Hydraulic and hydrochemical properties of the deep carbonate aquifers in SW-Germany

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Keywords: deep aquifers, carbonate aquifer, geothermal, hydraulics, hydrochemistry

ABSTRACT

The Upper Jurassic (Malm) limestone and the middle Triassic Muschelkalk limestone are the major thermal aquifers in the southwest German alpine foreland. The aquifers are of interest for production of geothermal energy and for balneological purposes. Thus, the hydraulic and hydrochemical properties of the two aquifers are evaluated and compared with each other.

1. INTRODUCTION

The deep Upper Jurassic carbonates are the most important reservoir rocks for hydrothermal energy use in Southern Germany. Especially in the Munich area of Bavaria (Germany), several geothermal power plants and district heating systems were installed since 2007 (Schellschmidt et al. 2010). In SW-Germany (Baden-Württemberg), the Upper Jurassic thermal aquifer is of shallower depth (Fig.1, 2), therefore colder and the thermal water is at present rather used for balneological purposes including heating of nearby buildings, but could as well be used for district heating systems as well. Far less well-known than the Upper Jurassic is the Upper Muschelkalk aquifer, which has a significantly higher temperature due to its deeper position and is therefore especially interesting for geothermal purposes.

First scanty hydraulic and hydrochemical results concerning the Upper Jurassic aquifer are given in Andres & Fritsch 1981, Bertleff 1986, Stober 1986, Andrews et al. 1987, Bertleff et al. 1988, or Prestel 1990. First investigations of the Upper Muschelkalk aquifer are presented in Bertleff et al. (1988), whereas newer hydraulic and hydrochemical investigation are presented in Stober (2013, 2014).

2. GEOLOGICAL FRAMEWORK CONDITIONS OF THE SW-GERMAN MOLASSES BASIN

Geologically, the investigation area is located in the southwestern part of the German Molasse basin, in the federal state Baden-Württemberg. The course of the river Danube and the Upper Jurassic of the Swabian Alb form the northwest border. The eastern border of the investigation area follows the river Iller and the southwestern border is linked to the lake Constance (Fig. 1).

Figure 1: Location of the investigation area in the SW-German Molasse basin. Fig. 1 shows the location of the cross section (Fig. 2).

The investigation area is part of the so-called Molasse basin, a foreland basin of the Alps that formed during the Cenozoic Oligocene and Miocene as result of the flexure of the European plate under the weight of the orogenic wedge of the Alps. The basis of these Molasse sediments – at least in the investigation area – is formed by the Upper Jurassic dipping from the outcrops at the Swabian Alb in southeastern direction below the Cenozoic sediments. Below the Jurassic, follow the Triassic series (Fig. 1, 2). Our investigations are focused on the Upper Jurassic and the Triassic Upper Muschelkalk, two carbonate aquifers, both dipping gently in southeastern direction below the Cenozoic Molasse sediments reaching a depth of more than 3,000 m at the boundary to the alpine orogeny (Bertleff 1986).

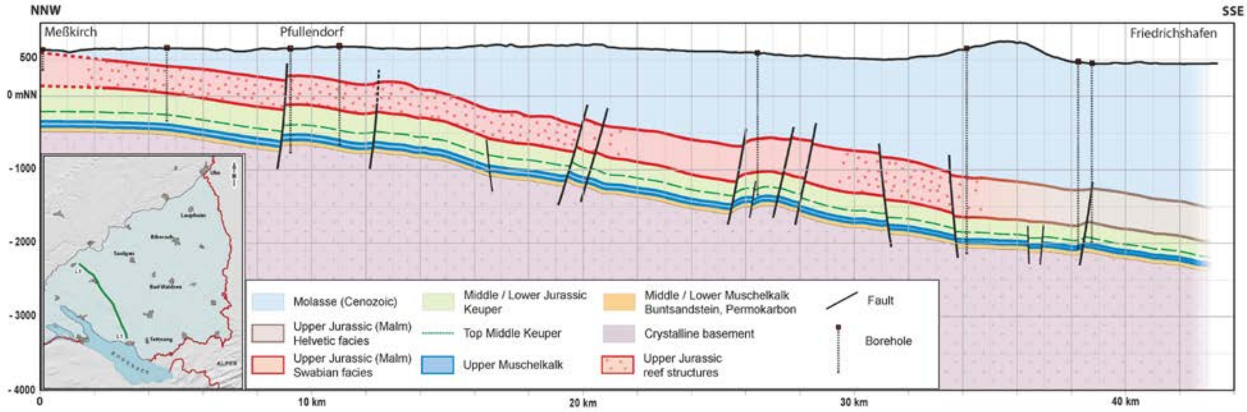

Figure 2: Geological cross section through the Molasse basin showing the Upper Jurassic and the Upper Muschelkalk aquifer. In the Upper Jurassic the different facies are illustrated: reef and basin carbonates of the Swabian facies and the Helvetian facies (modified after Jodocy & Stober 2009).

Between the two carbonate aquifers extends the 60 – 130 m thick lithostratigraphic unit of the Keuper, consisting of dolostones, shales, claystones and evaporates, followed by the Lower and Middle Jurassic series of 20 – 50 m and 120-180 m thickness resp. Especially the Lower Jurassic is composed of very tight clay and marlstones. Additionally in both series, there are thin layers of limestone and siltstone (Geyer & Gwinner 2011). Nevertheless, the hydraulic potentials of the Upper Jurassic and the Upper Muschelkalk aquifer are uncoupled from each other, showing very different flow directions and differences in hydraulic head of up to 300 m (Stober 2013). Obviously, there should be no hydraulic interaction between the two carbonate aquifers.

3. HYDRAULIC PROPERTIES OF THE TWO CARBONATE AQUIFERS

Reservoir quality of the Upper Jurassic varies strongly, depending on sedimentary facies, diagenesis, dolomitisation, karstification, and tectonic situation. The thickness of the total Upper Jurassic in the investigation area can reach values of up to 550 m (Geyer & Gwinner 2011). The Upper Jurassic carbonate aquifer consists of more than 250 m thick, locally dolomitisisied limestone (Bertleff et al. 1986, 1988, Villinger 1977). The Swabian facies, located in the middle and northwestern part of the investigation area, developed in a shelf environment with reef facies in the northwest and basin facies in the central part. While reef detritus built up the carbonates of the reef facies, the basin facies consists of banked limestone. Since the matrix-porosity of the reef facies tends to be higher than in the basin facies the recrystallization of limestone into dolomite, associated with a volumetric reduction, primarily takes place in the reef (Böhm et al. 2011). Therefore, the reef facies in the northwest has generally a higher porosity accompanied with a better hydraulic conductivity (>10-4 m/s) than the thinner bedded, banked basin facies in the central part of the investigation area, which has a lower hydraulic conductivity (Fig. 2). Karstification features are present in the entire Upper Jurassic, spatially related to faults and thick bedded to massive dolomites with a gentle decline in SE-direction. Signatures from borehole and seismic data for the central and northern zone characterize the karstification (Stober et al. 2013). Farther in the southeast the Swabian facies of the Upper Jurassic changes into the Helvetian facies, characterized by darker, very tight limestones with a significant amount of marls, developed under distral conditions (Meyer & Schmidt-Kaler 1996). As a result, the permeability is very low depending mainly on fissures or the very low matrix porosity of the carbonates (Koch & Sobott 2005) (Fig. 3).

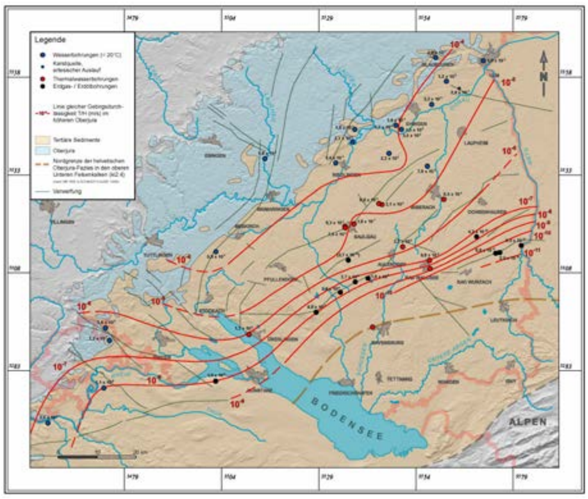

Figure 3: Hydraulic conductivity (T/H, m/s) in the Upper Jurassic aquifer.

Due to the above-mentioned tectonic stress together with the vertical displacement history, faults and fractures developed, leading to an additional increase in permeability. Fault zones are located preferentially in the northwestern, higher permeable Swabian reef facies and hence geomechanical weaker part of the Upper Jurassic aquifer.

Facies of the Upper Jurassic is changing from NW to SE, causing more intensive karstification and faulting in the NW-part of the investigation area. In consequence the hydraulic conductivity reduces by several orders of magnitude in SE-direction and thus with increasing depth (Stober & Villinger 1997, Stober et al. 2013a). So, the variation of the hydraulic conductivity is related to lithological variations in facies and the resulting degree of karstification and faulting.

The deeper laying Upper Muschelkalk aquifer (Middle Triassic) is a fractured and karstified limestone aquifer, with fractured dolomites. Karstification and fractures are preferentially in the upper part the so-called Trigonodusdolomit. Depending on the permeability of the underburden (Middle Muschelkalk) and overburden (Keuper formation, upper Triassic) the overall thickness of the aquifer can gain several meters (Hagedorn & Simon 2005). Generally, the thickness of the total Muschelkalk is decreasing in the investigation area in ESE-direction. While in the western part, the thickness of the Upper Muschelkalk is about 75 m it is dwindling away in the SE of the investigation area (Stober & Villinger 1977).

In SE-direction (Fig. 1) with increasing depth the dolomite-fraction of the Upper Muschelkalk-limestone is increasing and the Lower Muschelkalk develops as a sandstone aquifer. In the investigation area there should be no or hardly any saline deposits in the Middle Muschelkalk (Bock et al. 2009, Geyer & Gwinner 2011). In most parts of the investigation area, the crystalline basement underlies the Muschelkalk. Only farthest in NW thin Buntsandstein-layers form the basis of the Muschelkalk. North of the lake Constance, some relicts of a Carboniferous / Permian sedimentary basin of northern Switzerland extend, representing there a local basis of the Muschelkalk. Groundwater circulation in the Upper Muschelkalk occurs along fracture and bedding planes, often enlarged due to karstification processes. Doubtless, the before mentioned tectonic stress together with the manifold vertical displacement history leaded to an increase in fracture and fault systems.

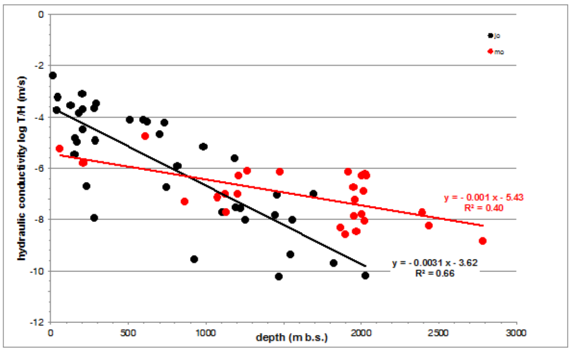

Figure 3: Decrease of hydraulic conductivity with increasing depth in the Upper Jurassic and the Upper Muschelkalk aquifer

All drilling cores of the deep wells showed karstification processes. In consequence, the hydraulic conductivity of the Upper Muschelkalk aquifer is only slightly decreasing with depth, resp. in SE-direction (Stober 2013), contrarily to the strong, facies derived decrease of hydraulic conductivity in the Upper Jurassic aquifer (Fig. 4).

4. HYDROCHEMICAL PROPERTIES OF THE TWO CARBONATE AQUIFERS

Hydraulic well tests provide amongst others water samples and thus are the key data on hydrochemical analyses and isotope studies. This paper compiles several hundred checked, validated hydrochemical data of two carbonate aquifers in the Molasse basin of SW-Germany. The presented data derive from deep wells in the depths range from several hundred meters to 3500 m.

The total of dissolved solids (TDS) in the Upper Muschelkalk waters are much higher than those in the Upper Jurassic, which often show drinking water quality up to depths of 1200 m b.s. (Fig. 5). Below 1300 m depth TDS in the Upper Jurassic is increasing significantly, reaching values of more than 10 g/kg in about 2000 m depth (Fig 5). The highest TDS-value of 35 g/kg is observed in 3500 m depth. Contrarily, TDS in the Upper Muschelkalk reaches already in 1300 m depth about 10 g/kg and in the 2000 m about 65 g/kg. The highest TDS-values of 75 g/kg are found in 2500 m depth (Fig. 5), showing a much higher salinity than seawater (35 g/kg). TDS-values of the Upper Jurassic and the Upper Muschelkalk aquifer follow distinct correlation curves, showing an increase of TDS with depth.

The hydrochemical data bear information on the origin and development of deep water. The composition of fluids at shallow depth (Upper Jurassic < 1300 m; Upper Muschelkalk < 900 m) having low TDS-values is strongly controlled by the minerals of the reservoir rock.

- Upper Jurassic aquifer: Ca-HCO3 water, related to fractured, karstified limestone (calcite, dolomite, quartz, clay minerals)
- Upper Muschelkalk aquifer: Ca-SO4-HCO3 water, due to the fractured, karstified limestone, with thin marly clay layers and dolomite, containing sulfate-rich strata underneath the aquifer, rarely within the aquifer.

The thermal waters in the Upper Jurassic with low NaCl-concentrations show in the majority of cases increasing calcium- with coexistent decreasing magnesium-concentrations (Fig. 5a), probably caused by dolomitisation of calcite. During this process, by which dolomite is formed, magnesium ions of the fluid replace calcium ions in the calcite. Therefore, the calcium-concentration in the fluid is increasing while magnesium is decreasing. This process does not affect HCO3 in the water. Calculations, using the computer-program PHREEQE (Parkhurst et al. 1980), show that the dolomitisation-process is strongly temperature dependent. Increasing the temperature from 20°C up to 100°C will double the Ca/Mg-ratio in water.

Increasing the NaCl-concentration in the fluid will only slightly enhance the Ca/Mg-ratio. The calculations support the observations and explain the findings in core-samples described by Geyer & Gwinner (2011).

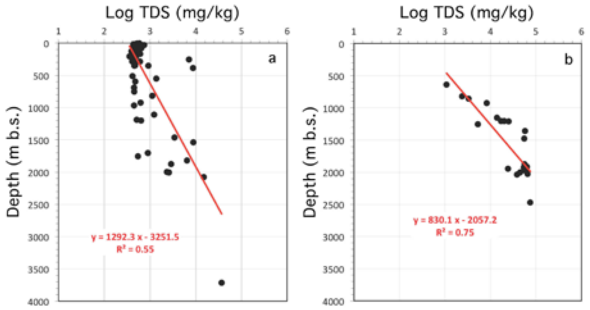

Figure 5: Total dissolved solids (TDS) in dependence of depth in the Upper Jurassic (a) and Upper Muschelkalk (b) aquifer. The figures show correlations of Log TDS vs. depth.

The NaCl-concentrations in the Upper Muschelkalk aquifer are almost in all analyses significantly higher than in the Upper Jurassic. In contrast to the Upper Jurassic waters Magnesium in the fluids of the Upper Muschelkalk is rising with increasing calcium, so no recent dolomitisation should occur. While calcium is increasing, HCO_3 is decreasing. To analyse the temperature and salinity effect on the calcium-carbon-ratio (Ca/C) we used the computer program PHREEQE (Parkhurst et al. 1980). The results showed that the Ca/C-ratio rises with both, increasing NaCl-content and/or increasing temperature. So, the observed increase in Ca and decrease in HCO_3 in the Upper Muschelkalk is most probably an effect of increasing salinity and temperature.

TDS increases with depth (Fig. 5) and the thermal water in both aquifers develop to a Na-Cl-type water independent of the type of the aquifer rock. In both aquifers the Chloride-concentration is increasing in SE-direction, resp. with increasing depth. While in the Upper Jurassic aquifer chloride in the area south of Ravensburg reaches values of up to 10 g/kg, the chloride-concentration in the Upper Muschelkalk is higher than 40 g/kg. However, the high salinity within the Upper Muschelkalk aquifer (and Upper Jurassic) is still far below saturation with respect to halite.

And now the example for a table; feel free to style the table as suits your needs, using 9 pt font preferably. Please make sure the captions for figures or tables are always on the same page and in the same column as the related figure or table! In case of larger figures

Acknowledgements

Many thanks to BMU (Ferderal Ministry for the Environment, Nature Conservation, and Nuclear Safety, Germany) for the generous support (grant nos: 0327542 and 0325136).

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