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Lessons learnt from Molasse Basin and other realms in Bavaria

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GENERAL INTRODUCTION

This report describes the application of the Structural Framework and Geomanifestation concepts in two areas of different geological settings in Bavaria: the Molasse Basin as agreed in the GeoConnect³d Project Proposal and Agreement, and the exposed Variscan basement of Saxothuringian Zone, west of the Franconian Line (Figure 1).

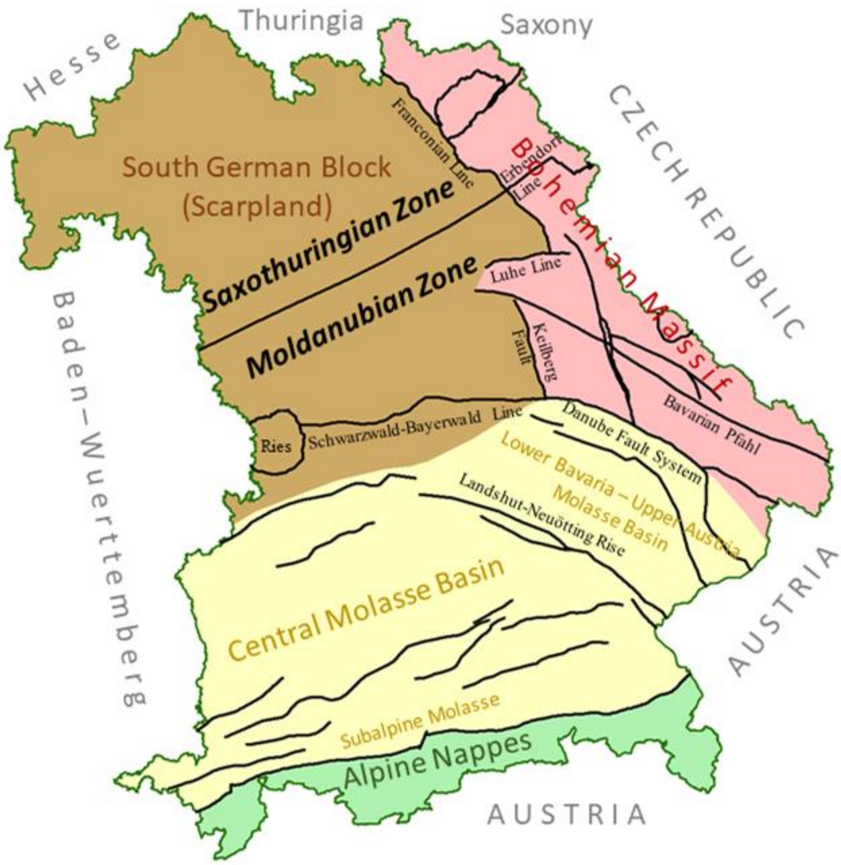

Figure 1: Principal geo-tectonic domains of Bavaria and their boundaries and subdividing limits represented by major fault systems or lineaments.

As for the Molasse Basin it turned out that the number of geomanifestations in the sense and definition of GeoConnect3d are next to nil. On screening of the rest of Bavaria, while preparing the Structural Framework for entire Bavaria, it became evident that the exposed or subcropping anchimetamorphic rock suites of the Saxothuringian feature there was a surpassingly dense occurrence of geo-manifestations. Thus this realm was chosen for testing the geomanifestations concept beyond the commitments made in the Project Proposal and Agreement.

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1 PILOT AREA DESCRIPTION

1.1 Overview of regional geological setting

Situated at the southern margin of the European Plate, Bavaria is characterized by a Mesozoic sedimentary sequence overlying and framed by Paleozoic rock suites of the Variscan basement and the Alpine Orogen to the south. Four structural domains can be distinguished: the Alps, the Molasse Basin, the Scarpland (Cuesta Region) and the Variscan basement terrain, namely the Bohemian Massif (Figure 1). Quaternary sediments are common to all regions.

The Alpine-Carpathian Orogen evolved owing to the collision of the Adriatic and European plates during Cretaceous and Tertiary, bequeathing four principal tectonic units on Bavarian territory. The nappes of the Northern Calcareous Alps, built up of Adriatic plate shelf formations, over thrusted the oceanic trench fill (Flysch), the European plate shelf sediments (Helveticum), and the southern rim of the foreland basin infill, the Subalpine or Folded Molasse (Figure 2).

Along the forefront of the emerging orogenic belt, due to the large-scale downwarping of the European plate, a foreland basin developed progressively infilled with 'molasse' sediments eroded off the northward thrusting Alps during Tertiary. In the south and west of the Alpine piedmont the top of the Molasse is shaped by several phases of Pleistocene glaciation. Jurassic and Triassic sedimentary sequences make up the footwall of the up to 5 km deep Molasse Basin. Hosting central Europe's most prolific hydrothermal aquifer at great depth, the karstified carbonate rocks of the Upper Jurassic on the surface feature the 15 Ma old Ries asteroid impact crater (Figure 2), and form the uppermost escarpment of the South German Scarpland revealing increasingly older strata towards the northwest.

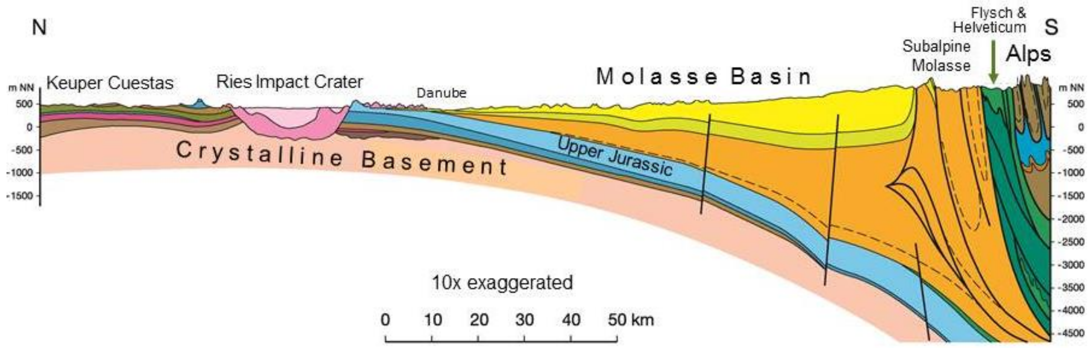

Figure 2: Geological section across the southern Cuesta Region, the Alpine Foreland and the Pre-Alps in western Bavaria (from Diepolder et al. 2015 modified after Doppler et al. 2004). Predominantly Miocene deposits of the Molasse Basin are depicted in yellowish hues. Its footwall, the south-dipping Upper Jurassic karstified carbonate rocks (light blue) feature the most prolific geothermal aquifer in Central Europe. The Crystalline Basement is made up of high-grade metamorphic rocks of the Moldanubian Zone, deformed during Variscan orogeny, and scattered late to post-Variscan plutonic stocks

The lowermost cuesta forming sequence, Buntsandstein, rests upon non-metamorphic Permian sediments accumulated in post-Variscan troughs or directly overlays the Variscan basement. This basement is divided into the anchimetamorphic rock suites of the Saxothuringian Zone, north of Saxothuringian Suture / Erbendorf Line [LfU-BY_1547], and high-grade metamorphic rocks of the Moldanubian Zone, deformed during Caledonian and Variscan orogenies, south of this suture, with both zones intruded by late to post-Variscan intrusive rocks. The basement crops out in the Bohemian Massif along the eastern border of Bavaria, and a small inlier of the Mid-German Crystalline Rise in Bavaria's very northwest (omitted in Figure 1).

1.1.1 Molasse Basin

The North Alpine Foreland Basin (NAFB), also known as the Molasse Basin, developed along the northern margins of the emerging European Alpine chain some 35 million years ago. As part of the Alpine-Himalayan orogenic belt the Alps have resulted from the collision of the African and Eurasian and associated smaller plates caught between them. The convergence of the African Plate from the south and the Eurasian plate from the north, caused the closure of the formerly extensive Tethys Ocean, and the progressive subduction of Tethyan oceanic crust culminating in a continent-continent collision between Africa and Europe. The mountain building processes culminated when the northward thrusting nappes emerged as a mountain range and the weight of the orogenic wedge made the adjacent European Plate bend downward, resulting in the formation of a deep elongated depression (the NAFB) north of the developing orogeny. In the Eocene (55 to 34 Ma ago) this foreland basin became deeper until it formed a small deep seaway, in which deep-water sediments including turbidites probably triggered by frequent seismicity, are preserved. In addition to these Flysch sediments, shelf sediments on the southern margin of European plate, were incorporated into the frontal part of the orogenic wedge and deformed. Migrating northward, the overthrusting load caused the gradual displacement of the NAFB farther north onto the downwarping foreland of the European plate. During this phase the NAFB became infilled with shallow marine and terrestrial sediments. Finally molasse sediments completed the infilling of the NAFB, creating a gently inclined depositional surface that was subsequently sculpted into an incised form by more recent erosion and glaciation. The preserved NAFB forms a northward convex arc extending for more than 1,000 km from Chambéry (in France) in the southwest to Brno (in the Czech Republic) in the northeast, overlapping parts of France, Switzerland, Germany, Austria and the Czech Republic. The basin has a maximum width of 130 km. Due to the last phase of tectonic uplift some 5 million years ago and the ongoing deposition of sediments washed down from the Alpine range the surface of the Alpine piedmont is now between 200 to 250 meters elevation at its eastern and western ends, but this rises to more than 1,000 m in the central areas adjacent to the mountain front. The southern border of the NAFB was overridden by the frontal Alpine thrusts and so is buried beneath the Alpine nappes. In marked contrast the northern border of the NAFB is simply the erosional limit of the Tertiary basin sediments onlapping onto the older bedrock of the foreland.

The infill of the Basin can be subdivided into two principal units, the Foreland Molasse and the Subalpine Molasse. The Foreland Molasse (or Plateau Molasse), represents the majority of the infill of the Basin that is exposed today. It consists of gently southerly-dipping strata that thin out north-wards where they onlap onto the older bedrock of the European Plate, whereas the inner rim is incorporated into the Alpine thrusting. This relatively narrow zone, 10 and 30 km in width, along the Alpine foothills is characterised by steeply inclined strata, tight folds and overthrusts, constituting the Subalpine Molasse, aka Folded or Imbricated Molasse (Figure 2).

The central part of the North Alpine Foreland Basin, the South German Molasse Basin, overlapping the territories of Baden-Württemberg and Bavaria, is characterized by syn- and antithetic normal faults related to flexure-like strain of the foreland basin. The faults, often arranged as trains of faults, predominantly trend subparallel to the basin's centreline and the Alpine Thrust Front. Close to the Landshut-Neuötting crystalline rise, the faults' strike is deflected subparallel to the counterfort of the northward Alpine thrust (Figure 3). All faults of the basin are blind faults, active until Badenian of mid-Miocene at the latest, solely evidenced by seismic surveys and deep drillings (cf. [DE-BY_1078]).

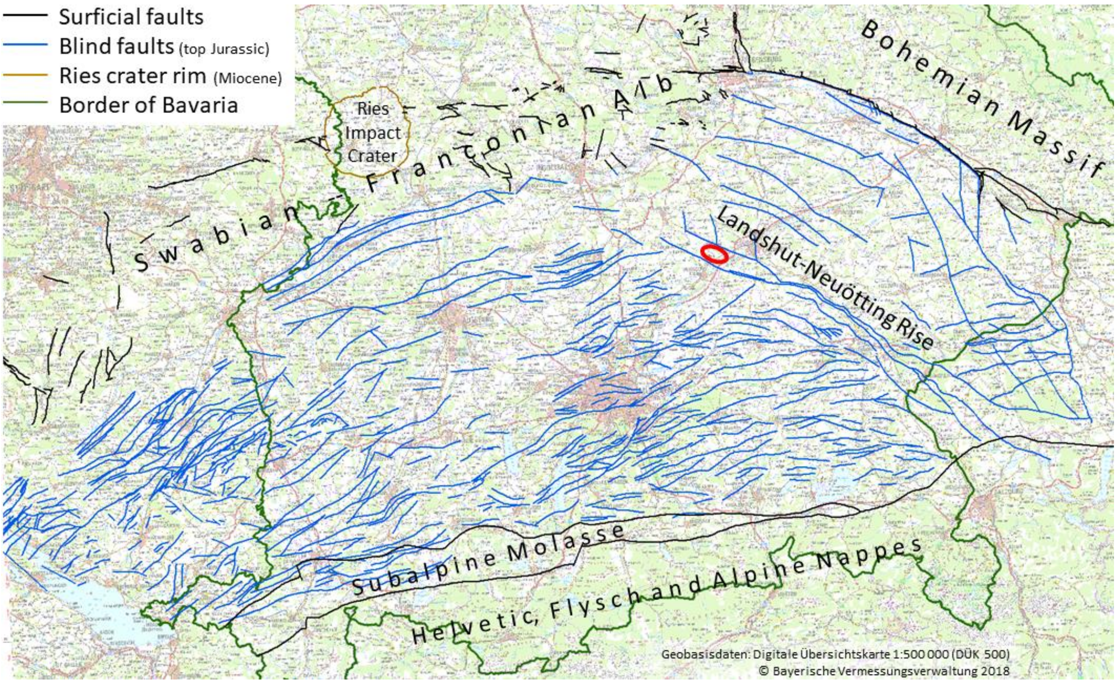

Figure 3: Fault pattern in the Foreland Molasse of the South German Molasse Basin (blue), shown as the traces at the top of Upper Jurassic (from https://data.geoscience.earth/ncl/geoera/hotLime/faults/3443). The red circle indicates the only known surficial geomanifestations of the Foreland Molasse (see text for discussion).

1.1.2 NE-Bavaria

The geomanifestations "transposing the case" testbed "Exposed Saxothuringian in north-eastern Bavaria" comprises the Thuringian Facies of the exposed Saxothuringian [LfU-BY_u4] east of Franconian Line [LfU-BY_1398] and north of Erbendorf Line [LfU-BY_1447] (Figure 4).

The Bohemian Massif is considered the largest inlier of the Variscan belt developed as a collage of several lithotectonic units. The northern part of Bohemian Massif on Bavarian territory, north of Erbendorf Line, is built up of the Saxothurigian, anchimetamorphic Cambrian to Carboniferous volcano-sedimentary sequences, folded during Variscan orogeny and intruded by late-Variscan granites and Lamprophyre dikes. The prevailing, normal (autochthonous) facies are anchi-metamorphic Cambrian (?) to Carboniferous volcano-sedimentary sequences of the Thuringian Facies.

This realm is characterized by NW-SE (high-angle Hercynian) to WNW-ESE (flat-angle Hercynian) trending faults and fault sets. The faults roughly trending SW-NE generally are paralleling major tectonic structures, such as Erbendorf Line [LfU-BY_1447], or, specifically in Franconian Forest, follow the fold axes of compressional tectonics during Early Carboniferous (Mississippian).

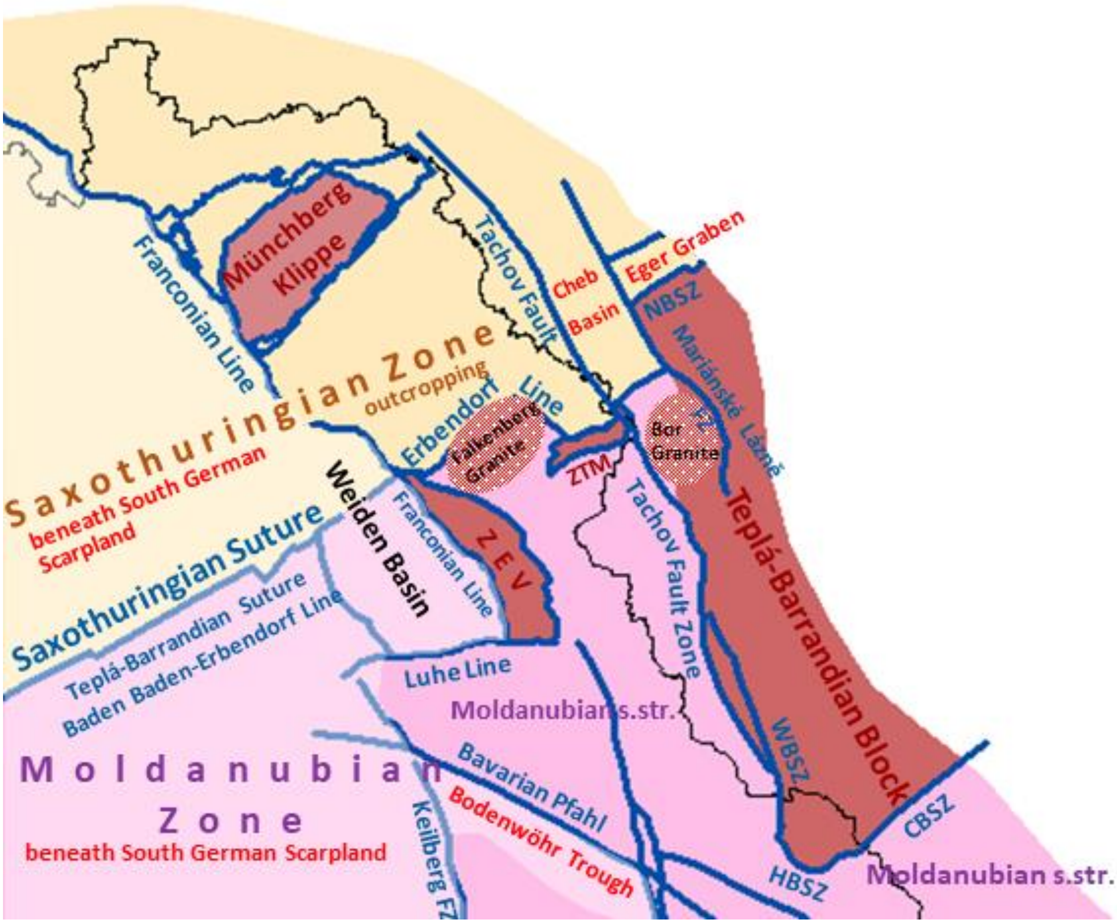

Figure 4: Variscan units of the Bohemian Massif in NE-Bavaria and eastern adjoining areas. East of the Bohemian Massif Western Margin fault systems *[LfU-BY_1583], formed by (from N to S) Franconian Line, Luhe Line and Keilberg Fault Zone, the three principal units of the Variscan basement in Bavaria emerge: Saxothuringian, Moldanubian s.str. and Teplá-Barrandian (TB) as well as outliers resembling the TB lithology. Also in exposed areas, sutures are traceable only in sections as often replaced by late Variscan intrusions (examples schematic). Post-Variscan units and structures are labelled in red. These structures are mostly reactivations caused by brittle Saxonian deformation, summarizing the Alpine orogeny's distant effects. (Clip of [LfU-BY_u19], for acronyms see [LfU-BY_ub3].)*

1.2 Specific Challanges

1.2.1 Molasse Basin

All tectonic features of the Molasse Basin are blind objects, i.e. buried under a thick succession of younger undeformed sediments, thus, they cannot be detected and traced from surface exploration. Owing to the industrial activities related to the utilization of the deep underground, specifically hydrocarbon exploration and production (E&P) culminating in the 1960th to 1980th and geothermal E&P continuously increasing since 2000, the deep subsurface of the Molasse Basin, except for its shallower parts, is well explored. However, due to the thick overburden, except for one, no surface or near surface geomanifestation can be related to the structural framework at depth. Virtually all geomanifestations observable in the Molasse Basin are the result of glacial and inter-/post-glacial processes sculpting the landscape.

1.2.2 NE-Bavaria

Unlike the Molasse Basin, the anchimetamorphic rock suites of the Thuringian facies in north-eastern Bavaria feature a vast variety of geomanifestations that can be related to the Structural Framework and neo-tectonics. As the geological setting of north-eastern Bavaria resembles the geology of the area where the idea of connecting the structural framework and geo-manifestations for an improved knowledge of the subsurface was born and conceptualised, that was to be expected.

1.3 Subsurface management

1.3.1 State of the art in Bavaria

The subsurface is the only primary source of essential resources (drinking water, hydrocarbons, raw materials, geothermal energy, etc.), and the principal provider of large storage capacities for fluids (natural gas, liquid or liquefied hydrocarbons, solar fuels such as compressed air, H_2, CH_4, etc.), and of wastes (specifically CO_2 or radwaste).

In Bavaria, of these subsurface uses only the ubiquitous groundwater abstraction for water supply, geothermal E&P and gas storage for balancing the seasonal energy variation (mainly after-use of hydrocarbon exploitation) presently play a major role, both concentrated in the Molasse Basin. Other utilisations of the deep subsurface are confined to the solution mining of salt and the valorisation of the small residuals of hydrocarbons left. Subsurface mining has been abandoned almost completely during the last decades. Only one graphite mine in the south of the Bohemian Massif is still in operation.

Except for the further boosting of geothermal E&P in areas that have been proved to be suitable and few projects of utilizing exploited hydrocarbon deposits for underground storage, no additional utilization of the deep subsurface are considered in Bavaria at present. Beyond these “mature” technologies no “prospective” utilization technologies are envisaged, not even “proved” ones: Likewise in all Germany, CO_2 storage or any extractive uses that require fracking are banned by federal law.

The present version of the mining law (Berggesetz) allows for one subsurface utilization per license area only. Case-related exceptions are very rare for the few cases where the applicant / user can ascertain, based on specific geological investigations, that there is no impact on the pre-existing use, neither short-term nor long-term.

The same applies for groundwater protection areas: within the protected area no drilling or mining activities that might endanger the aquifer are permissible. Exception: deep (> 2000 m) hydrothermal utilization beneath large scale groundwater abstraction (must be separated by at least one thick barrier horizon at depth and requires special precautions on drilling). Likewise it is permissible that the landing point of deflected deep drilling is located beneath a protection area. This specifically is the case for deep geothermal explorations, basically implemented as open loop doublets/triplets, to ensure a maximum distance of the production and re-injection wells.

For a more detailed synopsis of statutory provisions for subsurface utilization and licensing procedures for geothermal projects in Bavaria and various European states, refer to the HotLime Deliverable 5.1.1.

In consideration of the present first stage of the radwaste repository site selection, as long as no exclusion areas have been defined, all new subsurface utilizations are stalled and require a special permit according to the StandAG https://www.gesetze-im-internet.de/standag_2017/BJNR1074 10017.html by the BGE (Federal Company for Radioactive Waste Disposal). This includes all drillings of more than 100m depth and also all explorations deeper than the maximum target depth of the repository, as the exploration drillings might pierce the possible target horizons at higher levels.

All licensing is subject to case-related approval of the mining authority considering the expert opinion of all competent authorities to be involved in the procedure in-line with the statutory provisions. There is no standard or automatic auditing procedure applicable. Likewise, possible subsurface uses interactions (of similar and dissimilar utilizations) and prioritisation / optimisation of undertakings are reviewed in these case-related treatment based on the expertise of the competent authority, the Geological Survey and Water Administration Authority.

In brief: Consulting the different competent authorities (e.g. environment, water administration and geological survey) is a regular step in licensing processes for all subsurface utilizations. Thereby, if not just a routine procedure for everyday business, the decision maker / permit authority requires individual case assessments based on the knowledge of the experts of the competent authorities, not self-evaluation based on ready-made decision-making tools (maps, 3D-models, etc.).

1.3.2 Subsurface management: cross-border issues, tools for decision makers

As geology and the potentials connected with it do not respect political boundaries, for Bavaria as a landlocked state it has long been clear that an efficient subsurface management, must consider cross-border geo-information. Accordingly, various bilateral cross-border or multilateral regional EU granted projects have been implemented over the last decade, focused on areas with a high subsurface potential, e.g. GeoMol (GeoMol Team 2015), HotLime (Diepolder & HotLime Team 2020).

The crucial prerequisite to make cross-border geo-information understandable to non-geoscientists is the trans-national harmonisation of the information, or at least its annotated juxtaposition in a Semantic Web vocabulary: Due to the natural variability of the subject matter in space and time, many nomenclatures of factual scope have been set up. These standards with a limited areal validity evolved from regional approaches and only rarely have undergone cross-border harmonization. Descriptive texts are often used to caption those terminologies whose meanings are not standardized or are not conclusively clarified in the international context. This leads to distortion and ambiguousness when cross-border datasets are compiled, not only caused by national languages but also due to regional peculiarities and the semantic changes in historical evolution of terms. Standardization of geological interpretation terminologies, however, is virtually impossible to gain as pluralism of terms is fact-based, well-established and has been used in geoscientific publications over decades (Kondrová & Diepolder 2018).

Optimizing the use and management of the subsurface also requires the disclosure of this cross-border geo-information in a way that is understandable and tailored to the needs of different stakeholders and end-users (GeoConnect³d Project Proposal). The demand for cross-border harmonization and the disclosure of the results in a suitable tool to support decision making has been addressed in detail in GeoMol Project, focussed on the Molasse Basin overlapping 5 countries / 6 states and its southern Alpine counterpart, the Po Basin (GeoMol Team 2015). The collaboration of 6 states did not only involve Geological Survey Organizations but also regional permit authorities and decision makers. To further identify the requirements of users of subsurface information and potential clients with respect to products a stakeholder survey was conducted at an early stage of the project, with a questionnaire designed to gauge the need for specific types of subsurface information and formats for delivery (GeoMol Team 2015).

This survey clearly revealed a strong bipolarity of demands:

- Geoscientists who represented a major part of the respondents prefer digital datasets which allow for easy combination in GIS with other information, distinct evaluations and alternative interpretations. They prefer GIS information derived from 3D models rather than the 3D model itself, as only large enterprises or consultants of primary industries (typically being the provider of base data for the GSOs, not the other way round) normally hold the necessary software.
- Non-geoscientists favour off-the-shelf solutions, supplemented by clear recommendations and guidelines. Even “frozen state” analogue maps are highly demanded by respondents (non-geoscientists as well as geoscientists) involved in approval processes and licensing procedures, because such immutable, date stamped maps are indispensable in for the legal permits.

This result is lucidly in line with the proposition of Turner & d’Agnese (2009): The recent technological advancements have supplied tools which allow a straightforward insight into the Earth’s interior and to better comprehend subsurface geology. Modern 3D modelling and visualisation techniques enable an extended user community to explore and query the subsurface at arbitrary depths. However, unlike the established user community, such as resource focused primary industries and academia, many of today’s potential users of geological models and visualisations do not have the capability to interpret basic geoscience data or evaluate the merits of alternative interpretations. They may be unable to distinguish between theories and facts – in brief: these users clearly desire “solutions, not data” and “information in understandable form”.

Accordingly, the Geological Survey of the Bavarian Environment Agency, as the competent state authority for all issues with respect to the subsurface, “the legal custodian of the subsurface“, and the consultant to the Mining Authority as licensor, still is asked to deliver its expertise in reports with printed maps.

In Germany there are considerable reservations of the general public regarding the utilization of the deeper subsurface. Specifically deep geothermal energy or underground energy storage, which both are crucial to achieving the energy transition for the mitigation of global climate change, are under general suspicion to induce or trigger seismicity. To de-bias the public’s awareness of underground operations, hence, it is a core role of the GSOs to unveil "the hidden landscape beneath their feet" by providing straightforward insight into the subsurface. To this end a public access 3D explorer (Figure 5) was implemented for visualization and query of down-scaled 3D geo-models at a restricted zoom-in range.

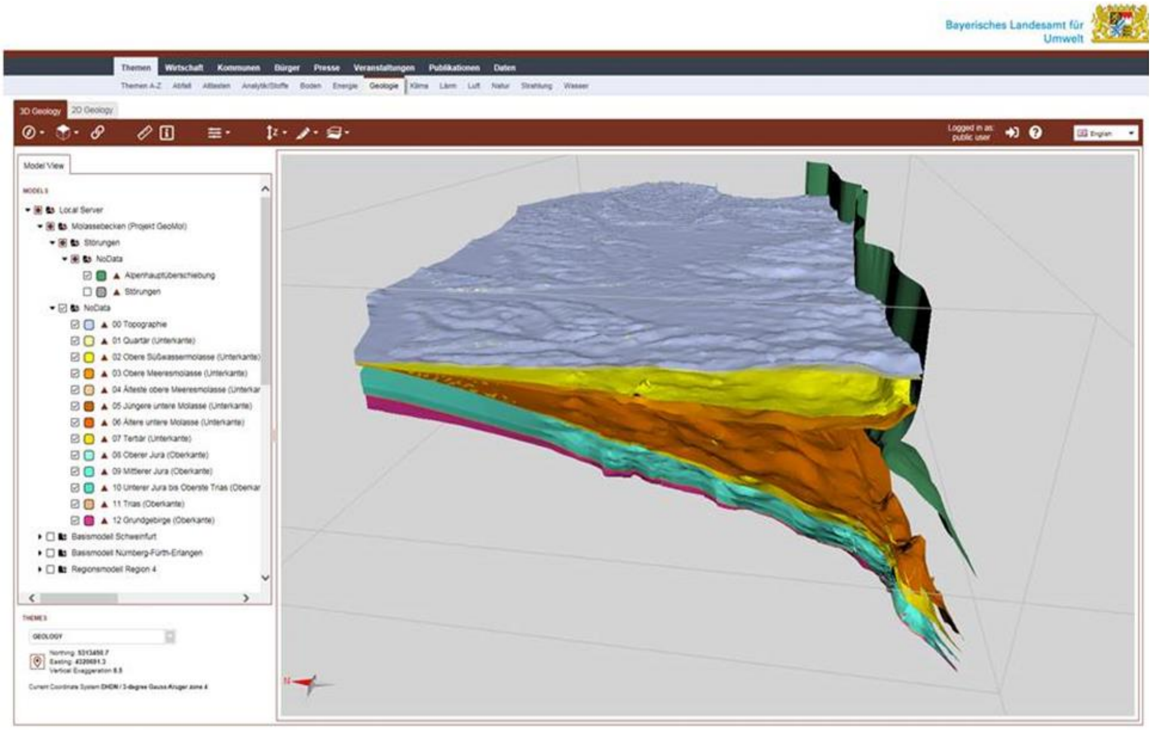

Figure 5: Screen dump of LfU's 3D explorer https://www.3dportal.lfu.bayern.de/webgui/gui2.php portraying the eastern portion of the Bavarian Molasse Basin of the GeoMol framework model. Fault planes (except for the Alpine orogenic front wedge in dark green) and the topographic overlay are disabled for clarity.

Even though LfU's 3D explorer is a sophisticated and easy to grasp tool, it must be admitted that it is definitely not a mainstream website. The 2D geological information of "Bayerischer Umweltatlas" (https://www.umweltatlas.bayern.de/) seems to be much more popular and the top"sellers" still are printed or printable products.

1.4 Starting material

1.4.1 Molasse Basin

Despite there being blind features at great depth, owing to several decades of intense investigation on subsurface potentials, the definition and description of the structural framework of the Molasse Basin could build upon a large data stock. However, this baseline data and interpretations are scattered and clustered in areas of hydrocarbon prospectivity and high geothermal potential, for the shallower parts of the Molasse Basin such information is scarce. The information stock we could build upon at the start of "transposing the case" have been lots of literature (e.g. the comprehensive GeoMol Report, GeoMol Team 2015) and 3D models of various resolution in depth domain (cf. Diepolder et al. 2019), based upon overall 2,500m scattered deep drilling data (approx. 800 with > 500 m depth), about 500 seismic lines, totalling more than 9,000 km, and about 3,000 km^2 3D seismic projects, predominantly claim-wide surveys of geothermal sites.

1.4.2 NE-Bavaria

The area of the testbed NE-Bavaria is almost completely covered by 1:25,000 scale geological maps with comprehensive explanatory notes, including a chapter on the tectonic setup. In addition, and bridging the gaps of the detailed maps, larger-scale maps and various literature on general and specific issues have been on hand.

2 ADOPTING STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS

2.1 Adopting Structural Framwork

The adoption of the structural framework, as implemented for entire Bavaria (except the Alpine domain) and eastern adjoining areas on Czech territory, is based on the present knowledge of the tectonic structures and their relationship with respect to the different tectonic phases that involved Bavarian territory. Mapped in various scales or inferred from indirect evidence, the Structural Framework compilation does not strive for giving a full inventory of tectonic features but aims at stressing the contextual relationship of the fault network and its relation to the geological units distinguished on Bavarian territory and the marginal Czech territory, as far as meaningful for the understanding of the structural framework of eastern Bavaria.

2.2 Adopting Geomanifestations

2.2.1 Molasse Basin

As the Molasse Basin is almost completely bare of Geomanifestations which can be assigned to or giving evidence of the Structural Framework (cf. paragraph 1.2), there actually was nothing at choice. The only such Geomanifestations in the Molasse basin are elevated temperatures in shallow wells at the north-western scarp of Landshut-Neuötting basement rise (Figure 3). Temperatures up to 18°C in wells of less than 100 m depth indicate the upwelling of thermal waters from the deeper levels, forced by the main scarp of the Landshut-Neuötting Step Fault [LfU-BY_701], cf. Wrobel et al. (2002).

Another Geomanifestation of the Molasse Basin, unquestionable related to the formation of a Structural Framework feature, but without any positional relationship to it (thus no Geomanifestations in the sense of GeoConnect^{3}d), is the Brock Horizont (boulders horizon) in the Miocene of the Upper Molasse. This layer comprises large blocks and boulders of Upper Jurassic limestone ejected on the formation of the most conspicuous structural feature in Bavaria, the Ries Impact Crater (cf. [DE-BY_4809], [LfU-BY_u24]) and can be found up to 180 km away from the crater, however only rarely exposed.

2.2.2 NE-Bavaria

On screening of the rest of Bavaria, while preparing the Structural Framework for entire Bavaria it became evident that the exposed or subcropping anchimetamorphic rock suites of the Saxo-thuringian feature there was a surpassingly dense occurrence of Geomanifestations considered to be directly related to faults. Thus this realm was chosen for testing the Geomanifestations concept beyond the commitments made in the Project Proposal and Agreement.

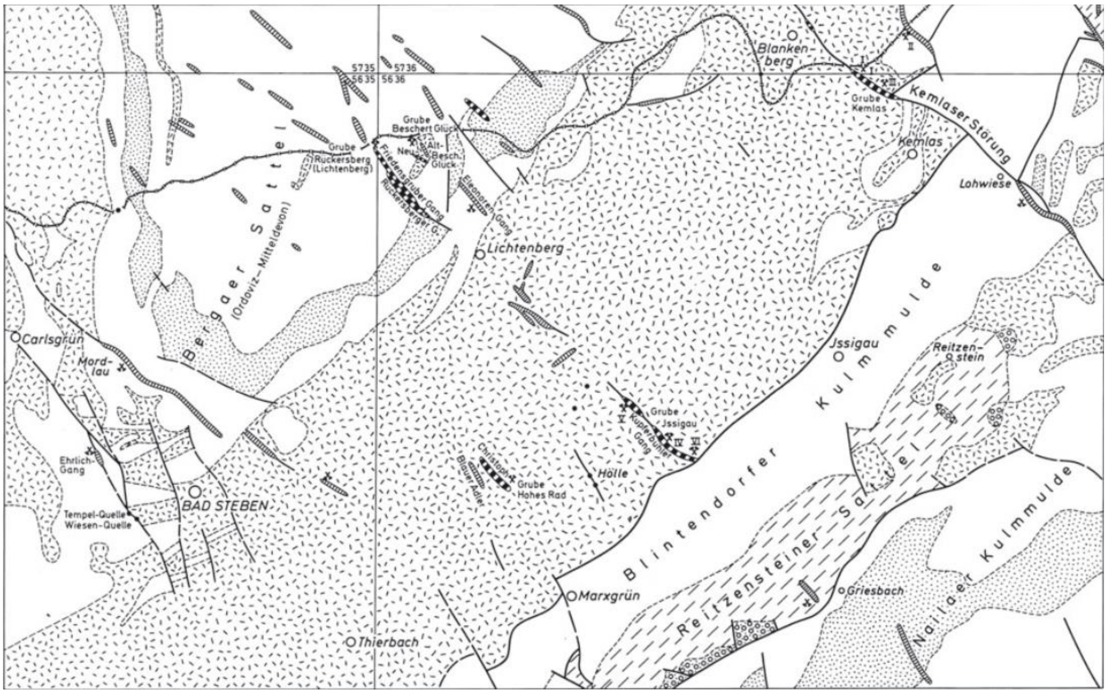

Figure 6: Geological sketch map of the Thuringian Facies in north-eastern most Bavaria, elucidating the linear features made up of mineral veins (predominantly fluorite and siderite) and CO2 rich springs (after Horstig 1972, from Eichhorn et al. 1999).

On the one hand, ore veins and linear arrays of CO_2 rich springs in the very north-east of Bavaria (Figure 6), on the other hand a linear array of dry maars and scoria cones, evidently "geo-connected" to a principal tectonic element, Tachov Fault Zone [LfU-BY_9920] (Figure 7), cutting across the extension of Eger Graben [LfU-BY_u8] and probably forming the eastern limit of Mitterteich Basin [LfU-BY_u9] (Figure 8).

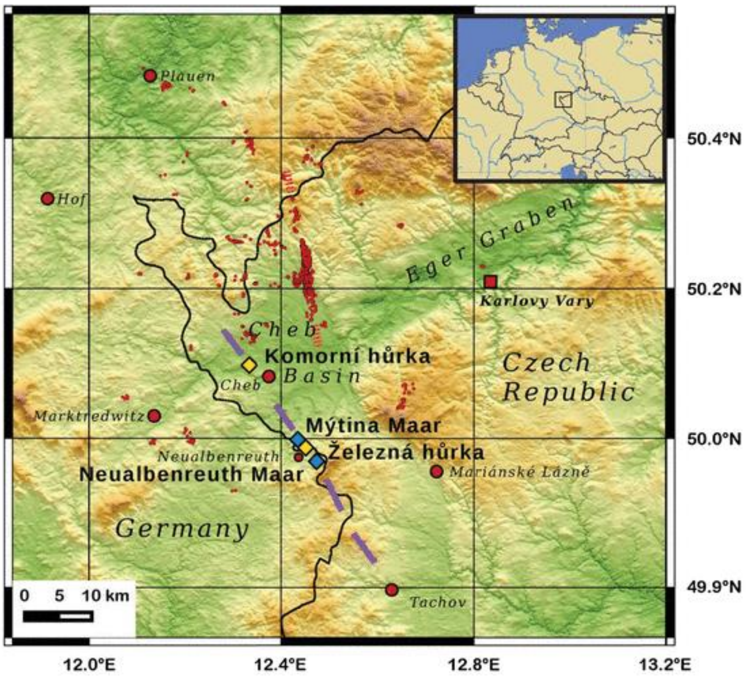

Figure 7: Linear area of volcanic evidence along Tachov Fault Zone. Small red dots mark the epicenters of the local swarm earthquakes in the period 1995-2015. (From Rohrmüller et al. 2018)

The latter area is also characterized by peculiar groundwater types and is subject to seismic events arguably emanating from Počatky-Plesná Fault Zone at Nový Kostel north of the Cheb Basin (Figure 7), recurrently prone to earth-quake swarms with a hypocenter at about 10 km.

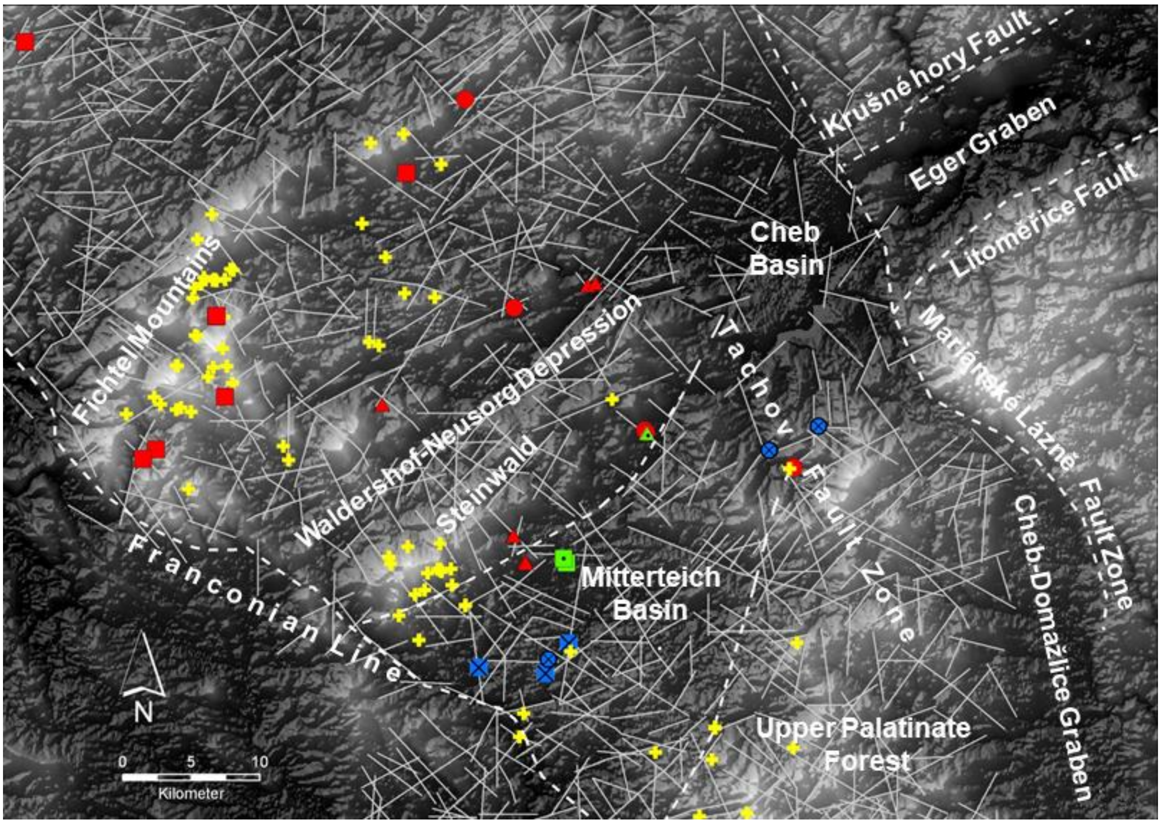

Figure 8: DEM visualizing the results of a lineament analysis (light grey lines) by Zeitlhöfler (2006). The dashed white lines mark the contours of the prominent tectonic features: The Eger Graben [LfU-BY_u8] on the Czech side is clearly visible, the outlines of its continuation in Bavaria, the Mitterteich Basin [LfU-BY_u9] are less distinct. Bright shades signify higher elevations such as Fichtelgebirge or Steinwald. Groundwater samples of "abnormal" chemistry inferring deep-seated structural features, are plotted according to typology:
Circles: TDS > 1000 mg/L, triangles: CO_2 > 250 mg/L, squares: Fe/F-enriched, crosses: Rn > 666 Bq/L; red: HCO_3 type, green: HCO_3-CL type, blue: HCO_3-Cl-SO_4 type, yellow: type not specified. (From Diepolder & Herold 2007, modified)

2.3 Combining Structural Framework and Geomanifestations

2.3.1 Molasse Basin

The only Geomanifestation in the Molasse Basin, elevated temperatures in shallow wells at the north-western scarp of Landshut-Neuötting Rise (Figure 3), only qualitatively verifies the inferred upwelling of deep waters in front of the Landshut-Neuötting Step Fault [LfU-BY_701]. Pumping tests, specifically in anisotropic aquifers like the karstified Upper Jurassic carbonates, integrate the physicochemical characteristics over a large, but non-determinable area, and does not allow the precise location of the fault(s). This had to be carried out by the interpretation of seismic surveys (Donner 2020).

2.3.2 NE-Bavaria

The tectonic boundary inventory within the verdant and regolith covered Bohemian Massif in general, thus in the Saxothuringian Zone as well, only rarely can be observed directly. Apart from larger scale faults manifested in fractured zones and tectonites or evidence in scarce quarries, most tectonic features are subcropping. Fault patterns are inferred mostly from indirect field evidence such as conspicuous lithological changes, extrapolating joint system measurements wherever exposed, and from linear features like quartz or ore veins, all aligned with remote sensing data and geophysical surveys in areas where available.

In particular, manifestly linear features (cf. Figure 6) serve as a mapping argument for delineating tectonic boundaries. Combining and correlating the Structural Framework and Geomanifestations in that cases, thus, has to be considered more a hindcast or back-testing, rather than the gain of new knowledge.

However, considered on a larger scale and stressing the contextual relationship of the Structural Framework and Geomanifestations, certain geomanifestations (primarily volcanic fingerprints) can help to revise and evidence the conceptual framework of the tectonic history and improve the understanding of the recent kinematic processes. For instance, the recently evidenced maar close to the Bavarian-Czech border (Rohrmüller et al. 2018, cf. Figure 7) helped to focus the trend of one of the most important, but rarely observable structural feature, Tachov Fault Zone [LfU-BY_9920].

3 EVALUATING THE STRUCTURAL FRAMWORK AND GEOMANIFES-TATIONS

Based on the author's comprehension about what exactly defines a Geomanifestation (as against indirect field evidence, outcomes from geophysical surveys and other mapping arguments regularly applied in geological mapping irrespective of the school of thought), combining the Structural Framework and Geomanifestations can be a powerful tool for revision and evidencing the conceptual framework, the tectonic history and the understanding of recent kinematic processes. This works specifically well in areas where non- or low-grade metamorphic bedrocks are exposed or covered by a thin undeformed overburden only. A true example is the northern part of the Bohemian Massif, the Saxothuringian Zone. This comes as no surprise, as this domain roughly resembles the Varican geology north of the Mid-German Crystalline Rise [LfU-BY_uB1], the Rhenish and Brabant Massifs, the areas where the idea of GeoConnect³d, connecting the structural framework and geomanifestations for an improved knowledge of the subsurface, was elaborated.

However, the method is not applicable in domains where the bedrock is buried under thick strata of overburden, as the superposition of undeformed rocks blurs or obliterates the Geomanifestations (if there are any) of the deep-seated Structural Framework.

The multi-scale method for the Structural Framework is a very good approach to visualize the "hierarchy" of the tectonic units and their subdivision. However, to ensure comparability of the level in the hierarchy applied by different authors, it requires a review and re-mastering following common criteria.

4 APPLYING THE STRUCTURAL FRAMEWORK TO PLANNING

A detailed knowledge of the fault inventory aka Structural Framework is a sine qua non for the subsurface management of, or including, hydrocarbon E&P, hydro-geothermal projects, underground storage of fluids, gas and radwaste, and for water administration in fractured aquifers. The Structural Framework not only defines the compartmentalisation of the reservoir and the seal integrity, the main conduits of (thermal) water e.g. for hydro-geothermal projects, and the structural traps for the formation and integrity of hydrocarbon deposits (and its storage potential in after-use). In brief: faults, fractures and other conduits are the connections, wished-for or unwanted, for material flow (fluid) in the subsurface, beyond the physico-chemical impact aureoles of subsurface utilizations might bring about (cf. HotLime Factsheet Faults). Thus, sound subsurface management has to take into account all discontinuities in a 3-dimensional workspace.

However, as emphasized in paragraph 1.3, due to the complexity of the subject matter this has to be implemented in an expert system run by geoscientists and is not deemed that even experienced laypersons have the capability to interpret basic geoscience data or interpretations.

Undoubtedly, the Structural Framework as conceptualized in GeoConnect^{3}d is the first step into the right direction, setting up an expert tool for a first approach on optimising subsurface planning. With further refinement it might become a powerful tool for the prioritisation/optimisation of subsurface utilizations and the derivation of recommendations and solutions and information in understandable form that can be used and exploited by planner and decision makers.

5 REFERENCES

Diepolder, G.W. & Herold, H. (2007): Mineral and Radon-rich waters in hardrock terrains of northeastern Bavaria. - In: Marques, J.M., Chambal, A. & Ribeiro, L. (eds.): Proceedings of the Symposium on Thermal and Mineral Waters in Hard Rock Terrains, AIH-GP, Lisbon, Portugal, 2007: 121-130.

Diepolder, G.W. & HotLime Team (2020): HotLime - Mapping and Assessment of Geothermal Plays in Deep Carbonate Rocks – summary of mapping and generic characteristics of eleven case studies. - HotLime Mid-term Summary Report, 10 pp. https://repository.europe-geology.eu/egdidocs/ hotlime/hotlime_deliverable_21.pdf [2021-07-10].

Diepolder, G.W., Pamer, R. & Großmann, J. (2019): Advancements in 3D geological modelling and geo-data integration at the Bavarian State Geological Survey. - In: MacCormack, K.E., Berg, R.C., Kessler, H., Russell, H.A.J. & Thorleifson, L.H. (eds.): 2019 synopsis of current three-dimensional geological mapping and modelling in geological survey organizations. – AER/AGS Special Report **112**: 48-61, Edmonton (Alberta Energy Regulator / Alberta Geological Survey). https://static.ags. aer.ca/files/document/SPE/SPE_112.pdf [2021-07-08].

Donner, E. (2020): Geologisches 3D-Modell Niederbayern. - UmweltSpezial, 35 S., Augsburg (Bayerisches Landesamt für Umwelt).

Doppler, G., Fiebig, M., Freudenberger, W., Glaser, S., Meyer, R.K.F., Pürner, T., Rohrmüller, J. & Schwerd, K. (2004): GeoBavaria – 600 Millionen Jahre Bayern. - 92 S., München (Bayerisches Geologisches Landesamt).

Eichhorn, R., Glaser, S., Lagally, U. & Rohrmüller, J. (1999): Geotope in Oberfranken. - Erdwissenschaftliche Beiträge zum Naturschutz **2**: 176 S., München (Bayerisches Geo-logisches Landesamt).

GeoMol Team (2015): GeoMol – Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources. - Project Report, 188 pp., Augsburg (Bayerisches Landesamt für Umwelt), www.geomol.eu/report [2021-07-10] and map viewer http://www.geomol.eu/mapviewer/ [2021-07-10].

Horstig, G. von (1972): Mineralabfolge und Tektonik in den flußspatführenden Mineralgängen des Frankenwaldes. - Geologica Bavarica **65**: 160-184, München (Bayerisches Geologisches Landesamt).

Kondrová, L. & Diepolder, G.W. (2018): Metadata for 3D geological models and their coherence with the Semantic Web. - 4th European Meeting on 3D Geological Modelling, Orléans 21-23 February 2018, Abstracts, p. 68. http://www.3dgeology.org/resources/orleans/3D_Workshop_Orleans_2018_AbstractsV1.pdf [2021-07-10].

Rohrmüller, J., Kämpf, H., Geiß, E., Großmann, J., Grun, I., Mingram, J., Mrlina, J., Plessen, B., Stebich, M., Veress, C., Wendt, A. & Nowaczyk, N. (2018): Reconnaissance study of an inferred Quaternary maar structure in the western part of the Bohemian Massif near Neualbenreuth, NE-Bavaria (Germany). - Intern. J. Earth Sci., **107/4**: 1381-1405. https://doi.org/10.1007/s00531-017-1543-0

Turner, K. & d'Agnese, F.A. (2009): The Role of Geological Modeling in a Web-based Collaborative Environment. - Three-Dimensional Geological Mapping, Workshop Extended Abstracts, Portland, Oregon – October 17, 2009, 58-62, https://library.isgs.illinois.edu/Pubs/pdfs/ofs/2009/ofs2009-04.pdf [2021-07-12]

Wrobel, J.P., Fritzer, T., Mikulla, C., Schuldes, D. & Suckow, A. (2002) : Forschungsbohrung Altdorf bei Landshut/Niederbayern – Erkundung einer geothermischen Anomalie im Bereich des Landshut-Neuöttinger Hochs. - Grundwasser **7** :14–24. https://doi.org/10.1007/s007670200002

Zeitlhöfler, M. (2006): Bericht zur Lineamentanalyse auf Basis von SRTM-Satellitenhöhendaten für die Hydrogeologische Landesaufnahme im Ziel-2-Gebiet. - Unveröffentl. Bericht, 51 pp., München (Bayerisches Landesamt für Umwelt).