Facies Analysis of an Upper Jurassic Carbonate Geothermal Reservoir

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ABSTRACT

The exploration of deep geothermal reservoirs is still a challenge. Therefore actual exploration procedures from the hydrocarbon industry are adopted. The aim is to improve reservoir models by facies prediction and support better well paths planning. The background for this study is a project of the "Stadtwerke München" to supply their district heating net with geothermal energy. This programme replaces conventional energy for 500.000 inhabitants by the year 2040. We applied frequency blending, attribute classification and seismic sequence stratigraphy to a 170 km^2 large seismic survey. The survey was shot to explore an Upper Jurassic carbonate platform. By these methods, we visualised the heterogeneity of the carbonate platform, constructed facies models and developed a zonation of the reservoir, which served as a base for a numerical reservoir model.

1. INTRODUCTION

Carbonate layers are favourable reservoirs for geothermal use. In Europe, these are the Dogger aquifer in the Paris Basin (Jaudin et al. 2009), the Dinantian carbonates in the Netherlands (Reijmer et al. 2017) and the Upper Jurassic carbonate platform in Southern Germany (Lüschen et al. 2011). There are several reasons for an enhanced permeability of carbonates. The brittle deformation and low shale content cause open fracture zones in the vicinity of faults. Karst features develop during terrestrial conditions. Dolomitization occurs during the subsequent burying process and leads to secondary porosity. Finally, the facies, depending on the local sedimentary environment, is the main reason for primary porosity and also has an impact on the dolomitization process.

In this study, we analysed the facies distribution of the Upper Jurassic carbonate platform in the South German Molasse Basin. Especially we want to find an answer to the question if seismic sequence stratigraphy can help to distinguish between different carbonate facies. Furtheron, which methods can be used or are useful and can we improve the construction of geothermal reservoirs?

The Molasse Basin of Southern Germany is the main region of geothermal energy production by deep wells. The water is produced from the 600 m thick carbonates. The main exploration targets up to now are prominent faults which strike subparallel the Alpine front and were successively active during the forming of the basin. In 2014 a project started by the local energy supplier 'Stadtwerke München' to provide the district heating net with geothermal energy. In this project, there will be approximately 20 wells at 5 locations drilled into the carbonate platform. The well paths will penetrate the platform within an area of about 170 km^2. A seismic survey covering this area should provide information to place the well paths at favourable locations. These comprise a major fault system within the subsurface of Munich and so-called carbonate build-ups. The latter consist of massif carbonate rocks, which are mostly dolomitized and are separated against each other by troughs, which are filled by carbonate mudstones (Pawellek and Aigner 2003).

A 2500 m thick sedimentary pile of Tertiary marine and fluviatile sediments covers the carbonate platform in the area of Munich. The stratigraphy of the platform is divided according to the dominant fauna (Schmid et al. 2005), but the overall development shows a successive shallowing upward of the sedimentary environment which has a strong impact on the size and distribution of the build-ups. It seems that patch-reefs developed only at the latest stage of the building of the platform (Meyer and Schmidt-Kahler 1989).

2. METHODS

Studies of outcrops 100 km north of the survey area and sparsely distributed wells within the molasses basin build the interpretation background for the facies interpretation (Pawellek and Aigner 2003). Here we analysed of a 170 km^2 large 3D-seismic survey for facies interpretation. CRS (common reflection surface) (Menyoli et al. 2004) processing and a PSDM (prestack depth migration) enhanced the quality of the data substantially. We applied several methods during the interpretation process. Because of the strong faulting we use a flattening to reconstruct the former geometry of the platform. Therefore we used a Tertiary key reflector above the platform, the so-called Lithothamnien calk. Thin Cretaceous sediments cover the carbonate platform partly toward the south. The Upper Jurassic Purbeck reflector marks the top of the platform but is less appropriate for flattening because of erosional structures. The mostly vertical fault planes facilitate the flatting without producing a broad strip of deformed signals near the faults. In this way, reflection could be correlated laterally and show the reflectivity distribution within the carbonate platform before the structural deformation. A similar procedure is the definition of horizons parallel to the Lithothamnien chalk within the carbonate platform. The horizons are called phantom horizons. Mapping on these horizons also compensates for the faulting. A reflection series above the crystalline basement crudely mark the base of the platform. We defined eight layers between the top of the platform and the base by dividing it into equal depth intervals. The top of the layers therefore run subparallel to the Purbeck reflector and the top of the crystalline basement. Each of these methods to compensate for faulting consider different aspects. The flatting helps for the interpretation of seismic sections, the phantom horizons compensate the faulting for mapping, and the layer construction guides the analysis of the internal composition of the platform.

Important information of the seismic signal resides in the local frequency content. The frequency spectra from the wavelet transformation visualise the frequency content on planes within the platform (Satinder and Marfurt 2008). Red, green and blue colours represent three spectral amplitudes (Fig. 1). The resulting colour shows the frequency distribution by mixing of different colours. These images on six so-called phantom horizons show the heterogeneity and zonation within the platform.

Another set of seismic attributes was used to construct a layer model of the platform, using the eight layers described above: we calculated the average seismic amplitude, the main frequency, and the average similarity within each of these layers. A classification scheme combined these attributes into 18 classes. The average amplitudes and the main frequencies were divided into three intervals and the average similarity into two intervals. The combination of these intervals resulted in 18 classes. In comparison to the wavelet transform this definition of classes results in a better separation of different areas within the survey. On the basis of the classification, similar areas were defined on top of each layer with a geographic information system.

Horizon tracking also was applied to map coherent reflections within the carbonate platform. The tracking was possible only in some parts of the survey. Also, the number of reflectors changes laterally. Therefore, we used these reflections to construct a sequence stratigraphy model at distinct seismic sections (Emery and Myers 1996). Very prominent reflections were used to divide the platform into layers. In contrast to the former partitioning according to the top and base of the reservoir, in high reflectivity areas, the layer is linked to a local maximum or minimum reflection. Besides at the top and base of the platform these reflections terminates, because they dip out or they stopped at diffuse or chaotic reflection areas.

On the other hand, single reflectors split into reflection series. The seismic stratigraphy method intends to map the stratigraphically correct plane within these seismic

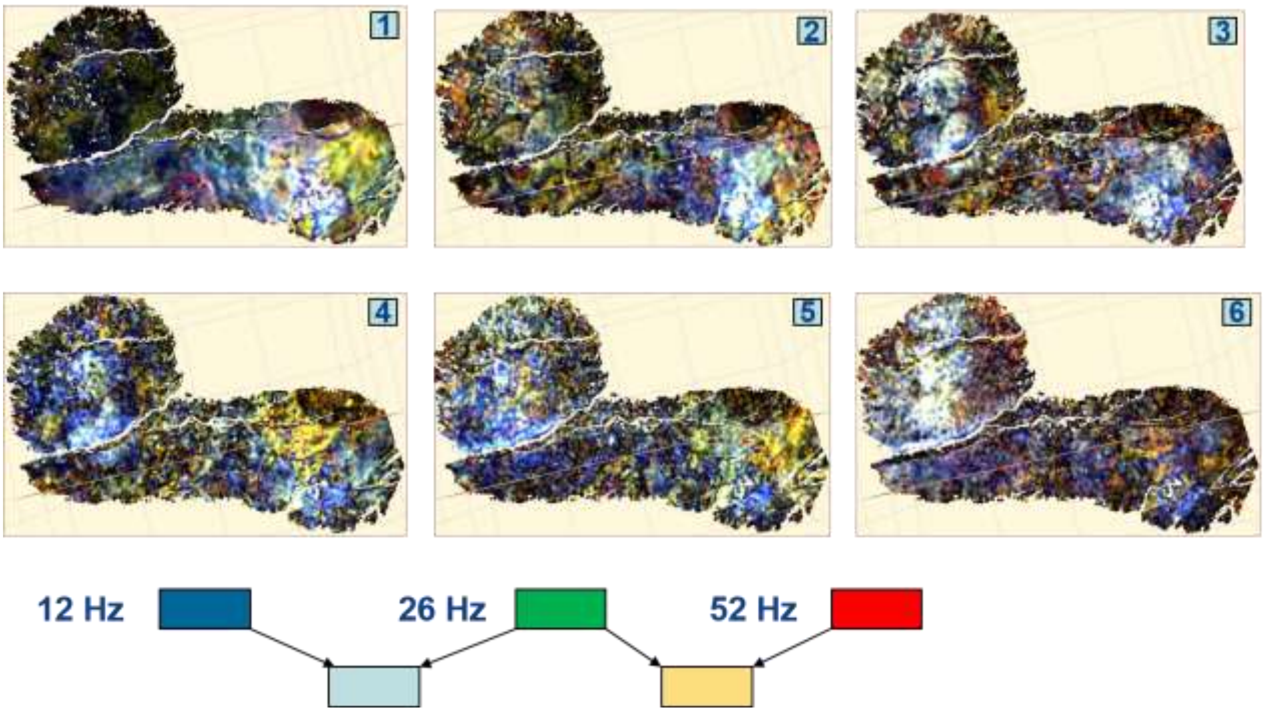


Figure 1. Three frequencies of the amplitude spectra of a wavelet transform were blended on six horizons. Horizon 1 marks the top of the carbonate platform. The others follow with a distance of 40 milliseconds. Bright areas are caused by higher amplitudes. They indicate reflections from basin and trough sediments. White lineaments indicate the fault system.

patterns. The supposed sedimentary process must correlate with the seismic reflectivity. In this way, horizons were defined at seismic sections in respect not only at sharp reflections but which also cut diffusive and chaotic parts.

The mapping using seismic attributes and the interpretation of seismic sections were interpreted together to get a picture about the sedimentary processes at this site and to define the facies distribution.

3. RESULTS

The blending of three frequencies of the wavelet-transforms shows the lateral and vertical distribution of the reflectivity (Fig. 1) Light colours show areas with high amplitudes and the colours itself are a measure of the frequency content. The images show the blended frequencies on six phantom horizons from the top of the platform downwards in a travel time distance of 40 ms, which means approximately 100 m. The general trend of the reflectivity distribution is in a west-east direction. The western and eastern parts of the seismic survey show areas of higher amplitudes, where the frequency distribution is smoother and more connected. In the middle of the survey and in areas to the high amplitude parts, the darker areas show a more stippled, i.e. heterogeneous frequency distribution. The overall frequency distribution changes a lot from horizon 6 to Horizon 1, but between the single horizons, the change is gradual.

Fig. 2 shows the classification of a layer in the middle of the platform, which top coincide approximately with phantom horizon 4 of figure 1. The amplitude distribution is comparable to this horizon. Lower amplitude parts in general, have a very heterogeneous frequency distribution. There are some circular low amplitude areas, surrounded by higher amplitudes.

Fig. 3 shows an interpreted seismic section, which runs in an east-west direction. The white lines mark seismic sequence borders. These lines follow prominent reflections, reflection series and mark the top and bottom of different seismic patterns. The description of sections follows this partitioning for better clearness. There are different groups of seismic patterns: a) Coherent, subparallel reflections, with a length of several kilometres and with strong amplitudes, b) subparallel, sharp reflections with lower amplitudes, c) diffuse and chaotic reflections, d) small clinoforms, e) larger sigmoidal reflections. In the first stratigraphic layer, count from the bottom subparallel reflections dominate. The reflection amplitudes decrease in the eastern part. In the next layer a, strong reflection band marks the top of this layer. In the middle of the section, a diffusive and chaotic part is visible. In the west of this structure, several clinoforms are dipping in the western direction, which is bordered by a ramp-like structure which dips in the opposite direction. At this slope, small triangle structures exist. In the most western part, a subparallel reflection series appears. Within the upper part, i.e. the uppermost layer divergent reflections, small triangles, and subparallel reflections appear.

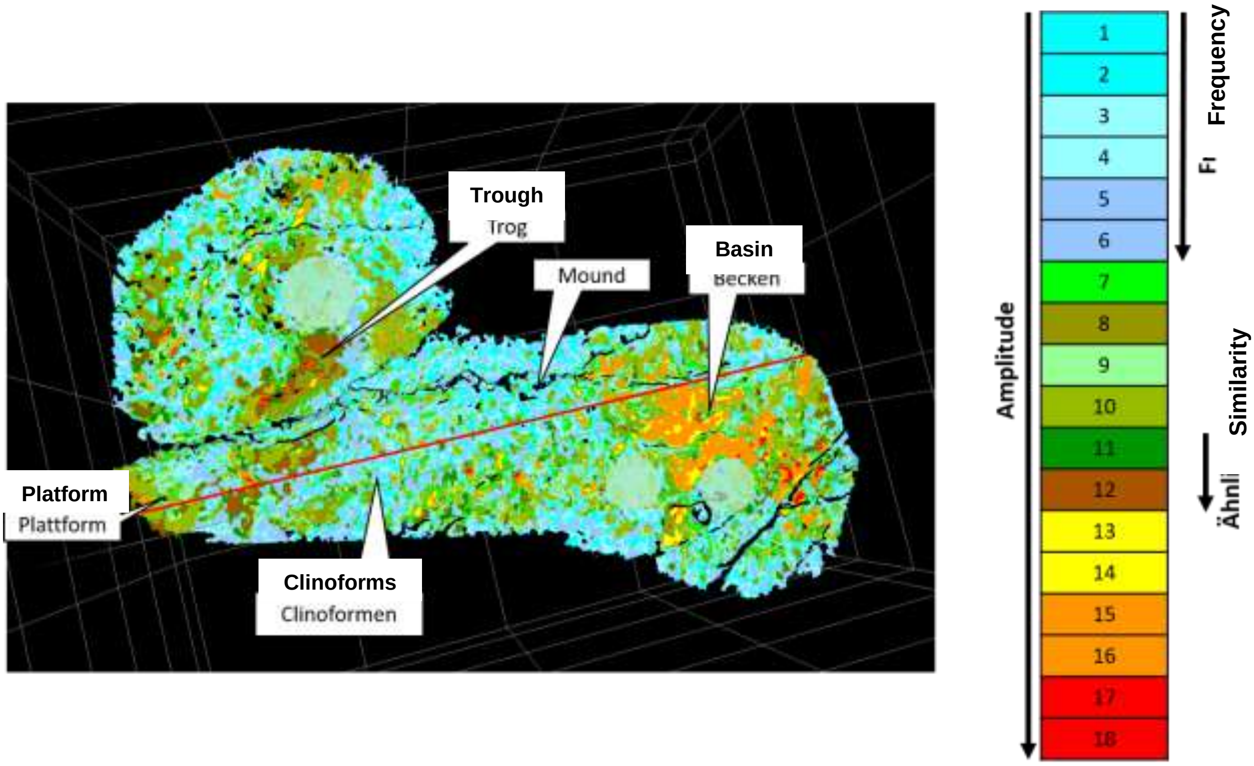


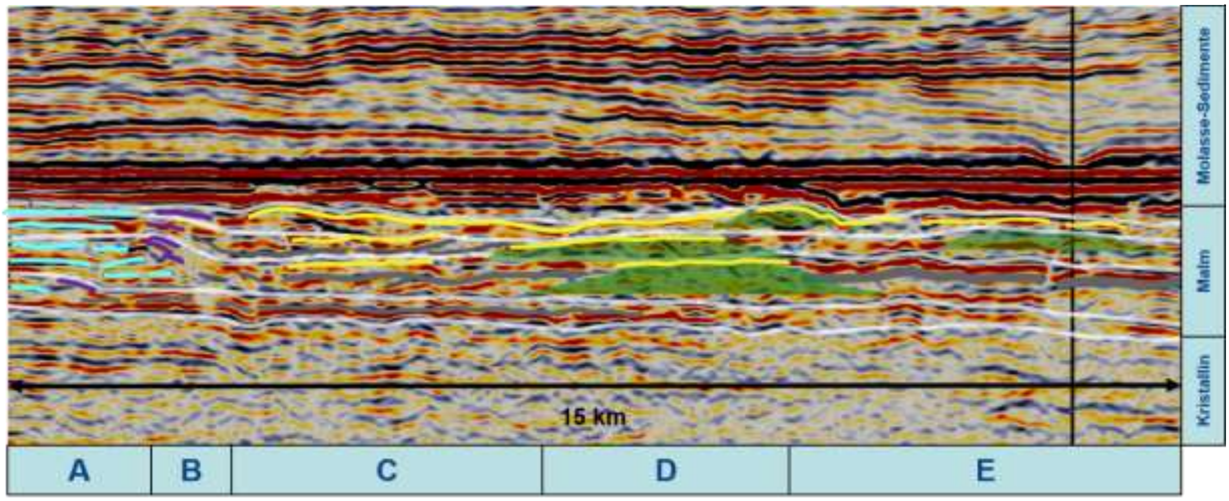
Figure 2. Classification map of three seismic attributes. The horizons runs approximately in the middle of the carbonate platform. The redline show the location of the seismic section of figure 3.

4. INTERPRETATION

The seismic facies distribution within the survey area is locally very heterogeneous, but also larger parts show a similar seismic attribute classification. In this way one can define areas were a special kind of carbonate sedimentation is dominant. We interpreted four kinds of carbonate sedimentation environments. These are basins and troughs, platforms, carbonate mounds, and ramps or slopes. The interpretation is based on the seismic sections and maps from the attribute classification. The seismic sections show the sedimentary process by the kind and distribution of seismic patterns and the map indicates the lateral extent of the signals characterised by their attributes. Strong reflections mark significant changes in carbonate precipitation. Sealevel changes cause this alteration in carbonate sedimentation. The number of reflections in a reflection series is an indication for the water depth. Shallow areas are more sensitive to sea level changes than deeper ones. Single reflection bands, therefore, hint to larger water depth in contrast to multiple reflections. Shingled, chaotic and more transparent reflections are seismic characteristics of carbonate mounds. Dipping reflections, clinoforms and sigmoidal structures indicate slopes and ramps. In this context, these both terms help to differentiate between two sedimentary processes. The ramp is a link between a platform and the adjacent trough. It can be recognised by a lateral change of reflection patterns, dipping reflection and termination of reflections at the ramp. Successive ramps form the shape of a sigmoidal pattern. Slopes in the form of the clinoforms indicate local sediment transport form higher areas into the basin. The clinoforms comprise in general vertically less than one wavelength of the seismic signals. Strong reflections were used to divide the platform into four seismic stratigraphic layers; besides that these reflections cannot be tracked continuously across the whole survey. There are several reasons for this. Reflection characteristics change across major faults, whereby near the faults often the coherency of reflections is disturbed. Single reflection also split into two or more reflections or the shape, i.e. the phase and amplitude of the signals changes. Missing appropriate reflections may be caused by a hiatus. In the areas where carbonate build-ups were identified the boundary take internal reflection groups into account. There are also dipping reflection, accompanied by small triangles. This reflection pattern was interpreted as the border of an isolated platform. In this case, the sequence boundary follows the dipping reflection upward.

Besides the vertical subdivision, there are also lateral differences in the seismic reflections. One can define five parts in the seismic section. In the eastern part, strong subparallel reflections dominate, which are bordered by more chaotic reflections. Inclined reflections and clinoforms and subparallel thin reflection band follow in in the most western part. The build-ups in the middle divide the platform into an eastern and a western part. These larger mud mounds are dominant in the second and third stratigraphic layer. Clinoforms are interpreted as transport of carbonate mud away from the mounts. The occurrence of these clinoforms more on the western side of the mounds is a hint of the sedimentation processes. One can differentiate between a leeward and a windward side. Erosion from the mounts fills an adjacent trough, leading to the clinoforms structures. Precipitation of carbonates, which lead to subparallel layers, filled a deeper basin on the eastern side.

Figure 3. Interpretation of a seismic section. The seismic was flattened at the Lithotamien chalk near the top of the carbonate platform. White lines indicate sequence boundaries. Blue lines: platform mudstone, yellow lines: grainstone, gray lines: basinal mudstone, green areas: boundstone. The letters indicate different sedimentary environments, which are dominant. A: platform, B. slope, C: trough, D: mud-mounds, E: Basin.



The classification map shows the attribute distribution approximately near the top of the second stratigraphic layer. The carbonate build-up stretches over a large area in the middle of the survey, indicated by low amplitudes. Surrounding parts, with erosional fans or slopes, have low to middle attributes which small patches. The basin in the eastern part has high and connected amplitudes. The trough shows middle amplitudes and high similarity. The frequency distribution helps to visualise the heterogeneity. The ramp-like structure west to the trough, for example, shows small amplitudes but a continuous frequency distribution. Circular low amplitude distributions were interpreted as smaller build-ups, which are distributed within the trough and basin areas.

From the local sedimentary environment, one can conclude on the facies at this place. In the western part subparallel fine laminations are platform mudstones. This area is bordered towards the east by grainstones at the edge of the platform. The adjacent trough is filled by a succession of mudstones and grainstones, depending on the erosion of the platform sediments. The mud mounts are built from mud- and boundstones. The basin sediments inherit different types of mudstones.

5. CONCLUSIONS

Different methods were used to visualise a heterogeneous carbonate environment: Blending of amplitude spectra analysed by the wavelet transform, classification by seismic attributes and the interpretation by the seismic sequence stratigraphy method. The latter gives hints to different sedimentary facies within the carbonate platform. The others show the areal distribution of the local carbonate environments. These are build-ups, which are carbonate mud mounds with different sizes, basin, troughs and local platforms with stratified sedimentation. From this analysis, lithological facies and distribution of reservoir quality can be derived. The construction of a reservoir model should account for the facies distribution by dividing the platform into several layers with lateral varying properties. Also, a statistical model is useful to consider a finer vertical layering. A reservoir incorporates these results, which is based on the layers of the classification scheme and take account of the facies distribution by defining a larger zone of similar reservoir properties. By this, the energy production in the long run from this reservoir is evaluated.

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