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Arbeitsbericht NAB 18-22

2D Reflection Seismic Exploration and Provisory Interpretation of Overdeepened Quaternary Valleys around the Nagra Siting Regions Zürich Nordost and Nördlich Lägern

August 2018

Nagra

National Cooperative
for the Disposal of
Radioactive Waste

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KEYWORDS

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1 Introduction

1.1 Project context and aims

In the context of the sectoral plan "Sachplan geologische Tiefenlager" (SGT) Nagra is currently investigating three sites in northern Switzerland to potentially host repositories for radioactive waste. The field exploration project "Quartäruntersuchungen" (QAU) is dedicated to the characterisation of Quaternary deposits within and around these siting regions to further constrain scenarios of their geological long-term evolution. The investigations support the reconstruction of Quaternary landscape evolution.

As part of the QAU project Nagra acquired a series of high resolution 2D-seismic profiles in winter of 2016/2017. The majority of the profiles (16 out of 23) aimed at verifying and characterising glacially overdeepened Quaternary valleys and troughs within and around the siting regions "Zürich Nordost" (ZNO) and "Nördlich Lägern" (NL) and thereby updating the investigation area's Base Quaternary model.

This report summarises the planning, acquisition, processing and first interpretation of these 16 profiles (Fig. 1-1). The presented seismic interpretation is meant to serve the planning of Quarternary exploration boreholes in the next phase of the QAU project. As the findings derived from these boreholes will likely require certain interpretation adjustments, the current version is considered provisory.

Project and report contributors

On behalf of Nagra, the acquisition of seismic profiles, planned with support of roXplore gmbh, was carried out by DMT GmbH & Co. KG (DMT) in the winter of 2016/2017. Processing of the seismic data was carried out by Geofizyka Torun S.A. (GT) in 2017. The companies roXplore gmbh (L. Keller) and geophytec GmbH (A. Hölker) provided support during acquisition and processing respectively.

The interpretation of the profiles was contracted to Geneva Petroleum Consultants International (GPCI) in July 2017. This work package also included additional interpretation and processing guided velocity modelling and the provision of post stack depth migration results by GPCI. Interpretation advice was provided by M. Büchi (University of Bern) and H. Naef (geosfer ag).

The report contributions are as follows:

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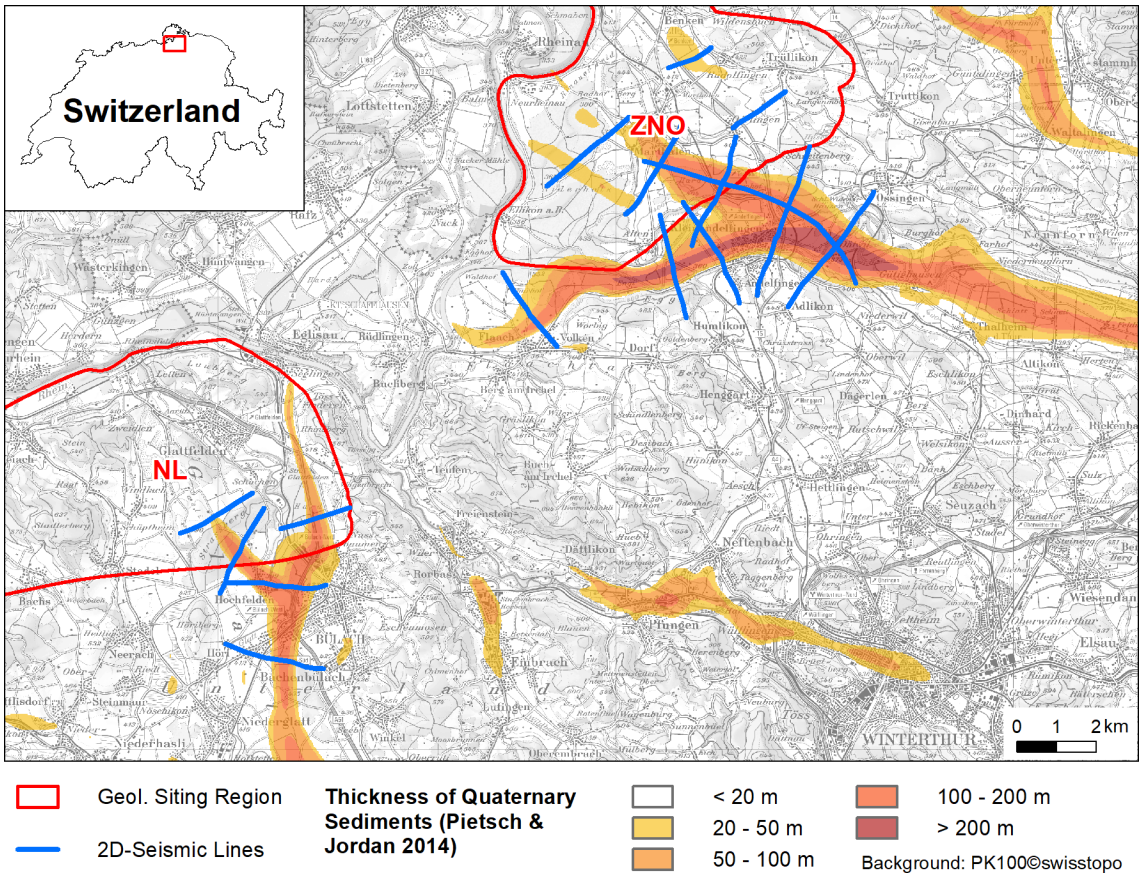


Fig. 1-1: Location map of the discussed 2D seismic reflection lines with geological siting regions Zürich Nordost (ZNO) and Nördlich Lägern (NL) as well as the outline of the targeted glacially overdeepened Quaternary valleys and troughs.

1.2 Investigation methodology

The geophysical investigation of Quaternary sediments is a challenging mission. Nagra's previous geophysical surveys were not targeting these deposits but designed to image deeper lying Mesozoic units (Birkhäuser et al. 2001, Madritsch et al. 2013, Nagra 2008). Previous investigations addressing the geophysical imaging of glacially overdeepened, buried valleys, such as those carried out by the BurVal and CARNEVAL consortia (BurVal Working Group 2006, Schmelzbach et al. 2014) suggested that seismic reflection profiling has a high potential to provide robust and detailed information on the Base of Quaternary valleys and on their internal structure.

As a start, existing scientific publications in similar geological settings (e.g. Büker et al. 1998a, Büker et al. 1998b, Schmelzbach et al. 2005, Spitzer et al. 2001, Spitzer et al. 2003, Dehnert et al. 2012) were reviewed to clarify the possible resolution of the proposed reflection seismic method. This supposition was confirmed in a multi-method test survey that was executed in the central part of the ZNO siting region in early 2016. The test benefited from reprocessing seismic data that was acquired for a low velocity layer (LVL) profile in the framework of the ZNO 3D-seismic survey. The resulting reflection and refraction test profiles were complemented by analyses of gravity data, electrical resistivity tomography and diverse S-wave investigations. A specific feature of the test profile was ground truthing through the adjacent borehole AZ-3D15-07 (Nagra 2017). The LVL profile proved beneficial to verify the generic acquisition parameters that were foreseen in the Quaternary investigation project. Furthermore, the basic feasibility for a combined seismic reflection and refraction tomographic survey could also be tested. In summary this test survey confirmed that reflection seismic is the method of choice for the imaging of Quaternary deposits at the given sites.

2 Survey conception

2.1 Survey design

The geometry of Quaternary deposits and overdeepened valleys is roughly constrained in all areas of investigation documented in a regional Base Quaternary model (Pietsch & Jordan 2014). On the basis of this existing model generic transects and the surrounding 500 m-wide corridors within which the seismic acquisition layout had to be arranged were derived. The first-order acquisition layout considered several aspects:

- uncertainties in the available Quaternary depth model
- proximity of borehole information along the corridor
- eventual outcrops of Tertiary sediments/Base Quaternary
- sufficient profile length to reach maximal expected depth of Quaternary sediments via refraction tomography
- feasibility of seismic data acquisition in view of topographic obstacles and along existing roads as long as possible
- feasibility of seismic data acquisition in view of permitting issues (e.g. conservation areas, no-permit tracts, traffic routes, pipes and power lines, etc.)

Each line was then planned on a GIS system using information from the available Base Quaternary model (Pietsch & Jordan 2014) and topographic maps (Fig. 2-1). The design corridors were scanned for acquisition challenges: steep topography, densely populated villages with ancient buildings, and rivers (Fig. 2-2). Once identified, those spots were scouted before the final line layout was fixed and released to permitting and tendering. Fig. 2-1 illustrates how such challenges led to changes between planned and actually realized layout in case of the seismic lines 16-QAU-02, -05 and -06. In a final step the layout was checked against simplified cross sections of the existing geological model. Ray tracing tests (2-layer case) were performed at selected locations where a strong relief of Base Quaternary (e.g. an overdeepened trough) was expected, aiming to understand the illumination of potential narrow features near the syncline-shaped base of Quaternary trough's.

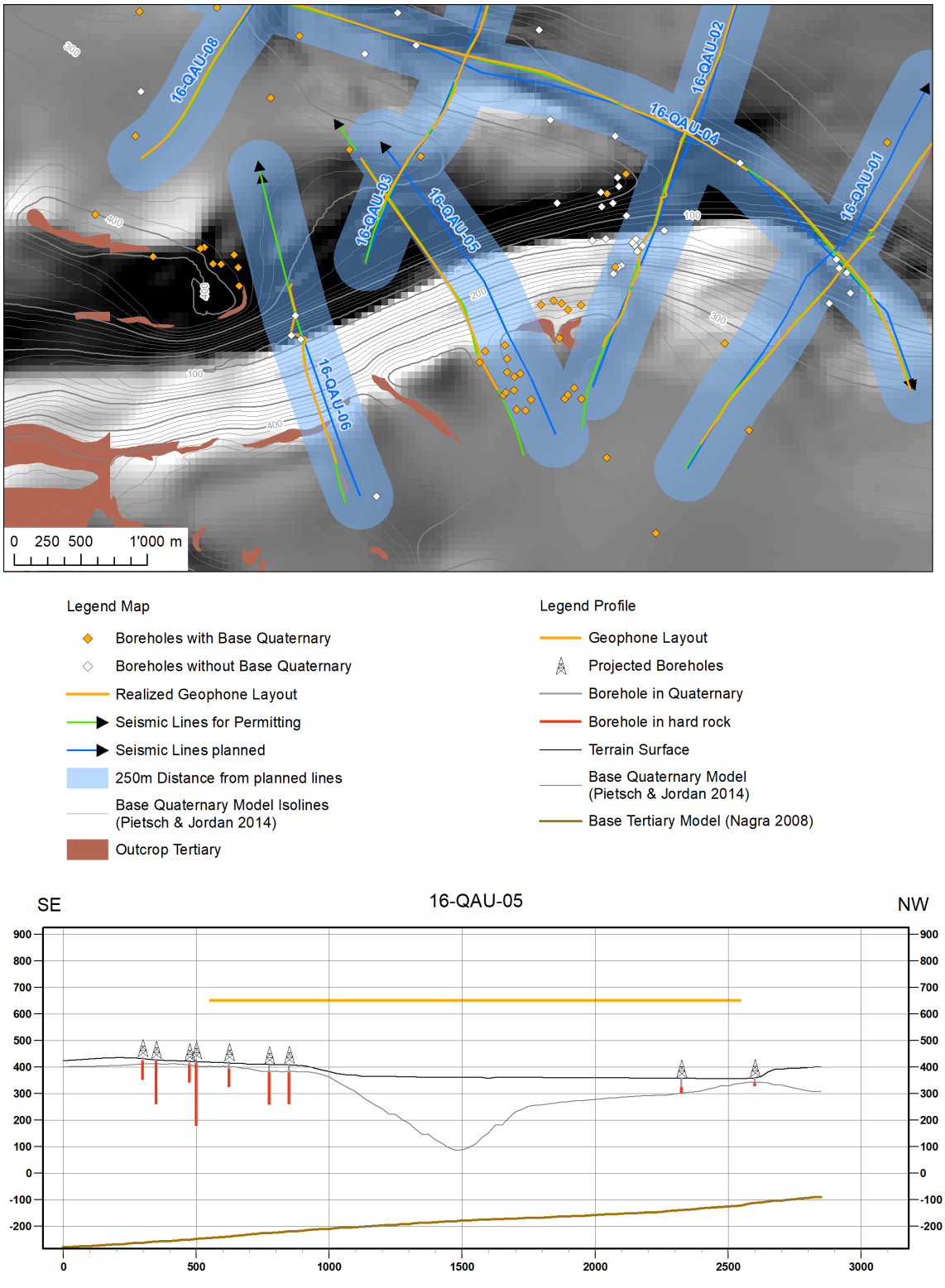


Fig. 2-1: Examplary acquisition layout design for seismic line 16-QAU-05.

Top: Shaded Base Quaternary map with contour lines and planned seismic lines showing layout evolution during planning. Bottom: Simplified cross sections along the foreseen section 16-QAU-05 used for line design and parameter studies. Projected location of nearby boreholes are included.

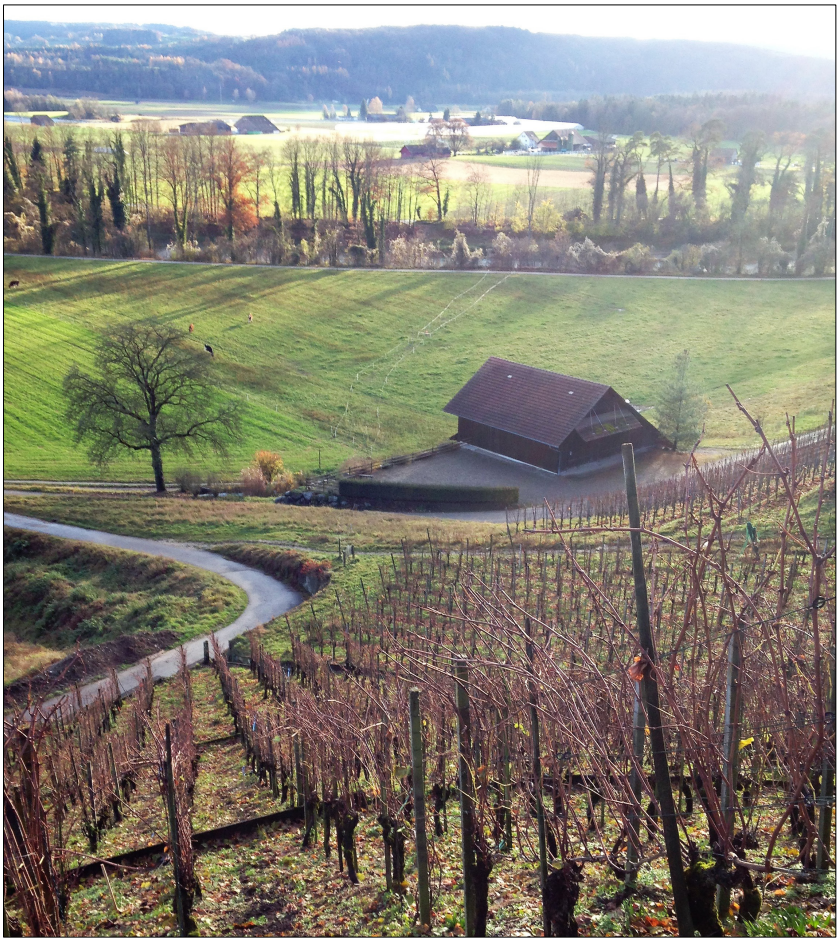


Fig. 2-2: View over Thur valley along line 16-QAU-05.

Rugged topography and the River Thur in the foreground represent acquisition challenges. Hilly forest in the background marks the southern flank of the overdeepened Andelfingen trough roughly following the geographic valley (see Fig. 2-1). Photo T. Spillmann, Nagra.

2.2 Field acquisition parameters

Field parameters were defined to reach the following goals:

- image the Base Quaternary ranging from 20 – ~ 300 m depth below surface (Fig. 1-1)
- image lithological boundaries within the Quaternary trough's infill
- provide sufficient source energy to undershoot the Base Quaternary at ~ 300 m depth

To facilitate a structured approach and tendering procedure the investigation targets were classified in two groups:

- shallow investigations for imaging targets at depth less than 200 m with nominal receiver spacings of 2.0, 2.5 or 3.0 m
- deep investigations for imaging targets at depths up to 400 m with nominal receiver spacing of 5.0 m

Acquisition parameters were adapted to the expected target depths to minimise spatial aliasing and obtain high-resolution images. For efficient field production the shot spacing was two times the receiver spacing. Nominal acquisition parameters are summarised in Tab. 2-1.

The profiles were typically acquired in split-spread mode with minimum 400 active channels, yielding a nominal fold of ~ 100. Recording such high-fold data is beneficial for obtaining high S/N ratios, particularly in densely populated areas and over attenuating underground such as gravel.

Inline offset sources were planned to ensure undershooting of the presumably deepest part of Andelfingen trough. Accordingly, inline offset source points were added in particular along the profiles 16-QAU-01, -02 and -03, -05 and -06.

During acquisition, a vibroseis source was used as much as possible since it provided highest quality data in terms of bandwith and repeatability of the source signal and also allowed for an efficient acquisition progress. On the other hand, the vibration truck was limited to operate along roads and constricted over fields and in forests. Here, buried explosive sources gave a good compromise between efficiency and signal bandwith.

Tab. 2-1: Field parameter for shallow investigations.

Parameter	**Shallow investigation**	**Deep investigation**
Nominal receiver spacing	2.0, 2.5 and 3.0 m	5.0 m
Receiver type	Sercel JF-20DX 10 Hz vertical geophone	Sercel JF-20DX 10 Hz vertical geophone
Number of active channels	> 400	≥ 400
Nominal source spacing	2 × receiver spacing	10.0 m
Max. source point lateral offset	4 × receiver interval	20.0 m
Source types	Vibroseis: 10 – 200 Hz linear sweep, 12 s, 2 vertical stacks Explosives: 60 – 110 g in 1.5 – 2.0 m deep shotholes Shotgun (fill in) Sledge hammer (add-on)	Vibroseis: 8 – 160 Hz linear sweep, 12 s, 2 vertical stacks Explosives: 60 – 220 g in 1.5 – 2.0 m shotholes
Nominal fold	100	100
Sampling interval	0.5 ms/1.0 ms (16-QAU-08)	1.0 ms
Record length	1'024 ms/'2560 ms (16-QAU-08) 100 ms pre-trigger time	2'560 ms 100 ms pre-trigger time
Field filters	0.8 Nyquist frequency	0.8 Nyquist frequency

3 Field operations and data acquisition

Seismic field work in densely populated und cultivated areas sets high demands in terms of technical requirements, public outreach and safe execution. Once the survey was designed, field operations followed the typical procedures for seismic acquisition:

1. permitting
2. geodetic survey and stake-out of source and receiver points in the field
3. drilling of shotholes
4. data acquisition and quality control
5. pick-up and cleaning

Based on the survey design described above, the field work for seismic data acquisition was commissioned after public tendering. The survey started on 14th November 2016 and ended 24th February 2017 with the pick-up of the equipment[1].

3.1 Permitting

Obtaining permission to access open and private ground is a critical step before the actual data acquisition can start. Being planned and documented in a GIS system, a small team permitted the lines well ahead of the acquisition. With exception of a few spots, the line layout could be implemented as planned beforehand. The only substantial gap of about 160 m with significantly reduced coverage occurred along line 16-QAU-04.

3.2 Topographical survey

The surveying crew was responsible for transferring the planned line layout into the field and obtain coordinates for each recording and source point with accuracy better than 30 cm. In addition, the surveyors checked source point positions for distances against water wells and sources, historical buildings, beehives, power lines and underground structures. A small fraction of receiver and source points had to be skipped due to those obstacles.

The total length of the 16 receiver lines was 41'692 m, and the length of source lines including inline offset sources added up to 43'717 m. Fig. 3-1 shows the density of survey marks for a typical line of the shallow type.

3.3 Drilling

In the course of the entire QAU seismic campaign, two drilling crews deepened a total of 1'933 shot holes, more than 50 % with a depth of 1.6 m or more. Typically, petrol driven portable drilling engines Cobra 148 from Atlas Copco were used. A Ground Hog drilling rig was selectively used where Cobra engines failed to reach the required shothole depth.

[1] Effectively, this duration includes acquisition of all 23 lines carried out within the QAU project.

3.4 Execution of field data acquisition

A single vibrator truck (INOVA UniVib with peak force of 115 kN) was used at 3’190 source points. At each point, two sweeps were executed (in-field correlation after vertical stack), with 70 %, 50 % or 30 % of peak force, depending on sensitivity of surrounding buildings. The sweep parameters depended on target depth (Tab. 2-1). Explosives were fired in 1'905 shotholes (Fig. 3-1). The seismic shot gun (12-gauge cartridge) was used at totally 139 locations, specifically as infill source in urban areas and in a restricted area around the water well "Schmugglerweg" (Rheinau, line 16-QAU-09). On line 16-QAU-11 a very shallow reflector was identified during the initial acquisition. Consequently, the line was partly repeated with a 6 kg sledge hammer source to investigate the possible benefit of a weaker but higher frequency source.



Fig. 3-1: Field setup at line 16-QAU-10.

Wooden pegs mark explosive source (red mark, gray dummy tube in hole) and receiver positions. Two geophones are connected to the yellow dual-channel seismographs. Photo: DMT.

3.5 Quality control

An extended quality assurance/control program was established and maintained throughout the survey to ensure steady performance. QA/QC included:

- inventory and control measurements of groundwater sources and wells within 250 m from the seismic lines
- inspection and acceptance test of all equipment at the beginning of the survey
- hardwire similarity test each time the vibroseis sweep was changed
- daily radio similarity test
- geophone and instrument noise tests
- field QC and client representative checked the geometry and seismic data at the end of each acquisition day

After the acquisition of seismic data of a complete line, an elementary reflection processing scheme was executed to obtain field brute stacks and velocity tomograms.

4 Seismic data processing

Objectives, requirement and tools

The processing was commissioned to GT and executed between March and September 2017 using the SeisSpace 5000.8.5 software and selected proprietary tools. The processing mission was to apply a basic and robust seismic data processing to the entire QAU seismic dataset. Essentially one processing flow was developed and - after exemplary parameter tests using line 16-QAU-05 – applied to the entire dataset. Velocity-related parameters were analysed line by line to respect variations of the local geology. Processing requirements were minimal static corrections, deconvolution, basic denoise filtering, amplitude scaling, NMO/CMP stacking and post-stack time migration.

Fig. 4-1 displays the processing scheme applied in combination with some of the most relevant parameters. Fig. 4-2 demonstrates the improvements and increasing significance of the data at important processing stages. Processing effects in the shot domain (left column in Fig. 4-2) illustrate how distinct portions of the recorded wavefield gain significance, and noise is attenuated. Raw stacks such as in the right column of Fig. 4-2 still show a rough, distorted image of the underground.

Static corrections were designed to enhance imaging of the Quaternary deposits. Consequently, refraction static corrections were restricted to a thin layer of dry sediments (weathering layer). The resulting stack enhances the imaging of structures in the Quaternary valleys and troughs (Fig. 4-3 shows exemplary profile 16-QAU-05), but deeper reflections (e.g. Base Tertiary at about 0.55 s in Fig. 4-3) show a push-down below these features. Diffractions are recognised at the edge and base of the Quaternary troughs.

The final step in the processing flow, migration, corrects specific geometrical distortions of the seismic images and collapses diffractions. Time migrated sections such as the example displayed in Fig. 4-3 were produced and delivered to the interpretation team for interpretation.

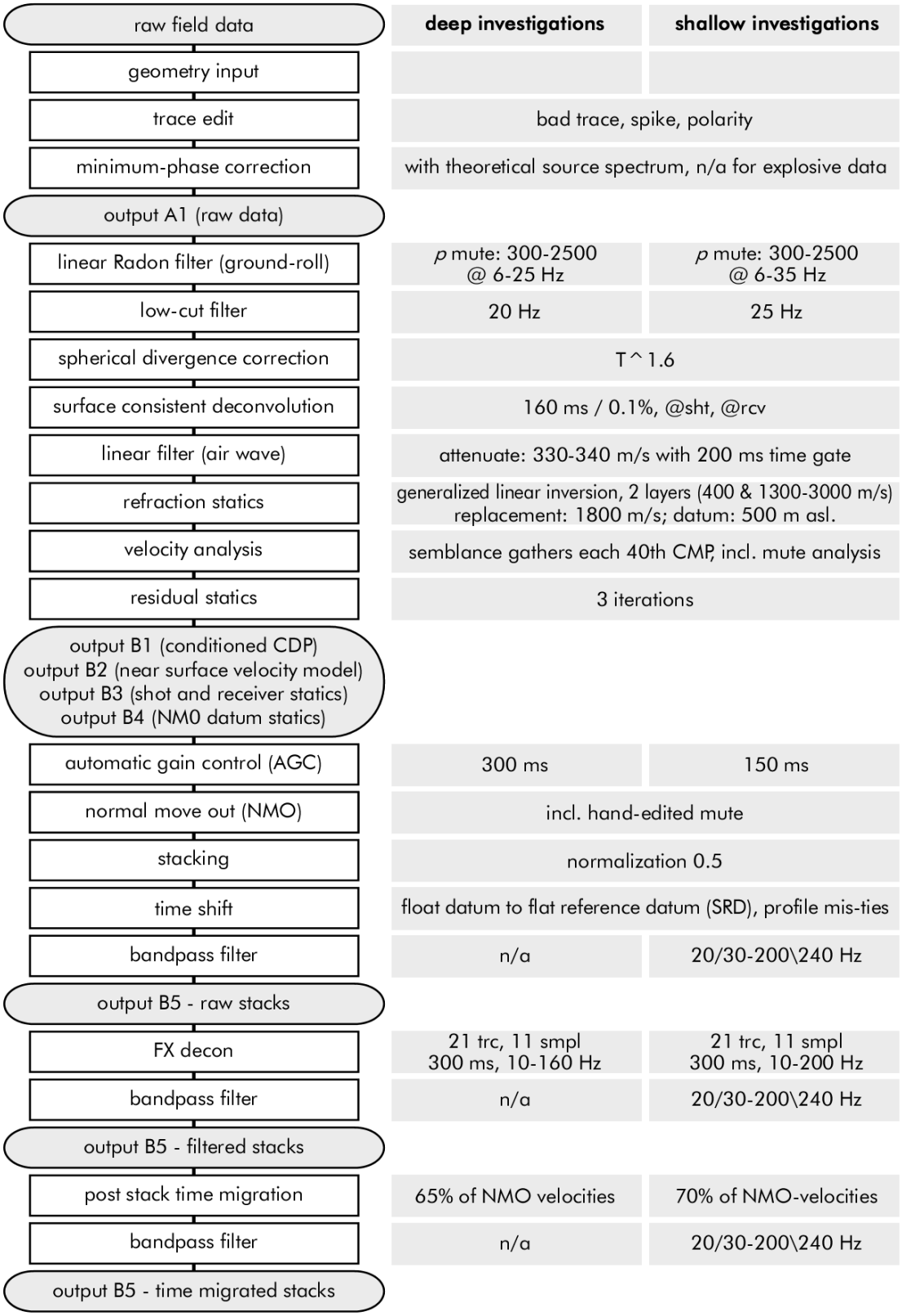


Fig. 4-1: Processing sequence for vibroseis and explosive data.

Most important parameters of each step are given in the columns to the right. Delivered products (output) are highlighted.

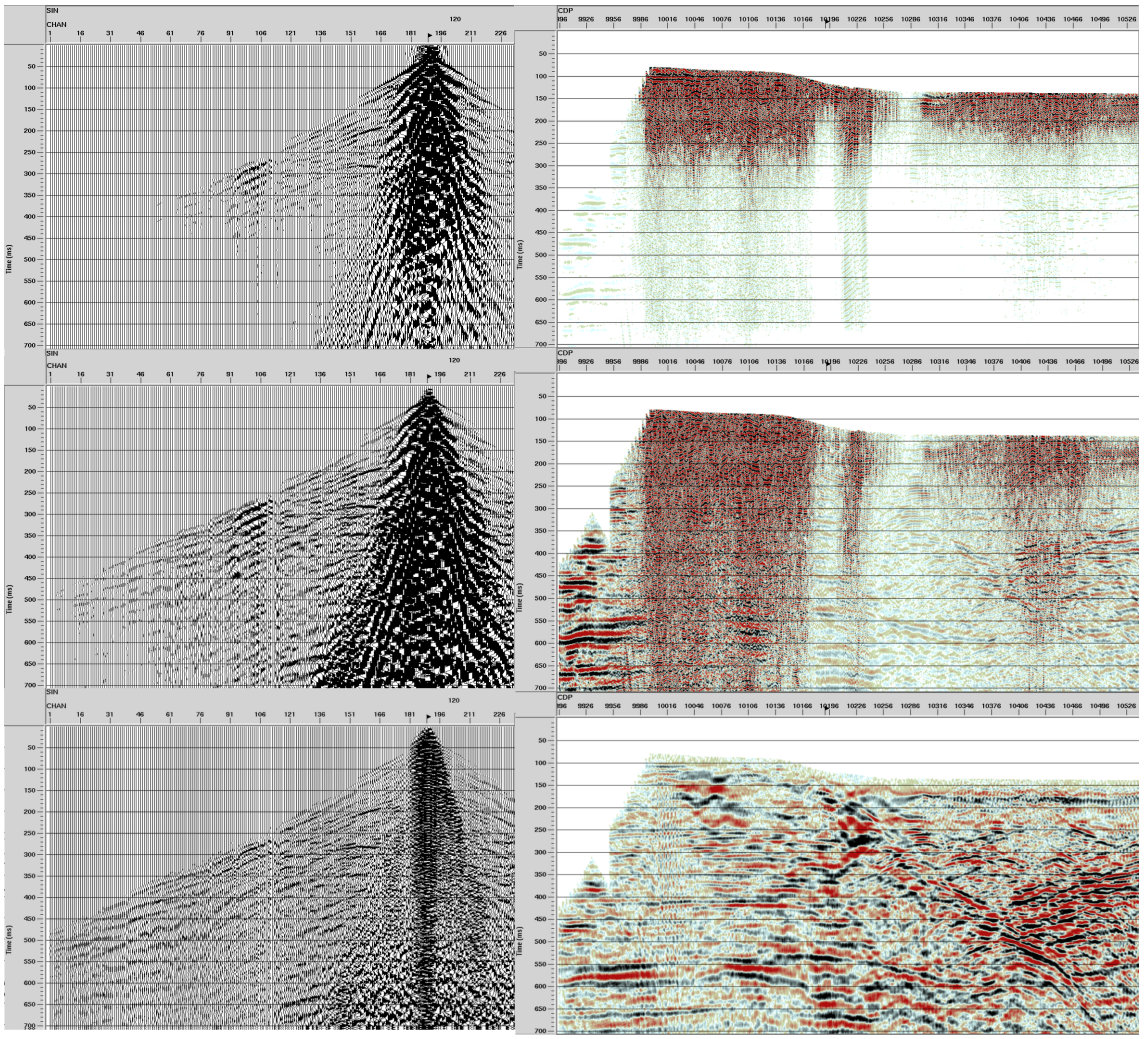


Fig. 4-2: Select processing products in shot domain (left column) and stack (right column).

From top to bottom row:

1. raw field record (output A1)
2. after spherical spreading
3. after ground-roll and linear noise (air-wave) removal

5 Seismic interpretation data base & workflow

The interpretation of the processed seismic section was commissioned to GPCI in July 2017. The objectives of the interpretation were to:

- determine the base of the overdeepened Quaternary valleys along the seismic sections
- characterise the internal architecture of the Quaternary infill of the valleys along these sections
- provide a preliminary depth conversion of the seismic sections including the interpretation of the Base Quaternary in the depth domain
- map and grid the Base Quaternary in the depth domain across the two investigation areas using the seismic interpretation and well data

In the following, the database available for interpretation and the chosen interpretation workflow are outlined.

5.1 Database

A set of geological and geophysical data was available for the interpretation composed of geological surface/topographic maps, geological sections, pre-existing digital elevation models (DEMs) of the Base Quaternary and Base Tertiary (compare Nagra 2014, Pietsch & Jordan 2014) as well as seismic and borehole data outlined in more detail below.

5.1.1 Seismic data

The following 2D-seismic profiles were made available:

- 16 high resolution seismic profiles containing:
  - 11 lines within and to south of the ZNO siting region named 16-QAU-01 to 16-QAU-11.
  - 5 lines in the southeasternmost part of the NL siting region named 16-QAU-14 to 16-QAU-18

For these 16 profiles, stacked and time migrated PostSTM versions were provided together with the related processing velocities:

In addition, regional seismic profiles were provided as reference. These lines were acquired in the 80s and 90s and were recently reprocessed (Rybarczyk 2012).

5.1.2 Well data

Well data used for this project were provided by Nagra at several opportunities and in different formats which considerably helped the seismic interpretation. For the maps presented in this report, the most recent and complete well data delivery (a total of 996 wells for ZNO and 169 wells for NL) was the key source of information. All wells used for this project are listed in the Encl. 42 and 43.

5.2 Workflow

The workflow applied for the interpretation is illustrated in Fig. 5-1. To optimise data utilisation, an iterative interpretation-processing approach was chosen. Before starting seismic interpretation, all sections needed to be individually conditioned. This so-called data preparation is described in detail in Chapter 6.

During the data preparation, particular emphasis was given to artificial push-down effects caused by low seismic velocities in the overdeepened Quaternary valleys. Seismic velocities provided by uphole measurements inside the valleys can be 200 m/s to 2'000 m/s lower compared to the surrounding Tertiary sediments (Nagra 2012, 2017). Such substantial contrast ranges, which vary vertically and laterally, can generate significant time delays on the images of deeper horizons, i.e. Base Tertiary. These time delays, also called push-down effects, have been corrected by applying appropriate velocity models and thus converting seismic sections into the depth domain applying Poststack Depth Migration (PostSDM). The PostSDM algorithm respects low velocities in the Quaternary, thus compensating for the time delay. This results in pre-Quaternary reflections to flatten underneath the Quaternary valleys and hence reveal a generally more plausible geological character.

For signal processing and algorithms, Matlab software was used; for interpretation and QC, IHS/Kingdom was applied. Finally, gridding and mapping was done in Petrosys.

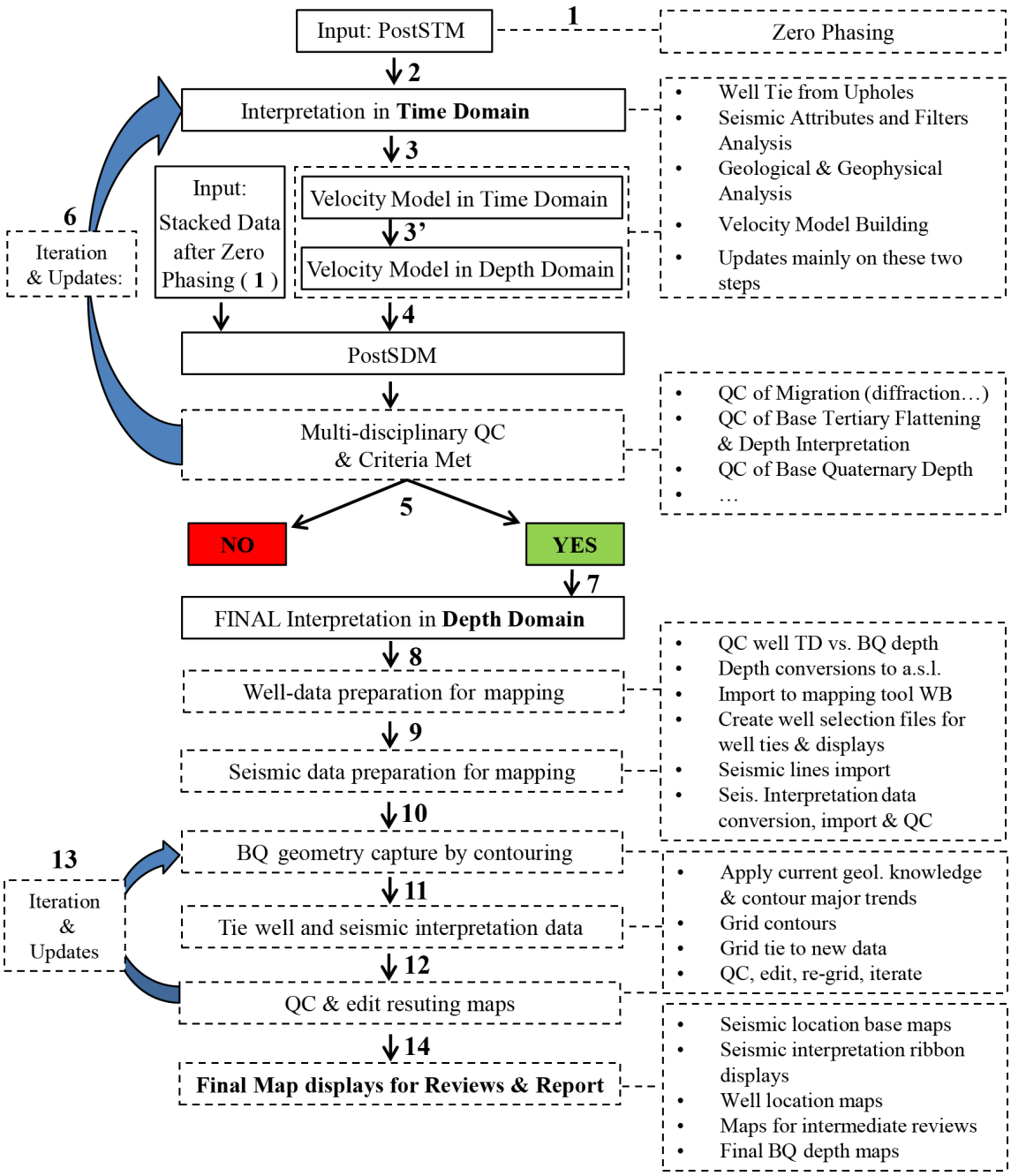


Fig. 5-1: Iterative interpretation-processing workflow.

This interactive workflow took up to 8 iterations of interpretation and velocity model building per seismic line. Interpreted data were then gridded, mapped, well-tied and hand-edited.

6 Preparation of data for interpretation

The data conditioning workflow applied by GPCI after processing consisted of zero-phasing, velocity model building, PostSDM, and QC. A crucial requirement for running PostSDM is the development of an interval (instantaneous) velocity model in depth. These velocity models were build individually for each seismic profile using available uphole and processing velocities together with time interpretation data. All preconditioning workflow steps are described in detail in the following sections.

6.1 Zero-phasing

The seismic sections initially provided by the processing centre were mixed phase. For geological interpretation, seismic data in zero-phase data is preferable. In case of non-zero-phase data the wavelets corresponding to seismic interfaces (horizons) are not symmetrical, and the strongest amplitudes are mispositioned in time against the actual reflectors. To fix the phase issue, a zero-phase operator was applied. The operator was chosen based on recommendation from the Nagra's external processing supervisor. After some tests and visualisation QC, we found that inverting the Vibroseis zero-to-min-phase operator (8 – 160 Hz) yielded good results. Albeit the data were acquired using different seismic sources with different frequencies (explosive and Vibroseis with 8 – 160 or 10 – 200 Hz sweeps), the use of the unique operator turned out to significantly improve the image in the zones of interest. For consistency, all provided data (stacked and time-migrated versions) were processed using this single minimum-to-zero phase operator. The phase of the obtained stacks is deemed zero (with symmetrical wavelets centred at seismic interfaces). The polarity is defined such that a positive reflection coefficient (transition from soft to hard sediments with increasing depth) is represented by a positive amplitude and a black peak on seismic displays.

6.2 Velocity Model Building (VMB)

VMB was carried out as an iterative interpretation-based process individually for each seismic line. Care was taken to develop geologically meaningful models taking into account the general geological characteristics of the subsurface. Accordingly, the final velocity models used for depth conversion consist of layers corresponding to the main geological units in the area (Quaternary, Molasse/Tertiary, Mesozoic) with variable velocities inside each layer.

The VMB process consisted of three main steps, namely

1. gathering uphole survey data to account for the near-surface velocity anomalies
2. interpreting the Quaternary and Tertiary reflections in time domain
3. estimating interval velocities in the corresponding depth intervals

At first, velocities from the uphole surveys (well specific time-depth curves extracted from shallow seismic measurements in wells) were loaded and extrapolated to all available wells. This allowed to tie all seismic lines to the well markers and to interpret the Base Quaternary and the Base Tertiary horizons consistently on all lines. The resulting interpreted horizons match the well data as well as crossing seismic lines. Subsequently, the Base Quaternary and Base Tertiary horizons previously interpreted in the time domain were used to quantify and estimate seismic velocities within the Quaternary section.

The next step in the VMB process entailed combining all available velocity data to fill the structural model with the corresponding interval velocities. The uphole data (Fig. 6-1) locally provide a good understanding of velocities within the Quaternary. In selected boreholes, it was even possible to relate lithofacies units to internal Quaternary intervals (Fig. 6-1C). Seismic processing velocities (Fig. 6-2) yielded an additional estimation for the velocity trends inside the Quaternary but also for velocities in the Tertiary.

In the last step, all available information was combined to establish interval velocities in depth using a standard algorithm (vertical stretch), see comparison in Fig. 6-2 and Fig. 6-3. As a result, the velocity values in each interval are the same in time and depth (compare Fig. 6-3 top in time and Fig. 6-3 bottom in depth).

The resulting velocity models for the seismic profiles general feature three major intervals:

- **Quaternary**

  This interval shows constant velocity in the first 200 ms below the topographic surface with a linear velocity gradient down to 100 ms above the Base Quaternary horizon in time. Velocities at the top start with 1'500 m/s and reach values of ~ 2'000 – 2'400 m/s at the bottom. The deepest 100 ms thick parts of the Quaternary channels were filled with constant values of 2'100 – 2'450 m/s, depending on the line.

- **Tertiary**

  Velocities applied for the Tertiary interval in time domain originated at the Base Tertiary (equivalent to Top Malm) with the constant values of 3'000 m/s, and were extrapolated upwards, reaching ~ 2'600 m/s at the Top Tertiary (Base Quaternary).

- **Mesozoic**

  Below Base Tertiary, a constant velocity of 5'000 m/s was used, which represents the best estimated average value, obtained from processing velocities. A higher precision is not required, since this interval is beyond the interests of the current study.

During the VMB process the velocity values for the above-mentioned major intervals were slightly adjusted on each individual line to respect the specific geological setting. Between 3 and 8 VMB iterations were necessary in order to obtain an optimised velocity model for each seismic profile.

Seismic velocities in Quaternary and Tertiary sediments can be significantly different. Fig. 6-1B shows velocities for well "2" starting from 500 at the surface to 2'500 m/s at 250 m MD, with the mean at ~ 2'000 m/s. Velocities in the Tertiary sediments extracted from processing velocities can be ~ 2'500 m/s, which is also reported for the Benken well (Nagra 2001). These differences in velocity trends between Quaternary valleys and Tertiary sediments generate time delay and artificial push-down below the Quaternary, see Fig. 6-2.

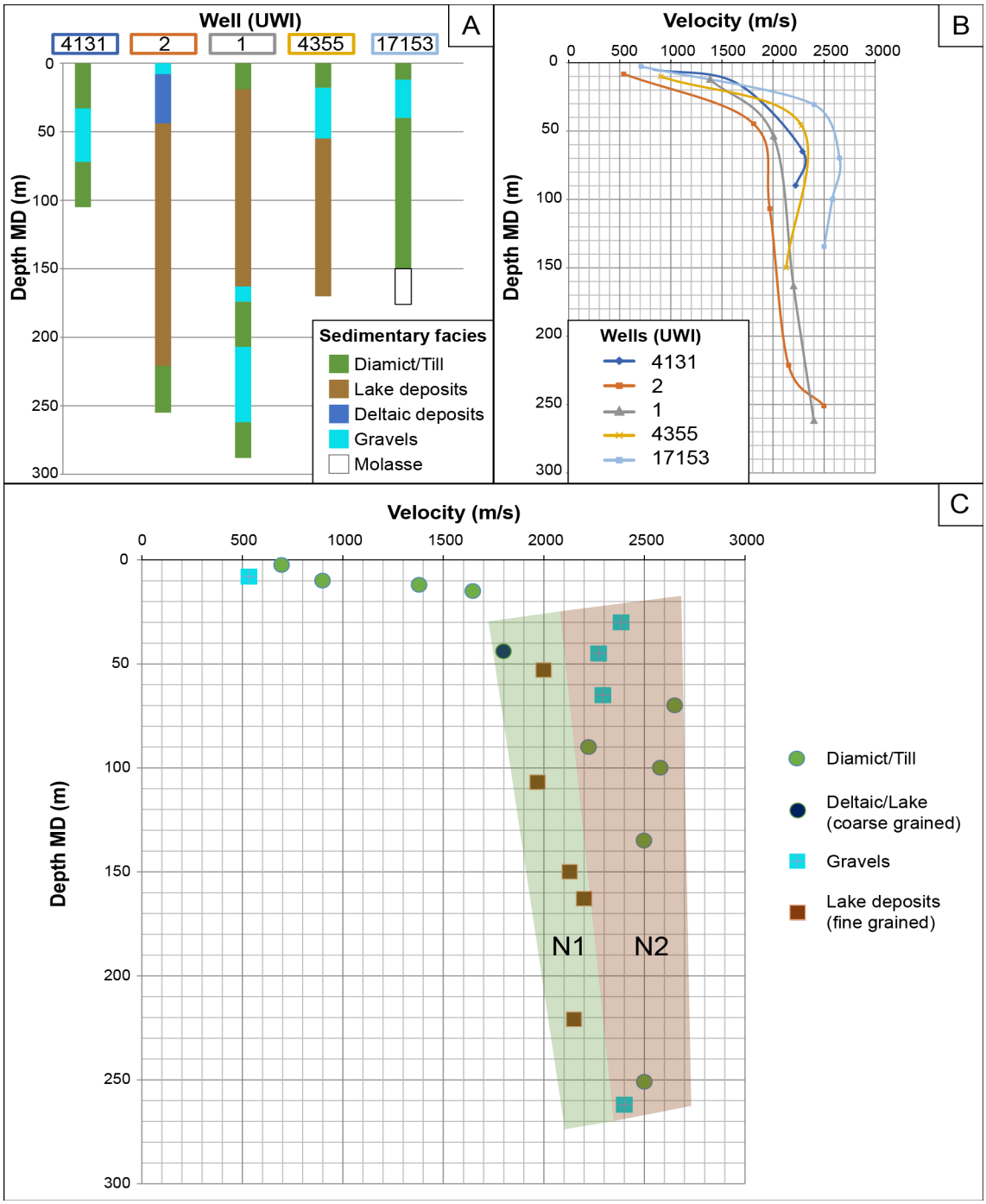


Fig. 6-1: Velocity information from a selection of upholes.

A: Plot of different lithological facies as recorded in the Nagra borehole database (numbers on top relate to borehole UWI) against depth.

B: Plot of Velocity vs Depth curves for the selected upholes. Interval velocities points are plotted in the middle of the calculated intervals and interpolated in-between.

C: Combination of A and B: Plot of Velocity vs Depth points of the selected upholes for each lithofacies. The coloured areas highlight the correlation between lithofacies and velocity. The green area (N1) shows the velocity range for finer grained sediments like lake deposits. The brown (N2) area corresponds to the observed velocity range for coarser grained sediments, like gravels and diamict/till deposits.

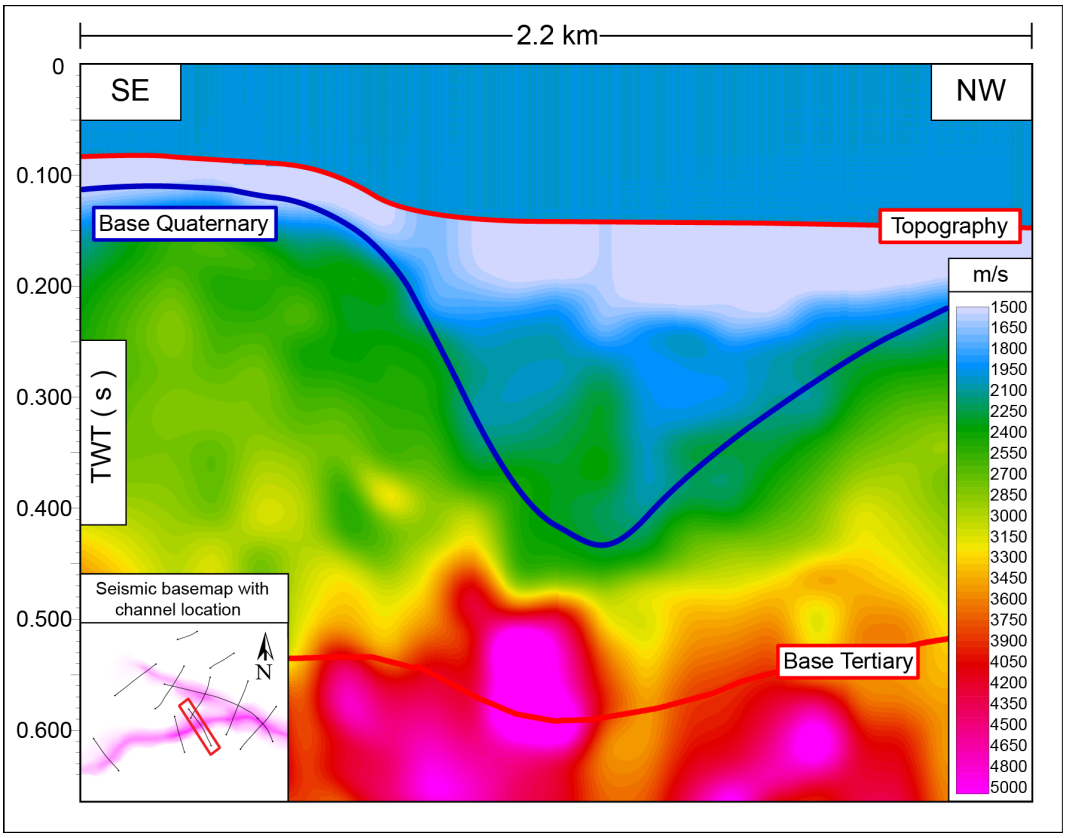


Fig. 6-2: Interval velocities as extracted from the PostSTM processing velocities for line 16-QAU-05.

Processing (RMS) velocities were converted into interval velocities in time and were used as initial model in the VMB process. This model can also serve as guide for the interpretation of the Base Quaternary, as this horizon roughly corresponds to the ~ 2'100 m/s isoline (e.g. the transition from the blue to the green areas). Notably, at the velocity of Quaternary sediments at the base of overdeepened valleys, can be significantly higher – on the current section they reach ~ 2'700 m/s.

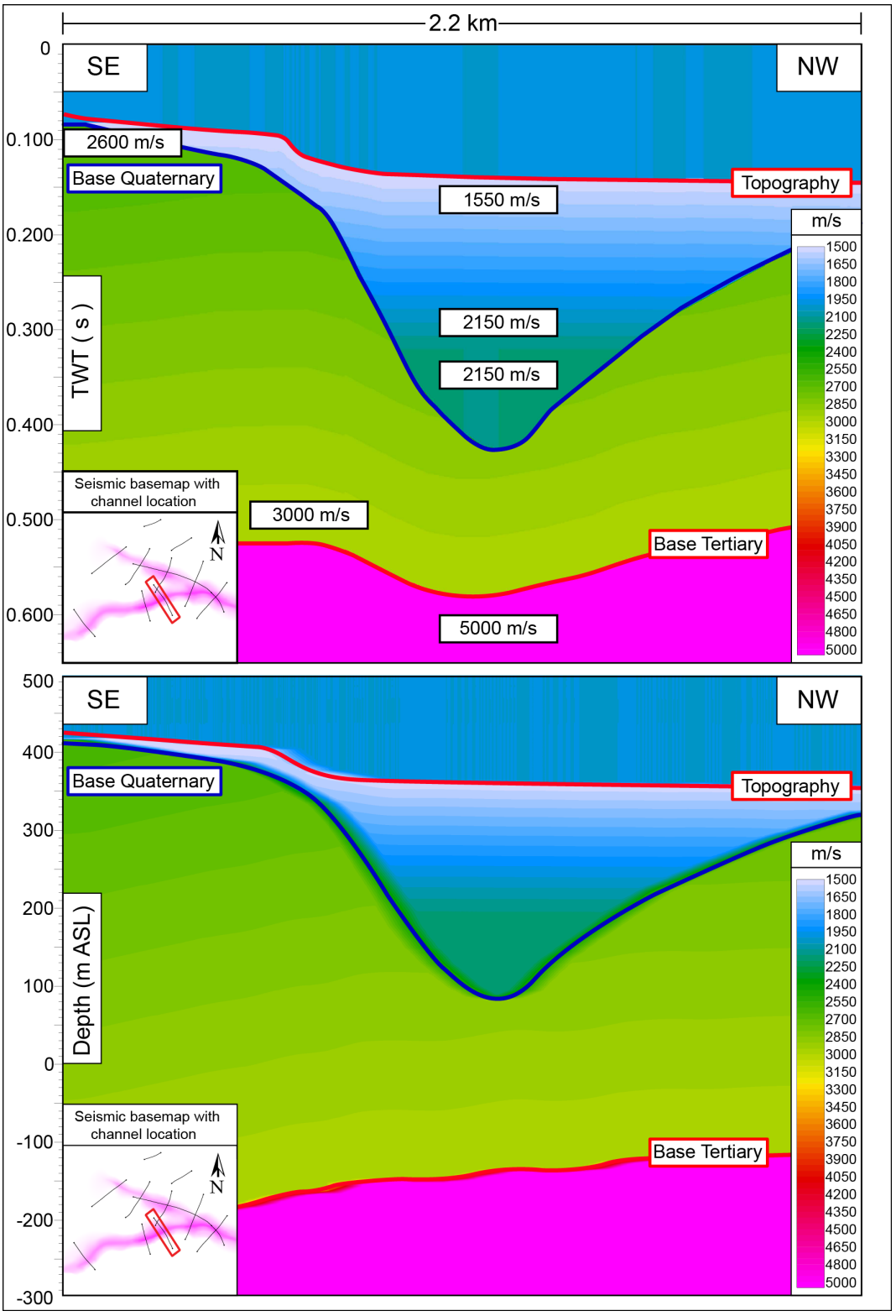


Fig. 6-3: Final interval velocity model in time (top) and in depth (bottom) for line 16-QAU-05.

The push-down effect observed along the Base Tertiary horizon below the Quaternary valley in time domain is clearly removed in depth domain.

6.3 Depth conversion (PostSDM)

Using the generated velocity models, the 17 seismic lines were converted into the depth domain referenced at 500 m ASL. Depth conversion was done using the PostSDM algorithm that corrects for vertical and lateral mis-positioning of the time migrated sections (see comparison in Fig. 6-5).

The PostSDM processing was performed on (non-migrated) stacks in the time domain using the Fourier finite difference zero-offset algorithm. This migration method is a hybrid approach that provides high quality results even when non-ideal velocity models are applied.

The results of PostSDM were carefully verified using three geoscientific criteria (Section 6.4). To meet these criteria, the velocity models were iteratively updated either by adjusting the interpretation of Base Quaternary and Base Tertiary in time domain or by changing the velocities in the respective depth intervals. Finally, the models have been fine-tuned to respect the geology and well data on each individual line.

Interpreted horizons originally picked in time domain were converted to depth using the final velocity model for PostSDM. Re-picking of the depth converted horizons was carried out locally to ensure consistency with the migrated seismic image in depth domain.

6.4 Quality control and estimation of uncertainties

The QC of the PostSDM results consisted in verifying both geological and geophysical criteria, respectively. Three key geoscientific criteria were considered to verify the choice of velocities used for depth migration and assures reliable interpretation results:

1. Attenuation of the diffraction hyperbolas as a good indicator for correctly chosen interval velocities.
2. Elimination of obivous push-down effects along the Base Tertiary horizon below Quaternary overdeepenings.
3. Tie of interpreted seismic horizons with correlated well markers on all depth migrated sections.

Additional criteria to verify the results of PostSDM relate to the depth migrated Base Quaternary that shall depict a coherent and plausible erosional surface. Reflections within the Tertiary interval shall be relatively continuous with a smooth and constant dip, i.e. having monoclinal shape. Where Tertiary reflections are cut by Quaternary channels, their correlation across the erosional feature from one flank to the other should still be possible after PostSDM. The interpreted Base Tertiary horizon in depth domain was cross-checked against pre-existing models for the siting region (Nagra 2014). Mismatches larger than 50 m were not accepted.

Finally, new uphole information became available for the NL area during the winter season 2017/18. This information confirmed to a large extend the validity of the velocity and depth models derived during this project (Fig. 6-6). From the four wells which were drilled after the interpretation results were available, three have encountered the Base Quaternary within ± 5 m accuracy. The fourth well encountered this surface some 20 m shallower as predicted. Nevertheless, even for this well only a minor adjustment to the velocity field and the interpretation was necessary for a plausible incorporation of these data. Notably, following this consistent check, all of the new well information was incorporated in the interpretations shown here.

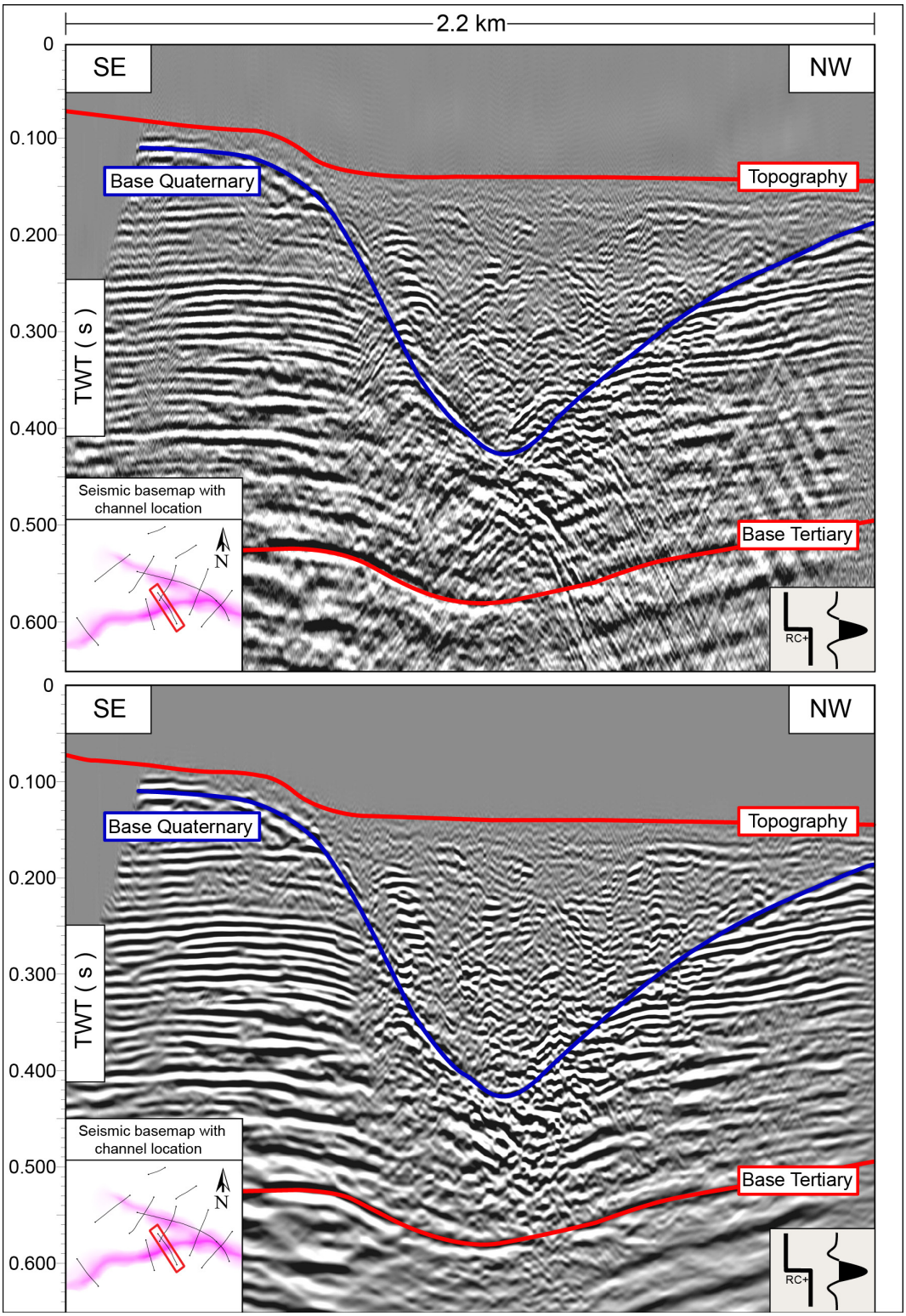


Fig. 6-4: Non-migrated, stacked version (top) and PostSTM version (bottom), both in time domain for line 16-QAU-05.

Note diffraction hyperbolas in the top section, which were attenuated (focused) after PostSTM.

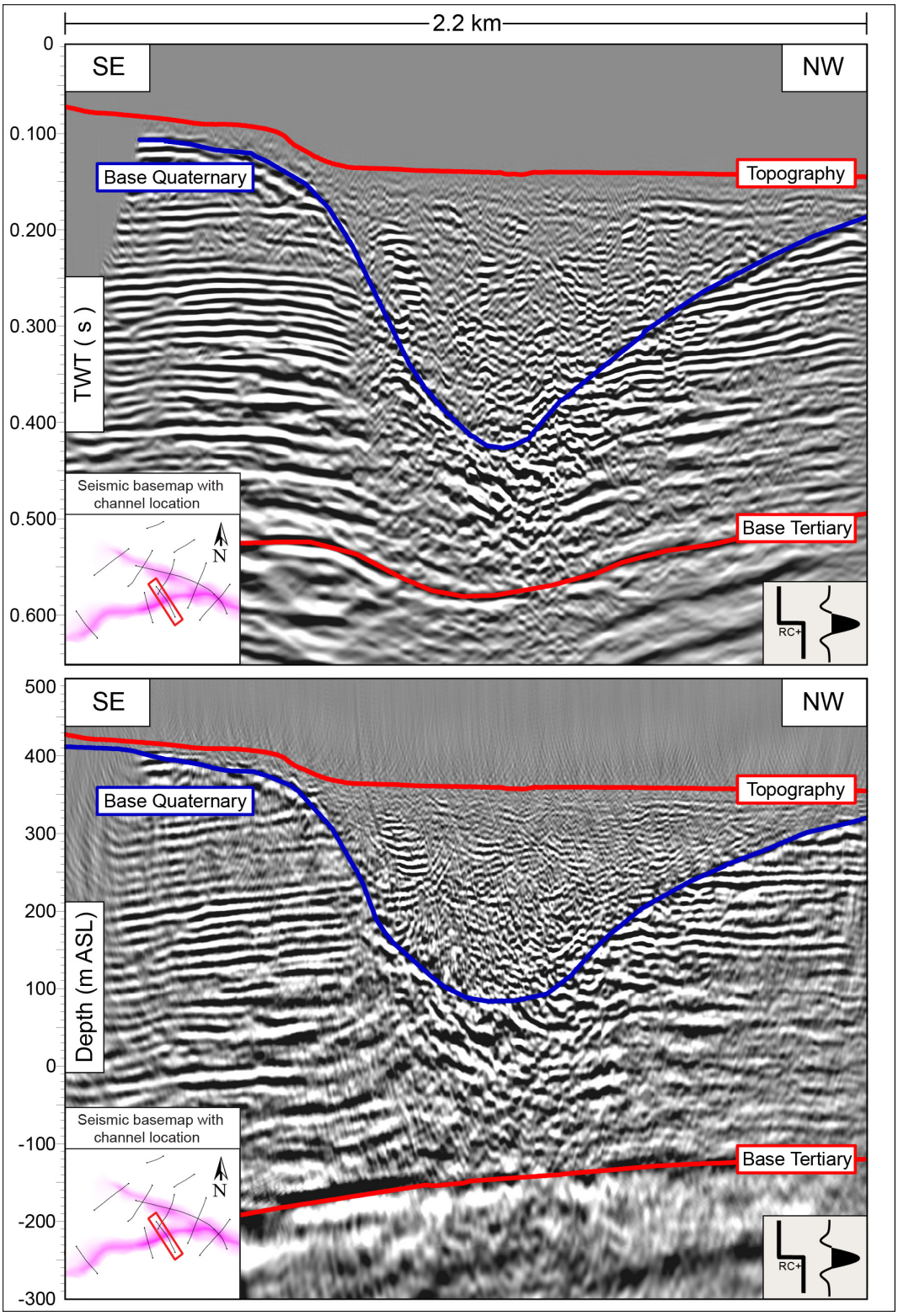


Fig. 6-5: PostSTM version in time domain (top) and PostSDM version in depth domain (bottom) for line 16-QAU-05.

The artificial push-down effect (lowering of the geology below the Quaternary valley) in time domain is clearly removed in depth domain. The Base Tertiary is flattened in depth and better represents the expected geology.

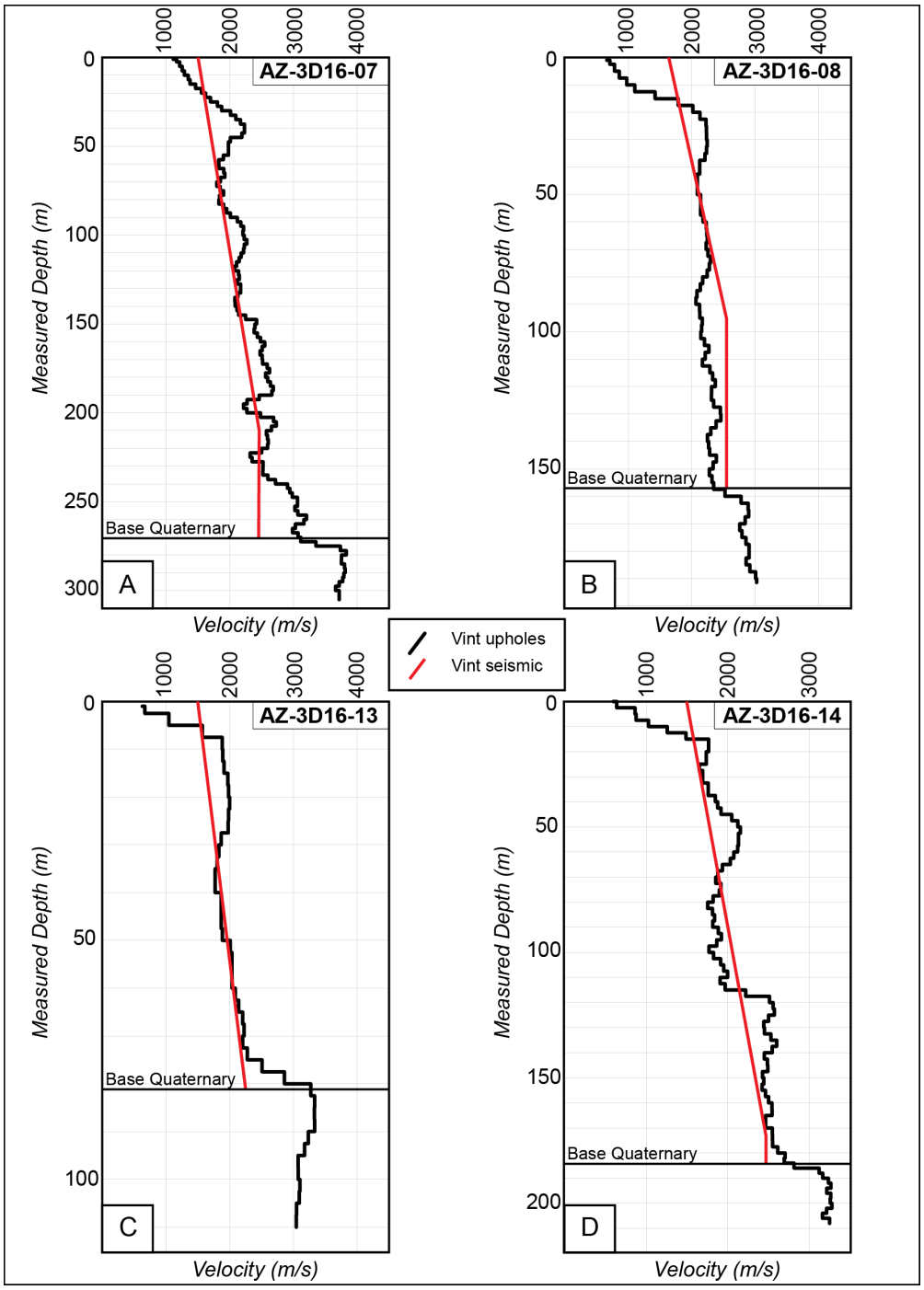


Fig. 6-6: Comparison between interval velocities derived from seismic line processing/ velocity model building (red curves) and upholes measurements carried out later (black curves).

A: Uphole AZ-3D16-07/ Seismic line 16-QAU-15, CDP 10700.
B: Uphole AZ-3D16-08/ Seismic line 16-QAU-16, CDP 10560.
C: Uphole AZ-3D16-13/ Seismic line 16-QAU-18, CDP 10540.
D: Uphole AZ-3D16-14/ Seismic line 16-QAU-17, CDP 10757.

Velocity models obtained from seismic data through interpretation guided processing fit quite well the velocity measurements in the upholes only received at a later stage.

7 Seismic interpretation

7.1 Interpretation approach

Seismic interpretation was carried out on IHS/Kingdom software. At first, Base Quaternary and Quaternary infill units were picked on time migrated sections. Subsequently, all horizons were re-picked using the same phase, e.g. peak, trough or zero on the newly produced depth-migrated sections. As expected, this process highlighted significant position differences.

Horizons were selected and traced as follows:

- Base Quaternary – The strongest peak just below the Base Quaternary/Top Tertiary unconformity or along erosional discontinuity of intra-Tertiary reflections
- Base Tertiary – The strongest peak, corresponding to the time converted or depth version of the Nagra structural model (Madritsch et al. 2013 and Meier et al. 2014, respectively)
- Base of intra-Quaternary facies bodies – selected based on well markers, seismic amplitude content and frequency facies; for details see also line by line descriptions in Encl. 4 – 37

7.2 Attributes and visualisation

Various seismic attributes and filters were used for visualisation and as support for interpretation. It is possible to highlight certain geophysical features or geological structures by adjusting parameters that characterise seismic wavelets, their amplitude/phase and frequency characteristics, see some examples in Fig. 7-1. These characteristics can be adjusted by the filters that are applied directly in the interpretation software on seismic displays:

1. AGC (Automatic Gain Control) – trace-by-trace attribute that balances the amplitude to improve visibility of late-arriving events due to amplitude decay within a pre-defined time window. The window should not be too short to preserve relative amplitude information between reflections and was selected as 400 ms, (see Fig. 7-1C).
2. Bandpass Filter – frequency filter with trapezoidal shape in the amplitude-frequency domain acting as both high-cut and low-cut filter. It is useful to adjust the frequency content of the data to remove high- and low-frequency noise. Thereby, it also allows to highlight selected reflections that would otherwise be masked by other reflections originating from overlying layers or from multiple reflections. As an example, Fig. 7-1D shows the effect of the removal of frequencies higher than 90 Hz predominantly constituting the Quaternary valley fill. As a consequence, the Base Quaternary/Top Molasse interface becomes more evident.
3. Colour Palette – different geological features can be highlighted using suitable colour displays. As a rule, multiple-colour bars are better suited to interpret different facies and to follow certain intervals, whereas the greyscale images are better for picking structures and unconformities, e.g. Base Quaternary. A comparison of the same section displayed with a triple-colour gradient palette (black-white-red) and with a grayscale palette is shown in Fig. 7-1D and Fig. 7-1E, respectively.
4. Pseudo-Relief – a special attribute that is calculated using an RMS amplitude formula in a vertical window followed by the inverse Hilbert transform, see Fig. 7-1F. It allows elevating high amplitudes which results in a pseudo-3D image emphasising sedimentary layering.

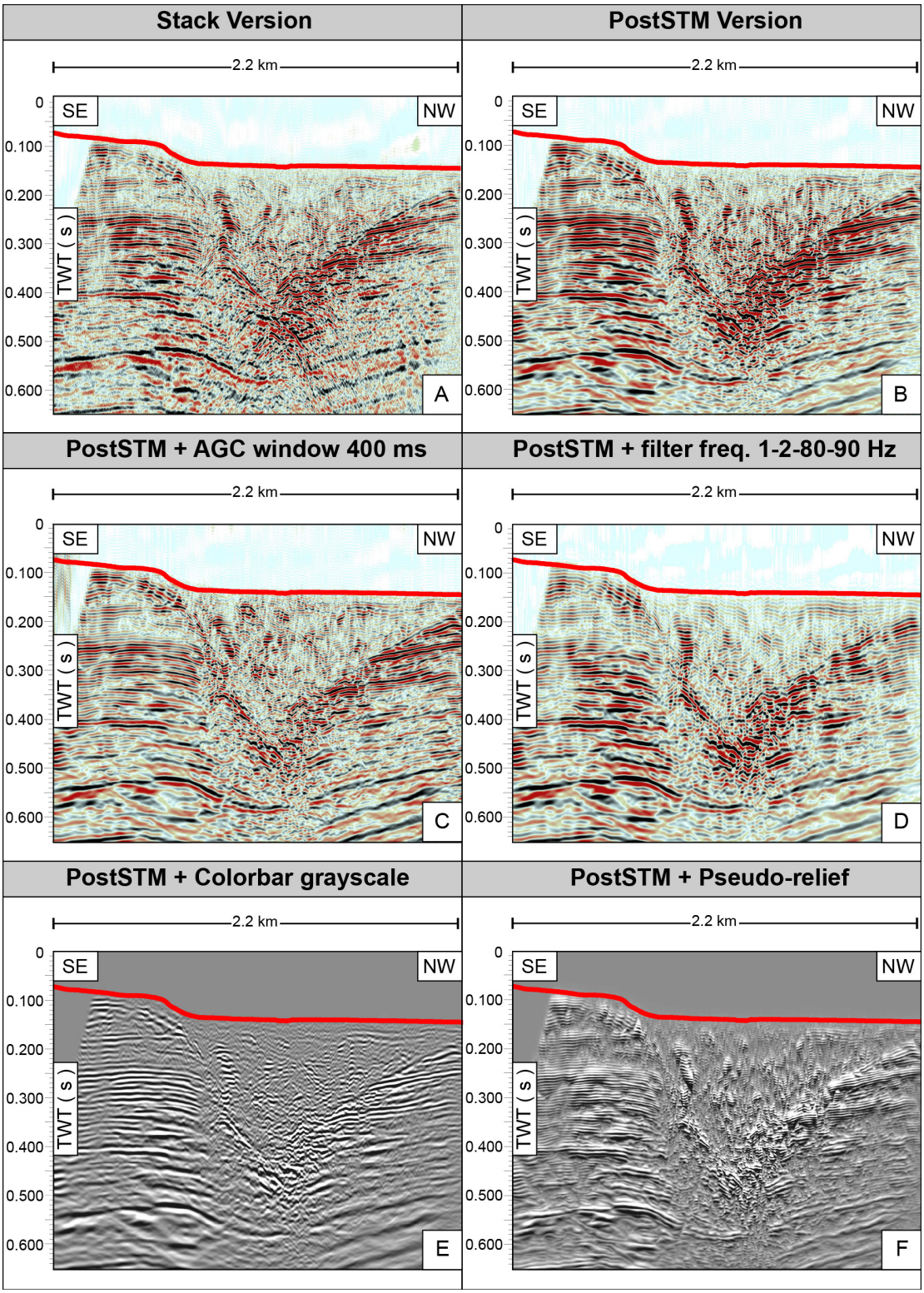


Fig. 7-1: Examples of attributes and filters used during the time and depth interpretation for line 16-QAU-05.

A: Unmigrated stacked data. B: PostSTM data. C: PostSTM with AGC window 400 ms. D: PostSTM with bandpass frequency filter 1-2-80-90 Hz. E: Same as D, in greyscale colour. F: Same as E with pseudo-relief display.

During interpretation in time and depth domains the mentioned attributes and visualisations were intensely applied. Repeated switching between different display modes and data sets allowed for a comprehensive interpretation and helped considerably to reduce picking uncertainties. Display parameters have been selected on a line by line basis due to variable quality and signal-to-noise ratio levels on individual lines.

7.3 Horizon picking & tracing

The final horizon picking was done iteratively on time and depth migrated sections, as the generated velocity models allow direct conversion of horizon and seismic data between both domains. Final results presented in this work are shown both, in the time and the depth domain (Encl. 4 – 37).

7.3.1 Base Quaternary

As Base Quaternary is an erosional surface its seismic expression is quite variable. A relatively clear way to pick it is to trace the reflection following the Quaternary-Tertiary unconformity. Where this reflection is present, Base Quaternary is picked on the strongest peak within the seismic envelope. Where absent or unclear, Base Quaternary is picked where either intra-Quaternary or intra-Tertiary (or both) reflections end. In-between and in no-data zones, the Base Quaternary horizon has been interpolated using the mentioned seismic attributes (greyscale colour bar, bandpass filter and pseudo-relief) and visualisation filters that helped significantly to trace the Base Quaternary.

For illustration, the NE flank of the Quaternary valley envelope imaged on line 16-QAU-03 is clearly marked by a strong black peak on the line's PostSDM version (Fig. 7-2). On the opposite SW flank, the bottom of the channel is marked by the termination of the intra-Molasse reflections. In addition, intra-Tertiary reflections and a relatively chaotic intra-Quaternary seismic pattern help to determine the position of the Base Quaternary.

Further constraints for the Base Quaternary picking were obtained through iterative velocity model updates in the PostSDM conversion process. Correction of the push-down effect below the Quaternary toughs provided high confidence in the velocity models and in the Base Quaternary interpretation.

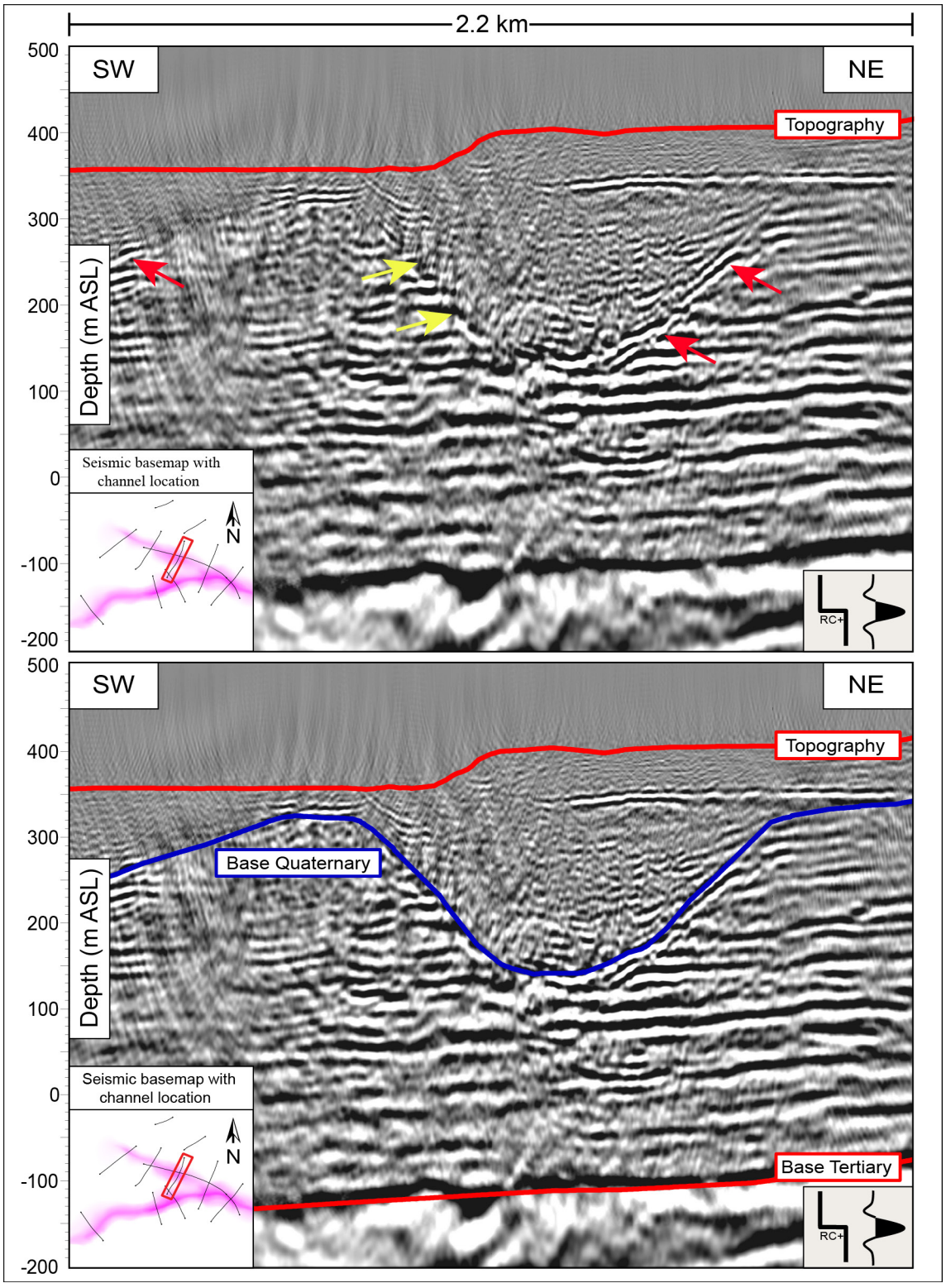


Fig. 7-2: PostSDM version of the line 16-QAU-03.

Top: Uninterpreted section with topography; Red arrows show strong reflections corresponding to Base Quaternary. Yellow arrows point to the termination of intra-Molasse reflections as indicators for Base Quaternary. Bottom: Interpreted section with traced Base Quaternary and Base Tertiary horizons.

7.3.2 Internal Quaternary units (Litho-Seismo-Facies)

Despite the mostly excellent seismic imaging achieved, the seismic interpretation of the Quaternary infill of the overdeepened valleys remains a major challenge. While seismic indications to differentiate intra-Quaternary facies units can be found on some profiles (e.g. when considering amplitude and or frequency content), it was mostly well information that guided it. In fact, the latter information often required a differentiation where the seismic data alone would have yielded none or would have not been regarded as being robust enough to decide on it (see Encl. 4 – 37 with descriptions).

Based on the existing well information in the investigation area, seven types of lithological units bounded by well markers were distinguished (Encl. 3). For the interpretation of each profile, the lithological markers for all wells within 500 m distance from a given lines were taken into account. Projecting the lithological markers of the wells onto the seismic lines allowed assigning certain lithological markers (well data) to certain seismic facies patterns. We applied the term "Litho-Seismo-Facies" (LSF; Encl. 3) to those units where a certain well derived lithofacies association can be clearly assigned to a certain seismic signature.

To distinguish the various LSF units within and along the various overdeepened valleys, each was assigned a two-digit code (Encl. 3). The first digit defines its areal occurrence (0, 1, 2, 3 in ZNO and 4, 5, 6 in NL with respect to the individual channels recognised in those areas). The second digit defines its vertical position within a channel starting with number 1 being the lowest or deepest occurrence. Furthermore, each LSF unit is also assigned a depositional environment, i.e. lake, deltaic, fluvial, diamict etc. according to the constraints from existing well data or previous Quaternary geological interpretation.

For details on the interpretation of individual lines we refer to Encl. 4 to 37.

7.4 Uncertainties

Remaining uncertainties in the interpretation of Base Quaternary and intra-Quaternary layers relate to the following:

1. Imaging issues unresolved in seismic processing. 3D effects and out-of-plane events typical for 2D surveys may be present in the sections affecting the interpretation.
2. Interpretation uncertainties in ambiguous data zones, where neither reflections nor terminations could be picked and no well data is available.
3. Non-ideal velocity models and ambiguities in well facies interpretation. These factors together may affect interpretation of intra-Quaternary horizons.

Comparison of initial seismic interpretations with well data and pre-existing Base Quaternary models and as well indications from the current Base Quaternary modelling (Chapter 8) suggest that the overall uncertainty of depth picking for Base Quaternary is mostly in the range of ± 30 m. However, where the Base Quaternary picking is not constrained by any borehole indications or clear unconformities/reflection termination, its uncertainty may locally exceed 50 m (compare Fig. 8-4).

The seismic facies interpretation of the Quaternary valley's infill is also fraught with intrinsic uncertainty whenever well data is absent. Additional uncertainty stems from potential mis-interpretation and/or -correlation of individual wells. This interpretation needs further verification and refinement once new well information becomes available.

8 Mapping of the Base Quaternary

The objective of this work step was to produce updated depth maps of the Base Quaternary (BQ) for the ZNO and NL area based on the interpretation of the new 2D seismic data and under consideration of the abundant well information. The mapping was done using the Petrosys software, considering the pre-existing regional Base Quaternary model (Pietsch & Jordan 2014) as a general guidance. In the following chapters, the considered datasets (compare Encl. 36 and 37) and their incorporation are discussed in detail. The resulting depth maps for both investigation areas, ZNO and NL, are presented as Encl. 38 and 39, respectively.

8.1 Well data handling

Well data was provided in the format of well listings in two separate files containing 996 wells for the ZNO area and 169 wells for the NL area. For each well, Nagra provided data quality factors that allowed well selections by the following features:

1. wells with reliable depth information for the Base Quaternary
2. wells with approximative depth information for the Base Quaternary
3. wells with reliable information that Base Quaternary was not reached by the well
4. wells with no records about geological results

For the ZNO area not only the 309 wells with "reliable" or "approximative" depth values of the Base Quaternary were used for interpretation and mapping, but also 87 wells which did not penetrate the Base Quaternary. For the NL area, 102 wells with depth information for Base Quaternary and 12 wells which did not penetrate the Base Quaternary were used, respectively.

Separate well selection files were created (Encl. 40 and 41) to split the wells that penetrated the Base Quaternary from those that did not reach that stratigraphic level for gridding operations and map displays.

All well data which was considered for the seismic interpretation and the construction of the Base Quaternary maps were entered and maintained in project-related well databases for usage in the IHS Kingdom and Petrosys interpretation software packages.

8.2 Seismic interpretation data transfer between interpretation packages

The results of the horizon interpretation were transferred from the IHS Kingdom project to the Petrosys project as a set of XYZ data points referenced to CDPs and the referenced seismic datum 500 m above sea level. The depth (Z) values were converted into meters above mean sea level values.

8.3 Mapping process workflow

The revised mapping of the Base Quaternary in the siting regions NL and ZNO set out from the depth interpretation of the newly available 2D-seismic data. Since this data is located mainly around the narrow and elongated overdeepened Quaternary valleys, the previously established model of the Base Quaternary (Pietsch & Jordan 2014) was used as a guidance for the extra- and interpolation of this surface. Newly available wells were integrated during this process.

8.3.1 Gridding and contouring

The gridding and contouring process was done in an iterative way, to consider the different data types, data density and geological constraints. The Minimum-Curvature algorithm provided by the Petrosys was used for gridding (bicubic interpolation). A gridding cell size of 25 m was selected to respect the level of detail of the seismic interpretation, the density of well data and the required resolution. This relatively small grid size was necessary to image the relatively steep slopes of the Quaternary valleys and generally fits the accuracy of the data picks (well, seismic, digitised contours etc.). The contouring interval (c.i.) for the map display is 25 m considering the values range and variation over the studied areas. Some parts of very steep valley slopes required a minor manual contour editing during an intermediate gridding stages to preserve all the data values without compromising geological plausibility. The hand edited contour maps were again re-gridded, merged with the available well data (well tied) and re-contoured.

8.3.2 Topography and surface geological data

As a part of the intermediate QC process, the digital elevation model and surface geological maps were imported into the IHS Kingdom and Petrosys interpretation systems. In addition, the information about outcropping Molasse sediments (e.g. Hofmann 1967, Haldimann et al. 2017) was used to constrain the grids.

8.4 Quality checks and remaining uncertainties

The obtained Base Quaternary grids were back exported to the seismic interpretation system and verified until the seismic interpretation remained fully honoured. In addition, the display of all updated information in Petrosys allowed for a visual data QC and mistie analysis. 87 wells located in the investigation area around the ZNO siting region did not reach the Base Quaternary according to the Nagra database. After a first gridding operation 14 of these wells still penetrated the initial BQ depth grid. . An additional gridding operation where the BQ at these well positions was defined to be located slightly below their TD was run to eliminate the conflictss.

The mapping QC also revealed discrepancies between neighbouring wells. These may be related to real depth variations of the Base Quaternary but can also signal erroneous interpretation of some well data. This is demonstrated by the following examples:

1. In the ZNO area, well k 16-00021 (UWI 32333) did not reach the BQ. However, its TD plots 34 m below BQ penetrated by the neighbouring well k 16-10012 (UWI 32345). A possible mapping solution to this well data configuration is depicted in Fig. 8-1. It results in a small side channel that allows the «reverse» BQ depth situation in wells k 16-00021 and k 16-10012. However, after consulting the actual well records, it was decided to use only wells k 16-10012 and 10003 (UWI 32336) for gridding in this area. The final mapping result is displayed in Encl. 38.

2. In the SE corner of the ZNO map, two closely neighbouring wells EWS_ZH_i 00-10203 and EWS_ZH_i 00-01131 show 20 m BQ depth difference where this surface seems otherwise very flat. In the absence of any seismic or well data in this area, it is impossible to say whether this situation is realistic. The depth information from the two wells was kept and creates a small BQ depth anomaly in the map (compare Encl. 38).
3. Fig. 8-2 shows the case of well EWS_ZH_k 00-01091 (UWI 24723) in the SW corner of the ZNO region. This borehole records BQ at 393 m a.s.l. and is located between two other wells yielding Base Quaternary at 366 m and 341 m. All three wells were kept for gridding causing an artificially looking contour closure (anomaly) to the east of the seismic line 16-QAU-07 (Fig. 8-2).
4. Fig. 8-3. illustrates the case of well k 16-00026 that records BQ at 288 m a.s.l. and results in a depth anomaly in the middle of 4 other wells; this well was excluded from gridding.

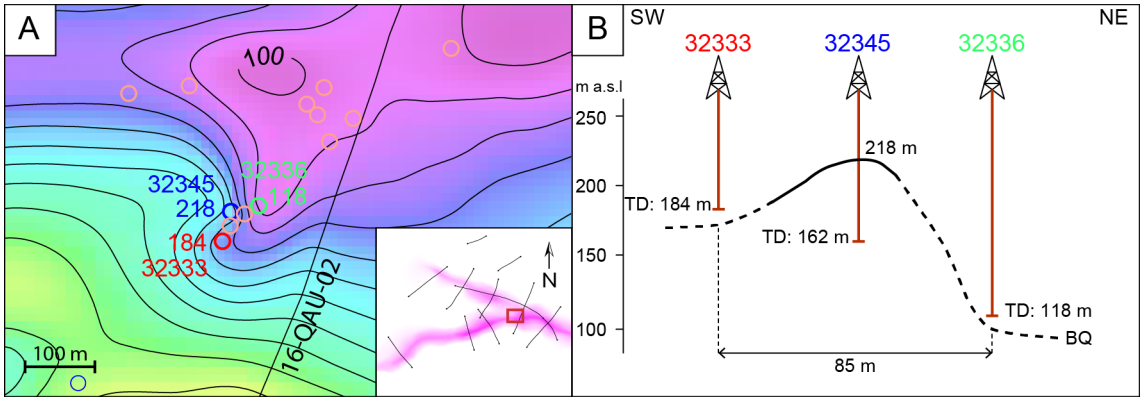


Fig. 8-1: Well-tied gridding & contouring QC example 1.

Map detail A displays the concerned well locations on the BQ depth map background; picture B demonstrates the significant BQ depth variations in a schematic cross section if we respect strictly well the depth data from these wells. Well k 16-10012 (blue) penetrated BQ at 218 m a.s.l.; well k 16-00021 (red) has TD at 184 m a.s.l. and reached TD above BQ. The slope is steeply dipping to the NNE. This means a minimum of 34 m discrepancy over a horizontal distance of some 50 m. Wells displayed in orange are those that did not reach the BQ; the northernmost well of the displayed group, k 16-10003 (marked in green), has TD at 118 m a.s.l.; if we respect this information the slope jumps at least 100 m down from k 16-10012 to k 16-10003 (over ca 45 m distance).

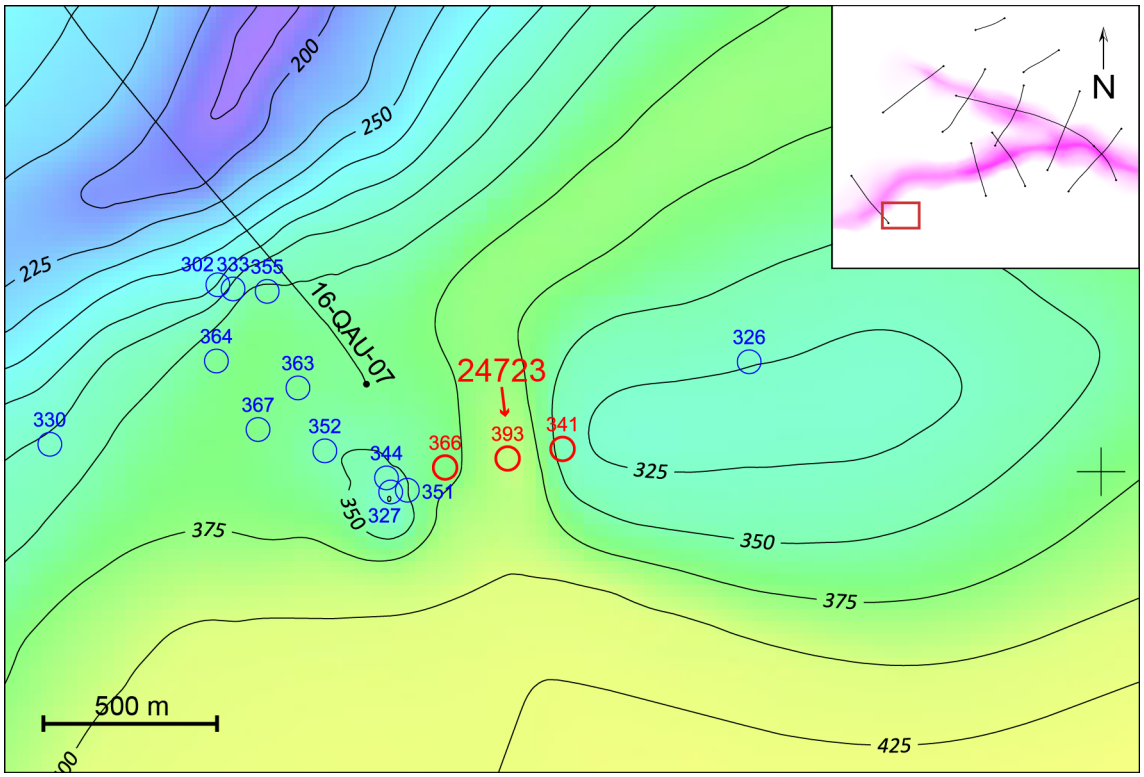


Fig. 8-2: Well-tied gridding & contouring QC example 3.

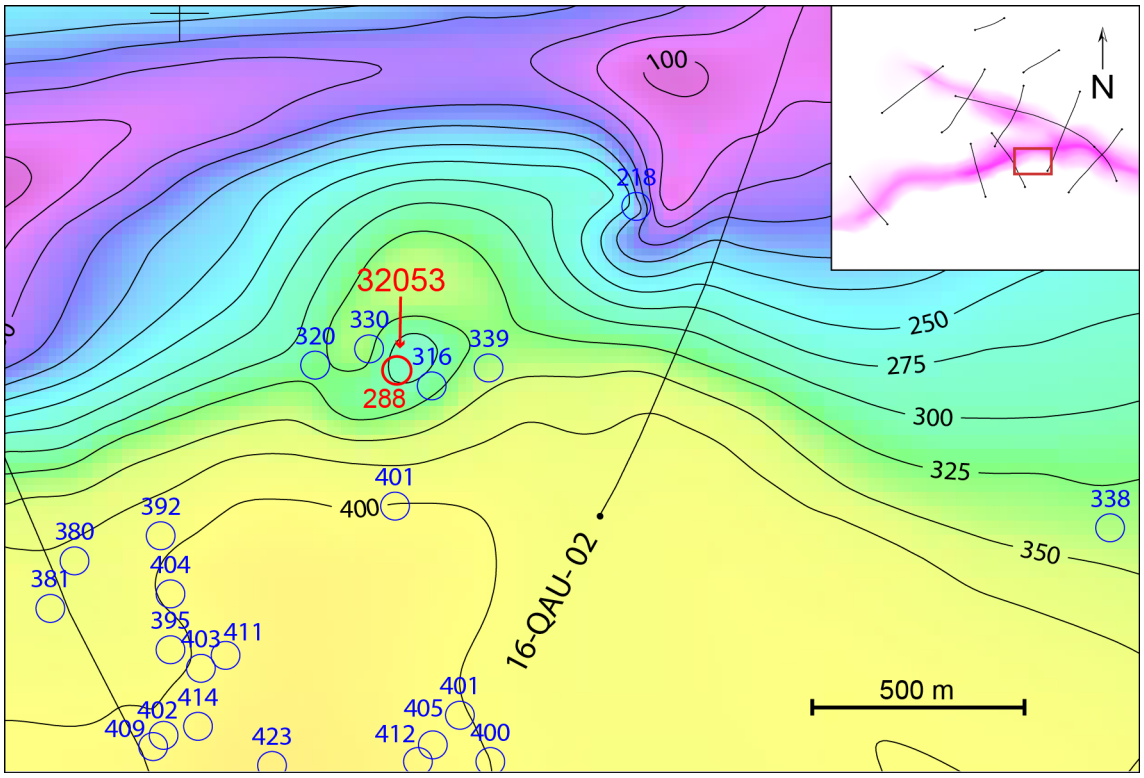


Fig. 8-3: Well-tied gridding & contouring QC example 4.

The examples above underline remaining uncertainties, particularly, that the given data density is insufficient to robustly evaluate small-scale variations of the BQ morphology.

Uncertainty is also inherent to the seismic interpretation of the overdeepened valleys, particularly their bottom depths as well as their slopes position and shape (compare Section 7.4). Fig. 8-4 and Fig. 8-5 illustrate examples where alternative interpretations of some seismic profiles are suggested from the Base Quaternary modelling.

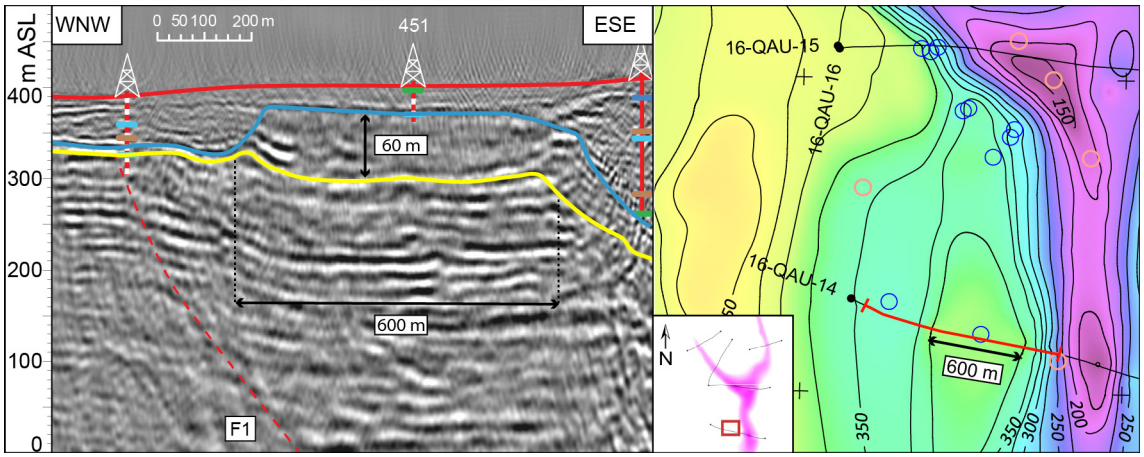


Fig. 8-4: Alternative seismic interpretation suggestions from Base Quaternary modelling for seismic profile 16-QAU-14.

The red line shows the topography, the blue is the seismic interpretation of BQ reported herein (e.g. Encl. 26 & 27). The yellow line shows a possible alternative interpretation that would eliminate the small culmination of BQ in the central part of the shown line segment. west of the NL major channel. BQ at that location would lower some 60 m (and could be interpreted even deeper), the additional space filled presumably with diamicts or glacio-lacustrine sediments (or both) as interpreted in the nearby well 17148. Well 451 is the only data point that indicated a shallow BQ. Could the lithology in the well have been misinterpreted?

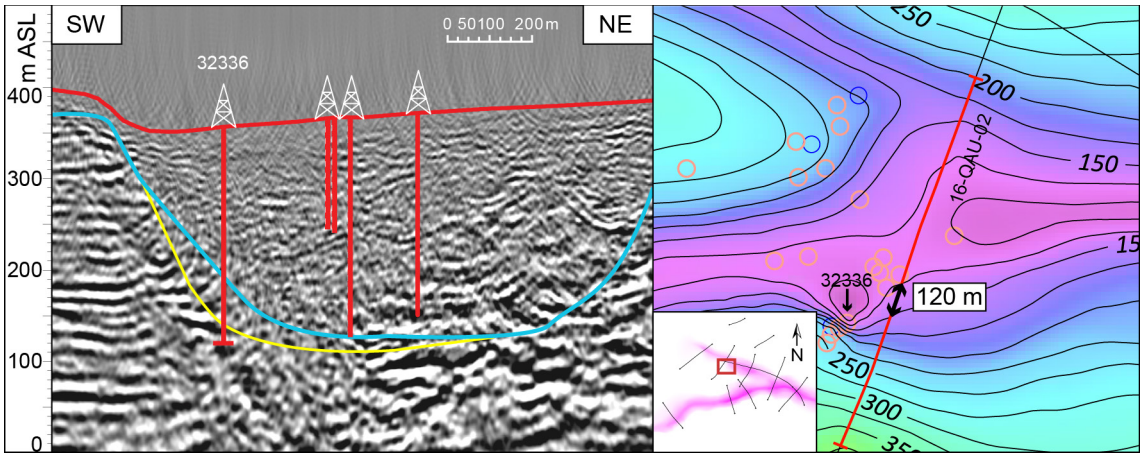


Fig. 8-5: Seismic interpretation suggestions from Base Quaternary modelling for seismic profile 16-QAU-02.

The red line shows the topography, the blue is the seismic interpretation of BQ reported herein (e.g. Encl. 6 & 7). The yellow line shows a possible alternative interpretation of the SW valley flank that would facilitate the 2D-mapping of the valley geometry.

9 Interpretation summary

The following sections provide a short overview of the interpretation results for the two investigated areas (compare Encl. 1 and 2). Details on the interpretation of the Base Quaternary and the infill of the various Quaternary overdeepenings for each seismic section are given as part of the Encl. 4 to 35.

9.1 Zürich Nordost (ZNO)

The eleven seismic sections available for the interpretation of overdeepened Quaternary valleys in this region are illustrated by Encl. 1. From south to north the valleys of interest here are the Andelfingen, the Marthalen and the Rudolfingen trough.

The seismic sections 16-QAU-01, -02, -05, -06 and -07 (Encl. 4, 6, 12, 14, and 16) provide cross sections of the Andelfingen trough. Furthermore, section 16-QAU-04 provides an oblique section through the easternmost part of the investigated valley section. This seismic dataset allows to characterise the valley geometry. Especially along the valley flanks, Base Quaternary can be picked quite reliably. Uncertainties remain concerning the interpretation of the valley's deepest part that were addressed by considering the PostSDM verification approach. For profiles 16-QAU-01 and -06 deep wells provide valuable information for the interpretation of the trough's fill. Nevertheless, a correlation of facies units remains difficult at this exploration stage.

The Marthalen trough further to the north is imaged on profiles 16-QAU-03, -08 and -09. In addition, section 16-QAU-04 provides a very valuable along-strike image of this overdeepened valley. The new seismic profiles across the western extent of the Marthalen trough imply that it is deeper here than previously presumed (e.g. by Pietsch & Jordan 2014). Furthermore, section 16 QAU-09 confirms the previous interpretation of a comparatively shallower side valley of the Marthalen trough, the so-called Niderholz trough in this area (Müller et al. 2002; Pietsch & Jordan 2014). Concerning the infill of the Marthalen trough, the seismic data allows a tentative division, based on the recognition of unconformities (particularly well visible on section 16-QAU-04). Notably this division is at this stage not yet constrained by borehole evidence.

The Rudolfingen trough is covered by section 16-QAU-11 delivering very valuable new insights concerning its depth, extent and infill (the latter being interpreted under consideration of borehole information). Section 16-QAU-10 on the other hand does not yield evidence for a continuation of this overdeepened valley towards the southeast.

The updated Base Quaternary map for the ZNO region is given in Encl. 38 and 40. Previous models (e.g. the one by Pietsch & Jordan 2014) are largely confirmed.

9.2 Nördlich Lägern (NL)

The five seismic sections available for the interpretation of overdeepened Quaternary valleys in this region are illustrated by Encl. 2. The main interest concerns the roughly N-S striking Bülach trough and the so-called Strassberg trough which branches of the earlier mentioned valley towards the northeast (compare Buechi 2016, Buechi et al. 2018).

The Bülach trough is imaged by the seismic sections 16-QAU-14, -15 and -17 (Encl. 26, 28, and 32). In case of section 16-QAU-14 and -15 the identification of the Base Quaternary was comparatively tricky. The given interpretation strongly relies on the indications from the PostSDM verification process. The internal trough fill, for which a complex architecture was proposed by Buechi (2016) on the basis of borehole data, is not very well interpretable in the given seismic images. Consequently, the presented interpretation is largely conceptual, following the genetic hypothesis of Buechi (2016). The geometric and chronological relationship between the Bülach and the Strassberg trough remains speculative. By comparison, seismic section 16-QAU-17, only covering the narrower, northern part of the Bülach trough, allows for a straight forward trough interpretation that is additionally constrained by recently completed wells.

The seismic sections 16-QAU-16 and -18 (Encl. 30 and 34) provide images of the Strassberg trough. Although the given seismic images are partly ambiguous, the interpretation of these profiles is comparatively well constrained by adjacent wells. The width of this valley branch remains uncertain.

The updated Base Quaternary map for the NL region is given in Encl. 37 and 39. Previous models (e.g. the one by Pietsch & Jordan 2014) are largely confirmed.

10 Conclusions

This report summarises the 2D reflection seismic exploration and provisory interpretation of overdeepened Quaternary valleys around the Nagra siting regions Zürich Nordost and Nördlich Lägern in northern Switzerland. The reported investigations demonstrate that significant information about the geology of these valleys can be obtained by these means.

The acquisition and processing of high resolution seismic data was a challenging task given the environmental conditions (e.g. land use and near surface conditions). Consequently, the obtained data quality varies locally but in general the 16 stacked and migrated 2D seismic sections discussed herein are of mostly good principal interpretability.

Nevertheless, the interpretation of the seismic section was a challenge in its own right. Whereas the rough outline of the overdeepened valleys is easily recognised in most sections, detailed mapping of the Base Quaternary was often found to be fraught with uncertainty. A key aspect in this regard was the development of an iterative interpretation-processing-interpretation workflow involving velocity model building and post-stack depth migration of the seismic sections. This allowed to identify the most likely Base Quaternary interpretation. Four upholes which were drilled only after the first interpretation results were available (Nagra 2018), confirmed the high predictability of the chosen interpretation, velocity modelling and mapping work-flow.

For the interpretation of the valley's infill an abundant amount of shallow boreholes had to be integrated. Based on these wells, a Litho-Seismo-Facies concept was developed in order to propose an often conceptual seismic interpretation of the valley infills. As such, the newly available high resolution seismic data permitted a tentative distribution of Litho-Seismo-Facies units (LSF) that will need to be verified once new well data becomes available. Such new data is likely to require an interpretation update. In the course of this process a seismic guided re-correlation of existing well information could also be attempted.

The results of the seismic interpretation laid the basis for a local revision of the Base Quaternary models for the NL and ZNO region. Pre-existing, regional Base Quaternary model were largely confirmed by this revision and only resulted in minor changes in depth and trace of some valley sections.

Overall, the 2D reflection seismic exploration of overdeepened Quaternary valleys in northern Switzerland was a success. While the presented seismic interpretation carries uncertainties related to the input data quality and the interpretation work itself, it provides important new insights into the geometry and geology of these valleys. The presented interpretation is considered provisory but can very well serve the current planning of Quaternary exploration boreholes. The results of these boreholes will build the foundation for future interpretation refinements.

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Glossary of Terminology

Abbreviations (in the order of importance

Nagra	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, the Swiss technical competence centre in the field of deep geological disposal of radioactive waste
DMT	Deutsche Montan Technologie DMT GmbH & Co. KG
GT	Geofizyka Toruń
GPCI	Geneva Petroleum Consultants International
SRT	Seismic Refraction Tomography
MASW	Multi-channel Analysis of Surface Wave
BQ	Base Quaternary
AGC	Automatic Gain Control, an algorithm commonly used in seismic processing for balancing of the amplitude gain and for improving visibility of late-arriving events, i.e. deep horizons on seismic sections
CMP/CDP	Common Mid-Point/Common Depth Point) – the middle point at the acquisition surface between a source and receiver positions; also, the theoretical reflection point that lies midway between a source and receiver assuming flat horizontal reflector without any velocity variations
GIS	Geographic Information System. Computer-based software package for management of all georeferenced information like maps, obstacles, properties, seismic lines with shot and receiver information and many more
DEM	Digital Elevation Model, a model of the terrain's surface relief as 3D grid including various cultural layers
Diffraction	A seismic event generated by a scattering point. Diffractions are visible on seismic stacked unmigrated sections and 3D volumes. By applying a seismic migration algorithm with the reliable velocity model, diffractions are collapsed to their apexes which also serves as indicator for correctness of the velocity model.
Facies	The characteristics that distinguish a rock from adjacent rocks, such as lithology, fossil content, colour, sedimentary structures, grain-size distribution etc. **Seismic facies** are reflection patterns (amplitude, continuity, shape etc.) that are characteristics of depositional environments.
Geophone	A sensor that records the particle velocity or acceleration created by a seismic wave. Geophones are commonly used in land seismic and in VSP surveys

Molasse Sediments such as sands, sandstones and conglomerates that form as terrestrial or shallow marine deposits in front of raising mountain chains e.g. Alps. The **Molasse basin** is a foreland basin north of the Alps which formed mainly during Oligocene and Miocene ages. The basin resulted from the flexure of the European plate under the weight of the orogenic wedge of the Alps. Herein, the term Molasse is used to describe all geological formations formed in the interval between Cretaceous and Quaternary periods, i.e. in the time interval formerly known as Tertiary.

Seismic phase A description of the seismic wavelets or waves measured in degrees. Waves that have the same shape, symmetry and frequency and that reach maximum and minimum values simultaneously are in phase. Waves that are not in phase are typically described by the angular difference between them, such as, "180 degrees out of phase". **Zero-phase** wavelets are symmetrical in shape about reference (zero) time, whereas non-zero-phase wavelets are asymmetrical. Non-zero-phase wavelets are converted to zero-phase wavelets to achieve the best resolution of the seismic data. Known zero-phase well seismic can be compared with local surface seismic data to determine the relative phase of the surface seismic wavelets. Such knowledge allows the surface seismic data to be "corrected" to zero phase.

Seismic polarity The nature of the positive and negative portions of the seismic wavelet, and the convention used to generate seismic displays. The polarity standard adopted in the current work is defined as: for zero-phase data, a positive reflection coefficient (transition from soft to hard sediments with increasing depth) is represented by a positive amplitude and a peak on seismic displays (black on greyscale and on colour plots).

Tertiary A former term for the geologic period from 65 million to 2.58 million years ago, a time span that covers the Paleogene and Neogene periods in the modern classification. In current work, the term Tertiary is used interchangeably with the term "Molasse".

TWT Two-Way Traveltime, the elapsed time for a seismic wave to travel from its source to a given reflector and return to a receiver at the Earth's surface

Uphole surveys Seismic measurements in boreholes used for studying the near-surface geology and distribution of seismic velocities. Seismic source is usually placed in the borehole at different depths starting below the low velocity layer, with detectors located at the surface.

UWI Unique Well Identifier, a standardized numerical code for drilled wells adopted in the petroleum industry

Vibroseis A seismic method, in which a vibrator is used as an energy source to generate a seismic wave. A sinusoidal vibration (sweep) of varying frequencies is applied during a certain period (sweep period) typically lasting up to 32 s. Frequency range applied in surface seismic usually starts at 8 Hz and reaches 120 Hz or higher, depending on the targets of the study.

Seismic migration algorithms

PostSTM Poststack Time Migration, a processing algorithm applied in the time domain on stacked traces to collapse diffractions and to improve resolution and position accuracy of a seismic image. Applied mostly for QC at the early processing stages due to limitations that can be fixed by more advanced PreSTM, PostSDM and PreSDM algorithms.

PreSTM Prestack Time Migration, a processing algorithm applied in the time domain to collapse diffractions and to improve resolution and position accuracy of a seismic image. The algorithm operates with a simplified velocity model, without any strong variations. Unlike the PostSTM, the PreSTM process is applied on unstacked seismograms which improves the quality of the seismic image.

PostSDM Poststack Depth Migration, a processing algorithm applied in the depth domain on stacked data to collapse diffractions and to improve resolution and position accuracy of a seismic image. The algorithm applies ray tracing to compute diffraction traveltimes and can cope with complex velocity models.

PreSDM Prestack Depth Migration, a processing algorithm, same as PostSDM, but applied on the prestack data. Currently, the most advanced imaging technique applied in the industry, which provides best positioning and quality of the seismic image. Crucial requirement for using this method is precise estimation of the velocity model, for which a large number of a-priory well markers are needed. The algorithm was not used in the current study, as the PostSTM process is less influenced by the precision of the estimated velocities, therefore providing best imaging results with the available velocity models.

Depth references

ASL Above Sea Level, reference datum in depth used for generation of interpretation grids and maps

MSL Mean Sea Level, commonly used as reference datum for seismic imaging, interpretation and drilling

MD Measured Depth, the length of the borehole. In vertical wells, this coincides with the True Vertical Depth. In non-vertical wells, measured depth can significantly deviate from the true vertical depth.

TVD True Vertical Depth, the measurement of a straight line perpendicularly from a horizontal plane at the well location downwards to a point in the well. **TVDSS** is True Vertical Depth Sub-Sea, true vertical depth measured from the Mean Sea Level.