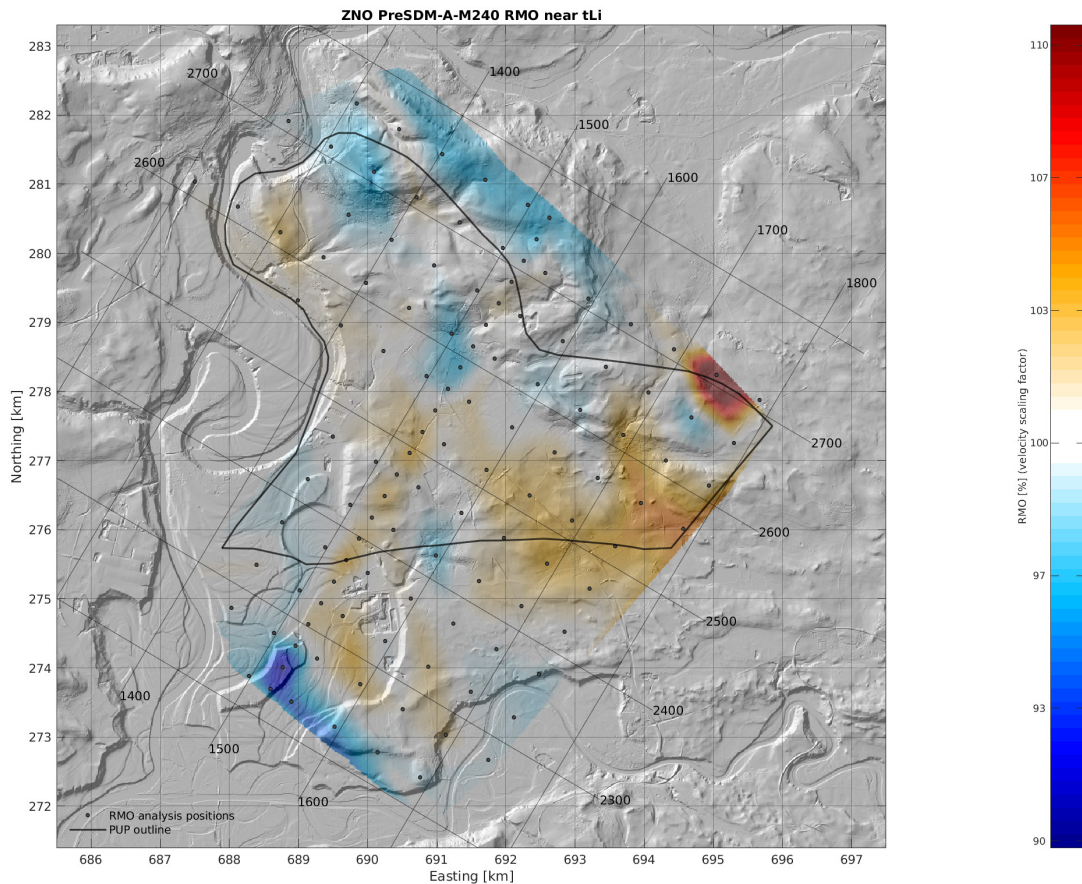


Fig. 6-17: ZNO Map of RMO near the Top Lias Group horizon overlayed on a shaded elevation map

Black dots: RMO picking locations, black line: AOI.

6.6 Discussion of the results

As the geology varies considerably, both within surveys and across surveys, the PreSDM workflow was optimised individually per siting region.

In the JO-15 area, specifically in the AOI, relatively thin Quaternary and Paleogene-Neogene sedimentary rocks cover the Malm Group. Near surface velocities vary locally but thanks to the competent Malm Group underneath, near surface imaging is generally better than for the other areas. Quaternary valleys south and east of the AOI as well as fault zones south and north of the AOI were excluded from the PreSDM imaging perimeter.

The velocity structure of NL-16 and ZNO-97/16 models reflects the following common geological features:

- Thick Paleogene-Neogene sedimentary rocks, thinning towards the north.
- Deep Quaternary valleys filled with unconsolidated sediments.
- Plateaus with compacted Quaternary gravels (Deckenschotter) of mixed saturation.
- Presence of the Malm Group close to the surface in the northern part.

Common to all areas is the tilted sediment layering below the Malm Group, characterised by a significant velocity inversion at the clay-rich Dogger Group.

The commonly applied refraction tomography in 3D provided the initial near surface velocity models with subsequent adaptation for the further reflection mode processing. The available data limits the use of RMO measurements for making near surface velocity updates, thus leaving room for further improvement in all surveys.

Providing significant contrasts to the formations above and below, the velocities in the Malm Group appear to be quite high, which is also observed in borehole logging information (see e.g. Fig. 1-5). The borehole logs also indicate significant intra-Malm Group and depth-dependent velocity variations. Consistently, in areas where the Malm Group gets close to the surface, velocities tend to decrease in the velocity models.

The Dogger Group is generally characterised by low velocities and relatively low reflectivity in all three areas. It exhibits relatively homogeneous and reasonably well resolved velocities as illustrated in RMO maps. An exception is the high-velocity Herrenwis Unit, a unit with limited extent and uniquely observed in the NL area. It was explicitly represented in the velocity model, aiming at optimal resolution of its seismo-stratigraphic expression.

At and below Base Muschelkalk Group, velocity uncertainties tend to increase. This is partly due to the limited offset range, but also the presence of thin layers and significant velocity variations challenged the velocity modelling in this zone outside the area of main interest.

The velocity model was extrapolated into the bedrock below the Base Mesozoic unconformity, but bedrock imaging is not considered a critical element in the detailed interpretation for the site selection evaluation. In conclusion, velocity model building at Muschelkalk Group and below has been generalized, and imaging can be improved in all areas.

The PreSDM imaging results have been produced using the acquisition geometry from topography, thus prioritising resolution of details over reflection continuity. The selection of the migration parameters, notably aperture, favoured high resolution of the target zone in the Dogger Group. In general, the migration apertures were kept relatively small, aiming more at optimizing the horizon imaging and minimisation of migration noise than at optimizing the imaging of steep fault planes.

7 Refinement processing – reference pre-stack time migration

7.1 Introduction

One of the main objectives of the refinement processing was to (re)process the data from the three seismic surveys in a way that would enable a direct comparison of the obtained seismic images and facilitate the evaluation of potential differences between the proposed siting regions. For this purpose, the advantages and disadvantages of Pre-stack time migration (PreSTM) versus Pre-stack depth migration (PreSDM) had to be considered.

In theory the PreSDM should have yielded a better image in the geologically complex areas than a PreSTM. Indeed, improved imaging in structurally complex zones was observed, however, the image was disturbed by numerous artefacts appearing in less deformed areas. In particular the sensitivity of the depth imaging with respect to the near surface velocity model, the requirement to obtain an azimuthally consistent velocity model as well as the restrictions on regularisation and interpolation of the data posed by the requirement to maintain positional integrity has limited the benefits of this technology for this project.

PreSTM tends to produce a laterally more stable image, since it essentially assumes local cylindrical symmetry of velocity around the output position (though e.g. in RMO picking this need not be the case) and imaging at deeper levels is independent of velocities picked at lesser times. PreSTM is also less dependent on the choices by processor and interpreter with respect to horizon selection, handling of thin or low velocity layers and inversion parameterisation.

For these reasons it was decided to produce a second PreSTM version as part of the refinement processing, in addition to the PreSTMs first produced as part of the QLP (see Chapter 4). The refraction statics model derived in the near surface velocity model building part of the refinement processing (Chapter 5) was integrated, and, as much as possible, equal parameters for all three areas were used. This results in a product well suited for site comparison which is called the reference PreSTM (PreSTM-ref).

The refinement processing PreSTM-ref and PreSDM use similar (for practical purpose, identical) near surface models, but incorporate them differently. The PreSTM-ref incorporates the near-surface model by means of long-wavelength static corrections, which makes it more robust to model errors than PreSDM, which represents it as propagation velocities in the velocity model.

The delivered refinement processing PreSTM-ref uses geometry-regularized data (offset and azimuth binning), which reduces migration artefacts in contrast to the PreSDM. It differs from the QLP PreSTM in static corrections and type of underlying geometry regularization. The QLP regularized the CMP gathers into offset bins only and did not preserve azimuth.

The work was contracted to TEEC GmbH and carried out from September through December 2021 with some follow-up work extending to May 2022.

7.2 Description of workflow

The workflow applied for the reference pre-stack time migration is shown in Fig. 7-1 below. The various workflow steps are detailed below the diagram.

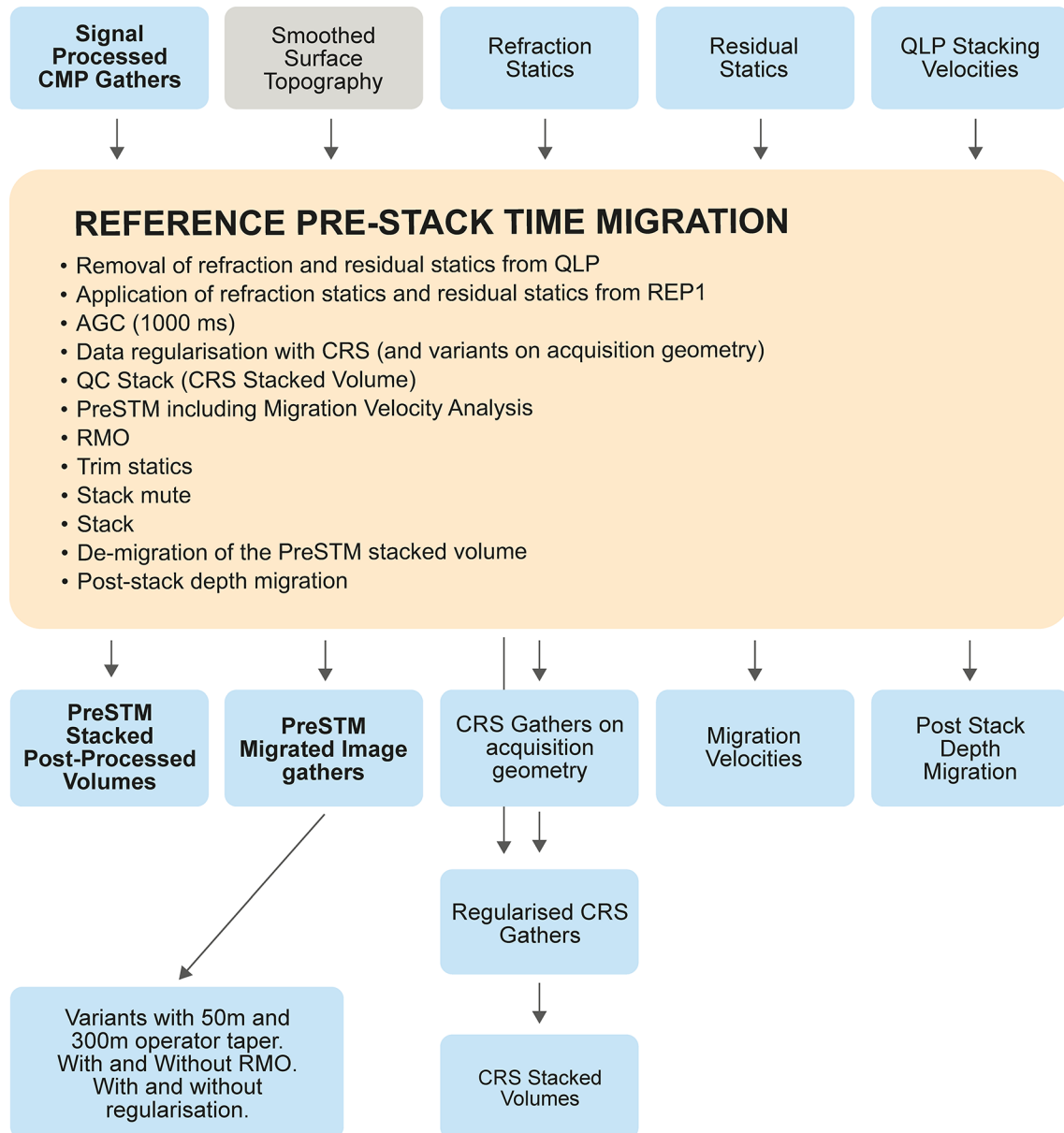


Fig. 7-1: Workflow applied for the reference pre-stack time migration

7.2.1 Removal of QLP statics and application of refinement processing statics

Any statics that had been applied in the QLP processing were taken out after which the input seismic data were back to the acquisition timing. Subsequently, the refraction statics and residual statics as determined in the REP (Chapter 5.2) were applied. For the refraction statics, only the part between the pseudo datum and the smoothed elevation was taken into account, thus bringing the data to smoothed elevation datum.

In more detail, there were refraction statics per source/receiver to SRD, SRD-to-FD temporary statics per CMP and residual statics per source/receiver to be replaced (Fig. 4-2).

7.2.2 Common Reflection Surface regularisation (CRS)

Data was regularised in CRS. After application of the NMO correction with velocities taken from the latest residual statics iteration, plane wave dip scans were run on stacked data. Due to small midpoint aperture, curvature modelling could be neglected. The objective here was to ensure that, within the possibility of the selected CRS aperture, every azimuth/bin combination was equidistantly populated in the offset domain. So, the CRS stacking targets for the PreSTM regularisation were slot centres for specific bin/azimuth/offset combinations.

Azimuth binning used 6 bins of 30 degrees each (azimuth aperture 50% bin width) and offset binning (offset aperture 50% bin width) was done at 30 m slot width and interval. The midpoint aperture varied in time from 5 at surface to 1 at about 300 ms below surface. As can be seen in Fig. 7-2, the CRS regularisation significantly reduced the noise level and yet does not appear to distort the stack.

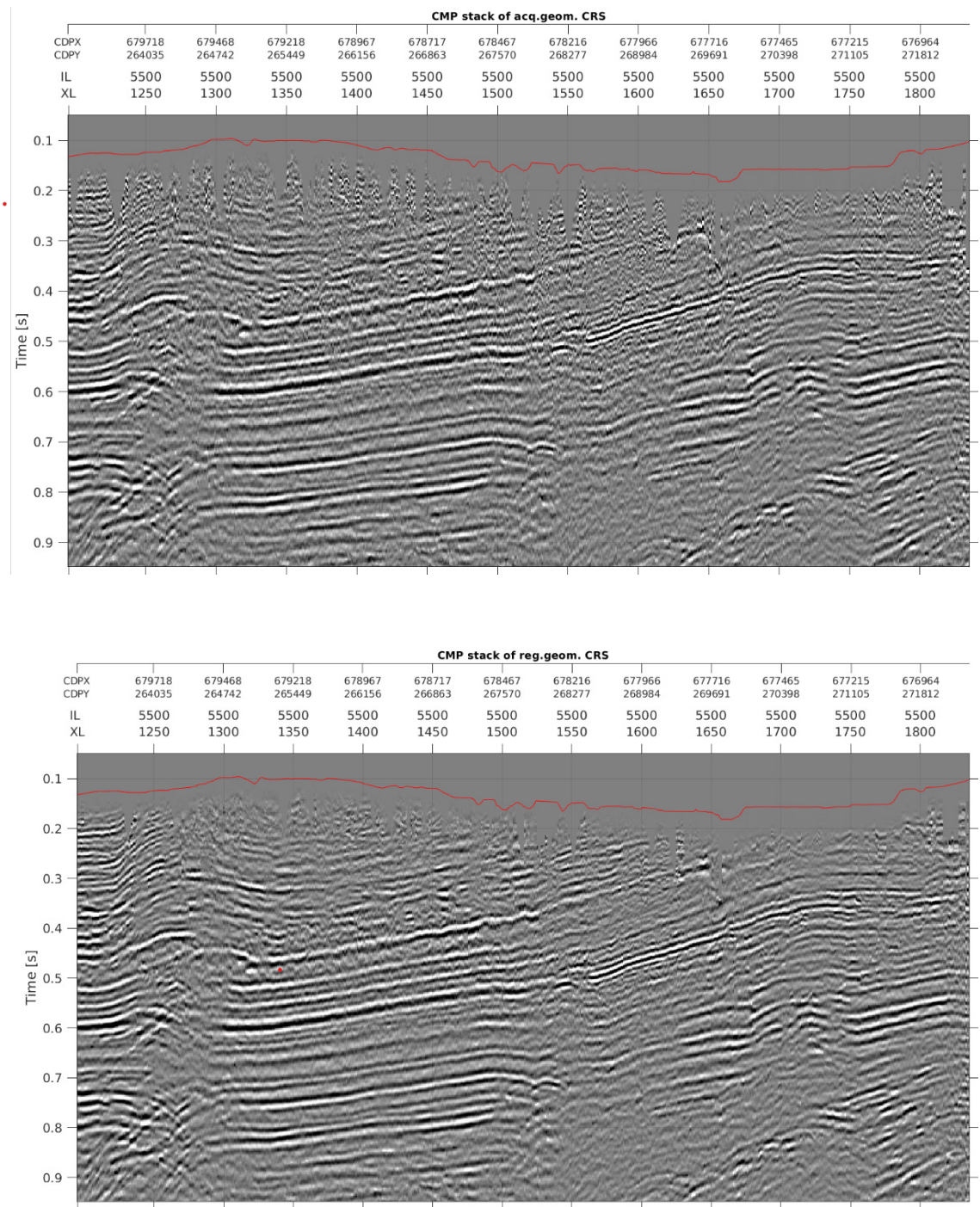
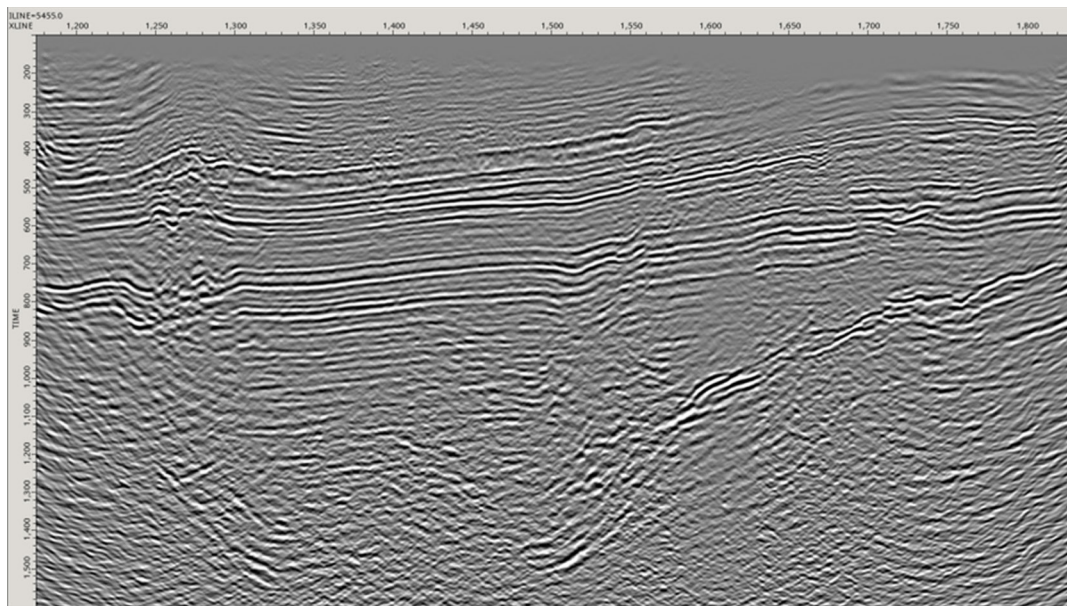


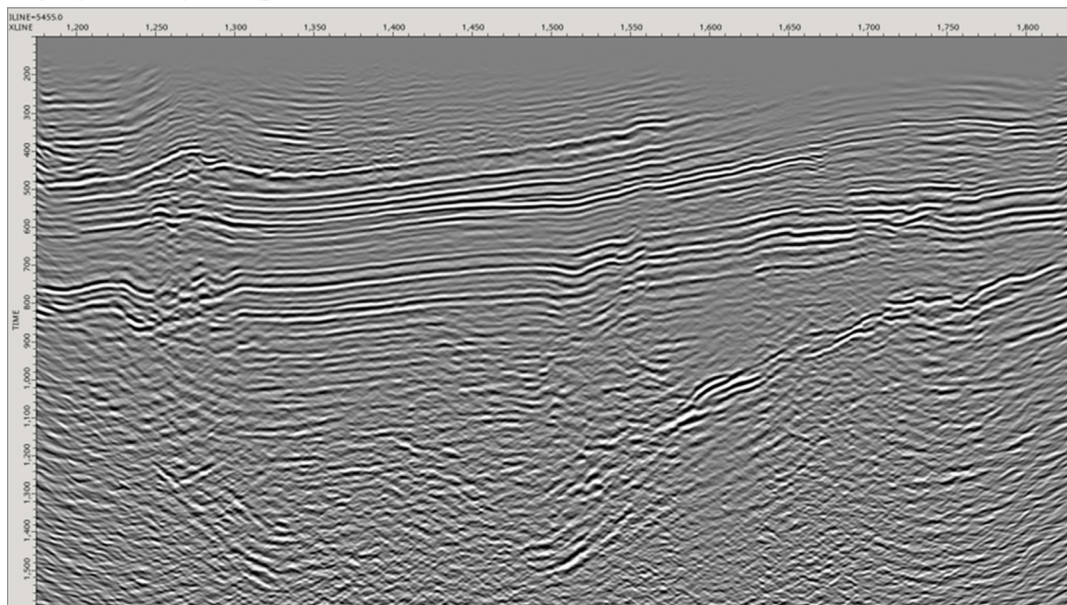
Fig. 7-2: Application of CRS: Acquisition Geometry Preserving stack (top) and Geometry Regularised stack (bottom)
Exemplary section from NL-16. Red line: topography

7.2.3 Pre-stack time migration

Using impulse response tests the optimal migration operator length was determined. The challenge was to find an optimal balance between correct imaging of dips (and faults) and limitation of migration noise. Dip-mutes between 20 and 40 degrees (with an interval of 5 degree) were tested, in the end a dip-mute of 30 degrees was selected for all three surveys. Since a sharp cut-off of the operator will cause edge effects, migration operator tapering was applied. Taper widths between 50 m and 300 m were tested where the 50 meter was preferred as its near-surface resolution appeared slightly higher (see the example in Fig. 7-3 on a stack from the NL-16 area). However, time migration products were made for both taper widths.



a) Dip mute taper length 50m, NL IL 5455



b) Dip mute taper length 300m, NL IL 5455

Fig. 7-3: Migration operator tapering length test

Subsequently, migration velocities had to be established. For this purpose, a migration velocity field was newly determined for each of the surveys. In the first iteration the objective was to establish a smoothly varying velocity model that should reflect the middle and long wavelength trends of the moveout velocities. Velocities were picked (as RMO) on a regular grid of common image gathers to facilitate easy interpolation and smoothing. In the second iteration, velocities were picked along specific horizons to ensure vertical velocity contrasts were represented correctly. An example of a typical NMO semblance panel and the grid and times of the picks are given in Fig. 7-4. The horizons used for velocity picking are provided in Tab. 7-1.

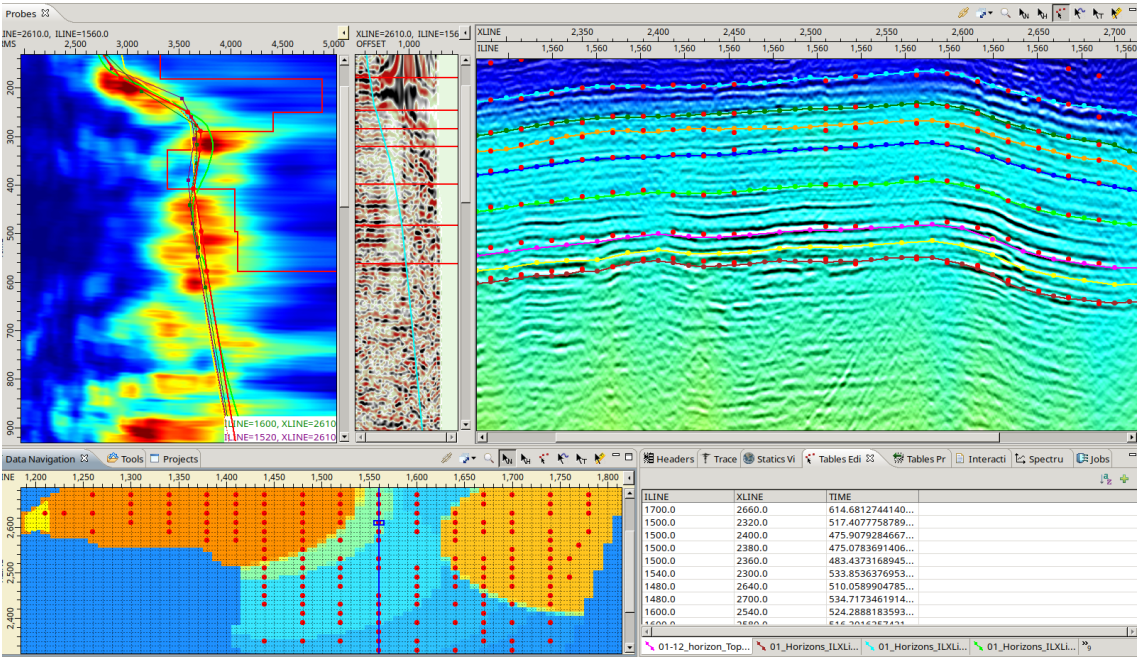


Fig. 7-4: Example of interactive velocity picking in ZNO-97/16
Top left: semblance panel and picks, top right distribution of picks along line, bottom: part of picking grid

Tab. 7-1: List of horizons for velocity analysis in the second round of picking for the three surveys

(Fig. 7-7, Fig. 7-12, Fig. 7-18)

JO-15	NL-16	ZNO-16/-97
Base Cenozoic	Base Cenozoic	Base Cenozoic
	Near Top Villingen Formation*	Near Top Villingen Formation*
	Near Top Wildegg Formation*	
Top Dogger Group	Top Dogger Group	Top Dogger Group
Top Opalinus Clay	Top Opalinus Clay	Top Opalinus Clay
Top Lias Group	Top Lias Group	Top Lias Group
Top Muschelkalk Group	Top Muschelkalk Group	Top Muschelkalk Group
Top Kaiseraugst Formation*	Top Kaiseraugst Formation*	Top Kaiseraugst Formation*
Base Mesozoic	Base Mesozoic	Base Mesozoic

* No reference in Fig. 1-5. Temporary pick for velocity analysis.

Having established the optimal migration velocities, the correction for non-hyperbolic effects was tested using the anisotropy parameter η (Alkhalifah & Tsvankin 1995). Essentially this acts as a higher order moveout correction to compensate for both ray bending and actual anisotropic effects. Results on a test line did not correlate with the geology and therefore it was decided not to apply this correction.

Pre-stack time migration aims to focus the energy of diffractors at their apex. In principle the 3D migration operator is rotationally symmetric around the image point position. While the basic implementation assumes straight rays, using an interval velocity model, the migration corrections can be adjusted to allow for ray bending. Essentially it is assumed that the minimum time path of any diffractor to the surface will be straight up. In case of laterally varying velocities this need not be the case. The resulting error can (partially) be corrected later by de-migration and depth-re-migration, which was done as QC output.

7.2.4 Stack mute function picking

The stack mute function was picked interactively for all three surveys. Fig. 7-5 top left shows an example of such a stack mute panel with the mute function picked at specific horizons and interpolated in between. The aim of the mute picking is to establish the maximum offset within which, for a specific time, the data contributes constructively to the stack response. Typically, this might be difficult at, and just below, significant velocity boundaries. For each survey, key horizons were established along which a laterally variable mute offset or mute angle was picked. An inner mute (e.g. muting noisy data near zero offset) was not considered necessary.

Mute functions were picked on a 600 m grid (40 bins) and densified where appropriate (Fig. 7-5 bottom panel).

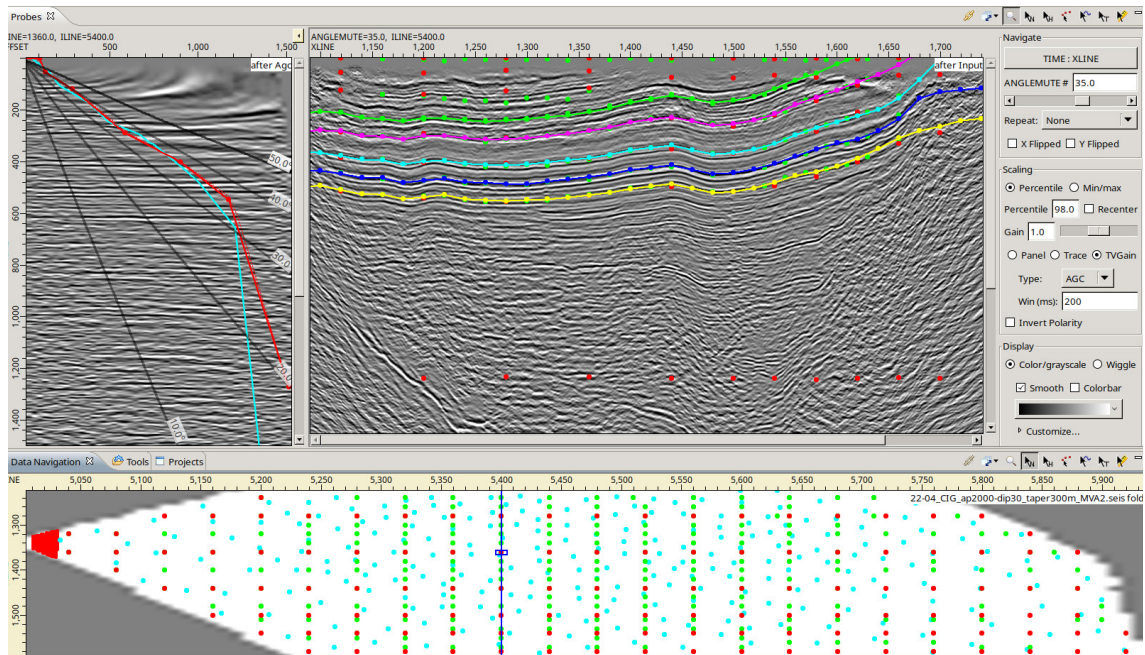


Fig. 7-5: Stack mute function picking panel

7.2.5 RMO and trim-statics

RMO analysis was carried out on an adaptive grid with a typical 300 m node spacing in the priority areas (larger outside) and with a maximum correction up to 10% in either direction. Example plots for the three surveys are provided with the results below.

7.2.6 De-migration and post-stack depth migration

In order to correct for the effect of image ray curvature and mispositioning of time migrated data, the PreSTM stack was de-migrated in the time domain using the migration velocities. De-migration is the inverse process to migration and is in implementation very similar to migration. Each trace (image point) is “smeared out” to neighbouring image points after correction with the de-migration operator (which is the adjoint of the migration operator) and per CMP position a stationary phase summation is carried out to position the energy at the correct time.

Subsequently the stack was post-stack depth migrated with an interval-velocity model in depth derived from a slightly modified PreSDM-A velocity model. Using the PreSDM-A model as the basis, the model was adjusted between floating datum and pseudo datum such that resulting velocities match the long-wave statics as applied to PreSTM input data to maintain the correct time/depth relation for the data with the applied statics.

7.3 Jura Ost

Fig. 7-6 shows a map of the PreSTM migration velocities at Top Opalinus Clay for the Jura Ost survey. Note that these displays show Root Mean Square (RMS) velocities which accumulate velocity information from the horizon to the datum and are fundamentally different from the interval velocities derived in the PreSDM (e.g. Fig. 6-7).

RMS velocities in JO are significantly lower than those for NL-16 (compare Fig. 7-11 for NL and Fig. 7-6 for JO, both with the same colour scale) reflecting the difference in overburden thickness and velocities in the Malm Group.

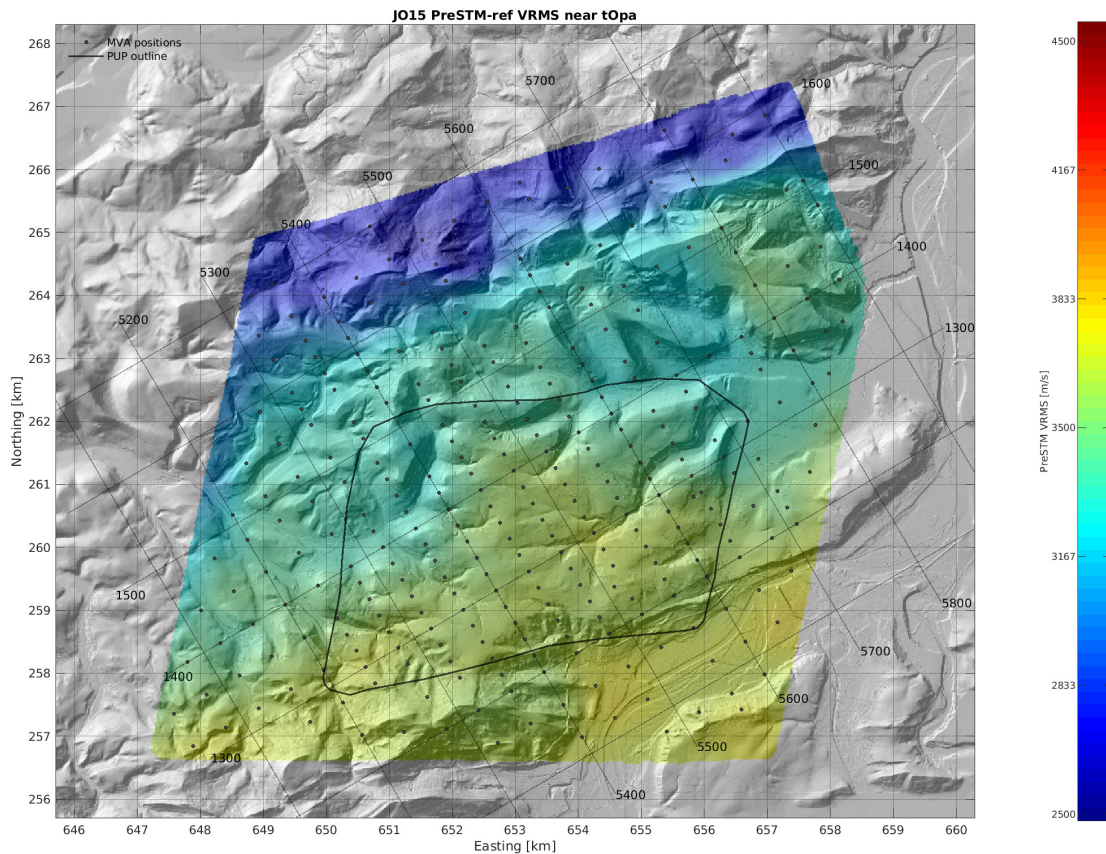


Fig. 7-6: JO Map of PreSTM velocities at Top Opalinus Clay
Black line: AOI; black dots: velocity analysis locations

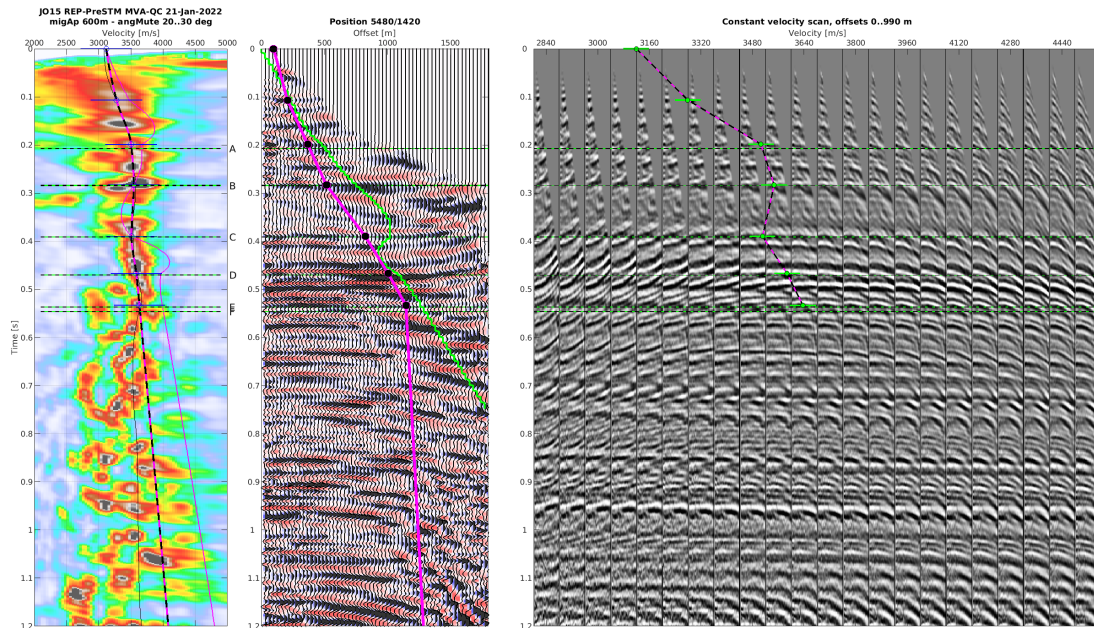


Fig. 7-7: JO-15 velocity picking QC panel

Left: semblance panel with support horizons A-F, RMS velocity picks (circles), interpolated RMS velocities (black/magenta), DIX interval velocities (magenta) and velocity guide (black), middle: migrated image gather with stretch (green) and picked (magenta) mute functions, right: constant velocity image gathers with overlain RMS velocity function

Fig. 7-7 shows a picking QC panel for JO-15. Such independent panels were used in QC to validate the velocity field from the processing company. RMS velocities were picked on reasonably well imaged horizons (A-F in Fig. 7-7), which not necessarily correspond to geological horizons. The Opalinus Clay is characterised by a mild low in RMS velocity below horizon B. A number of semblance maxima below 0.8 s may indicate multiples that frequently occur in the basement.

Interpolation of the velocity picks resulted in the RMS velocity field that was used for PreSTM as shown in a horizon slice in Fig. 7-6 and a vertical section in Fig. 7-8. The PreSTM velocity interpolation firstly used vertical interpolation at analysis positions, secondly horizontal inter/extrapolation along guide horizons, and finally vertical interpolation on all traces. The same procedure was applied for stack/mute interpolation, resulting in a 3D mute volume with mute offset as function of time, cross-line, and in-line.

Fig. 7-9 shows the RMO measurements on the final PreSTM migration on the same horizon as Fig. 7-6. Though the RMO map appears a bit patchy, overall levels of RMO are within acceptable limits.

The stack mute offsets for Base Malm Group in Fig. 7-10 demonstrate that the AOI is reasonably well covered by seismic data with offsets 300 – 600 m. Two peripheral patches with small offsets less than 300 m can be observed within the AOI.

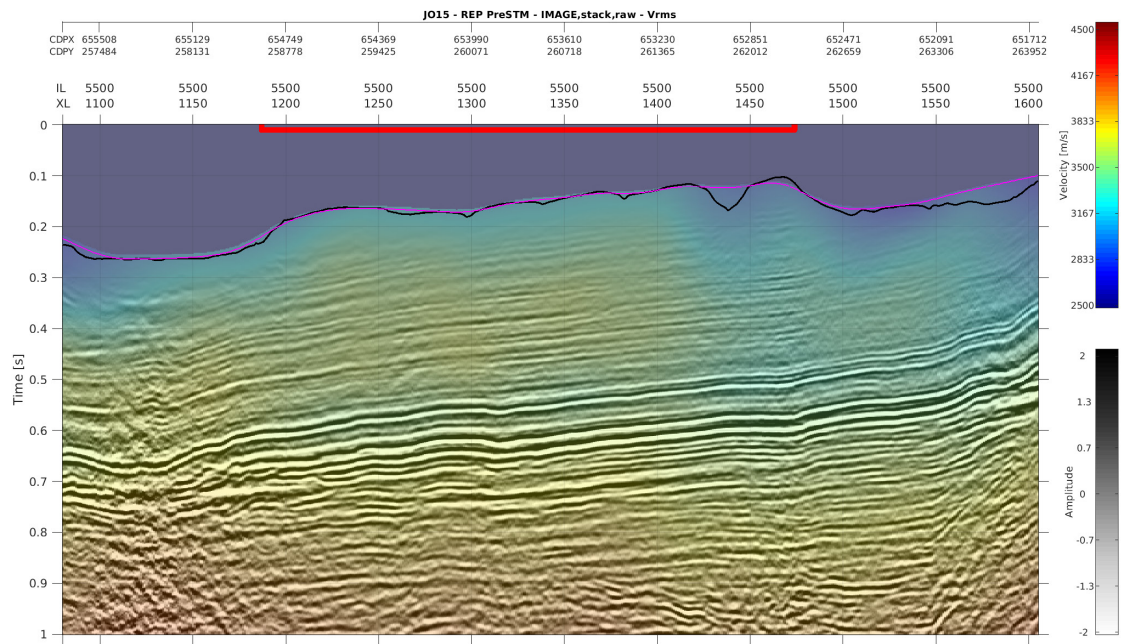


Fig. 7-8: JO-15 IL 5500 RMS velocities along a cross-section
 Red line on top: AOI; black: topography; purple: floating datum

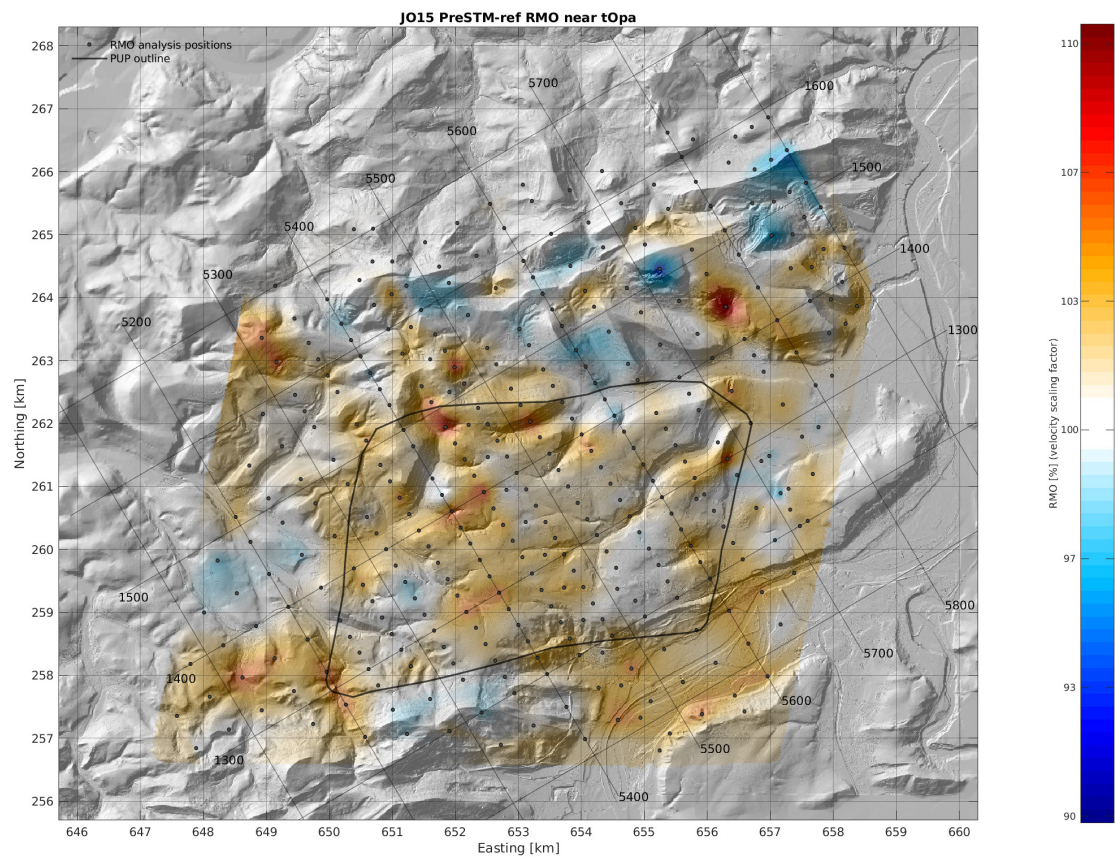


Fig. 7-9: JO-15 RMO map near Top Opalinus Clay
Black line: AOI; black dots: RMO analysis locations

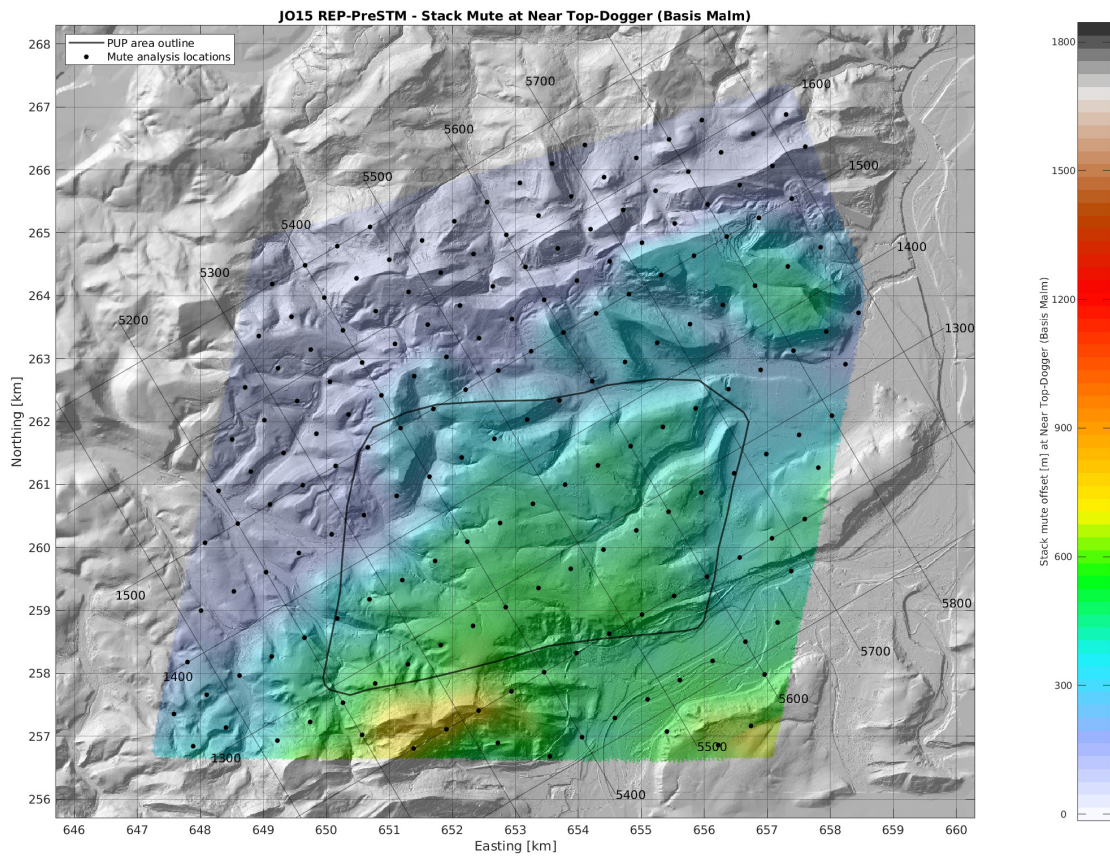


Fig. 7-10: Stack mute offset at Base Malm Group in JO-15
 Black line: AOI; black dots: stack mute offset analysis locations

7.4 Nördlich Lägern

Migration velocities near the Top Opalinus Clay horizon are shown in Fig. 7-11. Some imprint of topography appears to be present with higher areas having somewhat lower velocities. Overlain on this is the effect of the high-velocity Malm Group coming to the surface moving from the south to the north. This implies that NMO and migration velocities at Top Opalinus Clay increase towards the north even as the Top Opalinus Clay moves up in depth.

Fig. 7-12 shows a typical velocity analysis panel. Note that the RMS migration velocities only appear to decrease slightly below the velocity inversion and compare this with the pink line in the panel display that indicates the corresponding interval velocity. The data is of less quality than in the JO-15 area, note the generally noisy character (and often limited effective offset range) on the input panel.

The risk of not having effective near offsets is that the stacking power is less sensitive to RMO and that RMO, or non-hyperbolic effects, will raise or lower the image point of a reflection in time. Note that, contrary to selecting pick locations with good near offset coverage, as was done in the QLP and for the REP stacking velocities, picks for the PreSTM-ref were made on a regular grid.

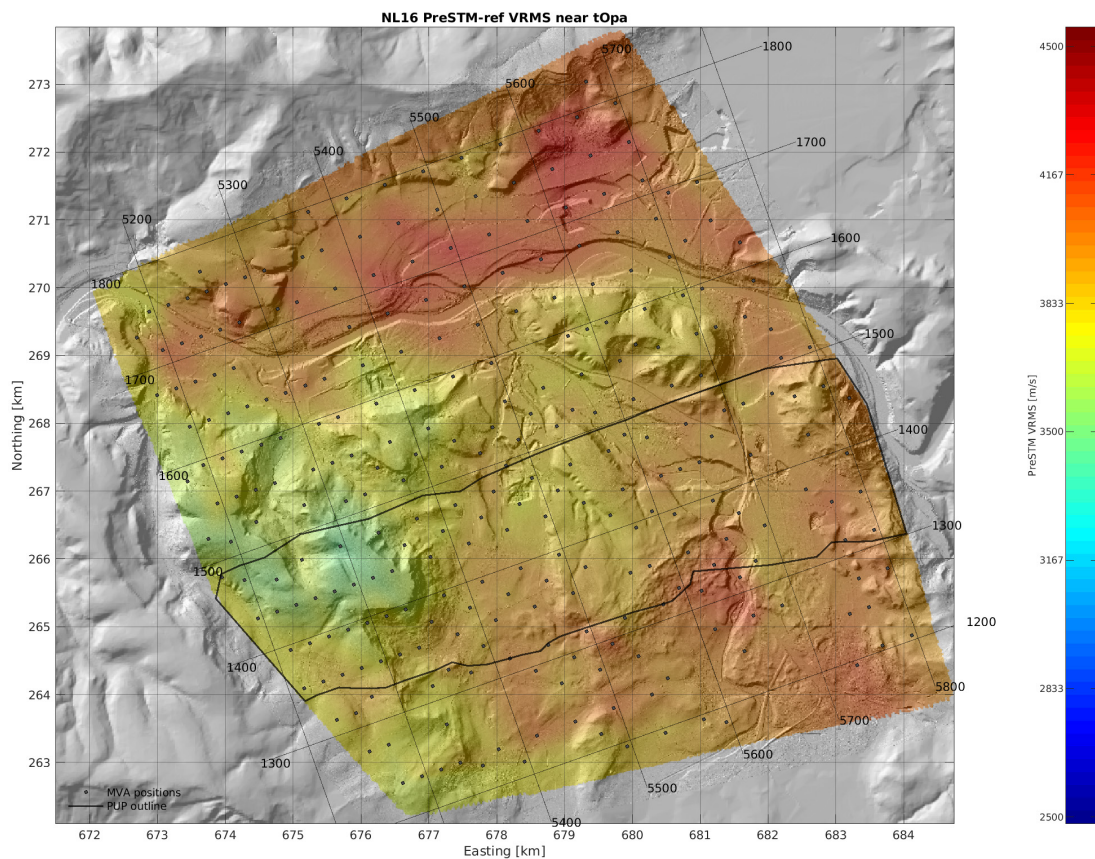


Fig. 7-11: NL-16 Migration velocities near Top Opalinus Clay

Black line: AOI; black dots: velocity analysis locations

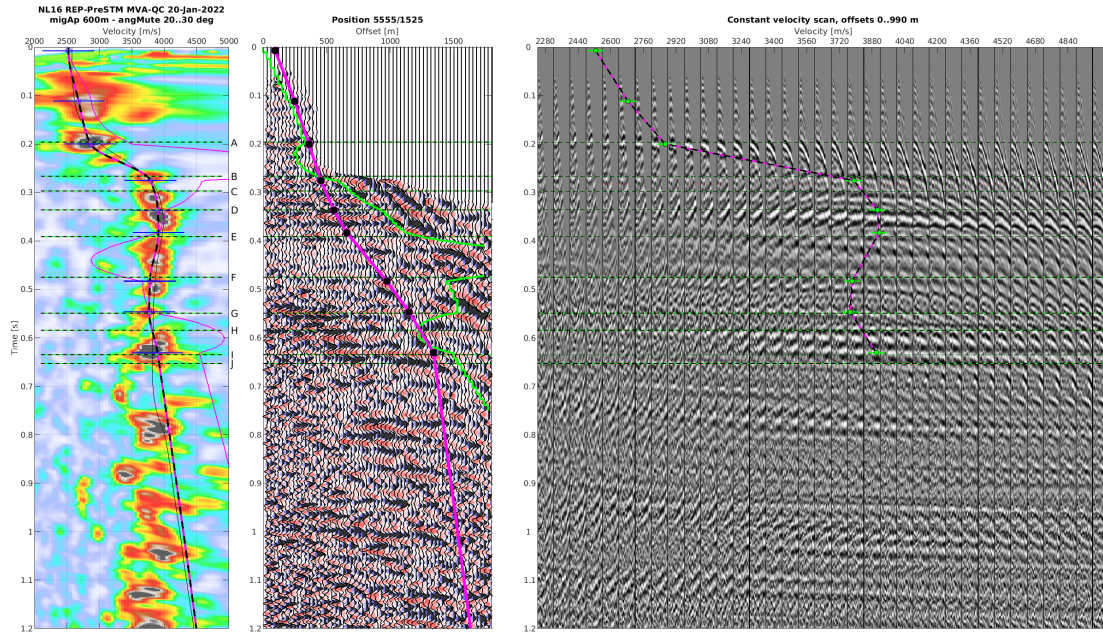


Fig. 7-12: NL-15 velocity picking QC panel

Left: semblance panel with support horizons A-F, RMS velocity picks (circles), interpolated RMS velocities (black/magenta), DIX interval velocities (magenta) and velocity guide (black);

Middle: migrated image gather with stretch (green) and picked (magenta) mute functions;
Right: constant velocity image gathers with overlain RMS velocity function

Fig. 7-14 and Fig. 7-15 show RMO as measured on the final migration. For comparison, the RMO map after PreSDM at a similar level has also been plotted in the same figure. RMO on these two, completely separately executed, migrations show quite some similarities, though the PreSTM tends to be a bit patchier. Both PreSTM velocities and PreSDM velocities are smoothed to avoid migration artefacts (such as wobbles in dipping horizons). RMO as measured on the final data is generally a more local effect that might reflect local geology or acquisition effects.

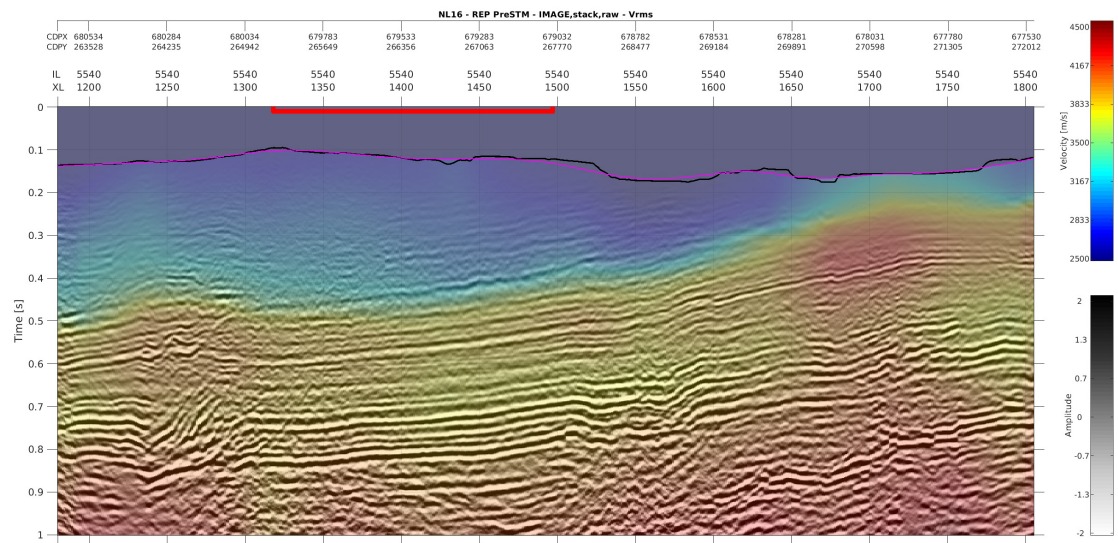


Fig. 7-13: NL-16 IL 5540 RMS velocities along a cross-section
Red line on top: AOI; black: topography; purple: floating datum

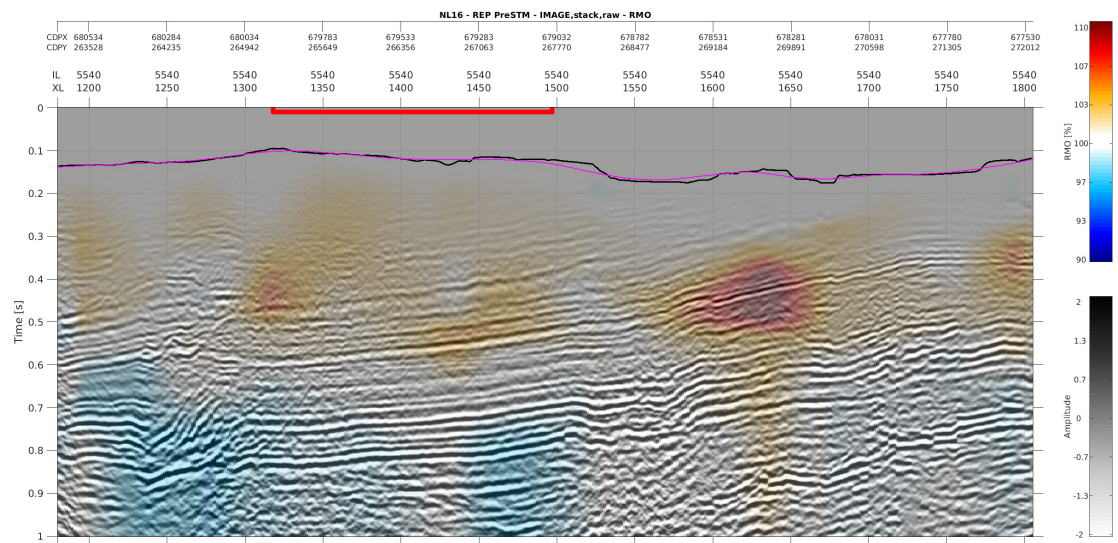


Fig. 7-14: NL-16 IL 5540 RMO along a cross-section
Red line on top: AOI; black: topography; purple: floating datum

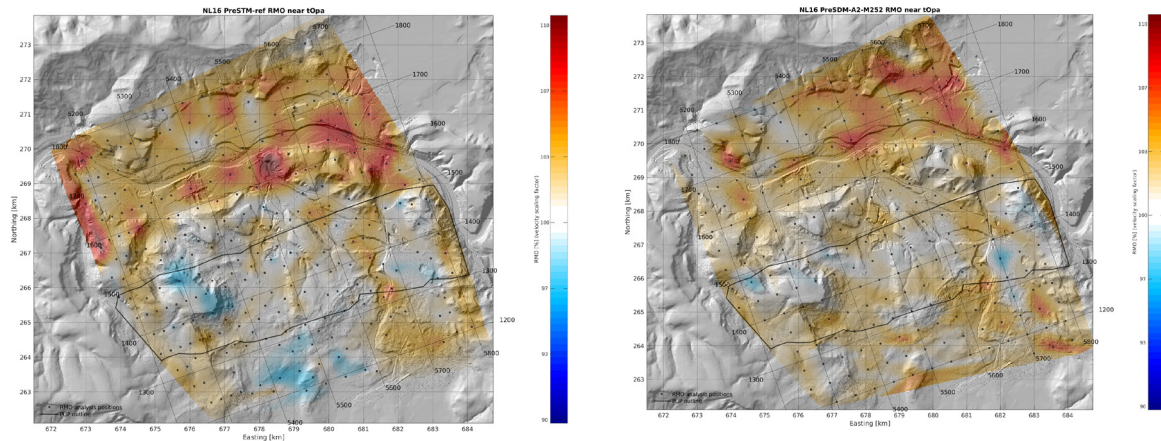


Fig. 7-15: NL-16 RMO map at near Top Opalinus Clay level

Left: PreSTM-ref; right: PreSDM

The stack mute map at Top Dogger Group as shown in Fig. 7-16 shows sufficient aperture. As the Base Malm Group moves up towards north, the T-zero becomes smaller and accordingly the stack mute gets tighter.

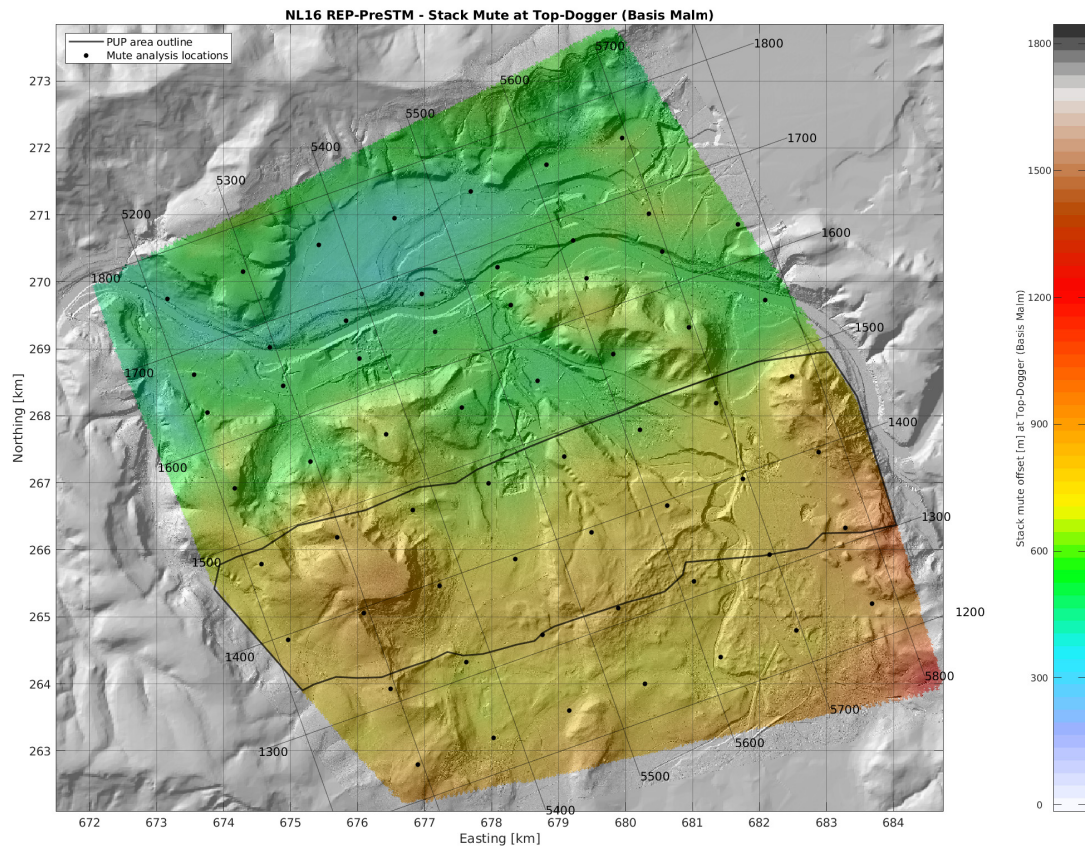


Fig. 7-16: Stack mute offset at Base Malm Group in NL-16

Black line: AOI; black dots: stack mute offset analyses locations

7.5 Zürich Nordost

Fig. 7-17 shows the PreSTM velocities at Top Opalinus Clay in ZNO. These are observed to be fairly constant over the whole survey. Towards the southeast some increase could be expected, but as the strata go deeper, the relative difference in depth is less than for the other surveys so the effect is much smaller.

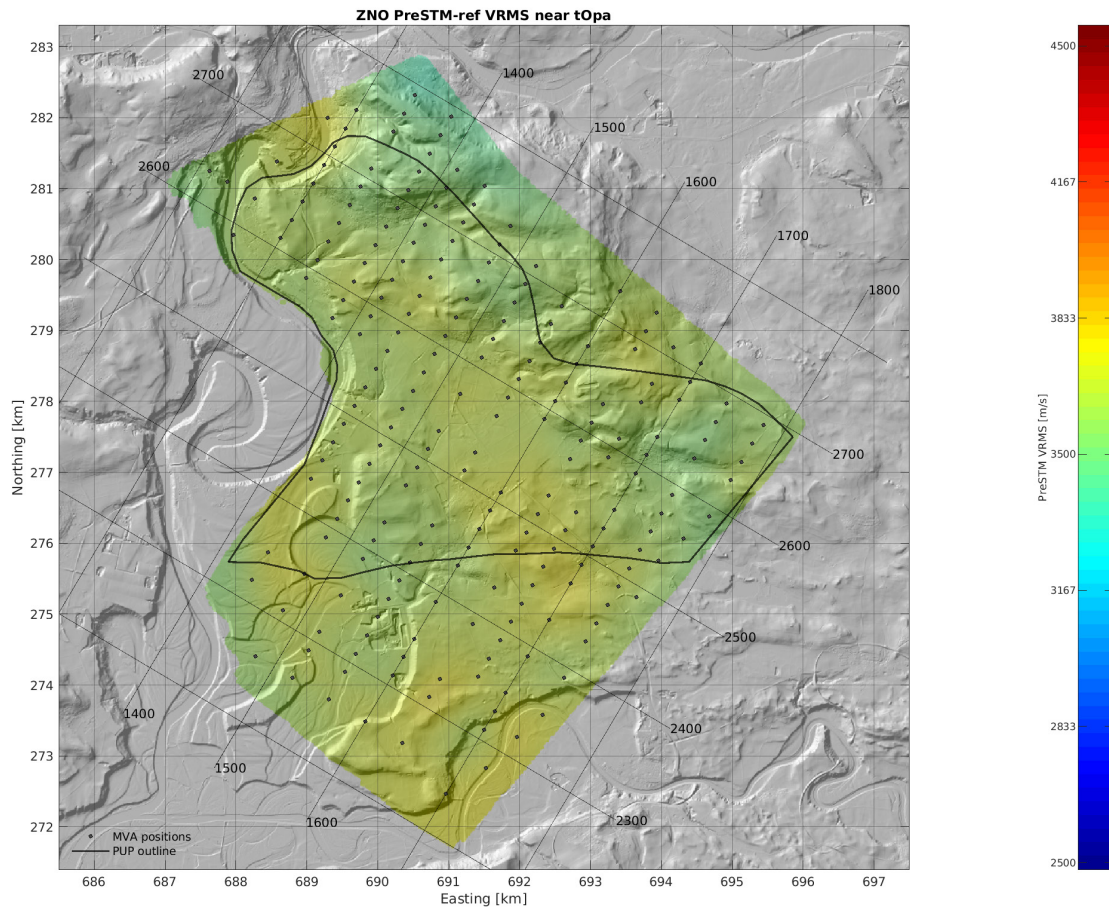


Fig. 7-17: ZNO map of PreSTM velocities near Top Opalinus Clay

Black line: AOI; black dots: velocity analysis locations

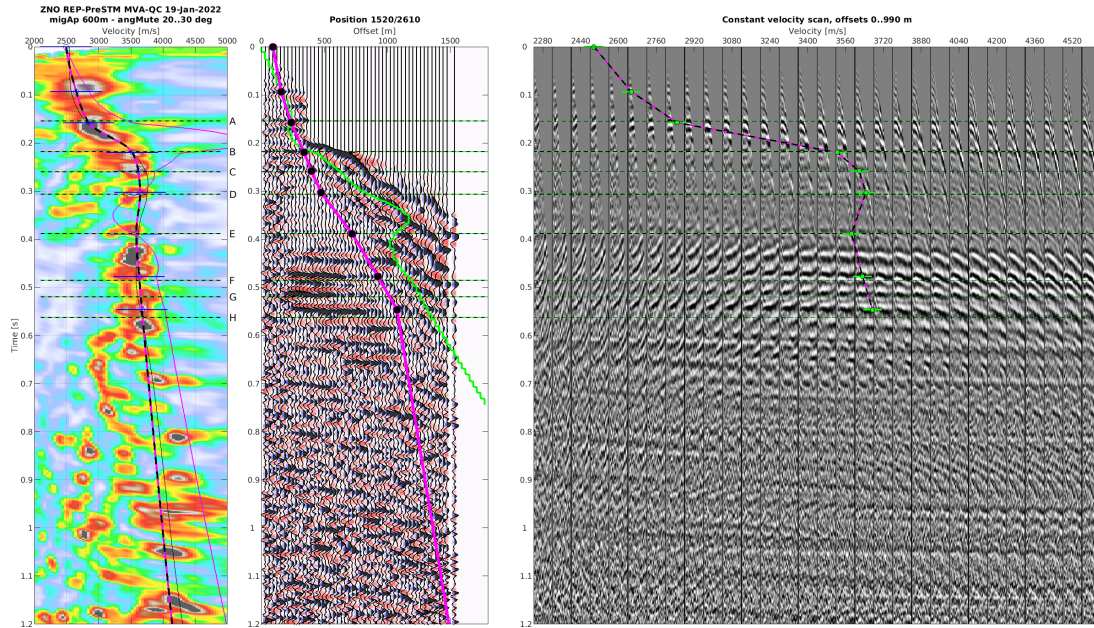


Fig. 7-18: ZNO PreSTM velocity picking panel

Left: semblance panel with support horizons A-H, RMS velocity picks (circles), interpolated RMS velocities (black/magenta), DIX interval velocities (magenta) and velocity guide (black);

Middle: migrated image gathers with stretch (green) and picked (magenta) mute functions;

Right: constant velocity image gathers with overlain RMS velocity function

The representative velocity picking panel and migrated image gathers in Fig. 7-18 provide an impression of the ZNO data quality. It is more comparable to the NL-16 (Fig. 7-12) results than to the better data quality observed in JO-15 (Fig. 7-7).

Fig. 7-19, Fig. 7-20 and Fig. 7-21 respectively give us the RMS velocities on a cross-section, RMO on the same cross-section and in map view near Top Opalinus Clay level. In general, the RMO appears to be reasonable. The extremes at the northwestern edge of the survey (Fig. 7-21) can be considered local edge effects – though the near surface may play a role here too.

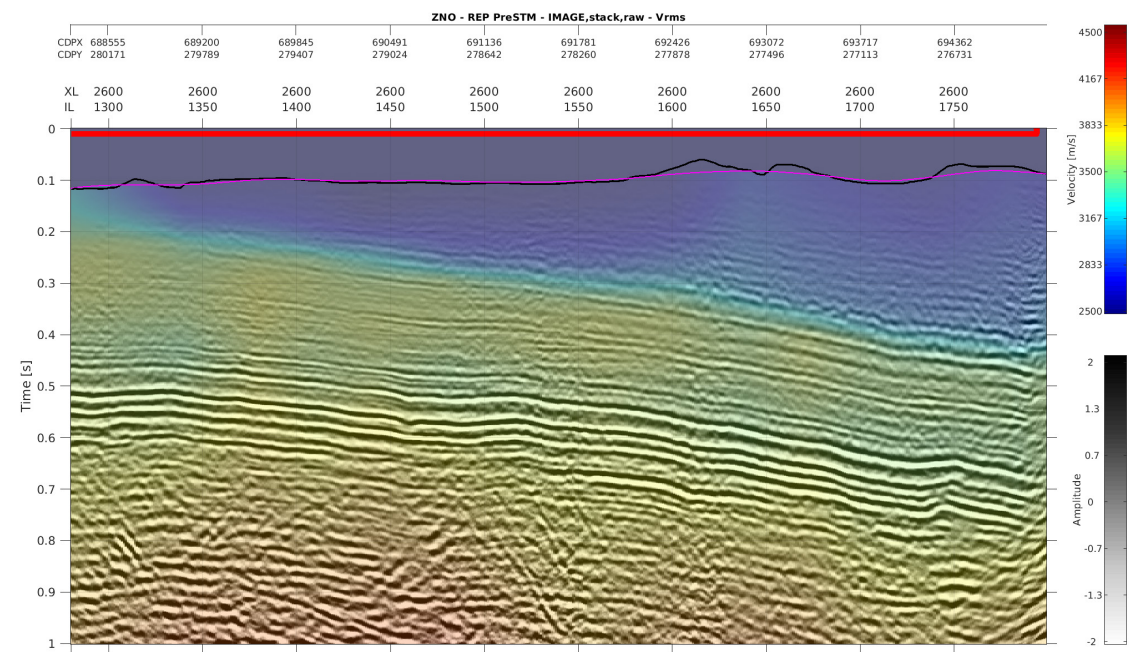


Fig. 7-19: ZNO-97/16 IL 2600 RMS velocities along a cross-section
Red line on top: AOI; black: topography; purple: floating datum

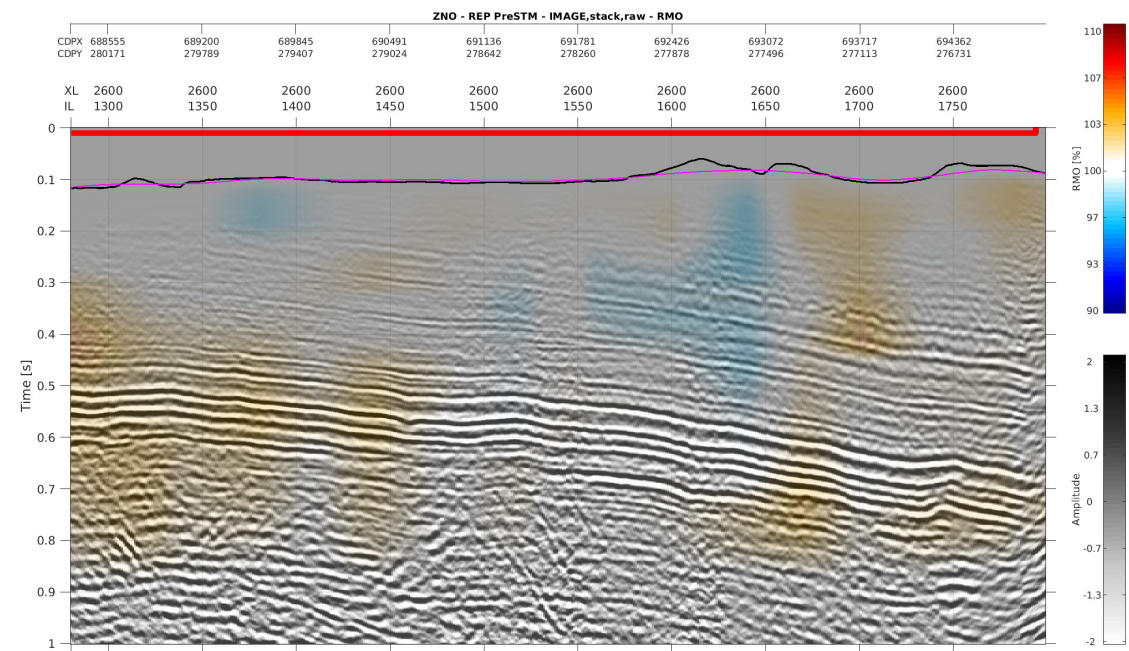


Fig. 7-20: ZNO-97/16 IL 2600 PreSTM stack with measured RMO
Red line on top: AOI; black: topography; purple: floating datum

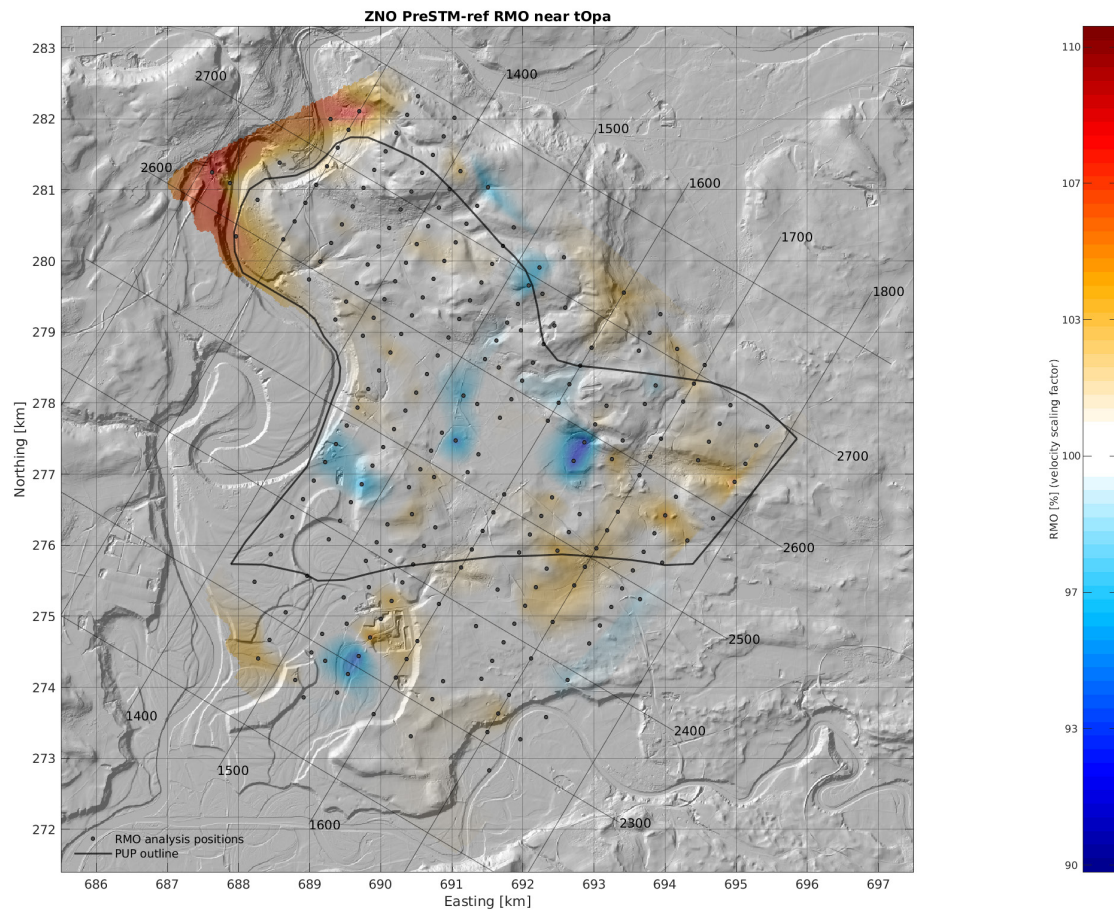


Fig. 7-21: ZNO PreSTM map of RMO near Top Opalinus Clay

Black line: AOI; black dots: RMO analysis locations

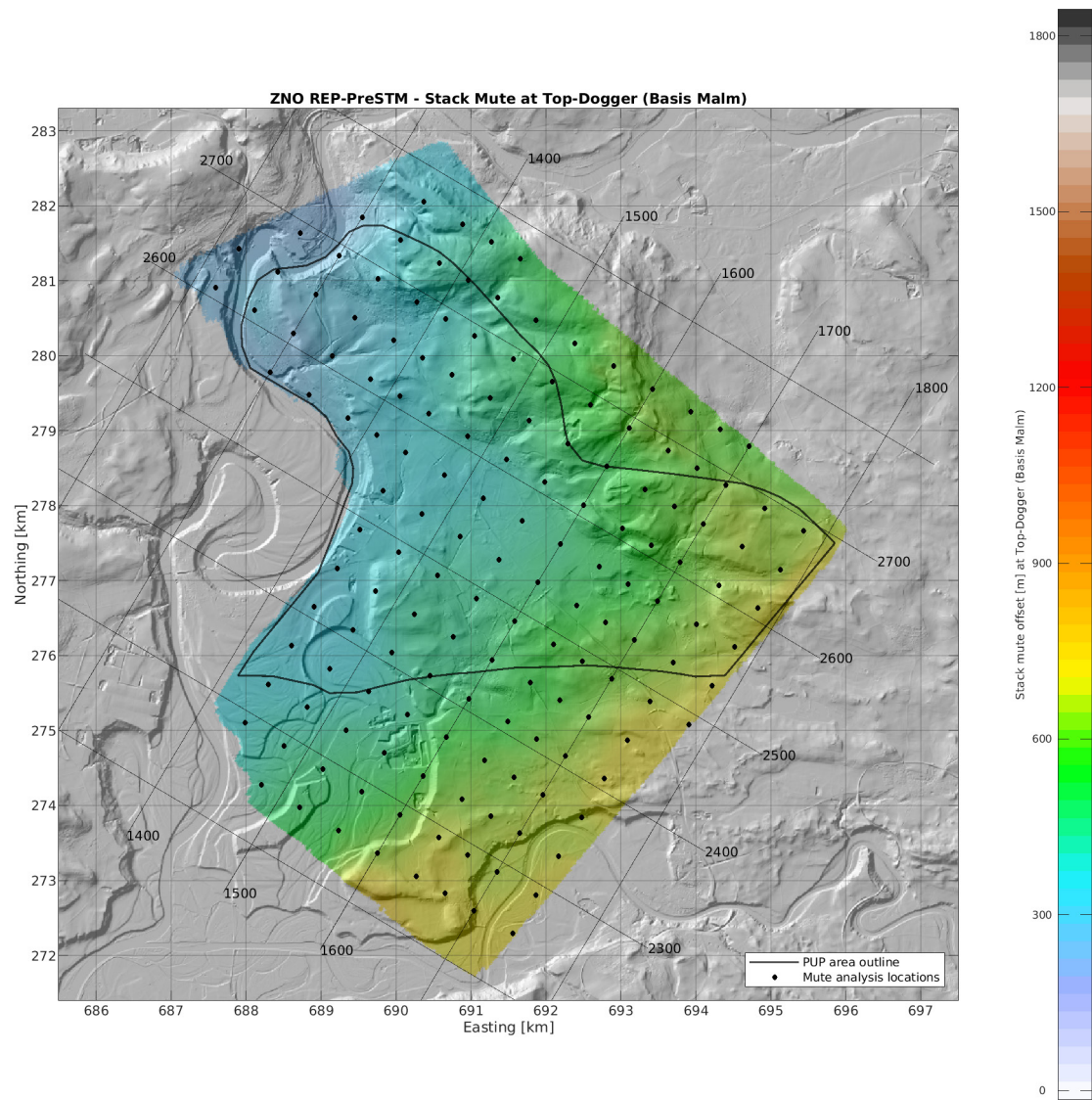


Fig. 7-22: Stack mute map for Top Dogger Group in ZNO-97/16
Black line: AOI; black dots: stack mute analyses location

7.6 Comparison of the results

Comparison of both the PreSTM-ref and the PreSDM seismic imaging results over the three areas led to the conclusion that the PreSTM-ref results are more suitable to be used as baseline datasets to compare the three siting regions than the PreSDM results.

For this comparison the following aspects have to be taken into account:

Geology

- While the near surface geology is complex in all three areas, there are significant differences between the areas. The geological complexity could not fully be resolved because of the limited tomographic resolution of the near surface models. Also, local surface conditions likely impacted strength and other characteristics of the source generated noise. Being difficult to remove, such noise contaminated the near-offset data and further limited the ability to correctly model the near surface velocities.
- Below the Quaternary the properties of the Malm, notably the acoustic velocity, also vary between the three areas, thereby directly impacting the illumination angle of the deeper objective layers.

Acquisition

- The survey design of the three modern surveys was similar. Given however the differences in target depth between the three areas, this will still lead to differences in illumination at target level.
- Notably the source positions of the three modern surveys have turned out to be quite irregular, deviating significantly from the notional design pattern (see Fig. 7-23).

Processing

- Various PreSDM attempts demonstrated that comparability of the three areas could not easily be achieved with a PreSDM exercise due to the strong variability in shallow geology associated parameters (statics) and due to overburden heterogeneities among the three sites (i.e., NL strong issues with statics and shallow velocities, JO issues with Opalinus Clay velocity and zones of artefacts). Achieving a better PreSDM product would require the processing to be further tailored to site-specific geology.

The PreSTM-ref processing was designed such that all the processing input parameters and the workflow were consistent across the three seismic surveys. While this might not result in the best processing approach for each individual survey, it best serves the objective of having the three siting regions comparably imaged. The PreSTM workflow was in general also better suited to deal with above named issues than the PreSDM workflow due to the following differences in characteristics:

- The PreSTM is less sensitive to near surface complexities than the PreSDM, as the migration correction and resulting image is optimised separately at each time level and for each surface position. Lateral and horizontal smoothing of velocities limits artefacts that could be caused by quick lateral changes and stretch effects.
- The PreSTM input data was spatially regularised, resulting in a better noise attenuation in the imaging and stack than observed in the PreSDM result where positional integrity had to be maintained.

- The small illumination angle range below the Malm worked to the relative advantage of the PreSTM compared to the PreSDM as, within this range, the PreSTM assumptions of hyperbolicity and azimuthal invariance were reasonably well met.

In conclusion:

- The PreSTM-ref has been determined to be adequate for seismic interpretation aiming to define top and base of the host rock and distribution of structural lineaments (faults), bridging the QLP and PreSDM imaging across undisturbed and structurally complex areas. Fig. 7-24 shows that all three datasets are well interpretable at the time zones of interest.
- The theoretically more accurate PreSDM provides supporting information on the structural inventory, however limited by significant uncertainties in the velocity models. An improved PreSDM with a more detailed near surface velocity model compared to a PreSTM will not change the relevant conclusions regarding the geology but may reduce the observed uncertainties. The current confidence in the uncertainty ranges is provided by the use and comparison of all three available seismic processing vintages (QLP, PreSDM and PreSTM-ref).

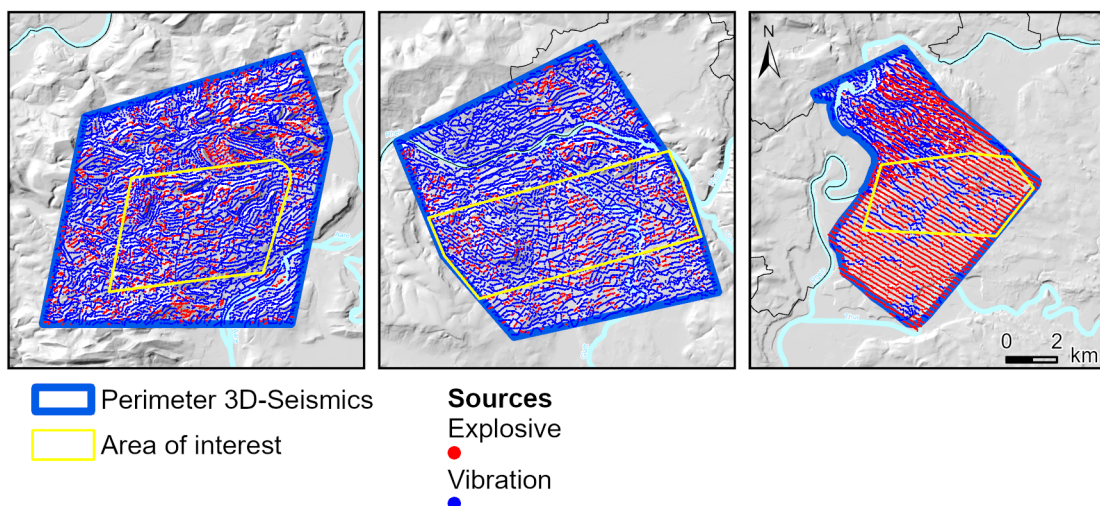


Fig. 7-23: Source positions for three surveys
Left: JO-15; centre: NL-16; right: ZNO

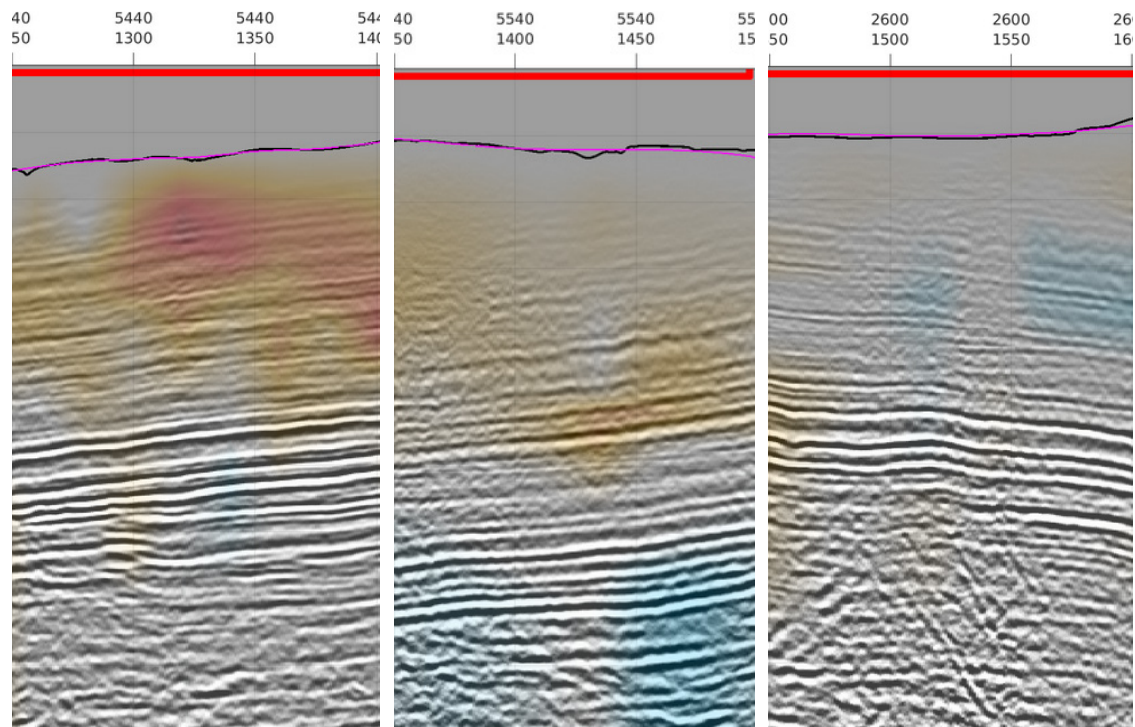


Fig. 7-24: Comparison of PreSTM raw stacks
 Left: JO-15; centre: NL-16; right ZNO

8 Zero-phasing

8.1 Introduction

In Module A of the OLP signal processing, the Vibroseis data has been converted to minimum phase and matched to the dynamite data. In principle this implies that the data should be minimum phase. During deconvolution in Module B of the processing, the data was whitened which in theory is a minimum phase process. Due to the presence of significant noise on the data, mainly low frequent, the phase of the signal was however distorted in this process, providing mixed phase data as processing output.

A zero-phasing project was planned and executed at the end of the REP work, including all exploration borehole information. The objective was to facilitate seismic to borehole matching and assess the quality of the borehole-logs by comparison of the borehole-synthetic with the available zero offset VSP stack. The work was done by Geophytec GmbH under supervision of Nagra in Q1/Q2 2023.

8.1.1 Workflow

The zero-phasing workflow is summarized in Fig. 8-1. Essentially, a survey-specific zero-phasing filter is derived by creating minimum phase synthetic traces matching the seismic data and matching those to their zero-phase synthetic equivalents derived from the VSP corridor stack. The zero-phasing filter is then applied to the 3D seismic dataset. Details of the various workflow steps are described below.

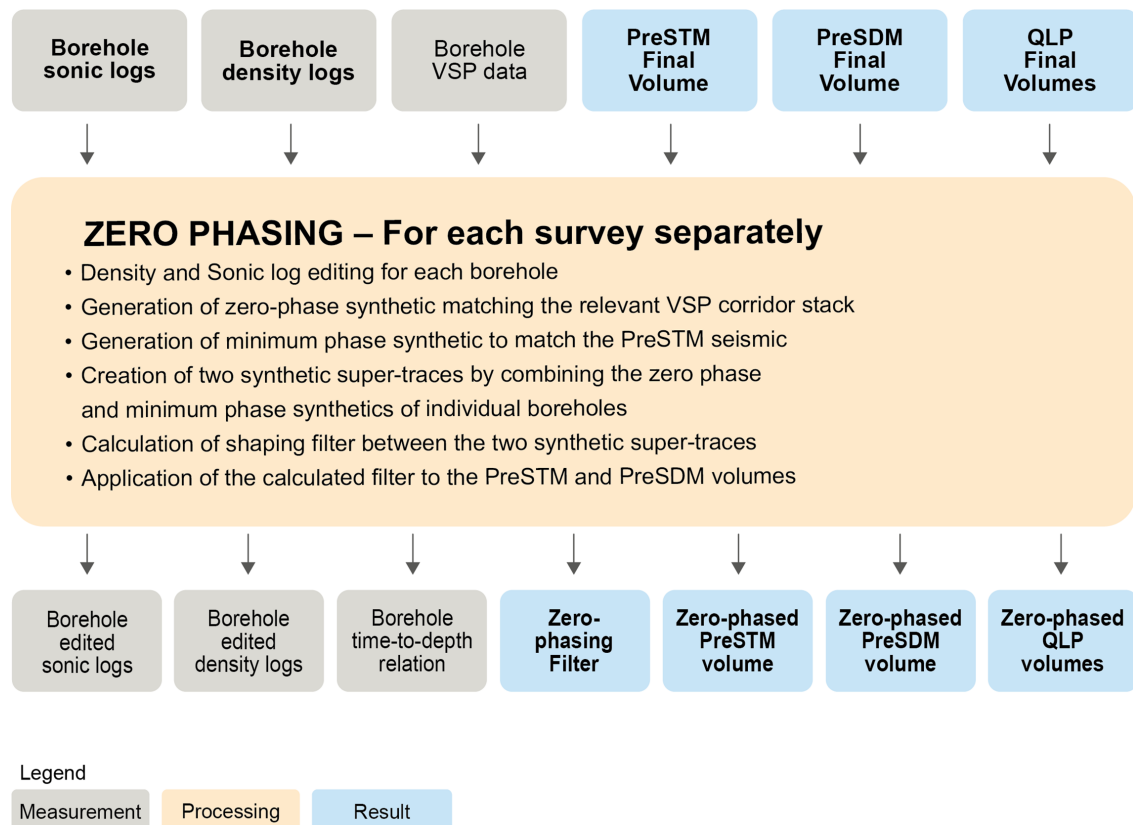


Fig. 8-1: Zero-phasing workflow

8.1.2 Density and log editing

The sonic logs generally needed editing between the topography and the depth at which a reliable measurement had been achieved. Typically, the shallow part (i.e. the Quaternary) was replaced by a continuous velocity curve. In addition, a median filter was applied to take out spikes.

The density log generally required more editing since it was often incomplete over the Cenozoic interval and in a number of cases also deeper. In addition, zones with spikes and non-plausible values, for example in the salt layers, had to be corrected. Non-plausible values were deleted and a short, typically 5-sample, median filter was applied to take out the spikes. Site specific trend curves were derived for the velocity/density relationship, enabling the interpolation of gaps and the replacement of the density logs in areas where the logs were deemed unreliable.

An example of the results of such an editing sequence is provided in Fig. 8-2.

8.1.3 Generation of zero-phase synthetic matching the relevant VSP corridor stack

The aim of this exercise was to assess the quality of the edited logs and assure that the synthetic generated from the logs matched with the seismic. The VSP corridor stack is generally considerably less noisy than surface seismic data and, after up/down deconvolution, free of multiples down to the level of the lowest receiver.

For the generation of a zero-phase synthetic trace a reflectivity sequence in time based on the logs was required. The reflectivity sequence was first derived in depth from the logs and subsequently, using the time/depth relation derived from the calibrated sonics, converted to time. Next, a zero-phase wavelet was derived using the amplitude spectrum of the zero-offset VSP and convolved with the reflectivity in time.

The zero-phase borehole synthetic was then matched with the VSP corridor stack, the results of which are displayed and discussed in Sections 8.2 – 8.4.

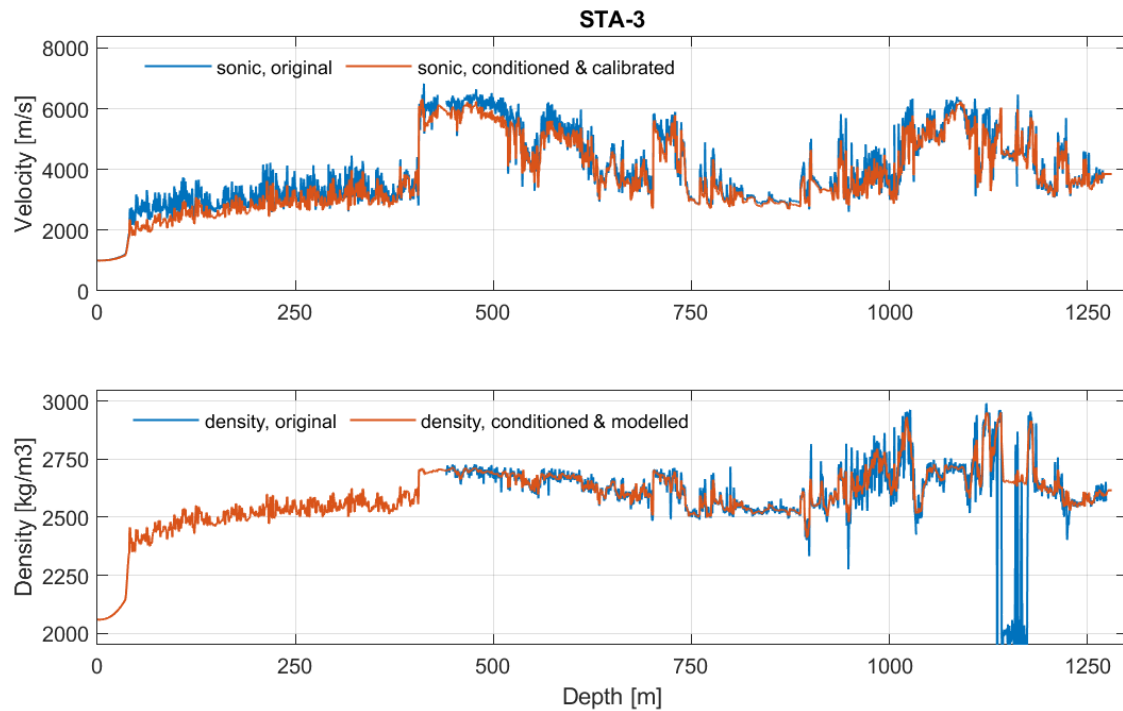


Fig. 8-2: NL STA-3 log editing
Original logs: blue; edited logs: orange; top: sonic; bottom: density

8.1.4 Generation of minimum phase synthetic and match to the PreSTM seismic for each borehole

In order to match the synthetic to the PreSTM seismic, first a smooth amplitude spectrum was derived for the near-borehole surface seismic data of each of the surveys. Subsequently the minimum phase wavelet was calculated for this amplitude spectrum. An example for one borehole (STA-2) is shown in Fig. 8-3. This wavelet was then convolved with the reflectivity sequence in time from the synthetic as earlier calculated, generating a minimum phase synthetic that could now directly be compared to the minimum phase PreSTM seismic data. Using cross-correlations between the minimum phase synthetic and the PreSTM seismic, an additional phase rotation was calculated. Given the fairly narrow bandwidth of the data, this was in general sufficient to get a reasonable match between synthetic and data.

To derive the filter function, a zero-phase synthetic using the modelled amplitude spectrum of the PreSTM and the frequency spectrum of the VSP was calculated.

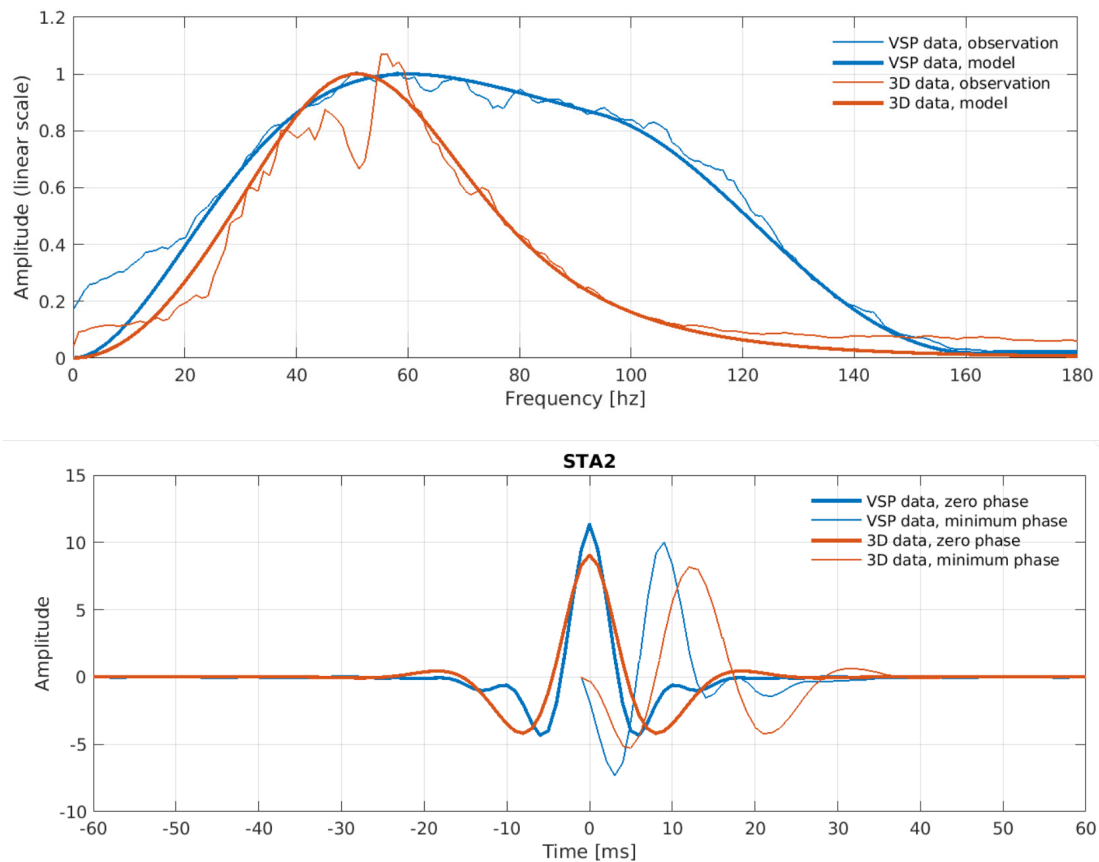


Fig. 8-3: Exemplary comparison of surface and borehole seismic traces in frequency and time domain for borehole STA-2

Top: observed and modelled spectra; bottom: modelled spectra related zero-phase and minimum-phase wavelets

8.1.5 Creation of super-traces of borehole synthetics for each survey

As only one filter per survey was to be applied, super-traces of the zero-phase and minimum-phase synthetics were created by laying the synthetics for all boreholes per area behind each other. An optimum filter matching the minimum phase super-trace to the zero-phase super-trace was then derived. Advantages of this method are:

- Spectra were modelled per borehole instead of for the whole survey. As the zero-phase synthetics and the minimum phase synthetics have the same amplitude spectrum for each borehole, this does not affect the amplitudes but the related minimum phase spectrum will vary between boreholes.
- Phase rotations were applied to the minimum phase synthetics of the individual boreholes prior to optimally match the synthetic with the seismic.

8.1.6 Application of filters to seismic data

For each survey the zero-phasing filters as derived in the previous step were applied to the QLP (minimum phase product) final volume, the PreSTM-ref final volume and the PreSDM final volume as used for interpretation. The zero-phased volumes could then directly be matched with the imported zero-phase borehole synthetic for horizon identification and time to depth conversion (see interpretation reports Nagra 2024a, Nagra 2024b, and Nagra 2024c). Due to the narrow bandwidth, the main effect of the filters was a time shift. However, the additional (average) phase rotation improved the match and the procedure provided assurance of the quality of the synthetics and the reliability of the match.

Fig. 8-4 shows the final operators as applied to each of the surveys.

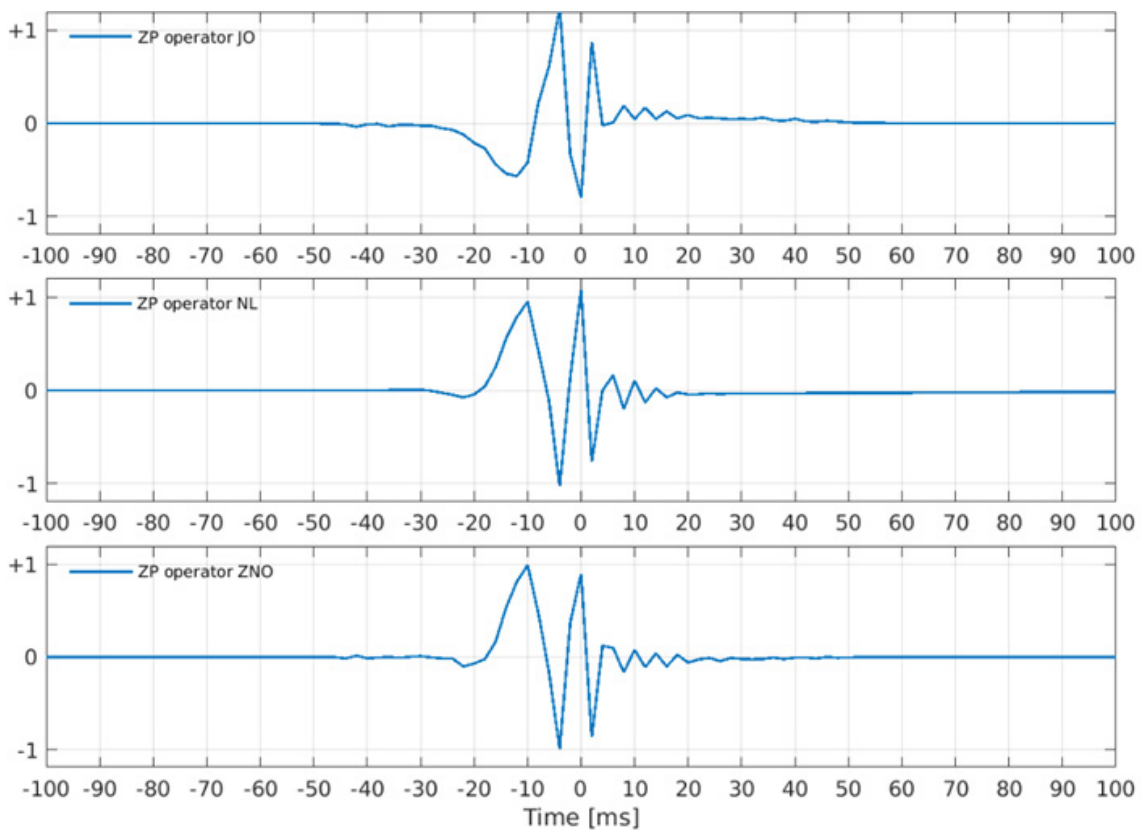


Fig. 8-4: Final Zero phasing operators for the three surveys

Top: JO-15; middle: NL-16; bottom: ZNO-97-16

8.2 Jura Ost

Frequency spectra of the JO-15 3D seismic processing product (red lines) and VSP corridor stack (blue lines) are shown in Fig. 8-5. Spectra for the processed field data (thin lines) and parametric model (thick lines) are shown. The spectra are fairly similar for the two newer boreholes BOZ-1 and BOZ-2, whereas the RIN-1 vintage VSP data shows a narrower spectrum. Note that only total spectra were measured.

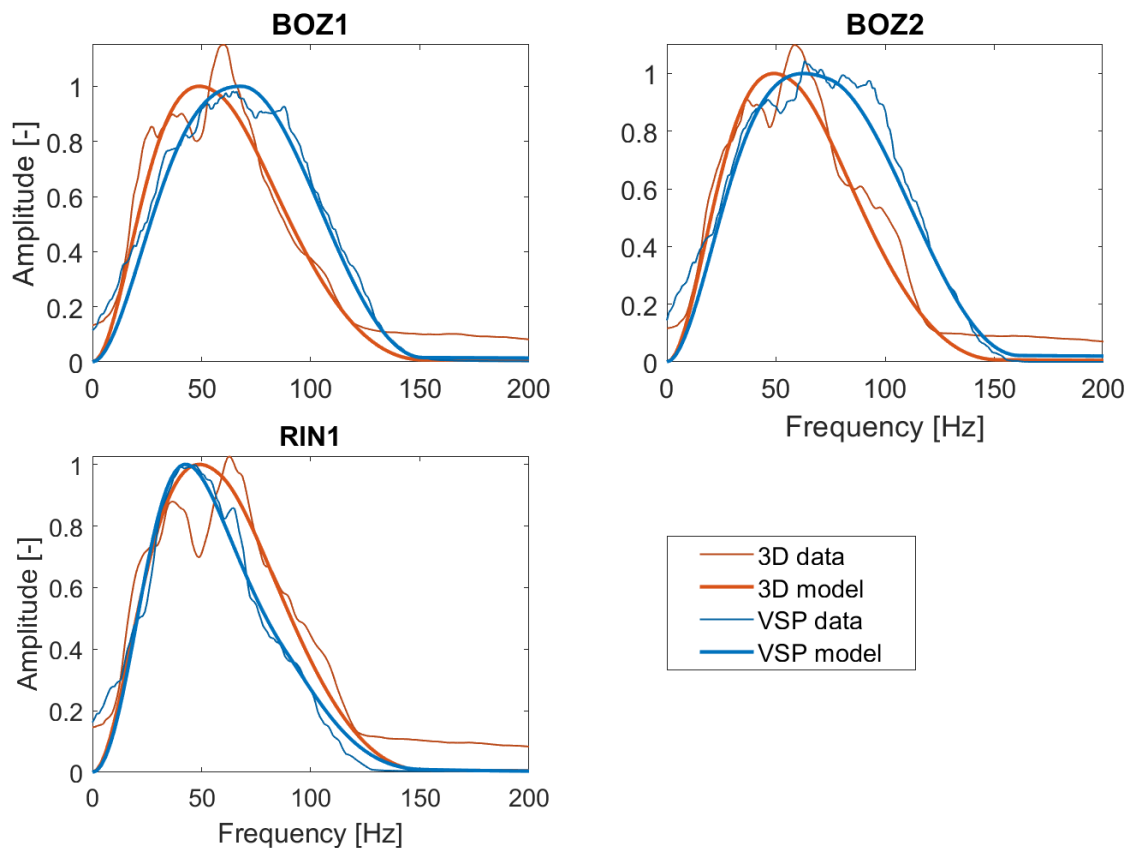


Fig. 8-5: JO-15 Spectra around boreholes

Red: 3D data and model; blue: VSP data and model; thin line: field data; thick line: parametric mode

Fig. 8-6 shows the effect of zero-phasing and correlations of zero-phased synthetics and VSP corridor stacks in JO. The matches are acceptable for the three boreholes with some discrepancies at shallow depths. Inspection of zero-phase correlations indicates some asymmetry for all three boreholes though, notably so for BOZ-2.

The match between 3D seismic data and synthetics is shown in Fig. 8-7 for each borehole in JO. The first two traces show the minimum phase PreSTM-ref trace, the second the VSP corridor stack. The third trace is the zero-phase synthetic used for filter derivation and the last trace is the resulting zero-phase PreSTM-ref trace after application of the final operator. The traces differ at shallow level but match reasonably for key horizons at deeper levels.

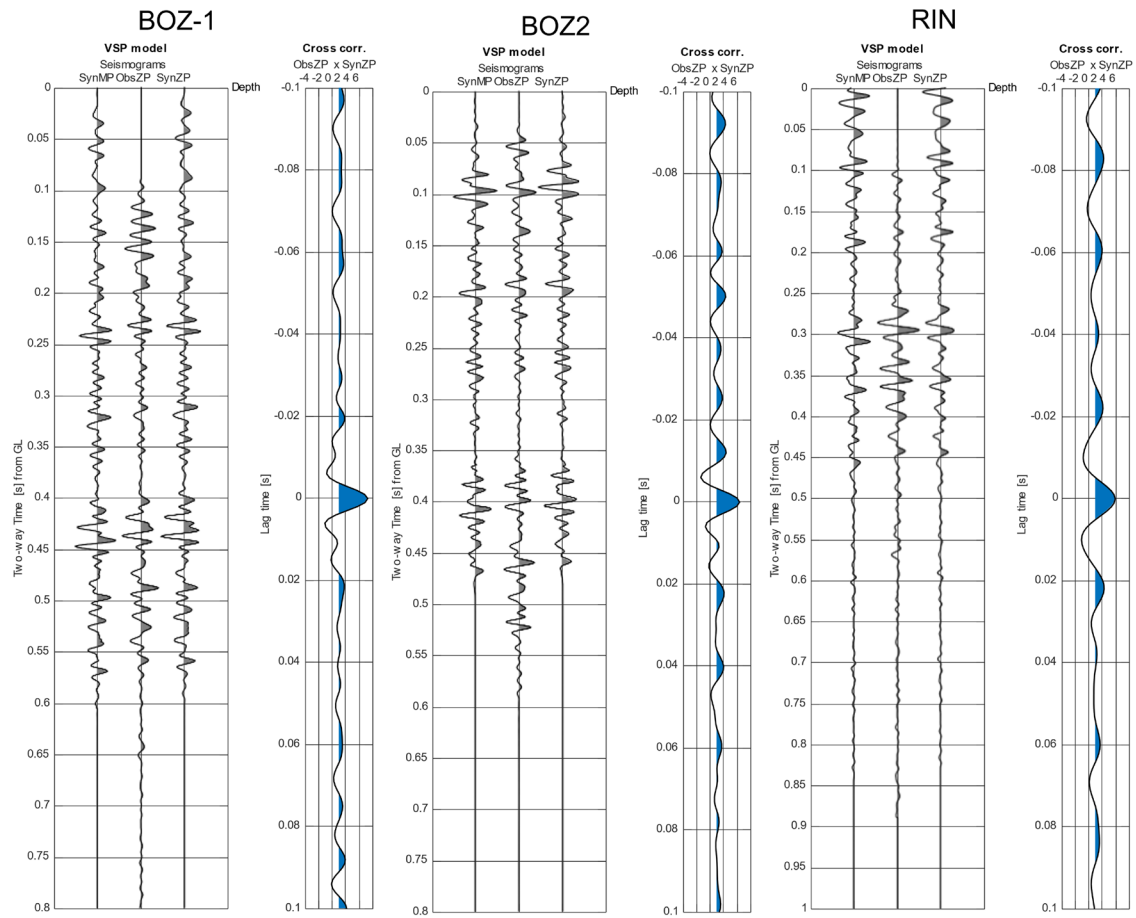


Fig. 8-6: JO zero-phase match of corridor stack and borehole synthetics

SynMP: minimum phase synthetic; ObsZP: zero-phase corridor stack; SynZP: zero-phase synthetic

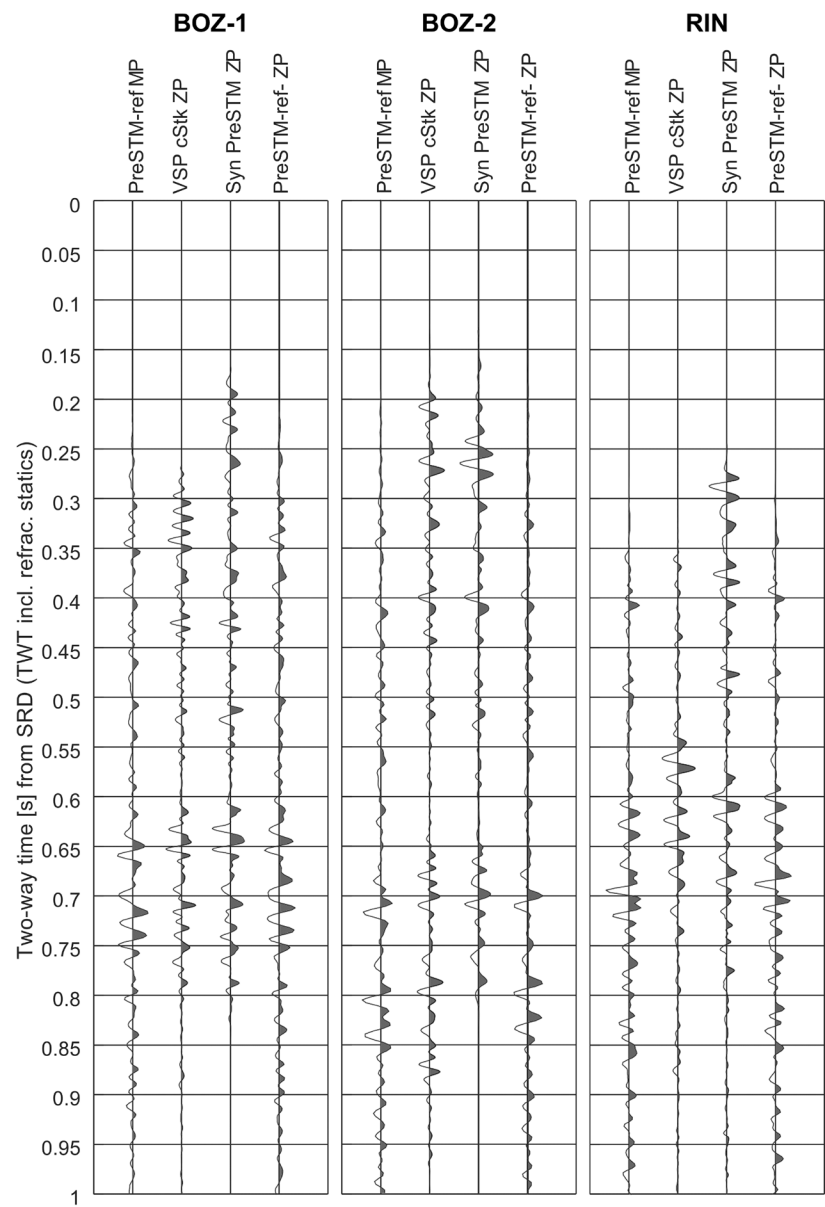


Fig. 8-7: JO Matches of minimum phase synthetic with surface seismic data

Each panel shows from left to right: minimum phase near borehole trace from surface seismic, zero-phase corridor stack, zero-phase synthetic, and zero-phase near borehole trace from surface seismic

8.3 Nördlich Lägern

The spectra for data around the various boreholes in NL-16 are compared in Fig. 8-8. As can be seen the surface seismic data (red lines) is fairly narrow bandwidth, dropping off below 30 Hz and above 70 Hz, so just over one octave, further affected by the 50 Hz notch filter in STA-2 and STA-3. The borehole seismic data (blue lines) was processed towards a significantly broader spectra to be filtered and fitted to the surface seismic spectra.

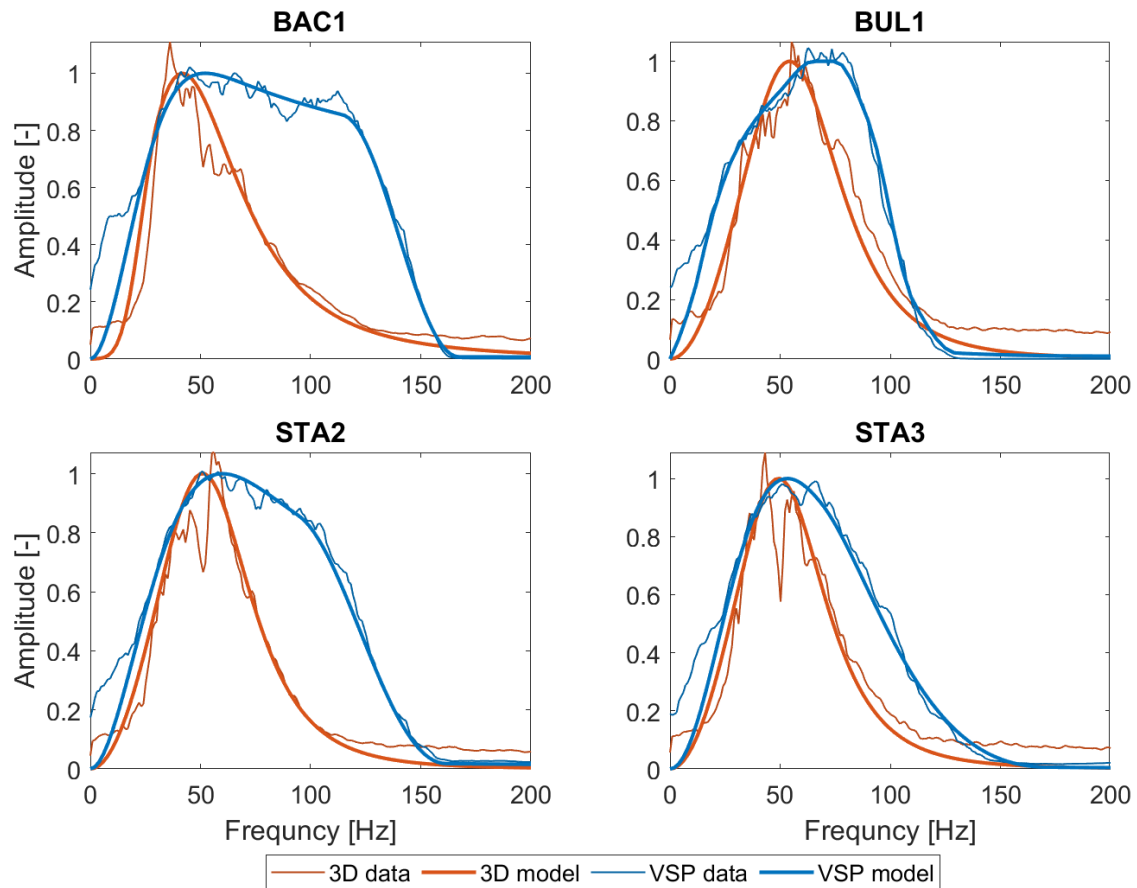


Fig. 8-8: NL-16 Spectra around boreholes

Red: 3D data and model; blue: VSP data and model; thin line: field data; thick line: parametric mode

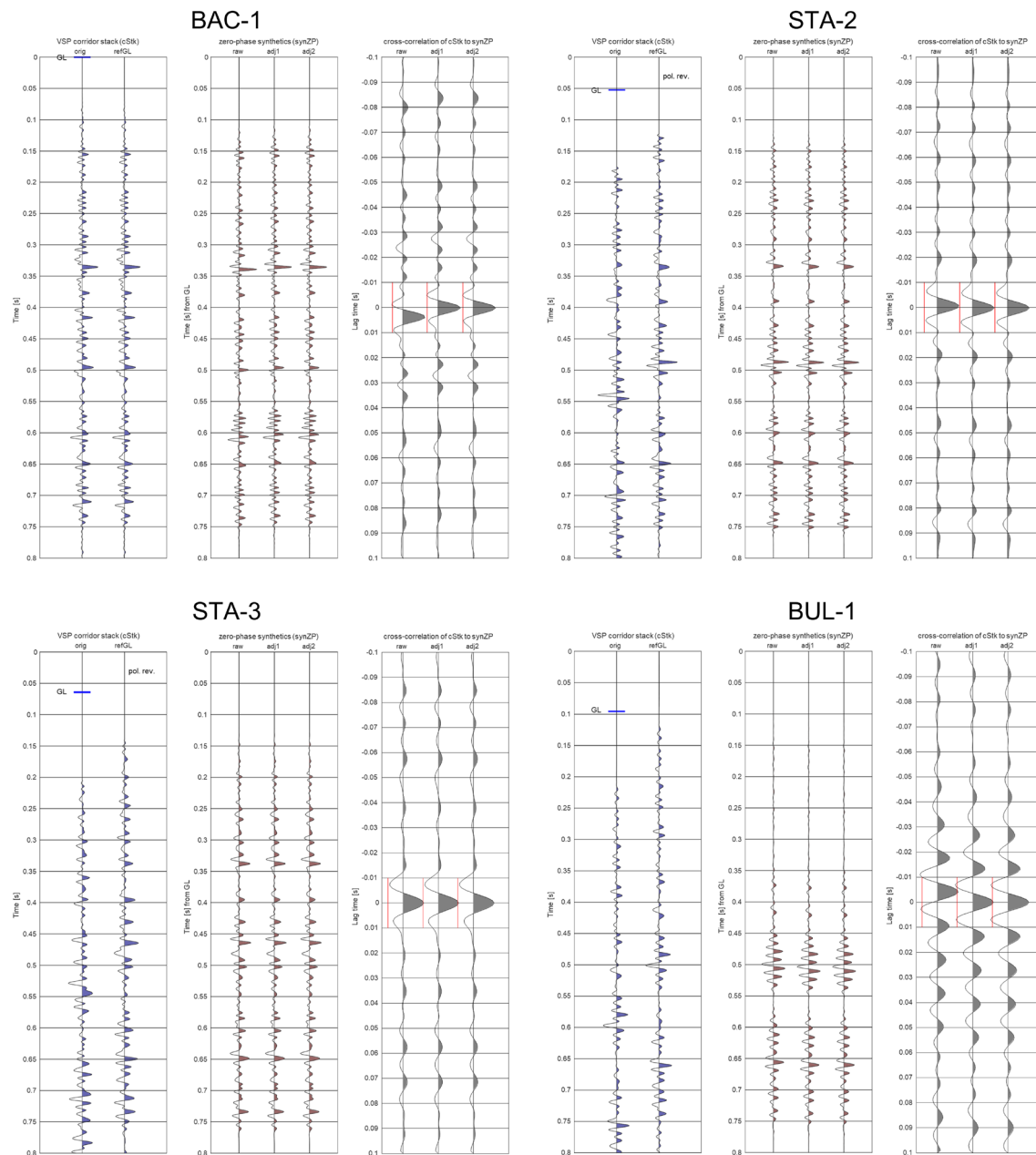


Fig. 8-9: NL-16 match of VSP corridor stack to borehole synthetics

Orig: original corridor stack; relGL: Orig shifted to ground level; aw: original zero-phase synthetic; adj1: raw plus time shift; adj2: adj1 plus phase rotation

Fig. 8-9 shows the VSP match to the synthetic in three panels for each of the four boreholes in NL-16. The first panel showing the VSP corridor stack (with and without time shift to ground level), the second showing the zero-phase borehole synthetic with a few minor adjustments and the third the cross-correlation between the two. As can be seen this is in general symmetric for most of the boreholes indicating neglectable rotational phase shifts. Only in STA-3 a more pronounced but acceptable asymmetry is noted.

Finally, in Fig. 8-10, the match of the zero-phase synthetic with the zero-phase filtered surface seismic data is shown. The first two traces show the minimum phase PreSTM trace, the second the VSP corridor stack. The third trace is the zero-phase synthetic used for filter derivation and the last trace is the resulting zero-phase PreSTM-ref trace after application of the final operator.

Results are reasonable, with exception of borehole BUL1 where the synthetic is quite ringy.

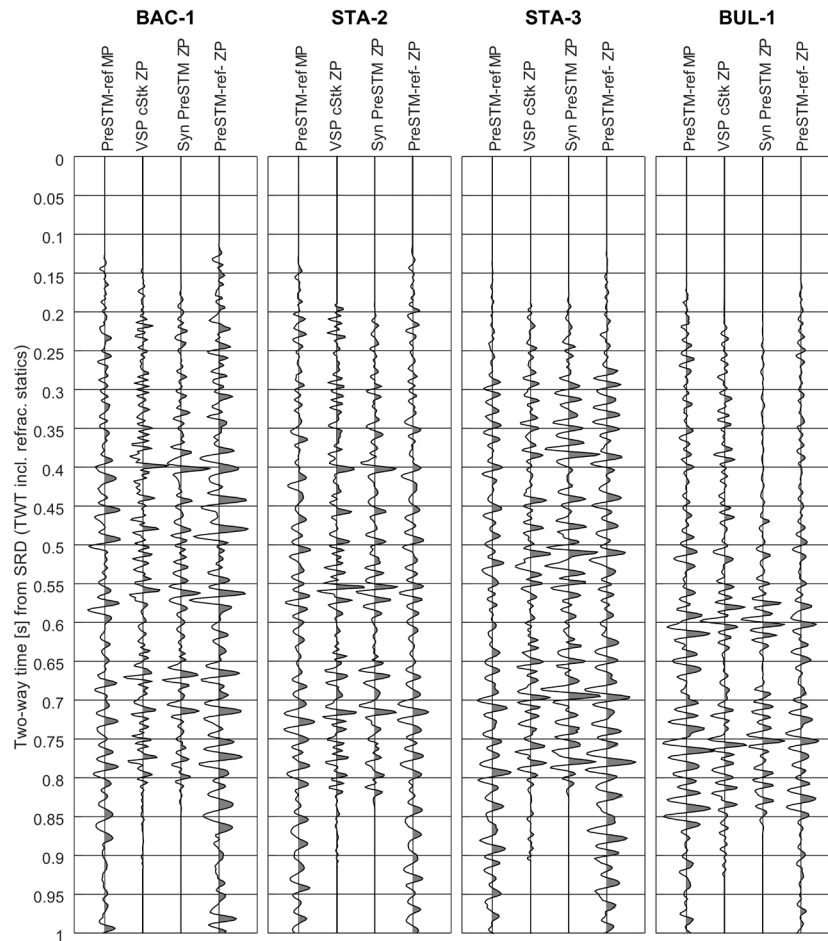


Fig. 8-10: Cross-correlation and match between synthetic and surface seismic traces

Each panel shows from left to right: minimum phase near borehole trace from surface seismic, zero-phase corridor stack, zero-phase synthetic, and zero-phased near borehole trace from surface seismic.

8.4 Zürich Nordost

The comparison of spectra between surface seismic (red) and VSP data (blue in Fig. 8-11) shows significant variation. The BEN-1 borehole VSP spectrum indicates quite high frequencies, which may help the match in the high-velocity zone. The peak of the TRU-1 borehole VSP spectrum is at much lower frequency, but velocities are also much lower in the upper part so it has a longer time sequence for the match. In the MAR-1 borehole high velocities are noted but, contrary to BEN-1, the VSP spectrum cuts off above 80 Hz. Note that VSP data was acquired in MAR-1 and TRU-1 with nominal source wavelet 10 – 140 Hz.

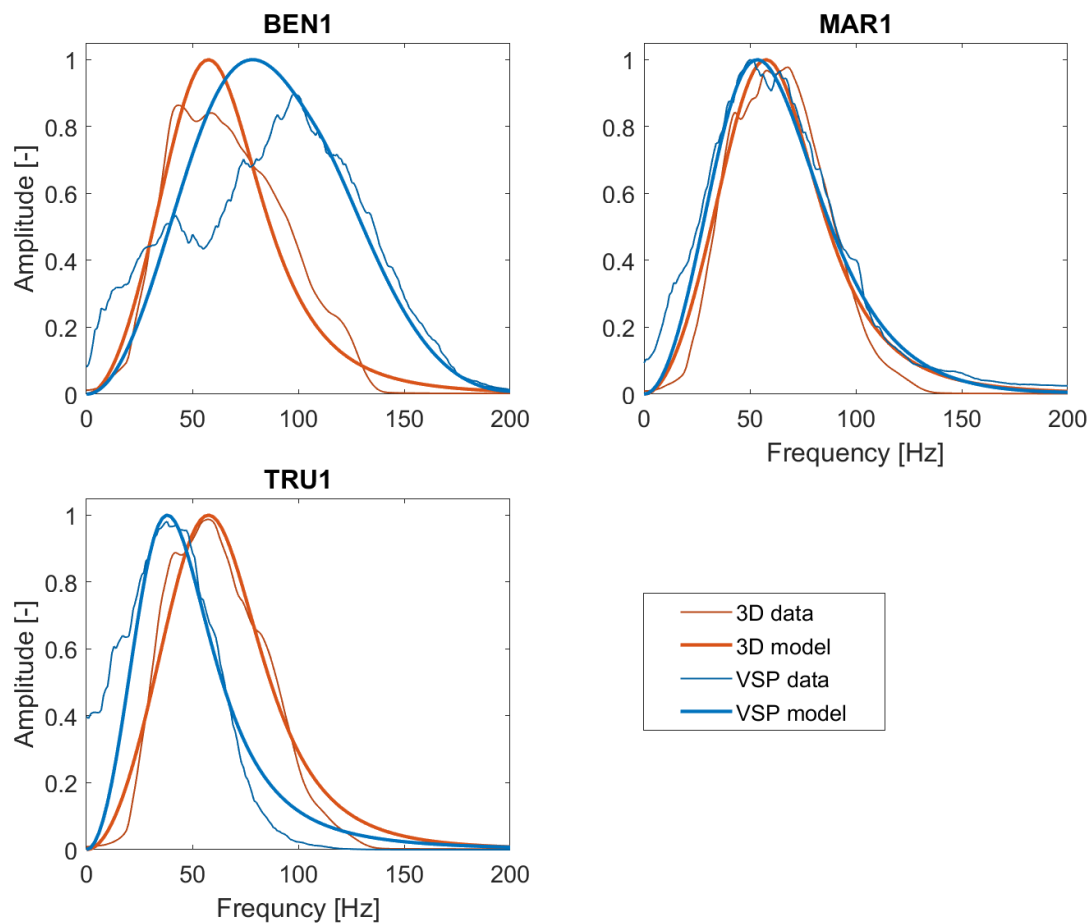


Fig. 8-11: ZNO Spectra around boreholes

Red: 3D data and model; blue: VSP data and model; thin line: field data; thick line: parametric mode

The match of the VSP with the borehole synthetics of the three boreholes, as shown in Fig. 8-12 varies significantly in appearance and quality. In case of BEN the high frequency VSP reasonably matches a high frequency synthetic. The TRU-1 indicates a fairly long matching sequence. MAR-1 synthetic to VSP match is rather poor, specifically at shallow levels. At deeper levels the synthetic to seismic match is reasonable. It is therefore recommended not to trust the VSP.

In Fig. 8-13 finally, matches of minimum phase synthetic with seismic are shown. While the borehole synthetics for BEN and MAR-1 match rather poorly with the seismic at shallow depth, deeper down they appear to match on the main events. The TRU-1 has the best match. Again, the VSP of MAR-1 clearly stands out as not making much sense with respect to the other data. Note that with the bandlimited spectrum for this survey, the zero-to-minimum phase operator is close to a polarity flipped linear phase with the “time shift” mainly governed by the order on the high side. A wider spectrum with specifically more low frequencies would have made the minimum phase wavelet less symmetric and the process better constrained.

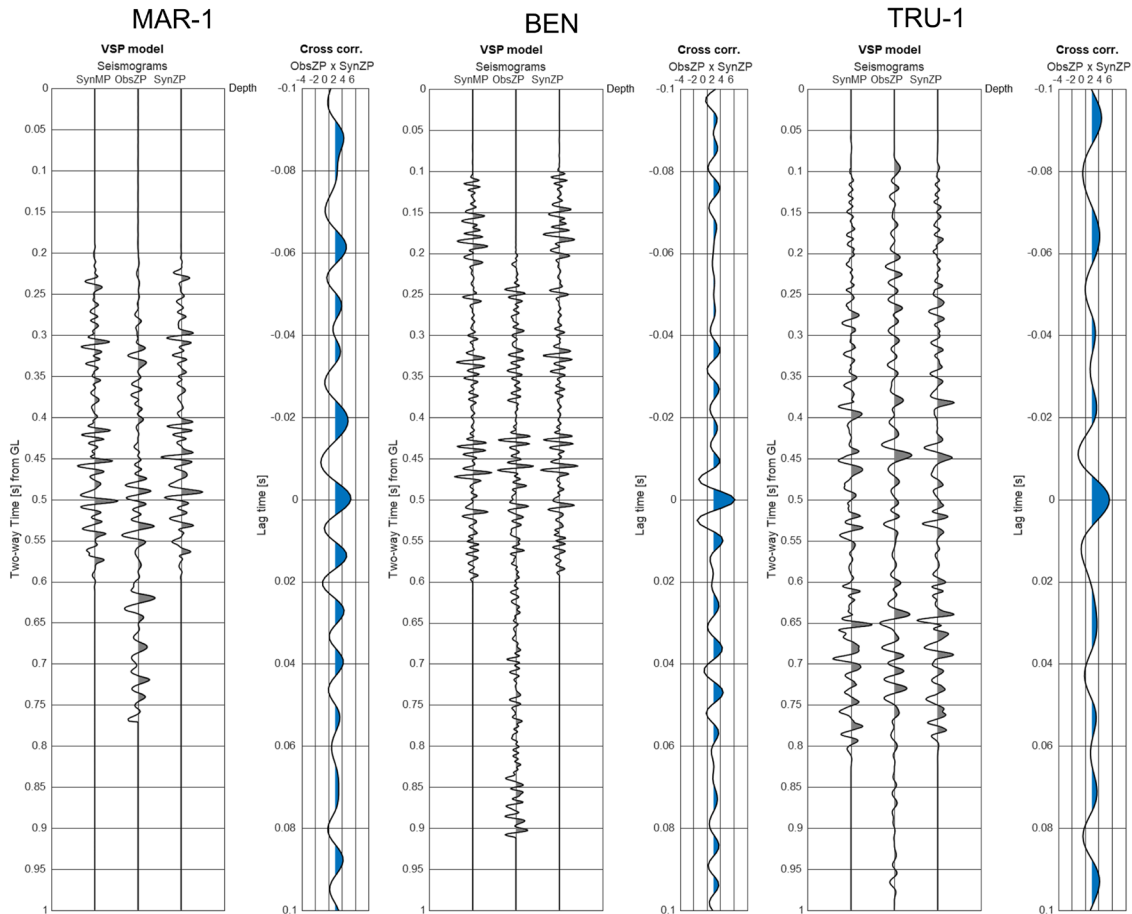


Fig. 8-12: ZNO matches of minimum phase synthetic with VSP data

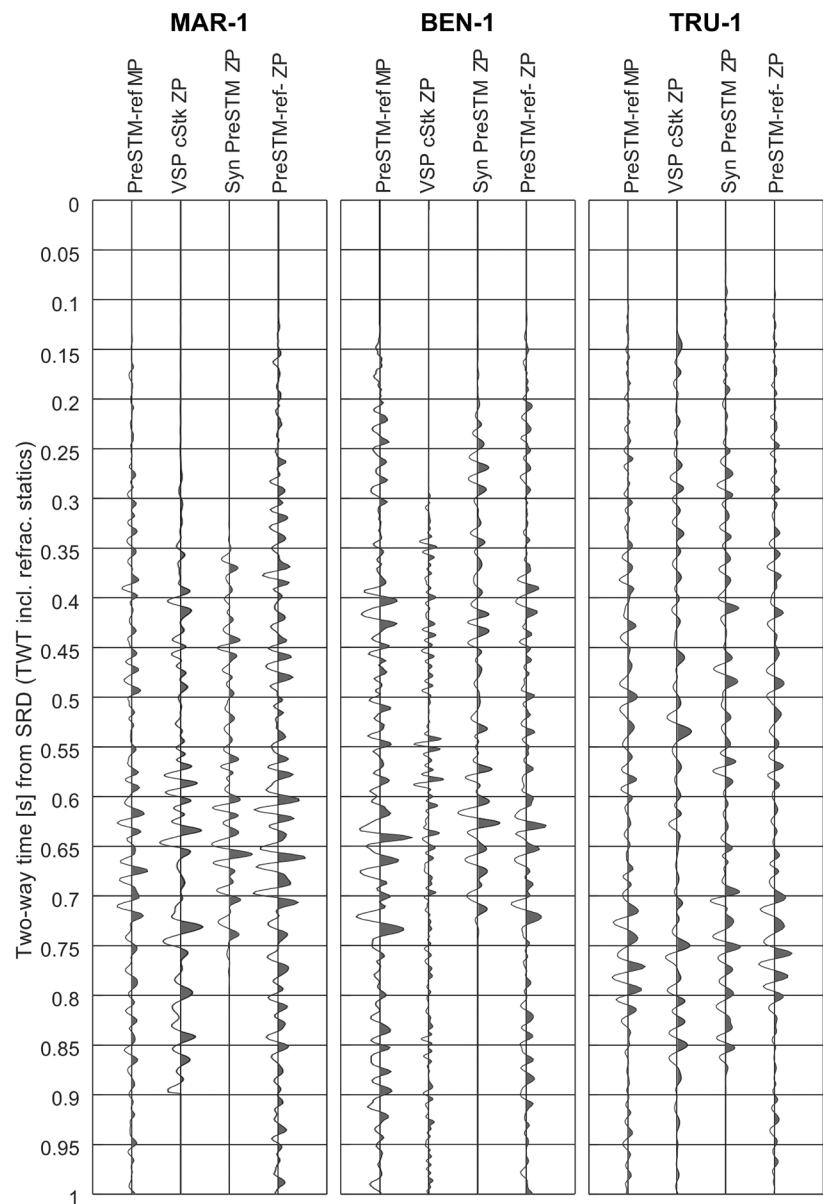


Fig. 8-13: ZNO matches of minimum phase synthetic with surface seismic data

Each panel shows from left to right: minimum phase near borehole trace from surface seismic, zero-phase corridor stack, zero-phase synthetic, and zero-phased near borehole trace from surface seismic

8.5 Discussion

For practical purpose it was decided to derive a single zero-phasing filter per survey. While by deriving one filter per borehole location, a better local match might have been obtained, the sparse boreholes were not deemed to properly sample the lateral variability in phase of the surveys.

Application of the zero-phasing filter enabled a better match between surface and borehole seismic traces. In general, matches of the zero-offset corridor stacks and the synthetics were quite reasonable, providing confidence in both the processing of the VSPs and in the quality of the synthetics. Given the narrow bandwidth, zero-phasing did not notably improve imaging quality.

9 Conclusions

9.1 Summary of the refinement processing strategy

As part of the site selection evaluation, three 3D seismic surveys were acquired and processed, in order to better characterise the subsurface of the three potential siting regions. The seismic data processing of these three surveys JO-15, NL-16 and ZNO-97/16 was conducted in two stages: a first stage referred as the Quick Look Processing (QLP), and a multi-stage second stage referred as the Refinement Processing (REP). This report summarises the QLP results and presents the REP workflow and its outcome in more detail. Note that the ZNO-97/16 imaging products merge the existing ZNO-97 survey with the newly acquired ZNO-16 survey.

After evaluation of the QLP results, the analysis of the velocity structure was identified as the primary objective and signal improvement as a secondary objective of the REP. Hence, the REP focussed on velocity-related topics and velocity model building, while signal-to-noise related topics were postponed. Both Pre-stack depth migration (PreSDM) and reference Pre-stack time migration (PreSTM-ref) imaging products were delivered.

The refinement processing was designed for, and the results addressed, the requirements posed by ENSI (2018) (see Section 1.4.1) by: (1) merging the two ZNO surveys, (2) providing zero-phased seismic imaging products and (3) providing detailed and comparable processing product series to support the interpretation of tectonic elements in the site selection process. Note that the borehole calibration is discussed in interpretation reports Nagra (2024a), (2024b) and (2024c).

9.2 Velocity model building and pre-stack depth migration

The REP near surface velocity model building improved the resolution and extended the illumination of the near surface velocity volume in depth in areas where the Malm Group is not close to the surface. This was an essential prerequisite towards the PreSDM model building from surface topography, and a basis for the subsequent reference PreSTM.

Through this approach, new statics solutions were derived as part of the REP. The long-wavelength component of the new solution was significantly reduced when compared to the QLP solutions. Slight deterioration of the short-wavelength statics components in some areas was resolved with residual statics derivation and application.

As the geology varies considerably, both within surveys and across surveys, the PreSDM workflow was optimised individually per siting region. In the JO-15 area of interest (AOI), relatively thin Quaternary and Paleogene-Neogene sedimentary rocks cover the Malm Group, and near surface imaging is generally good. Quaternary valleys south and east of the AOI could be and have been excluded from the PreSDM analysis perimeter. Velocities in the Mesozoic units within the AOI were developed layer by layer using residual move-out inversions and geological guidance. The final PreSDM images and velocity products are fit-for-purpose only within the AOI boundary.

The velocity models of the NL-16 and ZNO-97/16 areas included the thick Paleogene-Neogene sedimentary rocks, thinning towards the north, as well as the deep Quaternary valleys within the complete survey area. Plateaus with compacted Quaternary gravels of mixed saturation and presence of the Malm Group close to the surface in the northern part proved to be quite challenging during the model building. Geological-induced offset limitations and locally elevated noise level constrained the accuracy of the residual move-out inversions and resulting velocities in the Mesozoic units.

The PreSDM quality is sensitive to lateral variations in the near surface velocity structure. Significant velocity variations in the near surface have, since they have not been fully represented in the model, affected the ray based (Kirchhoff) imaging quality. These local inaccuracies in the near surface velocities have had an imprint on deeper velocities as well.

Different geology required independent choices on velocity boundaries, residual move-out ranges and inversion parameters for each survey in order to achieve results of comparable quality. Due to the requirement to maintain positional integrity and corresponding limitations on regularisation, the imprint of the acquisition and of residual noise is more notable on the PreSDM than on the PreSTM-ref.

In conclusion, the PreSDM results are less comparable to each other than the reference PreSTM-ref results and exhibit some artefacts which impair the geological interpretation. In places though, fault imaging was better on the PreSDM result than on the PreSTM-ref result because the physical model behind the depth imaging more closely approaches the subsurface reality.

9.3 Reference pre-stack time migration

The reference pre-stack time migration (PreSTM-ref) was executed with an identical workflow for all three siting regions, and with the same processing parameters, as far as geophysically acceptable given the differences in geology and related seismic characteristics. The purpose of this was to deliver three seismic images optimised for siting region comparison, as well as to address some limitations of the PreSDM, notably the dependency on velocity models of limited accuracy.

The PreSTM-ref workflow delivered consistent results for all three areas under investigation. Comparison of the PreSTM-ref stack quality over part of the area of interest confirms that the JO-15 survey is less noisy than the other two. All three datasets are well interpretable at the time zones of interest.

The PreSTM-ref seismic volumes have after delivery been used as primary vehicles (supported by the PreSDM volumes and velocity models) for the comparative interpretation and depth conversion of the three proposed siting regions, as described in the interpretation reports Nagra (2024a) (JO-15), Nagra (2024b) (NL-16) and (Nagra 2024c) (ZNO).

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11 Glossary

Term	Abbr.	Explanation	German
Base statics		Sum of refraction and elevation statics	Grundstatik
Datum statics		Temporary shift of datum from acquisition surface to e.g. floating datum	Datumsstatik
Elevation statics		Permanent shift of datum from acquisition surface to SRD	Höhenstatik
Refraction statics		Static correction from acquisition surface based on refraction analyses. Convention in this report: Negative static corrections move the trace up and positive move it down in time.	Refraktionsstatik
Residual statics		Refinement of base statics to reduce geometry errors and near surface velocity changes.	Reststatik
Residual moveout	RMO	Analyses of residual moveout on prestack data on the basis of a sufficiently accurate velocity mode.	-
RMS velocity	V_{rms}	V_{rms} is defined as the square-root of the summed square of the interval velocity multiplied by the transit time, divided by the sum of the transit times. It is used to simplify the traveltime computations in a layered medium and equals V_{stack} for isotropic horizontal layers and small source-receiver distances.	RMS Geschwindigkeit
Interval velocity	V_{int}	Discretised velocities in a structured (e.g. finite difference) or unstructured (e.g. layered) grid. If applied to stacked data: post-stack depth migration (PostSDM). If applied to unstacked data: pre-stack depth migration in depth domain (PreSDM).	Intervallgeschwindigkeit

Term	Abbr.	Explanation	German
Migration velocity	V_{mig}	RMS type velocities for migration of unmigrated data in time domain. If applied to stacked data: post-stack migration. If applied to unstacked data: pre-stack migration in time domain (PreSTM)	Migrationsgeschwindigkeit
Seismic reference datum	SRD	Arbitrary reference surface, the reduction to which minimizes local topographic and near-surface effects	Referenzdatum
Stacking velocity	V_{stack}	Is the velocity determined by velocity analyses for application in the unmigrated data domain.	Stapelgeschwindigkeit

App. A List of archived processing deliverables

A.1 Processing products for JO-15

I/O	Product	Description	Format
Module A – QLP Signal Processing Part 1			
Input	Raw field seismic data	Raw acquired seismic data of survey JO-2015 in shot domain	SEGD
	Positioning data	SPS Positioning data for shots and receivers	ASCII
Output	JO15.A1 raw nav-merged shot records, stacked	Minimum phase identified shot records	SEGY
	JO15.A2 first arrival times	First break times as picked with geometry	ASCII
	Weathering layer depths and velocities	LVL survey interpretations	ASCII

Module B – QLP Signal Processing Part 2			
Input		Output data of Module A	
		Weathering velocities from the LVL survey	ASCII
Output	JO15.B1 pre-processed CDP gathers	Signal processed minimum phase CMP gathers	SEGY
	JO15.B3 primary statics	Base static corrections	ASCII
	JO15.B3 secondary statics	Residual statics corrections	ASCII
	JO15.B4 Stacking Velocities	Stacking Velocities	ASCII
	JO15.B5 CDP stacks	Stack of CMP gathers	SEGY
	JO15.B5 Time migration	Time migration of stack of CMP gathers	SEGY
	JO15.B7 zero phase operator	Zero phasing operator	ASCII

Module C – QLP Imaging by CRS			
Input	See seismic output files of Module B	Signal processed minimum phase CMP gathers	SEGY
	See seismic output files of Module B	Stacking Velocities	ASCII
Output	JO15.C1 CRS gathers	Offset regularized pre-stack gather	SEGY
	JO15.C2 CRS stacks (raw/filtered)	Stack of the above JO15.C1 CRS gathers	SEGY
	JO15.C8 NIP_wave tomography	Interval velocity model as a function of depth	SEGY
	JO15.C4 PostSTM of CRS stack	Post-stack time migration	SEGY
	JO15.C5a PostSDM of CRS stack	Post-stack depth migration	SEGY
	JO15.C6a depth-to-time stretch	Post-stack depth migration JO.C5a stretched to time	SEGY

Module D1 – QLP			
Input	JO15.C1 CRS gathers	Offset regularized CMP gathers of Module C	
Output	JO15.D5.PreSTM gathers	Pre-stack migrated seismic gathers	SEGY
	JO15.D2 PreSTM velocities	RMS migration velocities for PreSTM	ASCII/SEGY
	JO15.D6 PreSTM stack	Stacked volume of pre-stack migrated gathers JO15.D5, with post processing incl. FXY-decon.	SEGY
	JO15.D7 PreSTM stack	Stacked volume of pre-stack migrated gathers JO15.D5, with post processing but no FXY-decon.	SEGY
	JO15.D9 CDP gathers interpolated	Non-migrated JO15.B1 gathers, after flex-binning	SEGY

Module D2 – QLP			
Input	See seismic output files of Module B	Signal processed minimum phase CMP gathers	SEGY
	See seismic output files of Module C	Regularized / non regularized CMP gathers of Module C	SEGY
Output	JO15.D13 PreSTM stack	Stacked volume after PreSTM in time	SEGY
	JO15.D12 migration velocity model	Interval velocity model in time	SEGY
	no such product in JO	Seismic image after PostSDM in depth	SEGY
	JO15.D18 postSDM dt-conv	Seismic image after PostSDM and depth-to-time conversion	SEGY

Refinement processing REP1 – Near surface velocity model building			
Input	JO15.B1 pre-processed CMP gathers	Acquisition geometry (Positioning data)	SEGY
	Topography	Surface topography from processing grid	ASCII
	JO15.A2 first arrival times	First break times as picked with geometry	ASCII
	JO15.B1 pre-processed CMP gathers	Shot Up-hole times	ASCII
	JO15.B1 pre-processed CMP gathers	Signal processed CMP gathers from Module B	SEGY
Output	JO15.RefracTomo3D invgrid full	3D near surface velocity tomogram in inversion grid	MATLAB
	product not archived	3D near surface velocity model after filtering and resampling	
	JO15.BaseStat PseudoDatum	Surface topography and pseudo datum elevation	ASCII
	JO15.REP Refraction statics	Calculated refraction statics	ASCII
	JO15.REP Residual statics	Calculated residual statics corrections G,H,F	TEXT
	JO15.Vstk	Stacking velocities based on REP residual statics	TEXT

Refinement processing REP2 – Velocity Model Building and Pre-stack Depth Migration			
Input	JO15.B1 pre-processed CMP gathers	Signal processed CMP gathers from Module B	SEG Y
	JO15.RefracTomo3D CMPgrid	3D near surface velocity model after filtering and resampling from REP1	SEG Y
	JO15.B3 secondary statics	Residual statics from QLP	TEXT
	JO15.Residual statics	Residual statics from REP1	TEXT
	JO elevation model	Elevation model from REP1	TEXT
Output	JO15.REP2.TEEC.M151	Final interval velocity model for PreSDM-A	SEG Y
	JO15.REP2.TEEC.RMO	Residual Moveout (RMO) Measurements	ASCII
	JO15.REP2.TEEC.M151 PreSDM-A gathers	Pre-stack depth migrated image gathers for model M151	SEG Y
	JO15.REP2.TEEC.PreSDM-A stacks	Raw stack of pre-stack depth migrated gathers model M151	SEG Y
	JO15.REP2.TEEC.PreSDM-A stack depth adjusted	Final post-processed PreSDM-A volume, depth adjusted	SEG Y

Refinement processing REP3 – Reference Pre-stack Time Migration			
Input	JO15.B1 pre-processed CMP gathers	Signal processed CMP Gathers of Module B	SEG Y
	JO15.REP Refraction statics	Refraction statics from REP1	ASCII
	JO15.REP Residual statics	Residual statics from REP1	ASCII
	JO15.B15 ProcGrid	Surface topography from processing grid	ASCII
	JO15.B4 stacking velocities	Stacking velocities from QLP	ASCII
Output	JO15.REP3.TEEC.CRS gather aquisition	CRS gathers on acquisition geometry	SEG Y
	JO15.REP3.TEEC.CRS gather regularized	Regularised CRS gathers	SEG Y
	JO15.REP3.TEEC.CRS stacks	CRS stacked volume with/without regularisation	SEG Y
	JO15.REP3.TEEC.CIG PreSTM	PreSTM migrated CRS gathers with/without CRS regularisation	SEG Y
	JO15.REP3.TEEC PreSTM	Final stack of PreSTM gathers with CRS regularisation	SEG Y
	JO15.REP3.TEEC Demigration	Demigrated stacks of PreSTM stack with CRS regularised gathers	SEG Y
	JO15.REP3.TEEC PostSDM	PostSDM of demigrated PreSTM stacks	SEG Y
	JO15.REP3.TEEC.CIG PreSTM CMP	PreSTM migrated CMP gathers	SEG Y
	JO15.REP3.TEEC PreSTM raw	Final stacks of PreSTM CMP gathers	SEG Y
	JO15.REP3.TEEC PreSTM MigVelVolume	PreSTM migration velocities	SEG Y

Zero-phasing			
Input	Reconditioned composite logs for BOZ-1, BOZ-2, RIN	Sonic and density logs for wells in the area	las
	Corridor stacks for BOZ-1, BOZ-2, RIN	VSP data for the wells in the area	SEGY
	JO15.C6 PreSTM stack JO15.D8 PreSTM stack	PreSTM migrated data from QLP	SEGY
	JO15.REP2.TEEC.PreSDM-A stacks depth adjusted	Final post-processed Pre-SDM-A volume	SEGY
	JO15.REP3.TEEC. PreSTM	Reference Pre-STM final volume	SEGY
Output	Edited composite logs for BOZ-1, BOZ-2, RIN	Edited sonic and density logs and time-depth relation for boreholes in area	las
	JO15.PreSTM-ref zero phased	Zero-Phased final PreSTM data	SEGY
	JO15.PreSTM-ref zero phase operator	minimum- to zero-phase operator for PreSTM-ref conversion to zero-phase	MATLAB
	JO15.C6 PreSTM stack REP-zero phased JO15.D8 PreSTM stack REP-zero phased	Zero Phased final QLP migrated data	SEGY
	JO15.REP2.TEEC.PreSDM-A stack (M151) zero phased	Zero-Phased final PreSDM data	SEGY

A.2 Processing products for NL-16

I/O	Product	Description	Format
Module A – QLP Signal Processing Part 1			
Input	Raw field seismic data	Raw acquired seismic data of survey NL-2016 in shot domain (correlated and uncorrelated)	SEGD
	Positioning data	SPS Positioning data for shots and receivers	ASCII
Output	NL16.A1 raw nav-merged shot records diversity stacked	Minimum phase identified shot records with diversity stacking	SEGY
	NL16.A1 raw nav-merged shot records, stacked	Minimum phase identified shot records with stacking (stack of correlated records)	SEGY
	NL16.A2 first arrival times	First break times as picked with geometry	ASCII
	weathering layer depths and velocities	LVL survey interpretations	ASCII

Module B – QLP Signal Processing Part 2			
Input		Output data of Module A	
		Weathering velocities from the LVL survey	ASCII
Output	NL16.B1 pre-processed CMP gathers	Signal processed minimum phase CMP gathers	SEGY
	NL16.B3 primary statics	Base statics corrections	ASCII
	NL16.B3 secondary statics	Residual statics corrections RS1 and RS2	ASCII
	NL16.B4 stacking velocities	Stacking Velocities	ASCII
	NL16.B5 CMP stacks	Stack of CMP gathers	SEGY
	NL16.B5 TimeMigration	Time migration of B5 CMP stack	SEGY
	NL16.B7 zero phase operator	Zero phasing operator	ASCII

Module C – QLP Imaging by CRS			
Input	NL16.B1 product	Signal processed minimum phase CMP gathers	SEGY
	NL16.B4 stacking velocities	Stacking Velocities	ASCII
Output	NL16.C1 CRS gathers	Offset regularized pre-stack gather	SEGY
	NL16.C2 CRS stack	Stack of the above NL16.C1 CRS gathers	SEGY
	NL16.C3 NIP_wave tomography	Interval velocity model as a function of depth	SEGY
	NL16.C4 PostSTM of CRS stack	Post-stack time migration	SEGY
	NL16.C5 PostSDM of CRS stack	Post-stack depth migration	SEGY
	NL16.C6 depth-to-time stretch	Post-stack depth migration C5 stretched to time	SEGY

Module D1 – QLP			
Input	NL16.C1 CRS gathers	Offset regularized CMP gathers of Module C	SEG Y
Output	NL16.D5 PreSTM gathers	Pre-stack migrated seismic gathers	SEG Y
	NL16.D2 PreSTM velocities	RMS migration velocities for PreSTM	ASCII & SEG Y
	NL16.D6 PreSTM stack	Stacked volume of pre-stack migrated gathers NL.D5, with post processing incl. FXY-decon.	SEG Y
	NL16.D7 PreSTM stack	Stacked volume of pre-stack migrated gathers NL.D5, with post processing but no FXY-decon.	SEG Y
	NL16.D8 PreSTM stack	Stacked volume of pre-stack migrated gathers NL.D5, with post processing, trim-statics and FXY-decon.	SEG Y

Module D2 – QLP			
Input	See seismic output files of Module B	Signal processed minimum phase CMP gathers	SEG Y
	See seismic output files of Module C	Regularized / non regularized CMP gathers of Module C	SEG Y
Output	NL16.D16 PreSTM stack	Stacked volume after PreSTM in time	SEG Y
	NL16.D12 migration velocity model	Interval velocity model in time	ASCII & SEG Y
	NL16.D18 postSDM	Seismic image after PostSDM in depth	SEG Y
	NL16.D18 postSDM dt-conv	Seismic image after PostSDM and depth-to-time conversion	SEG Y

Refinement processing REP1 – Near surface velocity model building			
Input	NL16.B1 pre-processed CMP gathers	Acquisition geometry (Positioning data)	SEG Y
	Topography	Surface topography from processing grid	ASCII
	NL16.A2 first arrival times	First break times as picked with geometry	ASCII
	NL16.B1 pre-processed CMP gathers	Shot Up-hole times	SEG Y
	NL16.B1 pre-processed CMP gathers	Signal processed CMP gathers from Module B	SEG Y
Output	NL16.RefracTomo3D invgrid	3D near surface velocity tomogram in inversion grid	MATLAB
	NL16.RefracTomo3D CMPgrid	3D near surface velocity model after filtering and resampling	SEG Y
	NL16.BaseStat PseudoDatum	Surface topography and pseudo datum elevation	ASCII
	NL16.Residual statics	Calculated residual statics corrections C1 and C12	TEXT
	NL16.VstkC1.PickSets	Stacking velocities based on C1 residual statics	TEXT
	NL16.VstkC1.Volume	Interpolated stacking velocities volume	SEG Y

Refinement processing REP2 – Velocity Model Building and Pre-stack Depth Migration			
Input	NL16.B1 pre-processed CMP gathers	Signal processed CMP gathers from Module B	SEGY
	NL16.RefracTomo3D CMPgrid	3D near surface velocity model after filtering and resampling from REP1	SEGY
	NL16.B3 secondary statics	Residual statics from QLP	TEXT
	NL16.Residual statics	Residual statics from REP1	TEXT
	NL elevation model	Elevation model from REP1	TEXT
Output	NL16.REP2.TEEC.VID_PreSDM-A2-M260-M261 NL16.REP2.TEEC.EPSILON_PreSDM-A2-M260-M261 NL16.REP2.TEEC.DELTA_PreSDM-A2-M260-M261	Final interval models for PreSDM-A2 (vP, epsilon, and delta)	SEGY
	NL16.REP2.TEEC.RMO	Residual Moveout (RMO) measurements	ASCII
	NL16.REP2.TEEC.CRP PreSDM-A2 gathers	Pre-stack depth migrated image gathers for model M260	SEGY
	NL16.REP2.TEEC.PreSDM-A2 stacks	Pre-stack depth migrated stacked volume for model M260	SEGY
	NL16.REP2.TEEC.PreSDM-A2 composite	Final post-processed PreSDM-A2 volume, optimised composite	SEGY

Refinement processing REP3 – Reference Pre-stack Time Migration			
Input	NL16.B1 pre-processed CMP gathers	Signal processed CMP Gathers of Module B	SEGY
		Refraction statics from REP1	MATLAB
	NL16.Residual statics	Residual statics from REP1	ASCII
	NL16.B15 ProcGrid	Surface topography from processing grid	ASCII
	NL16.B4 stacking velocities	Stacking velocities from QLP	ASCII
Output	NL16.REP3.TEEC.CRS gather aquisition	CRS gathers on acquisition geometry	SEGY
	NL16.REP3.TEEC.CRS gather regularized	Regularised CRS gathers	SEGY
	NL16.REP3.TEEC.CRS stacks	CRS stacked volume with/without regularisation	SEGY
	NL16.REP3.TEEC.CIG PreSTM	PreSTM migrated CRS gathers with/without CRS regularisation	SEGY
	NL16.REP3.TEEC. PreSTM	Final stack of PreSTM gathers with CRS regularisation	SEGY
	NL16.REP3.TEEC. PreSTM raw	Final stacks of PreSTM gathers without CRS regularisation	SEGY
	NL16.REP3.TEEC.demigration	Demigrated stacks of PreSTM stack with CRS regularised gathers	SEGY
	NL16.REP3.TEEC.PostSDM	PostSDM of demigrated PreSTM stacks	SEGY
	NL16.REP3.PreSTM MigVelVolume	PreSDM migration velocities	SEGY

Zero-phasing			
Input	Reconditioned composite logs for BAC1-1, BUL1-1, STA2-1, STA3-1	Sonic and density logs for boreholes in the NL area	las
	Corridor stacks for BAC1-1, BUL1-1, STA2-1, STA3-1	VSP data for the wells in the area	SEGY
	NL16.C6 PreSTM stack, NL16.D16 PreSTM stack	QLP migrated data from QLP	SEGY
	NL16.REP2.TEEC.PreSDM-A2 stacks (M260)	Final post-processed Pre-SDM-A2 volume	SEGY
	NL16.REP3.TEEC. PreSTM	Reference Pre-STM final volume	SEGY
Output	Edited composite logs for BAC1-1, BUL1-1, STA2-1, STA3-1	Edited sonic and density logs and time-depth relation for boreholes in area	las
	NL16.PreSTM-ref zero phased	Stacked & Postprocessed Time Volume with RMO, Trim Statics, AGC applied (Zero Phase)	SEGY
	NL16.PreSTM-ref zero phase operator	minimum- to zero-phase operator for PreSTM-ref conversion to zero-phase	MATLAB
	NL16.C6 PreSTM stack REP-zero phased NL16.D16 PreSTM stack REP-zero phased	Zero Phased final QLP migrated data	SEGY
	NL16.REP2.TEEC.PreSDM-A2 stacks (M260) zero phased	Zero-Phased final PreSDM data	SEGY

A.3 Processing products for ZNO-97/16

I/O	Product	Description	Format
Module A – QLP Signal Processing Part 1			
Input	Raw field seismic data	Raw acquired seismic data of survey ZNO-97 and ZNO-16 in shot domain	SEGD
	Positioning data	SPS Positioning data for shots and receivers	ASCII
Output	ZNO97.A1 raw nav-merged shot records, stacked ZNO16.A1 raw nav-merged shot records, stacked	Minimum phase identified shot records with stacking (stack of correlated records)	SEGY
	ZNO97.A2 First arrival times ZNO16.A2 First arrival times	First break times as picked with geometry	ASCII
	Weathering layer depths and velocities	LVL survey interpretations	ASCII

Module B – QLP Signal Processing Part 2			
Input		Output data of Module A	
		Weathering velocities from the LVL survey	ASCII
Output	ZNO16.B1 pre-processed CDP gathers ZNO97.B1 pre-processed CDP gathers	Signal processed minimum phase CMP gathers	SEGY
	ZNO16.B3 Primary statics ZNO97.B3 Primary statics	Base static corrections	ASCII
	ZNO16.B3 Secondary statics ZNO97.B3 Secondary statics	Residual statics corrections	ASCII
	ZNO97+ZNO16.B4 Stacking velocities	Stacking Velocities	ASCII
	ZNO16.B5 CDP stacks ZNO97.B5 CDP stacks ZNO97+ZNO16.B5 CDP stacks	Stack of CMP gathers	SEGY
	ZNO97+ZNO16.B5 Time migration	Time migration of stack of CMP gathers	SEGY
	ZNO16.B7 zero phase operators	Zero phasing operators	ASCII

Module C – QLP Imaging by CRS			
Input	See seismic output files of Module B	Signal processed minimum phase CMP gathers	
	See seismic output files of Module B	Stacking Velocities	ASCII
Output	ZNO.C1 CRS gathers	Offset regularized pre-stack gather	SEGY
	ZNO.C2 CRS stacks (raw/filtered)	Stack of the above ZNO.C1 CRS gathers	SEGY
	ZNO.C8 NIP_wave tomography	Interval velocity model as a function of depth	SEGY
Output	ZNO.C4 PostSTM of CRS stack	Post-stack time migration	SEGY
	ZNO.C5 PostSDM of CRS stack	Post-stack depth migration	SEGY
	ZNO.C6 depth-to-time stretch	Post-stack depth migration ZNO.C5 stretched to time	SEGY

Module D1 – QLP			
Input	ZNO.C1 CRS gathers	Offset regularized CMP gathers of Module C	
Output	ZNO97+16.D5 PreSTM gathers	Pre-stack migrated seismic gathers	SEGY
	ZNO97+16.D2 PreSTM velocities	RMS migration velocities for PreSTM	ASCII & SEG Y
	ZNO97+16.D6 PreSTM stack	Stacked volume of pre-stack migrated gathers ZNO97+16.D5, with post processing incl. FXY-decon.	SEGY
	ZNO97+16.D7 PreSTM stack	Stacked volume of pre-stack migrated gathers ZNO97+16.D5, with post processing but no FXY-decon.	SEGY
	ZNO97+16.D8 PreSTM stack	Stacked volume of pre-stack migrated gathers ZNO97+16.D5, with post processing, trim-statics and FXY-decon.	SEGY
	ZNO97+16.D9 CDP gathers interpolated	Non-migrated cdp gathers, after flex-binning	SEGY

Module D2 – QLP			
Input	See seismic output files of Module B	Signal processed minimum phase CMP gathers	SEGY
	See seismic output files of Module C	Regularized / non regularized CMP gathers of Module C	SEGY
Output	ZNO97+16.D13 CRS PreSTM stacks	Stacked volumes after PreSTM in time	SEGY
	ZNO97+16.D16 migration velocity model	Interval velocity model in time	SEGY
	no such product is available for ZNO	Seismic image after PostSDM in depth	SEGY
	ZNO97+16.D18 postSDM dt-conv	Seismic image after PostSDM and depth-to-time conversion	SEGY

Refinement processing REP1 – Near surface velocity model building			
Input	ZNO.A1 ZNO.B1	Acquisition geometry (Positioning data)	SEG Y
	Topography	Surface topography from processing grid	ASCII
	ZNO97.A2 first arrival times ZNO16.A2 first arrival times	First break times as picked with geometry	ASCII
Input	ZNO97.B1 pre-processed CMP gathers ZNO16.B1 pre-processed CMP gathers	Shot Up-hole times	ASCII
	ZNO97.B1 pre-processed CMP gathers ZNO16.B1 pre-processed CMP gathers	Signal processed CMP gathers from Module B	SEG Y
Output	ZNO.RefracTomo invgrid	3D near surface velocity tomogram in inversion grid	MATLAB
	product not archived	3D near surface velocity model after filtering and resampling	
	ZNO.REP BaseStat PseudoDatum	Surface topography and pseudo datum elevation	ASCII
	ZNO.REP Refraction Statics	Calculated refraction statics	TEXT
	ZNO.REP Residual statics	Calculated residual statics	TEXT
	ZNO.REP.VstkC	Stacking velocities	TEXT
	ZNO.REP.VstkC	Interpolated stacking velocities	SEG Y

Refinement processing REP2 – Velocity Model Building and Pre-stack Depth Migration			
Input	ZNO16.B1 pre-processed CDP gathers ZNO97.B1 pre-processed CDP gathers	Signal processed CMP gathers from Module B	SEG Y
	ZNO.RefracTomo3D CMPgrid	3D near surface velocity model after filtering and resampling from REP1	SEG Y
	ZNO.B3 Secondary statics	Residual statics from QLP	TEXT
	ZNO.REP Residual statics	Residual statics from REP1	TEXT
	ZNO elevation model	Elevation model from REP1	TEXT
Output	ZNO.REP2.TEEC.M240	Final interval velocity models (vP, epsilon, delta) for PreSDM-A	SEG Y
	ZNO.REP2.TEEC.RMO	Residual Moveout (RMO) Measurements	ASCII
	ZNO.REP2.TEEC CRS PreSDM-A gathers	Pre-stack depth migrated image gathers for model M240	SEG Y
	ZNO.REP2.TEEC CRS PreSDM-A stacks	Pre-stack depth migrated stacked volume for model M240	SEG Y
	ZNO.REP2.TEEC CRS PreSDM-A stack post proc	Final post-processed PreSDM-A volume	SEG Y

Refinement processing REP3 – Reference Pre-stack Time Migration			
Input	ZNO.B1 pre-processed CMP gathers	Signal processed CMP Gathers of Module B	SEG Y
	ZNO.Refraction statics	Refraction statics from REP1	ASCII
	ZNO.Residual statics	Residual statics from REP1	ASCII
	ZNO.B15 ProcGrid	Surface topography from processing grid	ASCII
	ZNO.B4 stacking velocities	Stacking velocities from QLP	ASCII
Output	ZNO.REP3.TEEC.CRS gather acquisition	CRS gathers on acquisition geometry	SEG Y
	ZNO.REP3.TEEC.CRS gather regularized	Regularised CRS gathers	SEG Y
	ZNO.REP3.TEEC.CRS stacks	CRS stacked volume with/without regularisation	SEG Y
	ZNO.REP3.TEEC.CIG PreSTM	PreSTM migrated CRS gathers with/without CRS regularisation	SEG Y
	ZNO.REP3.TEEC PreSTM	Final stack of PreSTM gathers with CRS regularisation	SEG Y
	ZNO.REP3.TEEC Demigration	Demigrated stacks of PreSTM stack with CRS regularised gathers	SEG Y
	ZNO.REP3.TEEC PostSDM	PostSDM of demigrated PreSTM stacks	SEG Y
	ZNO.REP3.TEEC.CIG PreSTM CMP	PreSTM migrated CMP gathers	SEG Y
	ZNO.REP3.TEEC. PreSTM raw	Final stacks of PreSTM CMP gathers	SEG Y
	ZNO.REP3.TEEC PreSTM MigVelVolume	PreSTM migration velocities	SEG Y

Zero-phasing			
Input	Reconditioned composite logs for BEN, MAR-1, TRU-1	Sonic and density logs for wells in the area	las
	Corridor stacks for BEN, MAR-1, TRU-1	VSP data for the wells in the area	SEG Y
	ZNO.C6 PreSTM stack ZNO.D8 PreSTM stack	PreSTM migrated data from QLP	SEG Y
	ZNO.REP2.TEEC CRS PreSDM-A stacks	Final post-processed Pre-SDM-A volume	SEG Y
	ZNO.REP3.TEEC PreSTM	Reference Pre-STM final volume	SEG Y
Output	Edited composite logs for BEN, MAR-1, TRU-1	Edited sonic and density logs and time-depth relation for boreholes in area	las
	ZNO.PreSTM-ref zero phased	Zero-Phased final PreSTM data	SEG Y
	ZNO.PreSTM-ref zero phase operator	minimum- to zero-phase operator for PreSTM-ref conversion to zero-phase	MATLAB
	ZNO.C6 PreSTM stack REP-zero phased ZNO.D8 PreSTM stack REP-zero phased	Zero Phased final QLP migrated data	SEG Y
	ZNO.REP2.TEEC.PreSDM-A stack (M240) zero phased	Zero-Phased final PreSDM data	SEG Y