Diagenesis of the Upper Jurassic Carbonate Rocks Within Deep Geothermal Boreholes of the North Alpine Foreland Basin in Germany

Elena Mraz, Markus Wolfgramm, Inga S. Moeck, and Kurosch Thuro

Abstract

Upper Jurassic carbonates serve as a geothermal reservoir within the north Alpine foreland basin (so-called Molasse basin). The pore space development of the Upper Jurassic is an important factor for the success of geothermal projects or any other reservoir production. Hitherto, successful geothermal projects have cumulated in the area around Munich (Germany), as porosity and permeability of the southward dipping strata decrease with depth towards the Alps. The porosity decline can be caused by a change in facies or by a different grade in diagenesis, which has not been sufficiently analyzed yet. The diagenesis of the Upper Jurassic, especially the porosity, was analyzed in the southern part of the Molasse basin at depths less than 3.500 m. The first step in our approach was the microfacies analysis of rock samples to characterize the primary pore space. The microfacies results show a change in facies (transition zone) southwards, indicated by planktonic organisms in black, low porose carbonate rocks. Due to Alpine tectonics and the formation of the typical wedge shaped north Alpine foreland basin, synsedimentary fractures and fault zones developed in the carbonates. Compared to the matrix those fracture and fault systems provide the main pathways for fluid flow. In the second step, diagenetic fluids were analyzed by fluid inclusion and cathodoluminescence measurements within calcite and dolomite crystals at different cement phases to understand the diagenesis of those deep buried carbonates. The microfacies analysis is important for the identification of high porosity domains and should be considered in reservoir exploration.

Keywords

Reservoir characterization • Diagenesis • Geothermal production • Carbonate rocks • Pore space

1 Upper Jurassic Carbonate Reservoir

1.1 Deep Geothermal Energy in Bavaria

The geothermal reservoir in Bavaria (south-east Germany) is provided by Upper Jurassic carbonate rocks, which host a warm to hot fluid within fractures and pore space. The Upper Jurassic is explored as a low enthalpy hydrothermal resource (Agemar et al. 2014) within the north Alpine foreland basin, the so-called Molasse basin. Hitherto, deep hydrogeothermal projects are concentrated in the area around Munich, Germany. There, the Upper Jurassic (Malm) reservoir is reached at depths of 2.500 to 3.500 m b.l.s. with fluid temperatures ranging between 65 and 150 °C. Due to the wedge shape of the foreland basin, the Upper Jurassic strata dips to the south, and therefore shows an increase in temperature and pressure southwards. However, the porosity and permeability of the strata decrease towards the Alps. Hence, for the success of geothermal projects, the pore space development of the Upper Jurassic carbonate rocks needs to be understood.

This paper aims to analyze and understand the porosity decline of the Upper Jurassic carbonates with depths towards the south. Nowadays, there are two theories about this decline; first it can be caused by a change in facies (depositional environment), and secondly by a different grade in diagenesis. Up to now, these possible causes have not been sufficiently analyzed for the deep buried Upper Jurassic, depths lower than 3.500 m. In the first part, the depositional

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A. Shakoor and K. Cato (eds.), *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018—Volume 4*, https://doi.org/10.1007/978-3-319-93133-3_9

environment of the Upper Jurassic carbonate rocks is described, which were then affected in a second step by diagenesis.

2 Geology and Tectonic Evolution of the Molasse Basin

Today, the north Alpine foreland basin is composed of an Upper Jurassic and Cretaceous basement, which is underlain by Permo-Carboniferous troughs and Variscan crystalline complex (Lemcke 1988). The basin is filled by Cenozoic sedimentary rocks, alternating sequences of sandstone with claystone. The Upper Jurassic carbonates were deposited within an epicontinental sea connected to the northern part of Tethys. The carbonate rocks encompass limestones, marlstones and dolostones, which interfinger with each other (Meyer and Schmidt–Kaler 1989). The Upper Jurassic is further subdivided into a bedded and massive facies in southern Germany. The bedded facies contains alternating layers of limestone and marlstone, whereas the massive facies, also called reef facies, is built by reef and reef-like organisms, and can additionally be dolomitized. The dolomitization is a diagenetic process, which affects the carbonate rocks differentially. During the Cretaceous, the Upper Jurassic sediment rocks were exposed and eroded; consequently the Upper Jurassic strata could be partially karstified (Koschel 1991). Nowadays, the Upper Jurassic crops out at the Franconian and Swabian Alb in the north of the Molasse basin and is reached at depths of around 5.000 m at the northern Alpine boundary.

The epicontinental Upper Jurassic sea (Franconian platform and Helvetic shelf) (Fig. 1) was connected by the Hessian Seaway to the north with the northern German Basin, to the west with the Paris Basin and to the south with the Tethys (Ziegler 1990). To the east and north east, the sea was restricted by the Bohemian massif and to the north and northwest by the Rhenish massif (Ziegler 1990) (Fig. 1). Accordingly, the biostratigraphy can be parallelized to the Paris Basin and the northern boreal realm of the Tethys. The depositional environment is a limestone sedimentation which is interrupted by marlstone layers. In the area around Munich, a large ooid platform is described by Meyer and Schmidt–Kaler (1989). The Upper Jurassic strata and reservoir can reach a thickness of up to 400 m (Pomoni-Papaioannou et al. 1989).

The Upper Jurassic depositional environment can be subdivided into five facies realms in the Molasse basin (Fig. 1). The two facies realms, Swabian and Franconian, are described at the type regions at the Swabian and Franconian Alb respectively in the north. To the south, the Swabian and Franconian facies merge into the Helvetian facies, which was deposited on the Helvetian shelf and not anymore on the Franconian platform (Fig. 1). To the west, the Swabian facies intersects with the northern facies of the Rauracien and the southern Argovian facies, in the area of Switzerland today. The Argovian facies further merges into the Helvetian facies to the south. The five facies realms are

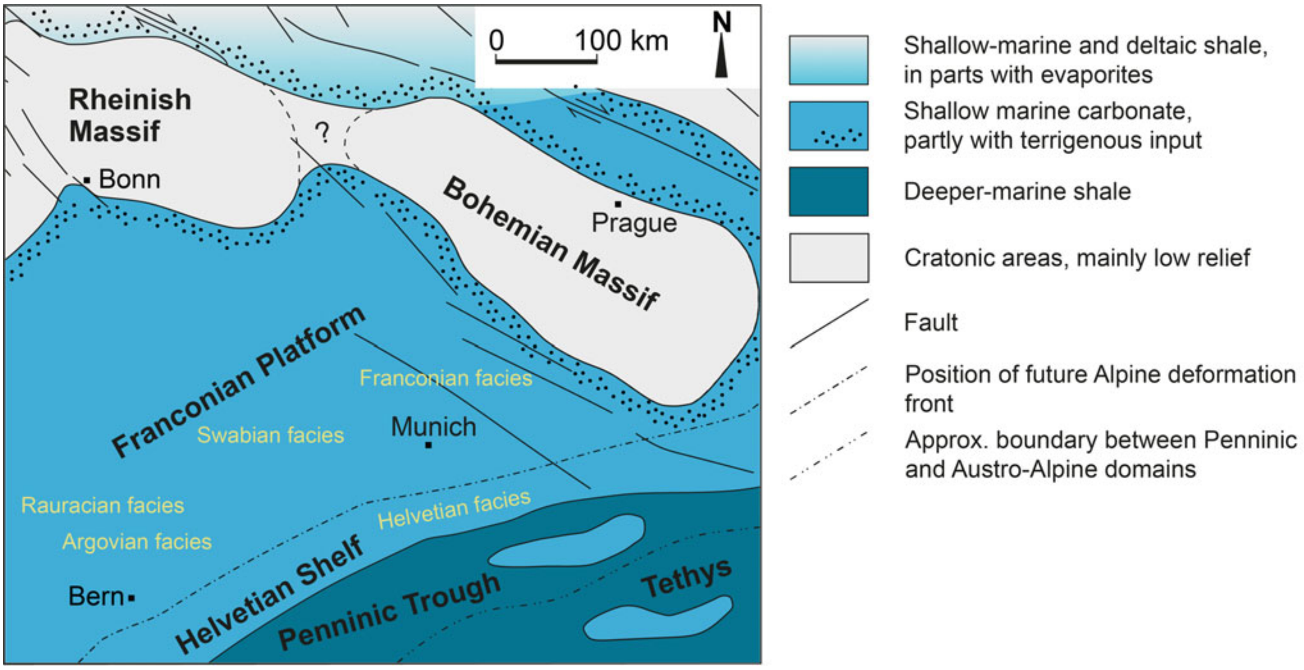

Fig. 1 Paleogeography of southern Europe during the Kimmeridgian to Tithonian (middle to late Upper Jurassic) [after Ziegler (1990)]

classified by lithostratigraphy and the Rauracien and Argovian facies are additionally classified by the biostratigraphy after Gygi (2012). The lithostratigraphy is not applicable at boreholes, where rock chips are the only rock samples and bigger fossils, such as the ammonites necessary for the biostratigraphy, are rarely included. Consequently, the lithostratigraphy and biostratigraphy cannot be applied at the deep boreholes where only rock chips are available.

During the Upper Jurassic, the Franconian platform was located at the passive northern margin of the Tethys and was affected by synsedimentary tectonics parallel to the passive margin (Ziegler 1990). During the latest Jurassic and early Cretaceous, the landmass was uplifted and the Penninic ocean was closed (Ziegler 1990). At the beginning of the Cenozoic, the Alpine orogeny started, which developed the wedge shape foreland basin in the north and south of the Alps. Consequently, the Upper Jurassic strata was influenced by Alpine tectonics, which caused synsedimentary fractures and fault zones (Büchi et al. 1965). Those fractures and fault zones were in part reactivated during the Cenozoic and strike east-west, parallel to the Alps.

3 Diagenesis

The porosity development of carbonate rocks is mainly influenced by diagenesis. Up to now, diagenesis of the Upper Jurassic has been studied (Liedmann 1992; Liedmann and Koch 1990; Reinhold 1996, 1998b) at outcrops at the Swabian and Franconian Alb, around 200 km northwest of Munich. Those studies are now extended to the southern part of the Molasse basin with the Upper Jurassic at depths lower than 3.500 m. The southern, deeper part of this study is around 50 km south of Munich.

The diagenesis encompasses multiple processes which form a sedimentary rock from a sediment. Carbonate rocks are altered by diagenesis (Machel and Buschkuehle 2008; Reinhold 1998a), around one meter below the sediment surface, very early in the process. In the Upper Jurassic carbonate rocks, mineralization is the main diagenetic factor, containing recrystallization processes such as dolomitization and calcification, as well as silification and hydrocarbon migration. The mineralization occurs in the pore space of the matrix and is linked to fractures, evident by partly or completely filled calcite fractures.

Pore space can be increased by up to 13% by the process of dissolution or by dolomitization (Böhm et al. 2011; Machel 2004), resulting in an effective porosity of around 20% (Beichel et al. 2014). However, it can also decrease by recrystallization and precipitation. Therefore, it is necessary to characterize the influencing processes.

In addition, there is the process of karstification, which needs to be separated from the term dissolution. Karstification phenomena, such as caves, are described for Upper Jurassic carbonate rocks by Frisch and Huber (2000), very critically by Villinger (1988) for outcrops, and were assumed for one borehole within the Molasse basin. However, karstification is not present within the Upper Jurassic rocks of the Molasse basin.

For precipitation of crystals and for some recrystallization reactions, fluid flow is necessary, like the process of dolomitization with Mg^{+2}-rich fluids. Those fluids can be stored in fluid inclusions within the crystals. Primary fluid inclusions contain the present fluid during the growth of the crystals. On the other hand, secondary fluid inclusions are along former fracture planes, and represent fluids at a later stage. In addition, the relative age of the fluid inclusions is analyzed by cathodoluminescence. Cathodoluminescence of crystals is caused by characteristic lattice defects of foreign atoms during diagenesis (Boggs and Krinsley 2006).

4 Methods

To analyze and characterize the processes which cause the porosity decline, rock samples of the Upper Jurassic in the Molasse basin were used. The rock samples were either rock chips (cuttings) or drill cores. The rock chips were produced in the drilling mud during drilling and were influenced by the drilling process. Rock samples of the Upper Jurassic carbonate rocks were from deep boreholes distributed all over the Molasse basin. Drill cores and cuttings were made to thin sections, which were half-colored with Alizarin Red S. The thin sections were analyzed by a polarization microscope and described according to rock color, microfossils, and texture (Dunham 1962; Folk 1959, 1962). The microfacies was analyzed by microfossils to determine the depositional environment, and further the primary pore space was described.

The diagenetic fluids were evaluated in fluid inclusions using microthermometry combined with cathodoluminescence. The fluid inclusions were located within calcite or dolomite crystals along growth zones or at former fracture planes. Therefore, it was possible to describe the evolution of the diagenetic fluids. In addition, the cathodoluminescence could determine, using a cold cathode, the relative age of the different cement generations. Using microthermometry at salty aqueous two-phase fluid inclusions, the salt content and minimal trapping conditions (T, P) could be measured (Goldstein 2001). The minimal trapping conditions were determined by the homogenization temperature, where the vapor phase homogenizes to the liquid phase in a

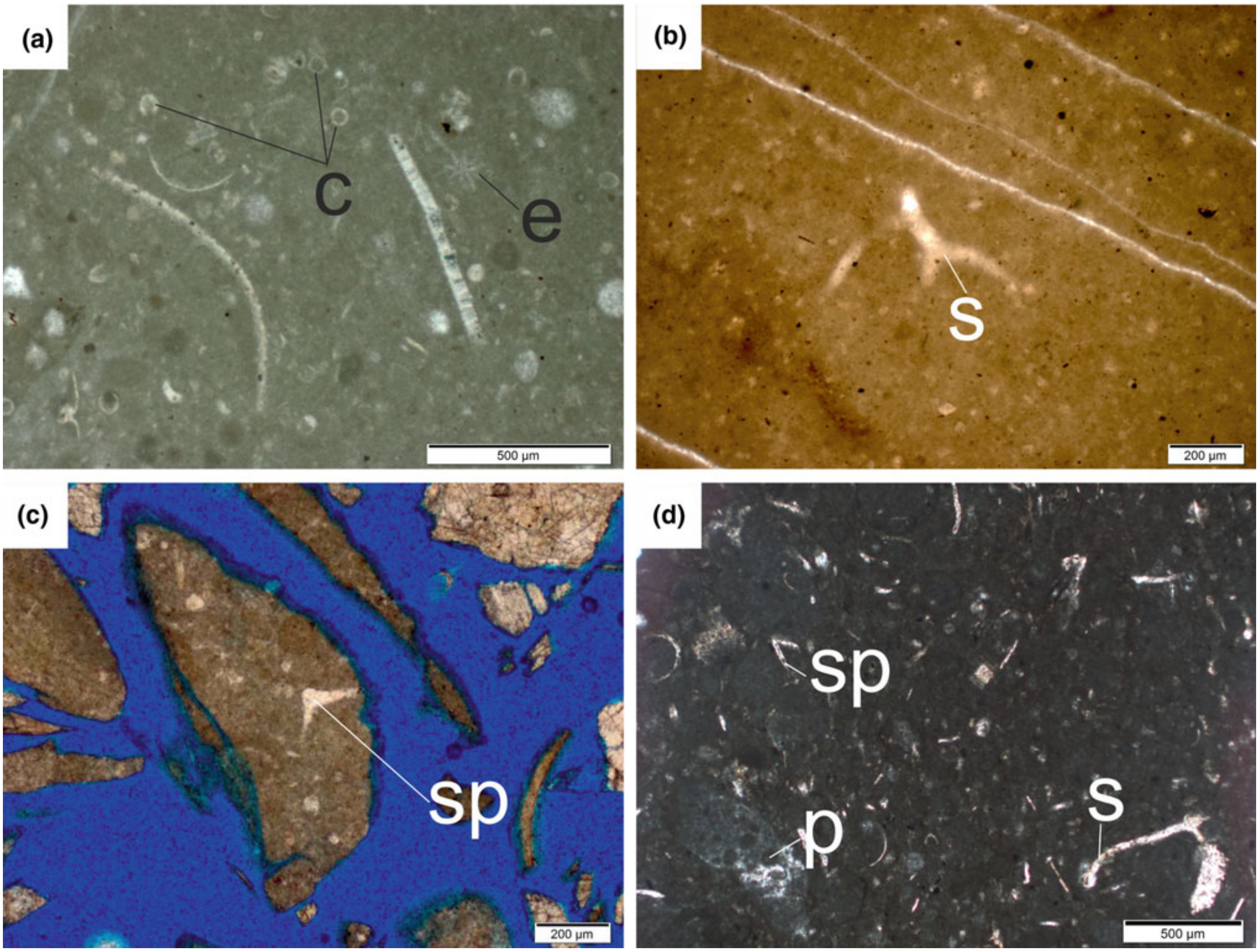

Fig. 2 **a** Quinten-Fm. (wackestone) with characteristic microfossils, the calpionellids (c), and bioclasts like echinoderms (e); **b** Transition zone wackestone with abundant Saccocoma (s); **c** Cuttings of a transition zone wackestone with sponge spiculae (sp); **d** Transition zone wackestone with peloids (p) sponge spiculae (sp), and Saccocoma (s). Thin section photos in transmitted light, **c** dyed with blue resin. *Photos* Elena Mraz

liquid-vapor system. The salt content was calculated from the ice-melting temperature after Driesner (2007); Driesner and Heinrich (2007).

5 Results

The microfacies analysis in the southern area of the north Alpine foreland basin indicates a change in depositional environment compared to the typical developed Franconian and Swabian facies. The depositional environment in the south of Munich shows a pelagic sedimentation due to an increase in planktonic organisms, like the planktonic crinoid Saccocoma (Fig. 2), for the early Upper Jurassic. Further, reef organisms are preserved as bioclasts within a fine-grained limestone with no visible porosity in regard to the thin sections (Fig. 2c, d). Accordingly, the bioclasts were transported as reef debris to the southern area. In addition, the encountered Upper Jurassic carbonates rocks in the deep, southern area show a grey to black rock color, no porosity, and no productivity. Still, the Helvetian facies (Quinten-Fm.), with characteristic calpionellids (Mohr and Funk 1995) (Fig. 2a), is not encountered within the analyzed boreholes of the Molasse basin. In addition, the Argovian facies (Wildegg-Fm.) is visible by clastic intermediated layers in a deep analyzed borehole east of Lake Constance (Fig. 3). Therefore, a transition from the Franconian platform to the Helvetian shelf is assumed in the area south of Munich and depicted in Fig. 3. Consequently, the depositional environment changes with increasing depth and becomes more diverse than was previously assumed.

The diagenetic fluids within the analyzed calcite and dolomite crystals showed a relative similar trend for the basin. All measured homogenization temperatures were

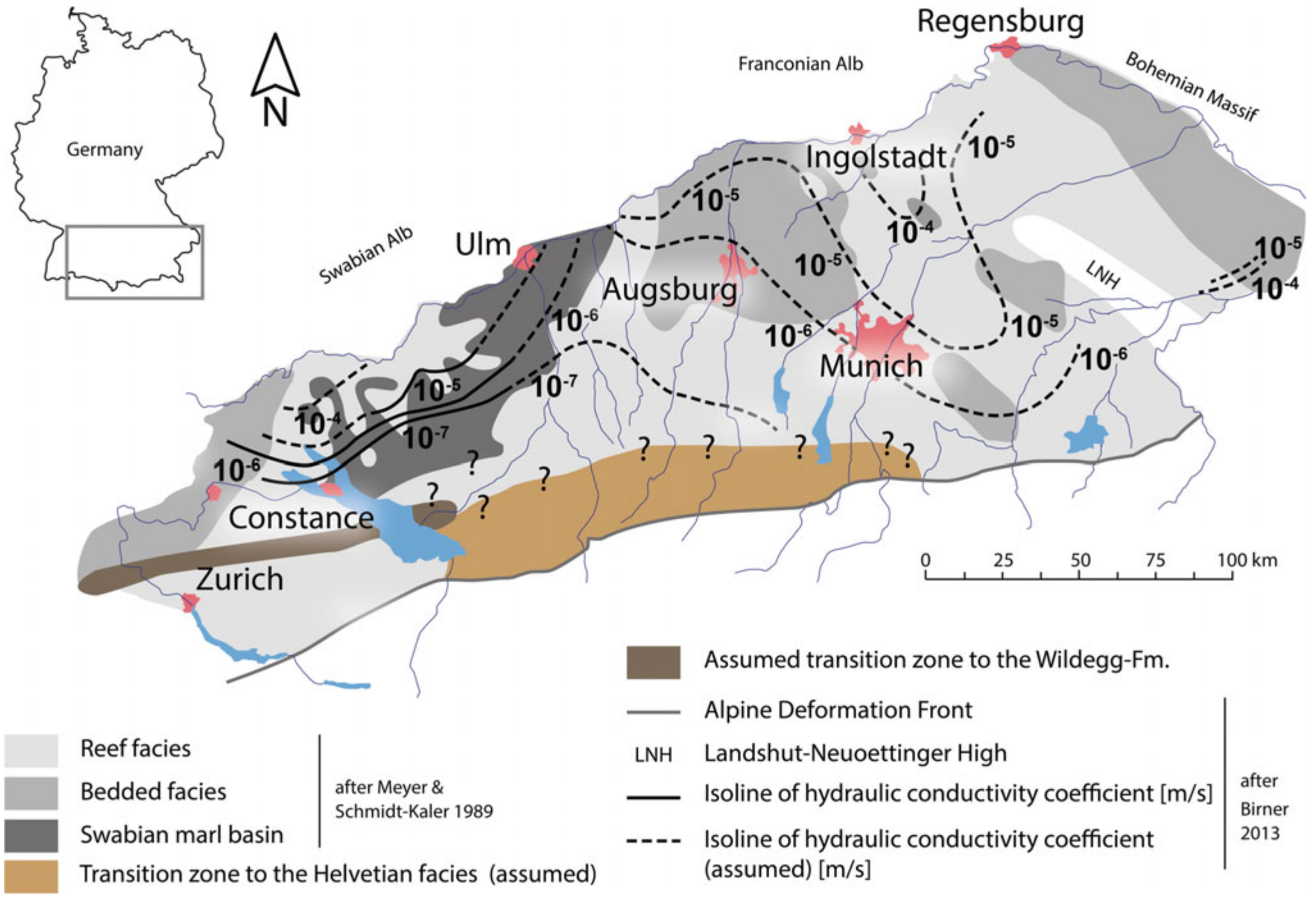

Fig. 3 Geological overview of the new facies distribution from the Franconian platform to the Helvetian shelf within the Molasse basin and coefficient of hydraulic conductivity during the late Oxfordian (Birner 2013; Meyer and Schmidt–Kaler 1989)

above the recent reservoir temperature. Additionally, the salt content of the fluid inclusions was diluted compared to the sea water present during the sedimentation within the Tethys.

6 Discussion

In some literature less intense karstification is named as a cause for the decline in porosity towards the south (Koschel 1991). Other studies named the Helvetian facies as a possible cause, due to its low porosity and black rock color (Lemcke 1988). However, the current microfacies studies show that the black carbonate rocks, intersected at the deep boreholes, contain no calpionellids and cannot be classified by the Helvetian facies. Hence, for the black, low porose Upper Jurassic carbonate rocks with planktonic organisms a new classification is needed, the so-called transition zone facies. The transition zone represents the change of the Franconian platform to the Helvetian shelf in the south, and thereby the change in depositional environment. Therefore, the Helvetian facies is suggested not to be the cause for the porosity decrease. It can be assumed that the transition zone might be the cause for the lowly porous limestones.

Higher homogenization temperatures than recent reservoir temperatures can either be caused by a change in the geothermal gradient or by an influx of hot fluids, perhaps from deeper formations. The two possible causes will be further analyzed by applying additional methods, such as isotope signatures. The dilution of the salt water, the former sea water of the Tethys, can be caused by a meteoric groundwater flow, as it is discussed in previous research (Prestel et al. 1991). The dilution of the former seawater indicates fluid flow within the low porous aquifer and is evident in calcite filled fractures. The matrix shows no visible porosity, therefore, fractures provide the main pathways for fluid flow in the Upper Jurassic reservoir.

The results indicate a porosity control by the facies type, as the platform to shelf transition facies is aligned with the low porosity domain, evidenced by low productivity wells. Hence, fluid flow is dominated by fractures within the transition zone in the deep southern basin, explaining the low reservoir productivity. The microfacies analysis is crucial for reservoir characterization and the localization of successful wells.

7 Summary

The rock sample analysis combined with fluid inclusions measurements shows that the matrix and thereby the facies (depositional environment) have a minor influence on the porosity and productivity of the Upper Jurassic carbonate rocks. Consequently, fractures and fault systems provide the main pathways for fluid flow. However, the change in depositional environment cannot be the only cause for the porosity decline.

There are differences in the pore space development between the area of Munich and the southern part of the Molasse basin, which need to be further characterized. One still unclear process is the dolomitization depending to a high extent on the supply of magnesium-rich fluids.

The microfacies analysis is a basic method in reservoir characterization and helps to determine high and low porosity domains. The presented results are important for hydrocarbon and geothermal exploration, as well as for subsurface storage.

Acknowledgements This research is supported by the Federal Ministry of Economic Affairs and Energy on the basis of a decision by the German Bundestag with the support code 0324004.

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