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# Enhancing Hydrogeothermal Reservoir Detection by Seismic Imaging and Attributes

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## ABSTRACT

In Germany, low enthalpy reservoirs are used for hydrogeothermal energy production. They are located at depths of 3 - 5 km and have average temperatures of 100 – 150 °C. At many sites natural permeability of the rocks is not sufficient for economic operation. Therefore, the value of reservoirs is often bound to small scale geologic features as e.g. fracture systems, karstified limestone or locally varying facies. The most appropriate geophysical method revealing these features is reflection seismic.

The Leibniz Institute for Applied Geophysics (LIAG) investigates the relevance of 3D seismic methods for the exploration risk mitigation of hydrogeothermal reservoirs. Modern reflection seismic techniques are applied to characterize these reservoirs. Attribute analysis highlights faults and collapse structures that are hardly seen otherwise, common reflection surface stacks allow a more reliable determination of faults, and supplementary high resolution-profiling helps to reconstruct the kinematics of fault systems and their periods of activity.

## 1. INTRODUCTION

The moderate temperature gradients of roughly 30 °C/km in Germany imply that hydrogeothermal reservoirs will be at great depth, if they are indented to be used for direct heat extraction or electrical power generation. In the later case temperatures of more than 100 °C are needed, which results in a minimum depth of about 3 km.

Adequate hydrogeothermal reservoirs can be found in Germany in different sediment basins, the most important of them are (1) the North German Basin, (2) the Upper Rhine Graben and (3) the German Molasse Basin (Figure 1). Depending on the geological setting, natural permeability of the formations is often not sufficient for economic operation. Therefore, the value of reservoirs is in many cases bound to special geologic features as e.g. fracture systems, karstified limestone or locally varying facies.

Since drilling is by far the largest cost factor in the development of a hydrogeothermal venture, the mitigation of the exploration risk is a crucial point. This is generally achieved by geophysical methods. In Germany, the reflection seismic method is favoured, whereas magneto-telluric and electrical methods suffer from low resistivity contrasts and high salinity values often found in sedimentary environments at greater depth, e.g. in the North German Basin and the Upper Rhine Graben.

In this context the Leibniz Institute for Applied Geophysics (LIAG) currently investigates the relevance of 3D seismic methods for the exploration risk mitigation of hydrogeothermal reservoirs. Often, engineers of geothermal ventures pose the question, whether a reservoir could be explored fairly enough but more cost efficiently with existing or new 2D seismic lines. Within the current study, an additional cost reduction by e.g. lowering of fold and application of special processing and interpretation methods is being investigated. Seismic attributes are tested with respect to their applicability to hydrogeothermal reservoir exploration.

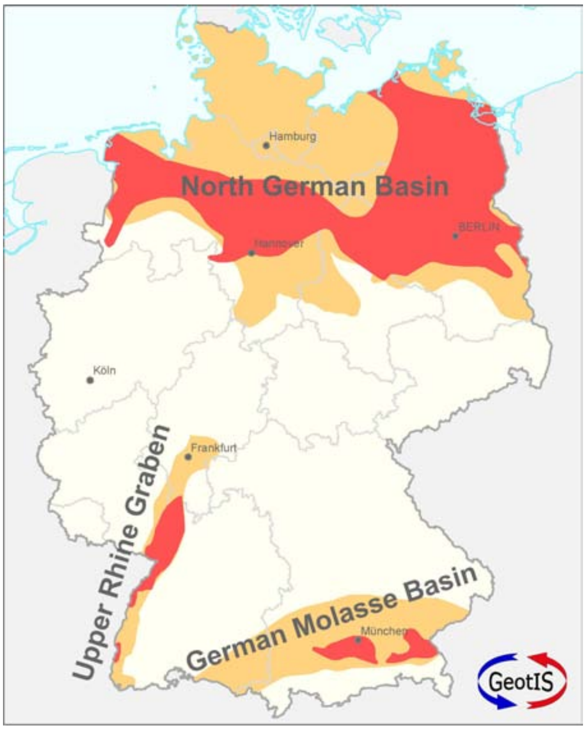


**Figure 1: In Germany, three regions are especially suited for hydrogeothermal energy extraction: The North German Basin, the German Molasse Basin and the Upper Rhine Graben. Areas with aquifers suitable for hydrogeothermal use offering temperatures above 60 °C are marked in ochre, above 100 °C in red. The map is derived from the Geothermal Information System for Germany (www.geotis.de, Schulz et al. 2007)**

We will present three aspects of the work done within the project: (1) seismic attributes characterize the Malm of the South German Molasse Basin, (2) the common reflection surface method images faults systems in the Upper Rhine Graben and (3) a very detailed picture of a fault system that was achieved by near surface high resolution profiling, giving temporal constraints to the periods of its activity.

## 2. ATTRIBUTE ANALYSIS IN THE SOUTHERN GERMAN MOLASSE

The data set for this study was recorded in the 1980's for hydrocarbon exploration. Having a bin size of 25 m x 25 m, the area of about 100 $km^2$ has a nominal fold of 12. Four vibrators served as energy source.

### 2.1 Geology

The Southern German Molasse Basin is located north of the Alps and was formed during the alpine orogeny as a foreland basin (Freudenberger et al. 1996). The basement of the Mesozoic sedimentary layer is built up by crystalline rocks. During the middle Jurassic deep clastic sediments were deposited. Within the Upper Jurassic a carbonate platform was formed, which shows an alteration of reefs, recifal limestone and layered limestone. The Lower Cretaceous consists of carbonates and clastic sediments which were deposited during a regression. Sediments are found in local basins. Most of the area was sub-aerially exposed, resulting in the formation of karst by dissolving the carbonate rocks. This process can be examined north of the Molasse Basin at the outcrops of the Upper Jurassic within the Fraenkische and Schwaebische Alb. Different carbonate sediments can be examined there as well. The subsurface was divided by several minor faults which results in a horst and graben structure during Cretaceous.

During Tertiary, the shelf was flexed downwards by the load of the Alpine Orogeny. Marine and paralic sediments were deposited. The southernmost parts of the basin were folded and thrust by alpine nappes. Jurassic layers dip southwards into the basin. During the Quaternary the Molasse Basin has been filled with debris from the Alps. Also a slight regional uplift of the basin can be recognized.

### 2.2 Seismic Interpretation

The top Upper Jurassic is characterized by two distinct amplitude maxima with a distinct minimum in between (Figure 2). This reflection pattern is typical for all of the investigated area. It is modulated by the strength of the amplitudes and the spacing between them. The seismic reflection pattern within the rest of the upper Jurassic layer differs in lateral correlation, reflection strength and dip.

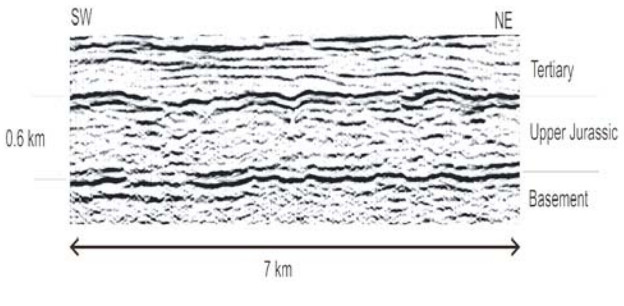


**Figure 2: Section of a 3D seismic survey within the Southern German Molasse Basin. The location of the section is indicated in figure 3 with a red line. The white cross marks a local depression of the top Upper Jurassic and is also shown in figure 3**

The seismic pattern at the Jurassic – Tertiary transition represents sedimentary, diagenetic and tectonic processes which are important for hydrogeothermal reservoir description. Tertiary and Cretaceous sediments were deposited according to the Upper Jurassic morphology. Reefs were covered by sediments, showing lateral pinch outs. Also, amplitude will change above these structures according to the varying velocity contrast. At the top Jurassic local depressions can be found, one is marked in figure 2 with a cross.

A combined map of amplitude and travel times (Figure 3) shows the structural style of the survey area. Two structural trends, termed A and B, can be recognized. B is a broad fault zone southeast of a major fault. The east-west trend A is represented by two distinct faults in the western part of the area. Circular amplitude and travel time anomalies indicate collapse structures, marked with a cross (Figures 2 and 3). These structures line up along the southwest to north-east striking fault zone.

The distribution of different carbonate facies can be visualized by an amplitude surface within the variance cube (Chopra et al. 2006) of the Upper Jurassic (Figure 4). Bedded limestone is distributed in circular patches with high variance values: A. This pattern changes during the sedimentation process, i.e. along the times axis. The variance is also affected by faulting, which can be seen at a smaller area with high variance values where two fault lineaments intersect: B.

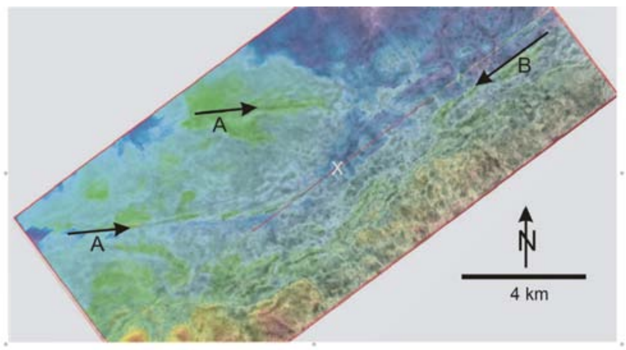


**Figure 3: Combined amplitude and travel time map of the top Upper Jurassic. Colours indicate travel times, grayscale indicates amplitudes. The location of the seismic line shown in figure 2 is marked with a red line**

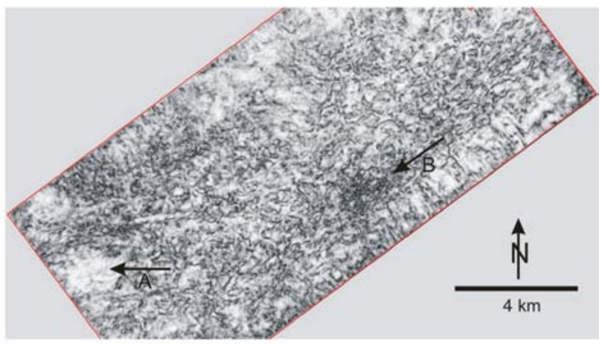


**Figure 4: Variance amplitude of a surface within the Upper Jurassic. High variance values are shown in dark shading, smaller values in light shading**

The attribute analysis hints to locations suitable for hydro-geothermal use. In our case, these are located along broad fracture zones and karstified units showing collapse structures. On the other hand, areas with patches of bedded limestone should be avoided.

## 3. CRS-PROCESSING IN THE UPPER RHINE GRABEN

This study is based upon a 3D seismic data set recorded in 2006 especially for a geothermal project. It covers 18 $km^2$ with a bin size of 25 m x 25 m and a strongly varying, average fold of 40. Three vibrators generated a non-linear sweep of 10 – 80 Hz. Receiver and shot distance was 50 m, and receiver and shot line distance was 500 m.

### 3.1 Geology

The Upper Rhine Graben (URG) forms the central part of the European Cenozoic rift system. It is located between the Jura Mountains to the south and the Rhenish Massif to the north. The strike of the approximately 300 km long and 30 km – 40 km wide graben is NNE-SSW (Ziegler 1992).

The URG is considered a passive rift system in the foreland of the Alps. It was governed by stress-induced lithospheric extension and accompanied by volcanic phases (Ziegler 1992). Up to four evolutionary phases are being investigated (Schumacher 2002). The rifting process started in late Eocene with strike-slip movement along inherited Palaeozoic fault systems. This led to the formation of separate sub-basins. The main rifting phase occurred in early Oligocene accompanied by regional normal faulting. Right-lateral strike-slip reactivated in the central graben segment in late Oligocene as a releasing bend. From Miocene until present a left-lateral strike-slip regime has overprinted the Palaeogene rift. The central graben now forms a restraining bend and young pull-apart basins have opened in the northern and southern graben segments.

The seismic survey partly maps the Kehler Mulde, a small basin east of Strasbourg. The Triassic Muschelkalk and Buntsandstein, i.e. the potential geothermal reservoirs, are expected at a depth of 2700 – 3000 m. Fault segments transect the deep aquifers and hence influence the local permeability. Temperatures around 120 °C are forecast here.

### 3.2 Seismic Processing

A standard NMO/DMO processing with a subsequent FD Migration was carried out first. Parallel, a common reflection surface (CRS) stack process was run. The CRS method (Hubral et al. 1999, Jäger et al. 2001) is generally used to obtain a better image of complex subsurface structures. Resolution and signal-to-noise ratio are increased especially for reflector elements with strong curvatures. The CRS method was applied successfully to sparse 3D acquisition due to its enhanced fold and resolution (Gierse et al. 2007). Eisenberg-Klein et al. (2008) presented some differences and advantages of the CRS method as opposed to NMO/DMO processing and its implication for tomographic velocity building and seismic depth imaging.

The NMO/DMO-stacked data shows strong reflections in the Tertiary and Jurassic sediments and a low reflectivity in the target region (Figure 5). The application of the CRS method with a relatively small aperture of only 55 m increased the fold and improved the data quality. Continuous reflector elements mark the geothermal reservoir and the margins of the basin. The displacement of the tectonic blocks is more clearly seen.

After FD time migration, the small tectonic blocks of the Kehler Mulde can easily be recognised (Figure 6). The basement rises stepwise to the left along blind faults. On the NMO/DMO processed migration, a prominent fault is imaged in the Jurassic sediments above the reservoir. Its prolongation into the basement can be assumed on the NMO/DMO-processed migration but is more clearly mapped by the CRS processed migration. Especially in tectonic block settings, the seismic energy can be trapped in blocks. The CRS-processed migration successfully improved the seismic image of the tectonic blocks and hence the geothermal reservoir.

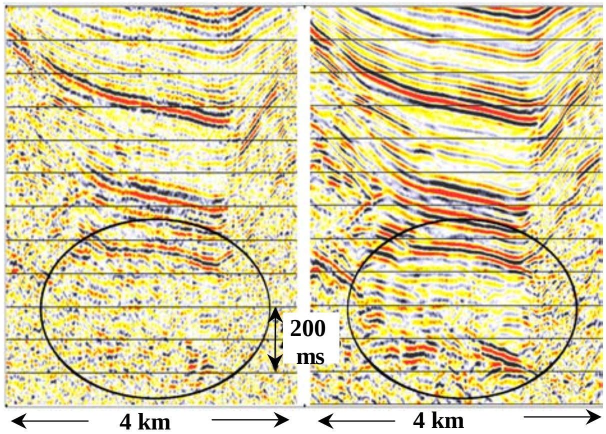


**Figure 5: Stacked section after standard NMO/DMO processing (left) and CRS processing (right).The ellipse marks the region of the expected geothermal reservoir. The vertical extent of the section is about 3 km**

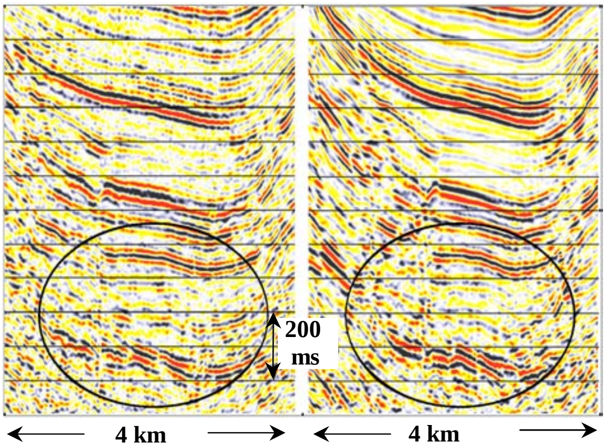


**Figure 6: FD migrated section after NMO/DMO standard processing (left) and CRS processing (right).The ellipse marks the region of the expected geothermal reservoir. The vertical extent of the section is about 3 km**

## 4. NEAR SURFACE HIGH RESOLUTION SEISMICS

In addition to the 3D seismic survey described in the last chapter, high resolution 2D seismic profiles were laid out perpendicular to the bordering master faults of the Kehler Mulde. Each of the two profiles is about 1.8 km long, with a geophone spacing of 2 m. A small vibrator, developed by LIAG (Buness and Wiederhold 1999), emitted a sweep of 30 – 240 Hz every 4 m.

One of the profiles crosses the eastern main border fault of the Kehler Mulde (Figure 7). Down to a depth of 200 m the migrated seismic section depicts Tertiary and Quaternary units in high resolution. High reflectivity accompanied by a moderate continuity of the reflectors represents the fluviatile origin of the sediments. A distinct reflector at a depth of 200 m resembles the Quaternary/Tertiary transition. Below, the reflectors are much more continuous, however, with strongly varying amplitudes. Two boreholes near to the profile enable a confident interpretation.

At the right part of the section the eastern main border fault system of the Kehler Mulde can be recognized clearly. It dips with roughly 65° to the west and has an extent of about 200 m. The single fault planes are approximately parallel to each other. Faulting clearly cuts the Pliocene Basis, and can be followed less distinctly inside the Pliocene up to base Quaternary. Whether the fault system was still active during Pliocene or the deformation of Pliocene is due to differential post-tectonic compaction is still a matter of discussion. The Pliocene sediments overlie dipping Oligocene sediments west of the fault zone, whereas east of it they rest on flat lying Jurassic units.

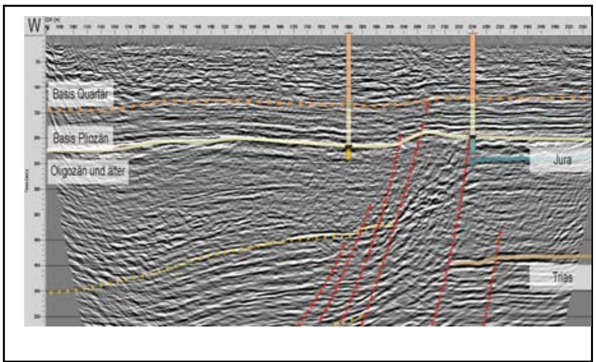


**Figure 7: Migrated section crossing the eastern main boundary fault of the Kehler Mulde. Profile length is 1.8 km, total depth is 570 m. Depth conversion was done with a constant velocity of 2000 m/s, causing that time in ms equals depth in m. Fault planes are marked by dashed red lines**

A typical 3D data set does not give information about the shallower part, which is illuminated by high-resolution 2D seismics as shown in figure 7. Reliable Information from the 3D data set analysed in this example can be deduced from 400 m downwards only. Therefore 2D data constitute a valuable supplement to 3D data. Moreover, due to the spatial density of stations and source points and the much higher frequency content of the near surface data, faults that cannot even be seen on 3D data can be detected. Fault kinematics and the chronology of tectonic movements can better be inferred than with 3D data alone.

## CONCLUSION

Modern reflection seismic techniques can contribute significantly to the detection of small scale geologic or tectonic heterogeneities, which are often a prerequisite for an economic exploitation of deep hydrogeothermal reservoirs in Germany. Attribute analysis, applied to carbonate units of the Upper Jurassic in the German Molasse Basin highlights faults and collapse structures that are difficult to see otherwise. Common reflection surface stacks allow a more reliable determination of faults in the Middle and Lower Triassic of the Upper Rhine Graben. Supplementary high resolution profiling helps to reconstruct the kinematics of fault systems and their temporal constraints.

These techniques add value to the seismic data, and they will influence the question, what kind of data is most cost effective for the exploration of deep hydrogeothermal reservoirs. The task for finding an adapted exploration strategy in this field is relatively new, and it will require more effort in the future.

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