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Exploration Risk Reduction for Hydrogeothermal Projects by use of 3D Seismic Surveys

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SUMMARY/ABSTRACT

The chance of success of exploration projects depend on the construction of a reservoir model. Seismic methods are the best choice to map the structural style and sedimentary process of the subsurface. A 3D seismic survey provides a dense raster of information. Interpretation is less ambiguous than a fence of 2D seismic sections. Geologic features become more obvious which might led to very detailed geologic maps. Considering the higher costs of 3D seismic surveys the decision about the exploratios method is linked to the adequate mapping of the preferred reservoir model. In Germany there are three different geologic provinces for deep hydrogeothermal use. One of it comprising a carbonate reservoir model is presented as an example to show interpretation techniques: seismic facies analysis, seismic stratigraphy, and attribute analysis and to compare results of 2D and 3D seismic interpretation.

INTRODUCTION

Deep hydrothermal reservoirs are formed by rocks having a moderate to high permeability and were restricted to depths were the geothermal gradient guarantee a temperature of a minimum of 60° C. In this case the water can be used for heating. Higher temperatures can be used for electric power generation. Normally these temperatures above 100° C are found in sedimentary layers in Germany below a depth of approximately 3500 m. Therefore exploitation of hydrogeothermal reservoirs requires expensive deep wells. Wildcat drilling for formation tests is not suitable because of lower profitability of geothermal ventures comparing with hydrocarbon projects. In this way the exploration by seismic means becomes a crucial part of reducing the probability to drill a dry hole, i.e. a small flow rate.

This is the main risk of a geothermal project: the probability of a loss in an amount of drilling and exploration costs. Seismics, as a geophysical method, is able to enhance the probability of success by providing information about a regional reservoir model and the local reservoir. The expected value of a hydrothermal venture depends on the energy or power which one gets out of the reservoir. The power is proportional to the product of temperature and flow rate, where the flow rate is a function of permeability and thickness. Whereas thickness can be measured from seismic images, permeability can only be measured during drill tests. One possibility is to inter- and extrapolate petrophysical values between wells and guide this interpolation by attributes derived from seismic signals. The analysis of geologic structure, tectonic and sedimentary processes can be used to derive a lithologic model of the reservoir which comprises the rock fabric. In this way a spatial distribution of permeability values can be derived. The aim is to construct a geologic model describing the reservoir at the well location.

In the first part a short overview about the hydrogeothermal conditions in Germany is presented. In the second part an introduction about seismic interpretation techniques: seismic facies analysis, seismic stratigraphy, and seismic inversion by an example of a carbonate reservoir, is given. In a third part I explain some differences between 2D and 3D seismic interpretation and show an example of a 3D seismic attribute analysis.

1 Regional Reservoir Models in Germany

1.1 Reservoir Characteristics

A hydrogeothermal reservoir has geologic and petrophysical characteristics, which are advantageous producing water at a high flow rate. Those characteristics are linked to lithologic units and geological structures. For example clastic sediments with low shale content typically show a high porosity and permeability. The hydraulic characteristics of carbonate rock depend on the origin and diagenetic processes within the rocks. Faults are able to transmit fluids between layers. They can be grouped in fault zones or build sharp lineaments. The conductivity of faults depends on the tectonic regime and the lithology adjacent to them. Areas with similar geologic and petropysical characteristics build a regional reservoir model. Normally they can be found in areas with the same geologic history.

Within these areas single fields have to be chosen, where the local reservoir characteristics are suitable for the location of production and injection wells.

1.2 Prospektive Areas in Germany

In Germany, there are two prominent sedimentary basins and one prominent graben: The North German and the Southern German Molasse Basins and the Oberrhein Graben (Fig. 1).

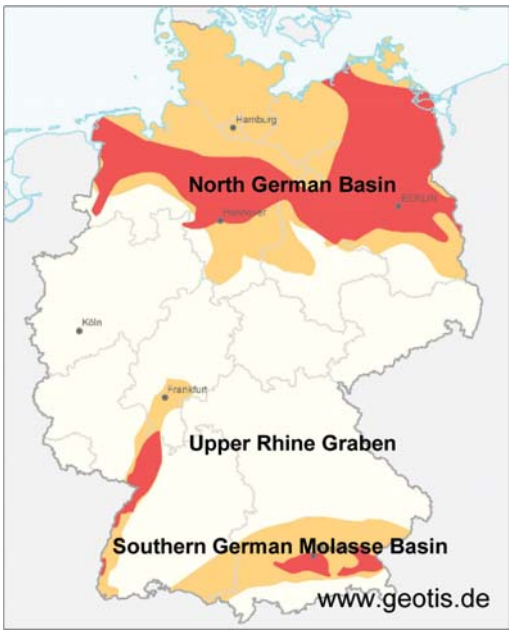


Figure 1. Provinces for hydrogeothermal use in Germany. In orange coloured regions temperatures above 60° C, in red temperature above 100° C can be assumed.

The North German Basin consists of sedimentary layers from the upper Palaeozoic up to the Quaternary. 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 follow a set of different tectonic lineaments. Potential reservoir rocks were deposited during early Mesozoic times, Bundsandstein and Muschelkalk, and are composed of clastic and carbonate rocks. Faults, providing a zone of enhanced permeability, are related either to tectonic lineaments or to the 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.

The Oberrhein Graben was formed during the Tertiary. Like in the North German Basin, early Mesozoic sediments of Bundsandstein and Muschelkalk form the hydrogeothermal reservoir rocks. They had been 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 as a result of the tectonic spreading in a young time span on a geologic scale (Walter, 2007).

The Southern German Molasse Basin was formed during the alpine orogeny (Freudenberger, 1996). Above the basement carbonates were deposited during the Jurassic (Fig.2). These layers nowadays dip towards the alpine border and reach depths below 3500 m. The carbonates have different origins, which is important for the reservoir quality. Bedded limestone is assumed to have lower permeability than recifal limestone, reefs, and reef debris. During Cretaceous and Tertiary times the carbonate layers were altered by carst formation, which raises the hydraulic conductivity by a large extent. Also tectonic lineaments are areas with increased permeability.

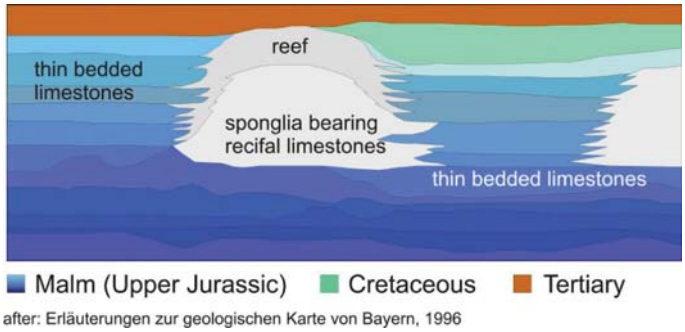


Figure 2. Geologic sketch of the Upper Jurassic within the southern German Molasse Basin, showing different types of carbonatic rocks.

2 Seismic Interpretation Techniques

2.1 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 Upper Jurassic of the cross section, there are areas with sub parallel and continuous reflections (Fig.3).

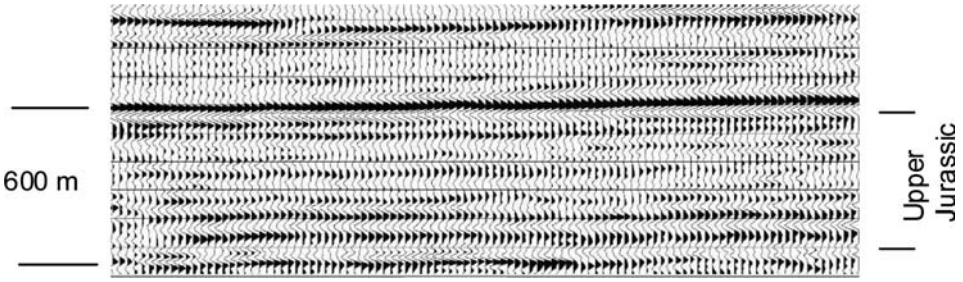


Figure 3. Seismic section showing a typical seismic expression of bedded limestone of the Upper Jurassic within the southern German Molasse Basin

They are caused by fine-grained carbonate layers, i.e. limestone, which was deposited uniformly during changing sea levels. By compaction the porosity of such rocks is strongly decreased. Other areas of the Upper Jurassic show short reflection patches with alternating dips (Fig. 4). These are 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 be not 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 the internal structure coral reefs show a chaotic reflection pattern.

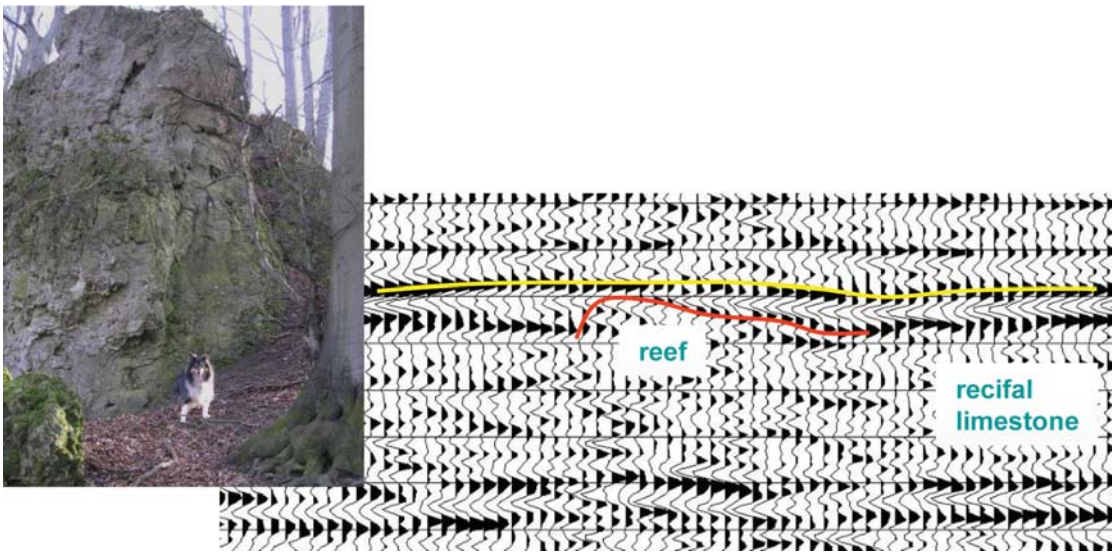


Figure 4. Seismic cross section of the Upper Jurassic within the southern German Molasse Basin, showing recifal limestone and probably a reef buried during late Jurassic sedimentation. An analogue example is shown on the left by a Zechstein reef, which forms an escarpment within in foreland of the Hercynian mountains.

The sequence of erosion and deposition is also imaged by the seismic pattern. The truncation of reflecting horizons reveal the surface of the former landscape formed by erosion. Diverging reflecting horizons indicate the filling of depression and basins by deposition of sediments either submarine or sub aerial. During the Cretaceous and early Tertiary a landscape was formed by partial erosion of the Jurassic carbonate rocks and the building of carst formation 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 the Tertiary covered those structures. The sequence of those processes is deciphered by seismic stratigraphy by relating reflecting horizons to each other.

2.2 Seismic Inversion

The seismic signal is formed by reflecting the seismic sound at impedance boundaries, i.e. where the wave velocity and rock density changes. Both parameters are functions of lithology and porosity of the layers. Velocity and density of rocks are normally proportional to each other. From the seismic signals the velocity field can be calculated, which is meant by the expression: seismic inversion (Veenken 2004). The image after the inversion shows the seismic velocity distribution within the subsurface (Fig. 5). 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 the carbonates the structure of the layer can be interpreted in more detail.

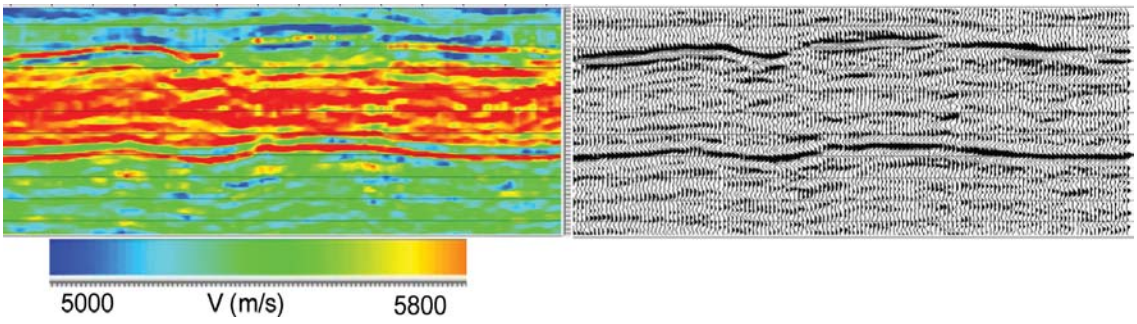


Figure 5. The left picture shows the velocity inversion of the seismic cross section on the right.

3 2D vs 3D Seismics

3.1 Shortcomings of 2D Seismic Imaging

A 2D seismic section 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 the optimal case all energy which is reflected back to the seismic receivers has its reflection point within this plain. In this way all and only those objects within this perpendicular plain can be seen on the cross section (Sheriff, 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 now to be located beneath the seismic line are called sideswipes (Fig. 6). If the objects strike in an acute angle to the seismic line, depth and dip of the objects measured from the seismic section can incorporate severe errors (Tucker 1985).

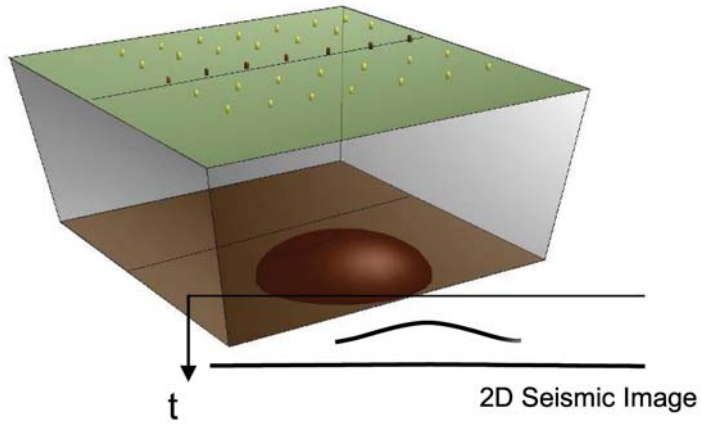


Figure 6. The origin of a sideswipe caused by a anticlinal which spreads energy back to the seismic receivers. The seismic section images this structure, though not pass it.

3.2 Structural Interpretation by use of 2D and 3D Seismics

Within a 3D seismic survey stratigraphic horizons can be mapped. This is done with the top of Upper Jurassic, which is the main aquifer for hydrogeothermal use within the southern German Molasse Basin (Fig. 7). This map reveals the overall structure of the target horizon. One southwest northeast striking and three parallel east west striking lineaments can be identified. These will be potential areas for well sites, whereby the hydraulic conductivity of the faults have to be tested during the 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 of a reservoir model, will not be considered here.

How does the interpretation from 2D seismic may look like? For this question hypothetical lines have been drawn 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 part, can be reduced. The faults can be interpolated between the seismic lines to get an areal distribution of the faults. An isobaths map of the target horizon can also be drawn. In practise the assignment of the fault cuts is ambiguous and the overall tectonic structure will be more hypothetical. The advantage by using 2D lines is, to get a crude overview of the geologic situation and a basis for placing additional seismic lines or the geothermal well. This causes much lower costs than shooting a 3D seismic survey.

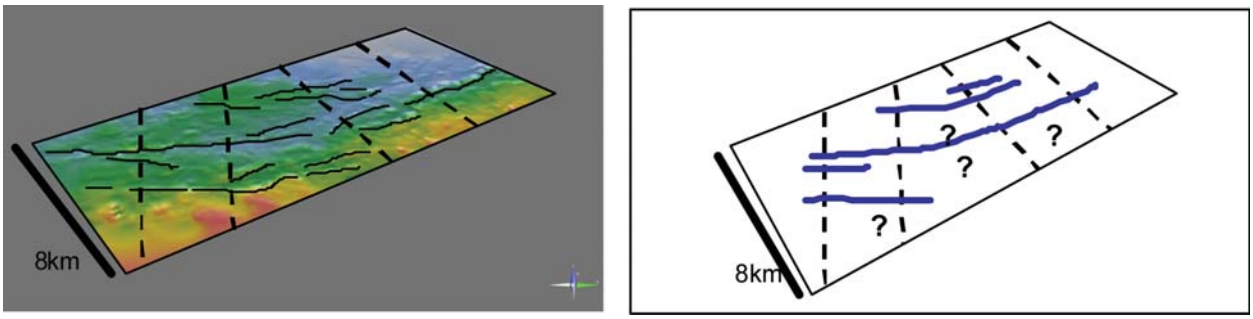


Figure 7. On the left, Travel time map of a stratigraphic horizon with interpreted lineaments. Hypothetical 2D surveys are drawn as stippled lines. A possible structural interpretation based on 2D seismic lines is shown on the right. The question marks point to the ambiguity of such interpretations.

3.3 Attribute Mapping

The seismic measurements primary consists of the amplitudes of the signals. In this way the interpretation make use of these amplitudes to map stratigraphic horizons and faults. As shown in part 2 geologic layers show a typical amplitude pattern. It can be translated into single values, so called attributes, by mathematical algorithms (Chopra, 2007). This is done as an example by calculating root mean square amplitudes of each seismic trace interval within the Upper Jurassic (Fig. 8). The result shows a distribution of amplitude values, which represent different facies of the Upper Jurassic Rocks. Banked limestone has higher rms-amplitudes and this map gives a first overview of the facies distribution. This result is not suitable to be reproduced by a 2D seismic survey because of the more irregular amplitude distribution pattern.

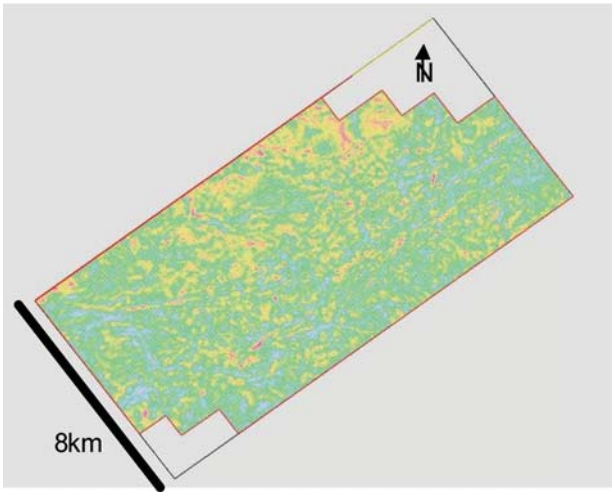


Figure 8. Root mean square amplitude transformation of the Upper Jurassic seismic interval. The different colours help to differentiate the distribution of carbonate facies.

4 Conclusion

The costs of seismic exploration contribute to the exploration risk of hydrogeothermal wells. 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 incorporate 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 view 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 typically geological objects which represent geological processes. The better geological processes can be derived from seismic data, the higher the probability of success.

5 Acknowledgements

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