Karlsruhe Institute of Technology

INSIDE

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Karlsruher Institut für Technologie

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P- AND S-WAVE VELOCITY MODELS FOR THE INSIDE STUDY AREA

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EXECUTIVE SUMMARY

The INSIDE project aims at enhancing our understanding of processes associated with induced seismicity in the southern Munich area, particularly around the active geothermal sites of Schäftlarnstraße and Pullach, as well as the planned Baierbrunn project. This report describes the construction of a 3D velocity model for the propagation of compressional (P-) and shear (S-) seismic waves in this zone. The velocity models should be as reliable as possible since they control the localization of seismic events and, consequently, their hypocenter and origin time inaccuracy.

First of all, this document presents the study area, which covers the geothermal sites under focus in INSIDE but also the Unterhaching and Oberhaching sites where a major part of the seismicity is observed. The datasets available to construct the models (borehole measurements, VSP surveys and previously developed seismic and structural models) are presented too. Then, the procedure to create layer-cake velocity models is explained. The seismic horizons resulting from the GRAME 3D project were used to define the geological interfaces where strong velocity changes occur. From borehole data acquired in several geothermal wells in the study area, the assumption could be made that the shear and compressional velocities are constant over the horizons and that the velocity can vary linearly within a layer, with a particular case for the "Liegende-Tonmergel" layer in which linear increase and decrease were considered. A model with constant velocity per layer was also investigated. The last part of the document presents several tests carried out to check the reliability and consistency of the created models with the VSP data acquired in the Pullach TH3 well. In particular it shows the adequacy of the VSP data with the reference KIT model. Finally, the impact of varying the reference KIT model on the seismicity recorded during INSIDE project is quickly discussed.

INTRODUCTION

The INSIDE project focuses on the passive seismic monitoring of the southern part of the Munich area, more specifically on the currently operated Pullach and Schäftlarnstraße geothermal sites, as well as on the future Baierbrunn project. Accurate velocity models are crucial for improving the reliability of seismic event localization and help to minimize errors in the calculated hypocenter and origin time. However, constructing such models is challenging due to the limited spatial coverage of available data. Developing a velocity model for the study area defined by the INSIDE project necessitates a robust methodology for combining, extrapolating, and interpolating available datasets, and finally test the capacities of the developed velocity model.

This technical report introduces the methodologies used for combining datasets available within the INSIDE project and leading to 3D velocity models that describe subsurface properties over the area of interest. It presents the data available for the development of a velocity structure describing the spatial distribution of compressional (V_P) and shear (V_S) wave velocities in the subsurface. It then focusses on the methodology followed to design the model and the technical steps involved in its testing.

In the following, we use these references and standards:

- DHDN / 3-degree Gauss-Kruger zone 4 ("GK4") coordinate system (EPSG 31468),
- Vertical coordinates are considered positive below MSL.

1 Model extent and structure

1.1 Model extent

The model is created with two key objectives:

- To locate the events detected by the INSIDE seismic network, by using the NonLinLoc (NLL) software package (Lomax et al., 2009, 2000) (Probabilistic, Non-Linear, Global-Search Earthquake Location in 3D Media).
- To model the seismic wave propagation, by using the SOFI3D software(Bohlen, 2002) (3D Finite-Difference Seismic Wave Simulation in visco-elastic medium).

To suit both finite-differences codes, the model is constructed as a 3D uniform structured grid. For event location, the model covers the entire INSIDE project area as well as the Unterhaching and Oberhaching sites, where most of the seismicity is observed. The extent of that study area is shown in Figure 1. The extent of the velocity model developed for event location with the NLL software is included in Figure 1b and detailed in Table 1. It also gives the inter-node distance (or sampling) used to generate the 3D grid of points.

Table 1: Extent of the velocity model used in Non-Lin-Loc for event location.

GK 4 (EPSG 31468)	Easting [m]	Northing [m]	Depth (positive down) [m MSL]
Start	4457000	5317000	-750
End	4480000	5333600	4500
Spacing	25	25	25

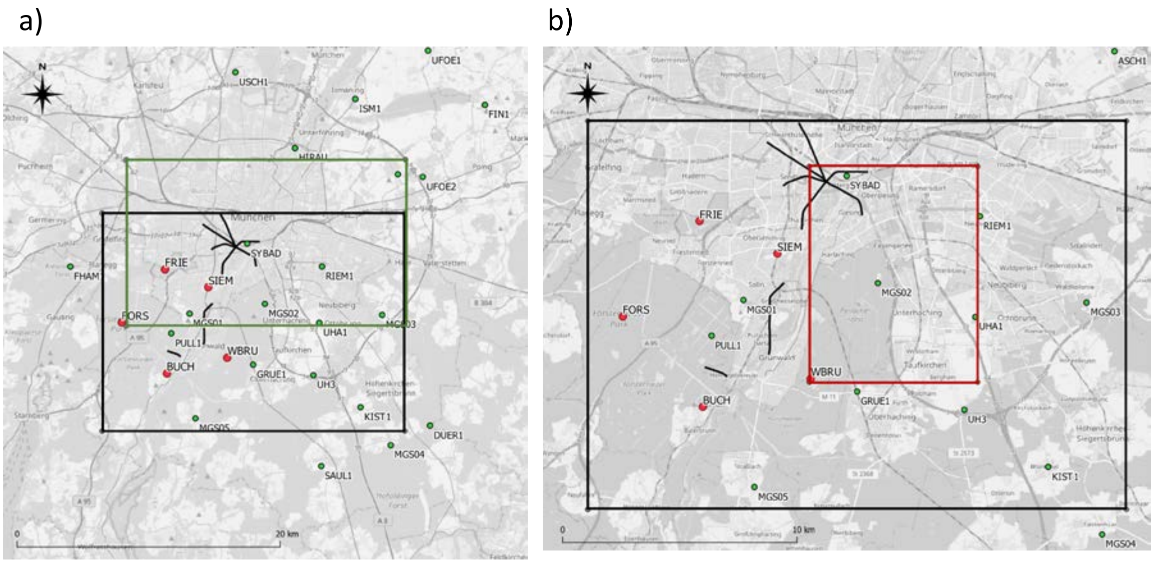

Figure 1: Projection on surface of the boundaries of the velocity structure used for event location (shown as a black rectangle). Panel a) also includes the extent of the velocity structure provided by Erdwerk GmbH. Panel b) consists in a zoom in the panel a), over the study area of the INSIDE project. The red rectangle indicates the extent of the model used in Sofi3D.

In SOFI3D, a finer inter-node distance is required and has been set at 10 m. The extent of the model was also decreased compared to the "location" model (see Table 2 and red rectangle, Figure 1b). The steps involved in the construction of the models dedicated to SOFI3D and NLL are the same and are presented hereafter.

Table 2: Extent of the velocity model used in SOFI3D for modelling wave-fields propagation.

GK 4 (EPSG 31468)	Easting [m]	Northing [m]	Depth (positive down) [m MSL]
Start	4466450	5322450	-650
End	4473650	5331650	3600
Spacing	10	10	10

1.2 AVAILABLE DATA

Figure 2 shows the extent of the study area and puts it in relation with the data available for the creation of the velocity model. The figure highlights that, apart from the interfaces, the velocity model is built upon locally available data.

The first step in the creation of the velocity model consists in organizing the grid of points in layers and define the seismic horizons where strong velocity changes may occur. The definition of the interfaces is based on the "Top" horizons mapped over the study area. The data are provided by the Erdwerk GmbH and are based on the results of a seismic migration study carried out within the GRAME-3D project.

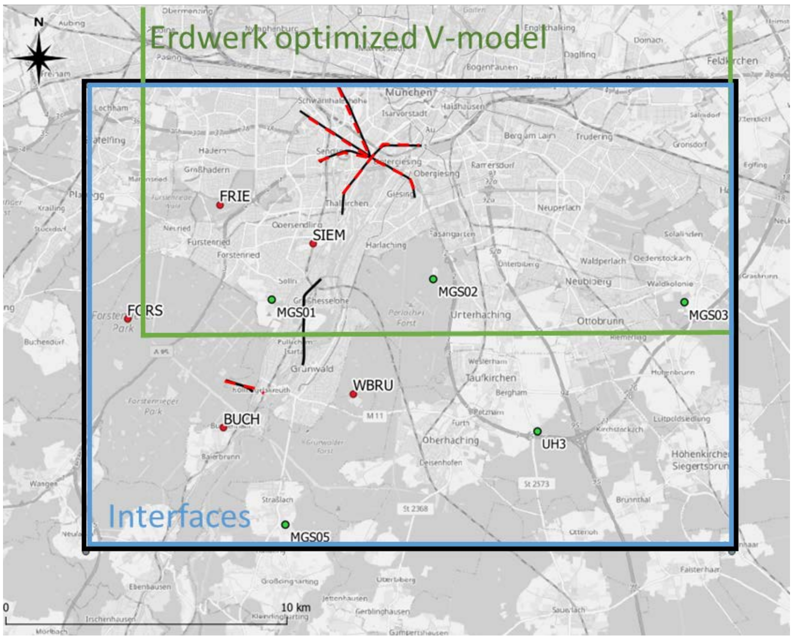

Figure 2: Extent of the study zone in relation to the coverage, on the surface, of available data. The dotted red lines show the trajectories of the wells from where velocity data have been used for the creation of the model.

In addition to the surface (topography), the mapped interfaces/horizons are the "Top" horizons of the following layers:

- Aquitan,
- Chatt Sandserie,
- Liegende Tonmergel,
- Lithothamnien Kalk,
- Purbeck,
- Malm Zetta,
- Malm Gamma.

The interface between Malm Gamma and the crystalline basement is not included in the model. Due to the proximity between both top horizons, we assumed that the interface "Top Gamma" marks the end of the Malm sequence. Figure 3a shows the horizons listed above in a 3D view. Figure 3b presents the same horizons in a topographic view.

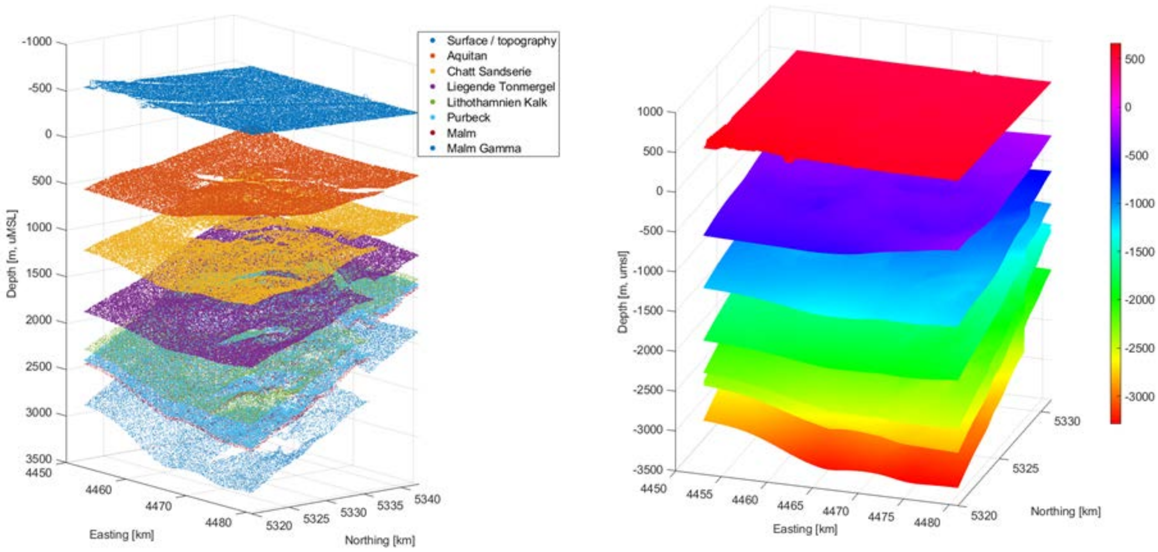

Figure 3: For each considered layer, the coordinates of the top horizon are represented in form of a structured grid of points.

The coordinates of the scattered points over the interfaces are extracted, for each layer, in form of individual data files using a local rectangular projection. Hence, the data files are structured so that each horizon is described by a grid of nodes with the same projected horizontal coordinates. This means that Easting/Northing coordinates remain consistent from one horizon to another.

The second step in the creation of the velocity model consists in filling the 3D volume with velocity values. We use first borehole data available from the Schäftlarntraße (SLS) and Pullach (PULL) sites. All relevant data are used, presented in Figure 4 and include:

- The sonic logs acquired at the SLS geothermal site,
- The outcomes of the VSP survey acquired in October 2020 at the SLS site,
- The results of the VSP survey acquired in PULL TH3 in August 2021.

The data from the different measurement campaigns were transformed to merge them into a common coordinate system. Hence, the along hole (measured depth) coordinates were uniformly converted to Total Vertical Depth (TVD) below ground level. Figure 4 also displays the intersection of the well trajectories and the interfaces previously listed.

Another input is the velocity model developed by Erdwerk GmbH. This model was created to merge data of different origins (borehole acquisition, seismic surveys) and was refined based on an AVO (Amplitude Versus Offset) analysis carried out in the frame of the GRAME-3D project. We show here data extracted from the depth-migrated velocity cubes and V_P/V_S structures from the pre-stack inversion. However, the area covered by the seismic data GRAME does not cover the entire INSIDE study area (see Figure 1, green rectangle). Moreover, the velocity blocks only cover depths below 600 m below ground level. Hence, the velocity structure provided by Erdwerk GmbH cannot be used to fully constraint the velocity model needed for the INSIDE project, as no data are available for comparison at the PULL TH3 well, for example (see Figure 4). On the other hand, the blocks provided by Erdwerk GmbH cover the area of the SLS project, which allow us to conduct a comparison between the borehole data we have in hand and the profiles extracted from the velocity blocks provided by Erdwerk GmbH.

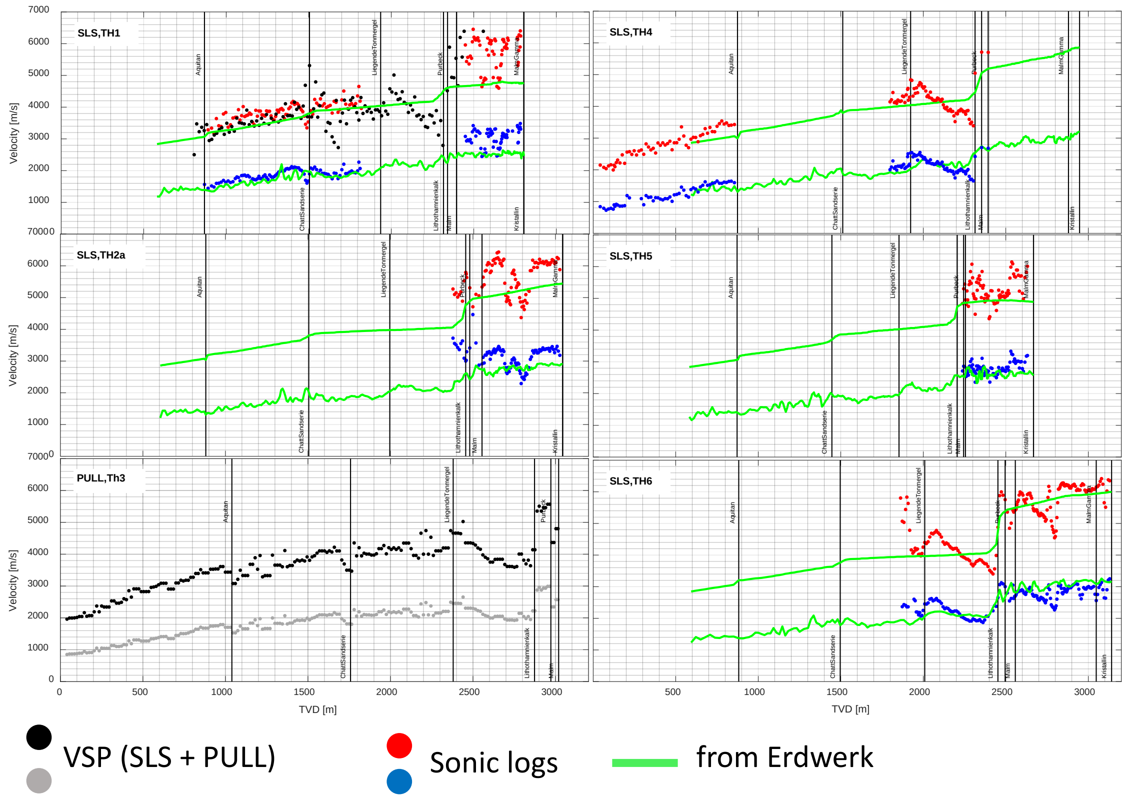

Figure 4: Velocity data available from VSP surveys and sonic logs used to fill the velocity model grid.

The borehole data and the model communicated by Erdwerk GmbH show different behaviors, especially in the so-called "Liegende Tonmergel" layer. In this clay-marl layer above Purbeck, the borehole data indicate a significant decrease of the compressional- and shear-wave velocities over depth. Velocities from the Erdwerk velocity blocks are also slightly shifted towards lower values. We therefore consider both data types for the creation of the INSIDE velocity model to represent the variability in the available velocity data. To build that model, we first chose to fit closer the trend indicated by the local borehole measurements. This includes the velocity decrease in "Liegende Tonmergel". However, the creation of another velocity model that fits closer the green lines in Figure 4 is considered to check the hypothesis about the trend in "Liegende Tonmergel" and to test the effect of the variability in velocity values.

The V_P/V_S ratios considered in the model can also be compared to the V_P/V_S ratio profiles resulting from the PULL TH3 multi-offset VSP. Figure 5 displays the latter along true vertical depth that wa obtained from each of the three vibration points. They show a significant change in V_P/V_S ratios at a depth of around 600 m TVD.

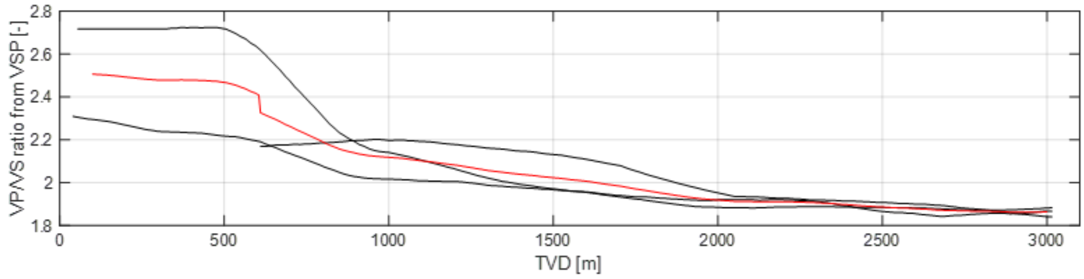

Figure 5: Evolution with depth of the V_P/V_S ratios from the Pullach multi-offset VSP. The figure shows the curves obtained from the three vibration points (black line). The red line shows the average.

2 MODEL BUILDING

2.1 MODEL STRUCTURE

After defining a structured and regular grid of points covering the area described in section 1.1, we determine the correspondence between each node in the 3D model and the layer of the structural model. For every Easting (X) / Northing (Y) coordinate of the 3D grid, all nodes along depth are assigned the layer they belong to. This is done by comparing the current node depth with the depth of the closest but shallowest top horizon, at these (X, Y) coordinates. The structure resulting from the procedure is illustrated in Figure 6 using two orthogonal slices.

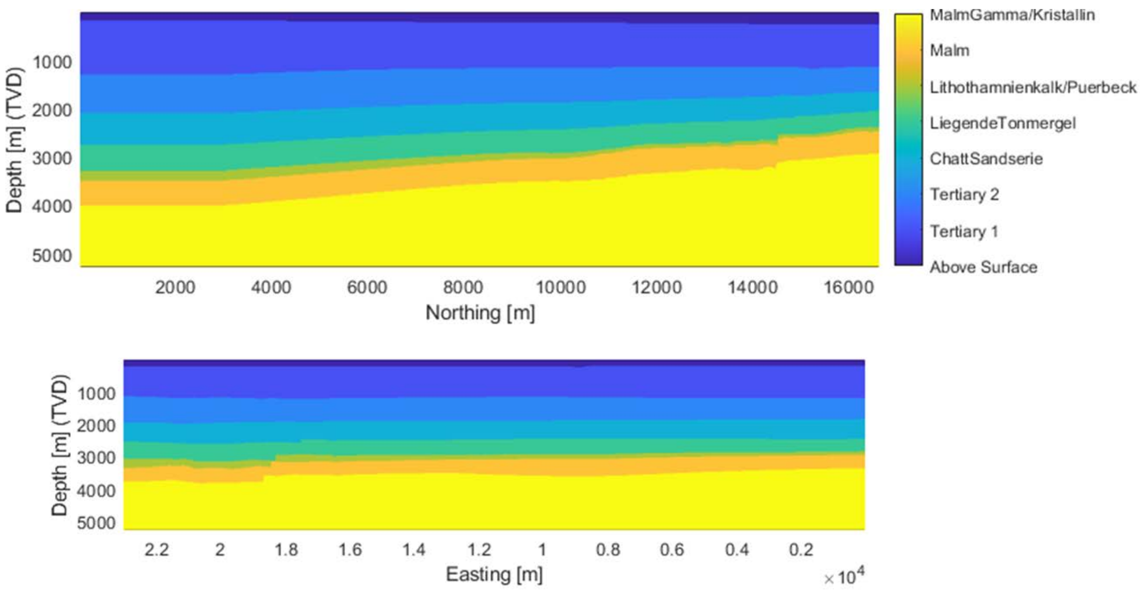

Figure 6: Identification of the layer to which each node in the uniformly structured grid of the velocity model belongs. Top: South-North vertical slice, bottom: West-East vertical slice.

2.2 VELOCITY DETERMINATION

The next step consists in determining the velocities within each layer. Our procedure is based on the observations that velocities vary quasi linearly between two following interfaces and that velocities are relatively consistent at the crossing point between well trajectories and horizons, from one well to another (see Figure 4). This is especially the case between Schäftlarnstraße and Pullach, despite a significant variation of the depth of the horizons at the wells (due to the southward inclination of the layers). This suggests that the velocities at depth are not significantly impacted by the change in overburden and the resulting compaction. The consistency in velocities is the strongest for the sedimentary cover. At greater depths, such as in the Malm layers, velocities are more difficult to determine or fix because of the fluctuations observed in the measurements (also at a given site or for a given survey) and because of shorter depth-range availability of the data. Finally, velocities cannot be assess in the crystalline basement due to the lack of data.

From the observations based on Figure 4, we propose to build a reference velocity model (KIT model) complying with the following hypotheses:

- V_P and V_S are fixed at a given interface, over the 3D volume.
- The velocity values between two successive interfaces are linearly interpolated between the values fixed at the interfaces.
- In the “Liegende Tonmergel” formation the velocity decreases with depth.

However, for comparison purposes, two other approaches are taken to determine the velocities in the layers:

1. Constant V_P and V_S will be given for each layer (blocky velocity model).
2. V_P and V_S will be linearly interpolated between values at the interfaces but closer to the trend indicated by the Erdwerk GmbH model (EW model).

So, for each horizon top and each model: the reference model (KIT), the blocky model (Blocky) and the Erdwerk-inspired model (EW), Table 3 indicates the assigned V_P values, Table 4 shows the assigned V_P/V_S values and finally Table 5 shows the assigned V_S values.

The velocity values listed in the tables are represented and compared to the available data in Figure 7, when fitting closely to borehole data (KIT model) and Figure 8, when fitting closely to the Erdwerk GmbH velocity blocks (EW model).

Table 3: P-wave velocities used for the V_P models, considering either variable velocity values (KIT and EW) or constant values (Blocky) in a given layer. The velocity values correspond to the value at the top of the indicated layer.

“Top” of / VP [m/s]	Tertiary	Aquitan	Chatt-Sandserie	Liegende Tonmergel	Lithothamnien-kalk	Purbeck	Malm	Malm Gamma/ Kristallin
KIT	2000	3600	4150	4500	3400	4700	5200	6000
Blocky	2800	3900	4300	3800	4000	4500	5500	6000
EW	2000	3200	3800	4050	4280	5000	5180	5700

Table 4: Applied V_P/V_S ratio of each layer for the KIT or Blocky velocity model (1st row) or for the EW model (2nd row).

“Top” of / Vp/Vs	Tertiary	Aquitan	Chatt-Sandserie	Liegende Tonmergel	Lithothamnien-Kalk	Purbeck	Malm	Malm Gamma/ Kristallin
KIT Blocky	2.50	2.11	2.07	1.90	1.87	1.87	1.86	1.84
EW	2.50	2.13	1.95	1.95	1.90	1.90	1.87	1.81

Table 5: Shear-wave velocities used for the V_S models, considering either variable velocity values (KIT and EW) or constant values (Blocky) in a given layer. The velocity values correspond to the value at the top of the indicated layer.

"Top" of / VS [m/s]	Tertiary	Aquitan	Chatt-Sandserie	Liegende Tonmergel	Lithothamnien-kalk	Purbeck	Malm	Malm Gamma/ Kristallin
KIT	800	1700	2000	2350	1818	2510	2790	3270
Blocky	1120	1841	2072	1980	2130	2400	2950	3250
EW	800	1500	1950	2080	2250	2510	2760	3150

2.3 VELOCITY ASSIGNMENT

To assign the velocities in the blocky velocity model, the constant velocities are assigned to each point of the 3D grid according to its layer ID and the associated V_P and V_S velocities given in the previous tables.

To assign the velocities for the KIT and EW models, we loop over all 3D grid points along depth. For one depth profile and one specific point the upper and lower horizons are identified and the velocities interpolated linearly according to the values set at the horizons and given in the previous tables.

All models also include a non-physical layer above the ground level (topography), which is not flat. Constant velocities are applied in this non-physical section above surface. A similar approach is taken for the lower end of the model, in the granitic basement.

The different models built are illustrated in Figure 9 for the KIT model and in Figure 10 for the Blocky and EW models.

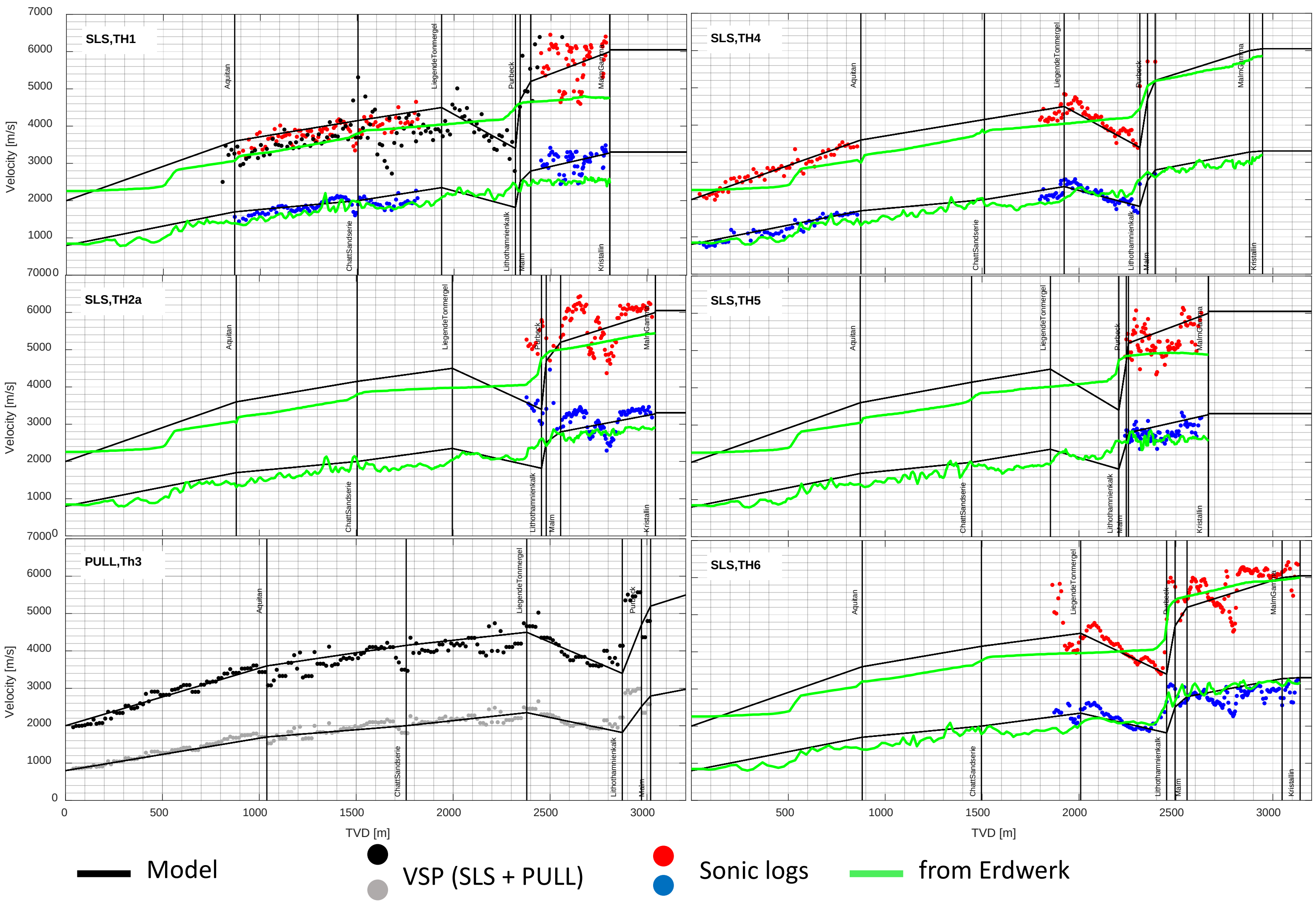

Figure 7: Velocity data available from VSP surveys and sonic logs (dots). The borehole measurements are compared to available data from an AVO analysis (green lines). They are compared to the profiles used to build the velocity structure, with the aim to fit closely the borehole data (KIT model).

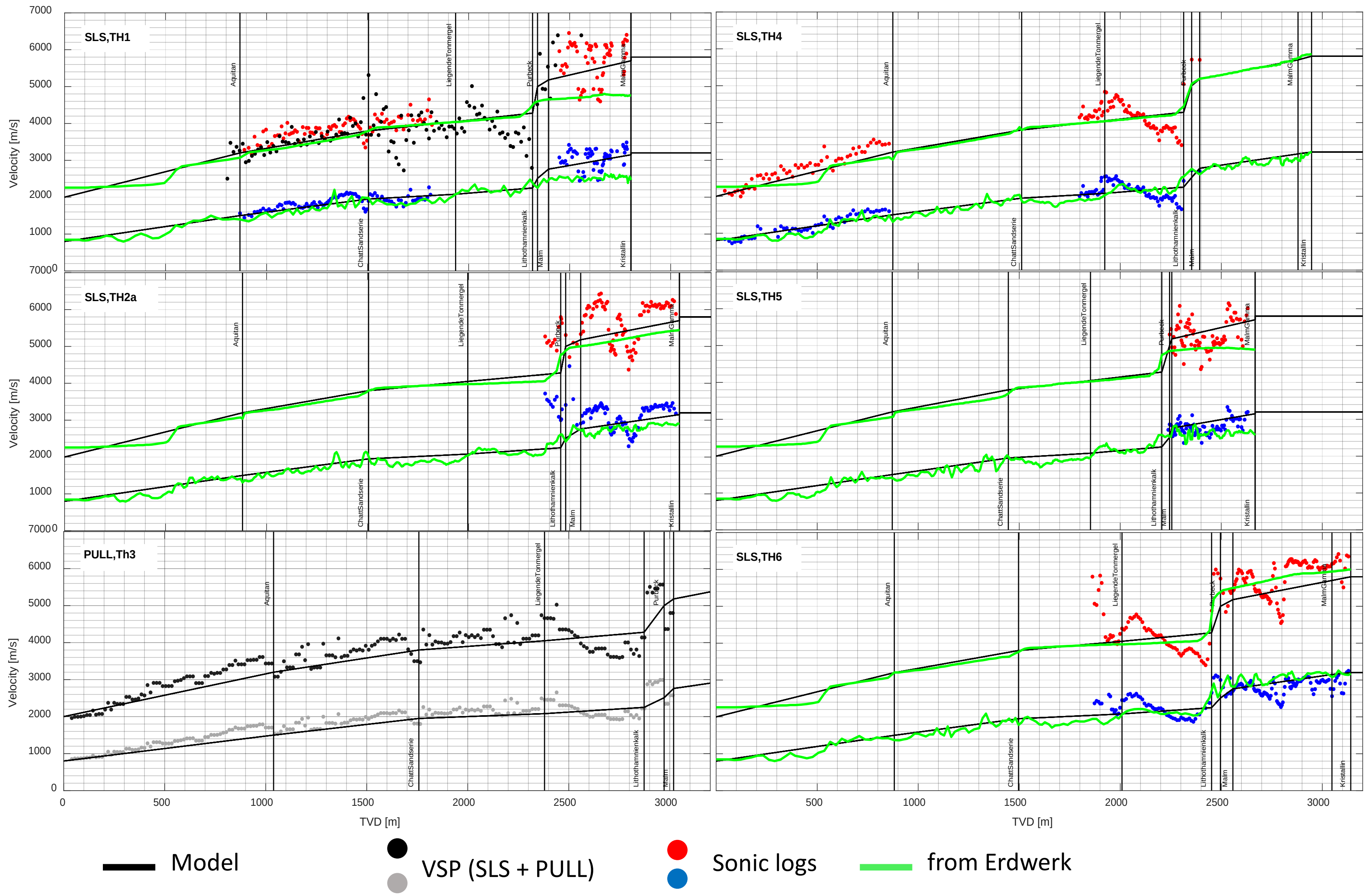

Figure 8: Same as Figure 7 with a model based on the velocity blocks from Erdwerk GmbH (EW model).

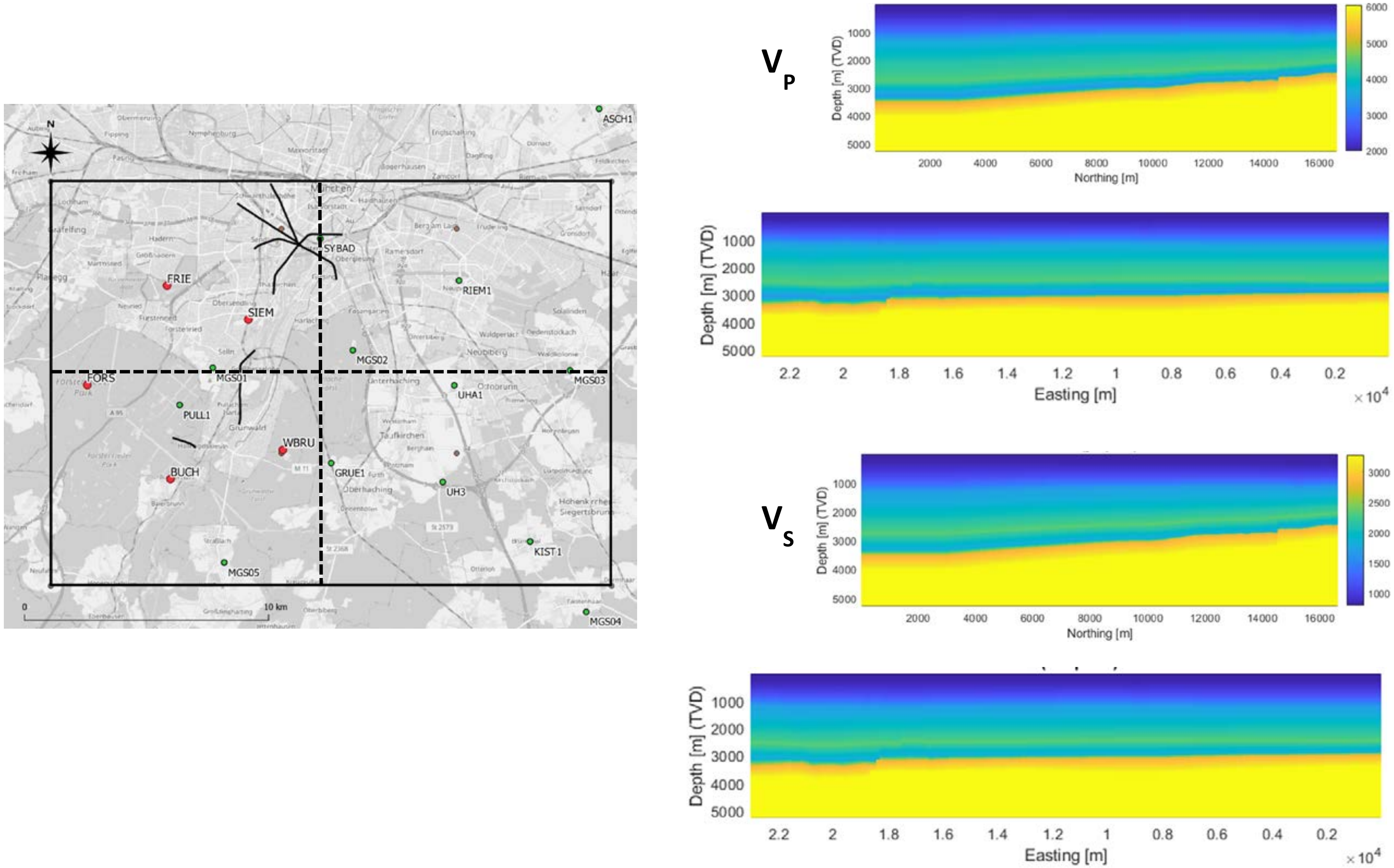

Figure 9: Left: Map of the velocity model limit. Right: vertical sections, along the dotted lines of the left map, of V_P and V_S for the KIT model to highlight the velocity gradient in each layer.

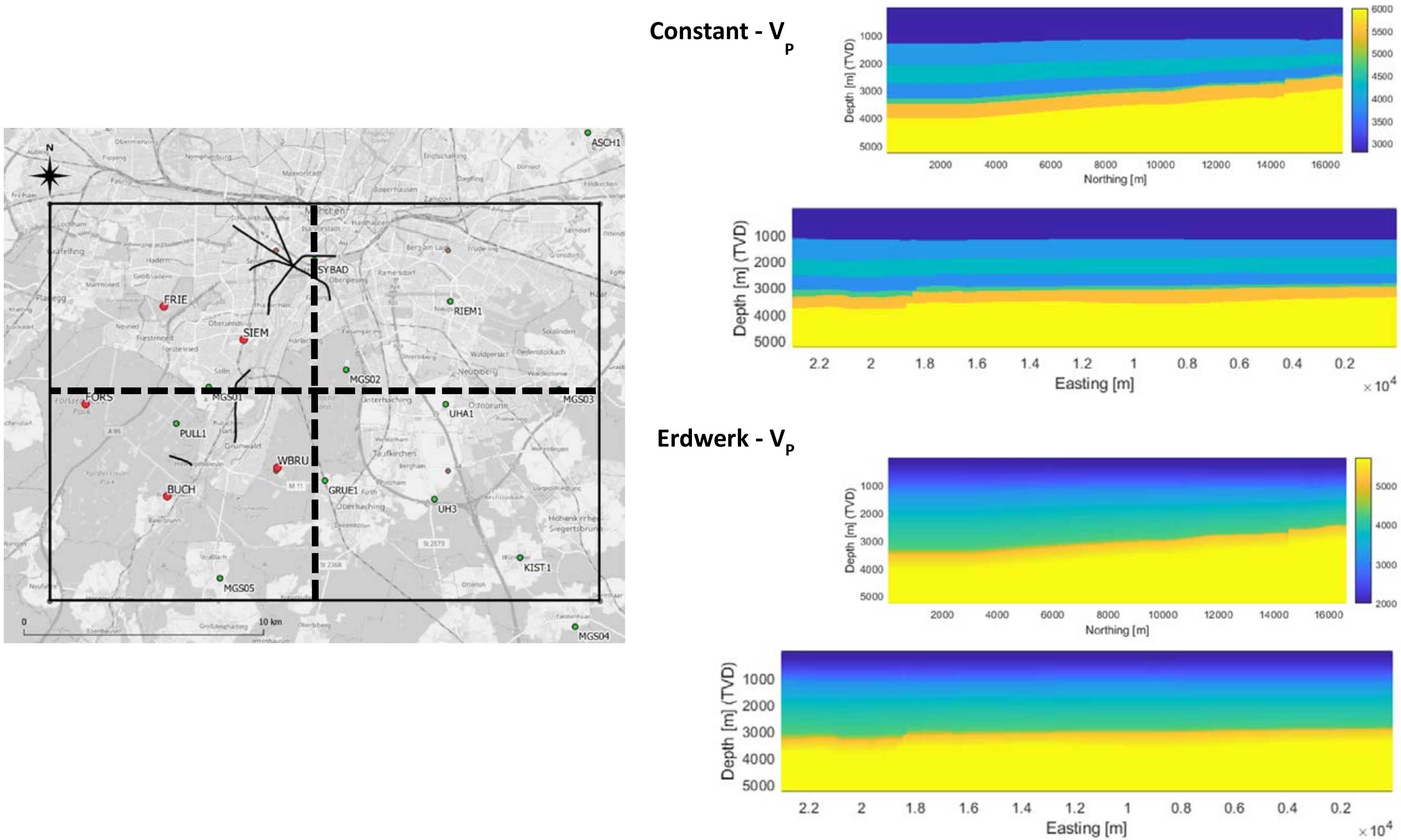

Figure 10: Left: Map of the velocity model limit. Right: vertical sections, along the dotted lines of the left map, of V_P for the Blocky model on top and the EW model on bottom.

3 Model quality-controls

3.1 Appropriate 3D model grid size

For the linearly varying velocity models (KIT and EW models), Figure 11 presents all V_P depth profiles of the 3D block. As observed, all profiles are consistent within one model. No abrupt change in velocity is evidenced and there is no layer within the structural model that is overlooked because of its thickness, in comparison to the inter-node distance.

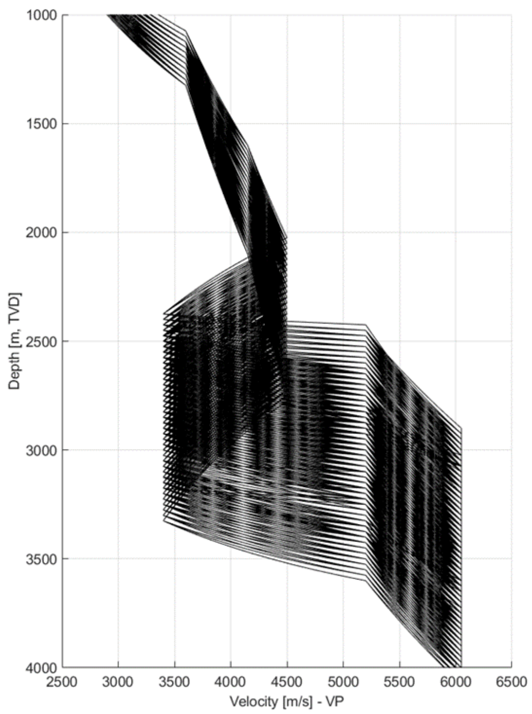

Figure 11: Plot of all V_P velocity depth profiles of the KIT model (left) and of the EW model (right).

3.2 Consistency with Pullach TH3 VSP data

Another quality control consisted in checking the evolution of seismic travel times from surface to depth and comparing it to the VSP survey results carried out in PULL TH3. In Figure 12 and Figure 13, we compare the travel times obtained by the VSP with those calculated using either the KIT model or the EW model respectively. In both figures, panel (a) shows the velocity profile extracted from the 3D model along the Pullach Th3 well, panel (b) shows the differential propagation time calculated between the velocity model (red) and the VSP (black) as a function of depth for the P-wave, and panel (c) shows the travel-time profiles of the velocity model (red) and the VSP (black).

As expected by model construction and the associated hypotheses, time differential between the KIT model and the VSP are smaller than those obtained between the EW model and the VSP. For the KIT model (Figure 12), the differential time is smaller than 15 ms over the range of depths covered by the VSP and decreases with depth below 1000 m. With the EW model (Figure 13), the differential times goes up to 50 ms for the second velocity model and increases with depth. So, at Pullach location at least, the KIT model is more consistent with the VSP data and, more interestingly, consistency increases with depth, in other words, where seismicity would most likely be induced.

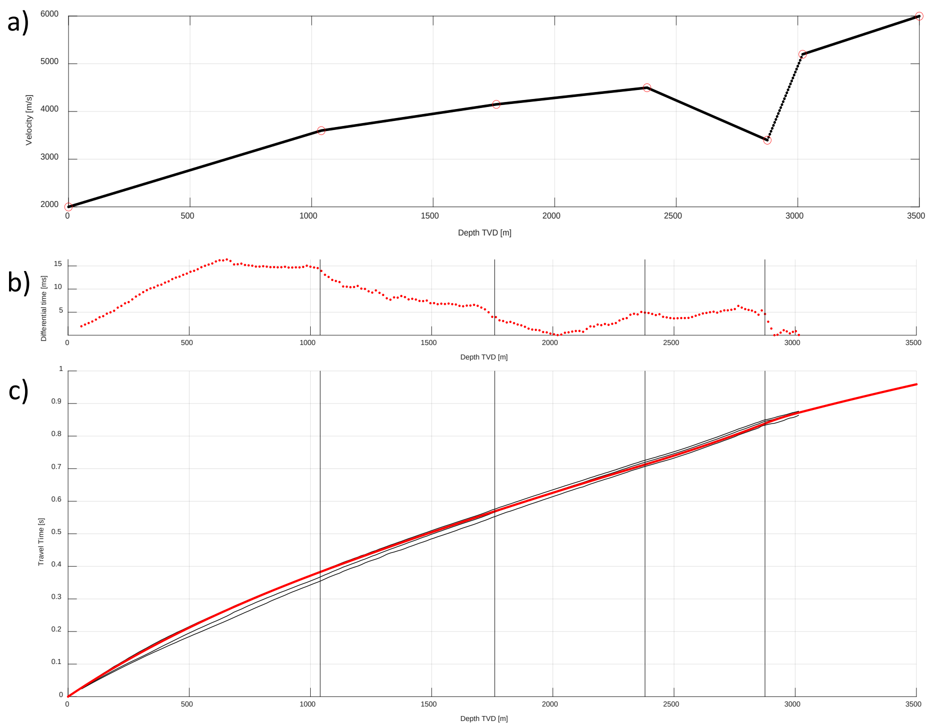

Figure 12: (a): Velocity profile of the KIT model extracted along the PULL-TH3 borehole trajectory. (b): Differential propagation time calculated between the KIT-model and the VSP average as a function of depth, for the P-wave. (c): P-wave travel-times measured from the Pullach VSP at the three vibration points (black curves) and calculated from the P-wave velocity KIT model (red curve).

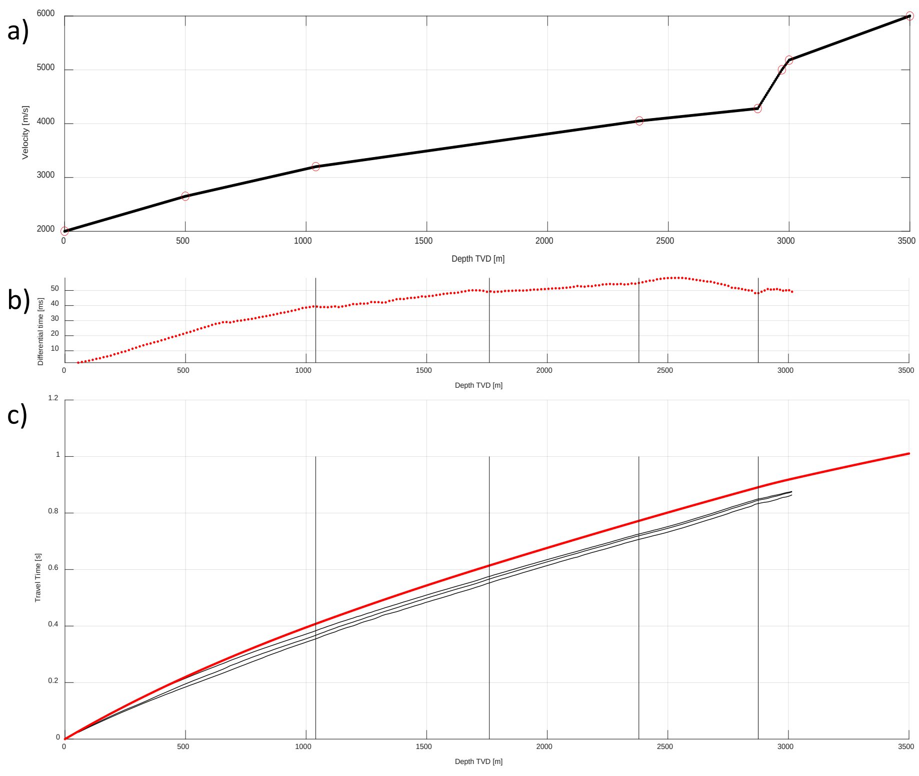

Figure 13: Same as Figure 12, but for the EW model.

3.3 INFLUENCE OF VELOCITY MODEL VARIATION ON SEISMIC EVENT LOCATION

In this section, the influence of the velocity model variation on the determination of the seismic event hypocenter is investigated. The procedure consists in varying randomly the KIT reference model and locating the seismicity that was recorded at INSIDE in order to estimate a location uncertainty accounting for the velocity model uncertainties.

To do so, for each geological interface considered in the creation of the velocity model (see section 2.2), a potential range of V_P velocities is defined, considering the dispersion of the input data in the Figure 4. Similarly, we consider a set of possible V_P/V_S ratios at each interface, based on Figure 5. Hence, a set of V_P and V_S velocity models can be randomly generated following the same procedure than the KIT model construction and keeping the constraints that the velocity profiles should increase with depth but decrease in the “Liegende Tonmergel”, and the V_P/V_S ratio should increase with depth. For this study, 1000 random draws have been done and the corresponding V_P and V_S profiles are shown in Figure 14.

The location of the seismic events is first performed using the NonLinLoc (NLL) software package (Lomax et al., 2009, 2000) and then a relative location of all seismic events is performed using the GrowClust3D (Trugman et al., 2023; Trugman and Shearer, 2017). To estimate the event relative llocation uncertainties and time residuals, a bootstrap of 1000 iterations is applied. Then, this location procedure is run 1000 times, once for each randomly generated velocity models, on the 79 seismic events detected during the INSIDE monitoring period[1]. This leads to one million probable hypocenters for each seismic event.

To obtain the event localization uncertainty, principal component analysis of the spatial distribution of the one million possible hypocenters is done. Hence, the 68% confidence ellipsoid of each event can be calculated and the length of the three main axes of the ellipsoid calculated to provide oriented spatial uncertainties.

Figure 15 illustrates, for one event, the steps to obtain its hypocenter uncertainty. Figure 16 shows the location results for the same event.

Besides the hypocenter uncertainties, the average root-mean-square (RMS) time residuals for the P- and S-waves across all events is calculated for every velocity model. Figure 14 illustrates the results for each velocity profile. Over all models, the minimum RMS residuals are 0.083 s for the P-waves and 0.101 s for the S-waves. For comparison, the reference KIT model yields RMS residuals of 0.087 s for the P-waves and 0.105 s for the S-waves. Compared to the reference KIT model, the “minimum” velocity profile (white curve in Figure 14) has reduced P- and S-velocities near the surface, a steeper velocity gradients in the "Tertiary" and "Lithothamnienkalk" layers and higher P- and S-wave velocities in the granite.

[1] Details about the results of the seismic monitoring during the INSIDE project can be found in the associated report: INSIDE-KIT-M311_SeisNetzMonitoring.pdf.

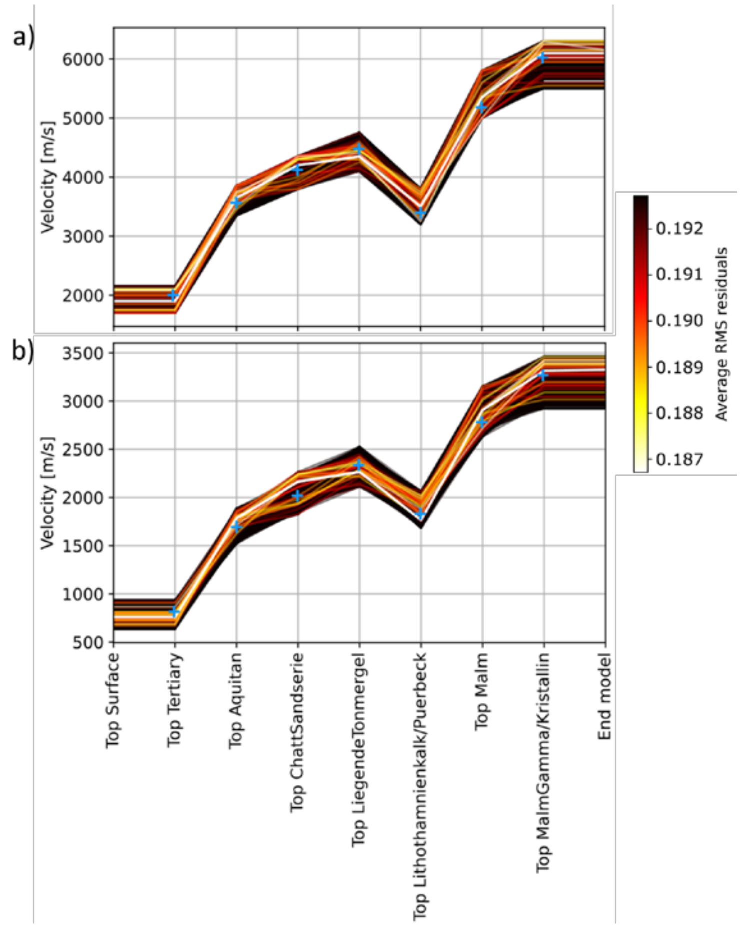

Figure 14: Set of the 1000 velocity profiles, V_P at the top, V_S at the bottom, randomly generated. The background color shows the average root mean square of the P- and S-wave residuals resulting from the relative location of the 79 seismic events within each model. The blue crosses indicate the profile initially selected.

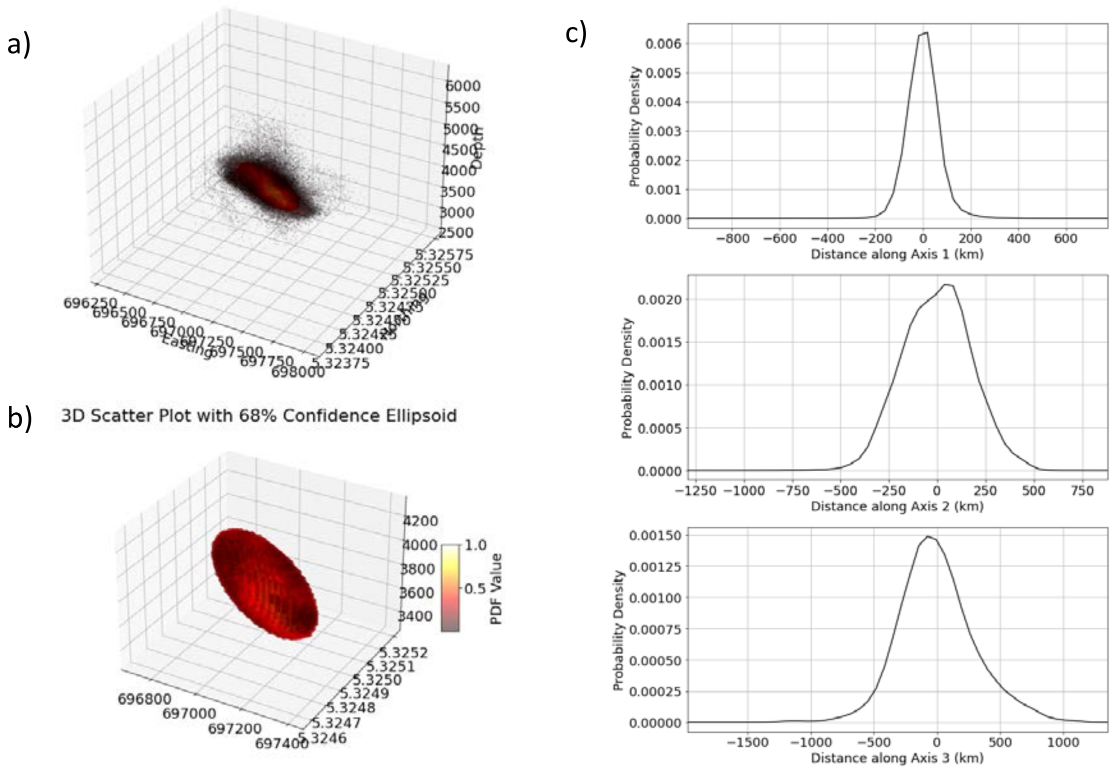

Figure 15: 2023-11-29 seismic event. Panel a) the one million hypocenters obtained by bootstrap for the 1000 velocity models, panel b) 68 % confidence ellipsoid obtained from the spatial distribution of points in a), and panel c) marginal probability density functions computed along the three main axes of the confidence ellipsoid.

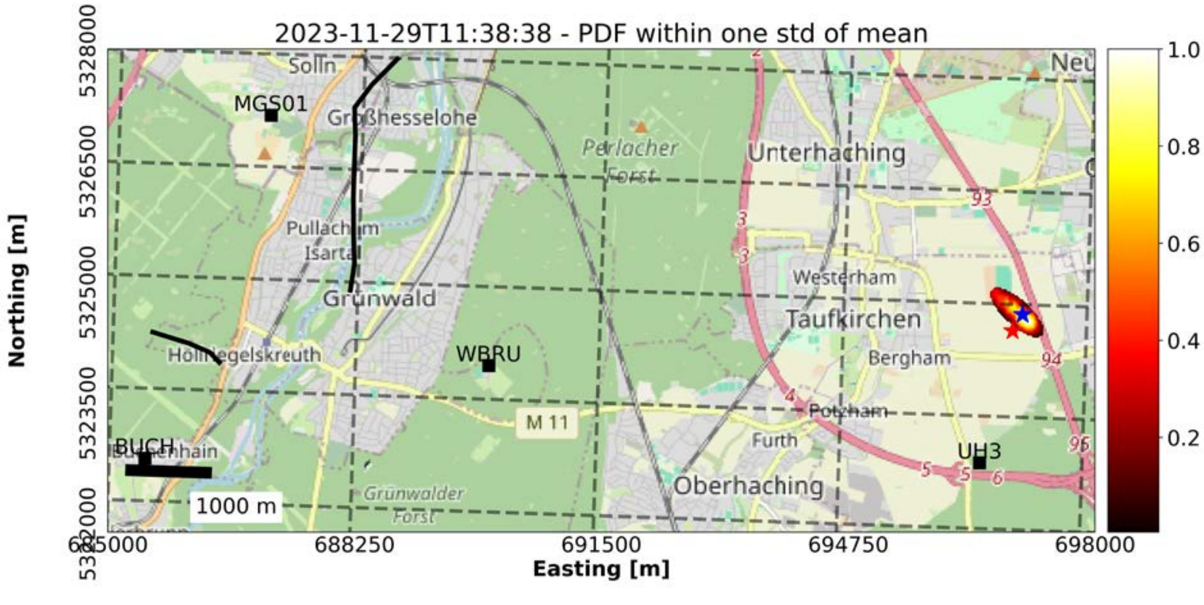

Figure 16: Epicenter of the 2023-11-29 seismic event obtained by absolute location in the reference KIT model (red star) with the associated relative location (blue star) and the projection of the 68% confidence ellipsoid color-coded between 0 (one standard deviation) and 1 (best hypocenter).

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