XXXVIII
IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University of Silesia Press 2010

abstract id: **215**

topic: **4**
Mineral and thermal water

4.1
Geothermal resources

title: **3D-seismics to detect preferential groundwater pathways and reservoirs in the deep buried geothermal carbonatic upper Jurassic aquifer in Greater Munich (South Germany)**

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keywords: hydrogeothermal energy, carbonate rocks, 3D-seismics, hydrogeological model, Germany

INTRODUCTION

The carbonatic Malm aquifer of the South German Molasse Basin represents the biggest hydrogeothermal reservoir in Germany. The first doublet system (array of extraction and injection wells) for heat production was implemented in Greater Munich in 2003. Seven doublet systems are in use and five other doublets and one triplet are under construction presently. To support the sustainable operation of the power plants for heat and electricity production the potential hydraulic and thermal interaction of several doublets is the object of investigation in the project "Geothermal characterization of karstic-fractured aquifers in Greater Munich" (South Germany) under the leadership of the LIAG (Leibniz Institute for Applied Geophysics) and the LfU (Bavarian State Office for the Environment).

STUDY AREA — GEOLOGY

In the greater area of the Bavarian capital Munich the upper Jurassic strata is outcropping in the North (Swabian-Franconian Alb) and in general dipping gently to the south-east to about 5000 m depth south of Munich according to the general downbending of the European crust towards the Alps (Fig. 1).

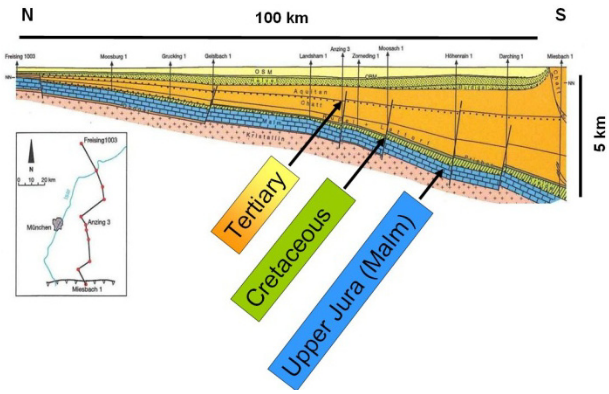

Figure 1. Downbending of the European crust towards the Alps (source: Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie, 2010, after Lemcke 1988).

In the upper Jura a vast carbonate platform with sponge reefs mainly distributed in the Malm delta and some coral reefs in the uppermost Jurassic strata stretched out over the study area. Diagenesis has lead to the formation of dolomites and dedolomites, which represents nowadays zones with higher secondary porosities. Main fault zones penetrating Jurassic and Tertiary strata are E-W and NE-SW striking syn- and antithetic normal faults with throws of more than 200 m (Fig. 2).

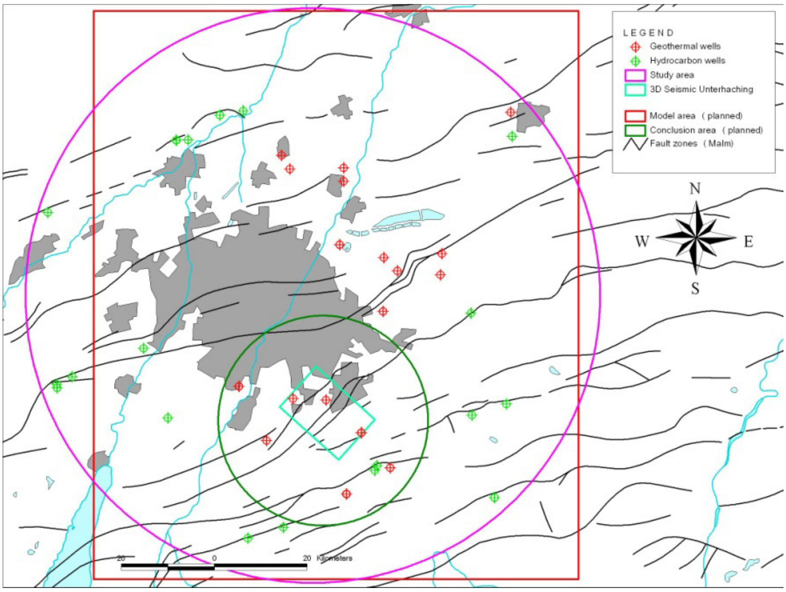

Figure 2. Greater Munich (study area).

As an analogue to the Danube rupture at the Northern border of the Molasse Basin, main tectonic structures strike 60-70° N ("swabian") and 45° ("erzgebirgisch").

HYDROGEOLOGY

In the study area well productivity of the deep buried and confined Jurassic aquifer is high. Transmissivities in a range between 0,1 to > 3000 m^2/day reflect the heterogeneity of the carbonatic aquifer. In general, and sometimes after massive acidification the doublets have production rates up to 150 l/s. Whereas the permeability of the Malm is slightly decreasing towards the south and as supposed by many authors, also the degree of carstification, temperatures are rising because of the greater depth (Fig. 3).

Inflow zones, derived from flowmeter measurements, zones of total loss of drilling fluid or geophysical borehole measurements (Temp log, FMI, etc.), vary in depth related to Top Malm from well to well. In a broader view over the Molasse Basin some wells indicate 2 or 3 zones of potential inflow associated with carstification: A carstified zone at Top Malm, sometimes showing total loss of drilling fluid, sometimes with collapse structures like dolines and two carstification levels in depths of ca. 100 m and ca. 250–300m beneath Top Malm. Except one well in the study area groundwater composition indicates a connected groundwater body. Regional groundwater flow is directed in the northern Greater Munich from Northwest to Southeast, whereas in the south eastern part they are very difficult to explain. Recharge for the deep buried upper jurassic limestones lie in regions North and west of Munich with a long travel time and low flow velocities, indicated by interpretation of the stable isotopic composition (ages of more than 10.000 years).

TEMPERATURES

Temperatures are rising from about 70°C in the north with increasing depth to 150° to the SE, in general according to the dip of the jurassic dolo- and limestones (Fig. 3).

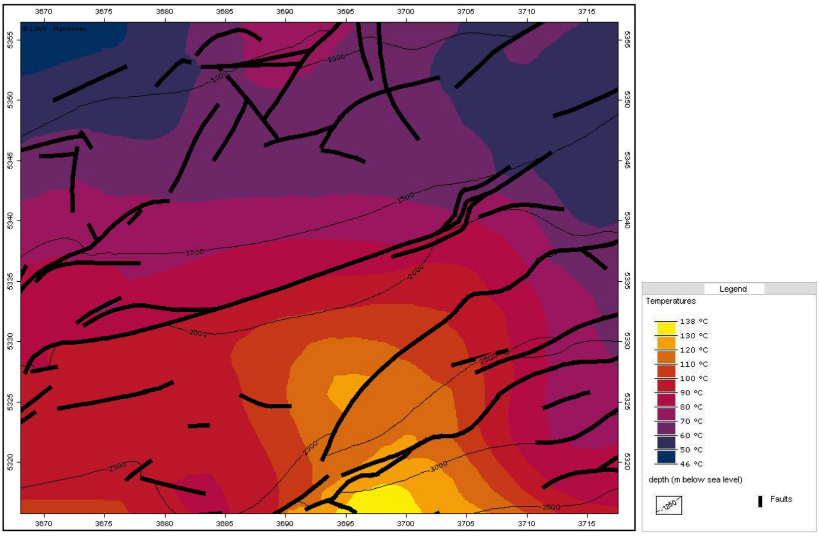

Figure 3. Temperature distribution TOP Malm. Isolines showing m bsl. (LIAG, 2009).

Temperature anomalies in the region are supposed to have their origin in convective heat transport linked to fault zones.

3D SEISMICS

In a first step a 3D-seismic survey was carried out in the central investigation area "Unterhaching" (5×5 km, see Fig. 2 and 4).

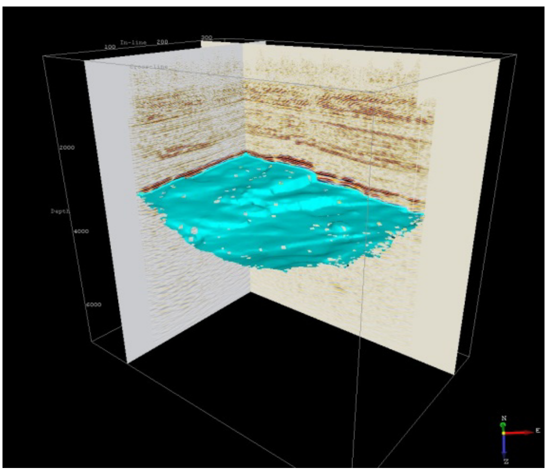

Figure 4. 3D-Cubus of the 3D Seismic research area "Unterhaching" (blue: Top Malm horizon with main fault zones).

Collapse structures with round appearance are often seen on coherency depth slices in the Malm (Fig. 5). Crossing points of different faults with different water hydrochemistry might be the reason because of the effect of mixing corrosion in carbonates. On the other hand, in the regional strike-slip framework north of the Alps, pull-apart-basins could also be a possible geometrical initial process to enhance karstification. An overlay of amplitudes and coherency directly underneath one collapse structure show a nearly vertical anomaly (Fig. 6, black arrow is pointing to the collapse structure seen in Fig. 5). In general faults and layering/facies differentiation could be displayed very well with an overlay of the amplitude section and coherency attribute.

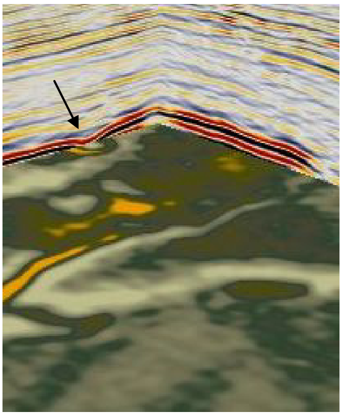

Figure 5. Subset of 3D cube with potential sinkhole (collapse structure, diameter ca. 50 m), view from south, inline 301, crossline 163, depthslice 2466 m below sea level).

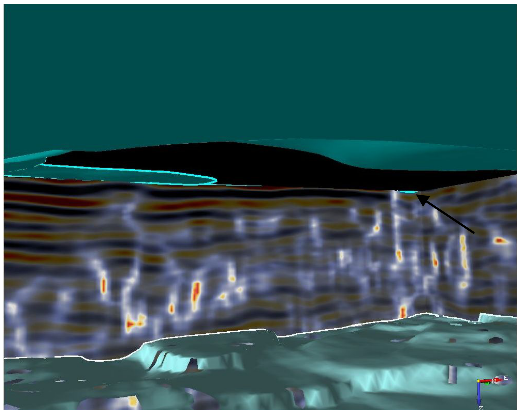

Figure 6. Subset of 3D cube, view on potential sinkhole (arrow, see fig. 5) from below, blue horizons: Top and bottom Malm, amplitude overlayed by coherency attribute).

CONCLUSION — FORECAST

It turned out to be that 3D-seismics is a very useful tool to characterize potential water-bearing fracture zones and facies, which are supposed to control the hydraulic behaviour and even the process of karstification. The high resolution of tectonic structures provided by the 3D-seismic model will be linked to the coarser 3D-model for greater munich, which was derived from 2D seismic profiles.

Studies of the tectonic evolution indicate that the present stress field of the region might be related with the newly registered micro-seismicitiy encountered since February 2008 SE of Munich.

Today, seven geothermal power plants in Greater Munich are producing ca. 65 MW geothermal energy and thus contribute ecologically to the energy consumption of the area. In order to get deeper insights to flow and transport mechanisms in the carbonatic aquifer detailed processing of the seismic data at the LIAG in combination with borehole logs and hydraulic tests will lead to a better understanding of the fractured and karstified carbonatic series. This will cumulate in a hydrogeological model (HGM) for Greater Munich. Finally, based on the HGM a numerical thermo-hydraulic model will be applied to simulate the interaction between neighbouring doublets.

ACKNOWLEDGEMENTS

The project "Geothermal characterization of karstic-fractured aquifers in Greater Munich" is financed by the BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany).

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International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0