Refinement of the geothermal play type concept by comparison of two foreland basins

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ABSTRACT

Geothermal resources are traditionally classified either in terms of shallow, intermediate and deep geothermal energy based on resource depth or in terms of low-, medium- and high-enthalpy resources according to reservoir temperature zones. The traditional definition is thereby primarily adapted to site development and drilling costs, and not to the geothermal resource itself. Particularly in Europe where the thermally conduction-dominated play types are widespread, this classical scheme is neither constructive for the assessment of geothermal resources nor for the comparison of learning curves within a same reservoir type.

The play type concept introduced by Moeck (2014) offers a classification scheme of geothermal resources based on geological criteria, notably on the characterization by heat transport mechanisms and geological parameters on reservoir type and quality. The PlayType project aims at comparing the three major geothermal provinces in Germany, namely the North German Basin, Upper Rhine Graben and Molasse Basin with similar geological structures and settings worldwide. The applied methods consist of a combination of seismics, quantitative structural geology, reservoir geology, geothermics and numerical thermal-hydraulic modelling.

In particular, the Molasse Basin in southern Germany as part of the North Alpine Foreland Basin is compared to the Alberta Basin in western Canada, thus taking advantage of findings and conclusions in both plays. By contrast to several existing studies, we focus on the assessment of the main fluid and heat transport processes for a better understanding of thermal anomalies induced by gravity-driven groundwater flow and paleoclimatic conditions. The selection of reference plays like the Molasse Basin ensures that the assessment of geothermal resources is based on geological criteria.

Furthermore, the existing play type definitions and criteria are critically evaluated, verified by the new findings and eventually updated. The work performed within the PlayType project will lead to the first national play type map in GeotIS and supplement the new e-learning platform, which is (like GeotIS) run by the Leibniz Institute for Applied Geophysics.

1. INTRODUCTION

The classical approach in geothermal exploration consists in cataloguing geothermal resources according to temperature or depth mainly for technical and economic reasons. The recent Play-Type concept (Moeck 2014) aims at classifying geothermal resources according to geological criteria and heat transport mechanisms to assess reservoir quality. Internationally applicable criteria allow worldwide comparisons between resources of similar geological settings and structures (play type).

Among the three main German geothermal provinces of Upper Rhine Graben, North German Basin and Molasse Basin, the latter shows the highest geothermal potential. The Molasse Basin has been studied for decades, for its geology, structures and stratigraphy (Meyer and Schmidt-Kaler 1996, Schwerd et al. 1996), for oil & gas (Bachmann et al. 1982, Bachmann et al. 1987, Bachmann et al. 1992, Brink et al. 1992, Reischenbacher and Sachsenhofer 2011, Sachsenhofer et al. 2006), and more recently for geothermal energy (Birner et al. 2012, Böhm 2012, GeoMol Team 2015, Jodocy and Stober 2009). Many boreholes tap the Upper Jurassic (Malm) carbonate aquifer mainly for district heating but also for electricity production. The Malm carbonate aquifer is considered to be the largest thermal water resource not only in Germany but also in Central Europe (Goldschneider et al. 2010). Indeed, carbonate aquifers frequently present a high secondary porosity and permeability due to karstification. Therefore they probably constitute the most important thermal water resources outside of volcanic areas (Goldschneider et al. 2010).

The Molasse basin has been studied hydrogeologically, and recently by coupled heat and fluid flow. However, the geostatistical assessment of the 3D thermal structure based on temperature measurements in boreholes to date represents the most reliable prognosis of subsurface temperature in the Molasse Basin.

Strikingly, a prominent cold temperature anomaly to the east and northeast of Munich could not yet be satisfactorily explained.

Cross-formational gravity-flow of groundwater is long known to act on geological timescales. Similar to studies in the Alberta, North German and Paris basins, we perform thermal-hydraulic modelling of the glacial influence on the present-day thermal and flow regime in the Molasse Basin. The result is compared with the geostatistically evaluated 3D thermal field. The calculation of the Rayleigh number for the heterogeneous carbonate aquifer permits to differentiate zones with a higher versus lower geothermal potential.

2. GEOLOGICAL SETTING

2.1 Molasse Basin

The Molasse Basin in southern Germany and Upper Austria is part of the North Alpine Foreland Basin (NAFB). The Molasse basin is up 130 km wide perpendicular to strike and 400 km long in Germany. The depth of the Upper Jurassic aquifer reaches more than 4000 m close to the Alpine front.

In southern Germany, marine transgression at the beginning of the Jurassic led to progressive flooding of the Variscan basement. In the Upper Jurassic (Malm), a carbonate platform formed under varying conditions (Meyer and Schmidt-Kaler 1990, Birner et al. 2012, Frisch and Huber, 2000). On the deeper shelf, in the southern and southwestern part of the Molasse Basin, rather dark carbonates rich in clay and organic material accumulated pertaining to the so-called Helvetic facies, being characterized by a generally very low hydraulic conductivity. In a northerly direction and towards the northwest, on the higher shelf, and in between reef complexes, carbonate sedimentation led to the formation of the stratified facies called ‘Schichtfazies’ with interbedded marls. The latter is also characterized by a relatively low hydraulic conductivity. Towards the east and northeast, mainly in the Bavarian and Austrian part of the Molasse Basin, carbonate accumulation formed the reef facies on top of submarine barriers in a higher energy environment (Meyer and Schmidt-Kaler 1990, Frisch and Huber 2000). These massive reef carbonates have the highest hydraulic conductivities and are prone to karstification (Birner et al. 2012, Birner 2013). After the maximum extension of sponge reefs in the Malm Delta, the shallowing sea caused the disintegration of the reef platform into smaller units (Meyer and Schmidt-Kaler 1990). Only in the Late Jurassic, the regression caused the sea to retreat into the deepest parts of the basin, the Wasserburg Trough.

The southeasterly emersion of the up to 600-m-thick Malm carbonates initiated an extensive karstification which could act earliest from the regression in the Latest Jurassic to the transgression of the Lower Marine Molasse in the Oligocene in the western part of the Molasse Basin (Bachmann et al. 1987, Frisch and Huber 2000). However, the massive carbonates of the reef facies being most prone to karstification are located in the central and eastern parts of the Molasse Basin, so that the magnitude of karstification in these parts was greatest in the depth realm of 150 to 200 m below the top of the Malm (Frisch and Huber 2000). The duration of karstification is about 45 Ma. By contrast to karst systems in the west, the rapid burial by Cretaceous sediments in the east appears to have caused a better preservation of these karst systems which are presently characterized by extraordinary high permeabilities (Frisch and Huber 2000).

The pre-Tertiary sediments and thus the foreland basin began to subside during the Late Eocene (Schmid et al. 2004), followed by the deposition of Lower Oligocene flysch units and of orogen-derived continental clastics during the late Oligocene to late Miocene (Roeder and Bachmann 1996). The post-flysch (Oligocene - Miocene) palaeogeographic evolution of the entire North Alpine Foreland Basin (NAFB) and the facies distribution in the NAFB was driven by two major types of processes, which are related to the tectonic evolution of the Alpine orogen (Kuhlemann and Kempf, 2002, Schmid et al 2004): (1) a direct influence by tectonic processes at the thrust front, and (2) an indirect impact of Alpine uplift and tectonics, transformed by varying sediment discharge.

Today, the Upper Jurassic (Malm) limestones are cropping out to the north of the Danube River where they are called Swabian and Franconian Jura west and east of the Ries impact crater, respectively. To the south, they are dipping beneath the thick Tertiary molasse sediments (Frisch and Huber 2000). Lying at a depth of about 2000 m below Munich, they reach a depth of more than 4000 m at the Alpine front (Brink et al. 1992). The molasse sediments are composed of cyclically deposited clayey and sandy series (from bottom to top Lower Marine Molasse, Lower Freshwater Molasse, Upper Marine Molasse and Upper Freshwater Molasse) (GeoMol Team 2015).

The Molasse Basin contains numerous faults which are related to thrusting and uplift of the Alps and the contemporaneous downbending of the European plate and formation of the Molasse Basin (Schmid et al. 2004). In the western and central parts, the W-E striking faults parallel to the basin axis and to the Alps were formed as synthetic and antithetic faults due to downbending and extension of the top of the European crust (Bachmann et al. 1982, Brink et al. 1992). In the eastern part, the WNW-striking faults are related to the uplift of the LNH and the Bohemian Massif (Bachmann et al. 1987).

In the east, the Malm terminates against the Danube Boundary Fault where the Variscan Bohemian Massif is uplifted up to 1700 m (Frisch and Huber 2000). In front of the boundary fault of the Bohemian Massif, another important basement structure, the horst of the Landshut-Neuöttinger Hoch (LNH) with a throw of up to 1300 m separates the Wasserburg Trough in the west from the Lower Bavaria Trough in the east (Bachmann et al. 1987, Frisch and Huber 2000).

2.2 Alberta Basin

The Alberta basin is part of the West Canada Sedimentary Basin (WCSB), which is about 25 times larger than the NAFB. The Alberta Basin is about 700 km wide perpendicular to strike and more than 1000 km long in Alberta. The thickness of the sedimentary wedge increases to about 6000 m close to the Rocky Mountains.

The Alberta Basin formed above the Precambrian basement corresponding to the Canadian Shield. Sedimentation started in the Cambrian, then paused until the Devonian (415 – 360 Ma) when it deepened during a first uplift of the Rocky Mountains. From the Devonian until the Late Cretaceous, marine sediments progressively accumulated in the deepest parts of the basin. This evolution was contemporaneous with Middle Jurassic to Eocene compressive deformation which formed the Cordilleran structural elements leading to the modern Rocky Mountains Syn-tectonically, loading caused downwarping of the western margin of the North American Craton and increasing sedimentation in the subsiding foreland, resulting in a thick Upper Cretaceous-Tertiary fill in the Alberta basin. Renewed uplift and consequent erosion immediately postdates the termination of compressive deformation in the Middle Eocene. The amount of erosion ranges between 1 and up to 2.5 km.

3. DATA AVAILABILITY

3.1 Hydrogeological models and data in the Molasse Basin

The groundwater flow regime in the western Molasse Basin was studied by Rühaak et al. (2010). They performed a 3D steady-state, purely conductive model with an emphasis on the Malm aquifer to compare modelled with observed subsurface temperatures. They explain deviations from their model by advective heat transport mechanisms and conclude that flow parallel to fault zones in accordance with the regional flow regime causes thermal anomalies at fault tips.

Frisch and Huber (2000) present a numerical groundwater model based on a detailed hydrogeological model, including measurements of hydraulic potential and thermal water mass balancing, to deduce flow directions within the Malm aquifer.

The highest hydraulic conductivities above 10^{-4} m/s are found along the northern basin margin and in the southern Lower Bavarian basin. Hydraulic conductivities of 10^{-5} m/s are characteristic for the karstified zones to the south of the Danube (Birner et al. 2012). Towards the Helvetic facies in the west, hydraulic conductivities decrease relatively fast to values lower than 10^{-8} m/s. In the Wasserburg trough and the region of Munich, high hydraulic conductivities of 10^{-5} m/s are related to high degrees of karstification (Birner et al. 2012). Knowledge about the distribution of hydraulic conductivities is important to reduce the geothermal risk.

Only the upper 200 m of the limestones are sufficiently karstified to represent a significant aquifer (Frisch and Huber 2000). The karstified Malm is hydraulically coupled to the overlying Upper Cretaceous Cenoman Sandstone. In general the Malm aquifer is confined. The water table lies well below terrain level towards the Alpine front but locally shows artesian conditions close to the Danube River (Andres and Frisch 1981, Frisch and Huber 2000). It has been known for long that pressure within the Malm aquifer is sub-hydrostatic and hydraulically connected to the Danube (Lemcke and Tunn 1956). Aquifer recharge occurs on the one hand along the Danube river and especially to the north of it through the outcropping Upper Jurassic mainly in the Swabian Alb and on the other hand by leakage through the overlying Quaternary and Tertiary sediments (Andres and Frisch 1981, Frisch and Huber 2000). The general groundwater flow follows the gradient of the Danube River and thus is directed from the west to the east (Birner 2013, Frisch and Huber 2000). By contrast to other sedimentary basins, the groundwater in the Malm aquifer in the central Molasse Basin is fresh water with a mineralisation below 1g/L (Frisch and Huber 2000, Fritzer et al. 2018, Stober et al. 2014). The chemical composition of the thermal water changes markedly from the northern margin towards the inner parts close to the Alpine front. Water-rock interactions lead to a higher mineralization going along with a higher sodium and chloride content and a decrease of carbon dioxide (Stober et al. 2014).

Przybycin et al. (2015) use a lithospheric-scale 3D structural model of the entire Molasse Basin area and the adjacent part of the Alpine orogen to model the present-day 3D thermal field. They assumed a conductive heat transport. According to Przybycin et al. (2015), the conductive thermal regime of the Molasse Basin, characterized by relatively low thermal conductivities, is influenced by the Alps and particular the Tauern Gneiss of significantly higher thermal conductivity. The sediments of the Molasse Basin show a blanketing effect by contrast to a chimney effect caused by the Tauern Window. More generally, Przybycin et al. (2015) argue that contrasts in thermal conductivity and radiogenic heat production are the main reason for the observed thermal anomalies. They conclude that local misfits can be explained by additional fluid flow contributing to the heat transport.

By contrast to conductive modelling, 3D numerical modelling of coupled fluid flow and heat transport requires a much higher horizontal and vertical resolution and more information about hydrogeological parameters (Przybycin et al. 2015).

Subsequently, Przybycin et al. (2017) performed 3D numerical modelling of coupled fluid flow and heat transport. Negative thermal anomalies, notably a zone to the northeast and east of Munich with temperatures up to 40 K colder than expected from its position

(Agemar and Tribbensee 2018, Agemar et al. 2012), present a particular risk for geothermal exploration and the reasons for their existence are still a matter of debate. The results by Przybycin et al. (2017) show that the shallow thermal field is strongly affected by basin-wide fluid flow. Most strikingly, they assign a strong thermal impact to the hydraulic conductivity of the Molasse sediments, but only a low thermal influence to hydraulically conductive faults. Some misfit between the observed and modelled subsurface temperatures is due to the relatively coarse resolution, a lack of details and the need for a better knowledge of thermal and hydraulic properties.

The most accurate prognosis of temperature at the Top Malm is given by the GeotIS composite model (Fig. 1, Agemar and Tribbensee 2018, Schulz et al. 2009) which results from a combination of a 3D structural model of the Malm aquifer and a purely statistical 3D subsurface temperature model evaluated by the LIAG (Agemar et al. 2012, Agemar et al. 2014). The largest temperature uncertainties originate from the input data of the temperature model, especially the temperature measurements in boreholes (Agemar and Tribbensee 2018). Model reliability and extent is limited horizontally by borehole distribution and data quality and vertically by borehole depth.

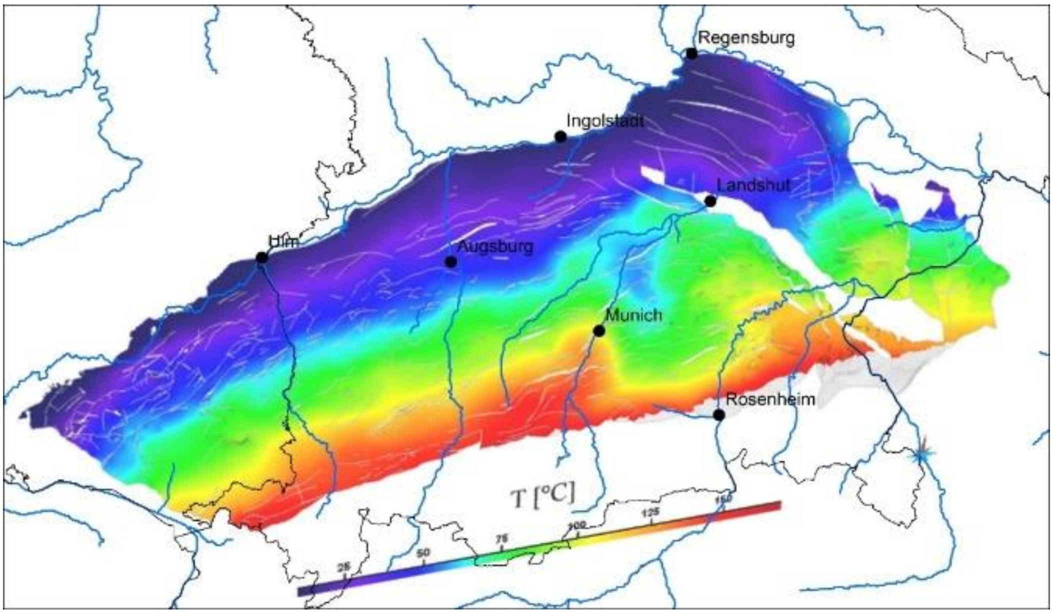

Figure 1: 3D structural model of the Top Malm (Upper Jurassic) for Baden-Württemberg, Bavaria and Upper Austria. The temperature distribution is derived from the 3D temperature model of the LIAG (Agemar and Tribbensee 2018).

3.1 Models and data in the Alberta Basin

In Alberta and neighboring British Columbia, the identification of oil and gas, but also of potential geothermal reservoirs, is based on the spatial distribution and approximate thickness pattern of Upper Devonian carbonate platforms (Weydt et al. 2017).

Jessop (1971) discovered that a glacial perturbation of heat flow exists in Canada. Under extreme conditions the observed perturbation can be as high as 20 mW/m^2, but in most cases is of the order of 10 % or less. The Alberta Basin studied by Gray et al. (2012) served as an example for their investigate of a glacial influence on subsurface temperatures in sedimentary basins using oil industry thermal data. Gray et al. (2012) found that geothermal gradients from wells shallower than 1000 m need to be corrected for paleoclimatic effects which can be derived from precise temperature logs in deep wells. Similarly, Majorowicz et al. (2012) conclude that the deep geothermal potential of the Alberta Basin is currently underestimated because thermal data from shallow wells still reflect a glacial base surface temperature of -4.4°C. Recently, Lemieux et al. (2008) numerically simulated the surface-subsurface water exchange flux and demonstrated that huge quantities of meltwater episodically infiltrate beneath glaciated areas.

4. METHODOLOGY

3.1 Importance of basin drainage pattern evolution and glaciations for thermal hydraulic modelling

Sedimentation in the (unfolded) NAFB ended progressively and diachronously, starting in the western NAFB in relation to the uplift of the Jura Mountains after 11 Ma and reaching Lower Austria around 6–5 Ma (Kuhlemann and Kempf, 2002). The Alps and the NAFB were affected by strong uplift starting at around 6 Ma in the Swiss and Western Alps and at 4–3 Ma in the Eastern Alps. The uplift resulted in reworking and erosion of more than 2 km of Molasse sediments in the western NAFB (Kuhlemann and Kempf 2002).

The drainage pattern of the NAFB and more specifically the Molasse Basin in southern Germany is highly dynamic over geological time. The Pre-Danube River started to form and evolve as soon as the sea retreated from the Molasse Basin some 7 Ma ago. The Pre-Danube plays a major role in removing the Molasse sediments eroded due to uplift. In the Late Pliocene about 3 Ma ago, the Pre-Danube loses the Aare River as headwater. At the transition from the Tertiary to the Quaternary, the Pre-Danube progressively loses tributaries from the region of the Main River to the Rhine River. The headwaters of the present-day Main River are finally lost during the Donau/Günz Interglacial between 900 and 800 ka. Only in the relatively recent past about 800 ka ago, the Danube loses the Alpine Rhine as headwater. Also, during most of the Quaternary, between 2.6 and 0.3 Ma, i.e. until the Riss glaciation, the Danube flowed in a more northern position though the Wellheim Valley into the present-day Altmühl Valley between Rennertshofen and Kelheim (Jerz and Peters 2002, Schäfer 1966). More recent dating by Fiebig and Preusser (2003) suggests that the Danube rerouting could be younger and possibly occurred during the last (Würm) glaciation (Doppler et al. 2011). In order to secure the present course, the Danube had to overcome two ridges of Upper Jurassic rock, which it crosses in the Neuburg and Weltenburg gorges (Jerz and Peters 2002). The southward shift resulted in a shortening of about 45 km (from 120 to 75 km) for an difference in altitude of about 50 m (between the confluence of the Lech River and the confluence of the Altmühl River).

River systems are highly sensitive to environmental changes, including the effects of tectonic, climatic, glacial and anthropogenic forcing (Cordier et al. 2017). In particular, the changes in the drainage pattern of the Danube River are directly or indirectly related to the glaciations in the Alpine realm.

The Early Pleistocene onset of glaciation in the Alps is still poorly understood (Ehlers and Gibbard 2008). The traditional quadripartite glacial classification in the Alps spans the Middle and Upper Pleistocene (0.78 – 0.0117 Ma) and comprises the Günz glaciation (about 800 – 600 ka), Mindel glaciation (about 460 – 400 ka), Riss glaciation (about 347 - 128 ka) and Würm glaciation (about 115 – 11.7 ka). The latter are parallelized with the Elbian, Elsterian, Saalian and Weichselian glaciations in northern Germany. The shapes of the ice sheets between glaciations and individual glacial advances can be very different (Ehlers and Gibbard 2008). The extent of glaciers at the late glacial maximum is shown by Van Husen (1987) and Geologische Bundesanstalt (2013). Recently, the last glaciation in the Alps has been numerically modelled by Seguinot et al. (2018).

3.1 Geothermal 3D modeling

3D modelling of coupled fluid flow and heat transport will be based on the 3D geological framework model built by the GeoMol Team (2015). As summarized by Frisch and Huber (2000), the consideration of hydrogeological parameters is crucial, including fluid velocities, flow direction, flow rates as well as the extent of recharge and discharge zones. Other constraints are the results from hydrochemical and isotopic studies (Mraz et al. 2019, in preparation).

A significant recharge into the Molasse Basin from the Alps in the south is excluded based on evidence from studies of other orogenic belts and adjacent forelands (Tóth 2009). The western limit of the flow system is marked by the Rhine-Danube groundwater divide which runs from the northwest to the southeast approximately 30 km to the east parallel to Lake Constance (Frisch and Huber 2000, Stober and Villinger 1997). The flow direction is from the divide to the east towards a groundwater depression in the Munich region from where the groundwater flows north and discharges in the direction of Bad Gögging to the Danube. As shown by long-term observations of decreasing hydraulic heads caused by production, the total flow rate in the Malm in the central Molasse Basin is relatively low and estimated at 1.5 m^3/s.

The LNH and related structures hydrogeologically decouple the central and western part of the Malm aquifer from the eastern part (Frisch and Huber 2000). From the groundwater apex between Landshut and Regensburg, the groundwater flows in southeastern direction towards Linz in Upper Austria where it discharges through Tertiary basal sandstone into the Danube (Frisch and Huber 2000). Another location of regional vertical discharge to the Danube is located near Straubing in Lower Bavaria. High artesian hydraulic heads and hydrochemistry near Straubing show evidence of lateral infiltration of fluid from the crystalline basement in the Bavarian Forest in the eastern Molasse Basin through deep-reaching faults (Frisch and Huber 2000).

A major difference between the Molasse Basin and the Alberta Basin certainly is the fact that the Alberta Basin is not so well drained by a major river like the Danube.

5. CONCLUSIONS

This study compares two foreland basins with a focus on the south German Molasse Basin and the western Canadian Alberta Basin. The objective is to use the results to verify, validate and refine the geothermal play type concept. In the Molasse basin, heat transport mechanisms within the Upper Jurassic (Malm) carbonate aquifer are numerically modelled by 3D coupled fluid and heat flow. Two main hypotheses are tested: (1) a possible glacial thermal influence within deeper parts of the basin by gravity-driven groundwater flow from Alpine glaciers during the last glaciation and (2) the possible effect of direct surface water-groundwater interactions between the dynamic fluvial system of the Danube River and the karstified carbonate aquifer.

REFERENCES

Agemar, T. and Tribbensee, K.: GeotIS-Verbundmodell des Top-Malm im Bereich des nördlichen Vorlandbeckens der Alpen, *Z. Dt. Ges. Geowiss.*, **169**(3), (2018), 335–341.

Agemar, T., Schellschmidt, R. and Schulz, R.: Subsurface temperature distribution in Germany, *Geothermics*, **44**, (2012), 65–77.

Agemar, T., Alten, J.-A., Ganz, B., Kuder, J., Kühne, K., Schumacher, S. and Schulz, R.: The geothermal information system for Germany – GeotIS, *Z. dt. Ges. Geowiss.*, **165**(2), (2014), 129–144.

Andres, G. and Frisch, H.: Hydrogeologie und Hydraulik im Malmkarst des Molassebeckens und der angrenzenden Fränkisch-Schwäbischen Alb, *Schriftenreihe Bayer. Landesamt für Wasserwirtschaft*, **15**, (1981), 108–117.

Bachmann, G.H. and Müller M.: Sedimentary and structural evolution of the German Molasse Basin, *Eclogae Geologicae Helvetiae*, **85**(3), (1992), 519–530.

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

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

Birner, J.: Hydrogeologisches Modell des Malmaquifers im Süddeutschen Molassebecken, Doctoral thesis, *Freie Universität Berlin*, (2013).

Birner, J., Fritzer, T., Jodocy, M., Savvatis, A., Schneider, M. and Stober, I.: Hydraulische Eigenschaften des Malmaquifers im Süddeutschen Molassebecken und ihre Bedeutung für die geothermische Erschliessung, *Zeitschrift für Geologische Wissenschaften*, **40**(2-3), (2012), 133–156.

Böhm, F.: Die Lithofazies des Oberjura (Malm) im Großraum München und deren Einfluss auf die geothermische Nutzung, Doctoral thesis, *Freie Universität Berlin*, (2012).

Brink, H.-J., Burri, P., Lunde, A. and Winhard, H.: Hydrocarbon habitat and potential of Swiss and German Molasse Basin: a comparison, *Eclogae Geologicae Helvetiae*, **85**(3), (1992), 715–732.

Cordier, S., Adamson, K., Delmas, M., Calvet, M. and Harmand, D.: Of ice and water: Quaternary fluvial response to glacial forcing, *Quaternary Science Reviews*, **166**, (2017), 57–73.

Doppler, G., Kroemer, E., Rögner, K., Wallner, J., Jerz, H. and Grottenthaler, W.: Quaternary stratigraphy of southern Bavaria, *Quaternary Science Journal*, **60**(2-3), (2011), 329–365.

Ehlers, J. and Gibbard, P.: Extent and chronology of Quaternary glaciation, *Episodes*, **31**(2), (2008), 211–218.

Fiebig, M. and Preusser, F.: Das Alter fluvialer Ablagerungen aus der Region Ingolstadt (Bayern) und ihre Bedeutung für die Eiszeitenchronologie des Alpenvorlandes, *Zeitschrift für Geomorphologie*, **47**(4), (2003), 449–467.

Frisch, H. and Huber, B.: Ein hydrogeologisches Modell und der Versuch einer Bilanzierung des Thermalwasservorkommens für den Malmkarst im Süddeutschen und im angrenzenden Oberösterreichischen Molassebecken, *Hydrogeologie und Umwelt*, **20**, (2000), 25 – 43.

Fritzer, T., Settles, E. and Dorsch, K.: Bayerischer Geothermieatlas 2018 – Hydrothermale Energiegewinnung, Bayerisches Staatsministerium für Wirtschaft, Energie und Technologie, München, (2018).

Geologische Bundesanstalt (Ed.): Der Alpenraum zum Höhepunkt der letzten Eiszeit, Posterkarte, Geol. B.-A., Wien, (2013).

GeoMol Team: GeoMol – assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources, Project report, *Bavarian Environment Agency*, Augsburg, (2015).

Goldschneider, N., Mádl-Szönyi, J., Eröss, A. and Schill, E.: Review: Thermal water resources in carbonate rock aquifers, *Hydrogeology Journal*, **18**(6), (2010), 1303–1318.

Gray, A.D., Majorowicz, J. and Unsworth, M.: Investigation of the geothermal state of sedimentary basins using oil industry thermal data; case study from northern Alberta exhibiting the need to systematically remove biased data, *Journal of Geophysics and Engineering*, **9**(5), (2012), 534–548.

Jerz, H. and Peters, M.: Flussdynamik der Donau bei Ingolstadt in vorgeschichtlicher, geschichtlicher und heutiger Zeit, mit Ergebnissen zur Landschafts- und Vegetationsentwicklung, in: Katastrophe oder Chance? Hochwasser und Ökologie: Rundgespräche der Kommission für Ökologie, **24**, Hagedorn, H. and Deigele, C. (Ed.), 95–108, *Pfeil*, München, (2002).

Jessop, A.M.: The distribution of glacial perturbation of heat flow in Canada, *Canadian Journal of Earth Sciences*, **8**(1), (1971), 162–166.

Jodocy, M. and Stober, I.: Geologisch-goethermische Tiefenprofile für den südwestlichen Teil des Süddeutschen Molassebeckens, *Z. dt. Ges. Geowiss.*, **160**(4), (2009), 359–366.

Lemcke, K. and Tunn, W.: Tiefenwasser in der süddeutschen Molasse und in ihrer verkarsteten Malmunterlage, *Bulletin der Vereinigung Schweiz.*

Petroleum-Geologen und –Ingenieure, **23**(64), (1956), 35–56.

Lemieux, J.M., Sudicky, E.A., Peltier, W.R. and Tarasov, L.: Dynamics of groundwater recharge and seepage over the Canadian landscape during the Wisconsinian glaciation, *Journal of Geophysical Research*, **113** (F1), (2008).

Majorowicz, J., Gosnold, W., Gray, A., Safanda, J., Klenner, R. and Unsworth, M.: Implications of post-glacial warming for northern Alberta heat flow – Correcting for the underestimate of the geothermal potential, *Transactions of the 36th GRC Annual Meeting 2012*, Reno, Nevada, (2012), 693–698.

Meyer, R.K.F. and Schmidt-Kaler, H.: Paläogeographie und Schwammriffentwicklung des süddeutschen Malm – ein Überblick, *Facies*, **23**, (1990), 175–184.

Meyer, R.K.F. and Schmidt-Kaler, H.: Jura, in: Erläuterungen zur Geologischen Karte von Bayern 1:500000, 4th edition, Geol. L.-Amt (Ed.), 90–111, (1996).

Moeck, I. S.: Catalog of geothermal play types based on geologic controls, *Renewable and Sustainable Energy Reviews*, **37**, (2014), 867–882.

Przybycin, A.M., Scheck-Wenderoth, M. and Schneider, M.: The 3D conductive thermal field of the North Alpine Foreland Basin: influence of the deep structure and the adjacent European Alps, *Geothermal Energy*, **3**(1), (2015).

Przybycin, A.M., Scheck-Wenderoth, M. and Schneider, M.: The origin of deep geothermal anomalies in the German Molasse Basin: results from 3D numerical models of coupled fluid flow and heat transport, *Geothermal Energy*, **5**(1), (2017).

Reischenbacher, D. and Sachsenhofer, R.F.: Entstehung von Erdgas in der oberösterreichischen Molassezone: Daten und offene Fragen, *Berg- und Hüttenmännische Monatshefte*, **156**(11), (2011), 463–468.

Roeder, D. and Bachmann G.: Evolution, structure and petroleum geology of the German Molasse Basin, *Memoires du Museum National d'Histoire Naturelle*, **170**, (1996), 263–284.

Rühaak, W., Rath, V. and Clauser, C.: Detecting thermal anomalies within the Molasse Basin, southern Germany, *Hydrogeology Journal*, **18**, (2010), 1897–1915.

Sachsenhofer, R.F., Gratzer, R., Tschelaut, W. and Bechtel, A.: Characterisation of non-producible oil in Eocene reservoir sandstones (Bad Hall Nord field, Alpine Foreland Basin, Austria), *Marine and Petroleum Geology*, **23**, (2006), 1–15.

Schäfer, I.: Der Talknoten von Donau und Lech; zur Frage des Laufwechsels der Donau vom ‚Wellheimer Trockental' ins ‚Neuburger Durchbruchstal', *Mitteilungen der Geographischen Gesellschaft in München*, **51**, (1966), 59–110.

Schmid, S.M., Fügenschuh, B., Kissling, E. and Schuster, R.: Tectonic map and overall architecture of the Alpine orogen, *Eclogae geologicae Helvetiae*, **97**, (2004), 93–117.

Schulz, R., Agemar, T., Alten, J.-A., Brunken, J., Heber, M., Kuder, J., Kühne, K, Maul, A.-A., Pester, S., Schönhofer, K., Fritzer, T., Birner, J., Schneider, M., Rauppach, K., Seibt, P., Wolfgramm, M., Brandes, J., Feldrappe, H., Obst, K., Jodocy, M. and Stober, I.: Aufbau eines geothermischen Informationssystems für Deutschland (Endbericht BMU Forschungsvorhaben 0327542), *LIAG*, Hannover, (2009).

Schwerd, K., Doppler, G. and Unger H.J.: Gesteinsfolge des Molassebeckens und der inneralpinen Tertiärbecken, in: Erläuterungen zur Geologischen Karte von Bayern 1:500000, 4th edition, Geol. L.-Amt (Ed.), 141–187, (1996).

Seguinot, J., Ivy-Ochs, S., Jouvet, G., Huss, M., Funk, M. and Preusser, F.: Modelling last glacial cycle ice dynamics in the Alps, *The Cryosphere*, **12**(10), (2018), 3265–3285.

Stober, I. and Villinger, E.: Hydraulisches Potential und Durchlässigkeit des höheren Oberjuras und des Oberen Muschelkalk unter dem baden-württembergischen Molassebecken, *Jh. Geol. Landesamt Baden-Württemberg*, **37**, (1997), 77–96.

Stober, I., Wolfgramm, M. and Birner, J.: Hydrochemie der Tiefenwässer in Deutschland, Zeitschrift für geologische Wissenschaften, **41**/**42**(5-6), (2014), 339–380.

Tóth, J.: Gravitational systems of groundwater flow; theory, evaluation, utilization, *Cambridge University Press*, New York, (2009).

Van Husen, D.: Die Ostalpen und ihr Vorland in der letzten Eiszeit (Würm) 1:500000, Geologische Bundesanstalt (Ed.), Wien, (1987).

Weydt, L.M., Heldmann, C.D.J., Machel, H.G. and Sass, I.: From oil field to geothermal utilization of two regionally extensive Devonian carbonate aquifers in Alberta, Canada, *Solid Earth*, **9**(4), (2018), 953–983.

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