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Seismic Exploration of Deep Hydrogeothermal Reservoirs in Germany

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ABSTRACT

Hydrogeothermal reservoirs that can be used for heating or electrical power generation are generally deeply seated in Germany, causing high drilling costs. Thus, it is essential for geothermal ventures to mitigate the exploration risk, which largely depends upon the flow rate encountered in a well. A geophysical method that images even small scale geological heterogeneities, is reflection seismic. Although proven for a long period in the hydrocarbon and mineral industry, its application to geothermal exploration poses new questions, which can only be answered if at least a regional reservoir model is established. The North German Basin, the Upper Rhine Graben and the German Molasse Basin constitute the most prospective areas in Germany.

By means of an example from the German Molasse Basin, the value of reflection seismic techniques like seismic facies analysis, seismic stratigraphy, structural interpretation, seismic inversion, and attribute analysis is shown to derive information about a reservoir model. The benefits of 3D data is discussed: In the case of 2D seismic surveys the geologic features have to be inter- or extrapolated, the results being more ambiguous than mapping 3D seismic surveys. Facies distribution mapping may not be possible at all with 2D data. However, the costs of seismic exploration may contribute significantly to the total costs of a geothermal project.

1. INTRODUCTION

Geothermal energy offers a large potential for power generation as well as for heat supply in Germany (Paschen et al. 2003). Geothermal utilization can be divided depending on the kind of reservoir system: (a) shallow geothermics (max. 25°C, < ~400 m depth), (b) hydrogeothermal systems (aquifers, faults) and (c) petrothermal systems (Schulz et al. 2007). Since high enthalpy hydrothermal systems (steam reservoirs) do not exist in Germany, only low enthalpy systems are considered. These systems can be used directly, i.e. without using heat pumps, for heating, if they have temperatures above 60°. The generation of electrical power generally requires temperatures above 100°. Due to the moderate temperature gradients prevailing in Germany, high temperatures are reached only at greater depth. On average, the 100° C isotherm is found at a depth level of about 3000 m (Jung 2007).

Nevertheless, a lot of projects have been initiated since about 2005 to use hydrogeothermal reservoirs, most of them in southern Germany. About 180 licences for exploration and use of geothermal energy have been granted so far. An actual overview about these projects is provided by www.geotis.de. A further stimulation is expected due to the last revision of the German Renewable Energy Act in 2009, which further increases the refund for geothermal power.

Since hydrogeothermal reservoirs are found in Germany typically at depths of 2500 - 4500 m, expensive deep boreholes are required. Drilling costs are responsible for roughly 70% of the average project costs (Stober et al., 2007). Due to the small number of wells (typically 2) and the lower profitability of geothermal ventures compared to hydrocarbon projects, wildcat drilling for formation tests is not suitable. It is essential to mitigate the exploration risk as much as possible.

The success of a geothermal well can be defined by the power that can be extracted from it. The power is proportional to temperature and flow rate of the extracted fluid. Whilst the spatial variability of the temperature field varies relatively little and is comparably well known, the variation of the flow rate is much more critical: it often depends on small scale (i.e. 50 – 1000 m) geologic and tectonic heterogeneities like fault systems, facies changes or karstifications.

2. SEISMICS

A geophysical method well suited to image these heterogeneities is reflection seismic, which has a long proven record in hydrocarbon and mineral exploration. Especially the advent of the 3D-technique at the end of the last century resulted in a dramatic risk reduction in the hydrocarbon industry (e.g. Brown 2004). However, the conditions for geothermal projects are different from the ones in the hydrocarbon industry, as stated above. Even a small 3D survey generates costs of several mio. €, which constitutes a significant part of the total project costs. An alternative to a 3D seismic survey is a net of 2D seismic lines, which would bring a cost reduction of about a magnitude. The most cost effective procedure is the reprocessing of existing 2D lines. The sediment basins in Germany, which are prospective for hydrogeothermal resources, are widely covered by 2D seismic lines; partly also with 3D seismic ventures. Up to 2003, about 21000 2D lines and 92 3D surveys were listed in the database of the Geological Survey of Lower Saxony (www.lbeg.niedersachsen.de).

Whereas in the beginning of geothermal exploration mostly reprocessing was carried out, in the years 2003 – 2008 some 25 projects came with newly measured 2D lines and three projects realized 3D seismic surveys. Comparing this with the number of 180 granted licences today provides a hint to the challenge of geothermal exploration. Questions arising in this context are e.g.:

Is it necessary to conduct a 3D seismic survey or are 2D lines sufficient for reservoir characterization? Which resolution is adequate for the geothermal reservoir? Do there exist special processing or interpretation methods that delineate a geothermal reservoir in respect to facies, lithology or fault zones?

It is apparent, that these questions cannot be answered universally, but only in connection with a regional reservoir model. Within a research project, funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the Leibniz Institute for Applied Geophysics (LIAG) is dealing with these questions.

3. PROSPECTIVE AREAS IN GERMANY

In Germany three regions are especially prospective for hydrothermal energy: the North German Basin, the German Molasse Basin and the Upper Rhine Graben (Figure 1, Schulz et al. 2007).

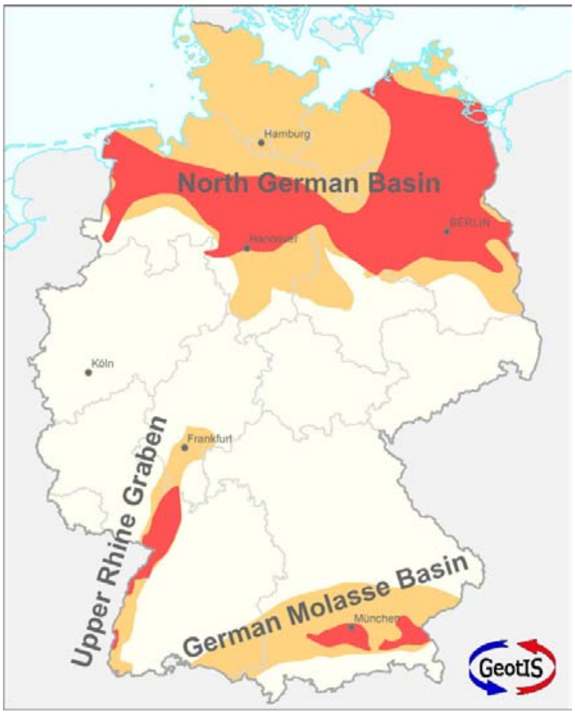

Figure 1: Provinces suited for hydrogeothermal use in Germany. Orange (red) colour marks regions, where deep aquifers reach temperatures above 60° C (100 °C)

The North German Basin consists of sedimentary layers from the upper Palaeozoic up to the Quaternary (Figure 2). Potential reservoir rocks were deposited during early Mesozoic times, Buntsandstein (early Triassic) and Muschelkalk (middle triassic), and are composed of clastic and carbonate rocks. The base of the Buntsandstein reaches a depth of 4000 m and locally up to 10000 m (Baldschuhn, 2001). The main characteristic of the basin is the overall distribution of salt accumulations. The spatial arrangement of salt domes and pillows follows a set of different tectonic lineaments. Faults, providing zones of enhanced permeability, are related either to tectonic lineaments or to salt movement. The shale content of the sediments differs on a regional scale and has to be mapped by use of log and well data.

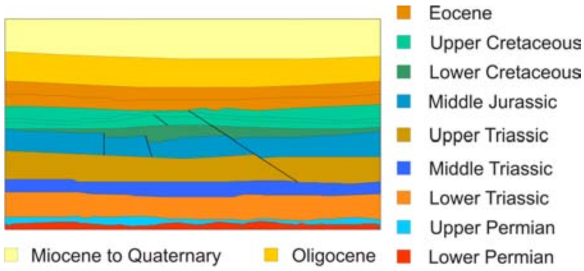

Figure 2: Geologic sketch of the sedimentary setting in the North German Basin

The Upper Rhine Graben formed during the Tertiary (Figure 3). Like in the North German Basin, early Mesozoic sediments of Buntsandstein and Muschelkalk form the hydrogeothermal reservoir rocks. They were lowered within local basins up to a depth of 3500 m. The borders of such basins are strongly faulted and may define areas of enhanced hydraulic conductivity. The area shows a higher geothermal gradient than on average in Germany as a result of the tectonic spreading in a short time span on a geologic scale (Walter, 2007).

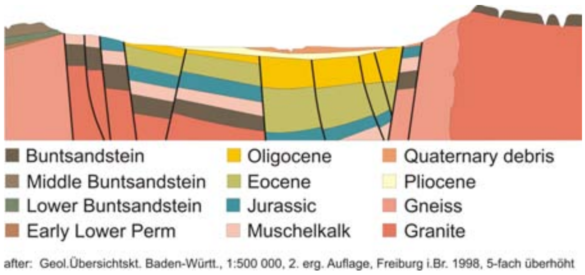

Figure 3: Geologic sketch of a section through the Upper Rhine Graben

The German Molasse Basin was formed during the Alpine orogeny (Freudenberger, 1996). Above the basement, carbonates were deposited during Jurassic (Figure 4). These layers nowadays dip towards the alpine border and reach depths below 3500 m. The carbonates have different formation history, which is important for the reservoir quality. Bedded limestone is assumed to provide lower permeability than recifal limestone, reefs, and reef debris. During Cretaceous and Tertiary times the carbonate layers were altered by karst formation, which raises the hydraulic conductivity by a large degree. Also, tectonic lineaments are areas with increased permeability.

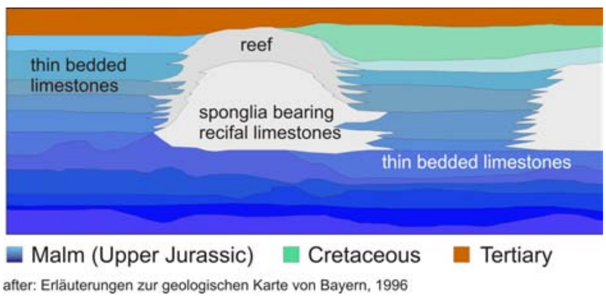

Figure 4: Geologic sketch of the Upper Jurassic within the German Molasse Basin, showing different types of carbonatic rocks

4. SEISMIC INTERPRETATION TECHNIQUES

Reflection seismic interpretation techniques and issues are discussed in the following by means of the exploration of geothermal resources in the German Molasse Basin.

4.1 Seismic Facies and Stratigraphy

The pattern of the seismic signals is an image of the sedimentary and structural processes within the subsurface and is called seismic facies. Within the cutout of a seismic section displayed in Figure 5 one can recognize sub-parallel and continuous reflections.

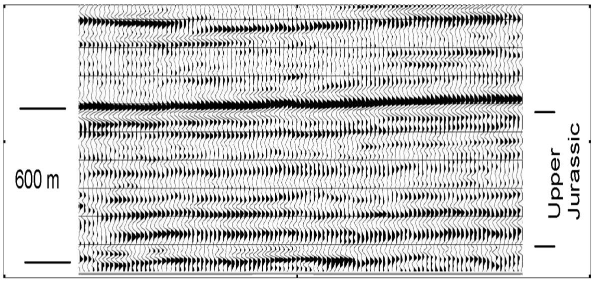

Figure 5: Seismic section of the Upper Jurassic within the German Molasse Basin showing a typical seismic expression of bedded limestone of the Upper Jurassic

These are caused by fine-grained carbonate layers, i.e. limestones, which were deposited uniformly during changing sea levels. By compaction the porosity of such rocks is strongly decreased. Another part of the seismic line shows short reflection patches with alternating dips in the Upper Jurassic (Figure 6). They are interpreted to be caused by recifal limestone, where reefs were formed by sponges. They formed buildups between smaller basins of bedded limestone. The porosity of these structures may not be very high, but on top of the sponglia bearing reefs, coral reefs were formed. The later can build up structures surrounded by reef debris and these areas retain high porosities. Because of their internal structure, coral reefs show a chaotic reflection pattern.

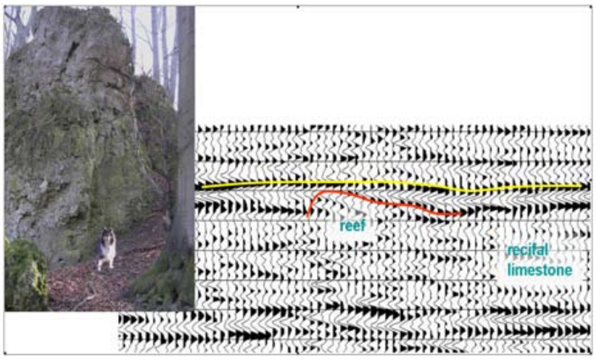

Figure 6: Seismic section showing recifal limestone and probably a reef buried during late Jurassic. An analogue example is shown on the left by a Zechstein reef, which forms an escarpment within in foreland of the Hercynian mountains in northern Germany

The sequence of erosion and deposition is also imaged by seismic patterns. The truncation of reflecting horizons reveals the surface of the former landscape formed by erosion. Diverging reflecting horizons indicate the filling of depressions and basins by deposition of sediments either submarine or sub aerial. During Cretaceous and early Tertiary a landscape was formed by partial erosion of the Jurassic carbonate rocks and the building of karst formations near the surface. Single buildups of harder material found within reefs rose above plains, which were divided by horst and graben structures. The transgression during Tertiary covered those structures. The sequence of those processes is deciphered with seismic stratigraphy by relating reflecting horizons to each other.

4.2 Seismic Inversion

The seismic signal is formed by reflecting the seismic wave at impedance boundaries, i.e. where the wave velocity and rock density change. Both parameters are functions of lithology and porosity of the layers. Velocity and density of rocks are normally proportional to each other. The velocity field can be calculated from the seismic signals, which is meant by the expression: seismic inversion (Veeken and Da Silva, 2004). The image after the inversion shows the seismic velocity distribution within the subsurface (Fig. 7). The seismic section becomes more readable: single layers are better recognized. The velocity contrast shows different lithological units. Carbonate rocks have a higher seismic velocity than clastic sediments. Within and near the top of the carbonates the structure of the layer can be interpreted in more detail.

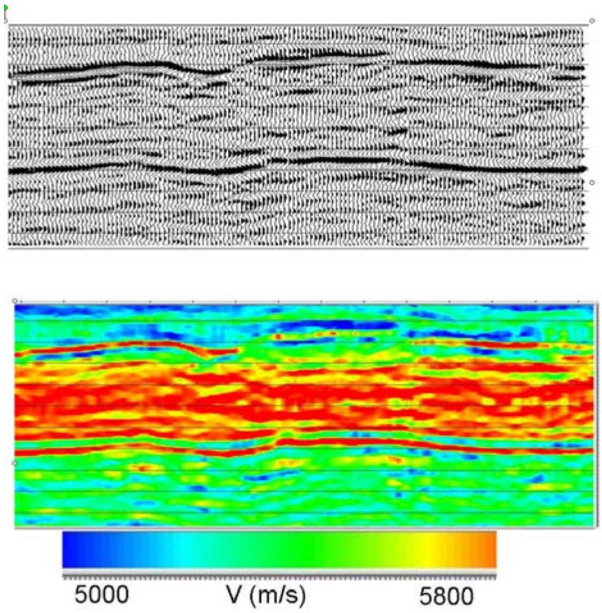

Figure 7: The lower picture shows the velocity inversion of the seismic cross section above

4.3 Shortcomings of 2D Seismic Imaging

A 2D seismic section ideally is an image plane perpendicular to the surface where the seismic sources and receivers had been arranged at a more or less straight line. In this case all energy which is reflected back to the seismic receivers has its reflection point within this plane; only objects within this perpendicular plane appear in the section (Sheriff and Geldart, 1995).

In reality geological objects or bodies, like faults, folds, or anticlinal structures may be located aside the seismic line. This results in reflecting seismic waves from these surfaces to the seismic image plain. The structures which seem to be located beneath the seismic line are called sideswipes (Figure 8). If the objects strike in an acute angle to the seismic line, depth and dip of the objects determined from the seismic section can incorporate severe errors (Tucker and Howard 1985).

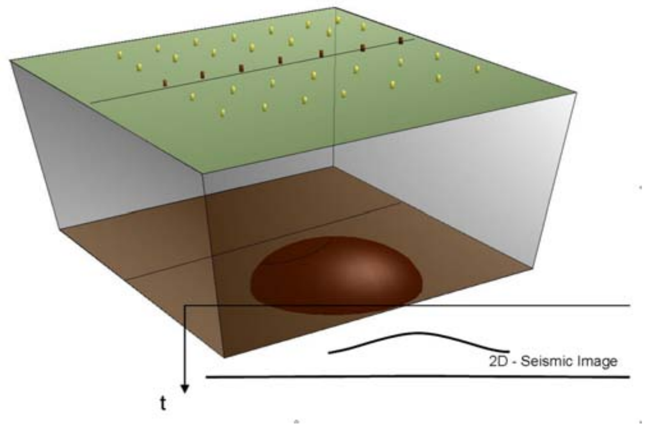

Figure 8: The origin of a sideswipe caused by an anticlinal which spreads energy back to the seismic receivers. The seismic section images this structure, although it does not traverse it

4.4 Structural Interpretation using 2D and 3D Seismics

Within a 3D seismic survey stratigraphic horizons can be mapped. This is shown here for the top Upper Jurassic, which is the main aquifer for hydrogeothermal use within the German Molasse Basin. This map (Figure 9) reveals the overall structure of the target horizon. Several south-west – north-east and east-west lineaments can be identified. These could be potential areas for enhanced hydraulic conductivity. However, this has to be tested during drilling. Further investigations, like the time of faulting and the morphology of the Upper Jurassic to Lower Tertiary landscape, which are also important for building a reservoir model, will not be considered here for simplicity.

The shortcoming of an interpretation from 2D seismic lines is illustrated in Figure 9. Dashed lines indicate hypothetical 2D seismic lines within the 3D seismic survey. If structural trends are known, the lines can be placed perpendicular to these structures. By doing so, image problems, mentioned in the foregoing chapter, can be reduced. The faults can be interpolated between the seismic lines to gain an areal distribution of the faults. An isobaths map of the target horizon can also be drawn. However, the assignment of the fault cuts in practice remains equivocal and the overall tectonic structure will be more ambiguous.

4.5 Attribute Mapping.

The seismic measurements primarily consist of the amplitude of the signals. Therefore, the interpretation makes use of amplitudes to map stratigraphy and faults. As shown above (Figure 7), geologic layers show a typical amplitude pattern. It can be translated into single values, so called attributes, by mathematical algorithms (Chopra and Marfurth 2007). As an example, the root mean square amplitude of each seismic trace interval within the Upper Jurassic is shown in figure 10.

The result shows a distribution of amplitude values, which represents different facies of the Upper Jurassic rocks. Since banked limestones have higher amplitudes, this map gives a first overview of the facies distribution. This result cannot be reproduced by a 2D seismic survey because of the more irregular amplitude distribution pattern.

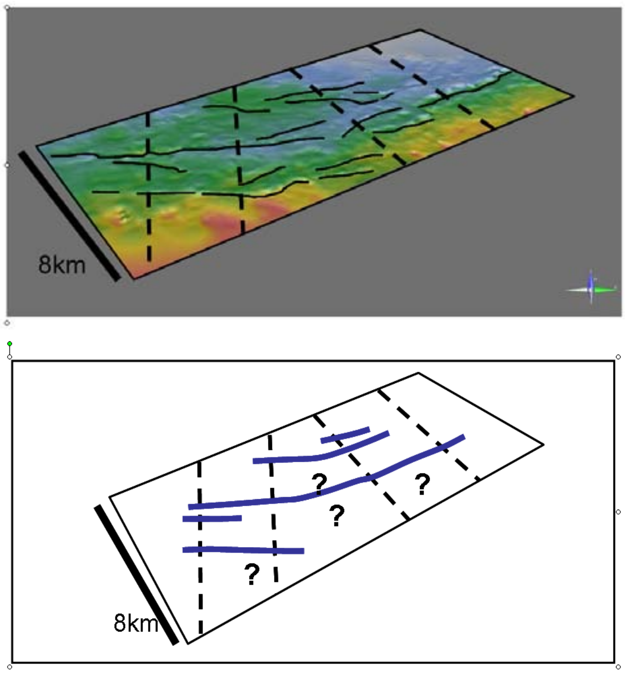

Figure 9: At the top a travel time map of the top Upper Jurassic is shown with interpreted lineaments (thin black lines). Hypothetical 2D lines are drawn as dashed lines. A possible structural interpretation based on 2D seismic lines is shown below. The question marks point to the ambiguity of such interpretations

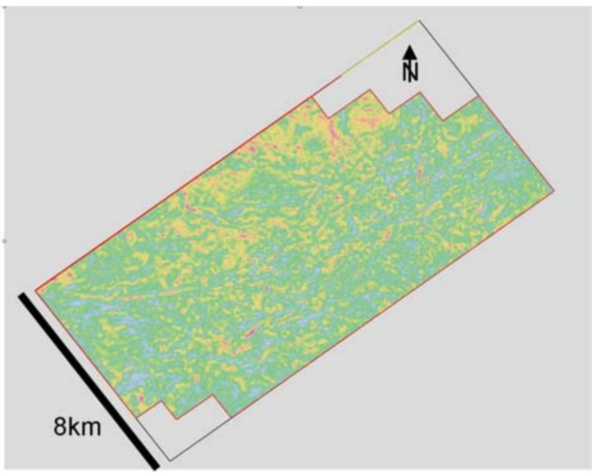

Figure 10: Root mean square amplitude transformation of the Upper Jurassic seismic interval. The different colours help to differentiate the distribution of carbonate facies

CONCLUSION

There is an increasing demand for seismic exploration of deep hydrogeothermal reservoirs in Germany. It is not yet clear, which techniques regarding acquisition, processing and interpretation of seismic data are most appropriate for geothermal projects. Due to the geological variability in Germany, the answer can only be given site-dependently.

The costs of seismic exploration contribute significantly to the exploration risk of geothermal projects. The probability of success depends on the quality and amount of information from seismic measurements. In a first step a regional reservoir model has to be defined which incorporates main exploration targets, like faults and rock facies. This information can be locally derived by using interpretation techniques like seismic facies analysis, seismic stratigraphy, structural interpretation, seismic inversion, and attribute analysis. These techniques can be used on 2D and 3D seismic surveys. In the case of 2D seismic surveys the results have to be inter- and extrapolated within an area. This interpretation is more ambiguous than mapping 3D seismic surveys. Facies distribution mapping may not be possible at all with 2D data.

A main advantage of 3D seismic data is to analyse geologic objects in three dimensions in contrast to a 2D cross section where these objects have to be constructed by geometrical assumptions. The ability to compare structures within an area led to the definition of typical geological objects which represent geologic processes. The better geologic processes can be derived from seismic data, the higher the probability of success.

ACKNOWLEDGEMENTS

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