Facies Distribution and Temporal Evolution of Faults in the Southern German Molasse Basin: A Case Study of Geretsried, Germany

Vladimir Shipilin[1, 2], Hartwig von Hartmann[1], David C. Tanner[1], Inga Moeck[1, 2]

[1] Leibniz Institute for Applied Geophysics, Stilleweg 2, D-30655 Hannover

[2] University of Göttingen, Goldschmidtstr. 3, D-37077 Göttingen

vladimir.shipilin@leibniz-liag.de

Keywords: German Molasse Basin, Upper Jurassic carbonate platform, Play Type, facies distribution, fault kinematics, fault controlled reservoirs, geothermal exploration.

ABSTRACT

Recently, foreland basins have become prime targets to host geothermal resources because of the existence of deep aquifers. Understanding of tectonic evolution, fault kinematics, and facies within the reservoir, i.e. the geothermal play type, is crucial to evaluate the potential for geothermal energy production. Based on a 3D seismic survey, acquired 30 km south of Munich, we analysis the facies within the carbonate platform and the faults within the entire stratigraphic sequence of the geothermal prospect of Geretsried in the southern German Molasse Basin. To determine the temporal activity of the interpreted faults, we built a 3D geological model, from which we derived juxtaposition diagrams of the faulted strata and thickness maps of seismic horizons. We show that the various strata at Geretsried have undergone different deformation phases; extension in the pre- and early-orogenic stages of basin formation and contraction in the Middle Miocene times. Furthermore, the deformation style at this part of the basin is characterised by decoupled faulting. The identified structures, their temporal activity, and deformation style indicate active stress regime and thus provide an insight into the hydraulic transmissivity of the fault zones.

1. INTRODUCTION

In the last decade, there has been an increasing interest in foreland basins to host geothermal resources because of the existence of deep aquifers (e.g. Schulz et al., 2004; Weides and Majorowicz, 2014). Fluid migration pathways in the foreland basins are controlled by facies distribution and fault inventory within a geothermal reservoir (Moeck, 2014). The main targets of geothermal wells are massive carbonate facies that consist of reef bodies. Reconstruction of the depositional environment and understanding of facies distribution are therefore of the utmost importance for successful geothermal exploration, as it provides hints to the lithological properties, such as initial porosity. With increasing depth of the geothermal reservoir, fracture and fault density become the primary factors that govern heat transport (Moeck, 2014). Foreland basins reveal complex deformation structures that range from extensional faults toward the foreland to contractional and inverted faults near the orogenic front (Tavani et al., 2015). Therefore, understanding of tectonic evolution and fault kinematics is crucial to evaluate potential geothermal reservoirs that lie at the required depths. Depending on the kinematic evolution and position in the current stress field, faults can act as hydraulic conduits or barriers.

Our working area is within the southernmost part of the German Molasse Basin (Fig. 1) — a typical foreland system. A number of basin-scale structural studies were carried out in the 80s and 90s, based on a large amount of 2D seismic data acquired during the decades of hydrocarbon exploration (e.g. Bachmann et al., 1982; Bachmann et al., 1987; Müller et al., 1998; Bachmann and Müller, 1992). However, until recently there have been only a few detailed structural studies in relatively weakly-deformed parts of the foreland basin. Only with the emergence of geothermal exploration in the recent years and the consequent availability of 3D seismic data, have such studies become possible (e.g. Lüschen et al., 2011; von Hartmann et al., 2016; Budach et al., 2017).

In the present work, as the first step we carry out classical sequence stratigraphic analysis in order to map favourable facies that might possess high initial porosities. The focus of the work, however, is an in-depth analysis of deformation structures within the geothermal prospect of Geretsried. Our aim is to understand the structure and tectonic evolution of an area proximal to the Alpine deformation front to optimize the geothermal exploration. As the second step, we analyse fault patterns within the Upper Jurassic carbonate reservoir and its Molasse overburden. In particular, using juxtaposition (Allan) diagrams (Allan, 1989) and thickness maps, we establish the relationship between sedimentation and faulting, as well as the temporal activity of faults. Based on the kinematic history of the faults and their orientation within the present-day stress field, we discuss the implications for the hydraulic connectivity of the deformation structures within the deep geothermal reservoir.

2. GEOLOGICAL SETTING

The German Molasse Basin (GMB) is part of the North Alpine Foreland Basin that evolved on the subducting European margin in front of the Alps since the Late Eocene (Lemcke, 1973; Bachmann et al., 1982). The Cenozoic deposits of the foreland basin unconformably overlie the peneplained Mesozoic sedimentary basement and locally, Permo-Carboniferous clastic sediments and crystalline rocks (Lemcke, 1988; Sissingh, 1997).

From Jurassic to middle Cretaceous times, the pre-Molasse region evolved into an extensional passive margin (Frisch, 1979; Ziegler, 1990; Pfiffner, 1992). Submergence of the southern European shelf by the Tethys Ocean in the Late Jurassic led to the deposition of a gently-dipping Upper Jurassic carbonate platform (Meyer and Schmidt-Kaler, 1990). At the present day, it serves as the main aquifer for the geothermal energy production in the Molasse Basin. In the study area, the carbonate platform is overlain by thin, lithologically heterogeneous Cretaceous sediments (Fig. 2; Bachmann et al., 1987).

After a profound hiatus in sedimentation caused by the Late Cretaceous contractional event, the deposition resumed in the Late Eocene (Ziegler 1995). It marks the inception of the foreland basin in response to the Euro-Adriatic collision (Frisch, 1979; Allen et al., 1991; Ziegler 1995). Loading and consequent flexure of the European foreland plate created a wedge-shaped basin fill (Allen et al., 1991). Flexural subsidence was accompanied by the formation of longitudinal (i.e. foredeep-parallel) normal faults, which show successively younger syn-sedimentary activity toward the north (Bachmann et al., 1982; Bachmann and Müller, 1992).

The Cenozoic Molasse cover was deposited in the course of two major transgressive-regressive cycles and can be subdivided into, from base to top; the Lower Marine Molasse (UMM), the Lower Freshwater Molasse (USM), the Upper Marine Molasse (OMM), and the Upper Freshwater Molasse (OSM) (Eisbacher, 1974; Fig. 2). The lowermost UMM consists of a transgressive sequence that ranges from shallow-marine sandstones and carbonates, to deep-water condensed shales and marls (Lemcke, 1988; Sissingh, 1997). This sequence passes upward into thick Rupelian Clayey Marls that were deposited during a sea-level standstill (Zweigel et al., 1998). Transition from UMM to USM is marked by the accumulation of regressive, shallow-marine to coastal Baustein Beds (Diem, 1986). These are overlain by fluvial Chattian and Aquitanian Sands.

Despite decreased subsidence in the Burdigalian, the second transgressive-regressive cycle began with transgression of OMM clay marls over the Aquitanian-Burdigalian erosional unconformity (Lemcke, 1988; Zweigel et al., 1998). By the beginning of Langhian, terrestrial conditions prevailed across the entire GMB, as OSM was deposited (Lemcke, 1988). From ca. 8.5 Ma onwards, the GMB has experienced isostatically-induced uplift and erosion (Lemcke, 1974). Our study area is within a weakly deformed part of the basin, referred to as Foreland Molasse immediately north of the frontal thrust of the Subalpine Molasse. The Subalpine (Folded) Molasse was formed by thrusting and incorporation of the proximal foreland basin sediments into the Alpine front (Bachmann et al., 1987; Reinecker et al., 2010).

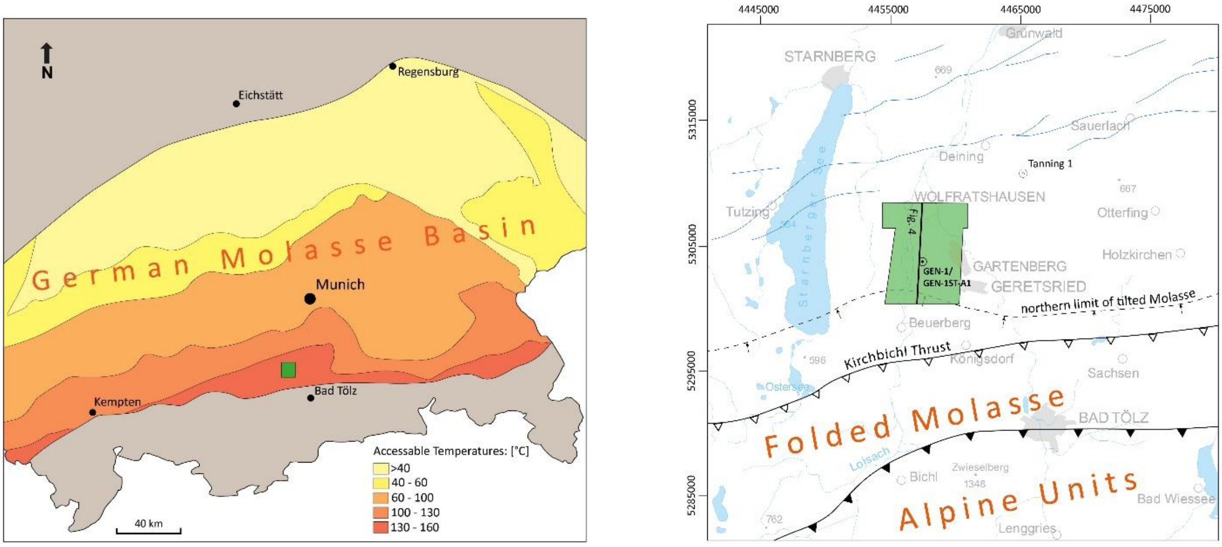

Figure 1: Location map. Left: outline of the German Molasse Basin with geothermal areas (www.geotis.de), right: location of the Geretsried 3D seismic survey. Black line marks profile within the survey area in Fig. 4, blue lines are major normal faults.

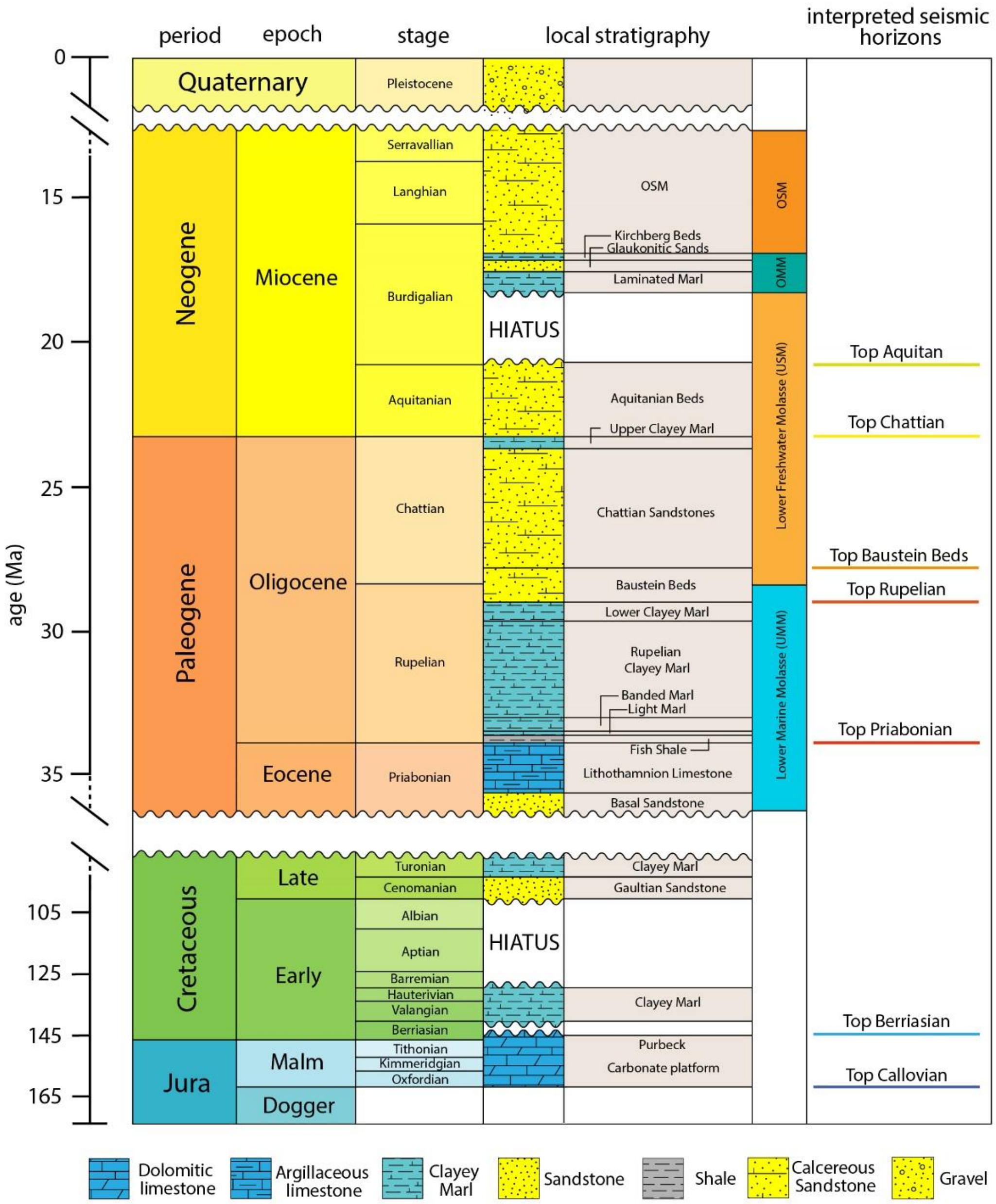

Figure 2: Detailed stratigraphy of the analysed area.

The Subalpine Molasse units are detached from the lowermost Foreland Molasse and its Mesozoic substrate by a major décollement within the mechanically weak Rupelian Clayey Marl (Bachmann et al., 1982; Ortner et al., 2015). The thrusting activity in the Alps abated in Early to Middle Miocene times (Zweigel, 1998). However, thermochronological data suggests that thrusting in the Subalpine Molasse continued into the Late Miocene (von Hagke et al., 2012).

3. DATA AND METHOD

Our study is based on a 40 km^2 large 3D seismic survey, acquired 30 km south of Munich in 2010 (Fig. 1). The maximum CMP fold was 163 m. Bin size was 25 m x 25 m. The seismic reflection data are supplemented by data from the Geretsried GEN-1 well, which was drilled down to the intermediate part of the Upper Jurassic carbonate platform. The well data comprises detailed lithostratigraphic log and vertical seismic profiling.

The seismic cube was depth migrated in the pre-stack domain and tied to the Geretsried GEN-1 well with the help of a vertical seismic profile. Six horizons were mapped using lithological markers from the Geretsried GEN-1 well; from the top of the Upper Jurassic aquifer/Purbeckian facies, which corresponds to the top Berriasian, up to the highest seismically recognizable horizon — the top Aquitanian (Figs. 2, 4). The base of the carbonate platform, which was not intercepted by the well, was predicted, based on the relatively uniform 600 to 650 m thickness of the platform in the southern part of the GMB.

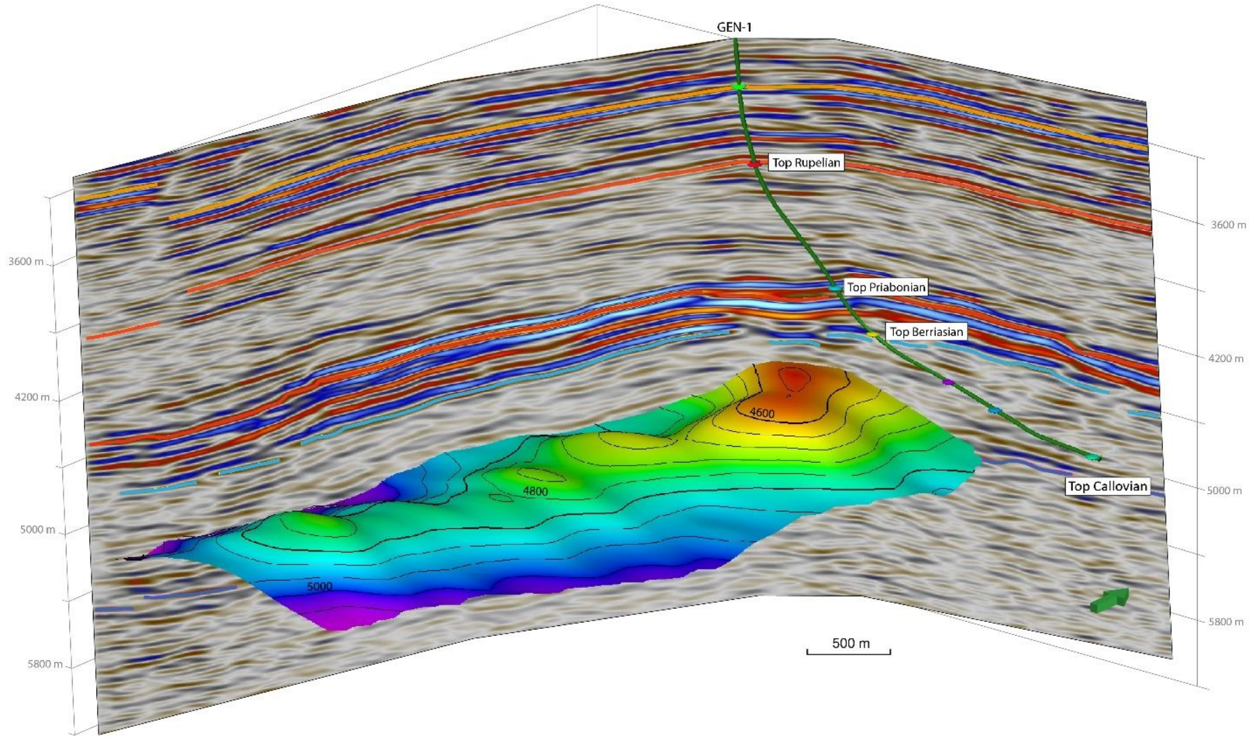

Figure 3: Depth map of the interpreted organic build-up within the Upper Jurassic aquifer.

For the facies interpretation in the Upper Jurassic sequence, we employed classical sequence stratigraphic approach that was based on the analysis of reflector shape. We studied reflector terminations and reflection configuration.

The next step was the structural interpretation. Here the primary objective was to accurately map fault patterns within the seismic volume. In the relatively weakly deformed Foreland Molasse, the majority of faults show subtle displacement of a few tens of metres (Bachmann et al., 1982). Detection of such faults poses a challenge to an interpreter, as resolution effects may result in a smeared fault image or pseudo-continuity of strata. In order to tackle this problem, we firstly applied data conditioning by implementing a structure-oriented filter to the migrated data. Having produced variance volumes with sharper fault edges, we then co-rendered them together with most-positive curvature and most-negative curvature cubes into one multiattribute cube. Such a multiattribute display allowed us to map faults where their displacement fell below seismic resolution and curved deformation instead of discrete fault edges was observed.

In order to analyse the temporal activity of the interpreted faults, we built a 3D geological model of the Geretsried area using modelling software (SKUA-GOCAD®; Paradigm Ltd., 2017). We firstly created horizon and fault surfaces and generated fault/horizon intersections to model fault displacement. We then produced juxtaposition diagrams by projecting fault throw onto the modelled fault planes to determine timing of faulting and fault growth. Additionally, we created isochore maps to analyse syn- and post-sedimentary features.

4. RESULTS AND DISCUSSION

The facies analysis reveals a prominent mound-like structure that is approximately 1 km wide and is elongated NNE-SSW (Fig. 3). The flanks of the identified structure are characterised by onlapping geometries and could be delineated with confidence. The internal reflection configuration is heterogeneous and shows chaotic to sub-horizontal reflectors of medium amplitude. We interpret the structure to be an organic build-up that may have possessed a higher initial porosity.

The structural interpretation of the Geretsried seismic data reveals three groups of faults; (1) normal faults in the Mesozoic and the earliest Molasse sediments, (2) normal faults in the Tertiary Molasse, and (3) later reverse and thrust faults that overprint the earlier Tertiary normal faults (Fig. 4). All the faults are longitudinal with respect to the Alpine deformation front. Interestingly, all Tertiary faults are detached from the faults that developed in the Mesozoic and the earliest Molasse sediments by the Rupelian clayey marls. Nevertheless, these faults have approximately the same strike direction (Fig. 5).

According to the results of the kinematic analysis, the interpreted faults reflect three distinct phases of tectonic evolution in the southernmost area of the German Molasse Basin. The main activity on the pre-Alpine normal faults occurred during the Cretaceous. We infer this from fault juxtaposition diagrams, which indicate that the maximum offset is between the Upper Jurassic and Late Eocene strata (Fig. 6).

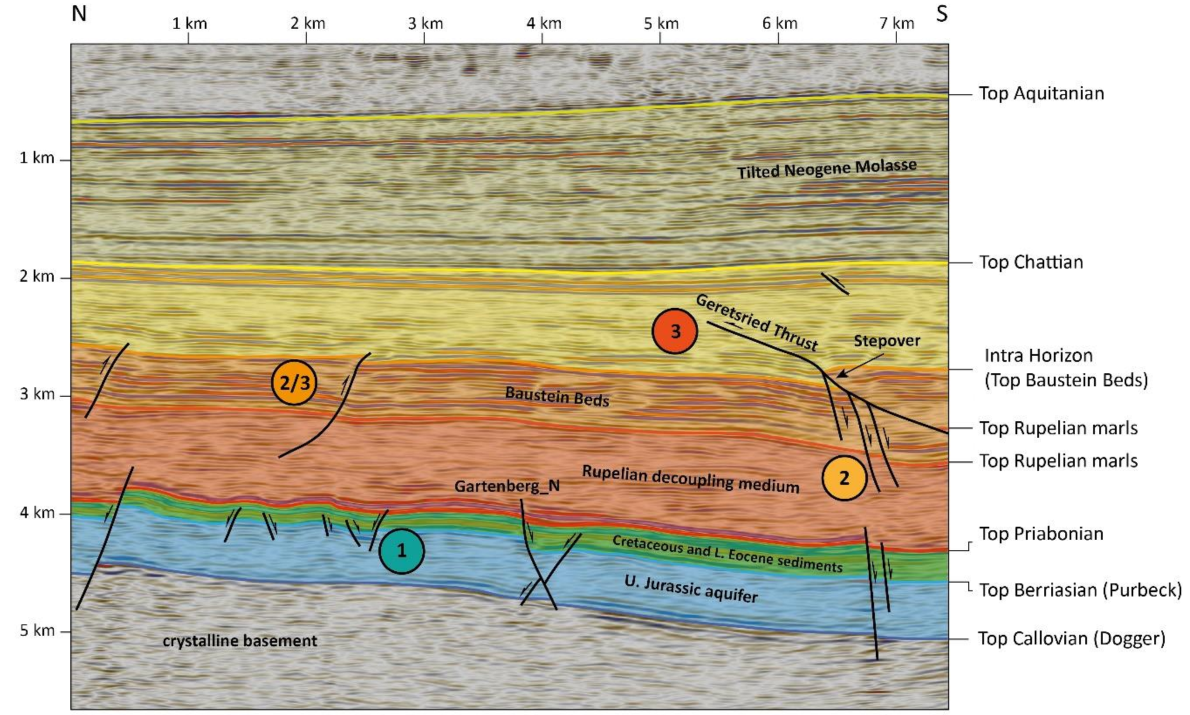

Figure 4: N–S seismic profile through the study area (for location, see Fig. 1), showing three phases of faulting: (1) Jurassic–Cretaceous extensional faulting; (2) Oligocene extensional faulting; (3) Middle Miocene contractional faulting.

The timing of the faulting activity correlates well with the separation of the Middle Penninic microcontinent from Europe at the Jurassic–Cretaceous boundary (Frisch, 1979).

The later phase of active continental collision and subsequent flexure of the European lithosphere triggered extensional faulting in the German Molasse Basin (Bachmann and Müller, 1992). In our study area, this phase is expressed by two intermittent faulting events; reactivation of the pre-Alpine faults, up to the top of the Priabonian strata in the Rupelian, and formation of new normal faults within the Baustein beds in the Chattian (Fig. 4). The relative timing of the faulting events were determined based on the fault throw analysis and thickness maps of the Rupelian and Chattian sequences. The Rupelian thickness map in Figure 7 shows thickness increase above graben structures and hanging walls of the reactivated pre-Alpine faults. This is indicative of the syn-depositional activity of these faults in the earliest Rupelian. The faults in the Baustein Beds must have developed after these beds were deposited, since they show relatively uniform thickness across faults and therefore were active during the accumulation of the overlaying Chattian Sands. The period of quiescence in faulting activity between the earliest Rupelian and the Chattian suggests a temporal decrease of subsidence in this area.

We postulate that, despite the absence of hard coupling between the reactivated pre-Alpine faults and the faults in the Baustein beds, the former pre-determined the locations of later faults. The up-dip fault propagation from Mesozoic strata during the Chattian faulting event was probably arrested by the intermediate 600 to 900 m thick, mechanically incompetent Rupelian clayey marls, in which displacement was accommodated by ductile deformation. This resulted in zones of mechanical weakening from which faults could initiate in the overlying, more competent Baustein beds.

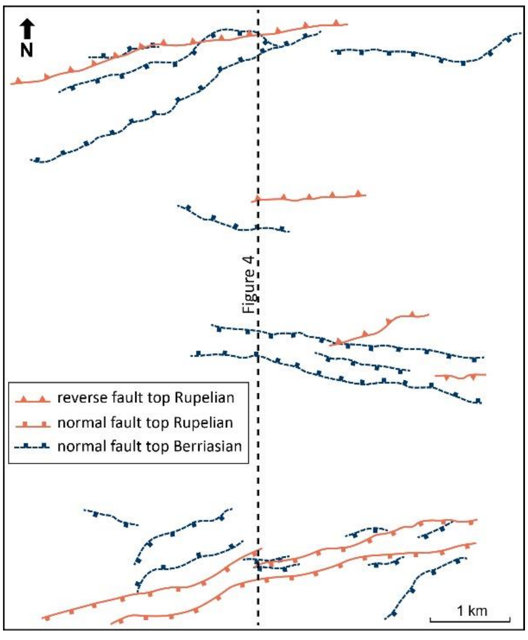

Figure 5: Map of fault traces picked within the 3D seismic volume. Faults in the Tertiary Molasse (orange lines) and faults in the carbonate platform (blue lines) have the same strike direction.

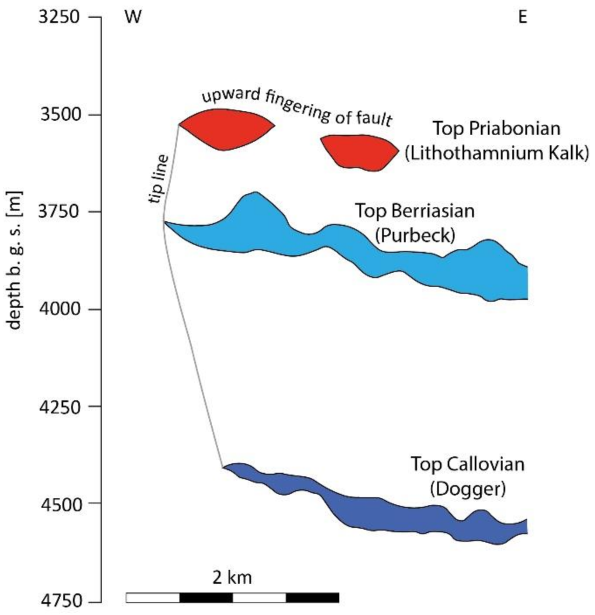

Figure 6: Along-strike projection of the throw of Gartenberg_N fault.

As the Alpine thrusts propagated north, the extensional deformation at Geretsried was succeeded by contraction. The foreland-flexure extensional faults within the Baustein beds were preferentially oriented within the active stress field, thus allowing reactivation as reverse faults. In the southern part of our study area, we interpret an extensive thrust fault (the Geretsried Thrust), which overprints the normal faults. A prominent stepover along the Geretsried Thrust is observed within a linkage zone between two normal faults (Fig. 4). Most probably the Geretsried Thrust branched off the Subalpine thrusts and propagated as a décollement within the Rupelian Clayey Marl until it encountered a zone of weakness in the form of pre-existing normal faults, along which it ramped up into the Chattian sequence.

Directly above the Geretsried Thrust, the Neogene sediments are tilted and dip northwards. According to the tectonic map by Ortner et al. (2015), this could be interpreted as footwall drag beneath the Kirchbichl Thrust of the Subalpine Molasse 3-4 km to the south. However, we observe that the tilted strata flattens eastward, as the displacement along the Geretsried Thrust decreases in the same direction. We therefore rather believe that the northward dipping strata formed as the result of hanging-wall folding above the Geretsried Thrust.

5. IMPLICATIONS FOR GEOTHERMAL RESERVOIR UTILIZATION

Results of the seismic interpretation and kinematic analysis show that the Upper Jurassic carbonate reservoir of the Geretsried area is controlled by organic build-ups and isolated, longitudinal normal faults. Having initially formed during passive margin extension in the Cretaceous, they were then reactivated in the Rupelian during the foreland flexuring.

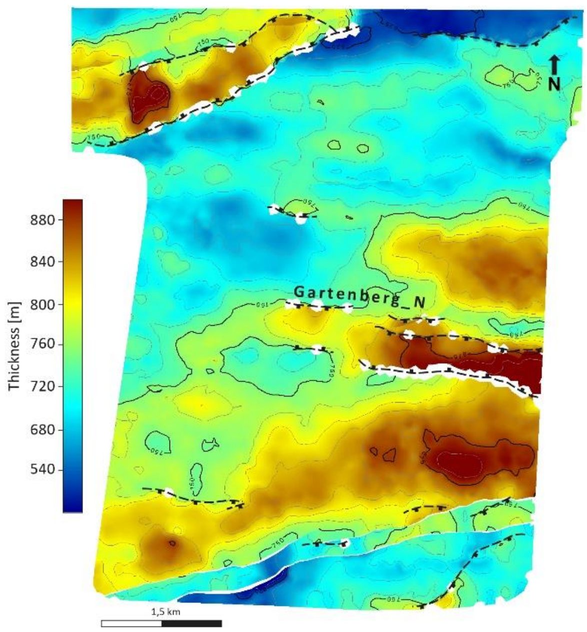

Figure 7: Isochore map of the Rupelian sequence. Dashed lines are the projections of the faults from below to show how the sediment thickness is controlled by the fault distribution.

However, the overlying mechanically weak Rupelian clayey marls impeded the later up-dip propagation of the faults further into the Tertiary Molasse. This might have prevented widening of the fault damage zone and the connected overall increase of fault conductivity.

The occurrence of contractional deformation in the Tertiary Molasse indicates high horizontal stresses in this region at the moment. Such an observation leads to the conclusion that the longitudinal faults should be experiencing high normal stresses and might be compressively locked and therefore act as barriers to fluid flow. This, however, contradicts the results of the drilling of the Geretsried GEN-1ST-A1 well: within the seismically interpreted fault zone of the Gartenberg_N fault, there were total mud losses of ca. 215 m^3. This suggests that despite high normal stresses at Geretsried, the stress regime within the carbonate platform is not compressional, but due to the high vertical stresses at 4-5 km depth, it remains to be of normal or strike-slip faulting. Thus, to the best of our knowledge, the faults remain conductive.

6. CONCLUSIONS

The present study shows that the various strata at Geretsried have undergone different deformation phases; extension in the pre- and early-orogenic stages of basin formation and contraction in Miocene times. The southern part of the German Molasse Basin is characterized by decoupled deformation, due to the southward thickness increase of the Rupelian clayey marls. We emphasize the importance of detailed structural analysis for reservoir characterization of deep geothermal aquifers in the Molasse Basin. The identified structures and deformation style indicate the active stress regime and thus provide insight into the hydraulic transmissivity of the fault zones.

REFERENCES

Allan, U. S.: Model for hydrocarbon migration and entrapment within faulted structures, AAPG Bull, 73, 1989, 803–811.

Allen, P.A., Crampton, S.L., Sinclair, H.D.: The inception and early evolution of the North Alpine Foreland Basin, Switzerland. Basin Res. 3, 1991, 143-163.

Bachmann, G. H., G. Dohr, and M. Müller: Exploration in a classic thrust belt and its foreland, Bavarian Alps, Germany, AAPG Bulletin, 66(12), 1982, 2529–2542.

Bachmann, G. H., M. Müller, and K. Weggen: Evolution of the Molasse basin (Germany, Switzerland), Tectonophysics, 137, 1987, 77–92.

Bachmann, G. H. and M. Müller: Sedimentary and structural evolution of the German Molasse Basin, Eclogae Geologicae Helvetiae, 85, 1992, 519–530.

Budach, I., I. Moeck, E. Lüschen, and M. Wolfgramm: Temporal evolution of fault systems in the Upper Jurassic of the Central German Molasse Basin: case study Unterhaching, Int J Earth Sci (Geol Rundsch), 107, 2017, 635–654.

Diem, B.: Die Untere Meeresmolasse zwischen Saane (Westschweiz) und der Ammer (Oberbayern): Ecl. Geol. Helv., v. 79, 1986, p. 493 – 559.

Eisbacher, G.: Molasse – Alpine and Columbian: Geoscience Canada, v. 1, 1974, p. 47-50.

Frish, W.: Tectonic progradation and plate tectonic evolution of the Alps: Tectonophysics, v. 69, 1979 p. 121-139.

Lemcke, K.: Zur nachpermischen Geschichte des nördlichen Alpenvorlandes: Geologica Bavarica 69, 1973, p. 5-48.

Lemcke, K.: Geologie von Bayern; I, Das bayerische Alpenvorland vor der Eiszeit: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, 1988, 175 p.

Lüschen, E., M. Dussel, R. Thomas, and R. Schulz: 3D seismic survey for geothermal exploration at Unterhaching, Munich, Germany, First Break, 29(1), 2011, 45–54.

Meyer, R. K. F., and H. Schmidt-Kaler: Paläogeographischer Atlas des Süddeutschen Oberjura (Malm), Geol. Jahrb., Reihe A: Allg. und Reg. Geol. BR Dtschl. und Nachbargebiete, 115, 1990, 77 pp., Fed. Inst. for Geosci. and Nat. Resour., Hannover, Germany.

Moeck, I.: Catalog of geothermal play types based on geologic controls, Renewable and Sustainable Energy Reviews, 37, 2014, 867-882.

Müller, M., F. Nieberding, and A. Wanninger: Tectonic style and pressure distribution at the northern margin of the Alps between Lake Constance and the Rivver Inn, Geol. Rundsch., 77(3), 1988, 787–796.

Ortner, H., S. Aichholzer, M. Zerlauth, R. Pilser, and B. Fügenschuh: Geometry, amount, and sequence of thrusting in the Subalpine Molasse of western Austria and southern Germany, European Alps, Tectonics, 34, 2015, 1–30.

Pfiffner, O. A.: Tectonic evolution of Europe - Alpine Orogeny. In: Blundell, D., Freeman, R. & Mueller, S. (eds.) A Continent Revealed: The Eropean Geotraverse. Cambridge, U.K.: University Press Cambridge, 1992.

Reinecker, J., M. Tingay, B. Müller, and O. Heidbach: Present-day stress orientation in the Molasse Basin, Tectonophysics, 482, 2010, 129–138.

Schulz, R., R. Thomas, R. Jung, and R. Schellschmidt: Geoscientific prospect evaluation for the Unterhaching geothermal power plant, Z. Angew. Geol., 50(2), 2004, 28–36.

Sissingh, W.: Tectonostratigraphy of the North Alpine Foreland Basin: correlation of Tertiary depositional cycles and orogenic phases: Tectonophysics, v. 282, 1997, p. 223-256.

Tavani, S., F. Storti, O. Lacombe, A. Corradetti, J. A. Muñoze, and S. Mazzoli: A review of deformation pattern templates in foreland basin systems and fold-and-thrust belts: Implications for the state of stress in the frontal regions of thrust wedges, Earth-Science Reviews, 141, 2015, 82–104.

von Hagke, C., Lujiendjik, E., Ondrak, R., Lindow, J.: Quantifying erosion rates in the Molasse basin using a high resolution data set and a new thermal model. Geotect. Res. 97, 2012, 94–97.

von Hartmann H., D. C. Tanner, and S. Schumacher: Initiation and development of normal faults within the German alpine foreland basin: The inconspicuous role of basement structures, AGU Tectonics, 35, 2016, 1560–1574.

Weides, S., and J. Majorowicz: Implications of spatial variability in heat flow for geothermal resource evaluation in large foreland basins: the case of the Western Canada Sedimentary Basin, Energies, 7(4), 2014, 2573–2594.

Ziegler, P. A.: Geological Atlas of Western and Central Europe: The Hague, Shell Internationale Petroleum Maatschappij, B.V., 1990, 239 p.

Ziegler, P. A., Cloetingh, S. & van Wees, J.-D: Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples. Tectonophysics, 252, 1995, 7–59.

Zweigel, J., 1998, Eustatic versus tectonic control on foreland basin fill. Sequence stratigraphy, subsidence analysis, stratigraphic modelling, and reservoir modelling applied to the German Molasse Basin: Contr. Sedimen. Geol, Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, v. 20, 1998, 140 p.