Introduction

Shear waves are well-known in seismic exploration as a valuable lithology indicator (Tatham 1985). Despite some testing in the 1980's (Edelmann 1985), pure S-wave surveys have not gained widespread popularity, mainly because of difficulties in obtaining appropriate sources and interpretation. Instead of direct exitation of S-waves, recording and processing of converted P- to S-waves has developed further, and is applied nowadays, to a limited extent, in exploration seismic (Hardage et al. 2011), mostly for solving specific tasks, such as illumination beneath gas-rich sediments or deriving fracture orientations, among others (Chopra & Steward 2010). Recording converted waves is more expensive because three- instead of one-component sensors must be used. However, because of increasing channel numbers in the seismic industry, this argument is weakening.

We think that the value of S-waves for geothermal exploration in the Bavarian Molasse Basin is under-estimated, and therefore we conducted a S-wave experiment during a conventional 3D seismic survey, which covered a large part of the southern and western part of the city of Munich (Fig. 1). The experiment comprised of active and passive parts. The active part consisted of direct generation of S-waves using the 'Shover' technique (i.e. vertical vibrators sweeping with opposite phase, Edelmann 1981). The passive part recorded the regular shots of the 3D survey using 3-component sensors. In this paper, we report only on the passive experiment, the active one is described by Wawerzinek et al. (2017). To our knowledge, only one similar test for a geothermal field exists in the US (Wei et al. 2014).

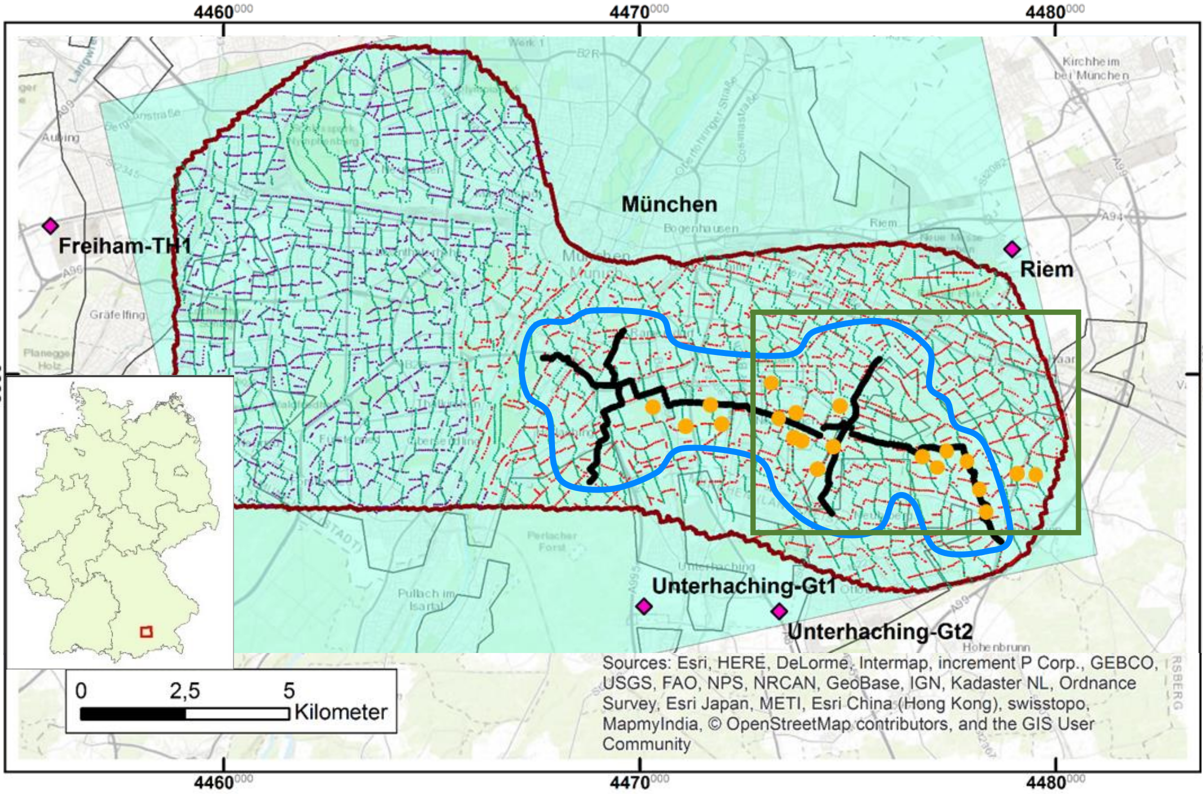

Fig. 1: 3D survey and complementary S-wave experiments. Small green dots mark 1C-receiver, large black dots 3C-receiver. Small purple and red dots mark shots of the regular 3D survey; the red ones were recorded by 3C-receiver. Large orange dots show the positions of 'Shover' shots, the blue line defines the area covered by converted wave reflections at reservoir level. The green box gives the position of Figure 2. Note that at the time of the survey no borehole existed inside the study area.

Study site

The Upper Jurassic carbonate platform is the target of the geothermal exploration in this area. It forms the uppermost layer of the Mesozoic basement of the South German Molasse Basin. This basin developed during the Alpine Orogeny (Ziegler et al. 1995) and its sediments cover the carbonate platform to a depth of 2000 to 2800 m at this site. The carbonate platform developed at the northern margin of Tethys Ocean in a large epicontinental sea. Typical in this formation is the alternation of carbonate mounds or build-ups and troughs (Meyer & Schmidt-Kaler 1990). The distribution and internal structure of the platform can be studied at outcrops in the Franconian Alp, 100 km toward the north. Within the basin, the carbonate platform has been tested by sparsely-distributed exploration wells. Dussel et al. (2016) presented a geological model of the platform in the area of Munich. Von Hartmann et al. (2012) showed seismic imaging of the internal structure of the platform.

The Upper Jurassic Malm is the most important hydrogeothermal reservoir in Germany. More than 25 geothermal facilities are already in operation (GeotIS, Agemar et al. 2014), however the potential is not in any way completely exploited. 'Stadtwerke München', a local company coordinating the drilling, 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 40 new boreholes in the southern part of Munich (Hecht & Pletl 2015). Geothermal boreholes in the Malm have shown that, despite many successful projects, failures also occurred (e.g. Geretsried, Mauerstetten), emphasizing the need for comprehensive characterization prior to drilling.

Survey and methods

A 3D seismic survey covering 170 km^2 was carried out in 2015/16; half of the ~7000 shots were recorded at 467 3C-receivers that were deployed along several 2D lines in the eastern part of the survey (Fig. 1). The 3C recording was carried out using single MEMS sensors (DSU3/Sercel). We compared the vertical component of the single MEMS sensors with the recording of the geophone groups (each consisting of 12 geophones spread over 50 m). Despite a slightly larger S/N ratio of geophones in the shot domain, the resulting stack shows no visible differences (Wawerzinek et al. 2017).

The processing of the converted-wave data comprised (1) integration of the MEMS data, (2) rotation into a radial-transversal coordinate system based on the acquisition geometry and (3) an asymptotic conversion point binning (ACP; Tessmer & Behle 1988). Since ACP binning requires the v_p/v_s ratio as input, we derived these values from VSP recordings in the borehole Freiham Th1, which shows remarkable clear S-waves despite a vertical vibrator source being used. The resulting v_P/v_S ratio for the Molasse of approximately 2 is significantly higher than expected and strongly influence the hypocentre determination of induced seismicity that occurs around Munich (Megies & Wassermann 2014).

Results

We used this estimate for ACP binning to get interpretable PS-wave sections. In both P- and PS-wave sections we identified a number of horizons that could be correlated. The interval traveltimes allow the derivation of the v_p/v_s ratio according to $\frac{v_P}{v_S} = 2\frac{\Delta T_{PS}}{\Delta T_P} - 1$ (Garotta 1987), where ΔT_{PS} and ΔT_P are two-way-traveltime differences of PS- and P-waves, respectively. We could confirm the high v_P/v_S ratio for the Molasse: 90% of the derived values are in the range of 1.8 to 2.1, with a median of 1.92.

Inside the carbonate reservoir, the values show a larger variation between 1.5 and 2.3. Since no borehole exists for our study area, we cannot verify this at the moment. However, we can assess its reliability by an comparison of an independantly-derived seismic classification: By using the seismic attributes of amplitude, frequency and similarity of P-wave data, a seismic facies characterization was carried out, which shows a differentiated picture of the reservoir (von Hartmann et al. 2018). This classification correlates well with the v_p/v_s ratios derived from S-waves (Fig. 2). An overlay of the v_p/v_s ratio onto seismic sections shows that very low ratios correspond to the diffuse reflection pattern. These regions show maximum values of P- and S-wave velocity. These findings lead to a differentiation of limestone and dolomites, i.e. the lithologies found in the nearby boreholes (Fig 1): Seismic velocities are higher in dolomite than in limestone (Marion & Jizba 1997), whereas the v_p/v_s ratio is lower in dolomite (Picket 1963).

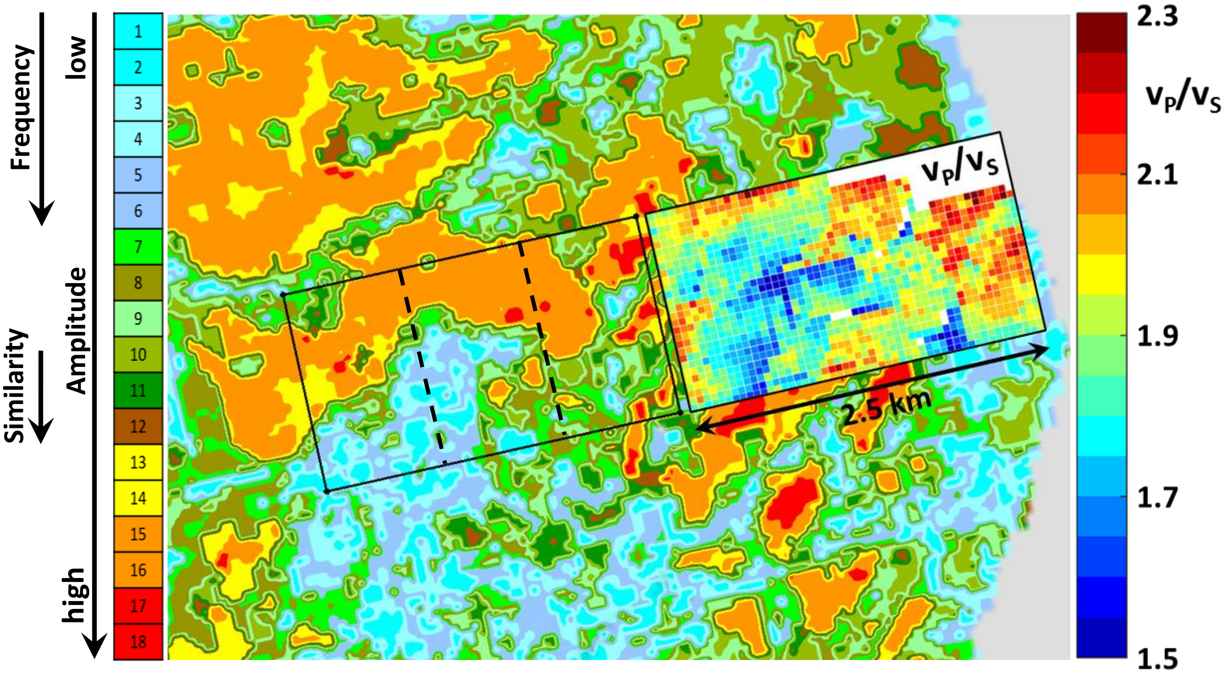

Fig. 2: Seismic facies classification compared to vp/vs ratio. The right-hand box shows the vp/vs ratio for the left-hand box. The classification scheme comprises three attribute- and frequency intervals and two similarity intervals. Each amplitude interval was divided into three frequency intervals and thereafter into two similarity intervals. It correlates well with the classification pattern. Dashed lines indicate the position of seismic sections in Fig. 3.

Conclusions

The deployment of 3C MEMS sensors allowed a derivation of the v_p/v_s ratio, both in the Molasse sediments as well as in the carbonate reservoir. We were able to build an attribute volume, although we recorded on only 2D lines with a limited number of sensors. Since the single sensors delivered a comparable stack quality to geophone group recording, the recording of the entire survey using this technique would be feasible.

The v_p/v_s ratio of the Molasse sediments is decisive for the analysis of induced seismicity. The ratios inside the reservoir indicate lithological variations, in this case the discrimination of limestone and dolomites, which is crucial for the prognosis of permeability within the carbonate plattform. A verification by boreholes is still to be carried out, but the comparison with independently-derived seismic classification strongly supports the reliability of the prognosis.

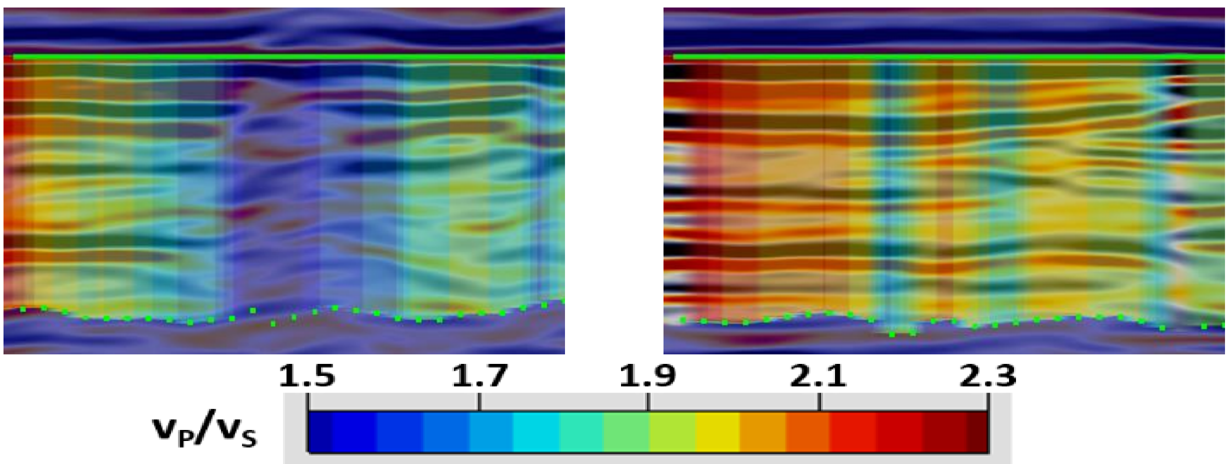

Fig. 3: Seismic sections overlain by v_p/v_s ratio (position see Fig. 2). Very low velocity ratios correlate with diffuse reflectivity.

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