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3D Seismic Survey for a Petrothermal (EGS) Research Project in Crystalline Rocks of Saxony, Germany

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ABSTRACT

3D seismic measurements have been performed in 2012 to explore a petrothermal reservoir in a granitic environment within the Erzgebirge (Ore Mountains) in Saxony. The intention and challenge is to image and characterize potentially permeable fracture zones at target depths of 5-6 km and temperatures well above 150 °C. This is considered as an EGS (Enhanced Geothermal System) project, if stimulation turns out to be necessary. New innovative and unconventional methods have been applied in field acquisition as well as in data processing and interpretation. The Vibroseis technique was used in the core experiment, accompanied by a special explosive seismic experiment. The 3D seismic reflection technique has been proven as an indispensable tool for geothermal exploration even in a crystalline environment. A rich repertoire of structures within a late-Variscan granite pluton has been imaged. Steeply dipping fault zones and conjugate faults within the granite pluton are imaged. Further analyses for interpretation of the reflective structures will help to define an optimum drill path for a research well which is considered as the next stage for a possible geothermal plant.

1. INTRODUCTION

In Germany, the exploration of hydrothermal reservoirs by 3D seismic measurements is common practice in sedimentary environments in the Bavarian Molasse Basin and in the Upper Rhine Graben since about 7 years. Such exercise has been performed now in granites and outcropping crystalline rocks of the western Erzgebirge in Saxony (Fig. 1) within the Gera-Jachymov fault zone. Its aim is to image and characterize steeply dipping fault and fracture zones for their hydraulic permeability. Granite is considered as a favorable host rock for a petrothermal reservoir, since it tends to brittle deformation under tectonic stress. Target depth is 5-6 km within a granite pluton where temperatures above 150 °C are expected. Such petrothermal reservoirs hold a much higher geothermal potential in Germany than known from hydrothermal reservoirs (Paschen et al., 2003). While the latter contain hot water already, particularly the limestone aquifer in the Bavarian Molasse Basin, petrothermal reservoirs are characterized by the storage of dry heat at depth where cold water needs to be injected first. The term "petrothermal" has been used and defined by the German Renewable Energies Act (EEG) in 2009; see also Rybach (2014).

Application and experience regarding 3D seismic measurements in crystalline environment throughout the world is quite limited. There are informative examples from mineral exploration and mine planning in hardrock environment (Malehmir et al., 2012) and in academic research (Harjes et al., 1997). There is no stratification compared to that in sedimentary basins, where seismic exploration for oil and gas reservoirs is best practice since a long time. A feasibility study of the research group “Deep Geothermal Resources of Saxony” (LfULG Sachsen, 2011) suggested the area Aue-Bad Schlema-Schneeberg to be qualified for a deep EGS project, mainly based upon favorable temperature conditions and the huge amount of knowledge available from mining activities. The Leibniz Institute for Applied Geophysics (LIAG, Hannover) undertook the task of exploring potential fracture zones within the granite pluton. The seismic measurements were performed using the Vibroseis technique between August and November 2012. Data processing is carried out at the LIAG and at geophysical institutes of the University of Hamburg and the Technical University of Freiberg. Its aim is to test several new and available imaging techniques, besides of conventional techniques.

2. 3D SEISMIC SURVEY

The survey area is characterized by a large, partly exposed granite body of late-Variscan age overlain by gneisses, schists and phyllites of pre-Variscan protolith age. A steeply dipping fault system consisting of post-Variscan synthetic and antithetic normal faults strikes in NW-SE direction. The approx. 70° dipping 'Roter Kamm' is of particular interest, since it is exposed at the surface. Its possible fracture porosity within the granite body at the target depth could provide the natural fluid permeability necessary for a geothermal plant. From mining mainly for uranium which lasted from end of the 1940s to the end of the 1980s, only the top of the granite is well known and documented. Structures within the granite are extrapolated to greater depth (Fig. 2).

The 3D reflection seismic experiment consisted of source and receiver lines with nominally 400 m spacing and 30 m point spacing within an area of 10 km x 10 km size, extended to 10 km x 12 km during the field campaign. Three heavy vibrators of 27 ton each were used as a simultaneously acting seismic source (Fig. 3) with a 12-96 Hz sweep signal of 10 s length and 8-fold stacking. A patch of max. 6000 recording channels was moved in role-along mode over the area of totally 8146 recording stations. There were 5348 vibrator points, resulting in a nominal common-midpoint (CMP-) coverage of up to 250 in the centre of the area for bin sizes of 15 m x 15 m. Considering all field layout parameters, the survey can be categorized as wide-azimuth and wide-offset survey (Fig. 4). An integrated explosive seismic experiment was designed with 23 shot points with 30 kg charge in 30 m deep holes on a circle of 30 km diameter around the centre of the study area (Fig. 5). Its aim was to record the refracted seismic wavefield that penetrates the target zone horizontally for tomographic studies.

Numerous deviations from the nominal survey design were necessary in order to cope with several unexpected bureaucratic barriers. Other problems were related to missing permits for large forest areas. For compensation of the failed subsurface coverage, the survey area was extended to 10 km x 12 km on the short term.

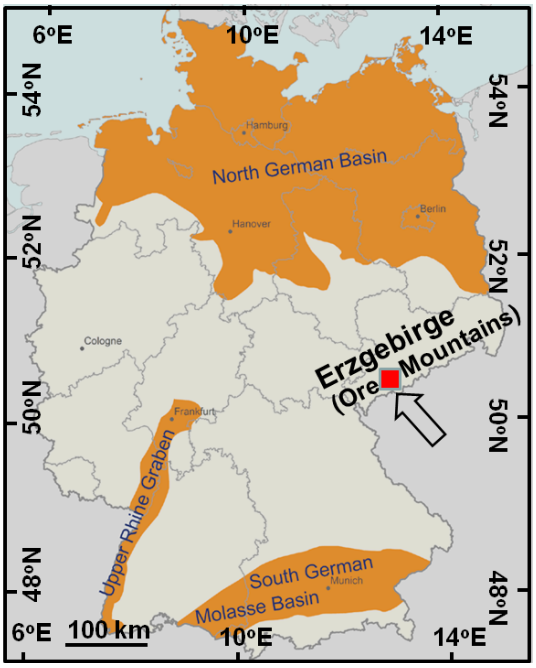

Figure 1: Location map of the areas of hydrothermal usage (coloured, http://www.geotis.de) and location of the study area (arrow, red rectangle) for exploration of the petrothermal reservoir in Saxony, Germany.

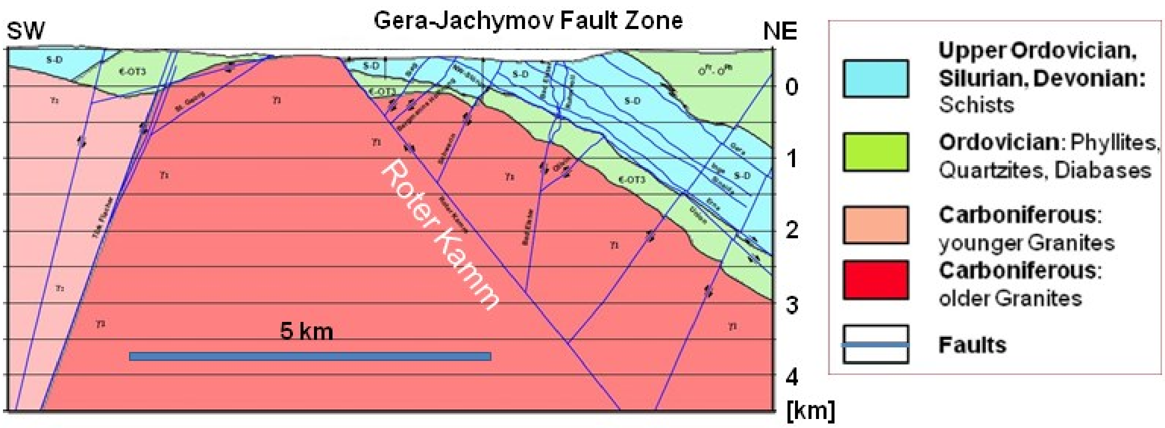

Figure 2: Simplified geological section through the study area (LfULG, 2011). Late-Variscan granites intruded into Schists, Phyllites, Quartzites and Diabases of pre-Variscan protolith age. The overburden of the granites including faults and the top of the granites is precisely known and documented by the past uranium mining down to the depth of ca. 1500 m b.s.l. Structures within the granites, particularly the faults and conjugate faults are tentatively extrapolated to greater depth and are therefore subject of seismic imaging.

3. PROCESSING AND RESULTS

First promising images after brute processing during quality control in the field showed a great number of reflecting elements within the granite pluton in the target zone which are of particular interest for an EGS project. Conventional common-midpoint (CMP) processing was done at the LIAG with further encouraging results. The pre-processing turned out to be of eminent importance, since reflections in the raw field records were rarely visible. This workflow consisted of automated noise-editing, field static corrections to the datum level of 300 m a.s.l. (from short-refraction surveys), refraction static corrections (from first arrivals of the Vibroseis records), automatic residual static corrections and surface-consistent amplitude scaling and deconvolution. All these steps were iteratively updated. Common-reflection-surface (CRS) processing (e.g. Jäger et al., 2001) was used to produce

Figure 3: Three 27-ton vibrators as seismic source on municipal roads of Schneeberg (Saxony).

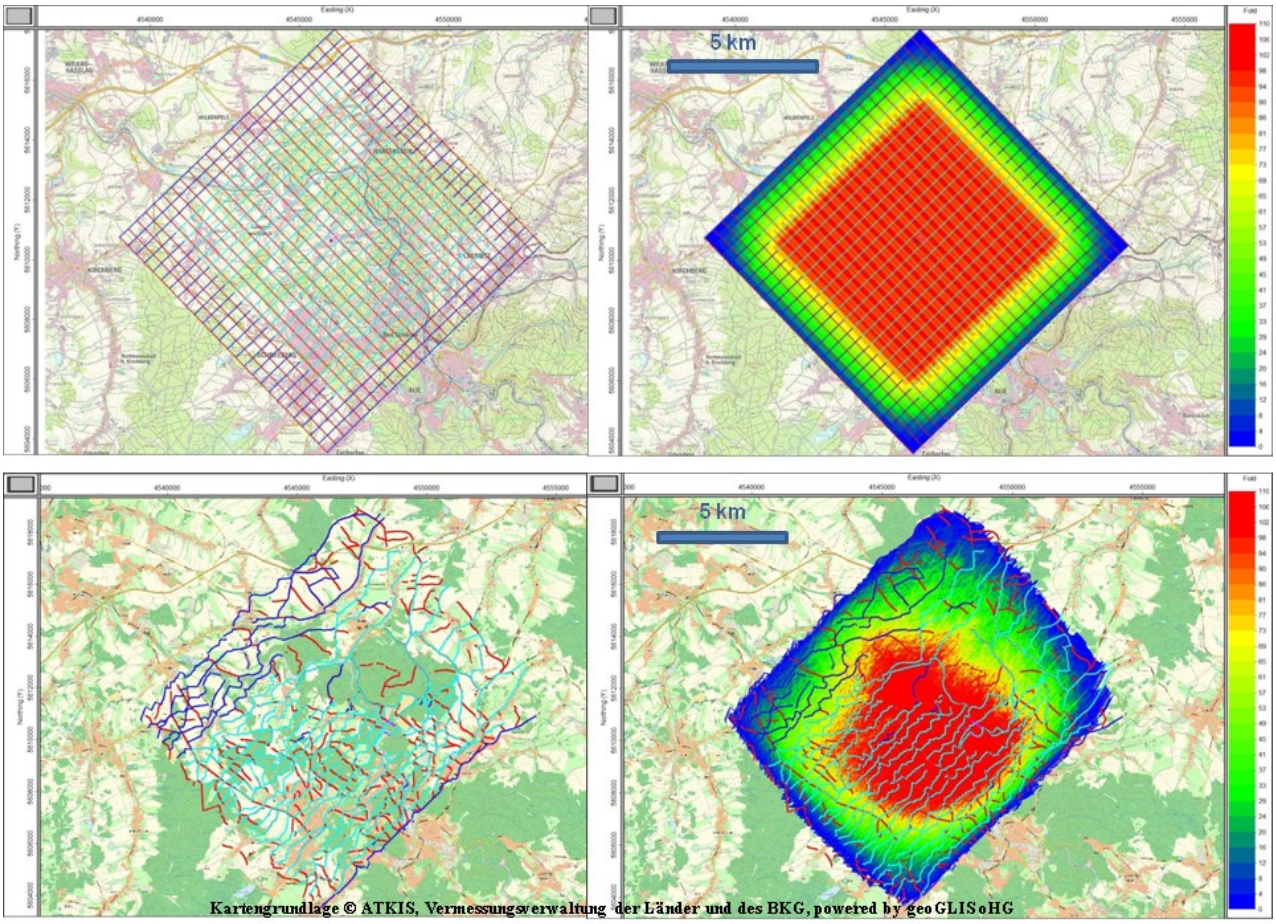

Figure 4: Survey layout (receiver lines blue, vibrator lines red, patch with max. 6000 recording channels light blue) and common-midpoint (CMP) fold for 15 m x 15 m bins (maximum 250 fold in the centre, red, however, truncated at 110 which is the maximum for pre-planning). Top: original layout during pre-planning for a 10 km x 10 km area; bottom: after implementation during the field campaign and extension to a 10 km x 12 km area. Note different scales between pre-planning (top) and realization (bottom).

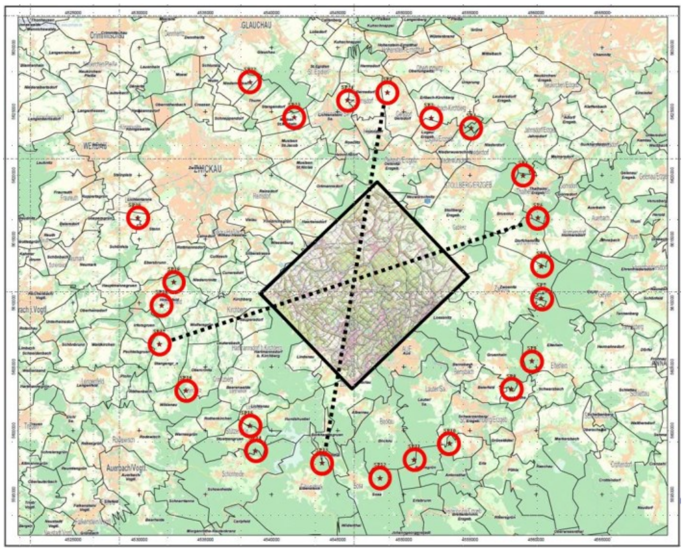

Figure 5: Configuration of the main 3D Vibroseis survey (rectangle with sourcepoint and receiver lines) and the integrated explosive seismic experiment with 23 shotpoints located on a 30-km-diameter circle. These shotpoints were recorded by 60 mobile seismographs located between each pair of opposite shotpoints (two lines shown here schematically as examples) and also by the Vibroseis recording unit.

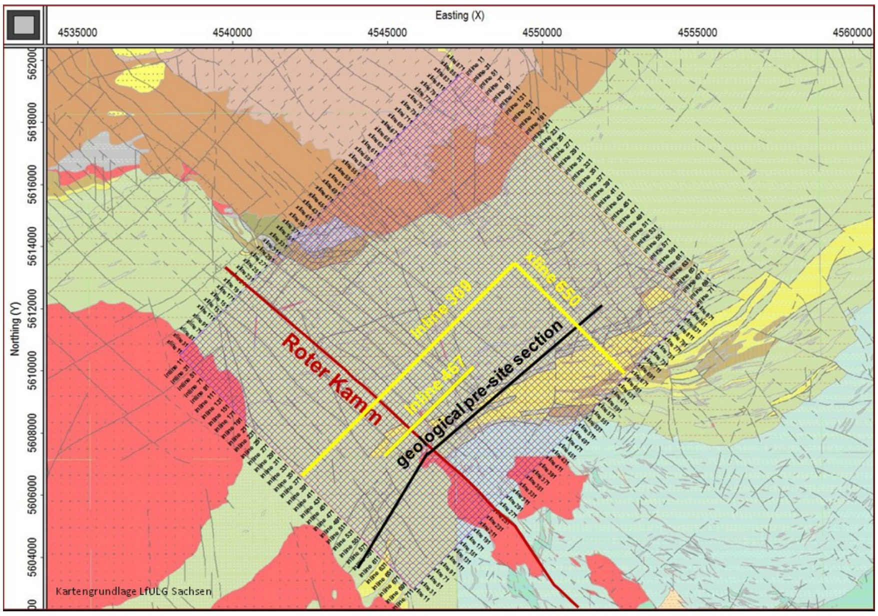

Figure 6: Geological and location map of the data volume after data processing. The volume consists of 712 inlines (SW-NE) and 868 crosslines (NW-SE). The data volume can be displayed on vertical sections at each inline and crossline (15 m apart, here only every 10th line displayed) as well as on arbitrary lines and horizontal time or depth slices. Outropping granites are displayed in red color. A permo-carbon sedimentary trough is located in the North (brown), other colors correspond the pre-Variscan metamorphic rocks. The black line marks position of geological section of Figure 2. The yellow lines mark the sections shown in Figures 7 and 8.

zero-offset stacks and enhanced pre-stack gathers. Finally, post-stack and pre-stack time migration with subsequent time-to-depth conversion was applied to produce the final 3D data cube. This volume can be displayed as vertical sections on 712 inlines and 868 crosslines, each 15 m apart, or on arbitrary lines, as well as on horizontal time or depth slices in 2 ms or 5 m intervals, respectively (Figure 6).

An excerpt of the resulting data volume is shown in Figure 7 after post-stack time migration of CRS-stacks and time-to-depth conversion. For depth conversion, a well-established macro model was used, since velocities in crystalline environment do not vary much horizontally. There are numerous structures below the top of the granite which is well-documented from mining information. Many of these structures within the pluton, besides of subhorizontal reflections at the base of the granite, are steeply dipping and can be interpreted as fault planes or zones, striking in NW-SE direction as expected. Even the 'Roter-Kamm' normal fault can be imaged (Figure 8), although not everywhere and not at all depths. Perpendicular to this fault or to its expected prolongation, there are numerous very sharply imaged conjugate faults. These faults are offset at the 'Roter Kamm' implying that the conjugate faults are older. This is in sharp contrast to the pre-site model shown in Figure 2. Sharp positive impedance contrasts indicate the healing of the conjugate faults due to mineralization, possibly containing various ores. This would be in contradiction to the concept during mining for uranium that ores only could be found outside of the granite. At greater depths, there are numerous predominant sub-horizontal structures, striking generally in W-E direction (Schneeberg body, Figure 7). They are obviously related to the base of the granite and demand further analyses.

The 'Roter Kamm' fault, originally considered as primary target at depth, is indirectly imaged by the pronounced offset of the conjugate faults and characterized by a zone of enhanced seismic attenuation, as indicated by low signal frequencies within the zone marked in Figure 7 (red dashed lines). This high attenuation is an indication of mechanically fractured (and thus porous) rock. At certain locations (Figure 8) the 'Roter Kamm' can also be directly imaged, particularly where its exposures at the surface can be found. In comparison with the pre-site geological section (see Figure 2), the 'Roter Kamm' shows a lower dip and a slightly listric form.

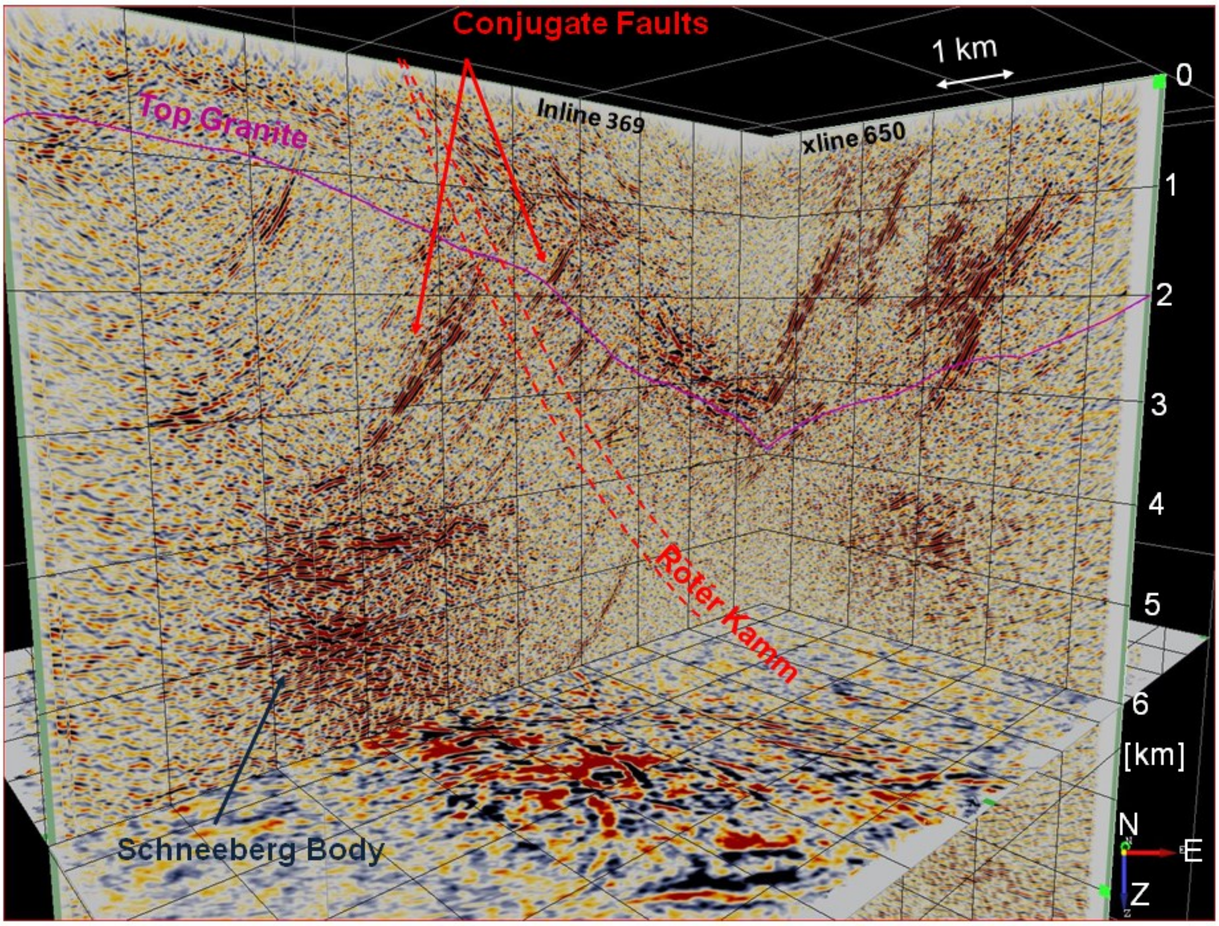

Figure 7: Vertical sections and depth slice through the data volume after CRS-stacking and FD migration (inline 369, SW-NE, crossline 650, NW-SE, for location see Figure 6). Purple line marks top of the granite according to detailed information from mining (LfULG Sachsen, 2011). Note numerous structures within the granite pluton, particularly the steeply SW dipping conjugate fault zones. Structures above the top of the granite (see the crossline) were prospective for uranium mining. The 'Roter Kamm' fault is characterized by the displacement of the pattern of conjugate faults. The highly reflective Schneeberg body is presumably located at or beneath the base of the granite.

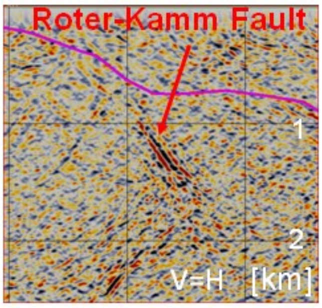

Figure 8: Image of the 'Roter Kamm' fault on inline 467 (for location see Figure 6). Gridlines are 1 km apart. Purple line denotes top of the granite.

4. CONCLUSIONS

The 3D seismic reflection technique has been proven as an indispensable tool for geothermal exploration even in a crystalline environment. A rich repertoire of structures within the granite pluton has been imaged. Steeply dipping normal faults and conjugate faults appeared, partly in accordance with the pre-site model, however, at different positions and with different characteristics. Further analyses for interpretation of their nature will help to define an optimum drill path for a research well which is considered as the next stage for a possible geothermal plant. The 'Roter Kamm' fault has been confirmed as a primary target at depth.

5. ACKNOWLEDGEMENTS

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