Introduction

The Upper Jurassic (Malm) carbonate platform in the Bavarian Molasse Basin is the most important hydrogeothermal reservoir in Germany. 27 geothermal facilities are already in operation, however the potenial is not exploited completely yet. In the southern part of Munich the 'Stadtwerke München' envisage a 100 % supply of sustainable heat energy for the year 2040; geothermal heat shall contribute by an area wide pattern of geothermal facilities comprising up to 50 new drillings (Project GRAME[1], Hecht & Pletl 2015).

Geothermal drillings in the Malm have shown that despite many successful projects also some failures occurred (e.g. Geretsried, Mauerstetten), emphasizing a comprehensive characterization of potential geothermal reservoirs. This is intended by the project GeoParaMoL[2] of the Leibniz Institute for Applied Geophysics (LIAG), that covers (1) attribute analysis, (2) S-wave experiments, (3) structural analysis including retrodeformation, and (4) thermal-hydraulic modelling. As a database for the project, a 3D seismic survey was acquired that covers 170 km^2 of the southern part of Munich (Fig. 1).

3D seismic exploration is a well-established method to explore geothermal reservoirs. A particular challenge often is the determination of geophysical parameters for facies interpretation without any borehole information. An approach to include shear waves in the interpretation workflow could help to narrow the range of lithological and petrophysical parameters.

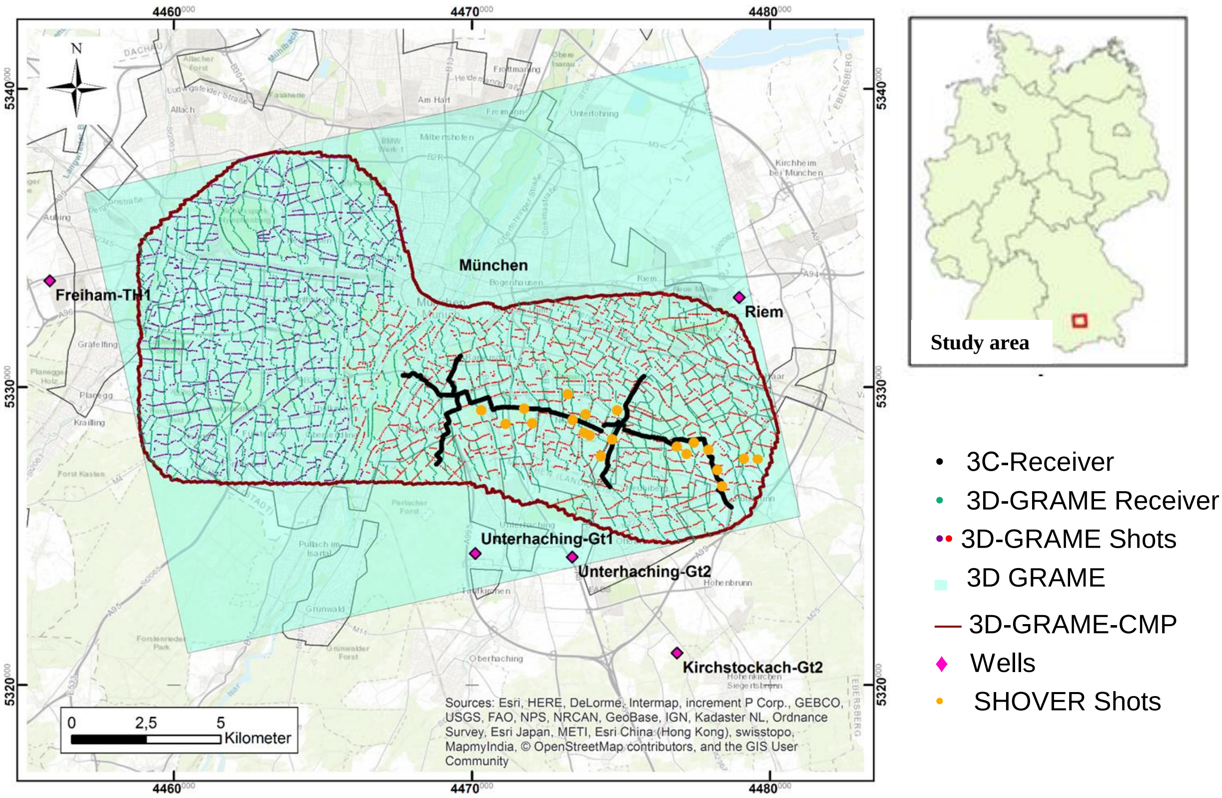

Figure 1: *Map of the GRAME seismic survey in the southern part of Munich. Black lines mark positions of 3C MEMS receivers, that recorded regular shots from the 3D survey (red points) as well as 20 SHOVER shots (yellow points).*

Shear wave measurements were conducted during the regular 3D seismic survey (Fig.1, Tab.1). In a passive experiment, the survey was additionally recorded on single, 3-component (3C), digital receivers. In this way another 3D P-wave as well as a 3D S-wave dataset was acquired. In the active shear wave experiment the SHOVER technique (Edelman 1981) was applied to directly excite shear waves using standard vertical vibrators.

[1] GRAME: https://www.swm.de/privatkunden/suche.html?query=GRAME (German only)
[2] GeoParaMoL: http://www.liag-hannover.de/en/fsp/ge/geoparamol.html

Table 1: Survey parameter

3-Component (3C) Receivers:		Passive experiment:	Active experiment:
• Main line:	312 receivers 15 km length	• Sweep: 12-96 Hz, 12 s • Recording: 5 s	• Sweep: 8-48 Hz, 20 s • Recording: 10 s
• 2 Crosslines:	76 / 79 receivers 4 km length	• Line distance: 400 (NW) – 500 (SE) m	• 2x12 sweeps
• Receiver dist.:	50 m / 30 m	• Shot distance: 50 m	

Passive experiment

3C recording and the use of converted S-waves is in use already a long time (e.g. Kendall, 2006, Chopra & Steward 2010, Hardage et al. 2014). However, this technique has never been applied to geothermal exploration of the Malm reservoir in the Bavarian Molasse Basin due to the additional effort necessary to collect (and interpret) the 3C data. As a test and to encourage further 3C surveys, we recorded the converted 3D wavefield along some 2D lines (s. Fig. 1). The shear components were recorded using MEMS as single sensors, whereas the regular 3D survey used groups of 12 geophones. Since the survey area is located in an urban environment often involving strong noise, we first had to check the comparability of the recordings. We did this by stacking a subset of that reciever stations, where both types of sensors were placed side by side and collected the same shots. The integrated MEMS recordings displayed higher frequencies and an overall lower signal/noise ratio (SNR) than geophone recording (Fig. 2, left). However, the stack of 1173 shots recorded at 51 receivers results in a very good comparability; obviously the stacking process compensates the additional high frequency noise.

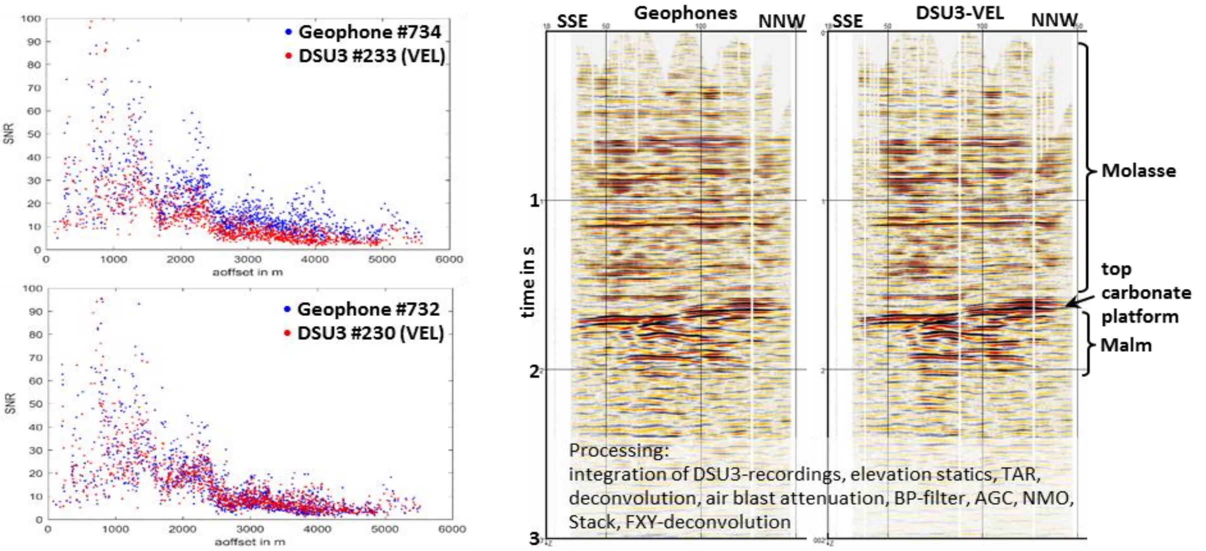

***Figure 2, left:** SNR of a geophone group (•) and a DSU3-sensor (•) recording at the same position. Two locations are shown, SNR was calculated using the RMS amplitude in a 150 ms long time window before and coincident with the P-Wave first break, respectively. **Right:** Stack of 51 geophone and DSU3 recordings, respectively. Processing steps are indicated in the figure.*

Reflections from the top of the carbonate platform are clearly visible on both horizontal components, e.g. H2 oriented 10° towards NNE (Fig. 3). If one assumes a pure SS reflection, a v_p/v_s ratio of only 1.55 results from the traveltimes of P- and S-waves. If a PS converted wave is assumed, a more realistic v_p/v_s ratio of 2.05 can be calculated. A recently measured VSP in a deep geothermal well south of Munich revealed a v_p/v_s ratio of nearly 2 for the lower part (1.6 km – 4.0 km) of the Molasse. Accordingly an asymptotic conversion point binning (ACP, Tessmer & Behle 1988) delivers a better result than a CMP binning. Reflections are also visible below the top of the platform; they give insight into the reservoir.

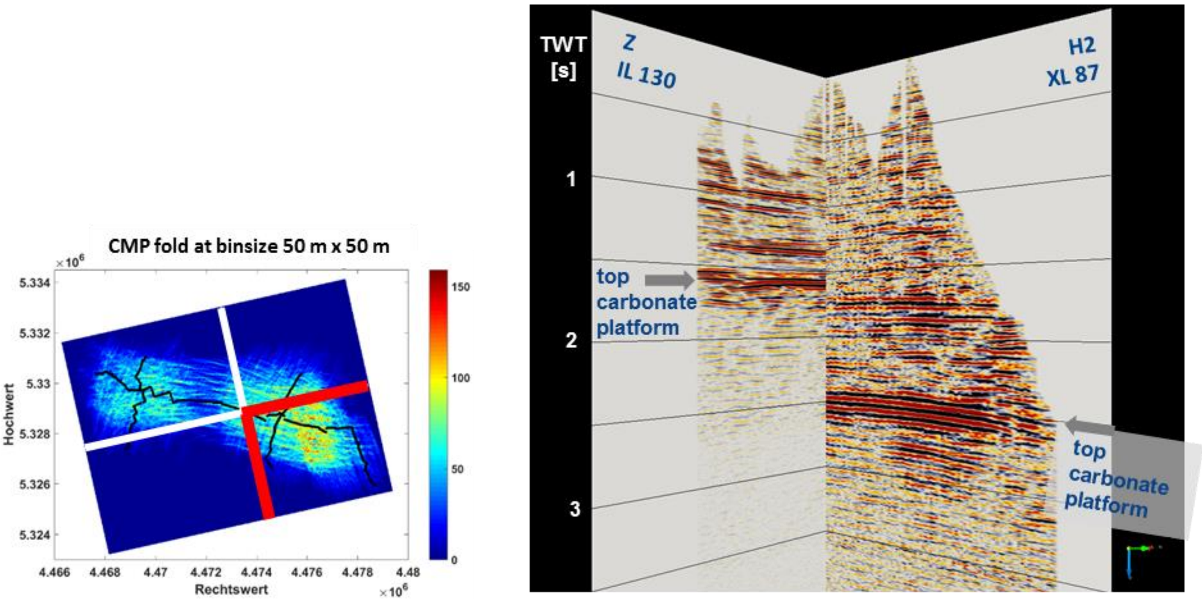

***Figure 3, left**: CMP fold of the MEMS receivers. Red lines show sections on the right. **Right:** CDP-Stack of Z- and H2-component face to face without time correction.*

Active experiment

Besides the passive recording of converted S-waves, we also tried to generate S-waves. Unfortunately, heavy S-wave vibrators are not available anymore, they had been used e.g. by Prakla-Seismos about 30 years ago. However, generating S-waves using P-wave vibrators can also be accomplished by operating them in a push-pull manner, which is also called the SHOVER technique (Edelmann 1981). Two (or more) vibrators are operating side by side with a 180° shift of the vibrator movements (Fig. 4). Thus the P-waves cancel out and (in theory) only transversal polarized S-waves (SH-waves) are transmitted.

It turned out during the survey to be quite difficult to find appropriate source points in the urban environment for the vibrators to sweep side by side. Thus only 20 SHOVER points could be realized, too few to generate a reasonable CMP fold. However, they are effective in emmitting S-waves, as reflections from the top of the carbonate platform show (Fig. 5). These reflections appear on the transversal and on the radial component; from theory they should only be visible on the transversal component. P-waves are not cancelled out as expected; they show up as refracted waves on the Z and on the radial component and even as reflection from the top of the carbonate platform on the Z component.

***Figure 4:** Four vibrators (two on either side) sweeping side by side with opposed polarity. In theory, P-waves cancel out and only SH-waves are generated. Vibrators were oriented 110°.*

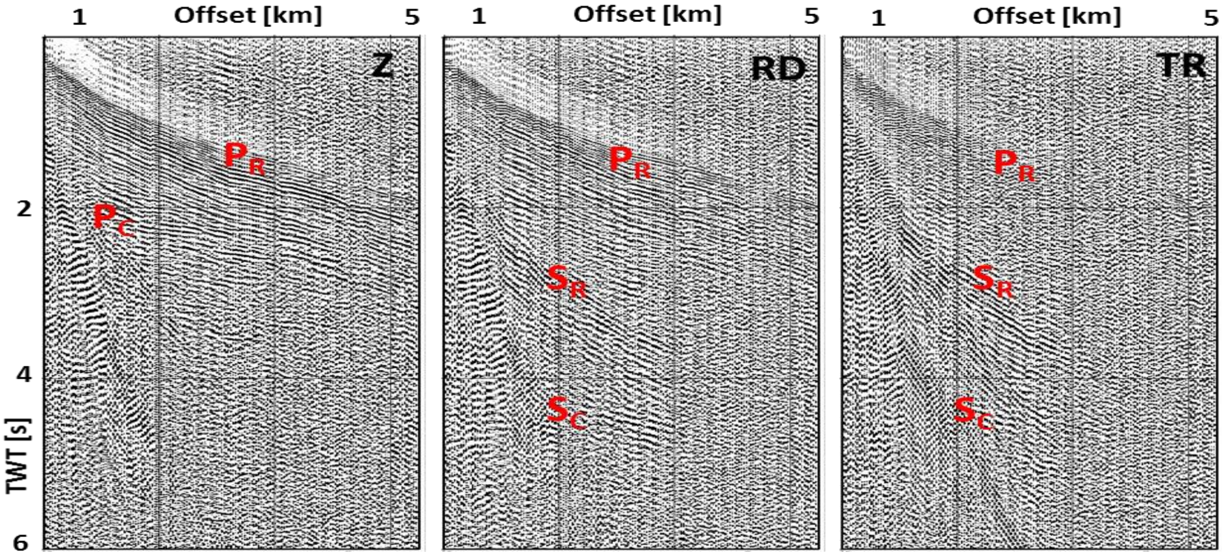

Figure 5: Single shot using the SHOVER technique. Shown are three components (Z vertical, RD radial, TR transversal). Traces are individual rotated according to receiver-source azimuth. P_r refracted P-waves, S_r refracted S-waves, P_c P-reflection and S_c S-reflection at the top of the carbonate platform.

Conclusions

The single 3C MEMS receivers show a slightly lower SNR than the geophone group recordings. However, the final stack of both sensor types are very similar. This favors on one hand the use of 3C recording and on the other hand a denser sampling due to less field effort.

The passive recording of converted waves enables an imaging of the top of the carbonate platform in the Bavarian Molasse Basin as well as intra-reflections. If interpreted area-wide they will give an additional benefit to the regular 3D dataset.

The SHOVER method is able to produce significant S-wave energy, reflections from the top of the carbonate platform are recognizable in single shots. P-wave attenuation does not work as good as assumed. Its application e.g. in urban environments, poses practical problems.

Acknowledgements

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