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Upper Rhine Graben: Seismic Methods as Basic Tool for Geothermal Exploration in Structurally Complex Tectonic Environments

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Geology of the Upper Rhine Graben

The Rhine Graben forms the most prominent segment of the European Cenozoic Rift System which traverses the Earth´s crust of Central and Western Europe with different parallel branches in a general NNE-SSW trend ("Rhenish" direction) for a distance of about 1000 km.

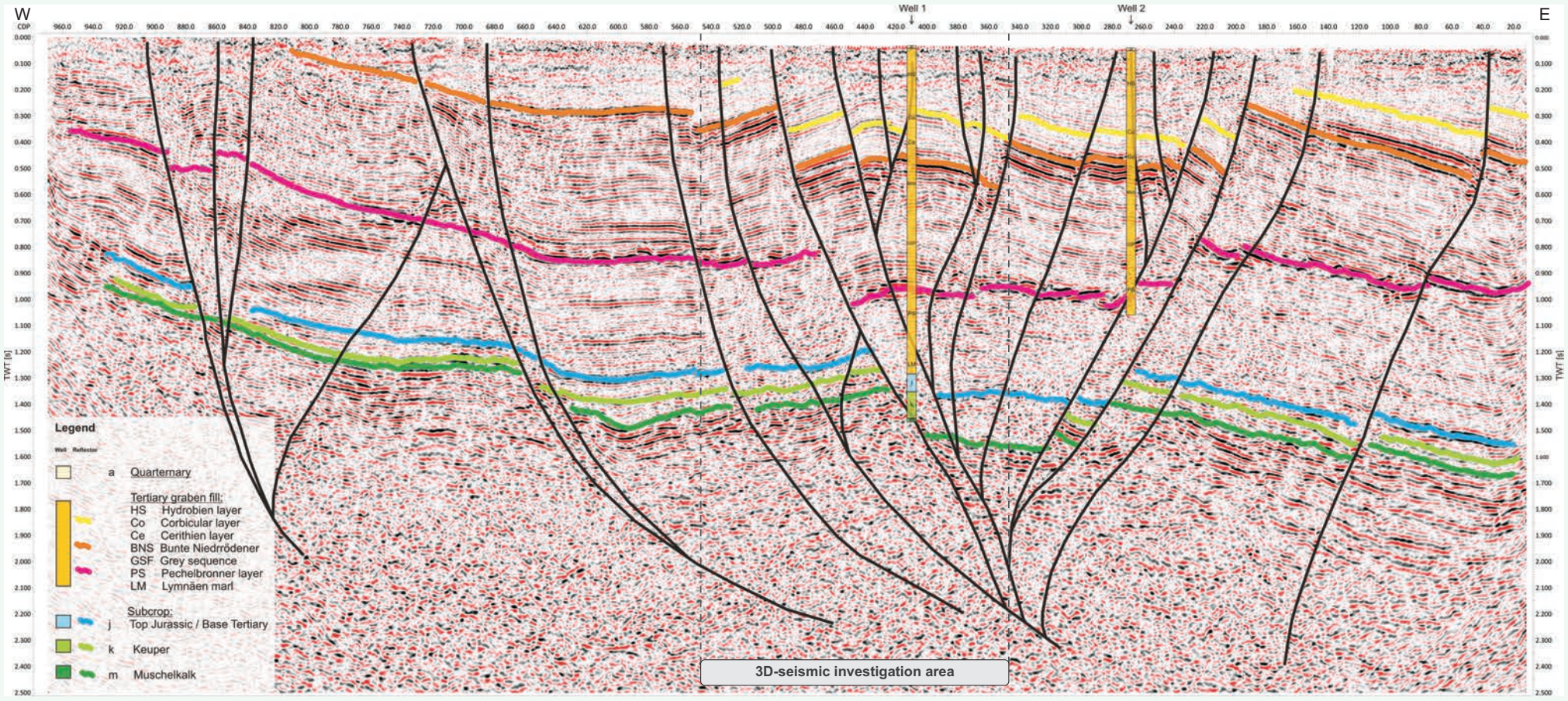
The formation of the Rhine Graben started in Mid Eocene times when the regional stress conditions in the Alpine foreland allowed the reactivation of a pre-existing weakness zone with Rhenish strike in the basement by dominantly normal faulting. Subsidence phases alternated with uplift periods as documented by the erosion of sediments of the graben fill. The maximum throw between the uplifted graben shoulders and the graben bloc is 5.500 m. Internally the graben is heavily faulted with different fracture spacing, major fracture zones and signs of horizontal displacement areas. Most of the faults reach the Pre-Tertiary subcrop and often penetrate far into the Hercynian basement (figure 1).

2D-seismic

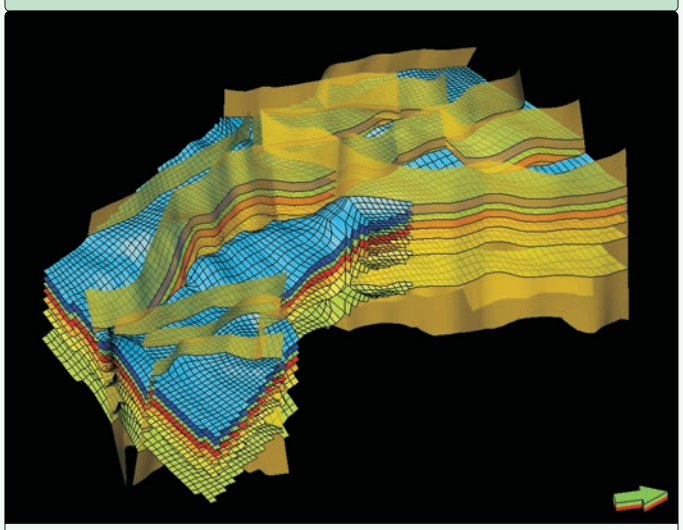
Due to recent tectonical activity the Upper Rhine Graben shows a higher geothermal gradient that stimulates the exploration for Triassic geothermal reservoirs, e. g. Muschelkalk and Bunter Sandstone. For this reason geothermal exploration is primarily interested in the size, shape and age of fault patterns and their accompanying fractures, their fault activities and the resulting flow of hot fluids through high permeable fracture zones. In a first step of the exploration activities all available geological data and older 2D-sections from the oil industry were acquired, reprocessed and interpreted. At this point problems arose as the seismic measurements in hydrocarbon exploration had different targets and different aims in resolution, the acquisition of modern 2D-seismic data was neccessary (figure 1).

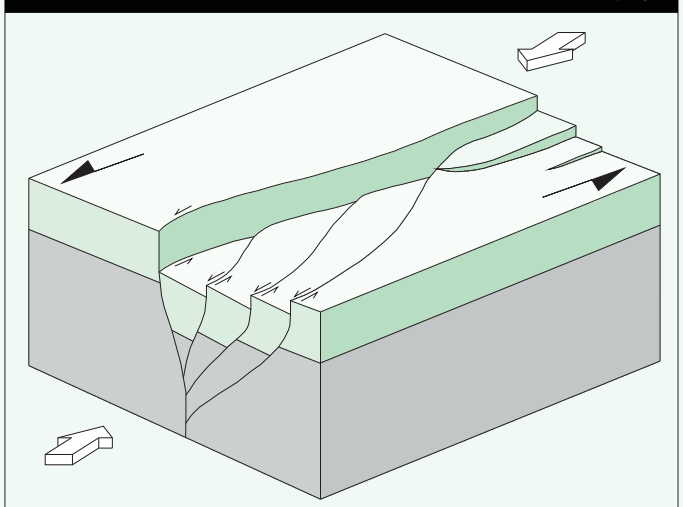
It was possible to finalize a structural analysis of the graben fill and the identification of geothermal reservoir horizons in depths of more than 3.000 m. In the shown example a well-defined fault pattern in form of a negative flower structure can be seen that interacts with a pull apart basin. Most of the faults strike at surface thus indicating recent tectonic activity.

▼ Figure 1: 2D-seismic section in the investigation area in time (TWT)



3D-seismic





2D-seismic investigations are used to obtain a general idea of the subsurface structure whereas 3D-seismic investigations are a serviceable tool to concretize geothermal project sites.

Over a selected area of the flower structure seen above 3D-seismic measurements were accomplished that offer high accuracy for following planning works:

- reservoir identification,
- building a geological model,
- well path planning

and

- hydrogeological modelling

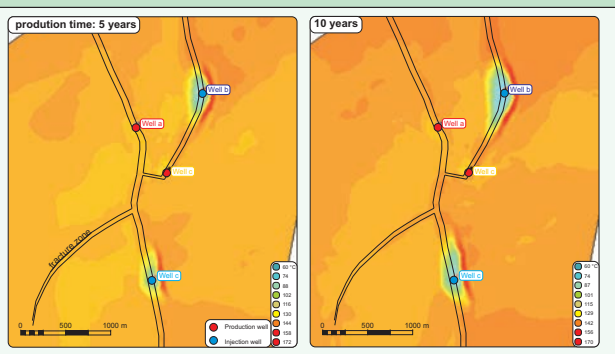
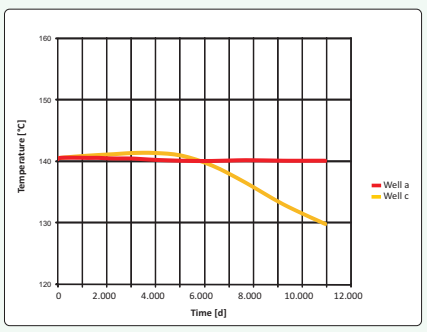
to optimize the reservoir exploitation for each site.

Figure 2a shows the structural model derived from 3D-seismic data interpretation - reservoir horizons and dominant tectonic elements are integrated. In the southern part of the investigated area the flower structure which forms a pull apart basin is clearly identified. The northern part is characterised by parallel nearly south-north trending faults forming an accommodation zone (figure 2b) under the regnant stress field. Both tectonical structure types indicate required extentional fractures.

Based on the 3D-seismic data the complexity of the Upper Rhine Graben subsurface structure could be transformed into a hydrogeological model. The main focus of this model was the determination of the optimized well configuration.

Figure 3a shows time slices of a continuous propagation of the cooling front through a hydrothermal system with high-permeable fracture zones. Furthermore it demonstrates that over a time period of 30 years of hydrothermal production an assembly of two production and two injections wells is feasible with a temperature decrease of about ten degrees at production side (figure 3b).

◄ Figure 2a: Structural model of the reservoir interval based on 3D-seismic data
Figure 2b: Structural expression of a pull apart basin

Figure 3a: Model of cooling of the underground: time-slices after production duration of 5, 10, 20 and 30 years ►
Figure 3b: Temperature-time-relation of a geothermal production period of 30 years

Hydrogeological model