3D-seismic investigations to search for a deep geothermal reservoir within crystalline rock

von Hartmann Hartwig[1], Lüschen Ewald[1], Thomas Rüdiger[1], Schulz Rüdiger[1]

[1] Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover; Germany

hartwig.von-hartmann@liag-hannover.de

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ABSTRACT

In 2012 a 100 km2 large seismic survey was carried out to image faults up to 6 km depth in a granitic environment in the Westerzgebirge (Saxony, Germany). The project investigates the possibility to image deep structures in crystalline rocks for geothermal use. The investigated area is located within the so called Gera–Jachimov fault zone, a part of a prominent lineament. The upper part up to 2 km depth is known by former mining activities; so in this part seismic data can be directly correlated with geologic models. The survey was performed using Vibroseis. Line distances of 400 m and group intervals of 30 m of both source and receiver patterns result in a bin size of 15 x 15 m2 and a fold of 110. The layout of the survey is therefore outstanding for seismic exploration within a crystalline environment. The topography of the survey area is characterized by different regions: agricultural, urban and forest areas, cut by valleys and small rivers.

The aim of the project, which is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, is to investigate exploration concepts for the search for low enthalpy geothermal reservoirs in crystalline rock. Actual projects conducted by geothermal companies in Germany concentrate on hydrogeothermal reservoirs. This project should enlarge the area of possible sites for geothermal use near local urban areas by including regions with shallow crystalline basement.

The seismic data image the overlying metamorphic piles, which dip in northeastern direction above the granitic intrusion. Beneath these metamorphic sediments, the granite is more seismically transparent, i.e. impedance contrasts are much lower und the seismic pattern is more chaotic. Several steep dipping reflections can be identified, which were forecasted by the former mining activities. These reflections are not continuous, but change their signal strength and signal form with depth. Time slices show lineaments with different strikes which means that different fault systems beside the main fault zone could be imaged. The reflection pattern differs within the granitic body. Areas with diffractions and elongated reflection areas can be observed. This may be an indication for different granitic bodies which form the whole crystalline complex and for faults which are not reflective themselves.

The faults have been enhanced by the seismic processing. These fault systems are the first step for defining well targets of a geothermal reservoir. Further interpretation will be based on attribute analysis of the original data to characterise seismic reflection patterns.

1. INTRODUCTION

Seismic exploration for geothermal reservoirs in Germany focused up to now on deep sedimentary aquifers. The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has started to fund projects to explore areas where geothermal energy will be produced from the crystalline basement. This will enlarge the area suitable for possible deep geothermal projects considerably. Because of normal thermal gradients in these areas, geothermal wells need to be drilled more than 5 km deep to reach sufficient temperatures. The exploration is based on preliminary studies and 3D seismic surveys. The main aspect of the seismic investigations is the imaging of fault zones. One of the survey areas is located near Wiesbaden, the regional capital of Hesse, the other within the western part of the Erzgebirge (Saxony) near the small town of Schneeberg. The latter region is characterized by a long mining history, which cumulated in an extensive production of uranium ore within the last century. Therefore, data from mining activities up to a depth of 2000 m could be used for the preliminary study (LFLUG 2011). The study aims at identifying a complex fault system, the temperature gradient as well as the stress field.

1.1 Geology

The survey is located in the Westerzgebirge, a part of the Central European Variscian orogeny. The geology is characterized by three main elements: large granitic intrusions, metamorphic piles and a large fault zone (fig. 1). The metamorphic rocks form a NE-SW striking syncline and are composed of pelites and metapelites of Ordovician to Silurian age. The granites intruded in late variscian, post cinematic time. They crop out over a large area at the eastern edge, but take up the most part of the subsurface beneath the survey area where its surface dips toward the east at an angle of approximately 60 degrees (fig. 2). Most faults run in northwest-southeast direction and are related to the Gera-Jachimov fault zone. The geologic model predicts a main fault dipping northeast at an angle of 60 – 70 degrees, which is accompanied by smaller conjugate faults up to 6 km depth. The faults can be mapped very well in the upper part, within the former mining area.

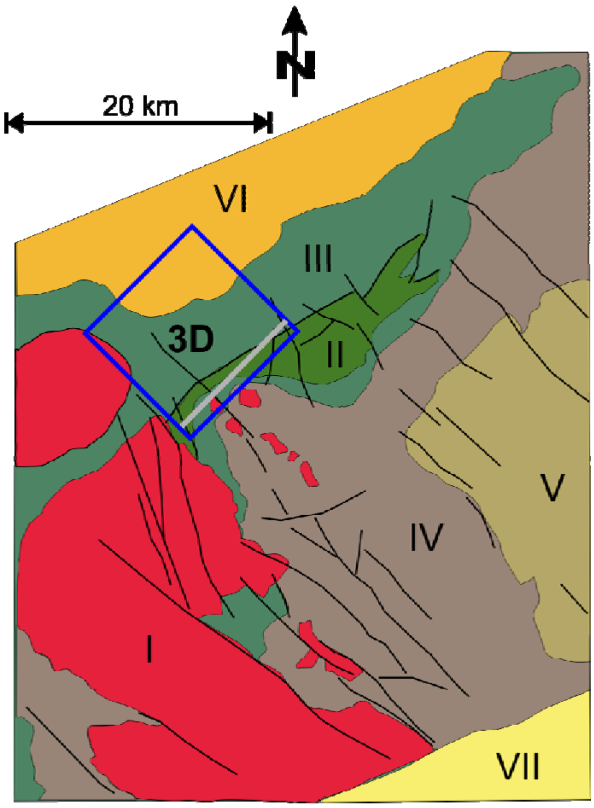

Figure 1: Geologic map of the survey area (after Franke, 2012 and Geologic Map Erzgebirge/ Voigtland 1:100.000, 1995, Freiberg). I: Granit, II: Silurian pelits, III: Ordovician metapelites, IV: Cambrian phyllites and schists, V: Proterozoic gneiss, VI: Permian molasse sediments, VII: Tertiary sediments, 3D: Area of the seismic survey, gray line: geologic cross section shown in fig. 2.

1.2 Concept

The concept for using geothermal energy in the region based on the additional heat production of the granites, the main faults, and the regional stress field. Measurements showed a heat production of the granites up to 11 µW / m^3. A value of approx. 7 µW / m^3 was used for the modelling. From mining activities a main normal fault and several conjugate faults are known. It is thought that one of the conjugate faults will intersect the main fault at depth pf approx. 5,5 km. This fault system runs in NW-SE direction and therefore coincides with the main stress direction, which results in a strike slip regime, advantageous for opening fissures in the vicinity of the faults.

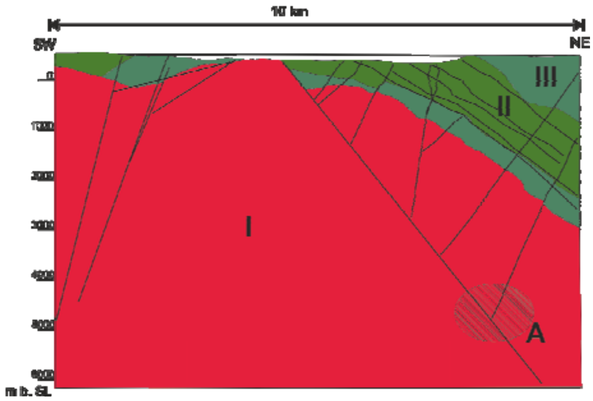

Figure 2: Geologic Section across the southern part of the survey area (after LFLUG, 2011). Roman letters correspond to explanations in fig. 1. "A" indicates the exploration target: the intersection of two faults at a depth of 5 km.

1.3 Seismic investigations in crystalline rock

In contrast to seismic investigations in sedimentary basins, seismic surveys within crystalline environments are rare although 2D surveys as well as 3D surveys have been acquired (Schmelzbach et al. 2007, Milkereit et al. 2000, Casini et al. 2010). The projects are often linked to nuclear waste storage, mining or geothermal sites. In case of geothermal exploration, targets are faults or intrusions in tectonically active environments. Seismic investigations of the crystalline basement are very challenging because of the lack of continuous seismic reflectors. Therefore, tools for seismic data processing and interpretation do not work very well. Often the impedance contrast within the crystalline rocks is low.

Within the Erzgebirge, a 2D seismic survey was acquired in 1990 as part of a seismic surveying of the upper crust in Germany (German Deep Reflection Seismic Programme, DEKORP, Dürbaum et al. 1994). The line ran 20 km south of the 3D survey acquired last year. Within the granitic intrusions the seismic shows a low reflectivity but steep dipping events can be recognized. In general, the middle crust exhibits a high reflectivity. 50 km toward the south at the location of the super-deep KTB- borehole (Continental Deep Drilling), a 3D seismic survey was acquired showing a high reflectivity fault (Harjes et al. 1997).

The aim of the current seismic investigations is to adapt the seismic measurements and data processing workflow to the crystalline environment, especially the imaging of faults.

2. 3D SEISMIC INVESTIGATIONS AND DATA PROCESSING

The 3D seismic survey in Schneeberg consists of 26 source lines und 31 receiver lines in a rectangular area. The distance between each line was 400 m. Source and receiver group distances were in each case 30 m. The whole area was 120 km2 in size. The source groups consisted of 3 vibrator trucks with a peak force of 27 t. Each receiver group consisted of 12 geophones. The template of each shot consisted of 6000 receiver groups. The sweep frequencies were from 12 to 96 Hz. The sweep length was 10 s and the listen time 16 s; the bin size 15 m2. The CDP fold is approximately 200 in the central area. The topography is characterized by a hilly and agricultural area in northward direction and a more urban area in the south.

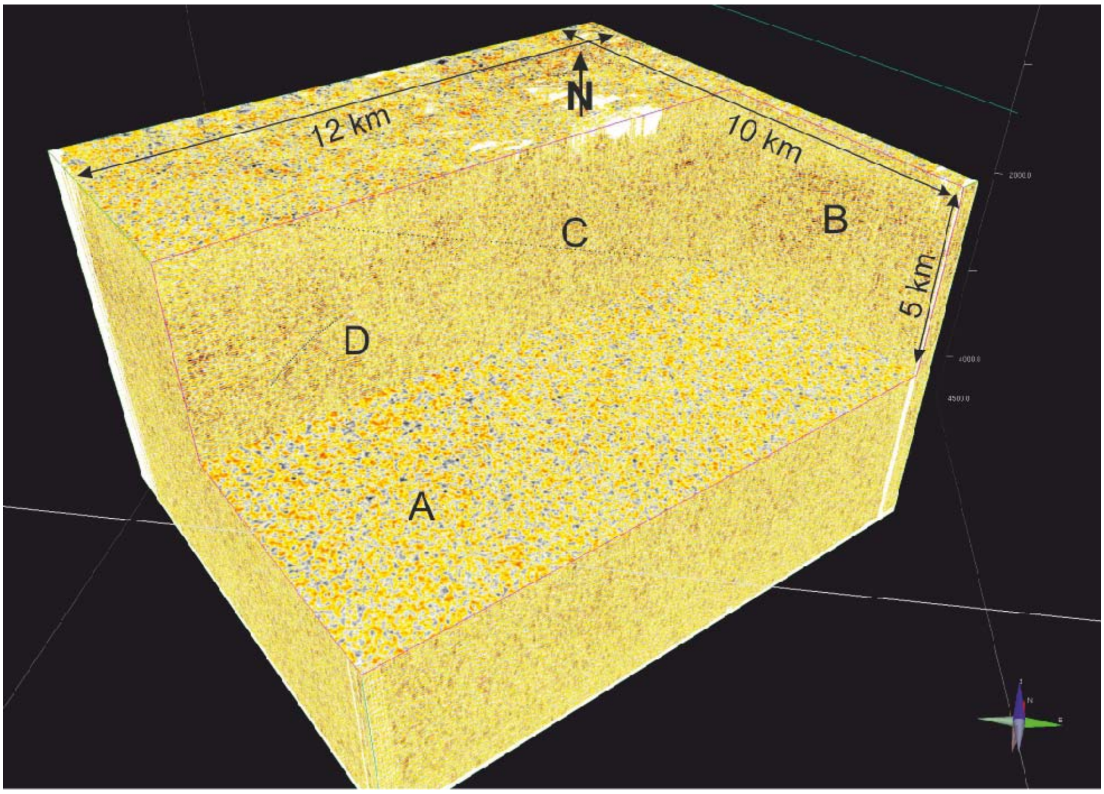

Figure 3: **Seismic Cube, Coherency filtering of the stack showing most obvious features of the subsurface within the granitic environment. A: Area of strong diffractions, B. Metamorphic piles covering the granitic body in the eastern part, C: indications of the master fault, D. Faults, showing strong reflectivity.**

The main condition was that the measurements had to be on streets and tracks. This is a common requirement for source lines but in this case it was also valid for the receiver lines. As a result, the offset distribution of the traces is partly irregular. In the north-eastern part of the survey, a large forest area had to be avoided. This was partly compensated by the enlargement of the survey area in north-eastward direction. Hundred short refraction lines were acquired for static corrections.

Static corrections were calculated by the analysis of the first breaks of the production shots. Data enhancement was performed by trace equalization, deconvolution, frequency-filtering and air wave attenuation. Velocity analysis was hindered by clustering of trace offsets. Tests were made by choosing locations with a continuous offset distribution. For the calculation of velocity time semblance analysis, azimuth dependent CDP gathers were summed into supergathers. The number of CDPs varied between 30 and 80. The semblance analysis and constant velocity stacks showed a wide spread of stacking velocities as a result of large reflector dips. The reflectivity of the stack was enhanced by a coherency filter.

3. CONCLUSIONS

The stack shows a varying reflectivity (fig. 3). Within the western part of the survey at a depth of approximately 4.5 km, strong reflections are visible, which may be caused by single diffractions, which are spread over a limited area (fig 3A). In the eastern part, strong reflections of the metamorphic piles are imaged (fig 3B). There are some hints of faulting along line C, which show the hypothetical path of the master fault. In contrast, the conjugate faults which dip in southwest direction are very well imaged (fig. 3D), not only in the northeast direction of fault C but also within the hanging block.

Migration results show a concentration of the reflection energy and a more correct imaging of the dipping events. Other methods will be tested to improve the imaging of faults (DMO, CRS, Reflection-Tomography). The actual results show many features within the granitic body, which go beyond the results of the preliminary study: complex fault systems and a high reflectivity area show that 3D seismic will be an important method for the exploration of geothermal reservoirs within crystalline basements.

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