Introduction

In the Alps, overdeepening resulted in buried elongated valleys, mainly oriented in the direction of former ice flow, and glacially scoured basins in the ablation area of glaciers (Preusser et al. 2010). These valleys and basins were primarily carved out by glaciers and refilled with deposits during Quaternary glaciations. Their sediment succession allows studying erosion and sedimentation processes of glacial cycles, which is the main purpose of the ICDP proposal DOVE (Drilling Overdeepened Alpine Valleys; Anselmetti et al., 2014).

Among various geophysical methods that can be used for the exploration of overdeepened valleys, the seismic method allows the most detailed imaging of the complete sedimentary structures. Whereas refraction seismics only reveals borders of gross geological units, e.g. top basement, shallow reflection seismics, established since the 1990's, can accomplish in principle the imaging of internal structures. It has been sporadically used in Alpine valleys since then (e.g. Pfiffner et al. 1997, Büker et al. 1998, Spitzer et al. 2001, Reitner et al. 2010, Brückl et al. 2010).

One limitation of this method applied to date is the resolution achievable with P-waves, since the elastic wave transmission and typical velocities in a water saturated environment restrict resolution to ca. 5 – 10 m. In addition, the uppermost 20 – 40 m beneath the surface are hard to image with P-wave surveys, leaving a considerable depth gap to, e.g. very high resolution radar measurements in the very near surface region.

A new development in shallow exploration seismics that may overcome these problems is the utilization of shear waves. Due to the very high Vp/Vs relations in unconsolidated sediments and their insensitivity to the presence of water, they promise a much higher seismic resolution. S-wave recording proved to be very useful in some environments (e.g. Inazaki 2004, Suarez & Stewart 2007, Pugin et al. 2009a,b, Polom et al. 2010) but have never been used for exploration of overdeepened structures.

Survey

How far DOVE can benefit from multi-component reflection seismics, is investigated in a DFG-funded project (grants KR2073/3-1, GA749/5-1; project start 12/2015). It intends a structural and facies characterization of sediments in overdeepened structures and the transfer of methodological results to the DOVE drill sites. Test sites are the Tannwald Basin, located about 50 km NE of Lake Constance, and the inner-alpine basin of Lienz, Austria (Fig. 1).

The Tannwald Basin is situated at the margin of the last glacial maximum (LGM), which is documented in the area under investigation by a terminal moraine of strongly varying lithology, flanked by a clayey ground moraine to the SE and sandy-rocky moraine debris to the NW (Fig. 1). The Depth to top Tertiary (Upper Fresh Water Molasse units) was estimated to be ~200 m based on sporadic drillings and refraction seismic profiles (Ellwanger et al. 2015, Behnke and Bram 1998). The Quaternary includes sediments from the last three glacial periods, i.e. Würm, Riss and Hoßkirch.

We accomplished several reflection seismic surveys using high-resolution P-wave, horizontally polarized SH-wave, and multi-component (SV- and SH-wave sources, 3-component receiver) techniques (Fig. 1). In addition, several cross-lines were registered to study 3-D effects and to test a 3-D multi-component approach. First results of the P-wave and SH-wave reflection seismic measurements are presented here (Fig. 2).

The surveys were carried out using LIAG's both P- and S-wave hydraulic 4 t vibrators. P-wave source properties were 20 – 200 Hz, 12 s, a vertical stack of 2 and an interval of 5 m. This was recorded by 360 spiked geophones at 2.5 m spacing in split spread configuration. The resulting average fold is about 120. The SH-wave surveys used a different layout, the main point being the application of a landstreamer, mounted with 240 SH-wave geophones at distances of 1 m in an asymmetrical split spread configuration. The sweep frequencies were reduced to 10 – 100 Hz, due to the more severe damping of S-waves at higher frequencies. Shot point distance was reduced to 4 m, and the 10 s sweep was repeated four times, the last two sweeps excited with opposite polarity to suppress remaining portions of P-waves.

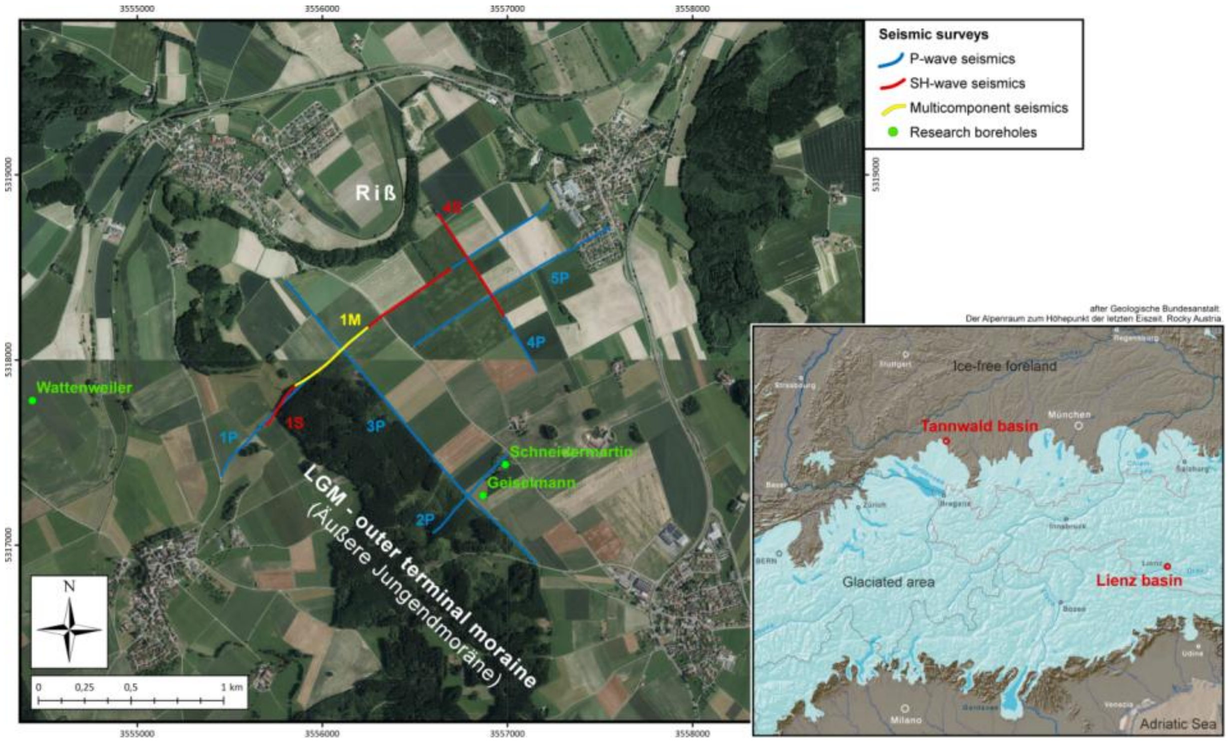

Figure 1 (a) *Overview of seismic surveys and boreholes in the study area of the Tannwald Basin,* ***(b)*** *position of the two exemplary investigation areas, the Tannwald Basin and the Lienz Basin plotted on the background of the last glacial maximum (right).*

Results

The processing of the P-wave data included refractions statics, spectral balancing using the full range of exited frequencies, i.e. 20 – 200 Hz, and prestack-depth migration (PSDM) iterated with reflection tomography. The PSDM improved the section significantly compared to NMO/DMO processing. The processing of the S-waves is still preliminary, the example presented here includes elevation statics, a f-k filter to suppress low velocity surface waves, a spectral balancing of the full frequency range, i.e. 10 – 100 Hz, DMO processing and a post stack FD migration.

Both the P-wave and SH-wave profiles turned out to have high quality and exhibit same overall structures. All P-wave profiles delineate strong reflections of the base of the Tannwald Basin, i.e. top Molasse and the basal till as lowermost Quaternary sedimentation. This preliminary interpretation is supported by nearby boreholes drilled in the 1990's, e.g. for groundwater exploration. Depth of the basement varies from ca. 80 m in the western part of the study area to at least 220 m at the deepest point in the eastern part of the study area. It is an open question whether the depression-like structure reaching down to 280 m depth (1400 – 1900 m in profile 1P) consists of Quaternary units. The shallow and deep portion of the basin are connected by a prominent ~ 10° dipping ramp. The Quaternary basin infill is characterized by strongly varying reflections, ranging from bright continuous reflections e.g. below the terminal moraine to nearly reflection free regions, e.g. the uppermost 40 m SW of the terminal moraine and a more extensive region NE of the moraine. The latter one shows strong scatter in the unstacked data.

Some of these structures are recognized in the SH-section as well, e.g. the prominent ramp-like structure, which seems to be imaged with even better resolution. However, the deepest part of the basin in the NE part is not imaged by SH-waves. The region with very faint (P-) reflections SW of the terminal moraine displays very high resolution (SH-) reflectors, similarly to the region NE of the moraine, where strong and continuous reflectivity shows up down to a depth of ~ 40 m. At larger depth the appearance of reflections is similar to that of the P-wave section.

These differences in data quality between P-waves and SH-waves may partly be attributed to higher damping and scattering of the SH-waves, which causes a lower depth of investigation or the response to different parameters in addition.

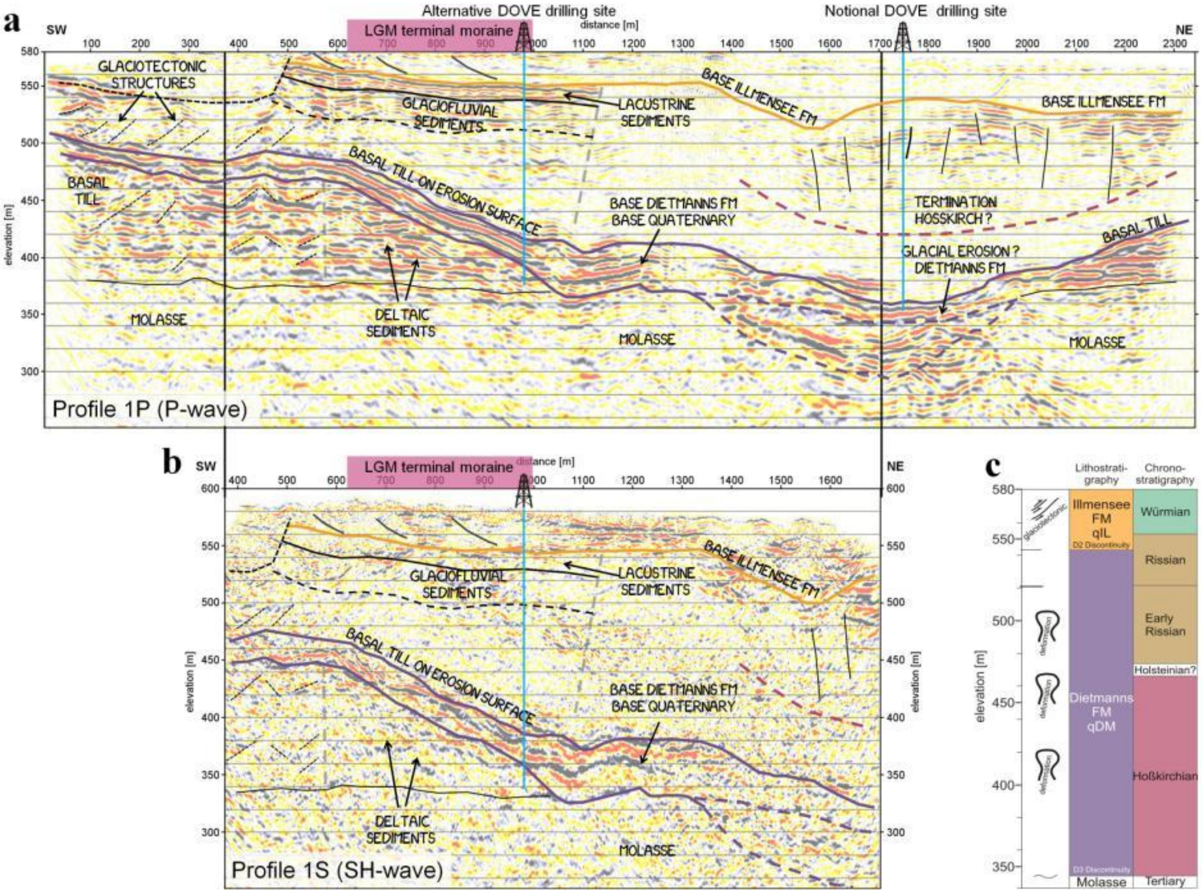

*Figure 2 **(a)** Prestack depth migration of profile 1P. A preliminary interpretation based on an older research borehole (shown in Fig. 2c) is superimposed. Planed drilling sites for the ICDP project are marked on top. **(b)** Poststack migrated and depth converted DMO section of profile 1S, with the preliminary interpretation of the P-wave section superimposed. Note: datum plane is different for both sections, vertical exaggeration is 2. **(c)** simplified lithostratigraphy and chronostratigraphy of the research borehole "Schneidermartin" (LGRB, pers. com.), location see Fig. 1. Note different depth scale.*

Conclusion

The seismic sections image well both the morphology and the internal structure of the Tannwald Basin, and different facies are distinguishable in the glacial sediment succession. A combined interpretation of P-wave and SH-wave reflection seismics reveal more details than one technique alone by providing complementary information. P-wave seismics shows a more coherent image with higher penetration depth, while SH-wave seismics resolves partly more details due to their higher resolution. The combination seems to be an enhanced tool to investigate sedimentary succession in advance of scientific drilling.

Future steps include a revised processing of the SH-wave data as well as the processing of the multi-component data. The interpretation has to be revised, when borehole information is available. A 3-D processing of the cross-lines for P-waves and multi-component data will estimate the potential and benefit for a complete 3-D multi-component survey. Two reflection seismic campaigns are scheduled for 2016 in the Lienz Basin.

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