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First results from a Seismic Survey in the Upper Salzach Valley, Austria

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Abstract

In late 2009 we conducted a refraction-and-reflection-seismic survey across the Salzach Valley in the Eastern Alps near Zell-am-See. The goal was to image the structure of the sedimentary infill, and the depth to bedrock. In this study we present the refraction data and first results from kinematic inverse modeling of first-arrival traveltimes. We use a damped matrix inversion to constrain the velocity for an irregular grid that is adapted to the resolving power of the data. According to our results, the valley is largely symmetric with a maximum depth to bedrock of ~400 m. Overall slow P-wave-velocities of the valley fill indicate that it is mostly unconsolidated sediments. A pronounced low velocity zone at ~100 m depth is interpreted as peat layer.

Ende 2009 haben wir ein refraktions- und reflexionsseismisches Profil quer durch das Salzachtal bei Zell am See in den Ostalpen vermessen. Ziel war es, die Felslinie und die Struktur der Talfüllung zu erkunden. In diesem Bericht stellen wir die Refraktionsdaten und erste Ergebnisse einer Laufzeitinversion der Ersteinsätze vor. Wir verwenden eine gedämpfte Matrixinversion, um die Geschwindigkeiten für ein unregelmäßiges Gitter zu bestimmen, welches an das Auflösungsvermögen der Daten angepasst ist. Unsere Ergebnisse zeigen ein weitgehend symmetrisches Tal mit einer maximalen Tiefe bis zum Fels von etwa 400 m. Geringe P-Wellengeschwindigkeiten für die Talfüllung weisen darauf hin, dass die Sedimente im Wesentlichen unverfestigt sind. Eine ausgeprägte Zone erniedrigter Geschwindigkeiten wird als Torfschicht interpretiert.

1. Introduction

The geophysical investigation of deep Alpine valleys is motivated by their importance for hydrogeology, Quaternary geology, glaciology and tectonics. The glacial and post-glacial aquifers constitute a major water resource, and knowledge of their structure is essential to predict the impact of river regulations and barrages. The structure and the volume of the sediments are also important parameters to model erosion and uplift rates (Pfiffner et al., 1997). The preferred investigation method is reflection seismology, sometimes combined with refraction or gravity measurements. Reflection images generally provide detailed structure, but the velocity, and, hence, the depth, are poorly constrained (Bickel, 1990). Classic refraction seismology, in contrast, yields few details on structure, but it provides velocity models that allow for calibrating reflection images, and for interpreting the large-scale structures. Therefore, we decided to combine reflection and refraction measurements.

Early investigations in the Eastern Alps probed the Inn Valley and its tributaries (Aric and Steinhauser, 1976; Weber et al., 1990; Weber and Schmid, 1991). Only in recent years did the focus shift to smaller valleys, such as Enns or Drau (Schmid et al., 2005; Brueckl et al., accepted manuscript). In the wider context of investigations related to the construction

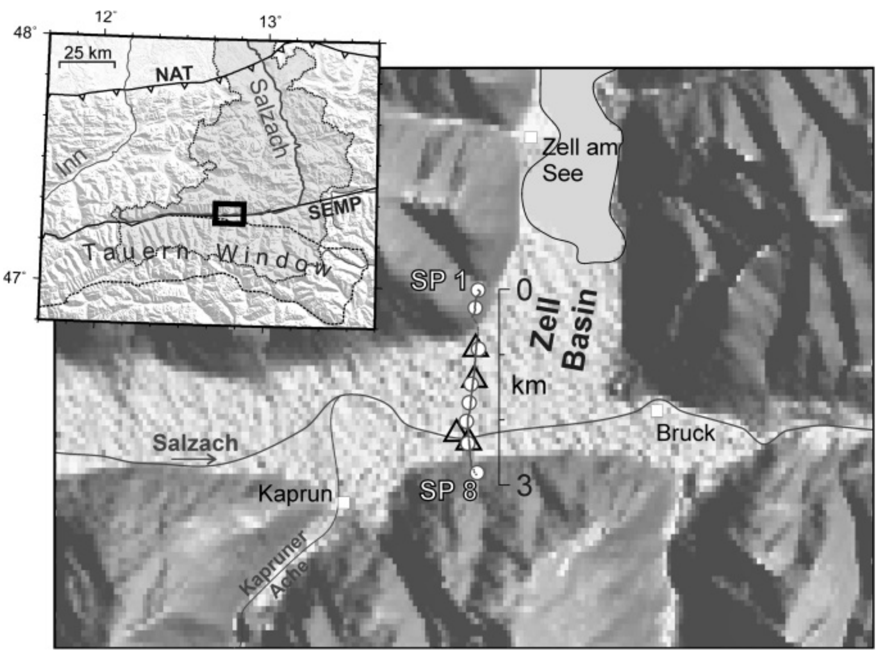

Figure 1: Map of the survey area. Black line and dots are receivers, circles are shot points, triangles are wells. The inset shows the location of the survey area in the Eastern Alps at the northern edge of the Tauern Window and the drainage area of the Salzach river (dotted). NAT – North Alpine Thrust front; SEMP – Salzach-Enns-Mariazell-Puchberg fault.

of a hydro power plant, we decided to investigate the upper Salzach Valley.

2. Geologic and Morphologic Framework

The 250-km-long Salzach River drains large areas of the northern Eastern Alps. It runs parallel to the strike of the Alps for ~100 km along the northern edge of the Tauern Window, before it bends northward and exits the Alps near the city of Salzburg (Figure 1). The upper portion of the Salzach valley is also part of a major fault zone in the Eastern Alps, the E-W striking Salzach-Enns-Mariazell-Puchberg fault (Linzer et al., 2002).

The elevation of the present-day ground surface of the upper Salzach valley ranges from 600 m above sea level in the East to 900 m in the West. At the peak of the Würm glacial, the ice surface in the upper Salzach valley was at ~2100 m elevation (van Husen, 1987), in the accumulation zone of the glacier. Assuming that much of the sediments are post-glacial, the average height of the ice column in the upper Salzach valley must have been ~1500 m. Basal erosion in combination with tectonically weakened basement rocks probably led to further deepening. To the East of Bruck, however, the Salzach valley narrows (Figure 1) and occasional outcrops of bedrock suggest that the bedrock surface must be very shallow, posing a significant obstacle to W-E-directed ice flow. This obstacle, and the mainly N-S-oriented gradient of the former ice surface, both suggest that parts of the ice flow were diverted to the North, resulting in the creation, or deepening, of the Zell Basin.

From boreholes in the much larger Salzburg Basin ~100 km downstream in the ablation area of the Salzach glacier, the maximum present-day depth to bedrock is estimated at ~350 m (van Husen, 1979). For the Zell Basin, however, there are no such constraints. From a few wells in the area we know that the upper 50 m of the valley fill consist primarily of sand, gravel, and some silt, suggesting predominantly fluvial, and occasionally lacustrine, deposition. Age-dating of wood and peat from 16-m-deep boreholes south of the Salzach river shows that the shallow deposits are at most 9 ka old (Poscher, 1994).

However, none of the wells encountered bedrock. Our survey aims at closing this data gap by profiling the structure and thickness of the sediments. Good knowledge of the sedimentary structure is crucial for modeling the groundwater flow, and the total volume of sediments is a key factor for the determination of erosion rates.

3. Data acquisition and quality

Our survey consists of a 3-km-long stationary receiver line perpendicular to the valley's axis, crossing the entire valley floor and a few hundred meters of bedrock at each end (Figure 1). The transition from valley fill to bedrock is well defined at the northern edge of the valley, but it is covered by an alluvial fan to the South. Further to the East, the Salzach valley merges with the N-S-oriented Zell Basin, but in the proximity of the profile, we expect the structural variations perpendicular to the line to be small. The profile consists of a main line of 216 channels, and a North line of 48 channels, separated by railway tracks, a highway, and a commercial zone at the northern edge of the valley. Both lines were equipped with 10 Hz vertical geophones at 10 m spacing, and the 350-m-wide gap was closed with ten continuously recording one-component stations ("DSS-cubes") manufactured by the GeoForschungs Zentrum Potsdam. Eight dynamite shots with a yield of 1 – 3 kg at 2 – 7 m depth were observed with the full spread. Except for the northernmost two shots, all boreholes penetrated the uppermost aquifer, and the shot coupling was excellent. These data provide good S/N in the 5 – 100 Hz range (Figure 2). Figure 3 displays two exemplary seismogram sections. The

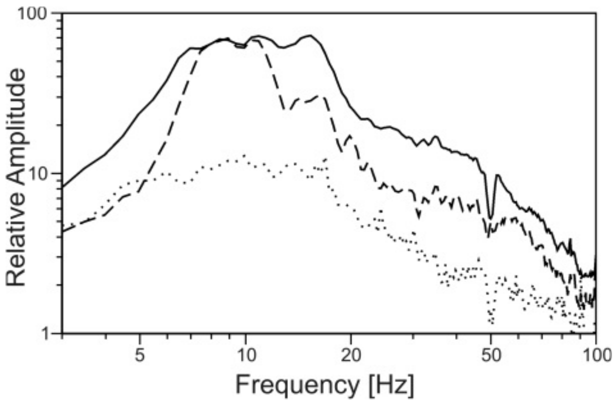

Figure 2: Spectra of signal at offsets greater than 700 m (solid line), 1400 m (dashed line) and noise (dotted line).

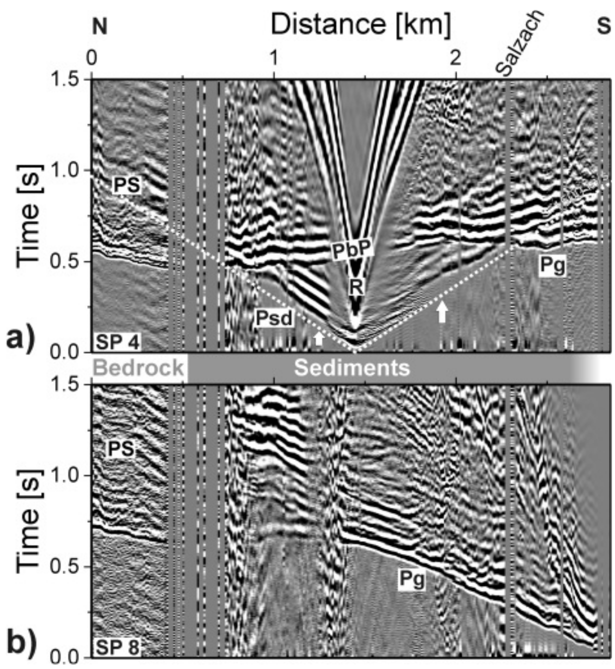

Figure 3: (a) Trace-normalized display of shot point 4 in the center of the valley and (b) shot point 8 at the Southern end of the line. Psd – direct P-waves in the sediments, Pg – refraction from the bedrock. PbP – reflection from the bedrock, partially superposed by R - Rayleigh waves. PS – converted waves. White arrows point at shadow zones. For comparison, the dotted line in (a) denotes an apparent velocity corresponding to water (1500 m/s).

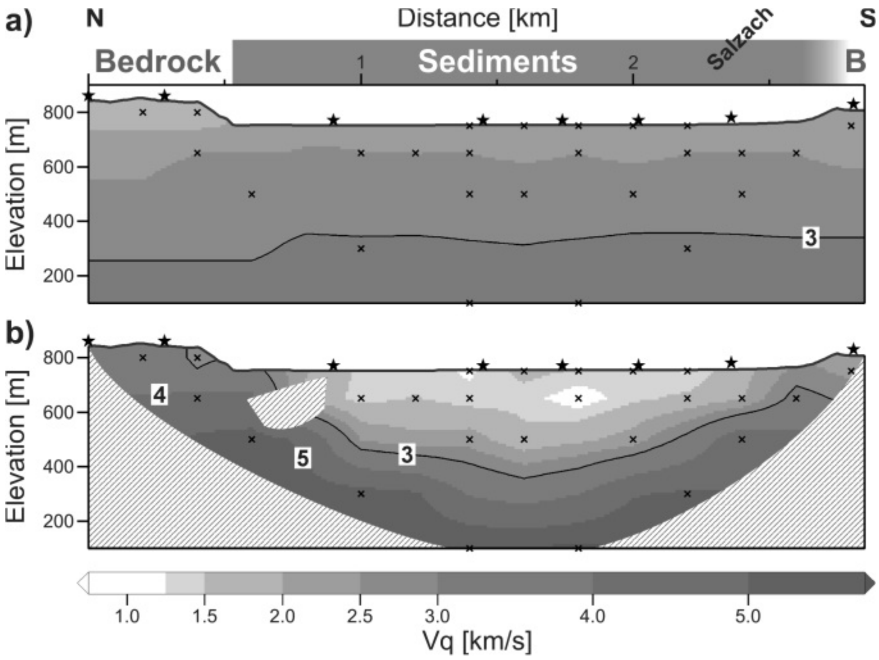

Figure 4: (a) Starting model and (b) final model after five iterations. Stars denote shot points. Small crosses are inversion nodes. Masked area has no ray coverage. The deviation of (a) from a 1D distribution is a result of the irregular grid.

shots in the sediments produce strong ground roll, a direct wave travelling through the sediments, and refractions and reflections from the bedrock. Note that the average p-wave velocity of the sedimentary phases is always slower than 1500 m/s (water). Several shots also show a shallow high-frequency arrival followed by shadow zones, indicative of Low Velocity Zones (LVZ). The most pronounced shadow zone is observed near 1.8 km distance. In contrast, the shots at the end of the line show a continuous refraction from the bedrock. Its apparent velocity is primarily affected by the varying thickness of the valley fill.

4. Diving-Ray Tomography

In order to constrain the deeper structure, we performed a diving-ray tomography based on a total of 1500 first-arrival travel-times extracted from the explosive data. For the forward modeling we used an eikonal solver of Vidale (1990). We chose the L2-norm of the travel-time misfit as objective function, and we used a damped matrix inversion to constrain an over-determined problem, following the approach of Thurber (1983), with adaptations for irregular model parameterization by Bleibinhaus and Gebrande (2006). The velocity distribution in our starting model is 1D with an average velocity of 2700 m/s and a vertical gradient of 2000 m/s per kilometer. The axis spacing of the inversion grid is 200 m in x-direction, and it varies from 100 m at the top to 200 m at the bottom in z-direction. The optimum damping number and number of iterations for this grid were estimated from the trade-off of data residual and model heterogeneity. After a complete inversion, the resolution matrix was evaluated. Its diagonal elements (RDE), which indicate the linear independence of each parameter (Crosson, 1976), were used to remove the least constrained nodes from the inverse grid. The whole inverse process was repeated with the updated node configuration until all RDE values were above 0.2, which can be considered as well constrained (Haslinger et al., 1999).

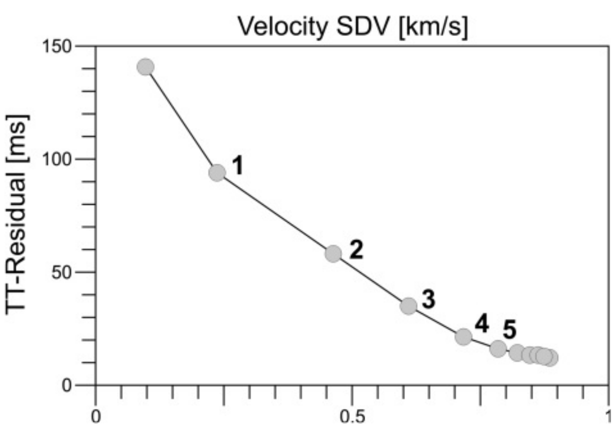

Figure 5: Traveltime residual versus model heterogeneity for consecutive iterations. The model heterogeneity is defined as the standard deviation of the velocity at a constant depth, averaged over all depth levels. The non-zero heterogeneity of the starting value is a result of the irregular grid.

Figure 4 displays the initial and the final model for the final configuration of 29 inversion nodes, and Figure 5 shows the residual reduction. The inversion was stopped after five iterations with a final traveltime residual of 17 ms. This is relatively large compared to our picking accuracy of ~10 ms, however, we were aiming at a minimum-structure model as a first result. In addition, further improving the data fit with a gradient model despite the supposedly strong and sharp contrast of sediments over bedrock might introduce artifacts.

The ray coverage (Figure 6a) shows that the model is generally supported by the data, except for the gap at 0.5 – 0.8 km distance. The RDE values (Figure 6b) roughly indicate the quality of the estimated values. From a comparison of inversions obtained for different node configurations, we estimate that the uncertainty is of the order of 10%. The spatial resolution of the model varies locally, and it is determined by the distance of the inversion nodes, which ranges from 200/100 m (x/z) near the surface to 500/200 m at depth.

5. Interpretation

The first order feature of our inverse model (Figure 4b) is a largely symmetric valley with a maximum sediment thickness of 400 m, if one takes the 3 km/s contour line as an indication of the top bedrock. Picking this contour is somewhat arbitrary, and the true value would depend on a lot of factors including lithology, compaction of the sediments, and erosion of the bedrock. More importantly, the vertical resolution at that depth is only 200 m, and the error could be up to +/- 100 m. However, from comparing inversion results obtained for different grid node depths we estimate the actual error to be only about half that value. To the South, the 3 km/s contour never reaches the surface, which we attribute to the influence of the alluvial fan overlying this contact. At the northern edge of the valley, the 3 km/s contour line is off by 100 m compared to the outcrop of the bedrock. This relatively large error is a result of the gap and the high noise level near the gap, and it is reflected by low ray coverage, and by low lateral resolution, i.e. large horizontal node spacing (Figure 6).

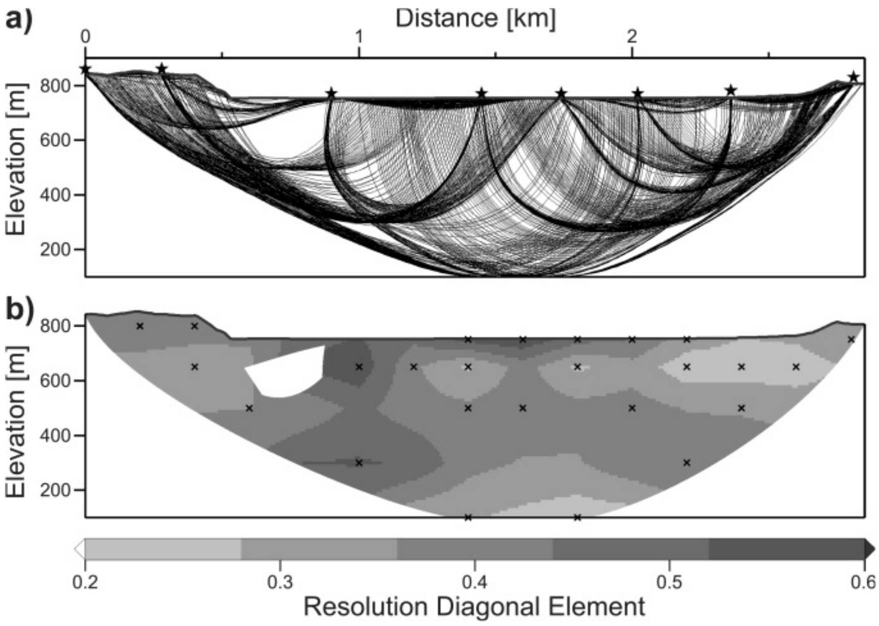

Figure 6: (a) Ray coverage and (b) RDE after the final inversion iteration. The distribution of the inversion nodes (crosses) determines the spatial resolution, and the RDE roughly indicate how well constrained each node is. Masked areas is no ray coverage.

Most of the valley fill is characterized by velocities below 2000 m/s, and down to 100 m depth even below 1500 m/s, indicative of unconsolidated sediments. The velocities of the deep sediments are not well resolved due to the lack of an explicit discontinuity in our model, but the maximum apparent velocity of the sedimentary phase in the shot sections (2 km/s, and up to 3 km/s updip) suggests that compaction is poor, even at depth. Embedded in these generally low velocities, our model shows a pronounced zone of even lower velocities (1100 – 1200 m/s) at 1.8 +/- 0.1 km distance at 100 +/- 50 m depth. This LVZ is consistent with the shadow zone of shot point 4 (Figure 3a), and its lateral position correlates with the last known position of the Salzach before the regulation of the river bed in the 16th century (Lahnsteiner, 1960). Such low velocities typically indicate dry, or only partially saturated, sediments. However, this is unlikely, given the abundance of saturated, or overpressured, aquifers encountered in all of the 50 m-deep boreholes, and the potential for groundwater recharge from the bedrock at all depth levels. A more likely explanation is clayey, organic soils, as are typically deposited in cut-off or abandoned streams, possibly mixed with chunks of dead wood from strong flooding events. We hope to obtain further constraints on this LVZ from the reflection data and from deep DC resistivity measurements to be carried out in the autumn of 2010.

6. Conclusions

The first result from the survey is a kinematic minimum-structure model that shows a largely symmetric valley with a maximum depth to bedrock of ~400 m. Overall low P-wave velocities for the valley fill suggest that it is mostly unconsolidated sediments. The data show no indication for significant lithification at depth, suggesting that glacial erosion removed much of the older sediments. A pronounced LVZ was found at ~100 m depth, which is interpreted as peat layer. More structural details will be revealed from ongoing work on reflection-and-refraction ray tomography, waveform tomography, and reflection imaging. In order to be able to constrain realistic sediment volumes, we also plan further seismic surveys upstream and in the Zell Basin.

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