



ARBEITSBERICHT NAB 24-49

Depth Conversion of the 3D Seismic
Interpretation for the Area of Interest in
the Jura Ost, Nördlich Lägern and Zürich
Nordost Siting Regions

November 2024

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

Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch



ARBEITSBERICHT NAB 24-49

Depth Conversion of the 3D Seismic
Interpretation for the Area of Interest in
the Jura Ost, Nördlich Lägern and Zürich
Nordost Siting Regions

November 2024

KEYWORDS

Seismic, seismic interpretation, 3D, depth conversion, velocity model, site comparison, depth maps, thickness, area of interest, uncertainty, host rock, upper confining unit, lower confining unit, Jura Ost, JO, Nördlich Lägern, NL, Zürich Nordost, ZNO

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

Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch

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

Abstract

In the course of the repository site selection process, 3D seismic evaluation for the Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) siting regions was carried out on the selected pre-stack time migration zero-phase reference seismic datasets (PreSTM-ref, Nagra 2024a, 2024b, 2024c, 2024d).

The interpretation results represent important input for the 3D geological models (Nagra 2024f) and directly and indirectly for the repository performance assessment (Nagra 2024g) and for radiological consequence analysis (Nagra 2024h). This implies a conversion of the interpreted horizons from time to depth domain.

Depth conversion was therefore performed together with an evaluation of depth uncertainties. The latter was carried out to explain the non-uniqueness of models built with impact on the top and base surfaces of the host rock (Opalinus Clays) and on thickness of the host rock, and upper and lower confining units¹.

Within the areas of interest (potential repository zones), an infill stage of interpretation was carried out. The number of stratigraphic horizons were increased from the regional (full survey) horizons to multiple local horizons, in order to generate a higher granularity in the stratigraphic framework and to identify and map velocity change interfaces.

Since critical anomalies were observed in the velocity model associated with the PreSDM seismic vintage, which impaired the confidence on the resulted depth surfaces, and to enable comparability in the approach and analysis of the three siting regions, a layered form of velocity model, i.e. Vo/K, approach, was used.

Several realisations were tested and evaluated exhausting all the available velocity inputs. Depth residuals, i.e. the difference between the computed depth of an event and the actual depth encountered in the well, were used as first level diagnostic for the validity of the velocity model for time depth conversion.

Among the several realisations, a reference case (solution of choice), generally referred to as base case, has to be selected.

There are no globally established criteria to define the base case. Considering the comparability scope of the site investigation, the base case was selected following the three established criteria below:

1. Use of comparable seismic products between sites: PreSTM-ref is the most comparable seismic processing product among the three surveys, thus the resulting surfaces from the PreSTM-ref interpretation had to be used
2. Conservative approach: selection of the interpretation of the base host rock (Top Lias- 174.7 Toa-100), which is by tendency the shallowest (smaller thickness of host rock)
3. Technically acceptable velocity model: model is consistent with data and captures relevant heterogeneity within the data.

Once the base cases for the top and base host rock (170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 -Top Lias, respectively) were defined, depth uncertainties were evaluated by a three-step approach: (i) the 2-standard deviation depth residuals accounting for the minimum value of depth uncertainty and (ii) the depth differences between the selected depth conversion scenarios,

¹ The term lower confining unit used in this report includes the whole Klettgau Formation and the Bänkerjoch Formation and thus a thicker section compared to the term confining units used in other reports (e.g. NTB 24-17, NAB 24-10).

providing depth uncertainty lateral distribution and (iii) tapering the uncertainty at well locations down to 2 m (i.e. almost no uncertainty at wells).

In the NL siting region, the depth differences between the Quick Look Processing (QLP) and the PreSTM-ref is relatively small, and it is generally below the 25 m standard deviation of two (2Stdev), except from a small area to the north, where uncertainties are around 45 m. In larger areas of the JO and ZNO siting regions, values are instead up to 45 m and < 60 m, respectively, even after tapering to wells.

Since the uncertainty maps were generated by the difference of PreSTM-ref and QLP depth converted surfaces, the uncertainty values appear to strongly depend on the different static solutions implemented in the two seismic vintages and should be interpreted as a conservative estimation.

The different statics applied in the two time migration data sets and the near-surface velocity model in the depth migration data sets are the largest contributor to depth uncertainty.

In addition, thickness uncertainties were assessed for the host rock and, for the upper and lower confining units¹. The thickness uncertainty is related to the uncertainty associated with the velocity of the interval.

In the NL siting region, the upper confining unit has a high velocity variability related to the presence of the fast Herrenwis carbonate platform penetrated by two of the four wells. Consequently, the thickness uncertainty value was derived by the average of the uncertainty values calculated separately for the wells penetrating the elastic sequence and for those penetrating the carbonate interval.

In the ZNO siting region, the thickness uncertainty for the upper confining unit might underestimate the uncertainty away from the well-controlled areas, especially when compared with the observed (large) depth uncertainty ranges.

Table of Contents

Abstract	I
Table of Contents	III
List of Tables.....	IV
List of Figures	VI
List of Acronyms.....	IX
1 Introduction	1
2 Dataset	4
3 Methodology	7
3.1 Areas of interest (AOI)	7
3.2 Horizon interpretation.....	9
3.3 Depth conversion and uncertainty analysis	13
3.3.1 Datum and statics.....	13
3.3.2 General depth conversion workflow.....	16
3.3.3 Application of the workflow.....	17
3.3.3.1 Depth conversion.....	17
3.3.3.2 Depth Uncertainty.....	21
3.3.3.3 Thickness Uncertainty	23
4 Results.....	25
4.1 Depth conversion and uncertainty analysis: JO	25
4.1.1 Horizon interpretation.....	25
4.1.2 Depth conversion.....	33
4.1.3 Depth and thickness uncertainties.....	41
4.2 Depth conversion and uncertainty analysis: NL	49
4.2.1 Horizon interpretation.....	49
4.2.2 Depth conversion.....	58
4.2.3 Depth and thickness uncertainties.....	69
4.3 Depth conversion and uncertainty analysis: ZNO	81
4.3.1 Horizon interpretation.....	81
4.3.2 Depth conversion	87
4.3.3 Depth and thickness uncertainties.....	95
5 Conclusions.....	109
6 References.....	113

List of Tables

Tab. 2-1:	Summary of the available seismic processing vintages.....	4
Tab. 2-2:	Reference datum and replacement velocity for the three seismic surveys	4
Tab. 3-1:	Summary of velocity data sources with quality indicators	19
Tab. 3-2:	Seismic thickness uncertainty associated with the variability of the interval velocity	24
Tab. 4-1:	The seven full survey horizons (light green) were complemented with eleven horizons within the AOI.....	25
Tab. 4-2:	Average velocity calculated at wells from upscaled sonic logs.....	34
Tab. 4-3:	Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces	35
Tab. 4-4:	Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces	36
Tab. 4-5:	Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces	37
Tab. 4-6:	Well top residuals and calculated standard deviations at 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias.....	41
Tab. 4-7:	Selected Vo/K realisation for the QLP dataset. Velocity source input and residuals at velocity break surfaces	43
Tab. 4-8:	Input and results for the velocity component of the thickness uncertainty of upper confining unit.....	48
Tab. 4-9:	Input and results for the velocity component of the thickness uncertainty of the host rock.....	48
Tab. 4-10:	Input and results for the velocity component of the thickness uncertainty of the lower confining unit.....	49
Tab. 4-11:	The six full survey horizons (light green) were complemented with thirteen horizons within the AOI	50
Tab. 4-12:	Average velocity calculated at wells from sonic logs edited from VSP.....	60
Tab. 4-13:	Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces	62
Tab. 4-14:	Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces	63
Tab. 4-15:	Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces	64
Tab. 4-16:	Selected Vo/K realisations: Model 4 velocity source input and residuals at velocity break surfaces	65
Tab. 4-17:	Well top residuals and calculated standard deviations at 168.2 Baj 300 - Base Herrenwis and 174.7 Toa 100 - Top Lias	70
Tab. 4-18:	Selected Vo/K realisation for the QLP dataset. Velocity source input and residuals at velocity break surfaces	71

Tab. 4-19:	Input and results for the velocity component of the thickness uncertainty of upper confining unit. Note the large value of the velocity Stdev	77
Tab. 4-20:	Input and results for the velocity component of the thickness uncertainty of upper confining unit for the wells penetrating the elastic interval.....	77
Tab. 4-21:	Input and results for the velocity component of the thickness uncertainty of upper confining unit for the wells penetrating the carbonate interval	78
Tab. 4-22:	Input and results for the velocity component of the thickness uncertainty of the clay interval proxy for the host rock.....	78
Tab. 4-23:	Input and results for the velocity component of the thickness uncertainty of the host rock.....	79
Tab. 4-24:	Input and results for the velocity component of the thickness uncertainty of the lower confining unit.....	80
Tab. 4-25:	The six full survey horizons (light green) were complemented with nine horizons within the AOI	81
Tab. 4-26:	Average velocity calculated at wells from upscaled sonic logs.....	88
Tab. 4-27	Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces	89
Tab. 4-28	Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces	90
Tab. 4-29	Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces	91
Tab. 4-30:	Selected Vo/K realisations: Model 4 velocity source input and residuals at velocity break surfaces	92
Tab. 4-31:	Well top residuals and calculated standard deviations at 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias.....	96
Tab. 4-32:	Selected Vo/K realisations: Model 1 QLP velocity source input and residuals at velocity break surfaces	97
Tab. 4-33:	Selected Vo/K realisations: Model 2 QLP velocity source input and residuals at velocity break surfaces	98
Tab. 4-34:	Selected Vo/K realisations: Model 3 QLP velocity source input and residuals at velocity break surfaces	99
Tab. 4-35:	Input and results for the velocity component of the thickness uncertainty of the upper confining unit.....	106
Tab. 4-36:	Input and results for the velocity component of the thickness uncertainty of the host rock.....	106
Tab. 4-37:	Input and results for the velocity component of the thickness uncertainty of the lower confining unit.....	107
Tab. 5-1:	Thickness uncertainty summary table.....	111

List of Figures

Fig. 1-1:	Lithological overview correlation with focus on Mesozoic sedimentary rocks of the three siting regions showing the important lateral variability in the Opalinus Clay overburden interval (Nagra 2024e).....	2
Fig. 1-2:	Base case velocity models for the three siting regions	3
Fig. 2-1:	Seismic data outline and well locations plotted on the Digital Elevation Model (DEM – Ground Level) – in the JO siting region.....	5
Fig. 2-2:	Seismic data outline and well locations plotted on the Digital Elevation Model (DEM– Ground Level) -in the NL siting region	6
Fig. 2-3:	Seismic data outline and well locations plotted on the Digital Elevation Model (DEM – Ground Level) -in the ZNO siting region	6
Fig. 3-1:	Diagram showing the proposed integrated workflow (NL as example display).....	7
Fig. 3-2:	JO area of interest (blue polygon) vs. identified “most” undisturbed area (green area; Nagra 2024a)	8
Fig. 3-3:	NL area of interest (blue polygon) vs. identified undisturbed area (green area; Nagra 2024b)	8
Fig. 3-4:	ZNO area of interest (blue polygon) vs. identified “most” undisturbed area (green area; Nagra 2024c)	9
Fig. 3-5:	Interpretation seedline methodology and grid building for the AOI in JO.....	10
Fig. 3-6:	Interpretation seedline methodology and grid building for AOI in NL.....	11
Fig. 3-7:	Interpretation seedline methodology and grid building in ZNO.....	12
Fig. 3-8:	Simple schematic showing the definition of TVD (true vertical depth), MD (measured depth) and TVDSS (true vertical depth subsea)	13
Fig. 3-9:	Schematic illustration showing the approach used to overcome the challenges by applying the replacement velocity down to the defined pseudo datum observed in NL and ZNO	15
Fig. 3-10:	Velocity models: approach and complexity depend on the velocity input data.....	18
Fig. 3-11:	Schematic drawing explaining the concept of residuals and their evaluation using the standard deviation approach.....	20
Fig. 3-12:	Four step workflow applied for the generation of depth uncertainty maps	23
Fig. 4-1:	Seismic section across the three wells within the AOI showing the 18 horizons	26
Fig. 4-2:	Seismic crossline 1390 showing the 154.8 Oxf 300 - Top Wildegg horizon	27
Fig. 4-3:	Seismic random line showing the 168.2 Baj 100 - Top Passwang horizon.....	28
Fig. 4-4:	Seismic crossline 1410 showing the 168.2 Baj 400 - Intra Passwang horizon.....	29
Fig. 4-5:	Seismic inline 5461 showing the 174.7 Toa 100 - Top Lias horizon	31
Fig. 4-6:	3D display of the 18 surfaces (TWT) generated for the AOI	32
Fig. 4-7:	Well correlation panel showing how major velocity breaks correspond to key stratigraphic units.....	33

Fig. 4-8:	Base case Vo/K velocity model translated into a velocity cube	38
Fig. 4-9:	Section from the PreSDM calculated velocity model showing the velocity anomalies within the Opalinus Clay interval.....	39
Fig. 4-10:	Time and depth surfaces of 170.9 Aal 300 - Top Opalinus.....	40
Fig. 4-11:	Time and depth surfaces of 174.7 Toa 100 - Top Lias	41
Fig. 4-12:	Velocity attribute map for the interval above the 170.9 Aal 300 - Top Opalinus calculated by extracting the average of the PreSDM velocity cube for this interval.....	42
Fig. 4-13:	170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage.....	44
Fig. 4-14:	Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data	45
Fig. 4-15:	Uncertainty depth maps for 170.9 Aal 300 - Top Opalinus Clay and 174.7 Toa 100 - Top Lias	46
Fig. 4-16:	Depth section across the three wells showing the base case enveloped by the upper- and lower-cases	47
Fig. 4-17:	TWT (A) and depth (converted, B.) seismic thickness for the interval 170.9 Aal 300 - 174.7 Toa 100 - Top Lias	47
Fig. 4-18:	Seismic section across the four wells within the AOI showing the 19 horizons	51
Fig. 4-19:	Seismic section across the three wells showing the 174.7 Toa 100 - Top Lias interpretation.....	52
Fig. 4-20:	Interpretation of the Herrenwis Carbonate Unit bounded by 168.2 Baj 200 - Top Herrenwis (carbonate) and 168.2. Baj 300 - Base Herrenwis	54
Fig. 4-21:	A. Random seismic section across the “thicker” area of the Herrenwis Unit (violet colour in the thickness map, B.) showing a potential push-down effect	56
Fig. 4-22:	Alternative interpretations were proposed for the Herrenwis Unit.....	57
Fig. 4-23:	3D display of the 19 surfaces (TWT) generated for the AOI	58
Fig. 4-24:	Well correlation panel showing how major velocity breaks correspond to key stratigraphic units.....	59
Fig. 4-25:	An eastward velocity trend was observed in the well average velocity for the stratigraphic interval between 154.8 Oxf 300 - Top Wildegg - 168.2 Baj 200 - Top Herrenwis	61
Fig. 4-26:	Base case Vo/K velocity model translated into a velocity cube	66
Fig. 4-27:	Depth conversion results capturing the two scenarios proposed for the base Herrenwis carbonate (168.2 Baj 300 - Base Herrenwis)	67
Fig. 4-28:	Time and depth surfaces of 168.2 Baj 400 - Top Clay Unit.....	68
Fig. 4-29:	Time and depth surfaces of 174.7 Toa 100 - Top Lias	69
Fig. 4-30:	168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage.....	72

Fig. 4-31:	Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data	73
Fig. 4-32:	Uncertainty depth maps for 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias	74
Fig. 4-33:	Depth section across the four wells showing the base case enveloped by the upper- and lower-cases	75
Fig. 4-34:	TWT (A) and depth (converted, B.) seismic thickness for the interval 168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias	76
Fig. 4-35:	Model statistics for the constructed 170.9 Aal 300 - Top Opalinus (isochore from 5 wells).....	79
Fig. 4-36:	Seismic section across three of the four wells within the AOI showing the 15 horizons	82
Fig. 4-37:	Seismic random line across the four wells showing the 154.8 Oxf 300 - Top Wildegg	83
Fig. 4-38:	Seismic random line across the four wells showing the 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias horizons	84
Fig. 4-39:	Seismic random line across the four wells showing the 149.2 Kim 100 - Top Malm and Plattenkalk (base) horizons	85
Fig. 4-40:	3D display of the 15 surfaces (TWT) generated for the AOI	86
Fig. 4-41:	Well correlation panel showing how major velocity breaks correspond to key stratigraphic units.....	87
Fig. 4-42:	Velocity attribute maps generated for the interval Plattenkalk (base) - 154.8 Oxf 300 - Top Wildegg.....	93
Fig. 4-43:	Base case Vo/K velocity model translated into a velocity cube	93
Fig. 4-44:	Time and depth surfaces of 170.9 Aal 300 - Top Opalinus	94
Fig. 4-45:	Time and depth surfaces of 174.7 Toa 100 - Top Lias	95
Fig. 4-46:	Section across three of the four wells showing the position of the QLP pseudo datum and the juxtaposition of low velocity wedges against the high velocity interval below the Plattenkalk (base) horizon.....	96
Fig. 4-47:	170.9 Aal 300 - Top Opalinus difference depth between maps PreSTM-ref base case and QLP velocity model example realisations expressed absolute value (m).....	100
Fig. 4-48:	170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage	101
Fig. 4-49:	Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data	102
Fig. 4-50:	Uncertainty depth maps for 170.9 Aal 300 - Top Opalinus Clay and 174.7 Toa 100 - Top Lias	103
Fig. 4-51:	Depth section across the three of the four wells showing the base case enveloped by the upper- and lower-cases	104
Fig. 4-52:	TWT (A) and depth (converted, B.) seismic thickness for the interval 170.9 Aal 300 - 174.7 Toa 100 - Top Lias	105

List of Acronyms

AOI	Area of Interest
DEM	Digital Elevation Model
FL	Seismic Floating Datum – smoothed Ground Level
GL	Ground Level
JO	Jura Ost
JO-15	Jura Ost Seismic Survey acquired in 2015
MD	Measured Depth
MSL	Mean Sea Level
NAB	Nagra Arbeitsbericht (Work Report)
Nagra	National Cooperative for the Disposal of Radioactive Waste
NL	Nördlich Lägern
NL16	Nördlich Lägern Seismic Survey acquired in 2016
PD	Seismic Pseudo Datum
PreSDM	Pre-Stack Depth Migration
PreSTM	Pre-Stack Time Migration
PreSTM-ref	Pre-Stack Time Migration zero-phase used as seismic reference dataset
QC	Quality Control
QLP	Quick Look Processing
SRD	Seismic Reference Datum
Stdev	Standard Deviation
TVD	True Vertical Depth
TVDSS	True Vertical Depth Sub Sea
TWT	Two Way-Travel Time
UCP	Undisturbed Central Panel
Vo/K	Layered Velocity Model (including linear gradient) for Depth Conversion
VSP	Vertical Seismic Profile measured in a well
ZNO	Zürich Nordost
ZNO-97/16	Zürich Nordost merged seismic survey of surveys acquired in 1997 and 2016
ZNO-97/16	Zürich Nordost merged seismic survey of surveys acquired in 1997 and 2016

1 Introduction

In the course of the site selection process, 3D seismic investigations were conducted in the three remaining siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) (Nagra 2024a, 2024b, 2024c). Several seismic processing vintages were available and used during the interpretation work. Despite the fact that Pre-stack depth migrated seismic cubes were available, the confidence in the derived depth maps was strongly impaired by the presence of anomalies (notably in the overburden and the Opalinus Clay) observed in the velocity models, which are not supported by well data and regional geological understanding. Such velocity anomalies align with observed local variations of top structure morphologies and they do not coincide with geological bodies. Therefore, to avoid velocity related artefacts and to ensure a comparable and balanced evaluation, the seismic data reprocessing was performed in the time domain and was designed such that all the processing input parameters and workflows were consistent across the three seismic surveys (Nagra 2024d).

Nevertheless, 3D models in depth (Nagra 2024f) within identified areas of interest are required as input for the repository performance assessment (Nagra 2024g) and for radiological consequence analysis (Nagra 2024h). Therefore, depth conversion was performed to convert the two-way travel time seismic horizons to depth. Evaluation of depth uncertainties was carried out to explain the non-uniqueness of models built with impact on the top and base surfaces of the host rock (Opalinus Clays) and on thickness of the host rock, and upper and lower confining units¹.

In this report, the term lower confining unit is used differently, than in other reports (Nagra 2024e, 2024f) and that you include a more extensive interval, which includes the whole Klettgau Formation and the Bänkerjoch Formation.

While trying to ensure a comparable approach, some flexibility needed to be implemented in the proposed depth conversion workflow to account for the lateral geological variability observed across the three siting regions (Fig. 1-1, Nagra 2024e). This mainly translated in different horizon framework (Nagra 2024a, 2024b, 2024c) as well as in alternative velocity model scenarios for the three siting regions, as mostly reflected in the Opalinus Clay overburden.

The Dogger Group overlying the Opalinus Clay (154.8 Oxf 975 – Top Dogger – 170.9 Aal 300 – Top Opalinus Clay) shows different lithostratigraphic nomenclature in JO compared to the NL and ZNO siting regions. In the lower part, this is partly due to historical reasons (Nagra 2024e), while in the middle and upper parts, a general facies trend from a more proximal to distal setting results in the important lateral heterogeneity with mostly silty to sandy claystone in ZNO and NL and in an increase in carbonate deposits in JO (Fig. 1-1, Nagra 2024e).

In the JO siting region, part of the overlying Wildegg Formation is locally partly eroded, while the overlaying Malm Group is almost not present. Therefore, as opposed to the NL and ZNO siting regions, where the Malm carbonates are covered by a thick interval of Quaternary and Molasse deposits, in JO fast units (i.e. remnants of Malm carbonates and calcareous marls) are either outcropping or subcropping below a thin interval of Quaternary deposits (Nagra 2024a, 2024e).

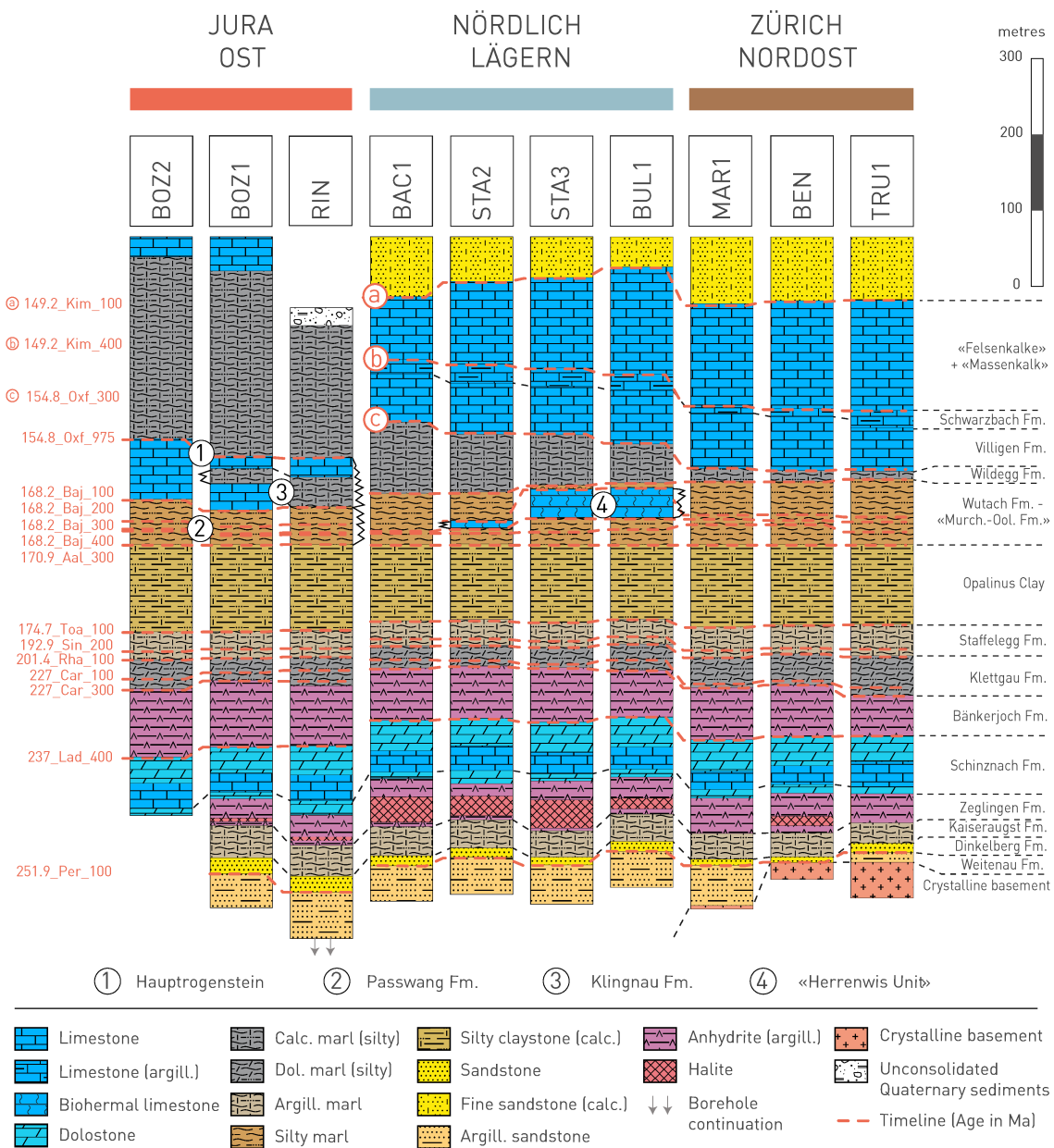


Fig. 1-1: Lithological overview correlation with focus on Mesozoic sedimentary rocks of the three siting regions showing the important lateral variability in the Opalinus Clay overburden interval (Nagra 2024e)

Well panel is flattened at 170.9 Aal 300 - Top Opalinus.

This report describes the applied methodology and results of the depth conversion performed for the area of interest (potential repository zone) in the Jura Ost, Nördlich Lägern and Zürich Nordost siting regions. Chapter 2 focuses on the description of the available dataset, while in Chapter 3 the applied methodology for the depth conversion as well as for the uncertainty quantification is explained. The results for each siting region are captured in Chapter 4 and summarised in the Conclusions (Chapter 5).

For each of the three siting regions several different velocity models were built. The selected base case models are as consistent as possible across the regions, taking into account the lateral geological variability.

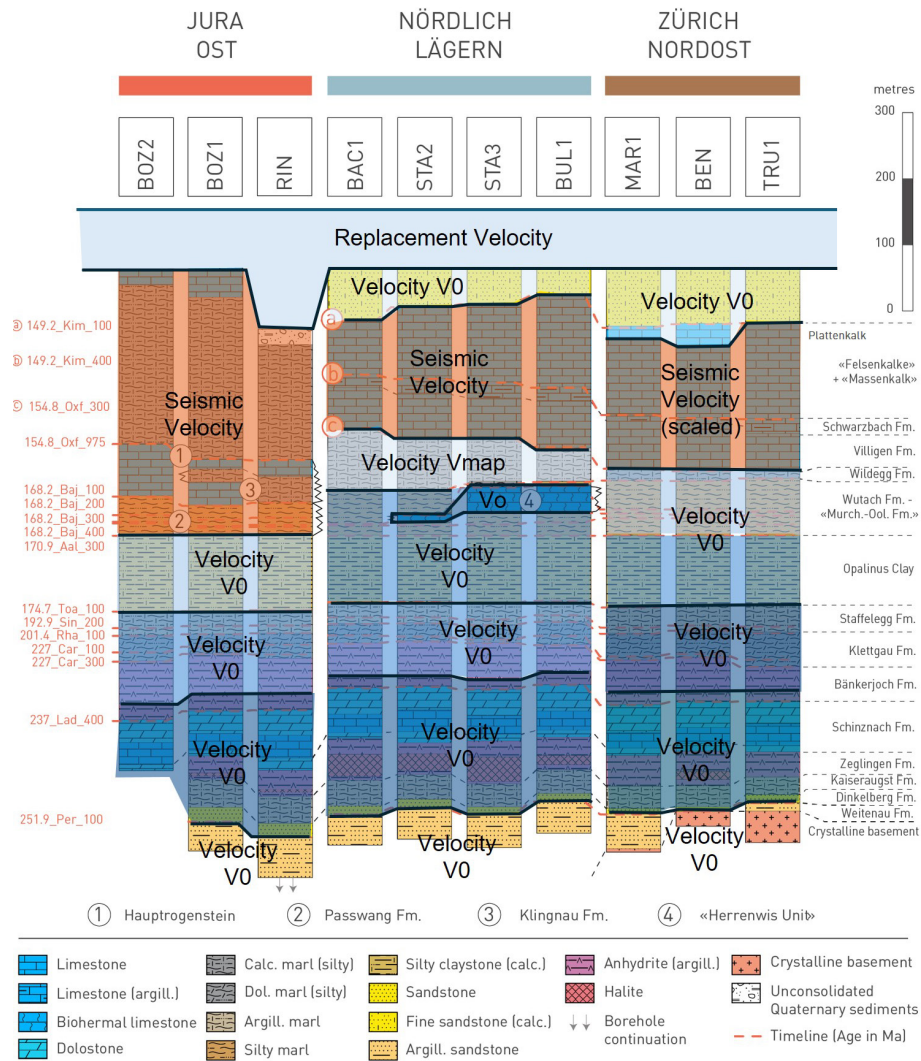


Fig. 1-2: Base case velocity models for the three siting regions

The base case models were selected to be as consistent as possible while considering the geological heterogeneity across the three siting regions.

Well panel is flattened at 170.9 Aal 300 - Top Opalinus.

2 Dataset

Consistently with the data used in the seismic interpretation of the three siting regions (Nagra 2024a, b, c), the dataset includes 3D seismic data originating from different seismic processing vintages (Tab. 2-1), seismic velocity cubes calculated during the PreSDM processing (Nagra 2024d) and the wells from Nagra’s deep borehole campaign as well as key legacy wells drilled within the seismic survey perimeters (Fig. 2-1, Fig. 2-2, Fig. 2-3).

Tab. 2-1: Summary of the available seismic processing vintages

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

The integrated dataset was loaded into Petrel software siting region dedicated projects for interactive interpretation. The Petrel project was set up using a seismic reference datum and a replacement velocity specific for each of the seismic survey (Tab. 2-2) and an X/Y coordinate system identical to that of the Swiss Reference System CH1903.

Tab. 2-2: Reference datum and replacement velocity for the three seismic surveys

Seismic Survey	Seismic Reference Datum	Replacement Velocity
JO-15	800 m	3600 m/s
NL-16	650 m	3500 m/s
ZNO-97/16	600 m	3500 m/s

The considered wells across the three siting regions are: Bozberg-1, Bozberg-2 and Riniken in JO, Stadel-2, Stadel-3, Bülach-1 and Bachs-1 in NL, and Marthalen-1, Trüllikon-1, Rheinau-1 and Benken, in ZNO. The selected wells have comparable wireline logs, vertical seismic profile surveys (VSP) and calculated synthetic seismograms (Nagra 2024a, b, c).

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

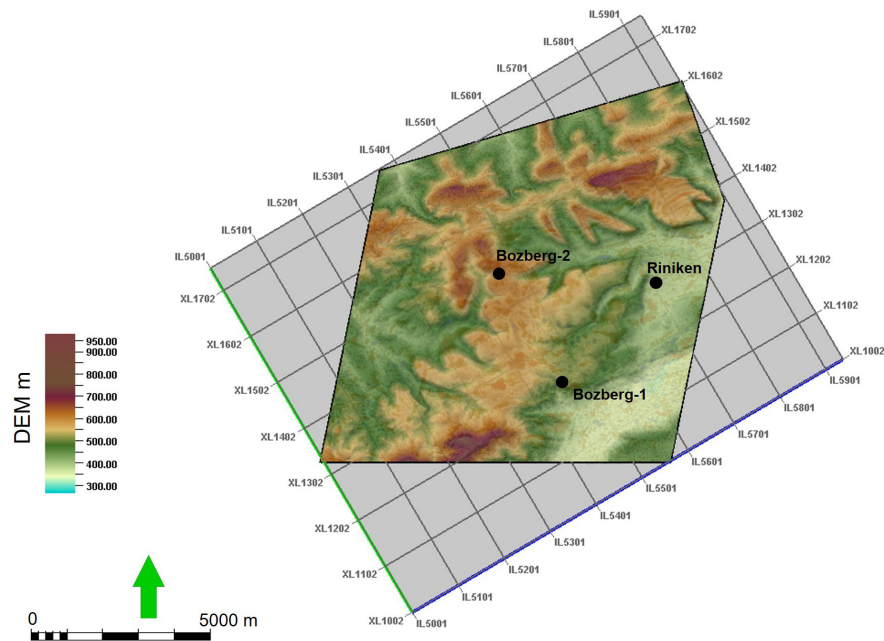


Fig. 2-1: Seismic data outline and well locations plotted on the Digital Elevation Model (DEM – Ground Level) – in the JO siting region

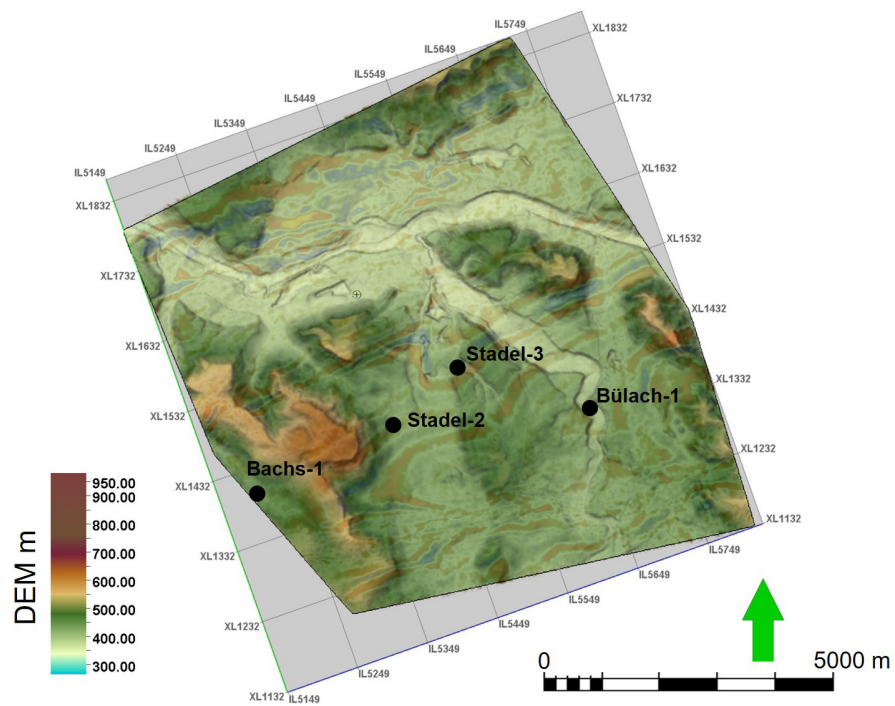


Fig. 2-2: Seismic data outline and well locations plotted on the Digital Elevation Model (DEM– Ground Level) -in the NL siting region

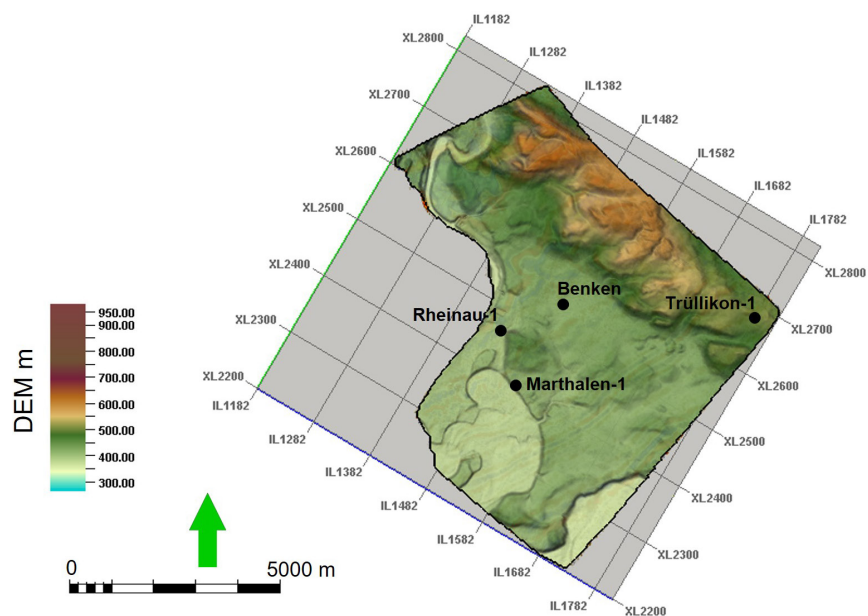


Fig. 2-3: Seismic data outline and well locations plotted on the Digital Elevation Model (DEM – Ground Level) -in the ZNO siting region

3 Methodology

3.1 Areas of interest (AOI)

The depth conversion and related uncertainty evaluation build on the seismic interpretation work performed on the three siting regions, JO, NL and ZNO (Nagra 2024a, b, c; Fig. 3-1). However, this was carried out in the defined areas of interest (AOI - potential repository zones) within the seismic survey perimeters. The selected areas of interest are directly linked to the perimeters associated with the identified undisturbed areas and they cover areas of 35 km², 27 km² and 17 km² for JO, NL and ZNO respectively (Nagra 2024a, b, c; Fig. 3-2, Fig. 3-3, Fig. 3-4).

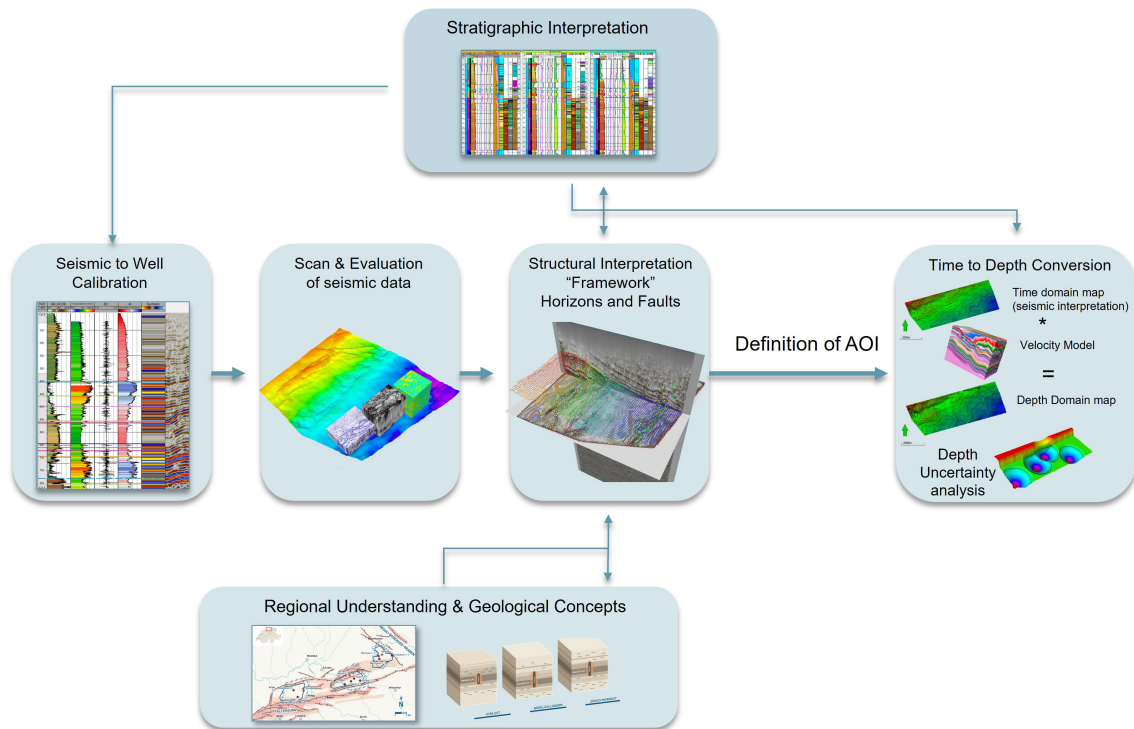


Fig. 3-1: Diagram showing the proposed integrated workflow (NL as example display)

Building from the key steps of the seismic interpretation workflow, which include the calibration to wells with an established robust stratigraphic framework, the screening of the seismic data and the interpretation of horizons and faults, within a regional geological understanding. An AOI is defined and time-to-depth conversion, as well as uncertainty analysis are performed.

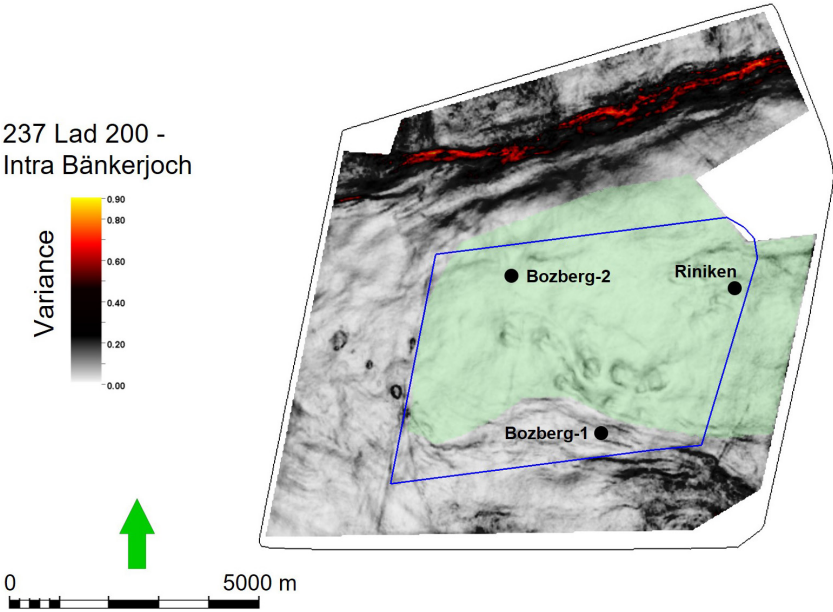


Fig. 3-2: JO area of interest (blue polygon) vs. identified “most” undisturbed area (green area; Nagra 2024a)

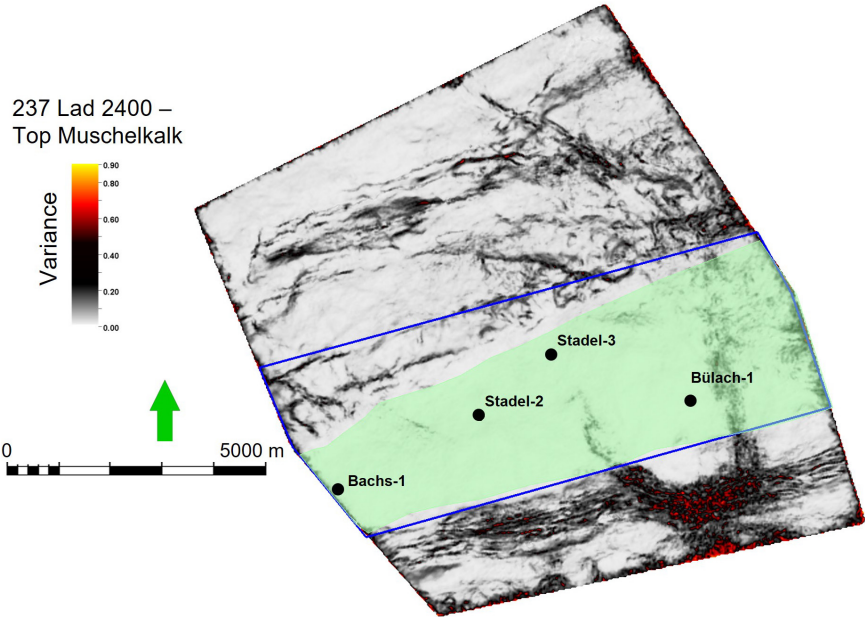


Fig. 3-3: NL area of interest (blue polygon) vs. identified undisturbed area (green area; Nagra 2024b)

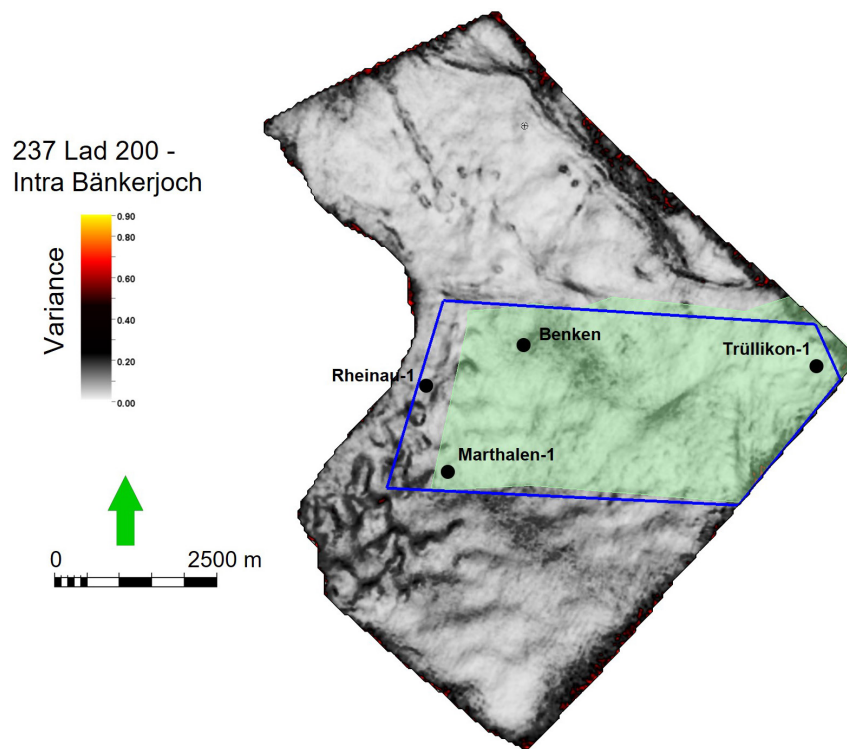


Fig. 3-4: ZNO area of interest (blue polygon) vs. identified “most” undisturbed area (green area; Nagra 2024c)

3.2 Horizon interpretation

After defining an area of interest (AOI), using the seismic-to-well ties, an infill stage of interpretation was carried out. The number of stratigraphic horizons was increased from the regional (full survey) horizons to multiple local (AOI) horizons, in order to generate a higher granularity in the stratigraphic framework and to identify and map velocity change interfaces. The latter represent a crucial step in the depth conversion workflow.

The interpretation approach followed the methodology proposed for the full survey horizons (Nagra 2024a, 2024b, 2024c). However such approach was only implemented within the defined AOIs (Fig. 3-5, Fig. 3-6, Fig. 3-7). Interpretation was carried out by means of the seedline square approach. Interpretation started from the inlines and crosslines at key selected wells (Fig. 3-5 A, B, Fig. 3-6 A, B, Fig. 3-7A, B) and closed the “square” at the remaining wells (Fig. 3-5 D, Fig. 3-6 D, Fig. 3-7 D). The latter wells were used as a blind quality check for horizon interpretation. The seedlines were manually picked using both Petrel manual and 2D autotrack options.

Inlines and crosslines were interpreted at an initial grid interval of 32 x 32 lines, which was first decreased to 16 x 16 lines and eventually to 8 x 8 lines. This narrowing-down seedline grid approach allowed for a consistent horizon pick between inlines and crosslines (Fig. 3-5, Fig. 3-6, Fig. 3-7).

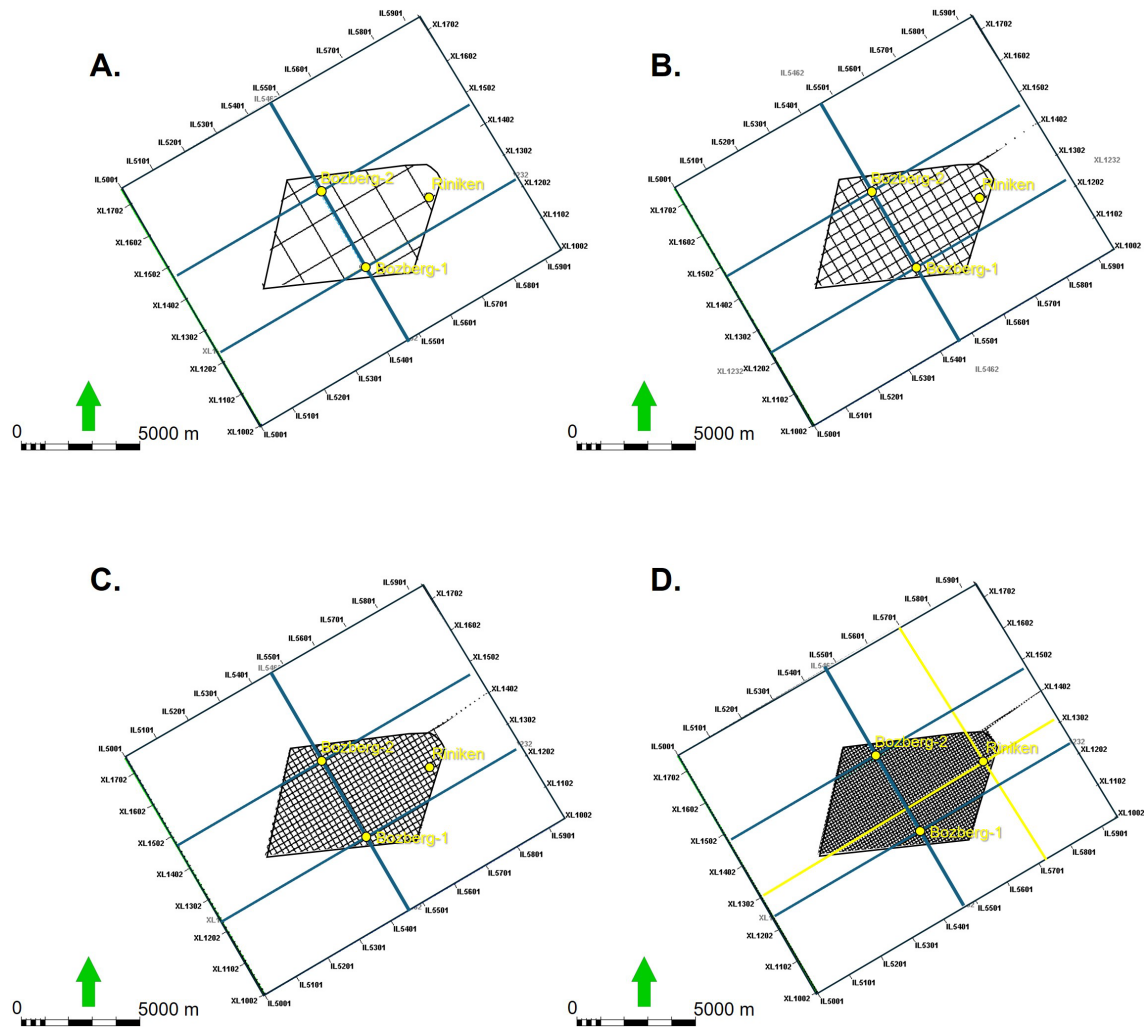


Fig. 3-5: Interpretation seedline methodology and grid building for the AOI in JO

A. Horizon interpretation is calibrated at inlines and crosslines (blue lines) crossing the Bozberg-1 and Bozberg-2 wells; B. interpretation is then performed with the initial grid of 32 x 32 lines; C. decreasing to 16 x 16 lines and finally to 8 x 8 lines (D.), and finally checked along the inline and crosslines crossing the Riniken well (yellow lines in D.).

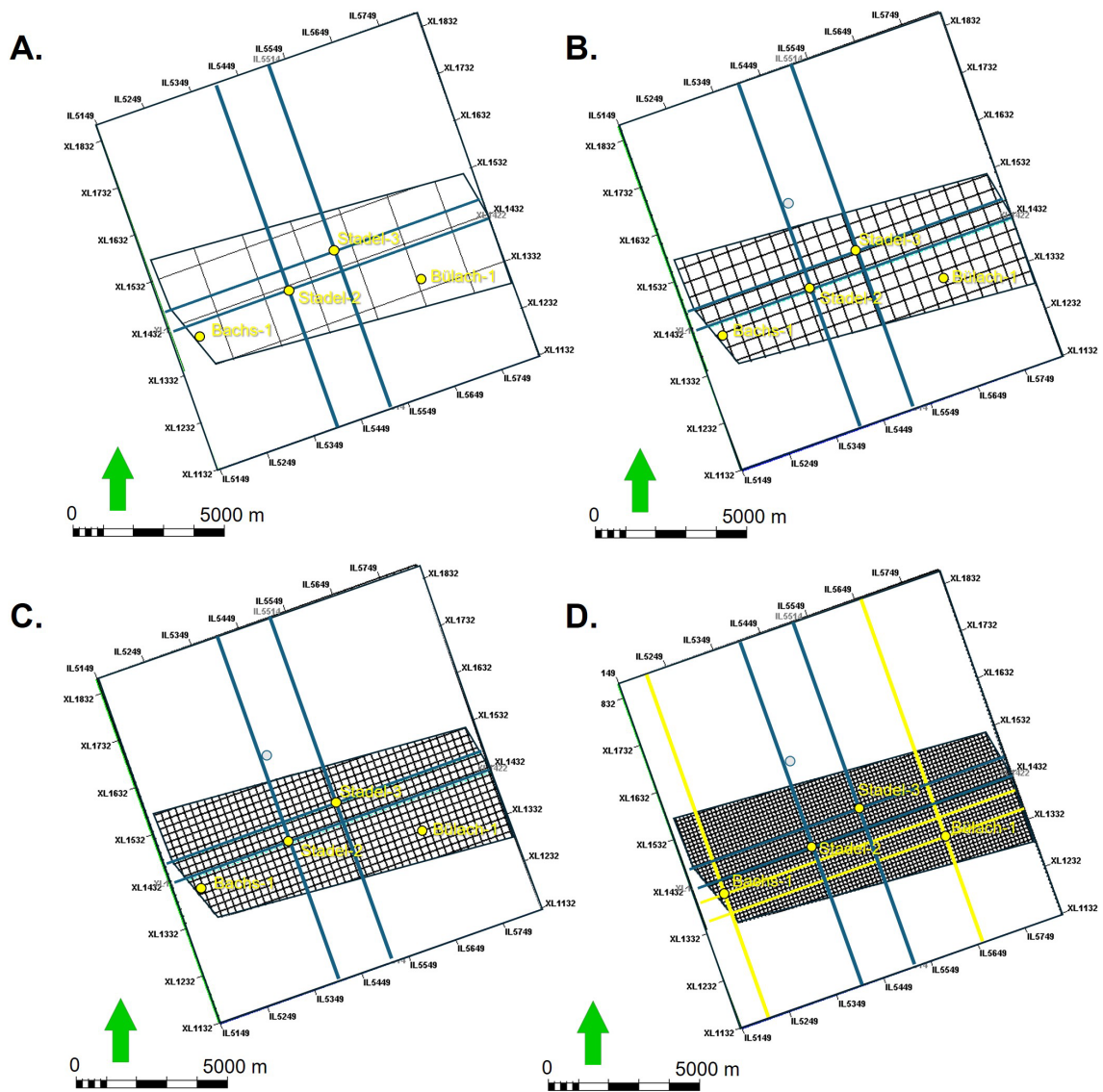


Fig. 3-6: Interpretation seedline methodology and grid building for AOI in NL

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

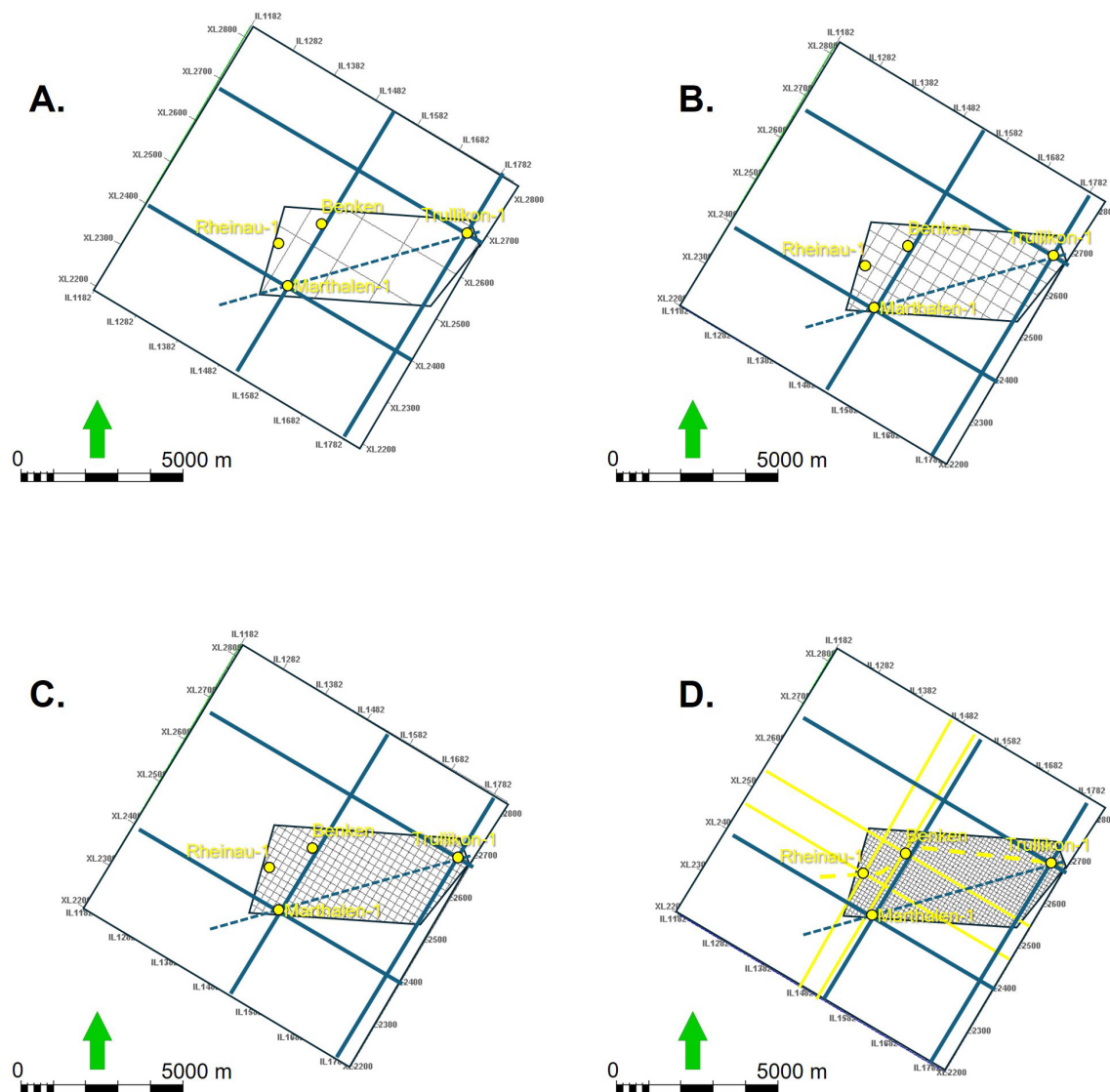


Fig. 3-7: Interpretation seedline methodology and grid building in ZNO

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

3.3 Depth conversion and uncertainty analysis

3.3.1 Datum and statics

Recorded seismic reflection travel-times are the two-way travel-time between Ground Level (GL) and the seismic reflector, since the seismic source and receivers are positioned at the topography surface.

In seismic processing, these recorded times are corrected to the Seismic Reference Datum, an imaginary horizontal surface above GL. The correction is based on a replacement velocity and the distance between SRD and GL. Time zero in the seismic data corresponds therefore to SRD.

Depth, on the other hand, can be specified as depth below SRD, as depth below GL (true vertical depth- TVD), measured depth (MD) or as depth below MSL (true vertical depth subsea -TVDSS).

The depth mentioned in this report are TVDSS (Fig. 3-8).

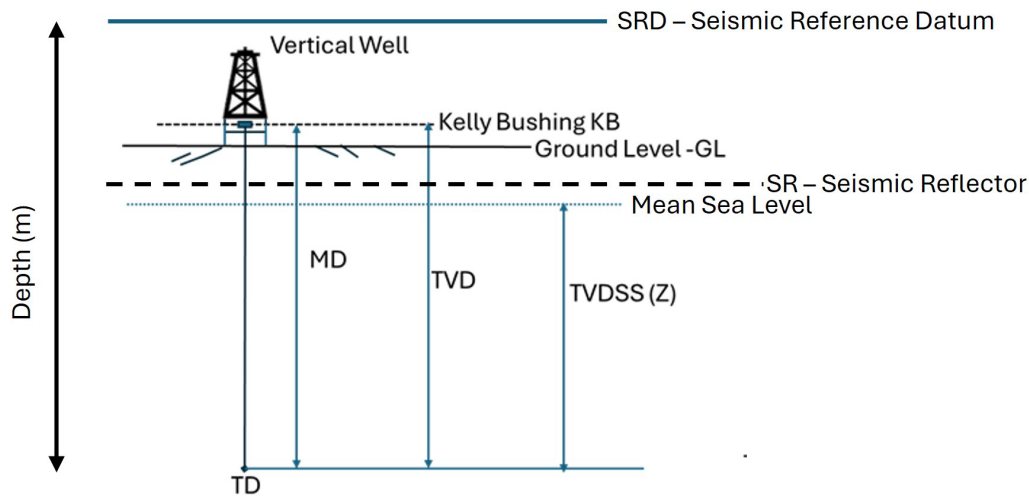


Fig. 3-8: Simple schematic showing the definition of TVD (true vertical depth), MD (measured depth) and TVDSS (true vertical depth subsea)

Note that for TVDSS the depth values are negative above Mean Sea Level (to ground level) and positive below mean sea level.

In the time-depth conversion, the first layer in the velocity model corresponds usually to this layer between SRD and GL and the velocity is the replacement velocity.

The layer below the GL surface is handled differently in pre-stack depth migration (PreSDM) than in pre-stack time migration (PreSTM). The lateral velocity variability of the near-surface rock is part of the seismic processing velocity model in the PreSDM. In the Time Migration processing, the variability is managed by applying statics; time shifts are applied to the recorded data based on a data-derived velocity model of the near-surface layer (i.e. the statics layer, the layer between GL and a so defined pseudo datum surface). After the statics correction has been applied, the seismic travel-times are those as if the waves had propagated through the statics layer with the replacement velocity.

Therefore, a second layer (between GL and pseudo datum) in the velocity model for the depth conversion of the PreSTM-ref seismic data should have been the static layer with the interval velocity being the replacement velocity (Fig. 3-9 A.). This scenario was tested in NL and ZNO and resulted in large depth residuals. A possible explanation could be that the data-derived near-surface velocity model may be incorrect (likely option since the low-frequency component of the statics solution is irresolvable as limited by the acquisition geometry). In this case, a shift between replacement velocity and an optimum depth conversion velocity is to be expected. Alternatively inaccurate time picks of a seismic horizon (due to seismic noise, poor seismic-to-well matching or wavelet phase errors) might result in an optimum depth conversion velocity (i.e. lowest depth residuals) that differs from the well velocities or, specifically in this case, by the replacement velocity.

A much better depth conversion result was obtained by replacing the static layer with a velocity layer bounded by a floating datum (corresponding to a smoothed GL) and the main velocity break reflector (i.e. 149.2 Kim - Top Malm) where the replacement velocity was substituted with a sonic-derived interval velocity (Fig. 3-9 B.).

In JO the statics layer is extremely thin or missing and therefore did not impact the depth conversion velocity model, as observed for NL and ZNO.

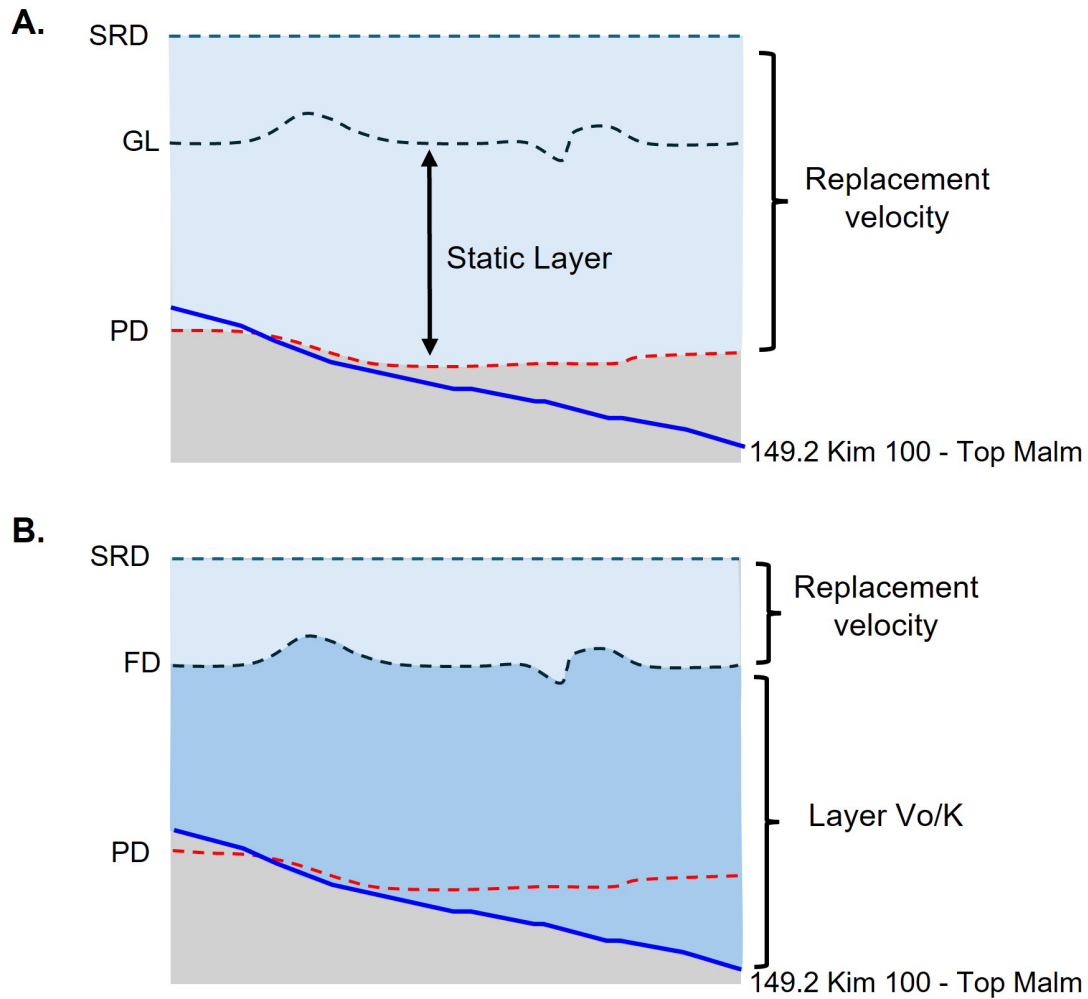


Fig. 3-9: Schematic illustration showing the approach used to overcome the challenges by applying the replacement velocity down to the defined pseudo datum observed in NL and ZNO

A. As for time migration the replacement velocity layer is the velocity characteristics for the layer between SRD and GL and for the “second” layer between GL and PD (including part of the shallow geology interval). B. Approach used in the time-depth conversion performed in this study. The replacement velocity was used from SRD down to the floating datum (smoothed ground level) and a second velocity layer was included from the floating datum to 149.2 Kim 100 – Top Malm reflector using sonic log derived velocities.

SRD is seismic reference datum, GL is ground level, PD is pseudo datum and FD is floating datum. Note that the floating datum is simply a smoothed version of the ground level.

3.3.2 General depth conversion workflow

The recommended workflow for performing time to depth conversion can be summarised in the below six fundamental steps:

1. Gather all available data:

- Wells, with geological formation tops depths, sonics and checkshots
- Seismic data sets, with seismic processing velocities
- Seismic horizon interpretations, plus information on interpretation uncertainty

2. Check the quality of each of these data items:

- Is the data correctly loaded onto the workstation (e.g. datum, replacement velocity...)?
- What is the quality of the data?
- What is the uncertainty in the data?

3. Use multiple velocity models, ideally from seismic processing velocities and from well data. Having a wide but still reliable range of velocity models is important to avoid an incorrect depth outcome with a false sense of low uncertainty:

- The quality of seismic velocities must be well understood (see previous step), with attention to the presence (or absence) of velocity anomalies and velocity scaling
- Well based velocity models, such as Vo/K models, should be kept as simple as possible and only be made more complex (such as Vo maps and/or K maps) if required
- Consider making hybrid velocity models, i.e. a combination of seismic velocities and Vo/K velocities.

4. Depth residuals are a key diagnostic; they should be small and random:

- If not, then the input data may be incorrect (or unreliable), or the velocity model needs to be updated.

5. For the selection of the base case a decision has to be made that involves which is the most likely horizon interpretation (in case of multiple scenarios) and which is the best velocity model. Various criteria can be used to decide which is best:

- Which scenario results in the smallest depth residuals
- Which depth matches best with other data (amplitudes for example) or makes most geological sense.

Best practice is that the choice for the base case is a joint decision of the seismic processor, the seismic interpreter and the geologist.

6. Depth uncertainty should be a deliverable of a depth conversion project:

- Uncertainty is associated with a probability. The uncertainty could, for example, be a minimum-to-maximum range or be the 1 standard deviation (Stdev) value
 - The range from -2Stdev to +2Stdev can be translated as a Min to Max range
- There are two approaches to estimate depth uncertainty, deterministically and probabilistically. It is advised to use both approaches

- The deterministic approach is to make several depth maps, using different velocity models combined with different seismic horizon interpretations (in case of interpretation scenarios)
 - The depth difference between the shallowest map and the deepest map is an indication of the depth uncertainty
- The probabilistic approach uses the base case depth map and requires estimates of the horizon pick uncertainty and the velocity uncertainty (and optionally the imaging uncertainty) as additional input
- A quick method is to provide the input uncertainties as Stdev values and then combine them via:

$$\sqrt{Stdev A^2 + Stdev B^2 + \dots}$$

- The next step is to compare the results from both approaches (deterministic and probabilistic):
 - Typically, the result with the largest value is chosen. This is because small depth differences between the various depth maps in the deterministic approach can result from the fact that all the velocity models are very similar. Alternatively, a small probabilistic depth uncertainty may capture the uncertainty in that model but miss the true depth.
- Finally, a health check should be made: ‘does the result look/feel reasonable?’. If not, re-evaluate/modify/re-run the performed workflow steps and results.

3.3.3 Application of the workflow

3.3.3.1 Depth conversion

Time-depth conversion is an important element of the seismic interpretation workflow. During their acquisition in the field, the seismic data are recorded in time, i.e. the travel times of the seismic waves. At some point during the processing of the data or during the interpretation, the data have to be converted to depth to obtain a representative depth image of the subsurface. The range of uncertainty in time-depth conversion can translate to a significant range of uncertainty in the depth and thickness of the target interval.

A key step is gathering and validating the input data, specifically velocity information and interpretation products, in order to define the velocity model. The velocity model is the complex part of the depth conversion exercise, as it is the translation box from time to depth (Etris al., 2001). The complexity of the velocity model depends on the velocity input data, the objective of the depth conversion and the complexity of the subsurface velocity (Fig. 3-10).

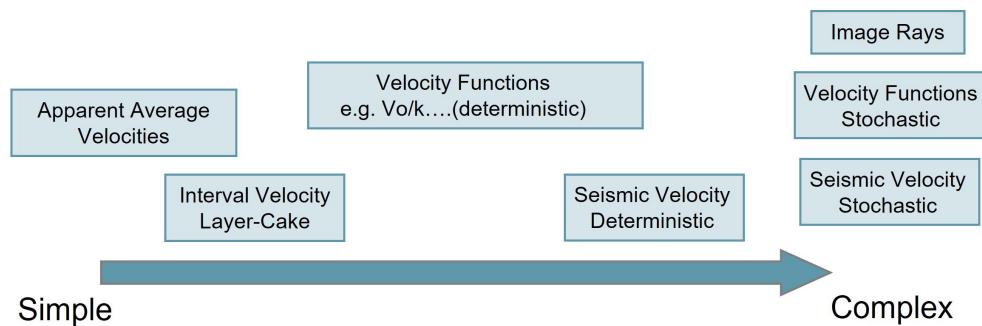


Fig. 3-10: Velocity models: approach and complexity depend on the velocity input data

Note that the most complex velocity models do not necessarily generate the best results.

When performing time-to-depth conversion, it should be kept in mind that: (i) complex velocity models do not necessarily mean better models, (ii) different models come with different depth solutions (basis for uncertainty analysis) and (iii) it is critical to understand the quality and limitations of the input data. This is the case especially for onshore projects as it is critical to understand at which absolute depth corresponds the zero TWT, which datum and replacement velocity were used during seismic processing and during the seismic data loading into the current seismic interpretation project.

Although seismic velocity is simply the velocity at which seismic wave travels through rock, several types of velocity can be used from different data sources, and these might not always show consistent velocities.

Velocity information can be derived from well data and seismic data.

The well-based velocities have a high degree of accuracy, also at larger depths where seismic velocities typically become less reliable. However, the drawback is that the velocities are only measured at the well locations (small calibration point) and not in between the wells, becoming, therefore, not predictive for strong lateral geological heterogeneity (= large lateral velocity variation). Typical well data sources are sonic logs and checkshots/VSP.

The seismic (processing) velocities include normal moveout (NMO) velocities, stacking velocities and migration velocities, and they are generated while processing the seismic data. The advantage of seismic processing velocities is that they are computed from seismic data at all subsurface grid points, capturing lateral variability in the velocities. Nevertheless, seismic processing velocities also have a number of disadvantages: (i) they are unreliable in poorly imaged or noisy seismic data, (ii) velocities lose their accuracy with increasing depth and below high-velocity intervals (e.g. carbonates), and (iii) seismic processing velocities are generally not vertical velocities. The scaling used to adjust the seismic imaging velocities to vertical velocities can be unreliable.

Several types of velocity input are available for the three siting regions. Some show more trustworthy quality than others, and their quality and availability are not always the same among the three siting regions.

Tab. 3-1 summarises the types of velocity input data and the results of the evaluation carried out to perform the depth conversion exercises.

Among the seismic velocities, no NMO or stacking velocities were available. The Time-Migration velocities were tested and resulted in very high residuals at depth. This means that the Time-Migration velocities were either unreliable, not scaled correctly, or they were not scaled with the accuracy required to meet the objective of the time-depth conversion project. Velocity

cubes were derived from the depth migration processing exercise, with different results across the three surveys. Despite some clear artefacts, PreSDM-derived velocities were not fully dismissed since they could be of interest potentially capturing the lateral variability of specific geologically heterogeneous intervals.

Tab. 3-1: Summary of velocity data sources with quality indicators

NMO and stacking velocities are not available.

Well Data	 Sonic Logs	
	 Checkshots/VSP	VSP variable quality
Seismic velocity	NMO Velocity	NA
	Stacking Velocity	NA
	 Time-Migration Velocity	The seismic imaging velocities from the PSTM-ref processing after Dix conversion resulted in very large depth mismatches with the well tops. Such values are a clear sign that the velocities are unreliable for depth conversion
	 PreSDM-derived velocity cube	Velocity anomalies observed causing artefacts (push-downs/pull-ups) – Can be used for specific interval after QC

For the purpose of the site investigation, comparability was highlighted as the fundamental component in the approach and analysis. Consequently, the velocity model, while exhausting all the best input data, should be built in a comparable manner for the three datasets (JO-15, NL-16 and ZNO-97/16).

Due to the observed limitations and unbalanced results of the processing velocities, and in-line with best practise depth conversion workflows to investigate the full range of velocity models, a layered form of velocity model (Vo/K approach) was used. This model consists of a limited set of layers. Each of these zones (layers) can have an independent set of rules to calculate velocity. The velocity in each layer can be described by (i) an interval velocity (constant velocity in the layer), (ii) a linear velocity-depth function via a depth factor K, (iii) average properties representing lateral velocity trends and (iv) average cubes where the velocity is represented by attribute volume (e.g. seismic velocity) such that vertical and lateral velocity trends can be capture.

Since the identified areas of interest represent relatively undisturbed areas with generically flat horizontal (layer-cake) geology no vertical trend within velocity layers are needed for depth conversion and therefore the K factor was assumed equal to zero. While a very simple model with a single velocity layer for the entire Mesozoic sequence with a depth dependency velocity trend (K), was considered geologically unreasonable due to the important vertical lithological heterogeneity.

Depth residuals, i.e. the difference between the computed depth of an event and the actual depth encountered in the well (Fig. 3-11), are a good diagnostic for the validity of the velocity model for time depth conversion. This holds if there is an adequate number of wells. In contrast, a limited well control and their locations can result in biased conclusions.

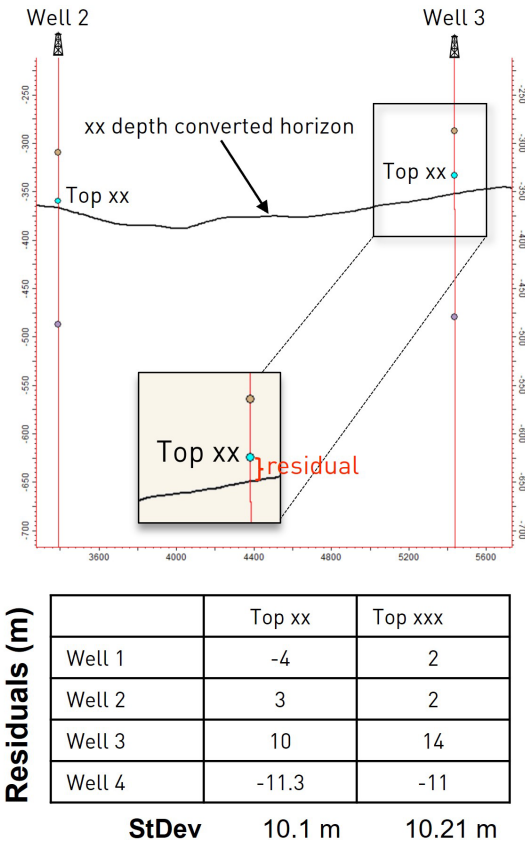


Fig. 3-11: Schematic drawing explaining the concept of residuals and their evaluation using the standard deviation approach

Residuals positive values: horizon is too deep (selected velocity too fast); negative values: horizon is too shallow (selected velocity too slow). An estimation of the uncertainty can be derived using the standard deviation calculated from the residual values.

Indications of a good depth conversion model are depth residuals with a small mean and a low standard deviation (Fig. 3-11). Large residuals indicate either incorrect input data (incorrect tops or time picks), incorrect velocities or lateral positioning errors of seismic events, while the spatial distribution of residuals should not show a strong trend, as this would indicate a velocity variation unexplained by the model. Any trend in the residuals should therefore be removed by capturing the trend in the velocity model in a geologically meaningful way.

Several scenarios and methodologies can be tested during the depth conversion exercise, resulting in several depth structures. However, a reference case (solution of choice) must be selected. The reference case is generally referred to as the base case. Its depth map can be chosen based on different criteria, e.g. it could be the map with the smallest depth residuals. Alternatively, it could be the map made with the most geology-consistent velocity model. Ideally, it is based on a model that has both. It is also important to analyse whether the map makes geological sense, by being able to explain structure and thickness trends within the regional geological framework.

There are no globally established criteria to define the base case. Considering the comparability scope of the site investigation, the base case was selected following the three established criteria below:

1. Use of comparable seismic products between sites: PreSTM-ref is the most comparable seismic processing product among the three surveys. Therefore the resulting surfaces from the PreSTM-ref interpretation have to be used
2. Conservative approach: selection of the interpretation of the base host rock (Top Lias - 174.7 Toa -100), which is by tendency the shallowest (smaller thickness of host rock)
3. Technically acceptable velocity model: model is consistent with data and captures relevant heterogeneity within the data.

3.3.3.2 Depth Uncertainty

The base case depth prediction for seismic horizons should always be accompanied by the uncertainty evaluation in the predictions. There are several contributing factors to depth uncertainty such as uncertainty in the velocity, in the seismic interpretation or in the seismic imaging. If the contributions of the individual factors can be estimated, they can be combined using the following mathematical formula:

$$\sqrt{2 \text{ Stdev } A^2 + 2 \text{ Stdev } B^2} + \dots$$

where A and B are two different sources of uncertainty, assuming that each contributor produces a Gaussian uncertainty distribution and that the various contributors are independent.

Independently from individual parameters, uncertainty must also be clearly defined. It can either be expressed as a standard deviation value or as a minimum-to-maximum range or as maps derived by comparison of different depth-conversion realisations. Depth residuals at wells usually already provide a good estimation of the uncertainty value (Fig. 3-11).

However, for the purpose of this evaluation, because of the small number of wells in the area of interest, the residuals alone were not considered representative of the depth uncertainty for the target surfaces (Top and Base Opalinus Clay interval).

Depth uncertainty was, therefore, estimated based on a combination of two criteria:

- (i) depth residuals at wells and
- (ii) depth differences between depth conversion scenarios.

When considering the standard deviation (Stdev), the range from +2Stdev to -2Stdev covers the 95% outcome range and can thus be interpreted as the minimum-to-maximum range.

For the first criterium (depth residuals at wells) the absolute values of the two Stdevs calculated at wells in each of the three siting regions are here considered to be the minimum values of depth uncertainty for both top and base of the target interval (Opalinus Clay).

Assessing depth uncertainty can also be performed by comparing results from depth conversions using different methodologies. Such scenarios, though, should have credibility and capture the main source of the uncertainty.

Results derived from the different Vo/K models with interval velocity only were tested and compared. For the three siting regions, this comparison shows very similar results with no important differences (generally smaller than the two Stdev values from well residuals) between the selected scenarios and therefore they do not provide a critical deviation for the uncertainty maps.

A further analysis of the depth residuals at wells indicates that the highest residuals, consistently in JO, NL and ZNO, are associated with the “shallow stratigraphic level”. This suggests that the heterogeneity of this interval is the key source for the uncertainty.

Since seismic data with different processing (statics) solutions are available, depth maps calculated from the different seismic vintages could provide insights into the lateral variability of depth uncertainty.

PreSDM data were processed with detailed near-surface velocity model which was further use to compute the PreSTM statics, and which resulted in top structure artefacts (Nagra 2024a, 2024b, 2024c). Subsequently, the PreSDM was only partly considered in this evaluation.

The QLP seismic dataset was processed with a different solution for the shallow geology (Nagra 2024d) and was, therefore, selected as the alternative scenario. A comparable Vo/K velocity model was built to convert the QLP legacy TWT interpretation to depth (Nagra 2019a, 2019b, 2019c).

The uncertainty maps for the top and base of the target interval (Opalinus Clay) were, thus, calculated by applying a four-step approach (Fig. 3-12):

1. The uncertainty base (minimum) value was defined to correspond to the absolute 2Stdev of the well residuals
2. Lateral variability of the uncertainty was estimated based on the difference (absolute value) between the selected conversion scenarios (base case PreSTM-ref and base case for QLP seismic data, the latter generated by mimicking the PreSTM-ref base case)
3. The uncertainty trend maps incorporate results from Step 1 and Step 2
4. The uncertainty values were tapered to a value of 2 m at well locations (assuming almost no uncertainty at well location) with an influence radius of 1500 m, which corresponds to the size of major observed topographic features.

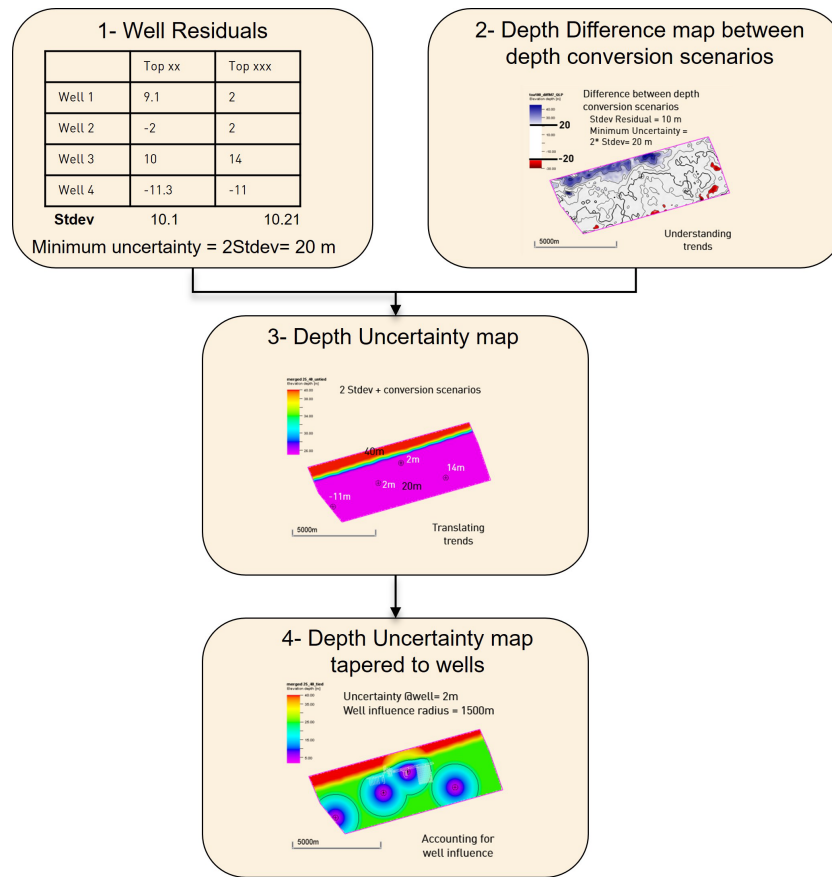


Fig. 3-12: Four step workflow applied for the generation of depth uncertainty maps

3.3.3.3 Thickness Uncertainty

Within the site characterisation process, an important parameter corresponds to the quantification of the thickness of the host rocks and the upper and lower confining units ¹, and the uncertainty associated with them (Nagra 2024f).

The (depth) thicknesses were calculated as seismic thickness maps from the depth-converted base case surfaces representing the top and base of the above-mentioned units.

The thickness of an interval is the velocity of the interval multiplied by the interval traveltime (i.e. time difference between top and base of the interval; $\Delta Z = V * \Delta T$).

The uncertainty associated with the thickness therefore depends on the uncertainties in:

1. the selected velocity for the interval of interest
2. the picking uncertainty (mapping of the horizon in time)

The variability in the well velocities is used to compute the velocity standard deviation. If the Stdev of the velocity is x% of the average velocity, then the impact of velocity uncertainty on the thickness is x% of the average thickness (Tab. 3-2).

Consistently with the depth uncertainty approach, an absolute value of 2Stdev was chosen to cover the 95% outcome range.

Tab. 3-2: Seismic thickness uncertainty associated with the variability of the interval velocity

This was calculated based on the Stdev of the average velocities at wells proportional to the average thickness of the interval. 1Stdev was calculated as 3.1 m which yields a 2Stdev of 6.2 m.

Example Calculation - Interval 1	
Well 1 – av. velocity	3400 m/s
Well 2 – av. velocity	3600 m/s
Well 3 – av. velocity	3350 m/s
Well 4 – av. velocity	3560 m/s
Average Velocity	3477 m/s
Stdev velocity	121 m/s
Average Thickness	90 m
Stdev (proportional to thickness)	3.1 m

} Values for calculation

The picking uncertainty depends on the thickness of the seismic loop which provides the “space” for the pick positioning.

However, horizon picking in each region is controlled by wells, which facilitate the seismic-to-well matching. Even when a horizon would have been picked incorrectly, for example on a maximum of the seismic loop while it should have been on the zero-crossing, this does not result in an incorrect depth conversion result. The reason being that the ‘incorrect’ time pick automatically leads to an ‘incorrect’ depth conversion velocity such that the resulting depth is correct (because the velocity is tuned to produce the smallest depth residuals). Therefore, as long as any picking error is laterally consistent, then there is no depth error due to time picking uncertainty. It can therefore be excluded in the computation of the thickness uncertainty.

4 Results

4.1 Depth conversion and uncertainty analysis: JO

4.1.1 Horizon interpretation

In accordance with the methodology described in Section 3.2, the seven full survey horizons (Nagra 2024a) were infilled with eleven extra horizons (Tab. 4-1, Fig. 4-1).

As in Nagra 2024a, a traffic light approach was used to show the quality (interpretability) of the resulting horizons (Tab. 4-1, column 1). Green (column 1) horizons are reflections that can be mapped with confidence across the AOI and do not show major changes in reflectivity (except across zones identified to be of low seismic quality, i.e. Quaternary valleys), variation in loop thickness and/or presence of doublets. Red horizons are extremely challenging horizons, generically associated with discontinuous and complex seismic patterns. Orange are horizons of variable quality and level of interpretability across the area of interest.

Tab. 4-1: The seven full survey horizons (light green) were complemented with eleven horizons within the AOI

Despite the area of interest coincides mostly with the undisturbed area, the quality and confidence with regard to picking the horizons can vary and is captured with a traffic-light classification shown using red (lower quality), orange (medium quality) and green (good quality) colours in column 1. Note that for the full survey horizons the quality is derived from the full survey evaluation.

	Stratigraphic Horizons	Lithostratigraphy	Phase
1	154.8 Oxf 300	Top Wildegg	peak
2	154.8 Oxf 700	Intra Wildegg	trough
3	154.8 Oxf 975	Top Dogger Gr	trough
4	168.2 Baj 100	Top Passwang	trough
5	168.2 Baj 400	Intra Passwang	peak
6	170.9 Aal 300	Top Opalinus Clay	trough
7	174.7 Toa 100	Top Lias Gr	peak
8	192.9 Sin 100	Top Frick Mb	Z-crossing
9	192.9 Sin 200	Near Top Klettgau	trough
10	201.4 Rha 100	Top Klettgau	S-crossing
11	227 Car 100	Top Gansingen Mb	Z-crossing
12	227 Car 200	Near Top Bänkerjoch	trough
13	227 Car 300	Top Bänkerjoch Fm	S-crossing
14	237 Lad 100	Intra Bänkerjoch Fm	peak
15	237 Lad 200	Intra Bänkerjoch Fm	peak
16	237 Lad 400	Top Muschelkalk Gr	Z-crossing
17	237 Lad 500	Top Stamberg Mb	trough
18	251.9 Per 100	Base Mesozoic Unconformity	S-crossing

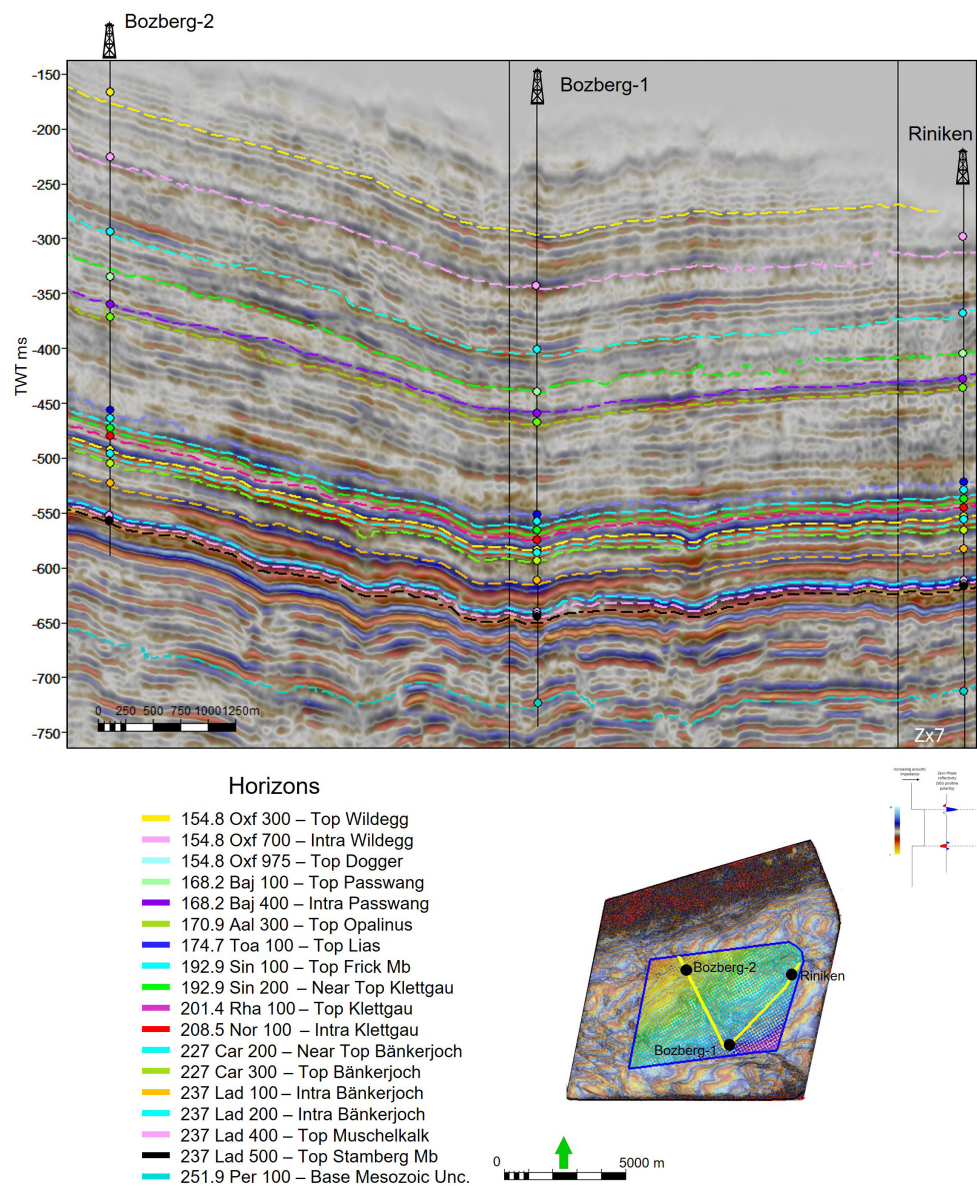


Fig. 4-1: Seismic section across the three wells within the AOI showing the 18 horizons

Confidence in horizon picking is captured in Tab. 4-1. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

When considering the interval target (Opalinus Clay) for the depth conversion and uncertainty evaluation, important criticalities were observed in the Opalinus Clay overburden and extra effort was invested to map the shallower stratigraphic horizons and their lateral extents (erosion or data muting, Fig. 4-2, Fig. 4-3, Fig. 4-4, Nagra 2024a).

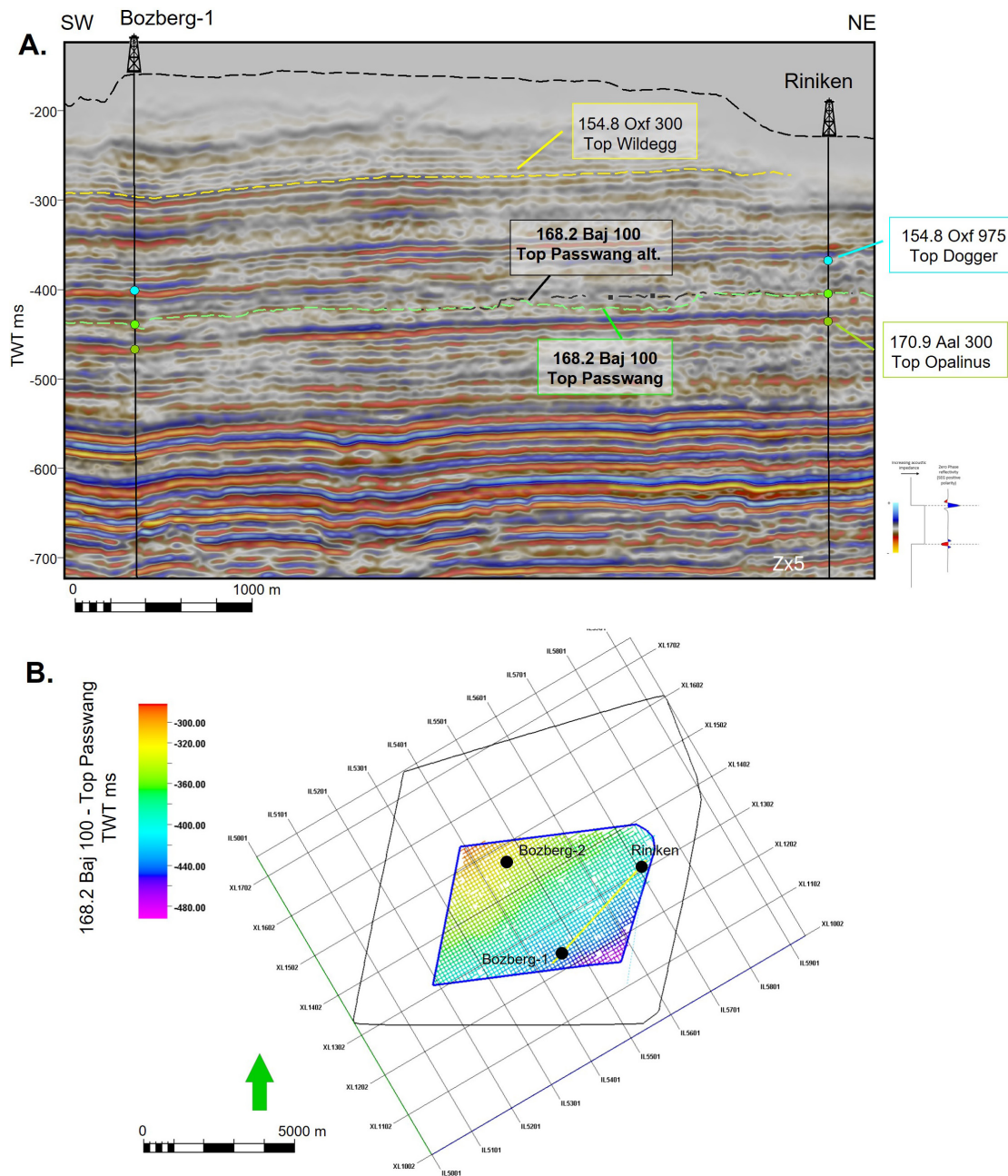


Fig. 4-3: Seismic random line showing the 168.2 Baj 100 - Top Passwang horizon

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map with wells (black circles). The 168.2 Baj 100 - Top Passwang horizon is a challenging horizon to map, characterized by discontinuous reflection variable in amplitude content and thickness, mirroring the complex geology of this stratigraphic interval. In the eastern side of the AOI, the picking becomes uncertain and two alternative interpretations were therefore considered, with the alternative interpretation (A. black) interpreted about 13 ms (TWT) higher.

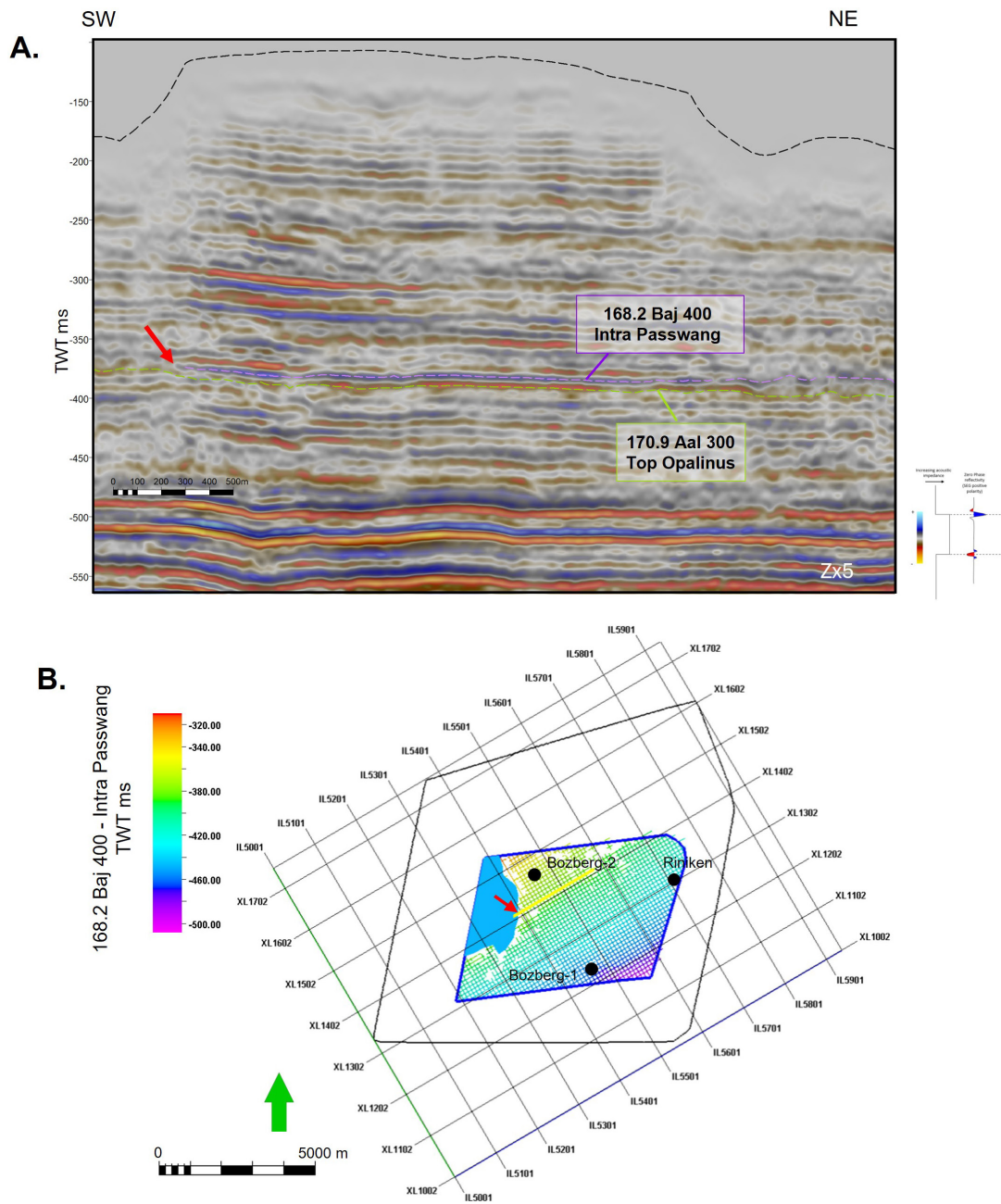


Fig. 4-4: Seismic crossline 1410 showing the 168.2 Baj 400 - Intra Passwang horizon

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map with wells (black circles). The 168.2 Baj 400 - Intra Passwang reflection appears to pinch-out against 170.9 Aal 300 - Top Opalinus towards the west (red arrow A. and B.). The limit of the pinching-out was mapped and the area where the horizon is not present was captured as a polygon to facilitate the surface building process (light blue area, B). Seismic data are PreSTM-ref.

For the 174.7 Toa 100 - Top Lias (Base Opalinus Clay) alternative interpretations were performed to constrain and overcome the recognised issues (Nagra 2024a, Nagra 2019a) yielding to a conservative interpretation (shallow as possible) such as not to overestimate the calculated host rock thickness (Fig. 4-5). Three different solutions were tested. The reflectivity mapping was compared with horizons derived from relative acoustic impedance and a high frequency filtered cube (i.e. the resulting seismic data with a frequency content of 30 to 60 Hz). The latter was selected since it represents the most continuous and the most conservative (thinner clay interval) solution.

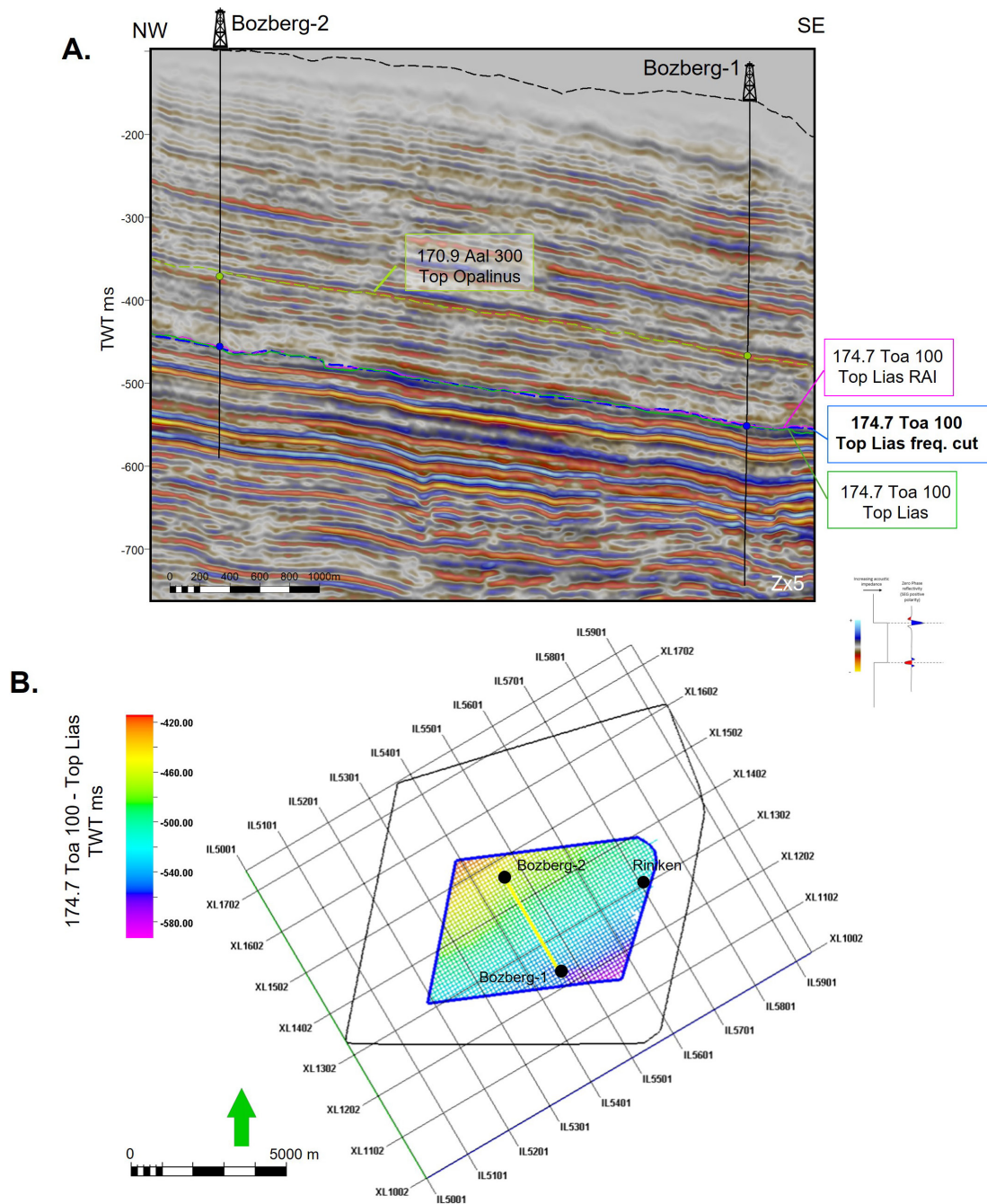


Fig. 4-5: Seismic inline 5461 showing the 174.7 Toa 100 - Top Lias horizon

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map with wells (black circles). Due to the low acoustic contrast with the overlaying Opalinus Clay the picking of this horizon is extremely challenging. Three alternative picking solutions were performed: (i) mapping the reflectivity as base line (green, A.) (ii) mapping using relative acoustic impedance translating the peak into a zero-crossing (pink, A.) and (ii) by generating a low-band (high frequency cut filter) seismic cube (blue). The latter was selected since it represents the most continuous and the most conservative (thinner clay interval) solution. Seismic data are PreSTM-ref.

Once the horizon interpretation was performed, the two-way travel time surfaces were generated by the interpretation of seed-line grids using convergent gridding algorithm with 25 x 25 grid. No autotracking, no smoothing, and no forced tie to well tops in time were applied.

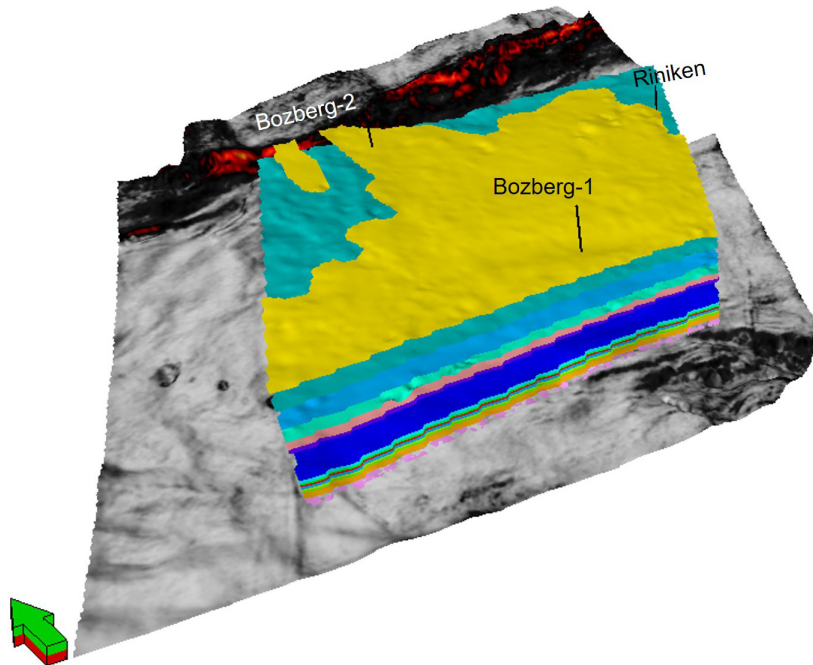


Fig. 4-6: 3D display of the 18 surfaces (TWT) generated for the AOI

237 Lad 200 - Intra Bänkerjoch variance horizon slice and the three key wells are shown to display the relative location of AOI within JO-15 survey. Green arrow points toward north. Vertical exaggeration is 5.

4.1.2 Depth conversion

The focus of the time-to-depth conversion exercise was to provide depth maps for the top and base host rock (Opalinus Clay) and an evaluation of the uncertainty associated with that. Furthermore, uncertainty was also estimated for the seismic thickness of the host rock as well as of the upper and lower confining units¹.

The host rock corresponds to the Opalinus Clay interval bounded by the 170.9 Aal 300 - Top Opalinus and the 174.7 Toa 100 - Top Lias horizons, the upper confining unit is the stratigraphic interval between 168.2 Baj 100 - Top Passwang and 170.9 Aal-300 Top Opalinus Clay and the lower confining units¹ is bounded by 174.7 Toa 100 - Top Lias and 237 Lad 400 -Top Muschelkalk.

The three key wells (Bozberg-1, -2, Riniken, Fig. 2-1) are located within the area of interest. Good sonic logs as well as TDR (time-depth relationship) from VSP and synthetics are available for the Bozberg-1, -2 wells and with lower quality also for the older Riniken well. Sonic logs were used to identify velocity breaks, which represent boundaries of critical velocity changes. The sonic logs were upscaled within the recognised velocity breaks correlating with key stratigraphic markers (Fig. 4-7). The upscaled/averaged velocity logs were used to calculate the input interval velocity for the velocity models (Tab. 4-2).

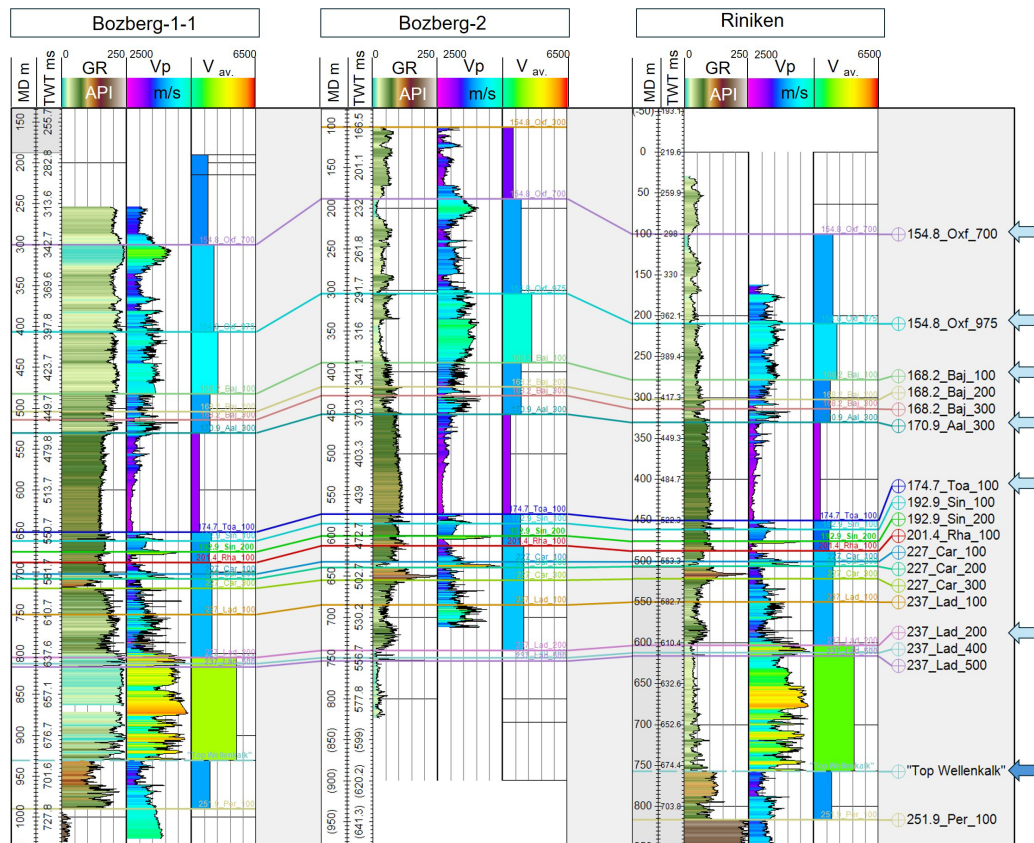


Fig. 4-7: Well correlation panel showing how major velocity breaks correspond to key stratigraphic units

Light blue arrows indicate the identified velocity breaks. Blue arrow indicates an extra velocity break corresponding to the top of the Wellenkalk lithological interval. This velocity break is positioned at the base of the velocity model and therefore was not considered. Displayed logs are gamma-ray, sonic velocity and upscaled average velocity.

Once the key velocity breaks were identified, several velocity models were generated and compared by evaluating and exhausting all the available velocity information. While building and testing the different models, key pragmatic rules were followed: (i) avoid thin layers, (ii) start simple (constant V_0) and increase complexity only if necessary (e.g. carbonate layers) (iii) aim for small and random residuals at wells, by starting with sonic-derived velocities, and tune them within the observed ranges.

Analysis of the velocities in the three wells as well as qualitative screening of the seismic velocity suggest that no obvious depth (vertical= increase of depth velocity) trend can be recognised for either the entire stratigraphic stack or within specific stratigraphic intervals (Fig. 4-7).

Tab. 4-2: Average velocity calculated at wells from upscaled sonic logs

Velocity Layers		Bozberg-1	Bozberg-2	Riniken	Average Vel.
Top	Base	Average Velocity per well m/s			
GL	154.8 Oxf 700 - Intra Wildegg	3224	2848	2500	2857
154.8 Oxf 700 - Intra Wildegg	154.8 Oxf 975 - Top Dogger	3637	3415	3137	3396
154.8 Oxf 975 - Top Dogger	168.2 Baj 100 - Top Passwang	3957	4143	3732	3944
168.2 Baj 100 - Top Passwang	170.9 Aal 300 - Top Opalinus	3504	3417	3325	3415
170.9 Aal 300 - Top Opalinus	174.7 Toa 100 - Top Lias	2861	2880	2772	2838
174.7 Toa 100 - Top Lias	237 Lad 200 - Intra Bänkerjoch	3485	3456	3421	3456
237 Lad 200 - Intra Bänkerjoch	251.9 Per 100 - Base Mesozoic Unc.	5053	-	4661	4857

Multiple realisations with multiple combinations of velocity inputs and ranges were tested. Among them, three scenarios are shown as examples of the approach, rationale and evaluation of all the velocity source combinations and results (Tab. 4-3, Tab. 4-4, Tab. 4-5).

Residuals at key velocity breaks were analysed, to evaluate the velocity model results. A small mean residual (indicating an unbiased depth conversion) and a low standard deviation (meaning the method explains the depth quite well) are indications of a good depth conversion model. The spatial distribution of residuals should not show a strong trend, which would indicate a velocity variation unexplained by the model. Residuals are also a direct measure of the depth conversion uncertainty at any horizon. Positive residuals mean that the horizon is too deep, and a too fast velocity was selected for the interval, while negative residuals mean that the horizon is too shallow and on the contrary the chosen velocity value was too slow.

Tab. 4-3: Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces

Model 1 is a simplified model, the shallow stratigraphic interval (above 170.9 Aal 300 - Top Opalinus) is represented by one interval velocity. The velocities are the well velocities (for each interval the average velocity was calculated from upscaled logs). The geological heterogeneities of the Opalinus Clay overburden were smoothed.

Model 1		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3600 m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3400m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2838 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3456 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4857 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Aal 300	Toa 100	Lad 200
Well				
	Bozberg-1	-4	-6.8	-3.28
	Bozberg-2	13	15	14
	Riniken	18	22	26

Tab. 4-4: Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces

Model 2 is a model with interval velocities. The detailed layering uses the key identified velocity breaks (Fig. 4-7). The velocities are again the well velocities. Residuals are relatively big, larger than the simple Model 1, specifically at shallower levels, suggesting that the higher granularity might introduce complexity, which does not improve the results.

Model 2		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3600 m/s
154.8 Oxf 700 - Intra Wildegg	V=Vint= Vconst	2857 m/s
154.8 Oxf 975 - Top Dogger	V=Vint= Vconst	3396m/s
168.2 Baj 100 –Top Passwang	V=Vint= Vconst	3944 m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3415m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2838 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3456 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4857 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Oxf 700	Oxf 975	Baj 100	Aal 300	Toa 100	Lad 200
Well							
	Bozberg-1	-35.7	-38.16	-42	-43	-44	-46
	Bozberg-2	5.3	-2.7	-24.3	-14.22	-9.84	-16.9
	Riniken	17.59	4	5.58	5.6	12.18	10.18

Tab. 4-5: Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces

Model 3 is a more complex (hybrid) velocity model, where seismic velocity was used to capture the heterogeneities associated with the Opalinus Clay overburden (Fig. 4-9). The interval velocities below the Top Opalinus are modified well velocities to improve the residuals at wells. Model 3 was selected as the base case.

Model 3		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	$V=V_{int}=V_{const}$	3600 m/s
170.9 Aal 300 - Top Opalinus	$V=\text{seismic velocity cube}$ (smoothed PSDM velocity)	
174.7 Toa 100 - Top Lias	$V=V_{int}=V_{const}$	2900m/s
237 Lad 200 - Intra Bänkerjoch	$V=V_{int}=V_{const}$	3600 m/s
251.9 Per 100 - Base Mesozoic Unc.	$V=V_{int}=V_{const}$	4800 m/s
Depth: -1500 ms TWT	$V=V_{int}=V_{const}$	4250 m/s

	Horizons	Aal 300	Toa 100	Lad 200
Well	Bozberg-1	-6.93	-7.46	-3.82
	Bozberg-2	-1.72	2.66	2.18
	Riniken	-6.69	-0.2	3.88

The interval velocities below the Top Opalinus are modified well velocities, which were optimised to produce the smallest depth residuals. There are several reasons why the optimum depth conversion velocities can be different from the well velocities. The sonics can have a drift or may not be calibrated with check shots. Seismic noise, wavelet phase errors and horizon time pick errors in general lead to incorrect time values which require adjusted velocities to produce correct depth values.

Model 3 was selected as the base case as it accounts for the geological heterogeneities and resulted in small and distributed residuals. Although some velocity anomalies were observed (Nagra 2024a), the anomalies did not generate critical artefacts. Therefore, the use of seismic velocities was preferred for this interval since it could capture the geological complexity associated with the Opalinus Clay overburden. In the JO-15 PreSDM seismic data, the key velocity anomalies were identified within the Opalinus Clay. Anomalies that showed a shape and trend that could not be geologically explained nor recognised in any of the wells within the JO siting region, as well as in NL and ZNO siting regions (Tab. 4-5).

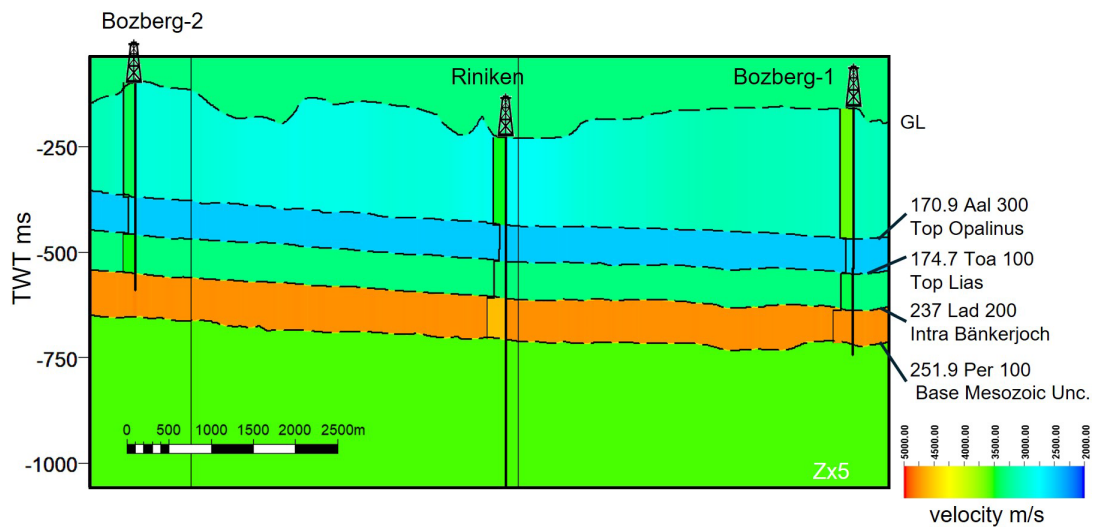


Fig. 4-8: Base case Vo/K velocity model translated into a velocity cube

Section across the wells showing the lateral and vertical trends of Model 3 (base case, Tab. 4-5) and the well average velocity per velocity layer. The velocity model is a hybrid model with interval velocities combined with seismic velocity for the interval above 170.9 Aal 300 - Top Opalinus. The seismic velocity was selected because of the geological heterogeneity of this interval. Although it is slower than the average velocity at wells, it still provides relatively small residuals (Tab. 4-5). GL is ground level.

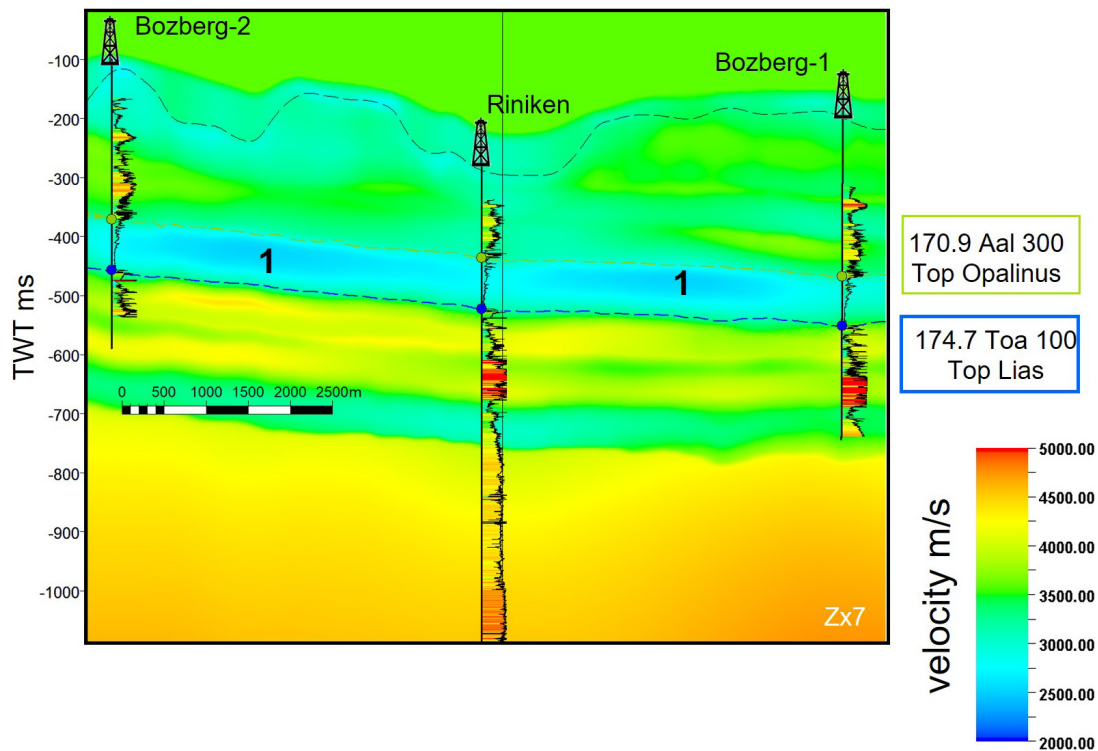


Fig. 4-9: Section from the PreSDM calculated velocity model showing the velocity anomalies within the Opalinus Clay interval

The velocity anomalies (1) are positioned away from the well control and show a lens-shaped low velocity body, a trend not recognised in any of the wells within the JO, NL and ZNO siting regions.

Velocity Model 3 (base case) was therefore used to perform depth conversion with focus on the top and base host rock (170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias, respectively, Fig. 4-10, Fig. 4-11).

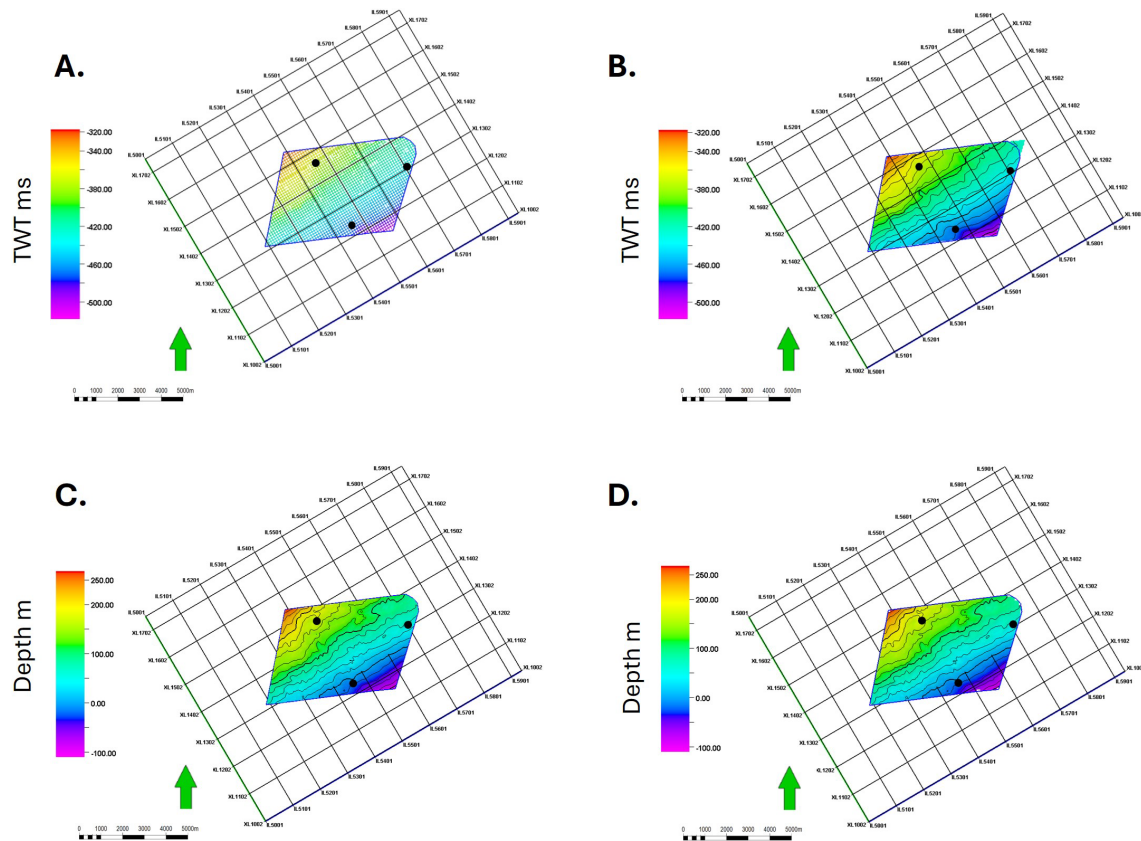


Fig. 4-10: Time and depth surfaces of 170.9 Aal 300 - Top Opalinus

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 3; Tab. 4-5) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

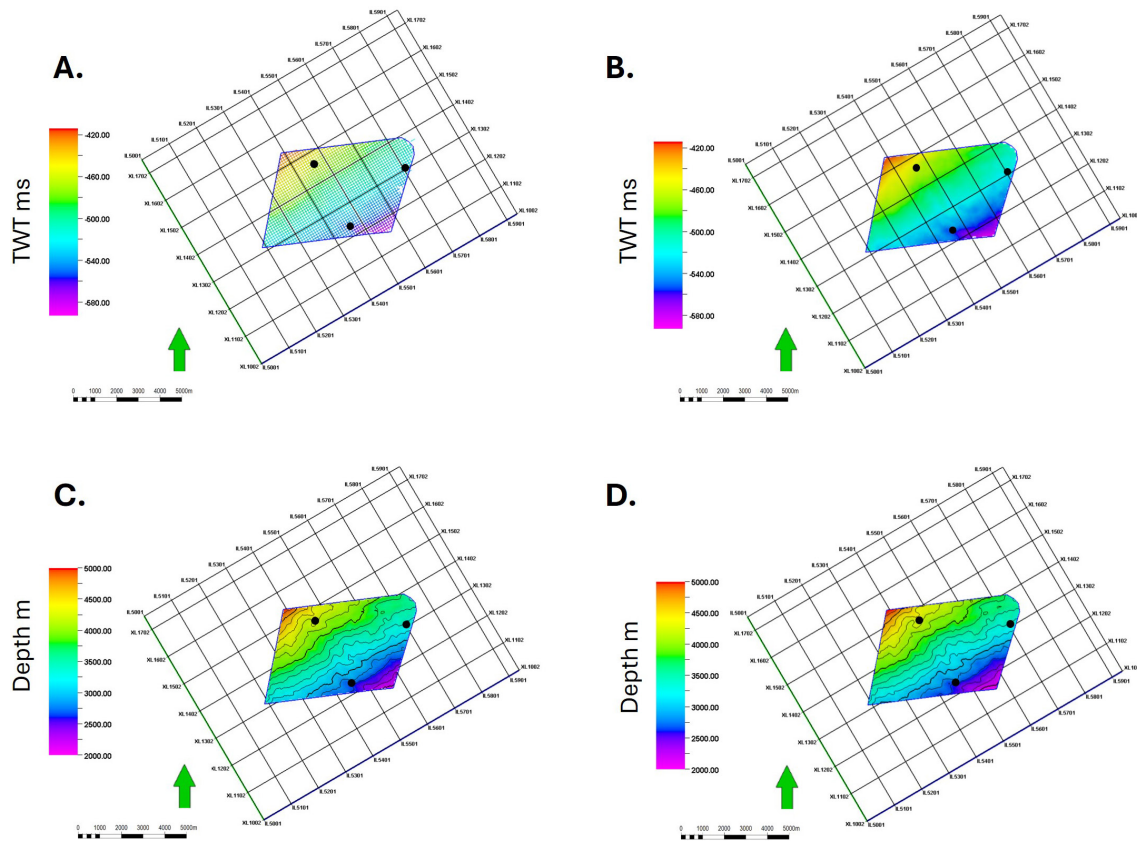


Fig. 4-11: Time and depth surfaces of 174.7 Toa 100 - Top Lias

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 3; Tab. 4-5) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

4.1.3 Depth and thickness uncertainties

Depth uncertainty was calculated for the depth converted horizons representing the top and base of the host rock (Opalinus Clay interval), 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias, respectively.

Depth uncertainty calculation followed the workflow proposed in Section 3.3, assuming as minimum uncertainty value the 2Stdev from the well top residuals (Tab. 4-6).

Tab. 4-6: Well top residuals and calculated standard deviations at 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias

		170.9 Aal 300– Top Opalinus	174.7 Toa 100 – Top Lias
	Bozberg-1	-6.93	-7.46
	Bozberg-2	-1.72	2.66
	Riniken	-6.69	-0.2
	Stdev	3	5
	2 Stdev	6	10

The 2 standard deviation value can be used as an indication for the depth uncertainty. The range from +2Stdev to -2Stdev covers the 95% outcome range. It could be interpreted as the minimum-to-maximum range. The low residuals resulting from the selected hybrid model can however be considered biased by the well calibration in the PreSDM seismic velocities. The low standard deviation likely underestimates the depth uncertainty. Therefore, for the JO dataset, the general rule of residuals being a direct measurement of the conversion uncertainty cannot be considered valid. A value of 12 m (= 4Stdev coinciding with 100% solution) was selected to represent the minimum uncertainty for 170.9 Aal 300 - Top Opalinus. The same value was also extrapolated to the 174.7 Toa 100 - Top Lias horizon, since this horizon was depth converted using a constant velocity from the 170.9 Aal 300 - Top Opalinus and since the 2 Stdev well residuals were already equal to 10m.

In accordance with the proposed workflow, the uncertainty trend maps were derived by difference of the PreSTM-ref depth maps with QLP depth maps converted with a similar base case velocity model.

The velocity model for the QLP dataset was therefore built at start with the aim of reproduce the base case hybrid model (Model 3, Tab. 4-5). However, due to the different static solutions the seismic velocity was not matching the QLP. A velocity attribute map was generated by extracting the average velocity from the seismic PreSDM velocity cube for the interval covering the shallow interval above the 170.9 Aal 300 - Top Opalinus horizon (Fig. 4-12). This velocity attribute map should have theoretically captured the heterogeneity observed in this interval.

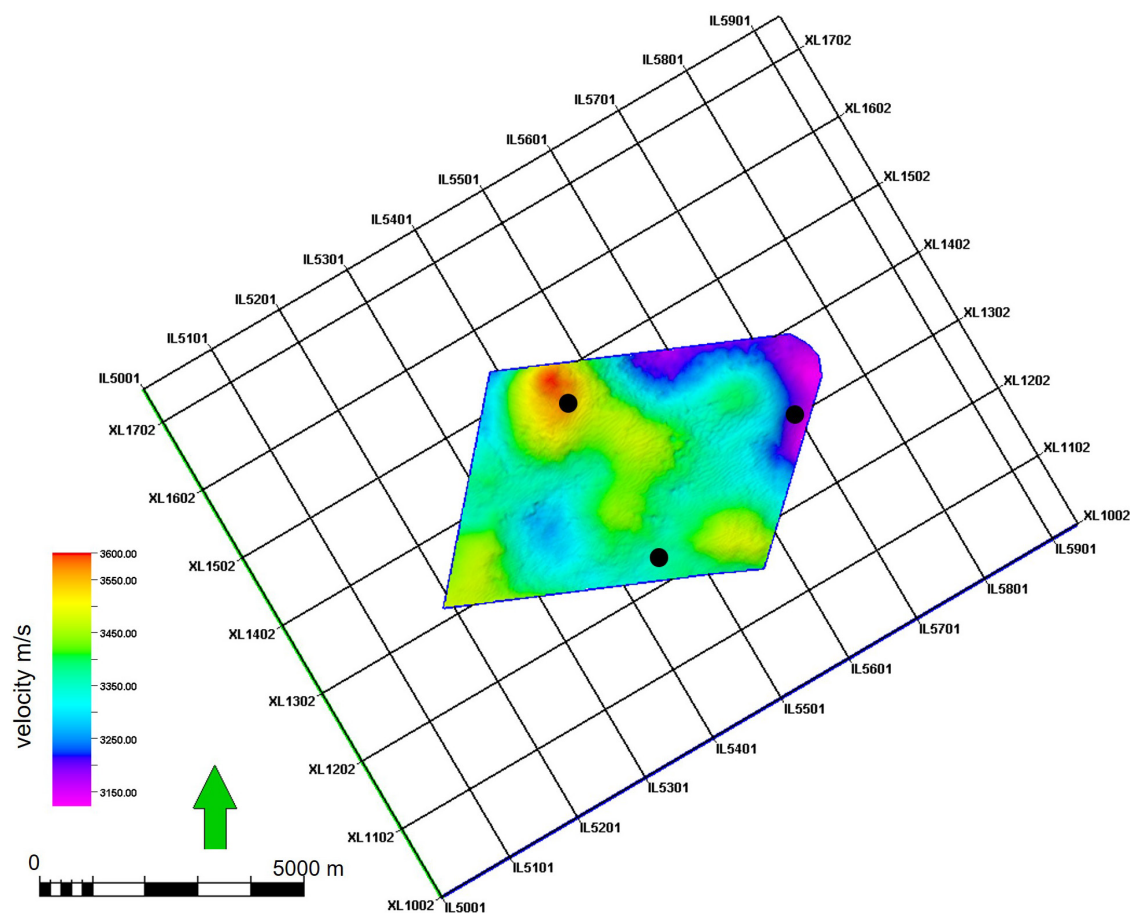


Fig. 4-12: Velocity attribute map for the interval above the 170.9 Aal 300 - Top Opalinus calculated by extracting the average of the PreSDM velocity cube for this interval

However, this hybrid model resulted in extremely high residuals at wells after depth conversion and simpler Vo/K models with interval velocities were tested and tuned to achieve smaller residuals, while keeping the velocity values within the velocity ranges observed in the PreSTM-ref testing. Among the several tested scenarios, a model with the lowest and best spread of residuals was selected (Tab. 4-7).

Tab. 4-7: Selected Vo/K realisation for the QLP dataset. Velocity source input and residuals at velocity break surfaces

The selected model is a simple velocity model, which results in relatively small residuals.

QLP Model Vo/K		
Horizon Base	Model (velocity sources)	Velocity Value
Pseudodatum	V=Vint= Vconst	3600 m/s
170.9 Aal 300 - Top Opalinus (QLP)	V=Vint= Vconst	3680 m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3500 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4857 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4000 m/s

Well	Horizons	Aal 300	Toa 100
	Bozberg-1	17	12.08
	Bozberg-2	-18.23	-14.23
	Riniken	-2.47	-2.55

The resulted QLP depth-converted surfaces for 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias are shown in Fig. 4-13.

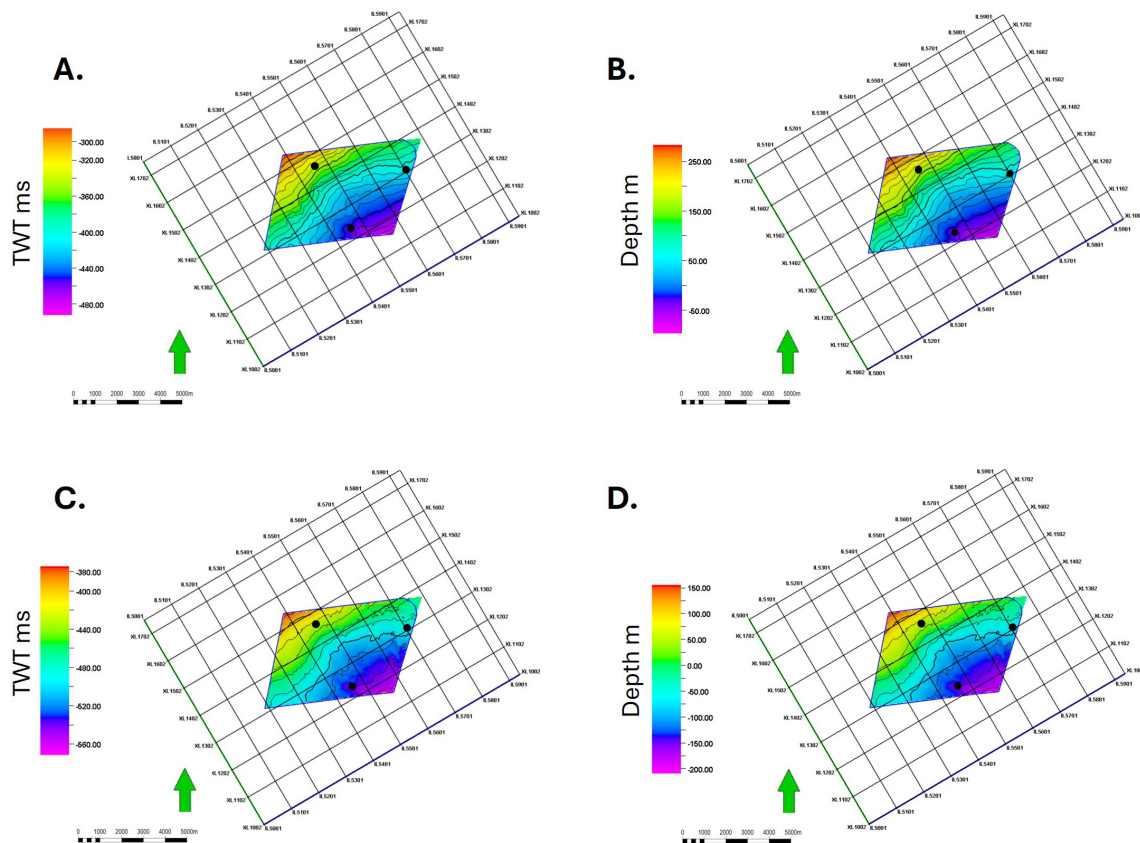


Fig. 4-13: 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage

170.9 Aal 300 - Top Opalinus t: A. in TWT and B. in depth; 174.7 Toa 100 -Top Lias; C. in TWT and D. in depth. QLP TWT key horizons were depth-converted using a Vo/K model. The QLP depth-converted surfaces for the top and base host rock were not forced to wells and they were used to calculate depth uncertainty trend maps. Black circles are wells.

Comparison between the two solutions (PreSTM-ref and QLP) shows an area of important difference (> 40 m) in the central area of the AOI (Fig. 4-14).

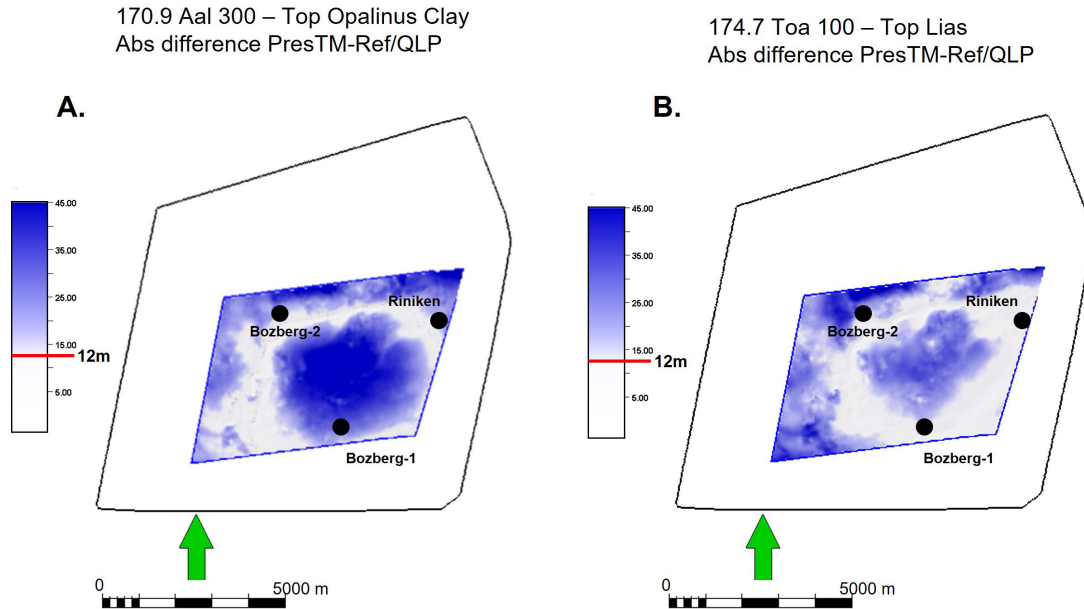


Fig. 4-14: Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data

A. 170.9 Aal 300 - Top Opalinus; B. 174.7 - Top Lias. Abs is absolute value. Values smaller than 12 m are white colour. 12 m represents the base uncertainty value, corresponding to the 4Stdevs, chosen to overcome the bias of the selected velocity model.

Depth uncertainty maps (Fig. 4-15 A., C.) were built by extrapolating uncertainty trends from the selected realisation comparison (Fig. 4-14) with a minimum (base) uncertainty value equal to the calculated 12 m of the well residuals for the base case scenario (Tab. 4-6) for both 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias. The uncertainty trends were then tapered to a value of 2 m at well locations with an influence radius of 1500 m (size of major topographic features). The well tapering accounts for an uncertainty value equal (almost) to zero at well location (Fig. 4-15 B., D.).

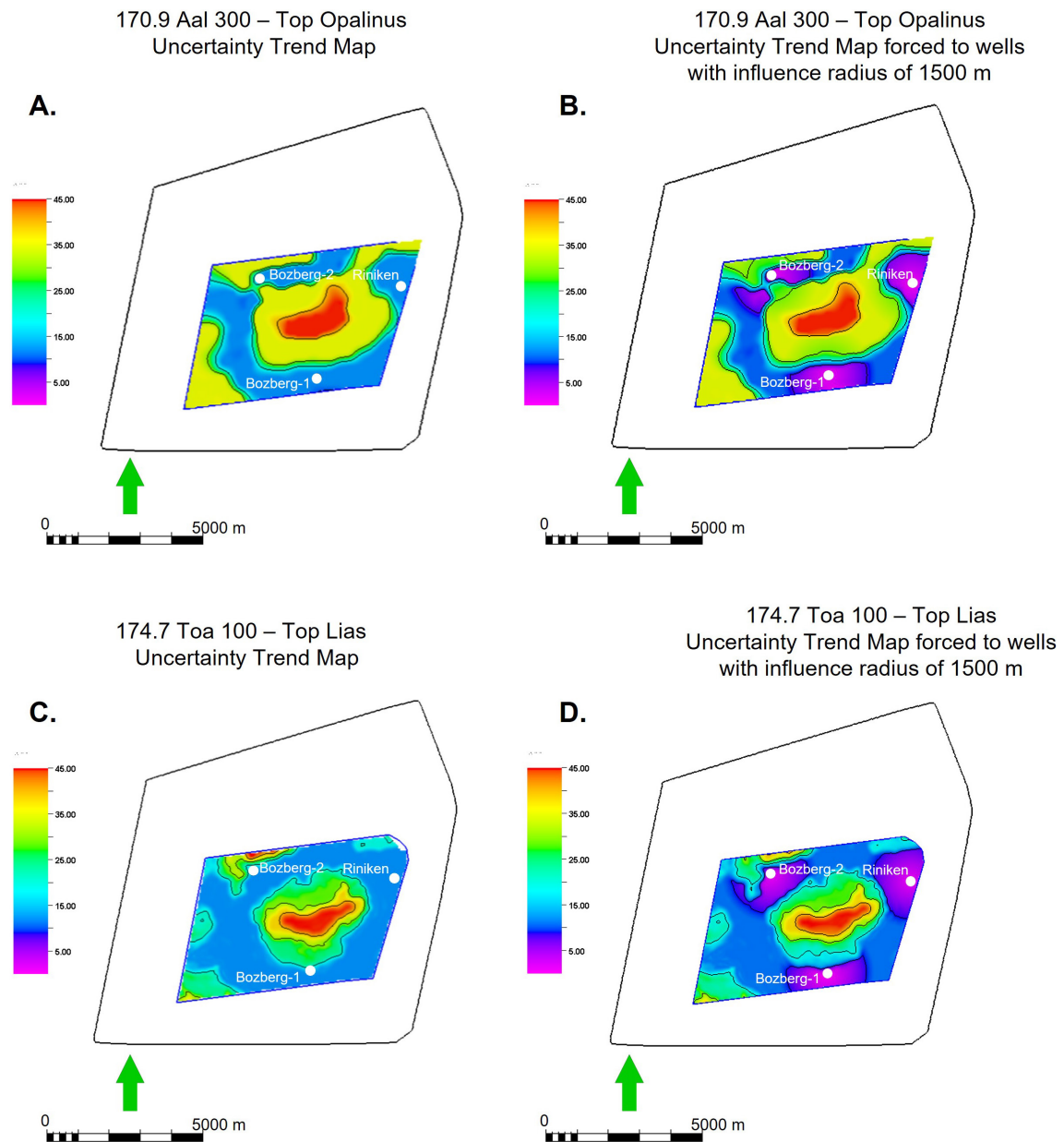


Fig. 4-15: Uncertainty depth maps for 170.9 Aal 300 - Top Opalinus Clay and 174.7 Toa 100 - Top Lias

Minimum value for the uncertainty is 12 m calculated from the residuals at wells. Trend maps (A., C.) were generated using difference maps from the selected realisations (Fig. 4-14) and further tapered to wells (2 m uncertainty at well location; B., D.)

A quality control on the depth uncertainty maps is provided by the calculation of an upper and lower case. The upper- and lower-cases are generated by adding or subtracting the absolute value uncertainty maps to the base case depth map. The upper- and lower-case surfaces should envelop the base case depth map (Fig. 4-16).

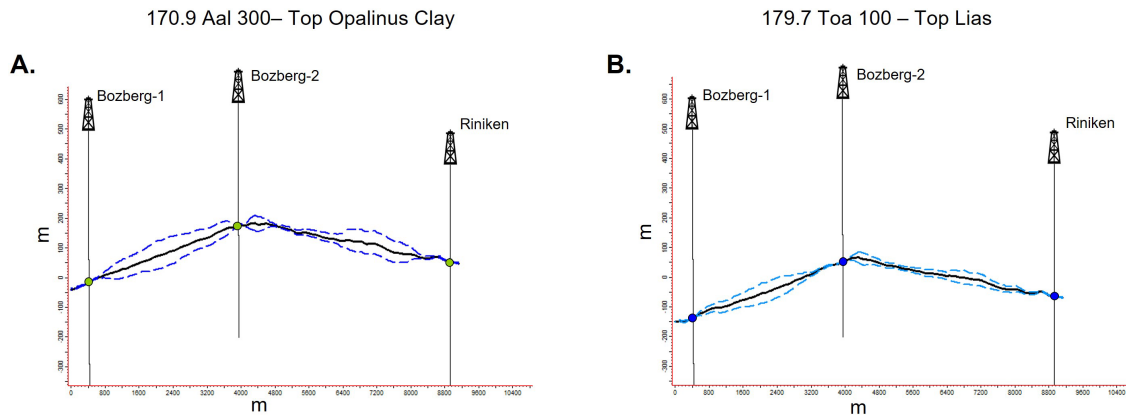


Fig. 4-16: Depth section across the three wells showing the base case enveloped by the upper- and lower-cases

A. 170.9 Aal 300 - Top Opalinus Clay. Black solid line is the base case surface, blue dashed lines are upper- and lower-case surfaces. Well tops are green circle. B. 174.7 Toa 100 - Top Lias. Black solid line is the base case surface, light blue dashed lines are upper- and lower-case surfaces. Well tops are blue circle.

From the PreSTM-ref base case depth converted surfaces, seismic thickness maps (Fig. 4-17) were calculated for the Opalinus Clay (host rock). The thickness maps were derived by untied (not forced to wells) surfaces and compared with thickness observed at wells.

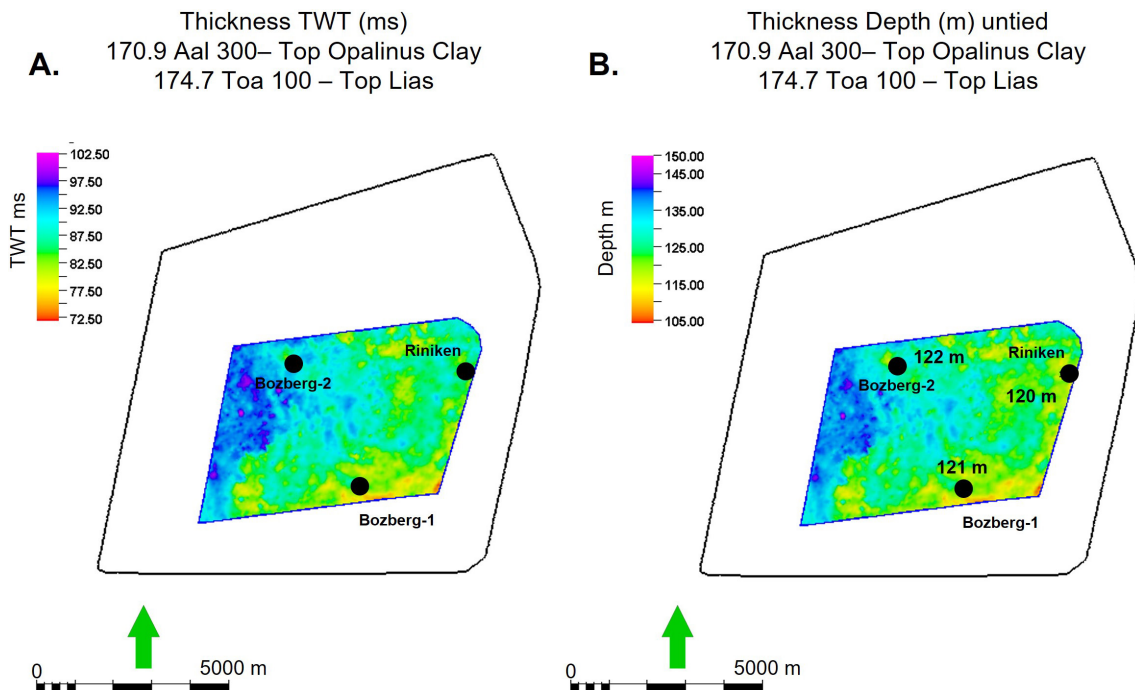


Fig. 4-17: TWT (A) and depth (converted, B.) seismic thickness for the interval 170.9 Aal 300 - 174.7 Toa 100 - Top Lias

The thickness depth is untied, surfaces 170.9 Aal 300 and 174.7 Toa 100 - Top Lias were not forced to wells. Despite not being forced to the wells, note the good match between seismic thickness and thickness measured in wells (black numbers, B.).

The thickness uncertainty associated with variability of interval velocity was, thus, calculated for the host rock (Opalinus Clay) and the upper and lower confining units¹ (168.2 Baj 100 - Top Passwang - 170.9 Aal 300 Top Opalinus and 174.7 Toa 100 - Top Lias to 237 Lad 400 Top Muschelkalk intervals, respectively).

For the upper confining unit (168.2 Baj 100 - Top Passwang - 170.9 Aal 300- Top Opalinus), the impact of the interval velocity, which is estimated as Stdev derived from the Stdev of the velocity ranges proportional to the interval average thickness (Tab. 4-8), is estimated equal to 2.8 m (2Stdev) for an average thickness of 54m.

Tab. 4-8: Input and results for the velocity component of the thickness uncertainty of upper confining unit

168.2 Baj 100 - Top Passwang – 170.9 Aal 300– Top Opalinus	
	Well Velocity
Bozberg -1	3504m/s
Bozberg -2	3417 m/s
Riniken	3325 m/s
Average Velocity	3415 m/s
Stdev (velocity)	89 m/s
Average Thickness	54 m
Stdev	1.4 m
2 Stdev	2.8 m

The same approach applied to the host rock (170.9 Aal 300 Top Opalinus - 174.7 Toa 100 - Top Lias) is shown in Tab. 4-9. The velocity contribution is estimated equal to 5 m (2Stdev).

Tab. 4-9: Input and results for the velocity component of the thickness uncertainty of the host rock

170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	
	Well Velocity
Bozberg -1	2861 m/s
Bozberg -2	2880 m/s
Riniken	2772 m/s
Average Velocity	2837 m/s
Stdev (velocity)	57.6 m/s
Average Thickness	127 m
Stdev	2.5 m
2 Stdev	5 m

The velocity contribution for the lower confining unit^l (174.7 Toa 100 - Top Lias to 237 Lad Top Muschelkalk) is capture in Tab. 4-10 and it is calculated equal to 2.4 m (2Stdev).

Tab. 4-10: Input and results for the velocity component of the thickness uncertainty of the lower confining unit^l

174.7 Toa 100 – Top Lias – 237 Lad 400 – Top Muschelkalk	
	Well Velocity
Bozberg -1	3485 m/s
Bozberg -2	3456 m/s
Riniken	3421 m/s
Average Velocity	3450 m/s
Stdev (velocity)	26 m/s
Average Thickness	157 m
Stdev	1.2 m
2 Stdev	2.4 m

4.2 Depth conversion and uncertainty analysis: NL

4.2.1 Horizon interpretation

The six full survey horizons (Nagra 2024b) were infilled with thirteen extra horizons in accordance with the approach proposed in Section 3.2. As in Nagra 2024b, a traffic light approach was used to show the quality (interpretability) of the resulting horizons (Tab. 4-11, Fig. 4-18). Green (column 1) horizons are reflections that can be mapped with confidence across the AOI and do not show major changes in reflectivity (except across zones identified to be of low seismic quality, i.e. Quaternary valleys), variation in loop thickness and/or presence of doublets. Red horizons are extremely challenging horizons, generically associated with discontinuous and complex seismic patterns. Orange are horizons of variable quality and level of interpretability across the area of interest.

Tab. 4-11: The six full survey horizons (light green) were complemented with thirteen horizons within the AOI

Despite the area of interest coincides mostly with the undisturbed area, the quality and confidence with regard to the picking the horizons can vary and is captured with a traffic-light classification shown using red (lower quality), orange (medium quality) and green (good quality) colours in column 1. Note that for the full survey horizons the quality is derived from the full survey evaluation.

	Stratigraphic Horizons	Lithostratigraphy	Phase
1	149.2 Kim 100	Top Malm	peak
2	149.2 Kim 700	Top Villigen Fm	peak
3	154.8 Oxf 300	Top Wildegg Fm	trough
4	154.8 Oxf 700	Top Gerstenhuebel Bd	Z-crossing
5	154.8 Oxf 975	Top Dogger Gr	S-crossing
6	168.2 Baj 200	Top Herrenwis Unit eq	Peak
7	168.2 Baj 300	Base Herrenwis Unit eq	Trough
8	168.2 Baj 400	Intra Wedelsandstein Fm (Top Clay Unit)	peak
9	174.7 Toa 100	Top Lias Gr	S-crossing
10	192.9 Sin 100	Top Frick Mb	Z-crossing
11	192.9 Sin 200	Near Top Klettgau	Trough
12	201.4 Rha 100	Top Klettgau	S-crossing
13	208.5 Nor 100	Top Seebi Mb	Z-crossing
14	227 Car 200	Near Top Bänkerjoch	trough
15	227 Car 300	Top Bänkerjoch Fm	S-crossing
16	237 Lad 100	Intra Bänkerjoch Fm	Z-crossing
17	237 Lad 200	Intra Bänkerjoch Fm	peak
18	237 Lad 400	Top Muschelkalk Gr	Z-crossing
19	251.9 Per 100	Base Mesozoic Unconformity	Z-crossing

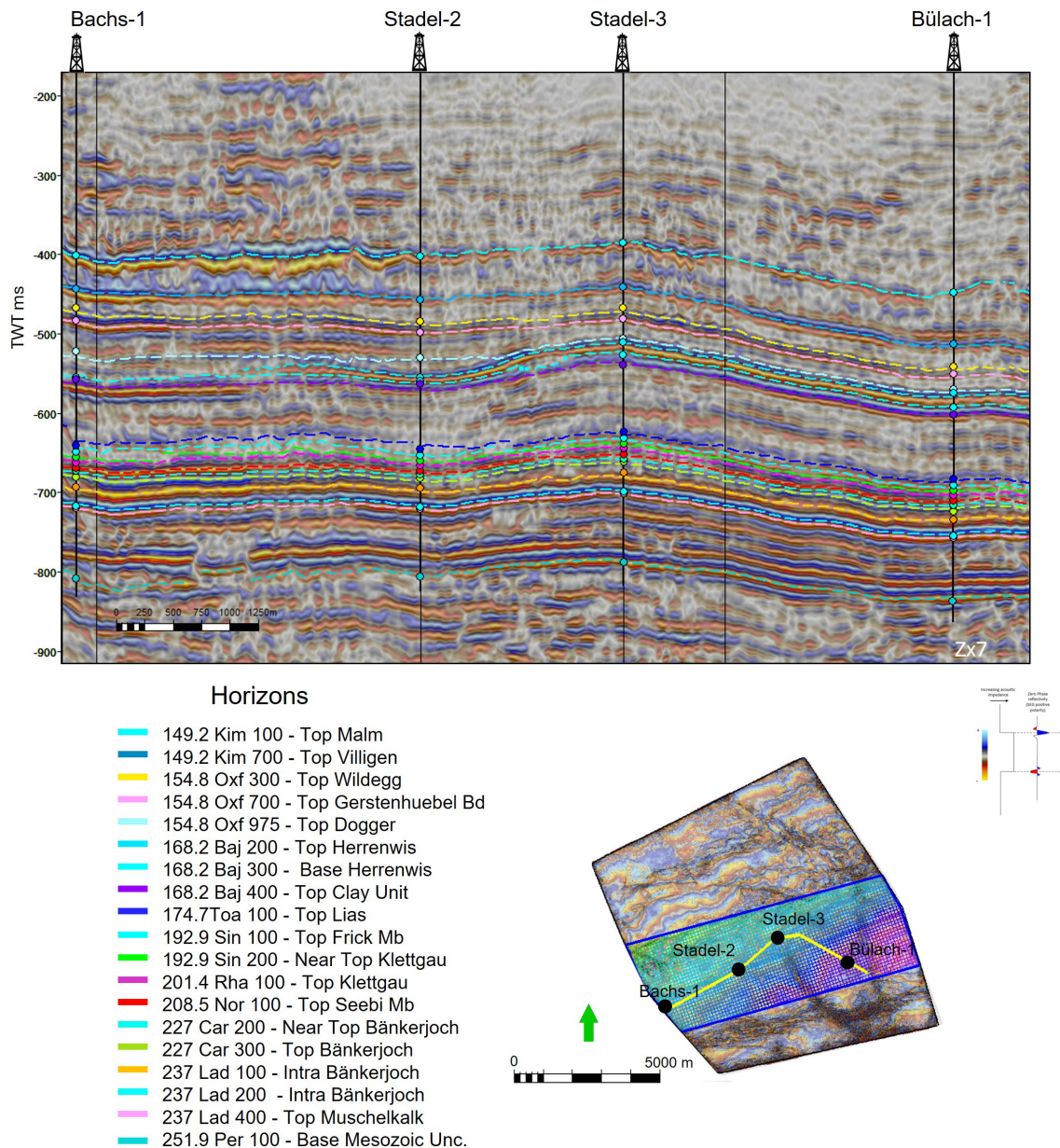


Fig. 4-18: Seismic section across the four wells within the AOI showing the 19 horizons

Confidence in horizon picking is captured in Tab. 4-11. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

The full survey horizon interpretation (Nagra 2024b) highlighted the challenge for the NL-16 seismic dataset to image with confidence the top and base of the Opalinus Clay (host rock). Even if the AOI represents a relatively simple “layer-cake” zone, away from the structurally complex areas, the traceability for the 170.9 Aal 300 - Top Opalinus and the 174.7 Toa 100 - Top Lias horizons remains difficult. Despite investing considerable effort, the 170.9 Aal 300 - Top Opalinus horizon could not be interpreted, due to the lack of an acoustic contrast as observed and explained in Nagra 2024b. As in the full-survey interpretation results (Nagra 2024b), the 168.2 Baj 400 - Top Clay Unit horizon was used as proxy for the top surface of the host rock.

The 174.7 Toa 100 - Top Lias (Base Opalinus Clay) horizon was interpreted by performing alternative interpretations to constrain and overcome the recognised issues (lack of a strong acoustic contrast). The interpretation exercise yielded to a conservative interpretation (shallow as possible) such that the calculated host rock thickness was not overestimated (Fig. 4-19).

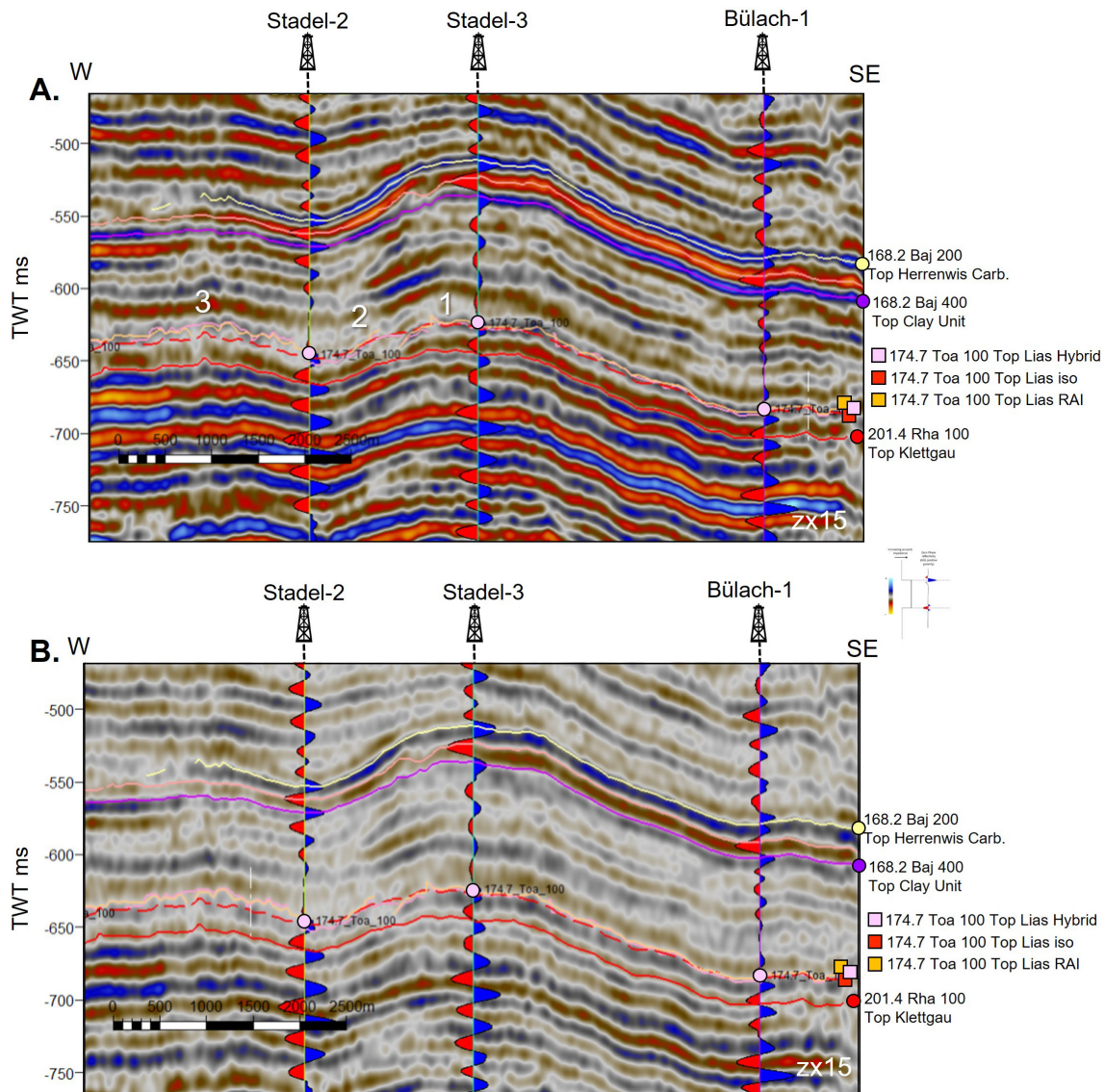


Fig. 4-19: Seismic section across the three wells showing the 174.7 Toa 100 - Top Lias interpretation

A. Reflectivity structural smoothing. B. Relative acoustic impedance.

Due to the low acoustic contrast with the overlaying Opalinus Clay and the presence of Herrenwis-sourced multiples (168.2 Baj 200 - Top Herrenwis Carbonates), the picking of this horizon is extremely challenging. 1. Area of continuous reflection below the Herrenwis carbonate platform; 2. area with split of loop with loss of continuity and 3. area with loop thickening. Two alternative picking solutions were performed: (i) mapping using relative acoustic impedance translating the peak into a zero-crossing (orange) and (ii) by isochoring up (red) the 201.4 Rha 100 - Top Klettgau horizon to bridge areas of continuity disruption. The result is a hybrid solution (pink). Seismic data are PreSTM-ref.

Several approaches were tested and implemented to map this horizon in order to reach a selected scenario, which reflects the conservative criterion. For this purpose, relative acoustic impedance and a high-frequency filtered cube (i.e. frequency content of 30 to 60 Hz) were generated and interpreted, and the resulting horizons were further compared with the isochroned-up 201.4 Rha 100 - Top Klettgau horizon, representing a very continuous and stable reflection. The 201.4 Rha 100 - Top Klettgau horizon was already identified as proxy for the Top Lias in the full survey interpretation (Nagra 2024b). The final 174.7 Toa 100 - Top Lias is a hybrid horizon, considering the shallowest outcome of the combination of the different solutions (Fig. 4-19).

When considering depth conversion and velocity model building, a further hurdle can be related to the presence of the Herrenwis Carbonate Unit, which coincides with a high-velocity carbonate body encased in a low-velocity volume (shale). Its presence and the thickness of the high velocity carbonate could have a direct impact on the depth conversion results (top structure morphology: push-down or pull/up). The Herrenwis Unit is interpreted as a Bajocian carbonate platform. Well data and outcrop analogues (Rouchat et al. 2024.) indicate both thickness and facies variation across the area of interest. The architecture of the Herrenwis carbonate platform (inner platform and peri platform wedge) can be interpreted seismically (Fig. 4-20).

The reflections correlating with the Herrenwis carbonates are in tuning away from the platform margin as seen in the Stadel-2 well (Fig. 4-20 B.). Where the thickness decreases from ~ 40 m to a value of ~ 22 m ($\lambda/4$ and/or tuning thickness = 23 m, assuming 4,500 m/s for 50 Hz), the acoustic contrast associated with the presence of carbonate facies can still be deducted, however the top and base carbonate cannot be separated. Away from Stadel-2 and in the direction of the Bachs-1 well (where only less than two metres of carbonate-rich interval were penetrated), the observed change in polarity can be inferred to reflect the transition from a carbonate-dominated to a clastic-dominated environment towards the west (Fig. 4-20). Consequently, despite being within the tuning zone, Top Herrenwis carbonate horizon was interpreted spatially until seismic polarity change was met (Fig. 4-20 B., C.). It is important to consider that the proposed extension for the carbonate deposits can therefore be only inferred/extrapolated and not firmly defined.

From the Stadel-3 to the Stadel-2 wells, the Herrenwis platform shows a step-like geometry, clearly visible as an imprint within the clay interval (Nagra 2024b, previously referred to as a “swallow zone”; Nagra 2019b). Its gentle change in slope does not correspond to a platform margin, *sensu strictu*, but resembles a transition boundary from a thicker (> 40 m) reef-dominated platform (Stadel-3 and Bülach-1) to a thinner (~ 20 m), more distal homogeneous facies related to a peri platform wedge (Stadel-2). Along this boundary (clear oval shaped discontinuity; Fig. 4-20, Fig. 4-21), thicker seismic packages were observed, where the base carbonate (168.2 Baj 300 - Base Herrenwis) splits into a reflection doublet enveloping a more transparent seismic body with a gently inclined reflection in it.

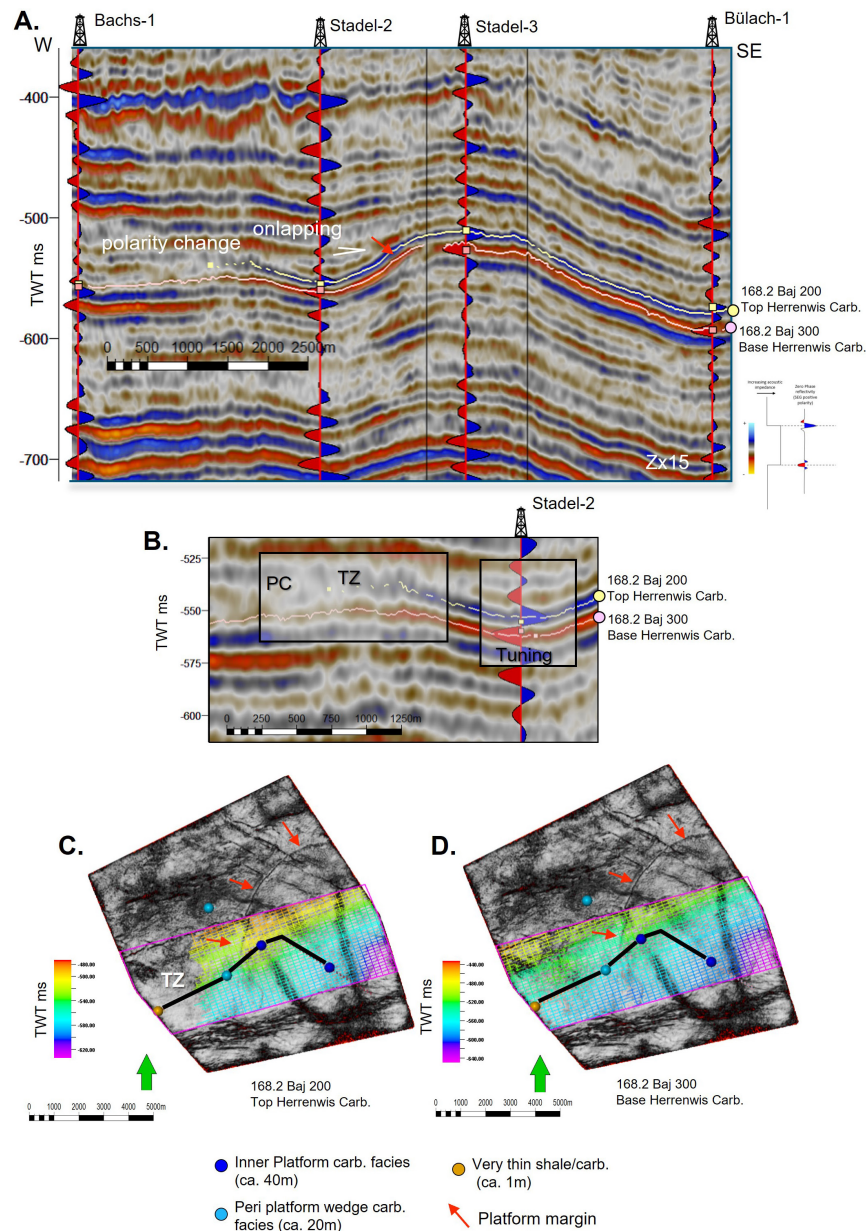


Fig. 4-20: Interpretation of the Herrenwis Carbonate Unit bounded by 168.2 Baj 200 - Top Herrenwis (carbonate) and 168.2. Baj 300 - Base Herrenwis

A. Seismic section across the four key wells showing the seismic-to-well ties for the Herrenwis unit top and base. Carbonate platform geometry is marked by the presence of a gentle step with onlapping sediment. The carbonate deposits thin towards the east, from a >40m thick in the Bülach-1 and the Stadel-3 wells to ~20m at Stadel-2 well and less than 2 m thick in the Bachs-1 well. B. Due to the vertical resolution, tuning effect is expected at the Stadel-2, and top and base carbonate cannot be seismically separated. Despite the tuning effect, however, in the transition zone (TZ - between Stadel-2 and Bachs-1 wells) a change of polarity (PC) is observed for 168.2 Baj-200 - Top Herrenwis (carbonate, yellow horizon), and it can be used to mark the termination of the carbonate-dominated area (B., C). The change in the platform-dipping angle generates a clearly visible step translating into a strong imprint in the variance display of the underlying 168.2 - Baj 400 - Top Clay Unit (A, C., D, red arrows) marking the transition from the platform to a peri platform wedge. The change in polarity from positive to negative acoustic response further indicates the transition from a carbonate-dominated to a clastic-dominated depositional environment. Note how depositional environments inferred from the seismic geometries correlates with the carbonate facies observed in the wells (C.). Seismic data are PreSTM-ref.

The observed thickness variability of the faster carbonate interval is expected to have a strong impact in the depth-conversion exercise, particularly since an apparent push-down effect in two-way travel time display is recognised below the transparent thicker body (Fig. 4-21).

This seems to suggest the presence of a low-velocity wedge. Therefore, two alternative base carbonate (168.2 Baj 300 - Base Herrenwis) interpretations were carried out, tested and geologically interpreted within the regional depositional environment framework (Fig. 4-22, Nagra 2024e).

In the first scenario, 168.2 Baj 300 - Base Herrenwis carbonate was interpreted as the lower reflection (i.e. base of the transparent body; Fig. 4-22 A., C.). Geologically, this implies that the seismic body represents a thick carbonate platform with more than one seismic-scale aggradational - progradational phase. Being all the observed thickness made up of carbonates (Fig. 4-22 C., E.; Abdellah Ait Addi, 2015), the “thick” wedge should be modelled with high (carbonate) velocity.

In the second (alternative) interpretation, the thickening is inferred not to be formed only by carbonates. The 168.2 Baj 300- Base Herrenwis Carbonate is therefore interpreted following the soft acoustic boundary, just below the 168.2 Baj 200 - Top Herrenwis peak (Fig. 4-22 A., D.). In this scenario, the “thicker transparent body” might represent either deposits with bioturbated mud-rich facies with silt intercalations as observed in drift (contouritic) systems (Rebesco et al. 2014;) or clay-dominated progradational clinoforms Fig. 4-22 E., F.). In both geological concepts, yet, the wedge has to be modelled with lower velocities typical for silty-clay, and clay deposits.

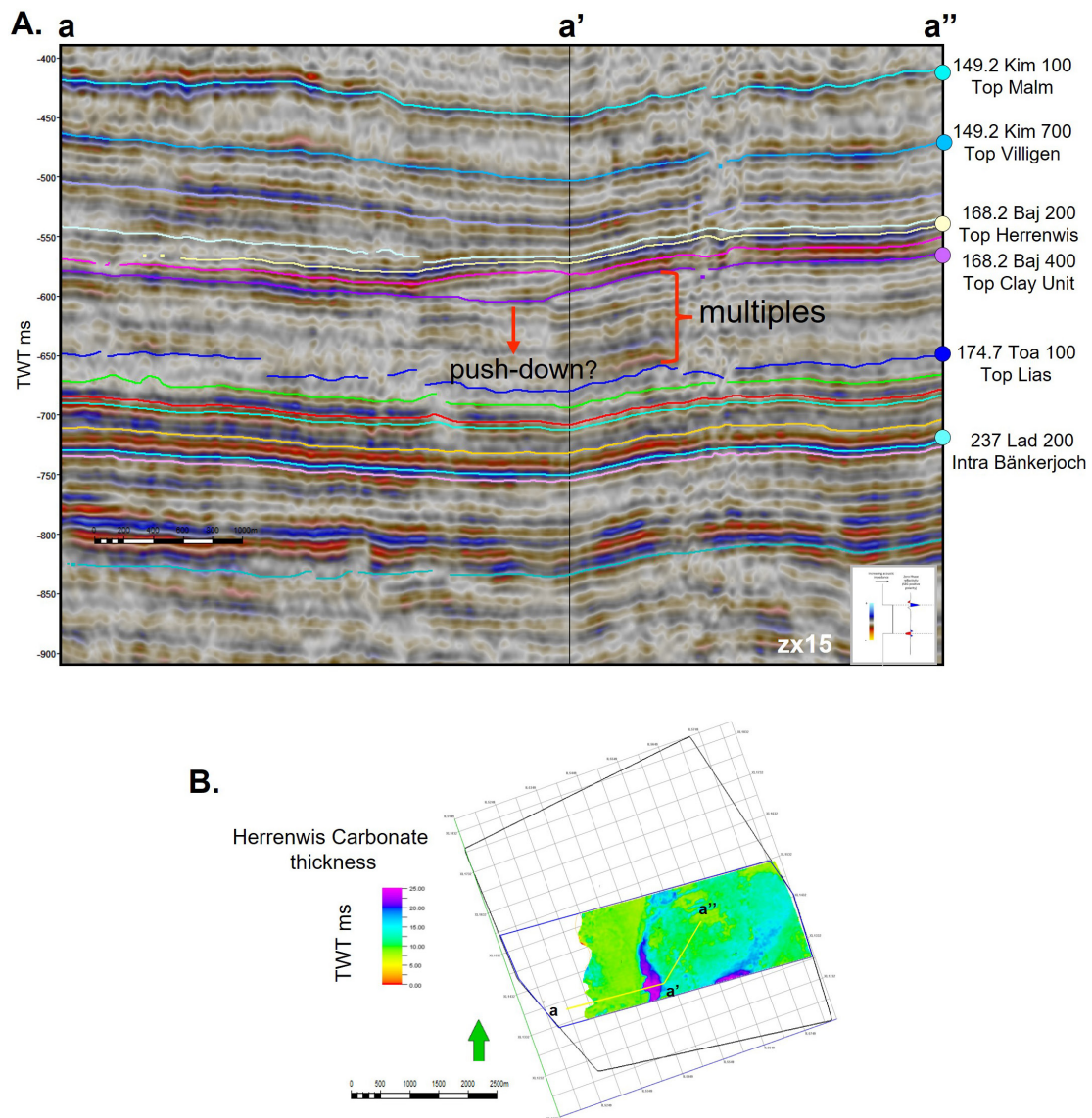


Fig. 4-21: A. Random seismic section across the “thicker” area of the Herrenwis Unit (violet colour in the thickness map, B.) showing a potential push-down effect

Between 168-2 - Top Herrenwis and 168.2 Baj 400 - Top Clay Unit a thicker body, towards the platform margin. Vertical display seems to suggest the presence of a “push-down” effect below this thicker body, suggesting the likely presence of a low velocity wedge. The reflectivity pattern within the Opalinus Clay interval is characterised by the presence of multiples. Seismic data are PreSTM-ref.

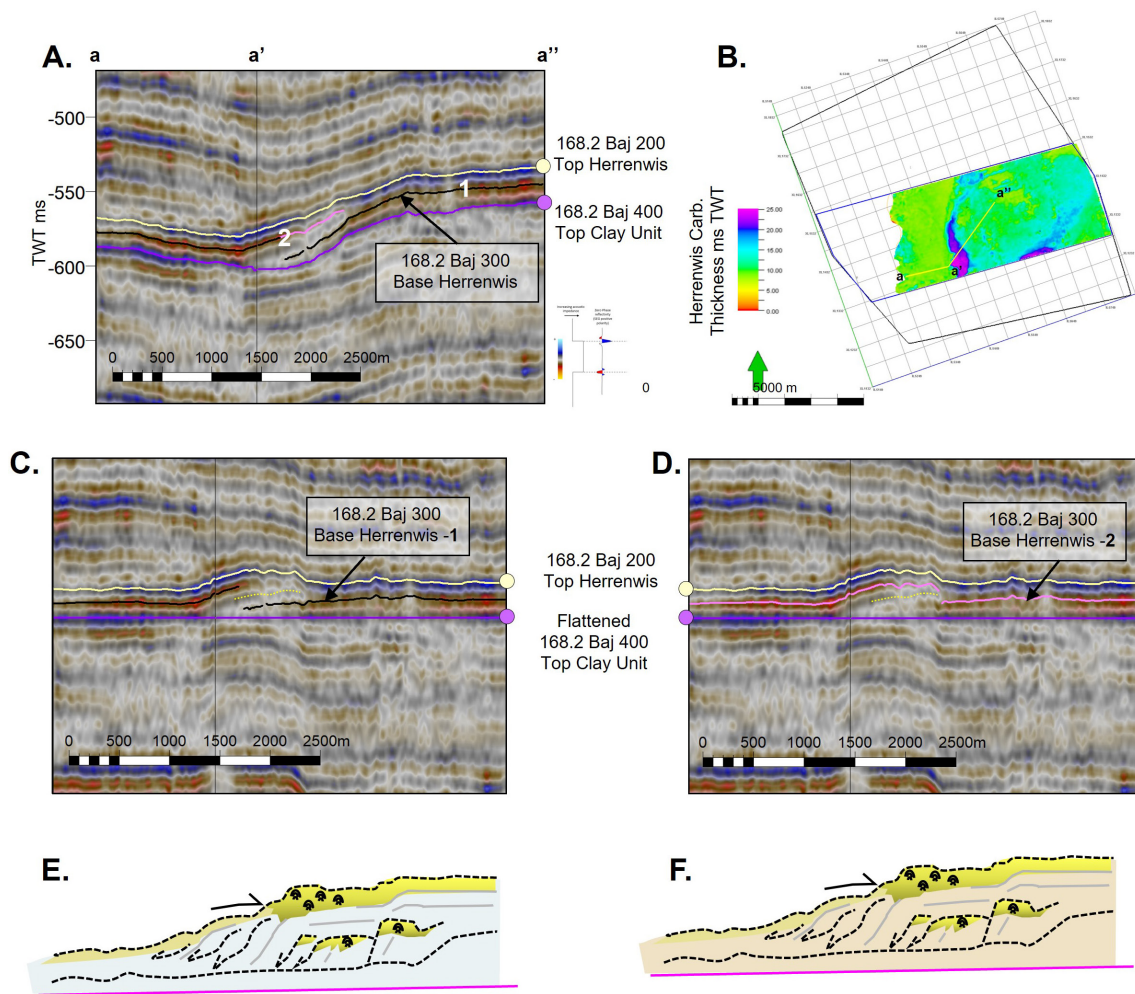


Fig. 4-22: Alternative interpretations were proposed for the Herrenwis Unit

A. Seismic section showing two potential interpretation scenarios of 168.2 Baj 300 - Base Herrenwis (carbonate) for the observed thicker seismic body (B.). Scenario 1 (A., 1 black horizon) implies a thicker carbonate-dominated interval resulting in a high-velocity wedge. Scenario 2 (A., 2 pink horizon) indicates a thinner carbonate layer and a clastic dominated wedge. C and D are part of the seismic section in A. flattened at the 168.2 Baj 400 - Top Clay Unit showing the seismic geometries associated with the two scenarios. The interpretation scenarios are then translated into geological concepts (E., F.). In scenario 1, the observed wedge is expected to be carbonate-dominated (light blue colour) with at least two phases of aggradation and progradation (black and dashed yellow horizons, C. and yellow layers E.). In scenario 2, the thicker reflection package is interpreted to be initially shale- dominated with potential incipient carbonate growth (i.e. internal loop, dashed yellow line, D., lower yellow layer, F.) and only in the last stage, to become carbonate-dominated (continuous yellow layer, F. pink horizon D.).

Once the horizon interpretation was performed, the two-way travel time surfaces were generated (Fig. 4-23) by the interpretation of seed-line grids using convergent gridding algorithm with 25 x 25 grid. No autotracking, no smoothing, and no forced tie to well tops in time were applied.

To capture the Herrenwis unit, two surfaces, which reflect the two interpretation scenarios, were transformed into wedges to mimic the carbonate-clastic transition.

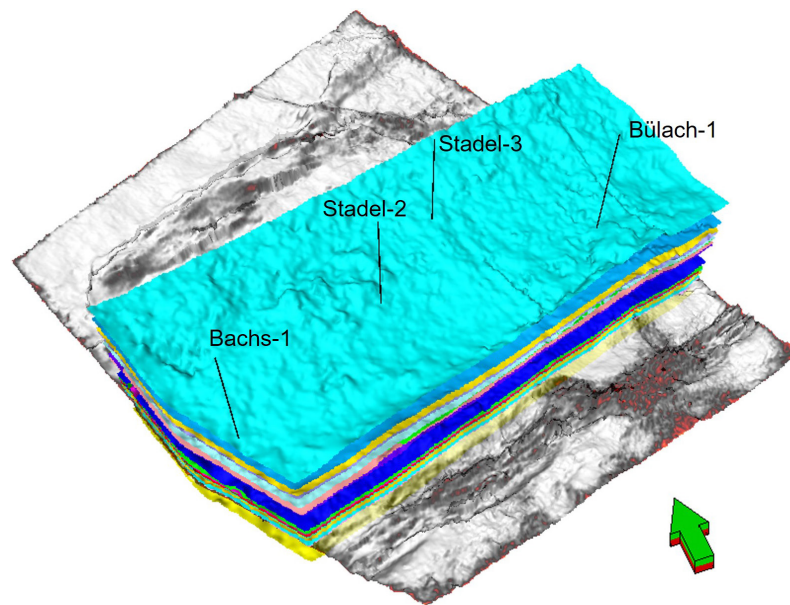


Fig. 4-23: 3D display of the 19 surfaces (TWT) generated for the AOI

237 Lad 400 - Top Muschelkalk variance horizon slice and the four key wells are shown to display the relative location of AOI within NL-16 survey. Green arrow points toward north. Vertical exaggeration is 5.

4.2.2 Depth conversion

The focus of the time-to-depth conversion exercise was to provide depth maps for the top and base host rock (Opalinus Clay) and an evaluation of the uncertainty associated with that. Furthermore, uncertainty was estimated also for the seismic thickness of the host rock as well as of the upper and lower confining units¹.

The host rock corresponds to the Opalinus Clay interval, the upper confining unit is the stratigraphic interval between 154.8 Oxf-300 - Top Wildegg and 170.9 Aal-300 Top Opalinus Clay and the lower confining units¹ is bounded by 174.7 Toa 100 - Top Lias and 237 Lad 400 - Top Muschelkalk.

Four key wells (Bachs-1, Stadel-2, Stadel-3 and Bülach-1, Fig. 2-2) are located within the area of interest. Good sonic logs as well as TDR (time-depth relationship) from VSP and synthetics are available for all the wells. Sonic logs were used to identify velocity breaks, which represent boundaries of critical velocity changes. The sonic logs were upscaled within the recognised velocity breaks correlating with key stratigraphic markers (Fig. 4-24). The upscaled/averaged velocity logs were used to calculate the input interval velocity for the velocity models (Tab. 4-12).

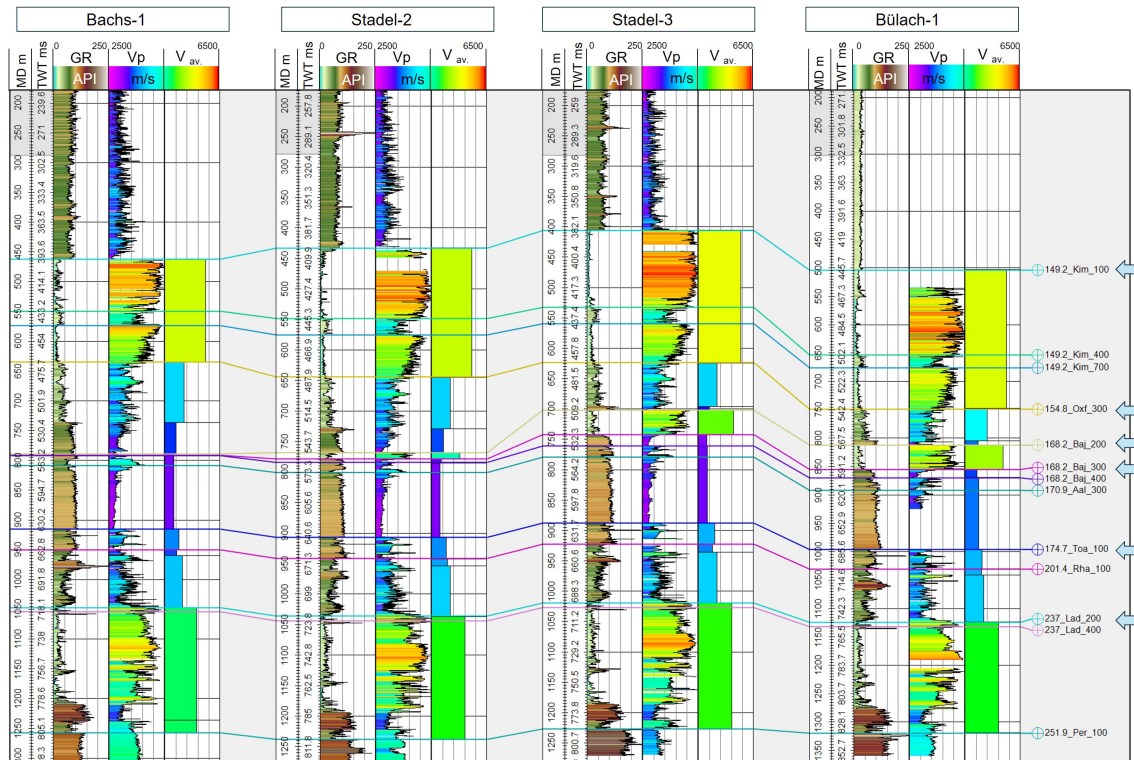


Fig. 4-24: Well correlation panel showing how major velocity breaks correspond to key stratigraphic units

Light blue arrows indicate the identified velocity breaks. Displayed logs are gamma-ray, sonic velocity and calculated average velocity.

Once the key velocity breaks were identified, several velocity models were generated and compared by evaluating and exhausting all the available velocity information. While building and testing the different models, key pragmatic rules were followed: (i) avoid thin layers, (ii) start simple (constant V_0) and increase complexity only if necessary (e.g. carbonate layers) (iii) aim for small and random residuals at wells, by starting with sonic-derived velocities, and tune them within the observed ranges.

Tab. 4-12: Average velocity calculated at wells from sonic logs edited from VSP

Velocity Layers		Bachs-1	Stadel-2	Stadel-3	Bülach-1	Average Vel.
Top	Base	Average Velocity per well m/s				
GL	149.2 Kim 100 -Top Malm	2886	2776	2665	3021	2836
149.2 Kim 100 - Top Malm	154.8 Oxf 300 - Top Wildegg	5272	5231	5355	5272	5282
154.8 Oxf 300 -Top Wildegg	168.2 Baj 200 - Top Herrenwis	3578	3570	3719	3965	3708
168.2 Baj 200 - Top Herrenwis	168.2 Baj 300 - Base Herrenwis	2837	4561	4833	4592	4205
168.2 Baj 300 - Base Herrenwis	174.7 Toa 100 - Top Lias	3013	3032	3029	3160	3058
174.7 Toa 100 - Top Lias	237 Lad 200 – Intra Bänkerjoch	3533	3601	3568	3649	3587.75
237 Lad 200 – Intra Bänkerjoch	251.9 Per 100 - Base Mesozoic Unc.	4717	4760	4798	4842	4778

Analysis of the velocities in the four wells as well as qualitative screening of the seismic velocity suggest that no obvious depth (vertical) trend (= increase of depth velocity) can be recognised for either the entire stratigraphic stack or within specific stratigraphic intervals (Fig. 4-24).

However, velocity variations in the wells show a lateral trend with velocity increasing towards the east within the Wildegg Formation (154.8 Oxf 300 - Top Wildegg - 168.2 Baj 200 - Top Herrenwis). Such a velocity change seems to correlate with the thickness of this unit.

A velocity map trend was therefore implemented where the velocity change mirrors the thickness change (Fig. 4-25).

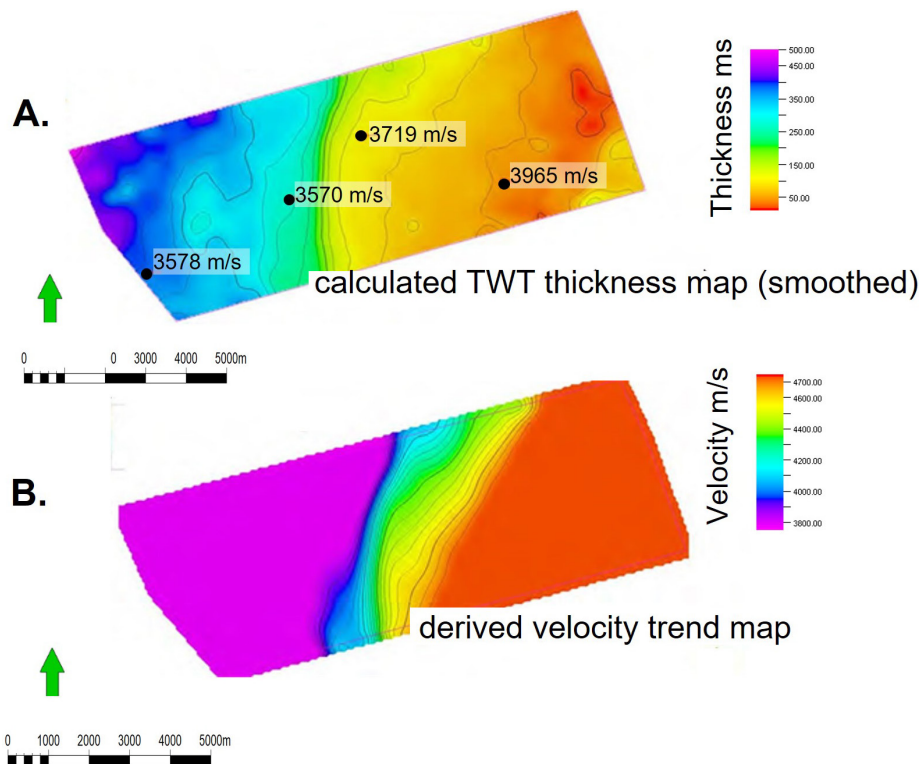


Fig. 4-25: An eastward velocity trend was observed in the well average velocity for the stratigraphic interval between 154.8 Oxf 300 - Top Wildegg - 168.2 Baj 200 - Top Herrenwis

This velocity changes appears to correlate with the interval thickness and therefore a velocity trend map was generated having the interval thickness as driver.

Multiple realisations with multiple combinations of velocity inputs and ranges were tested. Among them four scenarios are shown as examples of the approach, rationale and evaluation of all the velocity source combinations and results (Tab. 4-13, Tab. 4-14, Tab. 4-15, Tab. 4-16).

Residuals at key velocity breaks were analysed, to evaluate the velocity model results. A small mean residual (indicating an unbiased depth conversion) and a low standard deviation (meaning the method explains the depth quite well) are indications of a good depth conversion model. The spatial distribution of residuals should not show a strong trend, which would indicate a velocity variation unexplained by the model. Residuals are also a direct measure of the depth conversion uncertainty at any horizon. Positive residuals mean that the horizon is too deep, and a too fast velocity was selected for the interval, while negative residuals mean that the horizon is too shallow and on the contrary the chosen velocity value was too slow.

Tab. 4-13: Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces

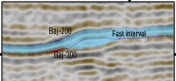
Model 1 is a simple model with interval velocity and uses the “thicker” scenario for the Herrenwis carbonates (168.2 Baj 200 - Top Herrenwis - 168.2 Baj 300 - Base Herrenwis scenario 1, Fig. 4-22 A., C.). Velocities are modified well velocities to improve the residuals at wells, since well velocities resulted in high residual values.

Model 1		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	$V=V_{int}=V_{const}$	3500 m/s
149.2 Kim 100 -Top Malm	$V=V_{int}=V_{const}$	3280 m/s
154.8 Oxf 300 - Top Wildegg	$V=V_{int}=V_{const}$	4925 m/s
168.2 Baj 200 -Top Herrenwis	$V=V_{int}=V_{const}$	3873 m/s
168.2 Baj 300 - Base Herrenwis	$V=V_{int}=V_{const}$	4712 m/s
174.7 Toa 100 - Top Lias	$V=V_{int}=V_{const}$	3060 m/s
237 Lad 200 - Intra Bänkerjoch	$V=V_{int}=V_{const}$	3580 m/s
251.9 Per 100 - Base Mesozoic Unc.	$V=V_{int}=V_{const}$	4685 m/s
Depth: -1500 ms TWT	$V=V_{int}=V_{const}$	4250 m/s

	Horizons	Kim 100	Oxf 300	Baj 200	Baj 300	Toa 100	Lad 200
Well	Bachs	10.97	10.69	19.76	17.56	14.16	22.31
	Stadel-3	-1.61	-5.82	-8.34	-8.87	-5.79	-7.78
	Stadel-2	4.95	12.05	15.46	19.13	16.79	19.28
	Bülach-1	-14.8	-20.55	-26.82	-25.19	-26.36	-33.68

Tab. 4-14: Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces

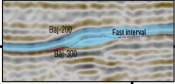
Model 2 is equal to Model 1, except that the interval velocity was increased from 3,060 to 3,100 m/s between 168.2 Baj 300- Base Herrenwis and 174.7 Toa 100 - Top Lias, and that the velocity map to capture the velocity trend observed between 154.8 Oxf 300 Top Wildegg and 168.2 Baj 200 - Top Herrenwis was used instead of a constant velocity for this interval. The “thicker” scenario for the Herrenwis carbonates (168.2 Baj 200 - Top Herrenwis - 168.2 Baj 300 - Base Herrenwis scenario 1, Fig. 4-22 A., C.) was chosen.

Model 2		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
149.2 Kim 100 -Top Malm	V=Vint= Vconst	3280 m/s
154.8 Oxf 300 - Top Wildegg	V=Vint= Vconst	4925 m/s
168.2 Baj 200 -Top Herrenwis	V=Vmap	
 168.2 Baj 300 - Base Herrenwis		
168.2 Baj 300 - Base Herrenwis	V=Vint= Vconst	4712 m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	3100 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3580 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4685 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Kim 100	Oxf 300	Baj 200	Baj 300	Toa 100	Lad 200
Well	Bachs	10.97	10.69	14.57	12.37	7.19	19.23
	Stadel-3	-1.61	-5.82	-5.82	-6.36	-1.31	-3.33
	Stadel-2	4.95	12.05	11.92	15.58	14.27	17.47
	Bülach-1	-14.8	-20.55	-22.75	-21.1	-21.11	-27.66

Tab. 4-15: Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces

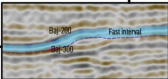
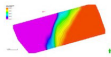
Model 3 is a more complex (hybrid) velocity model, where seismic velocity was used to capture the heterogeneities associated with the Malm carbonates. As in Model 2, the generated velocity map was used for the interval between 154.8 Oxf 300 - Top Wildegg and 168.2 Baj 200 - Top Herrenwis, and the “thicker” scenario for the Herrenwis carbonates (168.2 Baj 200 - Top Herrenwis - 168.2 Baj 300- Base Herrenwis scenario 1, Fig. 4-22 A., C.) was chosen.

Model 3		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
149.2 Kim 100 -Top Malm	V=Vint= Vconst	3280 m/s
154.8 Oxf 300 - Top Wildegg	V=seismic velocity cube (smoothed PSDM velocity)	
168.2 Baj 200 -Top Herrenwis	 V=Vmap	
168.2 Baj 300 - Base Herrenwis	V=Vint= Vconst	4712 m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	3100 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3580 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4685 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Kim 100	Oxf 300	Baj 200	Baj 300	Toa 100	Lad 200
Well	Bachs	10.97	5.63	9.52	7.32	2.14	14.17
	Stadel-3	-1.61	-1.74	-1.74	-2.3	2.74	0.7
	Stadel-2	4.95	10.96	10.78	14.44	13.13	16.33
	Bülach-1	-14.8	-13.12	-15.3	-13.66	-13.68	-20.26

Tab. 4-16: Selected Vo/K realisations: Model 4 velocity source input and residuals at velocity break surfaces

Model 4 is similar to Model 3 but with the “thinner” scenario for the Herrenwis carbonates (168.2 Baj 200 - Top Herrenwis - 168.2 Baj 300- Base Herrenwis scenario 2, Fig. 4-22 A., D.). Model 4 was selected as the base case, as it accounts for the geological heterogeneities and resulted in small and distributed residuals.

Model4		
Horizon Base	Model (velocity Sources)	Value
floating-datum	V=Vint= Vconst	3500 m/s
149.2 Kim 100 -Top Malm	V=Vint= Vconst	3280 m/s
154.8 Oxf 300 - Top Wildegg	V=seismic velocity cube [smoothed PSDM velocity]	
168.2 Baj 200 -Top Herrenwis	 V=Vmap	
168.2 Baj 300 - Base Herrenwis	V=Vint= Vconst	4712 m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	3100 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3580 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4685 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Kim 100	Oxf 300	Baj 200	Baj 300	Toa 100	Lad 200
Well	Bachs	10.97	5.63	6.61	8.08	2.9	14.93
	Stadel-3	-1.61	-1.74	-1.74	-2.12	2.95	0.92
	Stadel-2	4.95	10.96	12.51	12.92	12.22	15.42
	Bülach-1	-14.8	-13.12	-15.3	-13.78	-13.71	-20.27

Model 4 was selected as the base case. It shows a good representation of the geology accounting for the velocity trend observed in the Wildegg Formation (154.8 Oxf 300 - Top Wildegg - 168.2 Baj 200 - Top Herrenwis) and the strong heterogeneity associated with the Malm carbonates as well as good residual values and spread (Tab. 4-16, Fig. 4-26). It also considers a “thinner” Herrenwis carbonates, removing the push-down effect observed in Model 3 (Fig. 4-27). When depth converting the Herrenwis Units as a thicker high velocity wedge a deflection is observed in the underlying horizon suggesting an overestimation of the selected interval velocity. This observation is consistent with the observed pull-down in the time domain (Fig. 4-21) contrary to the typical pull-up effects recognised in many two-way travel time seismic examples of carbonate platforms.

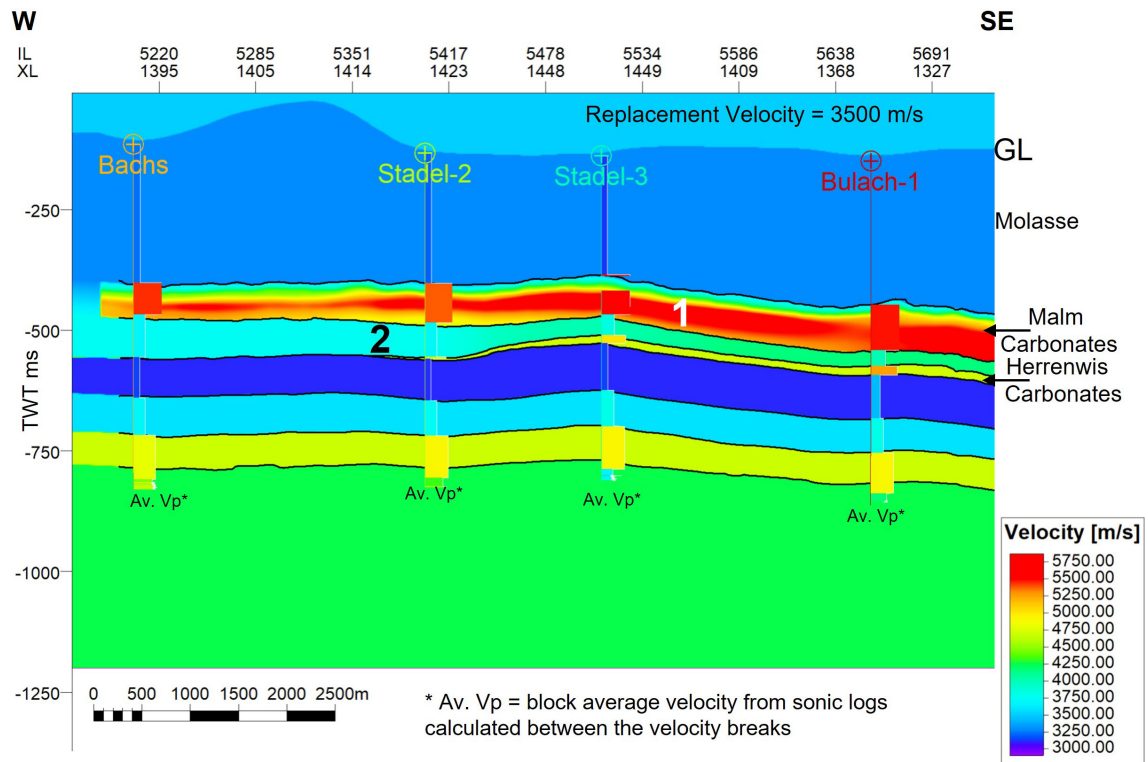


Fig. 4-26: Base case Vo/K velocity model translated into a velocity cube

A. Section across the wells showing the lateral and vertical trends of Model 4 (base case, Tab. 4-16) and the well average velocity per velocity interval. The velocity model is a hybrid model with interval velocities combined with seismic velocity (149.2 Kim 100 - Top Malm - 154.8 Oxf 300 - Top Wildegg, Malm carbonates, 1) and velocity trend (154.8 Oxf 300 - Top Wildegg - 168.2 Baj 200- Top Herrenwis, scenario 2).

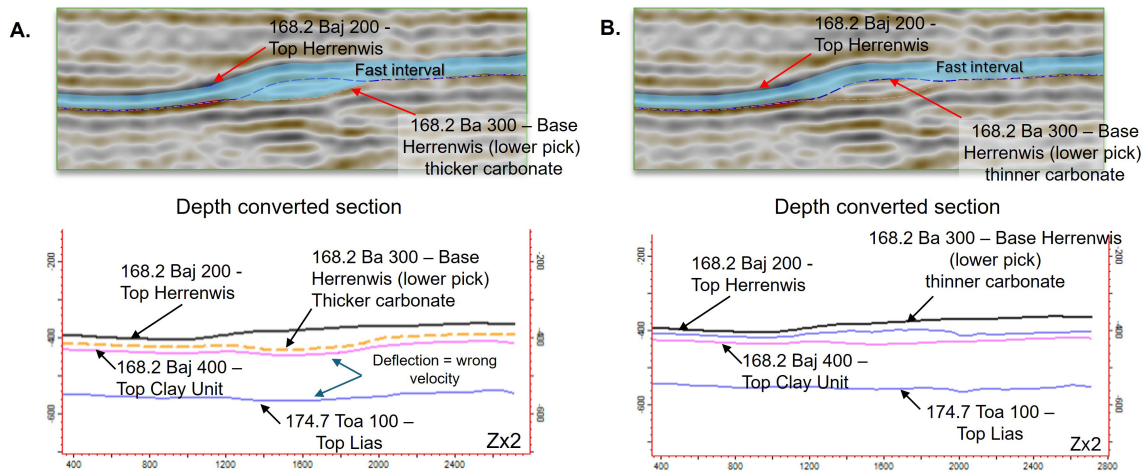


Fig. 4-27: Depth conversion results capturing the two scenarios proposed for the base Herrenwis carbonate (168.2 Baj 300 - Base Herrenwis)

A. Depth section assuming a thicker fast interval (Scenario 1, Fig. 4-22) and B. Depth section assuming a thinner fast interval (Scenario 2, Fig. 4-22). The high-velocity wedge results in a deflection below this thicker wedge, suggesting an overestimation of the selected interval velocity. The deflection is not visible anymore when a thinner wedge scenario is used, instead.

Velocity Model 4 (base case) was therefore used to perform depth conversion with focus on top and base host rock (168.2 Baj 400 - Top Clay Unit (proxy for 170.9 Aal 300 - Top Opalinus) and 174.7 Toa 100 - Top Lias, respectively, Fig. 4-28, Fig. 4-29).

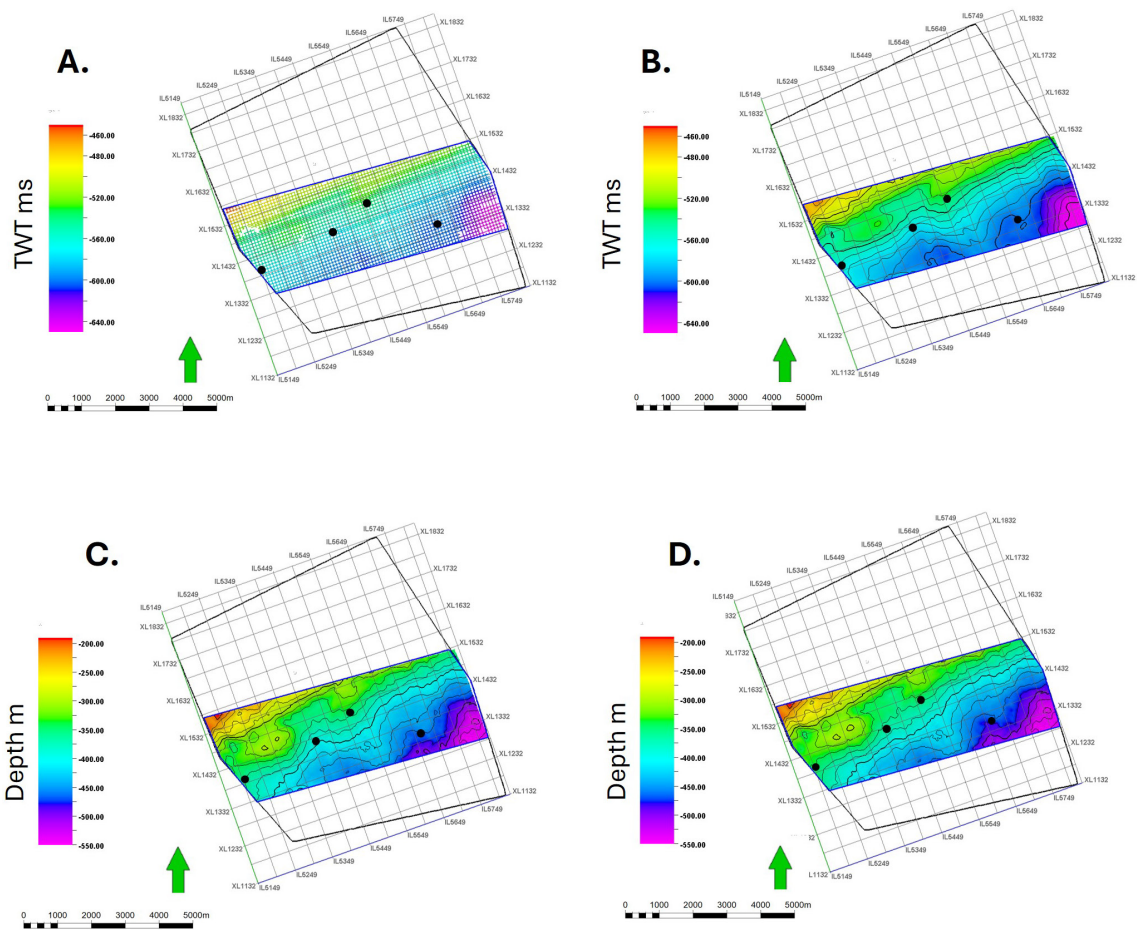


Fig. 4-28: Time and depth surfaces of 168.2 Baj 400 - Top Clay Unit

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 4; Tab. 4-16) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

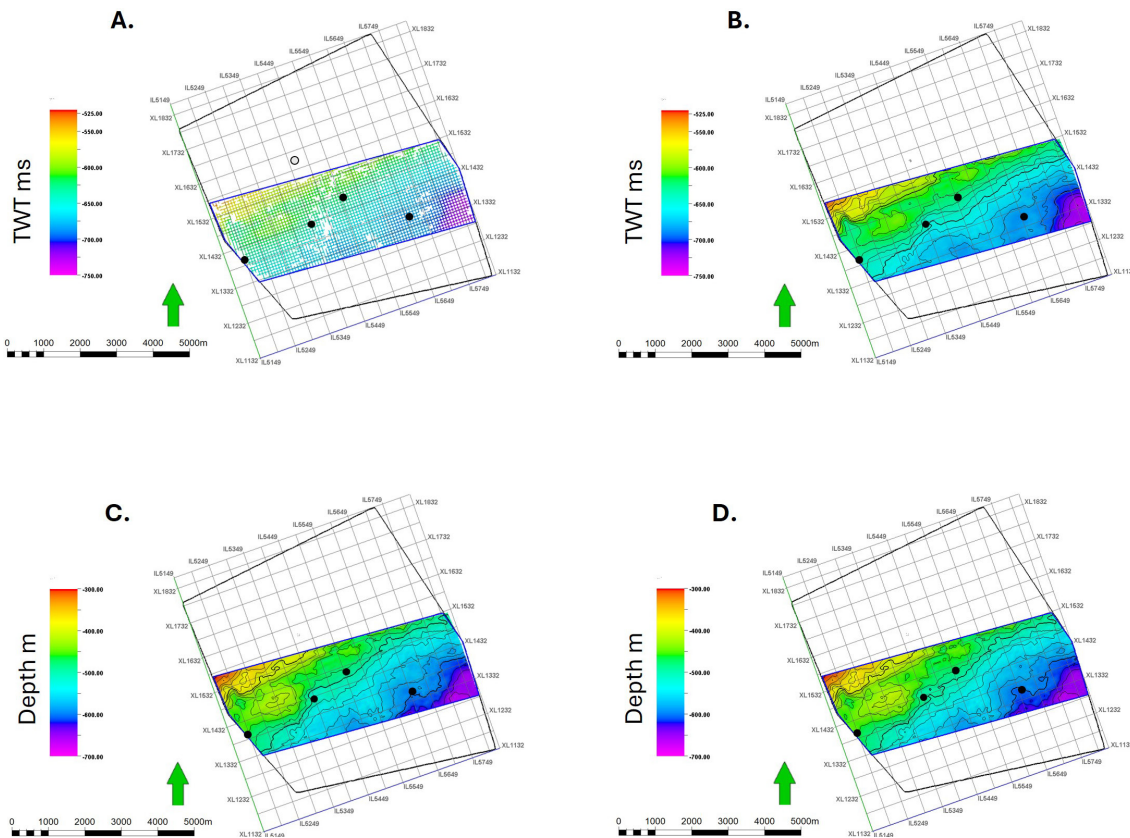


Fig. 4-29: Time and depth surfaces of 174.7 Toa 100 - Top Lias

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 4; Tab. 4-16) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

4.2.3 Depth and thickness uncertainties

Depth uncertainty was calculated for the depth converted horizons representing the top and base of the host rock (Opalinus Clay interval). For the NL siting region, 170.9 Aal 300 - Top Opalinus could not be seismically interpreted and therefore 168.2 Baj 400 - Top Clay Unit was used as proxy for it.

Depth uncertainty calculation followed the workflow proposed in Section 3.3, assuming as minimum uncertainty value the 2Stdev from the well top residuals. Since 168.2 Baj 300 - Base Herrenwis is the reflection just above 168.2 Baj 400 - Top Clay Unit and represents a velocity break, residuals for 168.2 Baj 400 - Top Clay Unit were considered as for 168.2 Baj 300 - Base Herrenwis. Considering then 2Stdev (95% solution), the base value for depth uncertainty is rounded to 25 m both for 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias, slightly more conservative to account for horizon simplification (Tab. 4-17).

Tab. 4-17: Well top residuals and calculated standard deviations at 168.2 Baj 300 - Base Herrenwis and 174.7 Toa 100 - Top Lias

		168.2 Baj 300 – Base Herrenwis	174.7 Toa100 – Top Lias
Wells	Bachs	8.08	2.9
	Stadel-3	-2.12	2.95
	Stadel-2	12.92	12.22
	Bülach-1	-13.78	-13.71
	Stdev	11.8	10.7
	2 Stdev	24	22

The uncertainty base value corresponding to the absolute 2Stdev was rounded to 25 m (slightly higher) and identification of larger uncertainty values and their trends was performed in accordance with the proposed workflow by comparing selected scenarios, i.e. by the difference of the PreSTM-ref depth maps with depth maps derived by reproducing the base case velocity model for the QLP dataset.

The velocity model generated for the QLP dataset should resemble the hybrid approach used for the selected Model 4 (base case). However, due to the different static solutions between the two seismic processing vintages the seismic velocity could not be used. Consistently with the approach used in JO, velocity trend maps were generated, but they resulted in high residuals. A simpler Vo/K model with interval velocities was tested and tuned to achieve smaller residuals, while keeping the velocity values within the velocity ranges observed in the wells. Among the several tests, a model with the lowest and best spread of residuals was selected (Tab. 4-18).

Tab. 4-18: Selected Vo/K realisation for the QLP dataset. Velocity source input and residuals at velocity break surfaces

The selected model is a simple velocity model, which results in relatively small residuals.

QLP Model Vo/K		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	$V=V_{int}=V_{const}$	3500 m/s
149.2 Kim 100 -Top Malm	$V=V_{int}=V_{const}$	3230 m/s
154.8 Oxf 300 - Top Wildegg	$V=V_{int}=V_{const}$	5200 m/s
168.2 Baj 200 -Top Herrenwis	$V=V_{int}=V_{const}$	3680 m/s
168.2 Baj 300 - Base Herrenwis	$V=V_{int}=V_{const}$	4712 m/s
174.7 Toa 100 - Top Lias	$V=V_{int}=V_{const}$	3125 m/s
237 Lad 200 - Intra Bänkerjoch	$V=V_{int}=V_{const}$	3200 m/s
251.9 Per 100 - Base Mesozoic Unc.	$V=V_{int}=V_{const}$	4100 m/s
Depth: -1500 ms TWT	$V=V_{int}=V_{const}$	4250 m/s

Well	Horizons	Baj 300	Toa 100
	Bachs	8.08	2.9
	Stadel-3	-2.12	2.95
	Stadel-2	12.92	12.22
	Bülach-1	-13.78	-13.71

The resulted QLP depth-converted surfaces for 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias are shown in Fig. 4-30.

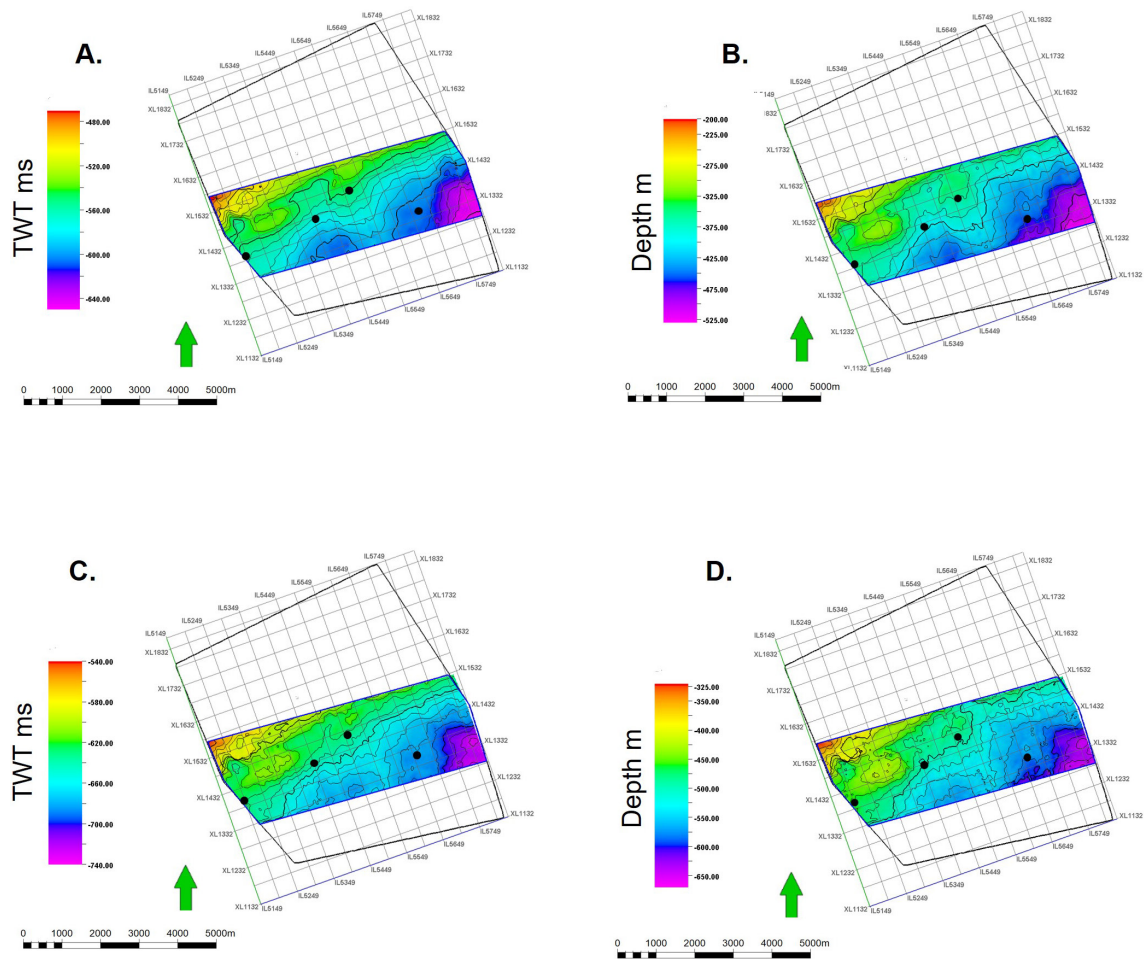


Fig. 4-30: 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage

168.2 Baj 400 Top Clay Unit: A. in TWT and B. in depth; 174.7 Toa 100 -Top Lias; C. in TWT and D. in depth. QLP TWT key horizons were depth-converted using a Vo/K model. The QLP depth-converted surfaces for the top and base host rock were not forced to wells and they were used to calculate depth uncertainty trend maps. Black circles are wells.

Comparison between the two solutions (PreSTM-ref and QLP) indicates that most of the area of interest is within the 2Stdev value and a sharp increase up to 47 m is observed only in the northern edge and in the east-southern corner of the AOI perimeter. (Fig. 4-31).

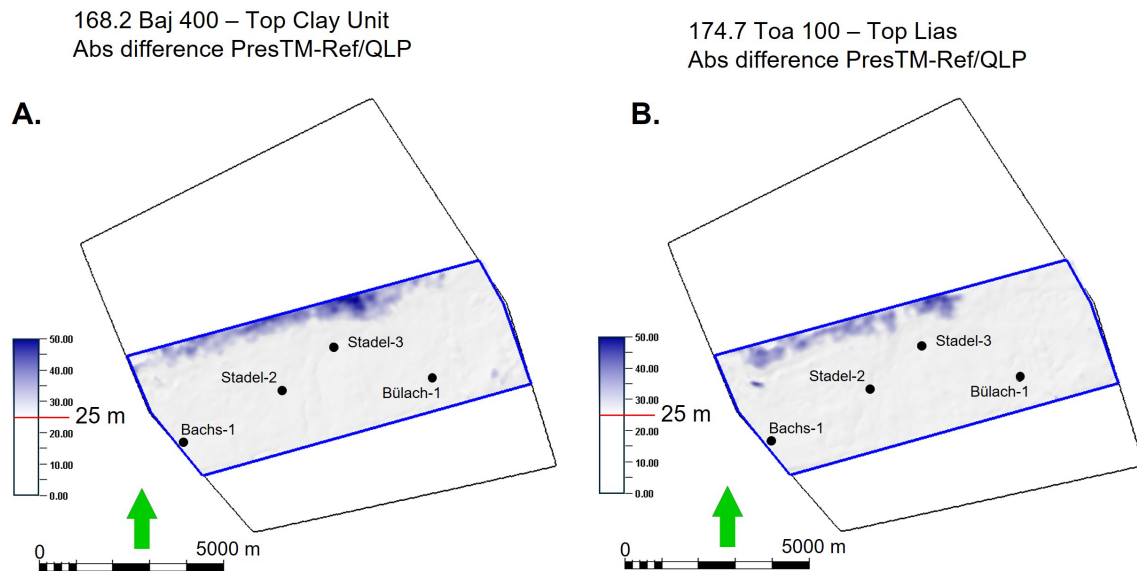


Fig. 4-31: Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data

A. 168.2 Baj 400 - Top Clay Unit; B. 174.7 - Top Lias. Abs is absolute value. Values smaller than 25 m are white colour. 25 m represents the base uncertainty value coinciding with the 2Stdev of the residuals at wells.

Depth uncertainty maps (Fig. 4-32 A., C.) were built by extrapolating uncertainty trends from the selected realisation comparison (Fig. 4-31) with a minimum (base) uncertainty value equal to 2Stdev of the well residuals for the base case scenario (Tab. 4-17, equal to 25 m for both 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias). The uncertainty trends were then tapered to a value of 2 m at well locations with an influence radius of 1500 m (size of major topographic features;). The well tapering accounts for an uncertainty value equal (almost) to zero at well location (Fig. 4-32 B., D.).

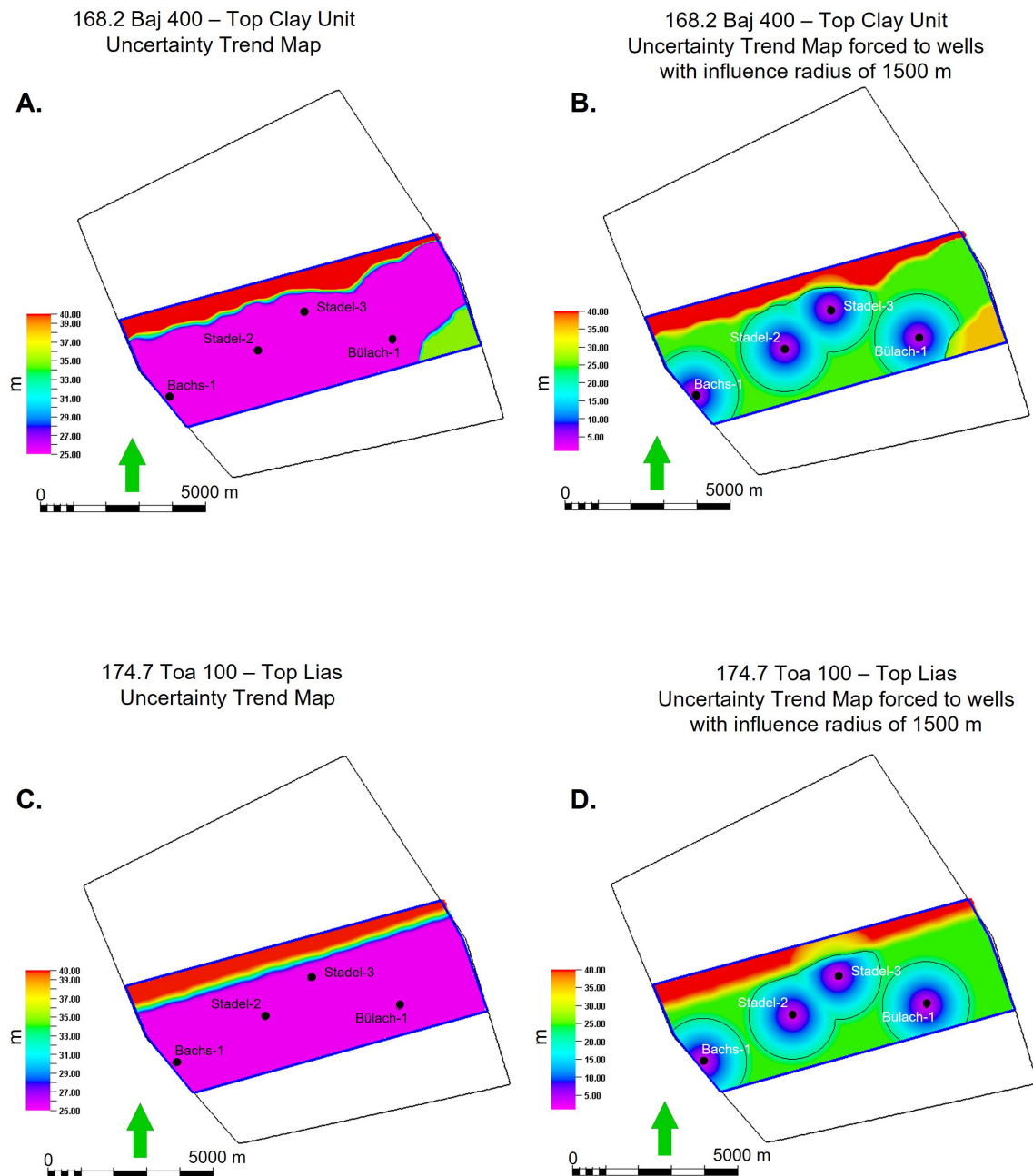


Fig. 4-32: Uncertainty depth maps for 168.2 Baj 400 - Top Clay Unit and 174.7 Toa 100 - Top Lias

Base value for the uncertainty is 25 m calculated from the 2Stdev of the residuals at wells. Trend maps (A., C.) were generated using difference maps from the selected realisations (Fig. 4-31) and further tapered to wells (2 m uncertainty at well location; B., D.)

A quality control on the depth uncertainty maps is provided by the calculation of an upper and lower case. The upper- and lower-cases result from adding or subtracting the absolute value uncertainty maps to the base case depth map. The upper- and lower-case surfaces should envelop the base case depth map (Fig. 4-33).

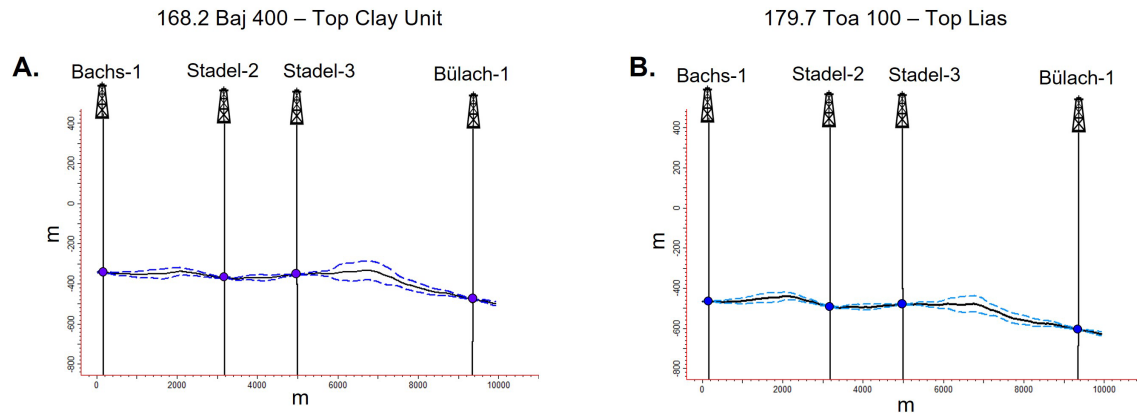


Fig. 4-33: Depth section across the four wells showing the base case enveloped by the upper- and lower-cases

A. 168.2 Baj 400 - Top Clay Unit. Black solid line is the base case surface, blue dashed lines are upper- and lower-case surfaces. Well tops are purple circle. B. 174.7 Toa 100 - Top Lias. Black solid line is the base case surface, light blue dashed lines are upper- and lower-case surfaces. Well tops are blue circle.

From the PreSTM-ref base case depth converted surfaces, seismic thickness maps (Fig. 4-34) were calculated for the clay unit (proxy for the host rock - 168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias). The thickness maps were derived by untied (not forced to wells) surfaces and compared with thickness observed at wells.

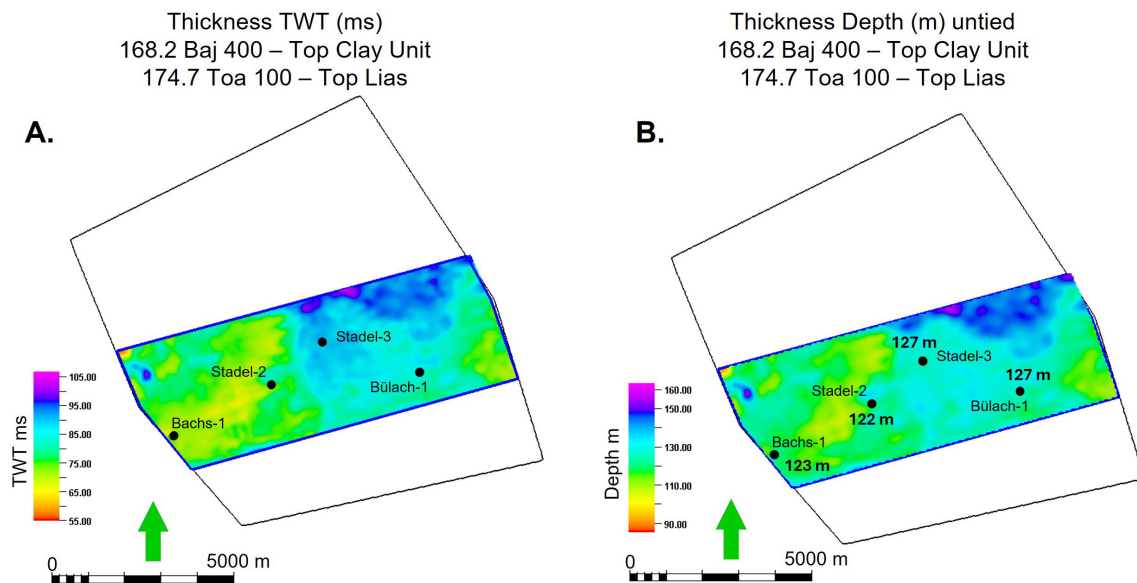


Fig. 4-34: TWT (A) and depth (converted, B.) seismic thickness for the interval 168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias

The thickness depth is untied, surfaces 168.2 Baj 400 -Top Clay Unit and 174.7 Toa 100 - Top Lias were not forced to wells. Despite not being forced to the wells, note the good match between seismic thickness and thickness measured in wells (black numbers, B.).

The thickness uncertainty associated with variability of interval velocity was, thus, calculated for the horst rock (Opalinus Clay) and the upper and lower confining units¹ (154.8 Oxf 300 - Top Wildegg - 170.9 Aal 300 and 174.7 Toa 100 - Top Lias to 237 Lad 400 Top Muschelkalk intervals, respectively).

For the upper confining unit (154.8 Oxf 300 - Top Wildegg - 170.9 Aal 300- Top Opalinus), the impact of the interval velocity, which is estimated as Stdev derived from the Stdev of the velocity ranges proportional to the interval average thickness results in relatively large value (Tab. 4-19) specifically when considering the depth conversion uncertainty for the 170.9 Aal 300 - Top Opalinus (entire overburden interval).

Tab. 4-19: Input and results for the velocity component of the thickness uncertainty of upper confining unit. Note the large value of the velocity Stdev

154.8 Oxf 300 – Top Wildegg – 170.9 Aal 300– Top Opalinus	
	Well Velocity
Bachs-1	3700 m/s
Stadel-2	3722 m/s
Stadel-3	4009 m/s
Bülach-1	4200 m/s
Average Velocity	3907 m/s
Stdev (velocity)	240.3 m/s
Average Thickness	154 m
Stdev	9 m
2 Stdev	18 m

A very large Stdev is observed for the average velocities, which is controlled by the presence of the fast Herrenwis carbonate penetrated only by two of the four wells (Stadel-2 penetrates the carbonate of the peri platform wedge, but the Upper Confining Unit interval is however clastic dominated). The velocity Stdev therefore is strongly influenced by the geological heterogeneity (carbonate to clastic transition) of this interval. The proposed approach was therefore applied independently for the wells penetrating the clastic interval and for those penetrating the carbonate platform (Tab. 4-20, Tab. 4-21). Considering the average value of the two independent evaluation results in a more reasonable uncertainty value, equal to 5.6 m (2Stdev).

Tab. 4-20: Input and results for the velocity component of the thickness uncertainty of upper confining unit for the wells penetrating the clastic interval

154.8 Oxf 300 – Top Wildegg – 170.9 Aal 300– Top Opalinus	
	Well Velocity
Bachs-1	3700 m/s
Stadel-2	3722 m/s
Average Velocity	3711 m/s
Stdev (velocity)	15.5 m/s
Average Thickness	154 m
Stdev	0.6 m
2 Stdev	1.2 m

Tab. 4-21: Input and results for the velocity component of the thickness uncertainty of upper confining unit for the wells penetrating the carbonate interval

154.8 Oxf 300 – Top Wildegg – 170.9 Aal 300– Top Opalinus	
	Well Velocity
Stadel-3	4009 m/s
Bülach-1	4200 m/s
Average Velocity	4104 m/s
Stdev (velocity)	135 m/s
Average Thickness	154 m
Stdev	5 m
2 Stdev	10 m

The same approach applied to the host rock proxy (168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias) is shown in Tab. 4-22. The velocity contribution is estimated equal to 5.2 m.

Tab. 4-22: Input and results for the velocity component of the thickness uncertainty of the clay interval proxy for the host rock

168.2 Baj 400 – Top Clay Unit - 174.7 Toa 100 – Top Lias	
	Well Velocity
Bachs-1	3013 m/s
Stadel-2	3032 m/s
Stadel-3	3029 m/s
Bülach-1	3160 m/s
Average Velocity	3058 m/s
Stdev (velocity)	68.1786868 m/s
Average Thickness	120 m
Stdev	2.6 m
2 Stdev	5.2 m

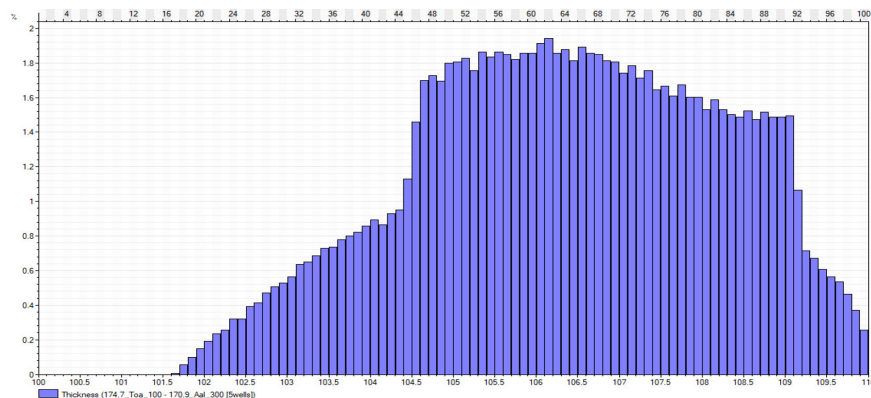
The interval 168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias does not correspond to the host rock *senso strictu* (Opalinus Clay interval, 170.9 Aal 300 - Top Opalinus - 174.7 Toa 100 - Top Lias).

Nevertheless, since the Opalinus Clay has the same interval velocity of the 168.2 Baj 400 - Top Clay Unit - 174.7 Toa 100 - Top Lias interval, the uncertainty associated with the Opalinus Clay can be calculated by reducing the thickness to the Opalinus Clay average thickness (Tab. 4-23).

Tab. 4-23: Input and results for the velocity component of the thickness uncertainty of the host rock

170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	
	Well Velocity
Bachs-1	3013 m/s
Stadel-2	3032 m/s
Stadel-3	3029 m/s
Bülach-1	3160 m/s
Average Velocity	3058 m/s
Stdev (velocity)	68.1786868 m/s
Average Thickness	100 m
Stdev %	2.2 m
2 Stdev %	4.4 m

However, the 170.9 Aal 300 - Top Opalinus surface does not directly result from seismic interpretation, but it was generated from a modelling exercise (i.e. constructed surface). The surface construction algorithm (interpolation) is based on well data, only. Consequently, the derived Opalinus Clay thickness is controlled exclusively by the thickness measured at the four wells and varies from 101.69 to 110.03 m, with a mean of 106.35 m, and a standard deviation of 1.8 m (Fig. 4-35).



Type of data:	Continuous
Number of grid points:	14003
Min:	101.69
Max:	110.03
Delta:	8.35
Mean:	106.35
Stdev	1.82
Variance:	3.32

Fig. 4-35: Model statistics for the constructed 170.9 Aal 300 - Top Opalinus (isochore from 5 wells)

Considering the modelling assumptions, for the 170.9 Aal 300 - Top Opalinus, the total value of the uncertainty results therefore from the combination of the uncertainty associated with the velocity and the one associated with the surface construction:

$$\sqrt{4.4^2 + 3.6^2} = 5.6 \text{ m}$$

where 4.4 m is 2Stdev from the velocity and 3.6 m is 2Stdev from modelling isochoring (Fig. 4-35).

For the lower confining unit^l, the velocity contribution (174.7 Toa 100 - Top Lias to 237 Lad Top Muschelkalk) is capture in Tab. 4-24 and it is equal to 4.6 m.

Tab. 4-24: Input and results for the velocity component of the thickness uncertainty of the lower confining unit^l

174.7 Toa 100 – Top Lias – 237 Lad 400 Top Muschelkalk	
	Well Velocity
Bachs-1	3353 m/s
Stadel-2	3601 m/s
Stadel-3	3568 m/s
Bülach-1	3649 m/s
Average Velocity	3587 m/s
Stdev (velocity)	49.37 m/s
Average Thickness	134 m
Stdev	1.8 m
2 Stdev	3.6 m

4.3 Depth conversion and uncertainty analysis: ZNO

4.3.1 Horizon interpretation

In accordance with the methodology described in Section 3.2, the six full survey horizons (Nagra 2024c) were infilled with nine extra horizons (Tab. 4-25, Fig. 4-36).

As for Nagra 2024c, a traffic light approach was used to show the quality (interpretability) of the resulting horizons (Tab. 4-25, column 1). Green (column 1) horizons are reflections that can be mapped with confidence across the AOI and do not show major changes in reflectivity (except across zones identified to be of low seismic quality, i.e. Quaternary valleys), variation in loop thickness and/or presence of doublets. Red horizons are extremely challenging horizons, generically associated with discontinuous and complex seismic patterns. Orange are horizons of variable quality and level of interpretability across the area of interest.

Tab. 4-25: The six full survey horizons (light green) were complemented with nine horizons within the AOI

Despite the area of interest coincides mostly with the undisturbed area, the quality and confidence with regard to the picking the horizons can vary and is captured with a traffic-light classification shown using red (lower quality), orange (medium quality) and green (good quality) colours in column 1. Note that for the full survey horizons the quality is derived from the full survey evaluation.

	Stratigraphic Horizons	Lithostratigraphy	Phase
1	149.2 Kim 100	Top Malm	peak
2	149.2 Kim 400	Top Schwarzbach Fm	trough
3	149.2 Kim 700	Top Villigen Fm	peak
4	154.8 Oxf 300	Top Wildegg	S-crossing
5	168.2 Baj 200	Intra Humphriesoolith Fm	Z-crossing
6	168.2 Baj 300	Intra Humphriesoolith Fm	trough
7	168.2 Baj 400	Intra Wedelsandstein Fm	S-crossing
8	170.9 Aal 300	Top Opalinus Clay	trough
9	174.7 Toa 100	Top Lias Gr	peak
10	208.5 Nor 100	Top Seebi Mb	Z-crossing
11	208.5 Nor 200	Top lw Gruhalde Mb	trough
12	227 Car 300	Top Bänkerjoch Fm	S-crossing
13	237 Lad 200	Intra Bänkerjoch Fm	peak
14	237 Lad 400	Top Muschelkalk Gr	Z-crossing
15	251.9 Per 100	Base Mesozoic Unconformity	Z-crossing

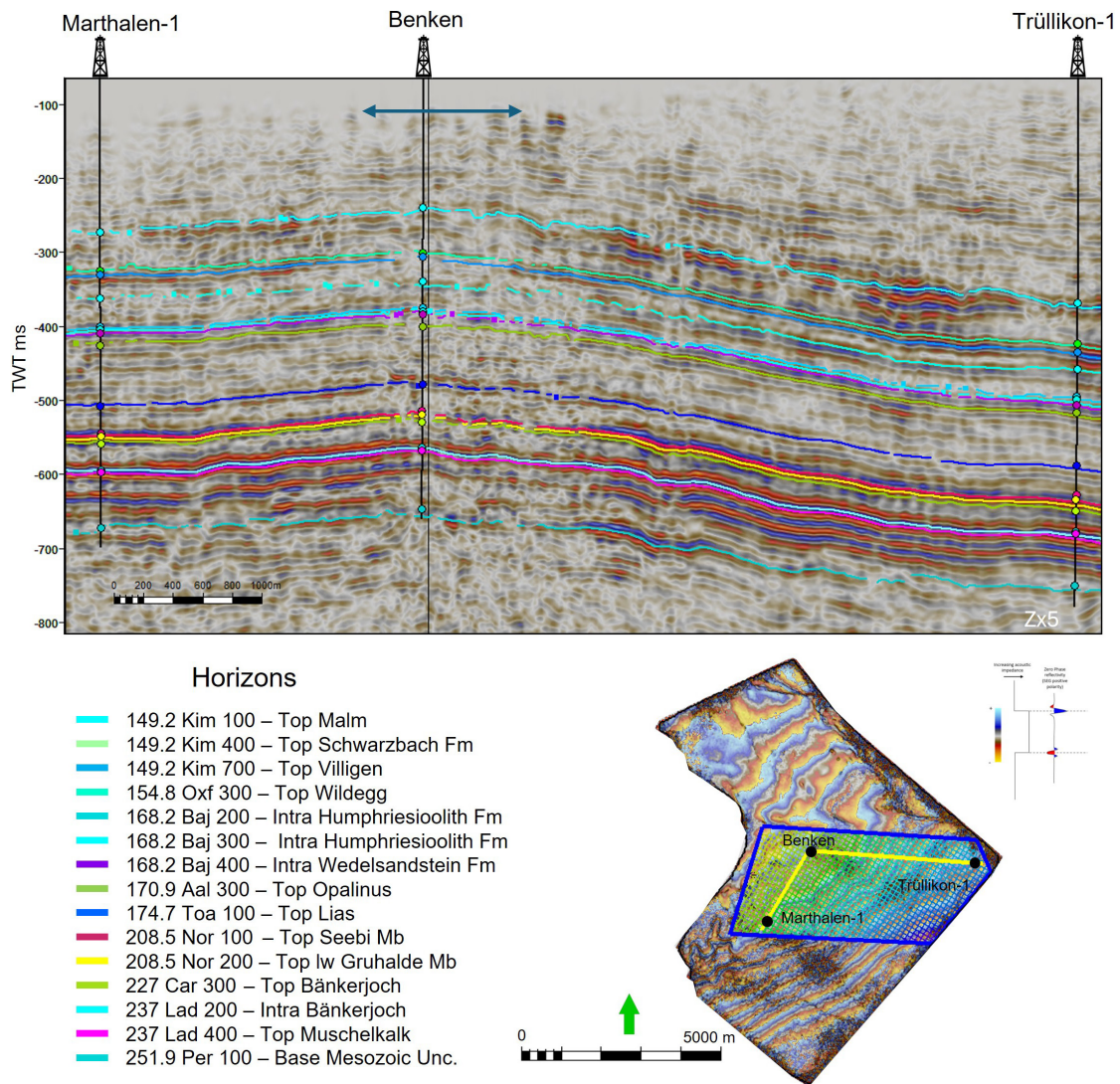


Fig. 4-36: Seismic section across three of the four wells within the AOI showing the 15 horizons

The seismic imaging around the Benken well (blue arrow) is characterised by the degraded amplitude associated with the presence of a Quaternary valley (Nagra 2024c). Confidence in horizon picking is captured in Tab. 4-25. Seismic display is PreSTM-ref reflectivity with an overlay of relative acoustic impedance.

When considering the target interval (Opalinus Clay) for depth conversion and uncertainty evaluation, important geological complexity was observed in the upper part of the Opalinus Clay overburden. Extra effort was therefore invested to map a recognised key horizon (154.8 Oxf 300 - Top Wildegg), which represents a very poorly imaged reflection.

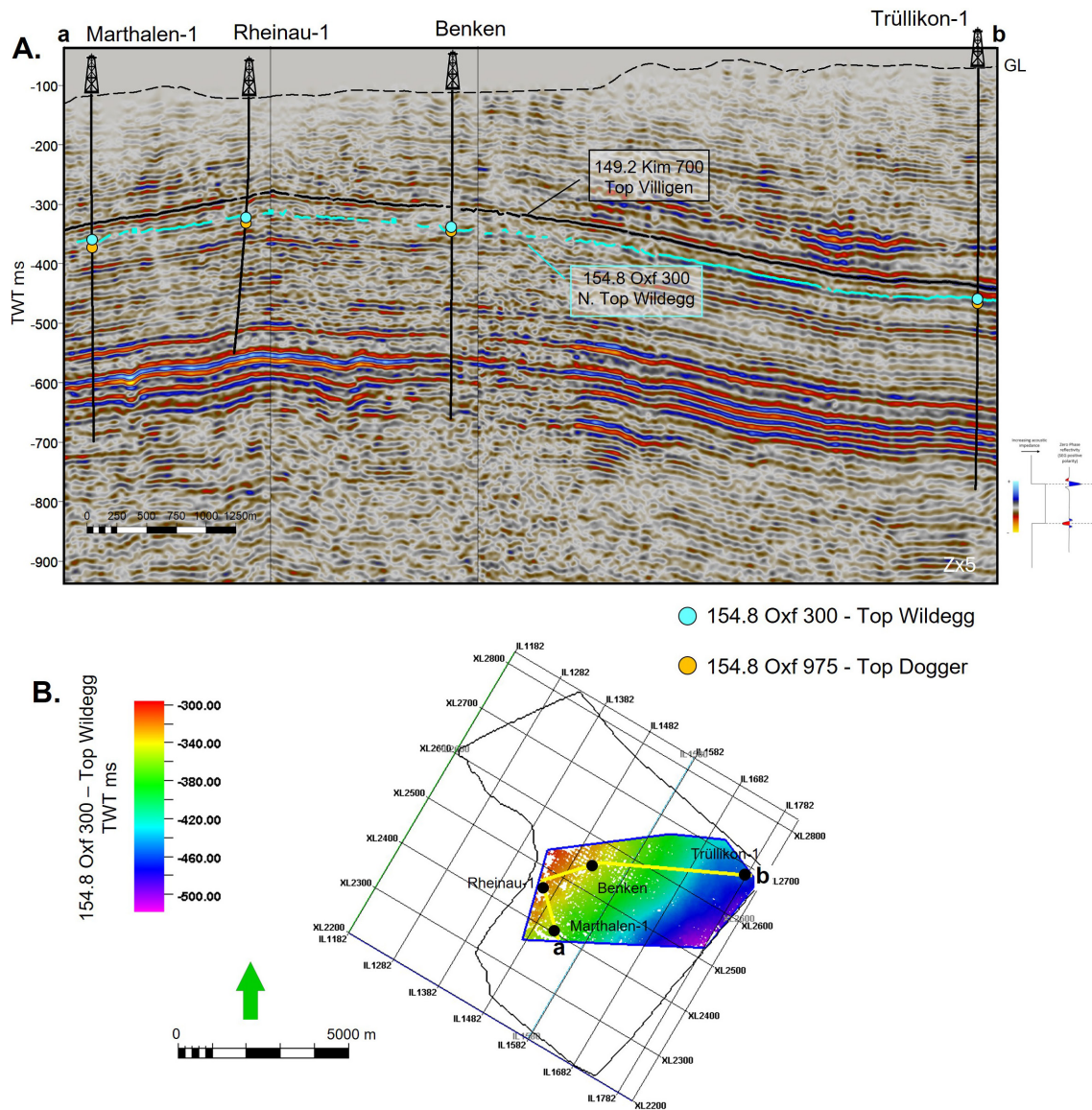


Fig. 4-37: Seismic random line across the four wells showing the 154.8 Oxf 300 - Top Wildegg

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map with wells (black circles). The 154.8 Oxf 300 - Top Wildegg interpretation is considered challenging in the eastern zone of the AOI, where it is characterised by very discontinuous amplitude. The upper horizon (149.2 Kim 700 - Top Villigen) is extremely continuous even in the amplitude degraded area around the Benken well and was thus used as interpretation guide. Note the proximity of the two key markers 154.8 Oxf 300 - Top Wildegg and 154.8 Oxf 975 - Top Dogger. The interpretation of 154.8 Oxf 975 - Top Dogger was therefore not performed. Seismic data are PreSTM-ref.

Alternatively to the other two siting regions, in the AOI of ZNO, the 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias (Base Opalinus Clay) horizons could be mapped with confidence. The orange flag in Tab. 4-25 for 174.7 Toa 100 - Top Lias is referred to the flag applied to the full-survey interpretation (Nagra 2024c). The pick within the AOI is very stable with a highly consistent seismic response (Fig. 4-38).

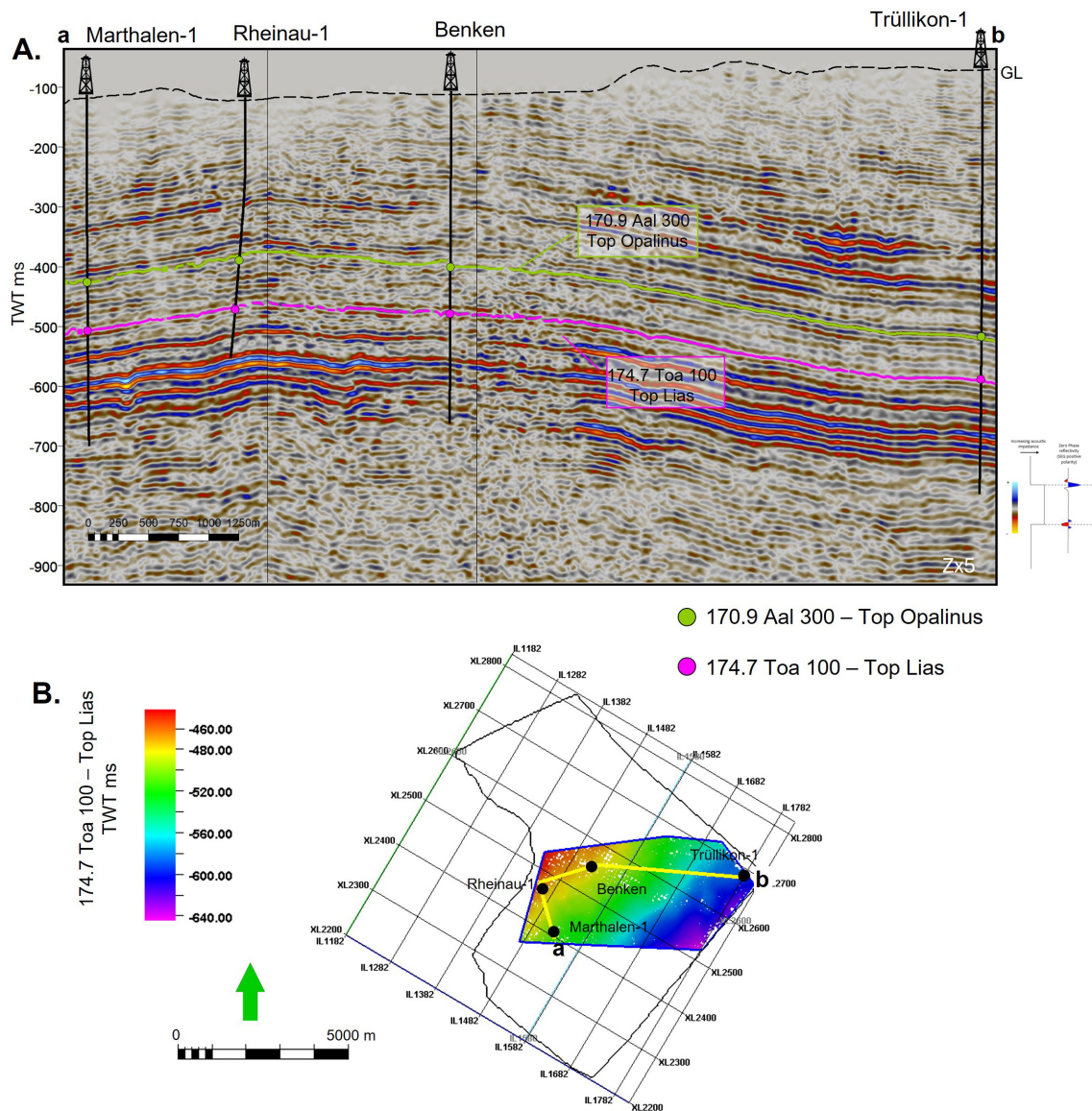


Fig. 4-38: Seismic random line across the four wells showing the 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias horizons

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map for the 174.7 Toa 100 - Top Lias horizon with wells (black circles). In the AOI these two important horizons can be mapped with confidence even in areas of degraded amplitudes associated with Quaternary valleys (i.e. around the Benken well). Seismic data are PreSTM-ref.

The performed full-survey interpretation highlighted the presence of a very complex architecture within the Malm carbonates (Nagra 2024c). Such complexity translates to important changes in the petrophysical properties (e.g. sonic velocity, Fig. 4-38, Fig. 4-39), which could influence the depth conversion results. Consequently, an extra horizon was interpreted, which coincides with a low velocity interval observed below the 149.2 Kim 100 - Top Malm horizon and corresponds to the lithological boundary of the Base Plattenkalk (Fig. 4-39).

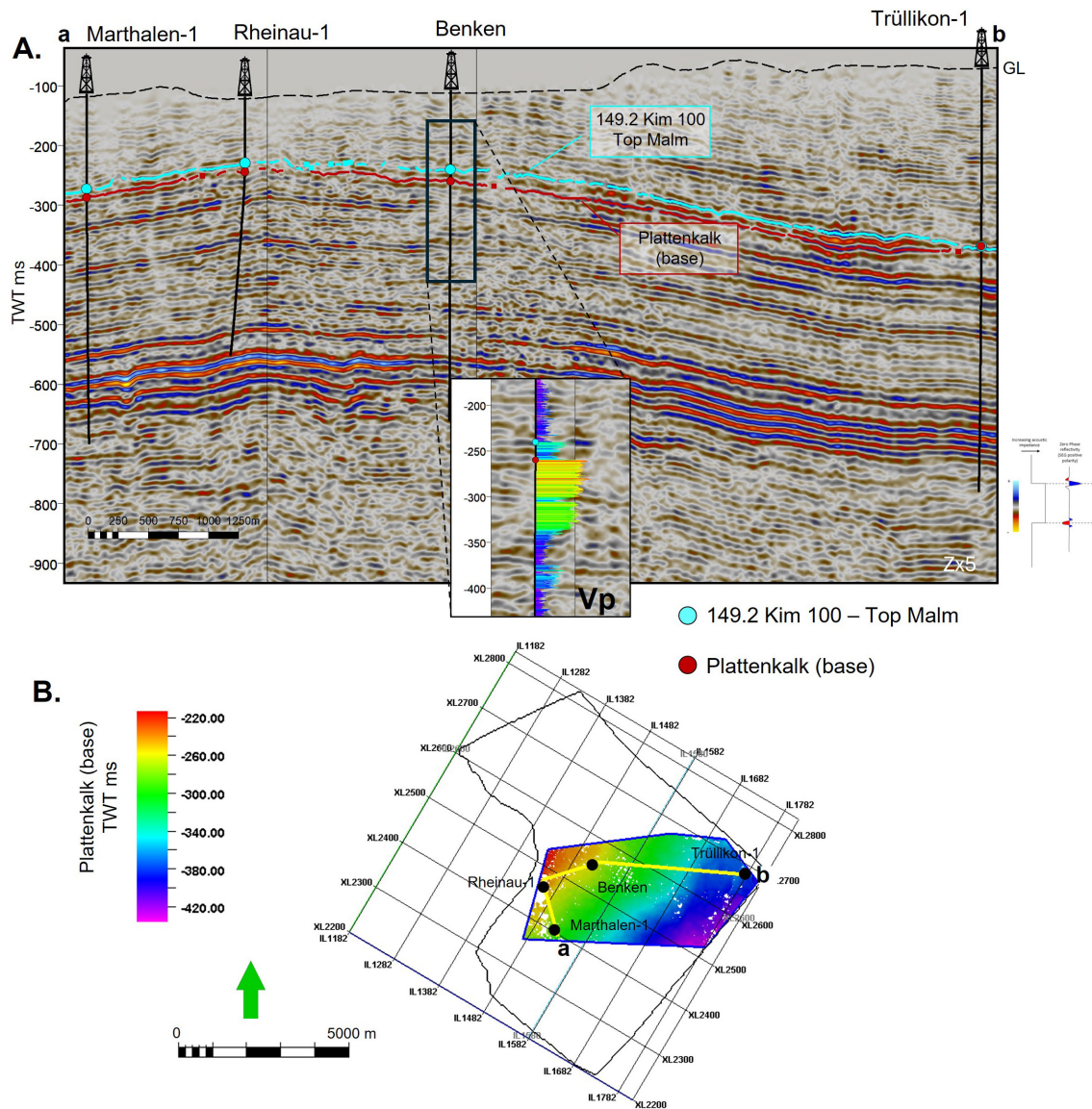


Fig. 4-39: Seismic random line across the four wells showing the 149.2 Kim 100 - Top Malm and Plattenkalk (base) horizons

A. Reflectivity with an overlay of relative acoustic impedance. B. Interpretation grid map for Plattenkalk (base) horizon with wells (black circles). The Plattenkalk (base) horizon was interpreted to capture a low velocity interval within the Malm carbonate (see insert in A.). Seismic data are PreSTM-ref.

Once the horizon interpretation was performed, the two-way travel time surfaces were generated by the interpretation of seed-line grids using convergent gridding algorithm with 25 x 25 grid. No autotracking, no smoothing, and no forced tie to well tops in time were applied.

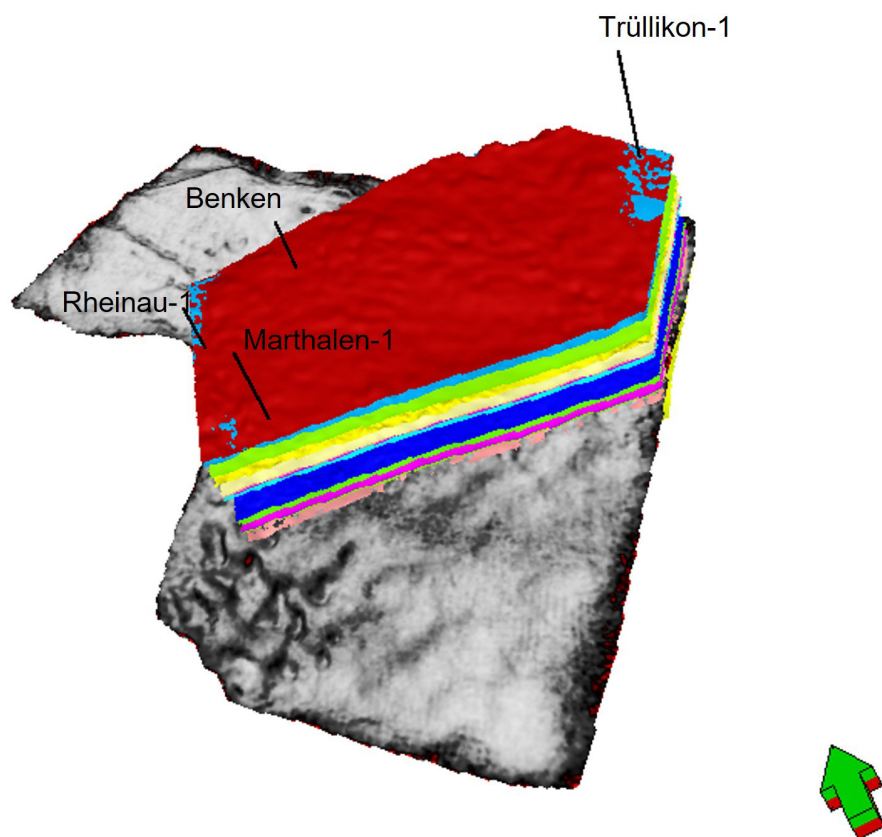


Fig. 4-40: 3D display of the 15 surfaces (TWT) generated for the AOI

237 Lad 200 - Intra Bänkerjoch variance horizon slice and the three key wells are shown to display the relative location of AOI within ZNO 97/16 merged survey. Green arrow points toward north. Vertical exaggeration is 5.

4.3.2 Depth conversion

The focus of the time-to-depth conversion exercise was to provide depth maps for the top and base host rock (Opalinus Clay) and an evaluation of the uncertainty associated with that. Furthermore, uncertainty was estimated also for the seismic thickness of the host rock as well as of the upper and lower confining units¹.

The host rock corresponds to the Opalinus Clay interval bounded by the 170.9 Aal 300 - Top Opalinus and the 174.7 Toa 100 - Top Lias horizons, the upper confining unit is the stratigraphic interval between 154.8 Oxf 300 - Top Wildegg and 170.9 Aal-300 Top Opalinus Clay and the lower confining units¹ is bounded by 174.7 Toa 100 - Top Lias and 237 Lad 400 - Top Muschelkalk.

The four key wells (Marthalen-1, Trüllikon-1, Rheinau-1 and Benken, Fig. 2-3) are located within the area of interest. Good sonic logs as well as TDR (time-depth relationship) from VSP and synthetics are available for Trüllikon-1, Rheinau-1 and Benken wells and with lower quality for Marthalen-1 well (Nagra 2024c). Sonic logs were used to identify velocity breaks, which represent boundaries of critical velocity changes. The sonic logs were upscaled within the recognised velocity breaks correlating with key stratigraphic markers (Fig. 4-41). The upscaled/averaged velocity logs were used to calculate the input interval velocity for the velocity models (Tab. 4-26).

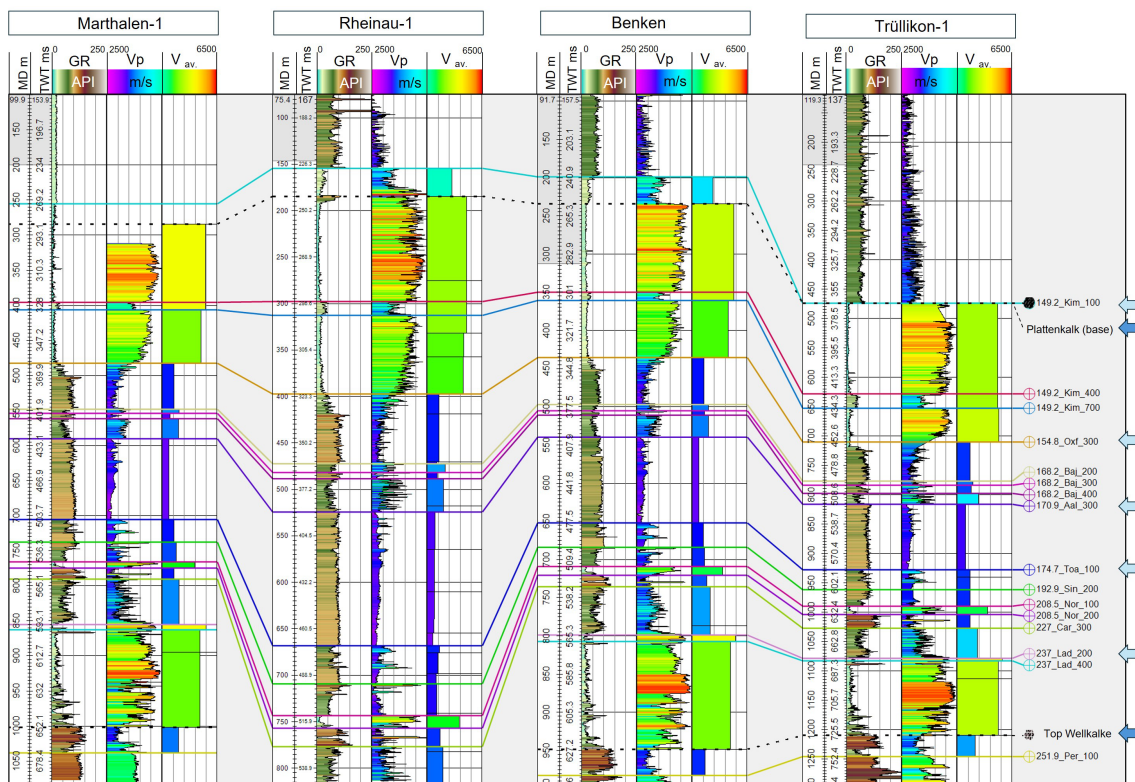


Fig. 4-41: Well correlation panel showing how major velocity breaks correspond to key stratigraphic units

Light blue arrows indicate the identified velocity breaks. Blue arrows indicate extra velocity breaks corresponding to the Plattenkalk (base) and to the top of the Wellenkalk lithological interval. The latter is positioned at the base of the velocity model and was therefore not considered. Displayed logs are gamma-ray, sonic velocity and upscaled average velocity.

Once the key velocity breaks were identified, several velocity models were generated and compared by evaluating and exhausting all the available velocity information. While building and testing the different models, key pragmatic rules were followed: (i) avoid thin layers, (ii) start simple (constant V_0) and increase complexity only if necessary (e.g. carbonate layers) (iii) aim for small and random residuals at wells, by starting with sonic-derived velocities, and tune them within the observed ranges.

Analysis of the velocities in the four wells as well as qualitative screening of the seismic velocity suggest that no obvious depth (vertical= increase of depth velocity) trend can be recognised for either the entire stratigraphic stack or within specific stratigraphic intervals (Fig. 4-41).

Tab. 4-26: Average velocity calculated at wells from upscaled sonic logs

Velocity Layers		Marthalen-1	Rheinau-1	Benken	Trüllikon-1	Average Vel.
Top	Base	Average Velocity per well m/s				
GL	149.2 Kim 100 -Top Malm	na	2700	3380	3021	3030
149.2 Kim 100 - Top Malm	Base Plattenkalk	na	4282	4022	na	4150
Base Plattenklak	154.8 Oxf 300-Top Wildegg	5464	5298	5287	5439	5372
154.8 Oxf 300-Top Wildegg	170.9 Aal 300 - Top Opalinus	3306	3481	3306	3577	3417
170.9 Aal 300 - Top Opalinus	174.7 Toa 100 - Top Lias	2838	3003	2876	3095	2953
174.7 Toa 100 - Top Lias	237 Lad 200 – Intra Bänkerjoch	3518	na	3495	3455	3484
237 Lad 200 – Intra Bänkerjoch	251.9 Per 100 - Base Mesozoic Unc.	4934		4949	5134	4805

Multiple realisations with multiple combinations of velocity inputs and ranges were tested. Among these four scenarios are shown as examples of the approach, rationale and evaluation of all the velocity source combinations and results (Tab. 4-27, Tab. 4-28, Tab. 4-29, Tab. 4-30).

Residuals at key velocity breaks were analysed, to evaluate the velocity model results. A small mean residual (indicating an unbiased depth conversion) and a low standard deviation (meaning the method explains the depth quite well) are indications of a good depth conversion model. The spatial distribution of residuals should not show a strong trend, which would indicate a velocity variation unexplained by the model. Residuals are also a direct measure of the depth conversion uncertainty at any horizon. Positive residuals mean that the horizon is too deep, and a too fast velocity was selected for the interval, while negative residuals mean that the horizon is too shallow and on the contrary the chosen velocity value was too slow.

Tab. 4-27 Selected Vo/K realisations: Model 1 velocity source input and residuals at velocity break surfaces

Model 1 is a simple model, where the 149.2 Kim 100 - Top Malm horizon was not considered and the Opalinus Clay interval velocity is 100 m/s slower. Smoothing the shallow geology heterogeneities and a slower Opalinus Clay velocity result in improved residual values and distribution, compared to similar tests. Velocities are modified well velocities to improve the residuals at wells.

Model 1		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
Plattenkalk (base)	V=Vint= Vconst	3150m/s
154.8 Oxf 300 –Top Wildegg	V=Vint= Vconst	5240 m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3400m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

Well	Horizons	B. Plattenkalk	Oxf 300	Aal 300	Toa 100	Lad 200
	Marthalen-1	-19.91	-16.46	-13.63	-11.89	-9.41
	Rheinau-1		6.64	14.68	17.74	
	Benken	-1.41	10.58	5.83	9.21	9.85
	Trüllikon-1	1.97	-9.62	-3.49	-15.67	-13.23

Tab. 4-28 Selected Vo/K realisations: Model 2 velocity source input and residuals at velocity break surfaces

Model 2 is a model with interval velocities. The detailed layering uses the key identified velocity breaks (Tab. 4-26, Fig. 4-41). Residuals are relatively large, specifically at 154.8 Oxf 300 - Top Wildegg level, suggesting that the higher model granularity at shallow level could introduce complexity, which does not improve the results. Velocities are modified well velocities to improve the residuals at wells.

Model 2		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
149.2 Kim 100 – Top Malm	V=Vint= Vconst	3100 m/s
Plattenkalk (base)	V=Vint= Vconst	4000m/s
154.8 Oxf 300 –Top Wildegg	V=Vint= Vconst	5240 m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3450m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2900 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Kim 100	B. Plattenkalk	Oxf 300	Aal 300	Toa 100	Lad 200
Well	Marthalen-1	-3.99	-5.04	-10.66	-13.96	-9.10	-3.09
	Rheinau-1	13.62		10.55	11.07	19.73	
	Benken	4.57	6.55	18.64	8.28	14.77	18.90
	Trüllikon-1	1.45	-2.11	-9.5	-9.59	-19.14	-13.13

Tab. 4-29 Selected Vo/K realisations: Model 3 velocity source input and residuals at velocity break surfaces

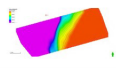
Model 3 is a more complex (hybrid) velocity model, where seismic velocity was used to capture the heterogeneities associated with part of the Opalinus Clay overburden. The use of seismic velocity worsens the results. Velocities are modified well velocities to improve the residuals at wells.

Model 3		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
Plattenkalk (base)	V=Vint= Vconst	3150m/s
154.8 Oxf 300 –Top Wildegg	V=seismic velocity cube {smoothed PSDM velocity	
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3400m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

Well	Horizons	B. Plattenkalk	Oxf 300	Aal 300	Toa 100	Lad 200
	Marthalen-1	-10.9	-21.68	-25.02	-24.13	-17.85
	Rheinau-1		-4.66	-2.73	2.41	
	Benken	-1.41	-3.26	-13.56	-11.20	-7.10
	Trüllikon-1	1.97	-5.60	-5.97	-19.13	-13.29

Tab. 4-30: Selected Vo/K realisations: Model 4 velocity source input and residuals at velocity break surfaces

Model 4 is a hybrid velocity model, where the complexity of the interval between Plattenkalk (base) and 154.8 Oxf 300 - Top Wildegg is captured using seismic velocities which were scaled and translated into a velocity attribute map (Fig. 4-42). This model was selected as base case since the good residuals and since it accounts for the geological heterogeneity of the shallow stratigraphic interval (Fig. 4-43).

Model 4		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
Plattenkalk (base)	V=Vint= Vconst	3150m/s
154.8 Oxf 300 –Top Wildegg	V=Vmap (scaled seismic velocity)	
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3496m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2825 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3484 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4924 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

Well	Horizons	B. Plattenkalk	Oxf 300	Aal 300	Toa 100	Lad 200
	Marthalen-1	-10.9	-13.17	-13.6	-11.66	-5.19
	Rheinau-1		4.15	9.22	15.47	
	Benken	-1.41	5.71	-1.95	5.69	5.69
	Trüllikon-1	1.97	4.58	7.32	-4.97	1.05

Model 4 was selected as the base case. The velocity heterogeneities observed in the interval between Plattenkalk (base) - 154.8 Oxf 300 - Top Wildegg could be captured through a velocity attribute map derived by the velocity extraction from the PreSDM velocity cube for this interval (Fig. 4-42). However, the seismic velocities appeared too slow and better results (smaller residuals) were achieved by increasing the velocity of 4.5%.

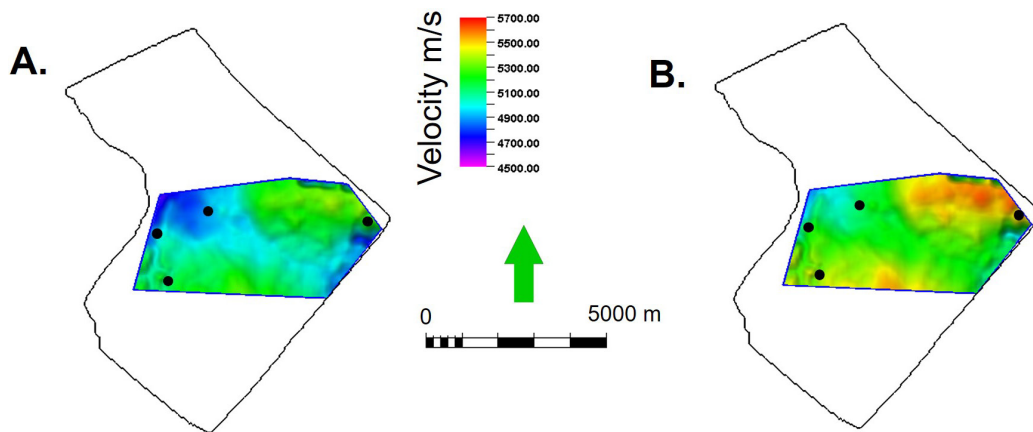


Fig. 4-42: Velocity attribute maps generated for the interval Plattenkalk (base) - 154.8 Oxf 300 - Top Wildegge

A. Velocity attribute map was derived by the velocity extraction from the PreSDM velocity cube for Plattenkalk (base) - 154.8 Oxf 300 - Top Wildegge interval. The implementation of the extracted velocity map into a velocity model resulted in well residuals, which indicate that the extracted velocities were too slow. The velocity was increased by 4.5% of the velocity was applied and the velocity map adjusted (B.). This velocity map was then used in Model 4 (base case, Tab. 4-30).

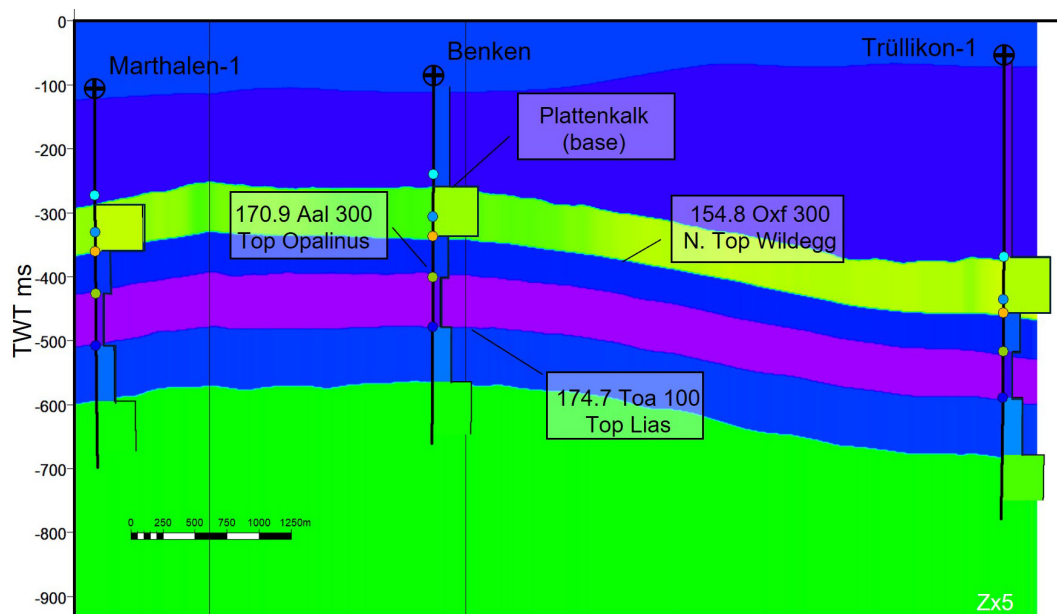


Fig. 4-43: Base case Vo/K velocity model translated into a velocity cube

A. Section across the wells showing the lateral and vertical trends of Model 4 (base case, Tab. 4-30) and the average well velocity per velocity interval. The velocity model is a hybrid model with interval velocities combined with velocity attribute map extracted from the seismic velocity cube for the Plattenkalk (base) to 154.8 Oxf 300 - Top Wildegge interval. The seismic velocity was selected because of the geological heterogeneity for this interval. Velocities were increased of 4.5% to improve the residual values and distribution at wells. GL is ground level.

Velocity Model 4 (base case) was therefore used to perform depth conversion with focus on top and base host rock (170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias, respectively, Fig. 4-44, Fig. 4-45).

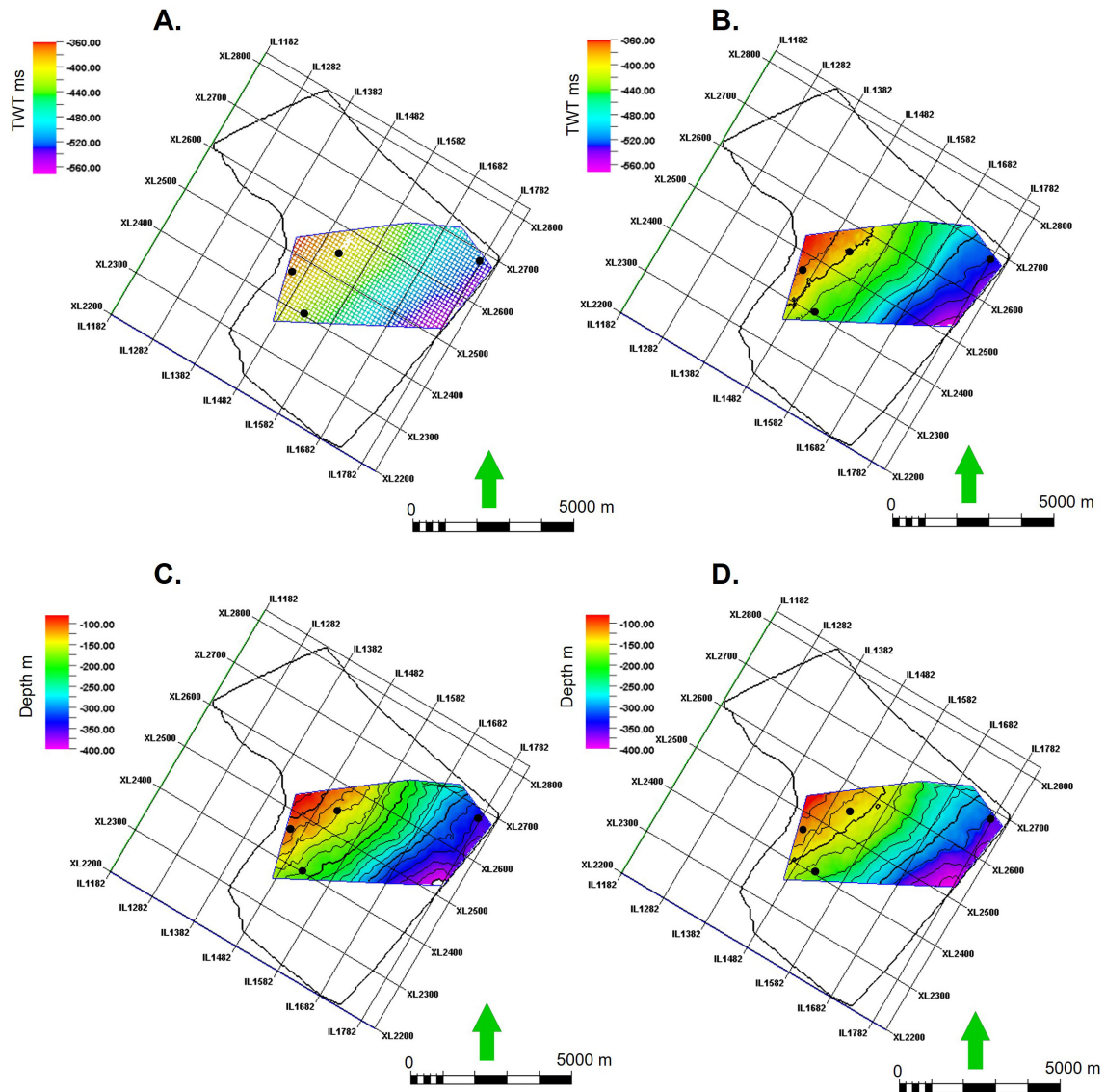


Fig. 4-44: Time and depth surfaces of 170.9 Aal 300 - Top Opalinus

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 4; Tab. 4-30) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

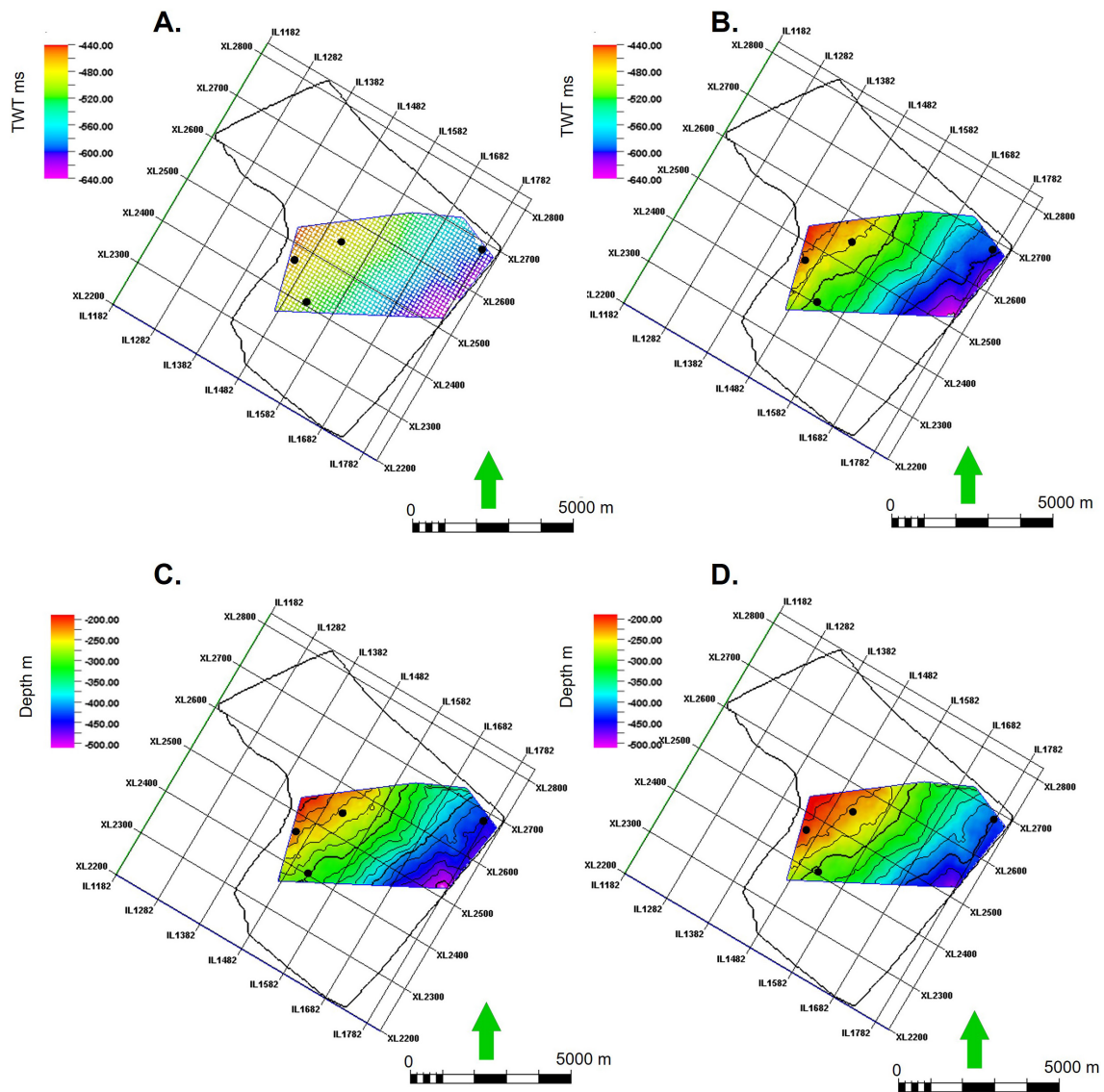


Fig. 4-45 Time and depth surfaces of 174.7 Toa 100 - Top Lias

A. TWT interpretation, B. Gridded in time with 25 x 25 grid, C. Depth-converted (base case Model 4; Tab. 4-30) and D. Forced to wells with an influence radius of 1.5 km. Black circles are wells.

4.3.3 Depth and thickness uncertainties

Depth uncertainty was calculated for the depth converted horizons representing the top and base of the host rock (Opalinus Clay interval), 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias, respectively.

Depth uncertainty calculation followed the workflow proposed in Section 3.3, assuming as minimum uncertainty value the 2Stdev from the well top residuals (Tab. 4-31).

Tab. 4-31: Well top residuals and calculated standard deviations at 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias

		170.9 Aal 300 – Top Opalinus	174.7 Toa100 – Top Lias
Wells	Marthalen-1	-13.6	-11.66
	Rheinau-1	9.22	15.47
	Benken	-1.95	5.69
	Trüllikon-1	7.32	-4.97
	Stdev	10.4	11.8
	2 Stdev	20.8	23.8

Once defined the uncertainty base value corresponding to the absolute 2Stdev (= 21 m and 24 m for 170.9 Aal 300- Top Opalinus and 174.7 Toa 100 - Top Lias, respectively), identification of higher uncertainty values and their trends was performed in accordance with the proposed workflow, by comparing selected scenarios, i.e. the difference of the PreSTM-ref depth maps with depth maps derived by reproducing the base case velocity model for the QLP dataset.

The velocity model generated for the QLP dataset should resemble the hybrid approach used for the selected Model 4 (base case). The key challenge for ZNO relies on the fact that the pseudo datum of 100 m above sea level crosscut the Malm unit. Low velocity wedges (Plattenkalk) are therefore juxtaposed to high velocity areas (Fig. 4-46). A new horizon (Plattenkalk (base-wedge)) was therefore constructed to capture the low velocity zones between the pseudo datum and the Plattenkalk (base).

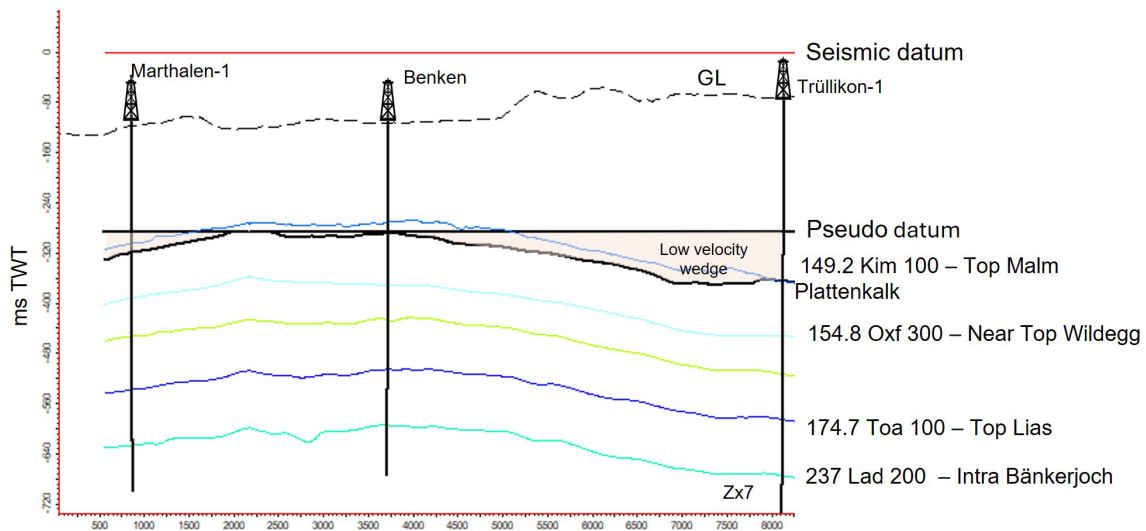
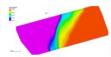


Fig. 4-46: Section across three of the four wells showing the position of the QLP pseudo datum and the juxtaposition of low velocity wedges against the high velocity interval below the Plattenkalk (base) horizon

The implementation of a velocity hybrid model mirroring the Model 4 (base case, PreSTM-ref) resulted in extremely high residuals at wells (Tab. 4-32). Several realisations were therefore conducted testing several input combinations and with increased simplification of the Vo/K layering (Tab. 4-33, Tab. 4-34).

Tab. 4-32: Selected Vo/K realisations: Model 1 QLP velocity source input and residuals at velocity break surfaces

Model 1 QLP is a hybrid velocity model, where the complexity of the interval between Plattenkalk (base) and 154.8 Oxf 300 - Top Wildegge is captured using the velocity attribute map established for this interval (Fig. 4-42) and mirroring the PreSTM-ref base case velocity model (Tab. 4-30).

Model 1 QLP		
Horizon Base	Model (velocity sources)	Velocity Value
floating-datum	V=Vint= Vconst	3500 m/s
Plattenkalk (base - wedge)	V=Vint= Vconst	3150m/s
154.8 Oxf 300 –Top Wildegge	V=Vmap	
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3400m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

	Horizons	Aal 300	Toa 100
Well	Marthalen-1	-1.14	-0.40
	Rheinau-1	18.07	25.65
	Benken	18.53	18.36
	Trüllikon-1	32.89	20.70

Tab. 4-33: Selected Vo/K realisations: Model 2 QLP velocity source input and residuals at velocity break surfaces

Model 2 QLP is a model with interval velocities. The detailed layering uses the key identified velocity breaks (Tab. 4-26, Fig. 4-41).

Model 2 QLP		
Horizon Base	Model (velocity sources)	Velocity Value
Pseudo datum	V=Vint= Vconst	3500 m/s
Plattenkalk (base - wedge)	V=Vint= Vconst	3150m/s
154.8 Oxf 300 –Top Wildegg	V=Vint= Vconst	5000m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3400m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

Well	Horizons	Aal 300	Toa 100
	Marthalen-1	-4.76	-4.22
	Rheinau-1	19.47	24.13
	Benken	22.73	22.57
	Trüllikon-1	18.73	6.02

Best residuals were, however, observed in Model 3 QLP, where the shallow part of the Opalinus Clay overburden, below the pseudo datum and down to 154.8 Oxf 300 - Top Wildegg, was collapsed into one single velocity layer.

Tab. 4-34: Selected Vo/K realisations: Model 3 QLP velocity source input and residuals at velocity break surfaces

Model 3 QLP is a model with interval velocities with a single simplified layer between the pseudo datum and 154.8 Oxf 300 - Top Wildeg, smoothing the pseudo datum - Plattenkalk (base) lateral velocity contrast.

Model 3 QLP		
Horizon Base	Model (velocity sources)	Velocity Value
Pseudo datum	V=Vint= Vconst	3500 m/s
154.8 Oxf 300 –Top Wildeg	V=Vint= Vconst	4200m/s
170.9 Aal 300 - Top Opalinus	V=Vint= Vconst	3500m/s
174.7 Toa 100 - Top Lias	V=Vint= Vconst	2800 m/s
237 Lad 200 - Intra Bänkerjoch	V=Vint= Vconst	3480 m/s
251.9 Per 100 - Base Mesozoic Unc.	V=Vint= Vconst	4805 m/s
Depth: -1500 ms TWT	V=Vint= Vconst	4250 m/s

Well	Horizons	Aal 300	Toa 100
	Marthalen-1	-14.96	-3.95
	Rheinau-1	-8.36	1.84
	Benken	-7.84	-3.95
	Trüllikon-1	29.30	19.98

To gain confidence that such simplified model (Model 3 QLP) was the best solution for the comparison scenarios (i.e. input for depth uncertainty trend maps), differences with the PreSTM-ref base case were calculated in absolute value (Fig. 4-47). The simplified Model 3 discounts the important anomaly (~80 m) in the eastern corner observed when comparing the results from Model 1 QLP (Tab. 4-32) and Model 2 QLP (Tab. 4-33).

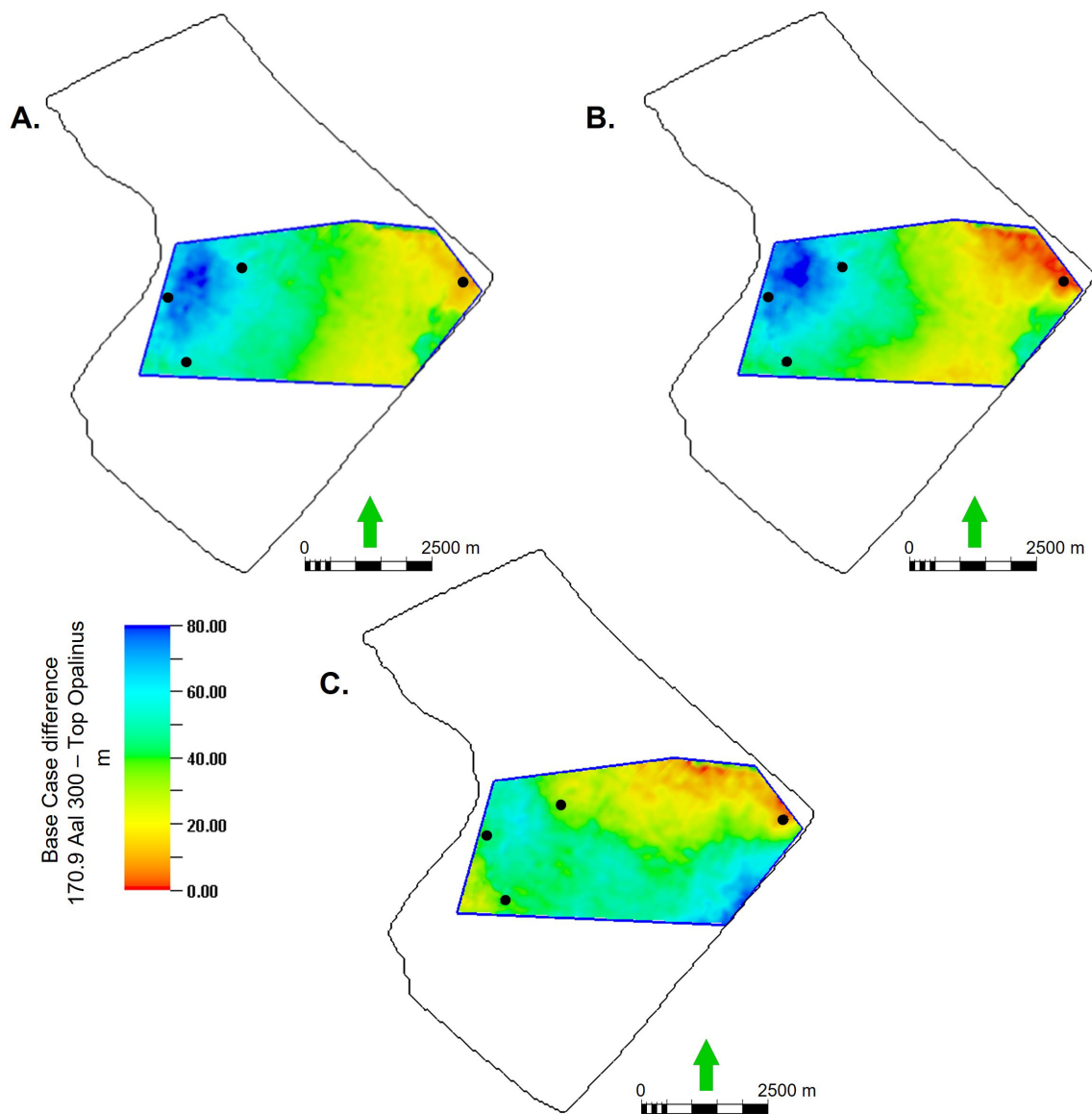


Fig. 4-47: 170.9 Aal 300 - Top Opalinus difference depth between maps PreSTM-ref base case and QLP velocity model example realisations expressed absolute value (m)

A. Difference between PreSTM-ref base case and QLP depth map from Model 1 QLP (Tab. 4-32) B. Difference between PreSTM-ref base case and QLP depth map from Model 2 QLP (Tab. 4-33) C. Difference between PreSTM-ref base case and QLP depth map from Model 3 QLP (Tab. 4-34). Note how the important anomaly in the eastern corner is smoothed using a simpler velocity model. Black circles are wells.

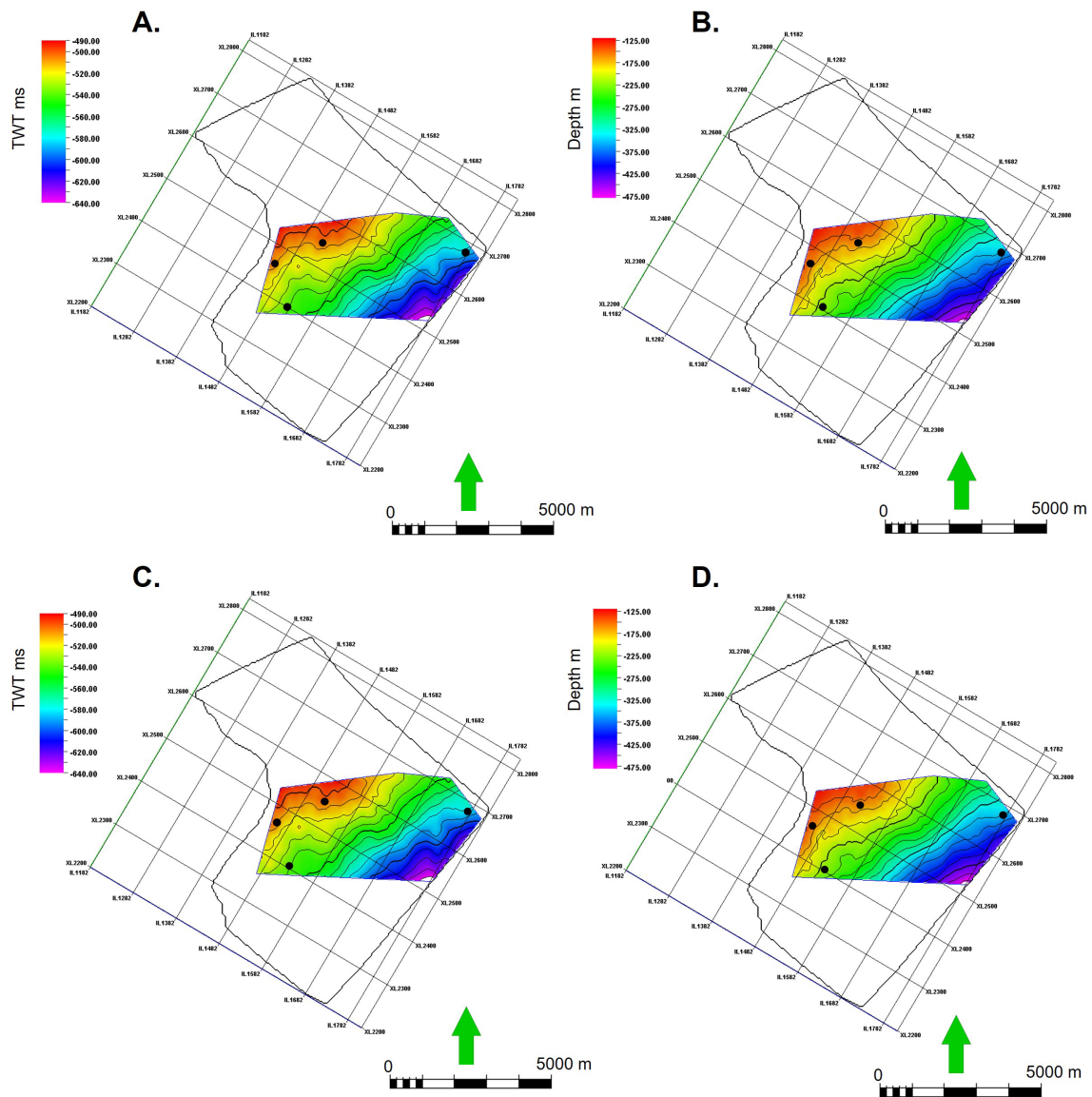


Fig. 4-48: 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias maps: QLP seismic vintage

170.9 Aal 300 - Top Opalinus: A. in TWT and B. in depth; 174.7 Toa 100 -Top Lias; C. in TWT and D. in depth. QLP TWT key horizons were depth-converted using a Vo/K model. The QLP depth-converted surfaces for the top and base host rock were not forced to wells and they were used to calculate depth uncertainty trend maps. Black circles are wells.

Comparison between the two solutions (PreSTM-ref and QLP) shows an area of important difference (> 60 m) in the eastern and south-western corners of the AOI (Fig. 4-49). The latter coincides with an area of low confidence associated with potential survey edge effects (Nagra, 2024c).

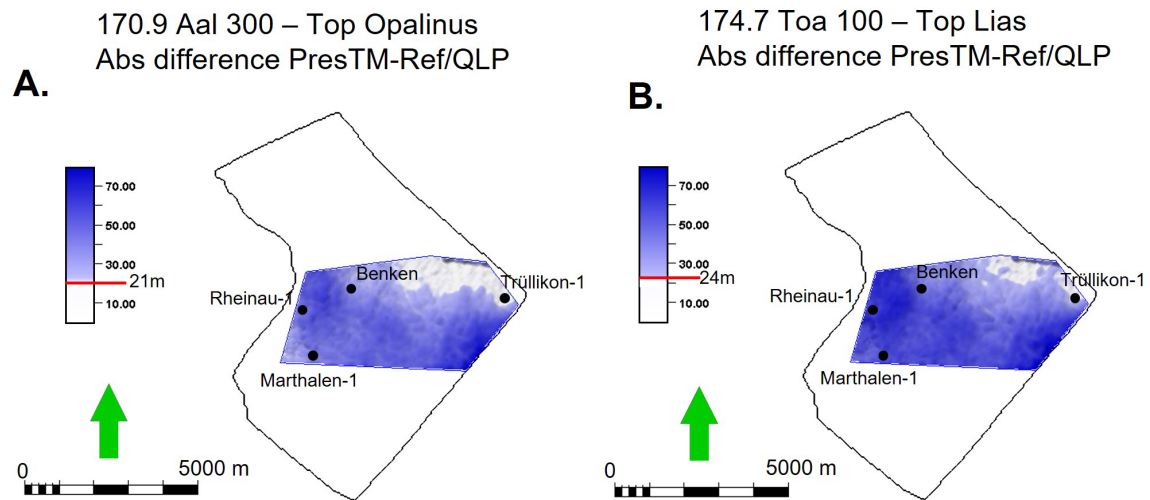


Fig. 4-49: Absolute values of calculated difference between the base case realisations for PreSTM-ref and QLP seismic data

A. 170.9 Aal 300 - Top Opalinus; B. 174.7 Toa 100 - Top Lias. Abs is absolute value. Values smaller than 21 m and 24 m (respectively for the two horizons) are white colour. 21 m and 24 m represent the base uncertainty values coinciding with the 2Stdev of the residuals at wells.

Depth uncertainty maps (Fig. 4-50) were built by extrapolating uncertainty trends from the selected realisation comparison (Fig. 4-49) with a minimum (base) uncertainty value equal to 2Stdev of the well residuals for the base case scenario (Tab. 4-31, equal to 21 m and 24 m for 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias, respectively). The uncertainty trends were then tapered to a value of 2 m at well locations with an influence radius of 1500 m (size of major topographic features;). The well tapering accounts for an uncertainty value equal (almost) to zero at well location (Fig. 4-50 B., D.).

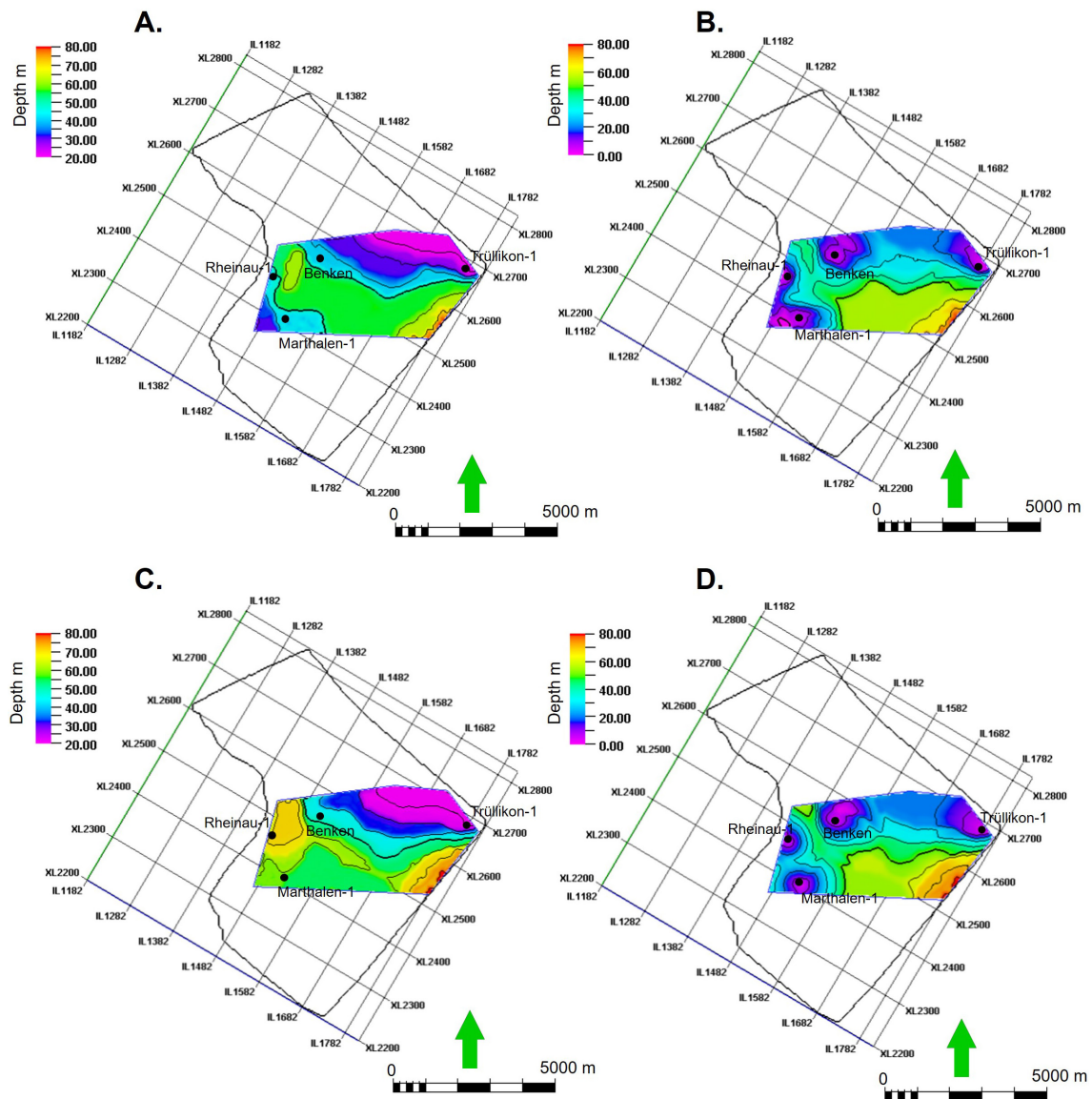


Fig. 4-50: Uncertainty depth maps for 170.9 Aal 300 - Top Opalinus Clay and 174.7 Toa 100 - Top Lias

Minimum value for the uncertainty is 21 m and 24 m calculated from the residuals at wells for the 170.9 Aal 300 - Top Opalinus Clay and 174.7 Toa 100 - Top Lias. Trend maps (A., C., respectively) were generated using the difference maps from the selected realisations (Fig. 4-49) and further tapered to wells (2 m uncertainty at well location; B., D.)

A quality control on the depth uncertainty maps is provided by the calculation of an upper and lower case. The upper- and lower-cases are generated by adding or subtracting the absolute value uncertainty maps to the base case depth map. The upper- and lower-case surfaces should envelop the base case depth map (Fig. 4-51).

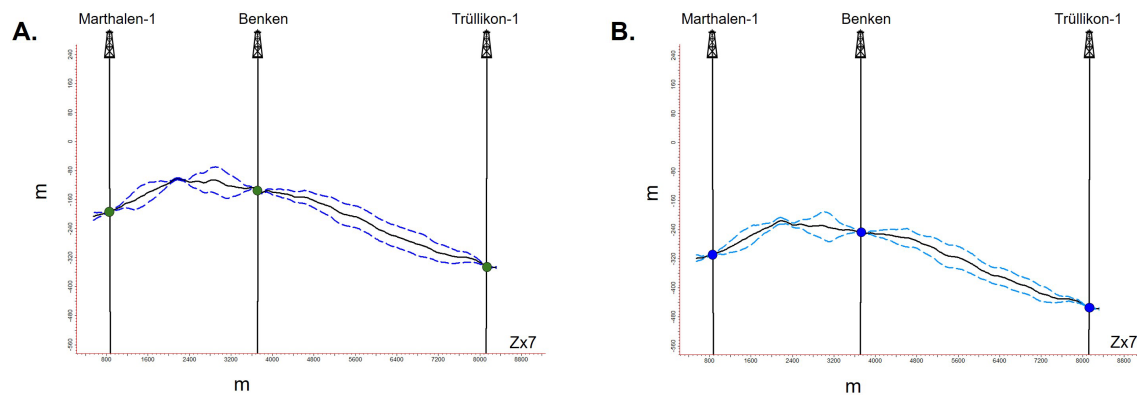


Fig. 4-51: Depth section across the three of the four wells showing the base case enveloped by the upper- and lower-cases

A. 170.9 Aal 300 - Top Opalinus Clay. Black solid line is the base case surface, blue dashed lines are upper- and lower-case surfaces. Well tops are green circle. B. 174.7 Toa 100 - Top Lias. Black solid line is the base case surface, light blue dashed lines are upper- and lower-case surfaces. Well tops are blue circle.

From the PreSTM-ref base-case depth-converted surfaces, seismic thickness maps (Fig. 4-52) were calculated for the Opalinus Clay (host rock). The thickness maps were derived by untied (not forced to wells) surfaces and compared with the thickness observed at wells.

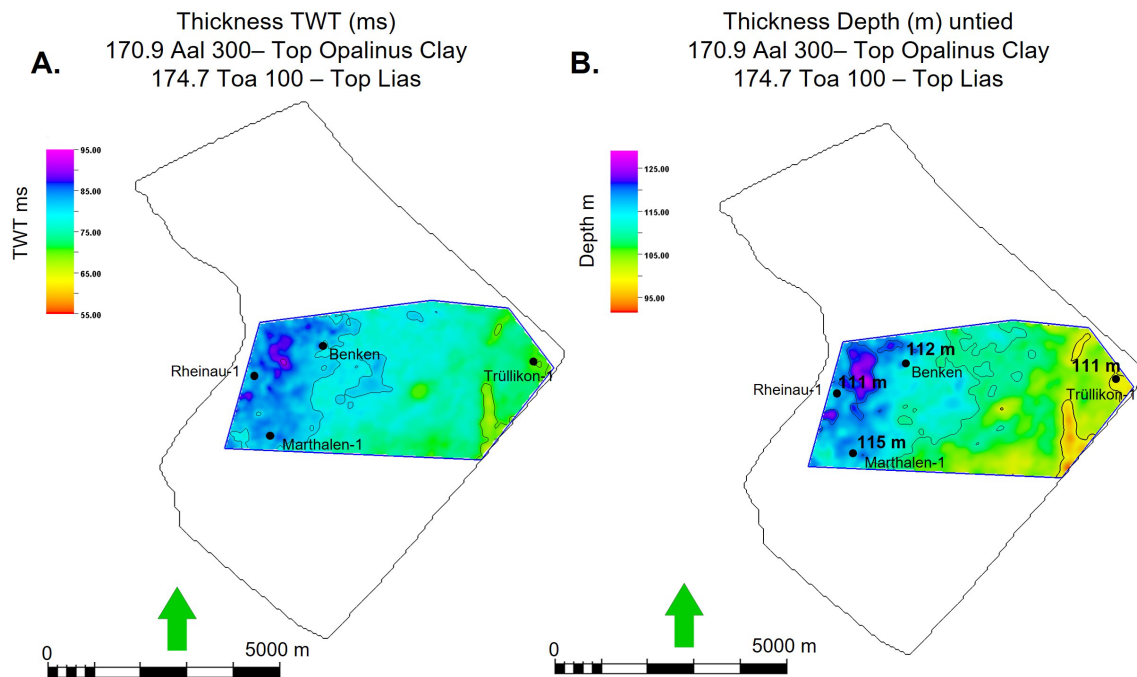


Fig. 4-52: TWT (A) and depth (converted, B.) seismic thickness for the interval 170.9 Aal 300 - 174.7 Toa 100 - Top Lias

The thickness depth is untied, surfaces 170.9 Aal 300 and 174.7 Toa 100 - Top Lias were not forced to wells. Despite not being forced to the wells, note the good match between seismic thickness and thickness measured in wells (black numbers, B.), except for the Trüllikon-1 well, where the thickness appears to be underestimated. Thinner Opalinus Clay at the Trüllikon-1 well in depth could be associated with the higher Opalinus Clay velocity observed in this well and modelled with lower velocity in the selected velocity model (Tab. 4-26).

The thickness uncertainty associated with variability of interval velocity was, thus, calculated for the host rock (Opalinus Clay) and the upper and lower confining units¹ (154.8 Oxf 300 - Top Wildegg - 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias to 237 Lad 400 Top Muschelkalk intervals, respectively).

For the upper confining unit (154.8 Oxf 300 - Top Wildegg - 170.9 Aal 300 – Top Opalinus interval), the impact of the interval velocity, which is estimated as Stdev derived from the Stdev of the velocity ranges proportional to the interval average thickness (Tab. 4-35), is estimated to equal 3.5 m (2Stdev) for an average thickness of 111 m.

Tab. 4-35: Input and results for the velocity component of the thickness uncertainty of the upper confining unit

154.8 Oxf 300 - Top Wildegg – 170.9 Aal 300– Top Opalinus	
	Well Velocity
Marthalen-1	3449m/s
Rheinau-1	3485m/s
Benken	3469 m/s
Trüllikon-1	3575 m/s
Average Velocity	3495 m/s
Stdev (velocity)	55 m/s
Average Thickness	111 m
Stdev	1.75 m
2 Stdev	3.5 m

The thickness uncertainty for the upper confining unit calculated using the Stdev approach could underestimate the uncertainty away from the well-controlled areas and should be further evaluated, when considering the observed large range of depth uncertainty.

For the host rock (170.9 Aal 300 Top Opalinus - 174.7 Toa 100 - Top Lias) the velocity contribution is estimated equal to 9 m (2Stdev) (Tab. 4-36).

Tab. 4-36: Input and results for the velocity component of the thickness uncertainty of the host rock

170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	
	Well Velocity
Marthalen-1	2838 m/s
Rheinau-1	3003 m/s
Benken	2876 m/s
Trüllikon-1	3095 m/s
Average Velocity	2953 m/s
Stdev (velocity)	120 m/s
Average Thickness	112 m
Stdev	4.5 m
2 Stdev	9 m

The velocity contribution for the lower confining unit¹ (174.7 Toa 100 - Top Lias to 237 Lad Top Muschelkalk) is captured in Tab. 4-37 and it is calculated equal to 2.6 m (2Stdev).

Tab. 4-37: Input and results for the velocity component of the thickness uncertainty of the lower confining unit¹

174.7 Toa 100 – Top Lias – 237 Lad 400 – Top Muschelkalk	
	Well Velocity
Marthalen-1	3518m/s
Rheinau-1	
Benken	3495 m/s
Trüllikon-1	3455 m/s
Average Velocity	3489 m/s
Stdev (velocity)	89 m/s
Average Thickness	149 m
Stdev	1.3 m
2 Stdev	2.6 m

5 Conclusions

A dedicated and fit-for-purpose depth conversion and a quantification of the associated uncertainties were performed since 3D depth models (Nagra 2024f) were required as input for the local geological characterisation of the central areas of the three siting regions acting as basis for numerical modelling of repository performance assessments and radiological consequence analysis.

PreSDM datasets were available, however velocity anomalies observed in the processing velocities impaired the confidence in the final depth top structures and the interpretation results were captured in the PreSTM-ref seismic dataset (Nagra 2024a, 2024b, 2024c, 2024d).

Consequently, the time-to-depth conversion was executed through an industry standard workflow, which implies the generation and the testing of velocity models using the so-called Vo/K approach, carried out in a similar and most comparable way for the three siting regions.

Several scenarios and methodologies can be tested during the depth conversion exercise, resulting in several depth structures. However, a reference case (solution of choice) has to be selected. The reference case is generally referred to as the base case.

There are no globally established criteria to define the base case. Considering the comparability scope of the site investigation, the base case was selected following the three established criteria below:

1. Use of comparable seismic products between sites: PreSTM-ref is the most comparable seismic processing product among the three surveys. Therefore, the resulting surfaces from the PreSTM-ref interpretation have to be used
2. Conservative approach: selection of the interpretation of the base host rock (174.7 Toa-100 – Top Lias), which is by tendency the shallowest (smaller thickness of host rock)
3. Technically acceptable velocity model: model is consistent with data and captures relevant heterogeneity within the data.

Evaluation of a good velocity model was performed by the analysis of the residuals at wells, with focus on the 170.9 Aal 300 - Top Opalinus and 174.7 Toa 100 - Top Lias horizons (i.e. top and base host rock) and a base case was selected for each of the three siting regions. For NL siting region, the horizon 168.2 Baj 300- Base Herrenwis was used as proxy for the Top Opalinus, since it marks the velocity change to a velocity consistent with the one measured within the Opalinus Clay interval.

The “base case” velocity model was used to depth convert the time surfaces into depth surfaces as input for the 3D geological models (Nagra 2024f).

Depth uncertainty was then estimated by (i) the depth residuals of the base case models and (ii) the depth differences between the selected depth conversion scenarios.

(i) The 2 standard-deviation of the depth residuals (representing a min -max range) was considered as a low estimate (base value) for the uncertainty due to the small number of wells.

(ii) Different realisations of the Vo/K models on PreSTM-ref data did not show major differences, with values generally lower than the 2Stdev residuals. Since it appeared that the different statics applied in the time migration data sets and the near-surface velocity model in the depth migration data sets are the largest contributor to depth uncertainty, a different processing vintage was chosen as input for the depth difference maps. Similar Vo/K velocity models were reproduced to depth-convert the QLP time horizons.

The resulting uncertainty maps therefore resulted from the selected scenario depth difference maps with a minimum value equal to the 2Stdev from well residuals and finally tapered to wells, assuming an uncertainty of 2 m at well locations.

In the JO area of interest, the depth differences between the QLP and the PreSTM-ref are up to 45 meters even after well tapering.

In the NL siting region, the depth differences between the QLP and the PreSTM-ref are relatively small, and it is generally below the 25 m Stdev, except for a small area to the north, where uncertainties are around 45 m.

In the ZNO siting region, the uncertainty values exceed 60 m, although they decrease to values < 50 m for most of the AOI, when tapered to wells.

Due to the clear impact of the different static solutions in the uncertainty values and distribution, it should be considered that the resulted uncertainty maps are representative of very conservative scenarios.

Thickness uncertainties were also assessed for the Opalinus Clay host rock as well as for the upper and lower confining units¹. The thickness uncertainties were calculated considering the variability of interval velocity and the resulted estimation are captured Tab. 5-1.

In NL siting region, the uncertainty for the upper confining unit showed a relatively high value associated with the high-velocity Stdev, which is related to the presence of the fast Herrenwis carbonate platform penetrated by two of the four wells. Consequently, the thickness uncertainty value was derived by the average of the uncertainty values calculated separately for the wells penetrating the elastic sequence and for those penetrating the carbonate interval.

In the ZNO siting region, the thickness uncertainty for the upper confining unit was calculated using the velocity Stdev approach might underestimate the uncertainty away from the well-controlled areas, especially when compared to the observed (large) depth uncertainty ranges.

Tab. 5-1: Thickness uncertainty summary table

JO Siting Region	Thickness Uncertainty
Upper Confining Unit 168.2 Baj 100 - Top Passwang – 170.9 Aal 300– Top Opalinus	3 m
Host Rock 170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	5 m
Lower Confining Unit 174.7 Toa 100 – Top Lias – 237 Lad 400 – Top Muschelkalk	3 m
NL Siting Region	Thickness Uncertainty
Upper Confining Unit 154.8 Oxf 300 - Top Wildegg – 170.9 Aal 300– Top Opalinus	6 m
Host Rock 170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	6 m
Lower Confining Unit 174.7 Toa 100 – Top Lias – 237 Lad 400 – Top Muschelkalk	4 m
ZNO Siting Region	Thickness Uncertainty
Upper Confining Unit 154.8 Oxf 300 - Top Wildegg – 170.9 Aal 300– Top Opalinus	4 m
Host Rock 170.9 Aal 300 – Top Opalinus - 174.7 Toa 100 – Top Lias	9 m
Lower Confining Unit 174.7 Toa 100 – Top Lias – 237 Lad 400 – Top Muschelkalk	3 m

6 References

- Ait Addi, A. (2015): Builders and taphonomic processes of Bajocian coral patch reefs in the Moroccan Central High Atlas. *Arabian Journal of Geosciences*, 8(10), 8583-8600.
- Abrahamsen, P. (1996): Geostatistics for seismic depth conversion. NR-notat (SAND/06/96), Norsk Regnesentral, Oslo.
- Etris, E. L., Crabtree, N. J., Dewar, J., & Pickford, S. (2001): True depth conversion: more than a pretty picture. *CSEG recorder*, 26(9), 11-22.
- Nagra (2019a): Preliminary horizon and structure mapping of the Nagra 3D seismics JO-15 (Jura Ost) in time domain. Nagra Arbeitsbericht NAB 18-34.
- Nagra (2019b): Preliminary horizon and structure mapping of the Nagra 3D seismics NL-16 (Nördlich Lägern) in time domain. Nagra Arbeitsbericht NAB 18-35.
- Nagra (2019c): Preliminary horizon and structure mapping of the Nagra 3D seismics ZNO-97/16 (Zürich Nordost) in time domain. Nagra Arbeitsbericht NAB 18-36.
- Nagra (2024a): 3D Seismic Interpretation of stratigraphic horizons and structures in time domain Jura Ost. Nagra Arbeitsbericht NAB 23-17.
- Nagra (2024b): 3D Seismic Interpretation of stratigraphic horizons and structures in time domain Nördlich Lägern. Nagra Arbeitsbericht NAB 23-18.
- Nagra (2024c): 3D Seismic Interpretation of stratigraphic horizons and structures in time domain Zürich Nordost. Nagra Arbeitsbericht NAB 23-19.
- Nagra (2024d): Processing 3D Seismic Surveys Jura Ost, Nördlich Lägern and Zürich Nordost. Nagra Arbeitsbericht NAB 23-16.
- Nagra (2024e): Geosynthesis of Northern Switzerland. Nagra Technical Report NTB 24-17.
- Nagra (2024f): Geological Properties of the Jura Ost, Nördlich Lägern and Zürich Nordost Siting Regions for Safety Assessment. Nagra Arbeitsbericht NAB 24-10.
- Nagra (2024g): Radiological Consequence Analysis for a Deep Geological Repository in Northern Switzerland. Nagra Technical Report NTB 24-18.
- Nagra (2024h): Synthesis of the Performance Assessment for a Deep Geological Repository for Radioactive Waste. Nagra Technical Report NTB 24-22.
- Rebesco, M., Hernández-Molina, F. J., Van Rooij, D., & Wählin, A. (2014): Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology*, 352, 111-154.
- Ruchat, A., Lathuilière, B., Wohlwend, S., Deplazes, G., Eberli, G.P., Feist-Burkhardt, S. & Samankassou, E. (2024): A Bajocian event of global coral reef growth: Record from northern Switzerland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 655, 112504.