Chapter 7: Advancements in 3D Geological Modelling and Geo-Data Integration at the Bavarian State Geological Survey

Gerold W. Diepolder[1], Robert Pamer[1], and Johannes Großmann[2]

[1] Bavarian Environment Agency (LfU) – Geological Survey, Bürgermeister-Ulrich-Str. 160, 86179 Augsburg, Germany – gerold.diepolder@lfu.bayern.de

[2] Bavarian Environment Agency (LfU) – Geological Survey, Hans-Högn-Str.12, 95030 Hof, Germany – robert.pamer@lfu.bayern.de

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Introduction

After more than a decade of producing digital 3D geological models and model applications tailored to the requirements and scope of a wide range of projects, 3D modelling has become a routine business of the Bavarian State Geological Survey. The guiding concepts and workflows have been incrementally improved and practice-approved over years in various geological settings with disparate data background. Presently the advanced workflows are applied in two product lines of distinct scale, objective and scope. Over the course of augmentation, revision, and upgrade of the 3D geo-models it has become clear that safeguarding sustainability in further progression of model building requires a substantial redesign of those parts of the 3D modelling cascade beyond the 3D modelling procedure as such: We identified the increasing importance to further develop an IT- and geo-information infrastructure that supports integrated data storage and barrier-free data availability. Since all principal data for geological model building is held available in digital repositories, peripheral processes like data integration and evaluation, model documentation and version control must be interlinked and tied in on the fly, thus forming an integral part of the modelling procedure. To facilitate knowledge sharing, models and associated data sets must comply with the principles of FAIR data – Findable, Accessible, Interoperable, and Re-usable, whereby all concepts have to be supported by controlled vocabularies as part of the Semantic Web.

Organizational Structure and Business Model

Similar to the USA, Canada, and Australia, Germany is a federation of states. For geological mapping, surveying, and data storage this means that each state has a jurisdictional geological survey organization as the legal custodian of the subsurface (cf. Diepolder 2011a).

In charge of the largest German federal state covering a territory of about 70,500 km^2, the Bavarian State Geological Survey (hereinafter referred to "the Survey") is among the larger ones of Germany's 16 State Geological Survey Organizations (Staatliche Geologische Dienste, SGD). Dating back to 1850 and reorganized several times, the Survey, since 2007, is a department of the Bavarian Environment Agency (LfU), a subordinate authority to the Bavarian State Ministry for the Environment and Consumer Protection (StMUV). Unlike some other German SGD the Survey does not incorporate the Mining or Water Administration Authorities. As the central authority providing geoscientific advice to the Bavarian government, e.g. the Mining Authority and geo-energy regulator, it is tasked to acquire, store, process and synthesize geoscientific data, and to make this data available for economic and societal needs.

Basically, LfU overall is financed by the StMUV. A minor support for the Survey is provided by the Bavarian State Ministry of Economic Affairs, Regional Development and Energy (StMWi) specifically for programs related to raw materials and geothermal issues. Many projects, especially cross-border projects with neighboring countries or in a pan-European context are acknowledged by co-funding of the European Union or its regional funding schemes. Entirely run by public money the Survey is a public sector, non-profit organization and not entitled to accept private commissions or to compete otherwise with consultants and planners of the private sector. Accordingly, and pursuant to the Environmental Information Law, product distribution follows non-commercial principles as well. Digital products retrievable via web map and information services or the online shop are free of charge for non-commercial use and printed material against payment of only a nominal fee. However, data privacy requirements imply that not all products are freely available.

Overview of 3D Modelling Activities

All multi-layer 3D models produced so far or presently under development pertain to the Scarpland (Cuesta Region) and the Molasse Basin that altogether cover more than two-thirds of the Bavarian territory (Figure 1). The intensely folded and thrusted Alps as well as the terrains of exposed crystalline basement are only included in their marginal areas and, due to the complex internal structure, are just captured as undivided and unstructured bodies. Kept generic and not tailored to any specific application, all 3D geo-models in their original version are lithostratigraphic layer models featuring the general geological setup and characteristics. However, through conversion into volume models and specific parameterization they can be made useful for many geoscientific and cross-cutting applications.

The first 3D geological framework models have been built in the 2000s, conceived to supplement thematic map sets of holistic mapping campaigns addressing administrative units (Regionen). These first exercises in digitally stacking lithostratigraphic layers for making clear the spatial relationship of the subsurface layers and the principal faults have been elaborated in a regional scale corresponding to the 1:100,000 scale thematic maps of the holistic mapping. For a concise synopsis of the early years of 3D modelling at the Survey see Pamer and Diepolder (2010). With new regions added, adjusted to an overarching concept evolved over time and refined with substantial new information coming up, the 1:100,000 scale models are now integral parts of the LOD2 framework model product line of the Survey. The LOD2 geo-models provide the framework to integrate smaller, more detailed models and form the nuclei for incrementally setting up a statewide 3-dimensional overview – still waiting for capacity increase of computer power to be fully implementable. The first step towards an all-encompassing statewide model is the harmonization and integration of various 3D geo-models into a supra-regional, cross-border Molasse Basin model (cf. Figures 1 and 2).

Local to regional scale detailed models, which focus on lithostratigraphic and structural features for characterizing the near-surface sedimentary sequence and the shallow bedrock, are generally considered to be of most use in urban planning and development (Kessler et al. 2005). At the Survey, such 3D models (Figure 3) are developed for specific agglomeration areas and growth axes surrounds (LOD3 in Figure 2), based on a resolution equivalent of about 1:25,000 scale. Aimed at a stratigraphic subdivision to group or formation level these geo-models synthesize all available geoscience information from boreholes, geological maps, cross-sections as well as contour plans and, where implemented, the interpretations of ground- and air-borne geophysical surveys. This accumulated knowledge underpins geological advice for construction and engineering projects, draws attention to potential hazards and impacts, in particular regarding groundwater and foundation conditions, and helps to unlock the subsurface potential e.g. with respect to geothermal use (Figure 4). At present, this second product line of the Survey consist of overall 23 mostly interconnected 1:25,000 scale map grid tile 3D models of 8 principal agglomeration areas and environs (Figure 2).

The largest challenge of 3D modelling activities the Survey is presently facing includes compiling a consistent structural model of the Bavarian part of the Molasse Basin (cf. Figures 1 and 2). Representing an important reservoir for drinking water production but also hosting central Europe's most prolific hydrothermal aquifer that presently features more than 25 geothermal installations >3,000 m in depth, it also holds a high potential for underground storage and economic residual quantities of oil and gas. Thus, the Molasse Basin is a paramount example for the imperative necessity of an unbiased and holistic subsurface management system. Aimed at assisting the regulators in their task to avoid use conflicts and to ensure resource efficiency, the Bavarian Molasse Basin has been the principal focus of 3D modelling activities for almost a decade, resulting in a vast variety of regional and sub-regional 3D geo-models of varying coverage, resolution and depth (Figure 2). The effort of integrating these segments, filling the gaps in between, adding marginal areas, and ultimately compiling one homogenous and seamless "super"-model, is hampered by various obstacles. They list an uneven distribution of baseline data, different modelling approaches – borehole-based for shallow, seismic-focused for deep portions of the basin – and the lithostratigraphic disparity with neighboring territories. Furthermore, the ongoing boom in geothermal exploration continuously generates new state-of-the-art datasets (3D seismic surveys, deep well downhole data) that make a rigorous revision of the legacy models inescapable.

The first 3D geo-models addressing parts of the Molasse Basin have been implemented in the marginal (Reg. 10) and shallow (Reg. 13) parts of the basin (cf. Figure 2), geared to hydrogeological applications, and are entirely based on borehole evidence or contour plans derived thereof. Modelling the deeper portions of the basin (down to about 4 km depth) started in 2010, focused on the hotspots of geothermal exploration at that time (5-Seen, München; cf. Figure 2). These models are based on a selection of digitized seismic sections and a few "golden spike" downhole data.

The transnational project GeoMol (Diepolder et al. 2014, GeoMol Team 2015, see also http://www.geomol.eu), running from 2012 to 2015, was spearheading the Survey's efforts to put all 3D geo-models of the Molasse Basin in a common context. Aimed at the cross-border assessment of the

Geology of Bavaria

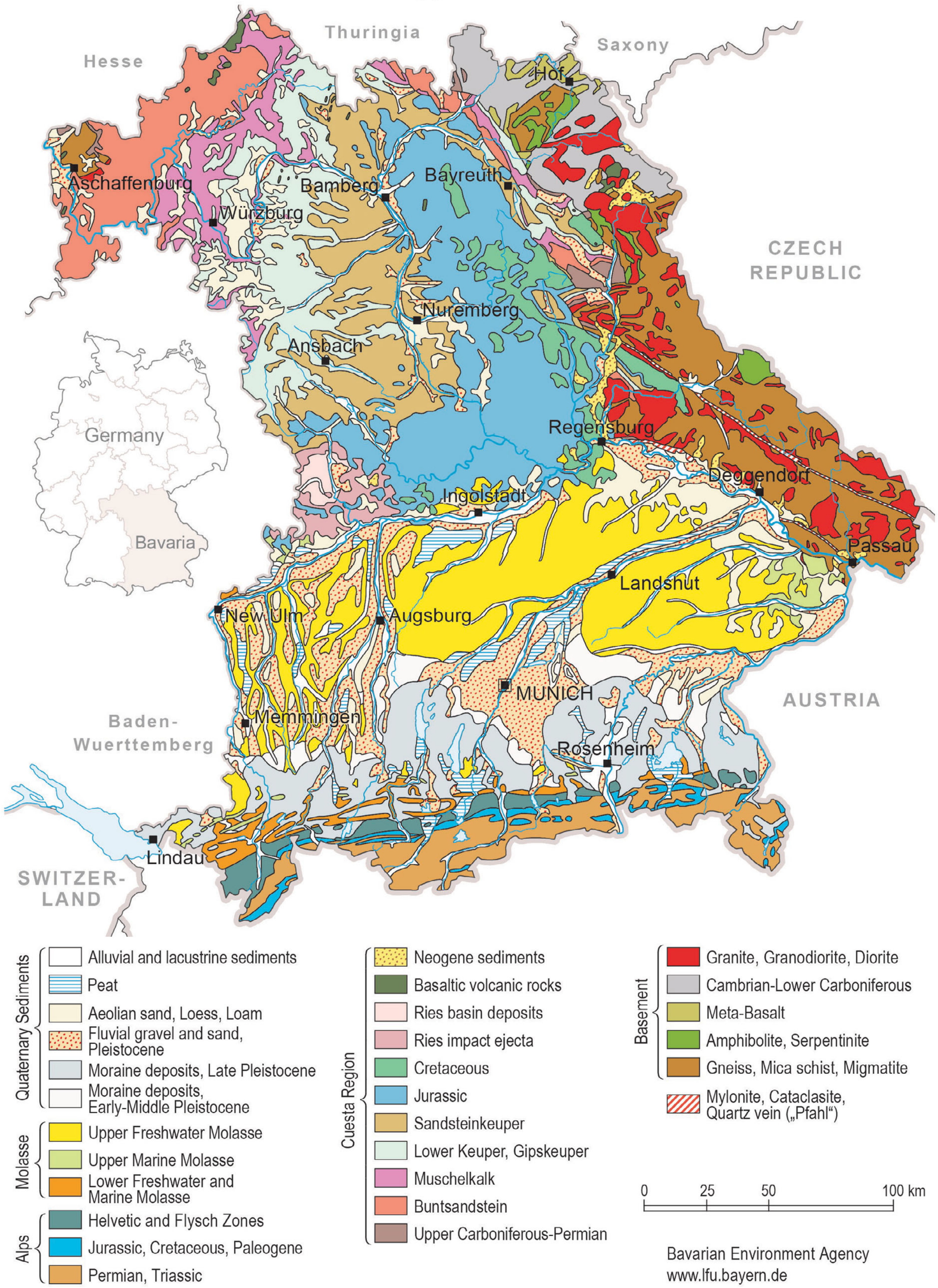

Figure 1. Geological overview of Bavaria portraying the principal geological units and the location of Bavaria within Germany (inset). See section 'Overview of regional geological setting' for discussion.

subsurface potential for various utilizations based on common criteria, a 3D geological model was set up to elucidate the structural controls of the resources. Funded by the European Union's Alpine Space Programme, the project offered the opportunity to substantially enlarge the areal backdrop and to develop a harmonized 3D model of the entire Molasse Basin including a cross-border concerted lithostratigraphic subdivision.

A major challenge in 3D modelling of basin structures that reach down to more than 5 km, is the availability of data with an adequate distribution and resolution to address issues properly. Principal baseline data for GeoMol's 3D geological models have been seismic data, scattered and clustered deep downhole data (Figure 5) – both originating primarily from the 1960s and 1970s hydrocarbon exploration and production and secondarily from the investigations for geothermal installations that commenced in the early 2000s – and contour line drawings, all held together by the conceptual model of the Molasse Basin evolution. The use of different baseline data originating from multiple sources and various dates of origin imperatively required data harmonization from the very beginning of the model building workflow starting with the selection and preparation of the input data. Applying consistent methods and common parameters for model preparation and fault assessment (Figure 6), the integration of data in time domain and information in depth domain imposed particular requirements on the velocity models employed and the modelling workflow that requires toggling back and forth between depth and time domains depending on the point of departure (Maesano and the Italian GeoMol Team 2014).

Data preparation and the 3D modelling workflows applied in GeoMol are described in detail in the GeoMol

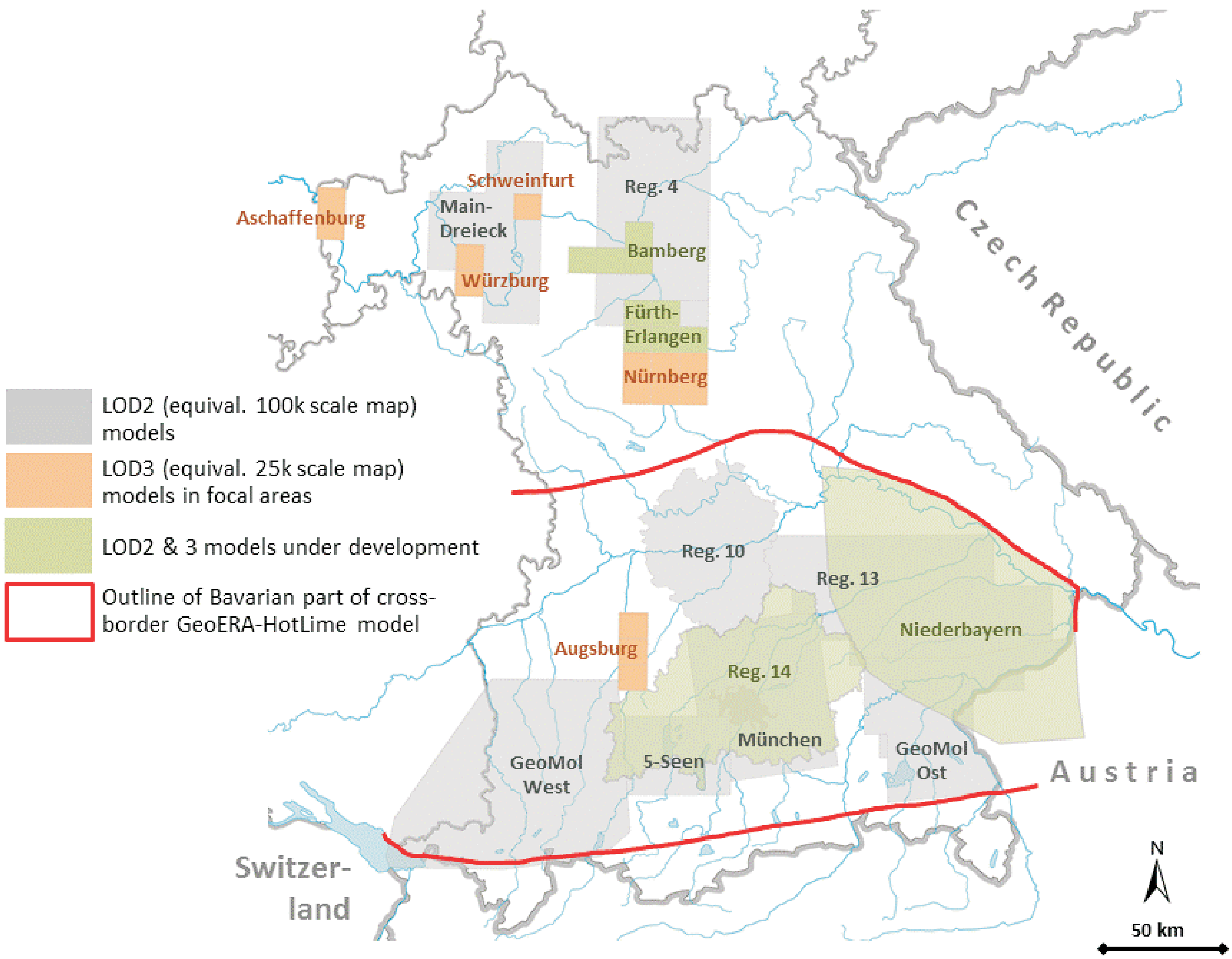

Figure 2. Outline of the model areas of the 3D geological models prepared at the Bavarian Survey. All LOD3 models and "Niederbayern" are prepared within the BAB (Subsurface Atlas of Bavaria) project. Modelling of "Reg. 14" is commissioned to the Technical University of Munich and comprises a shallow LOD3 part and a deeper LOD2 part connected to the deep models "München" and "5-Seen". See text for details.

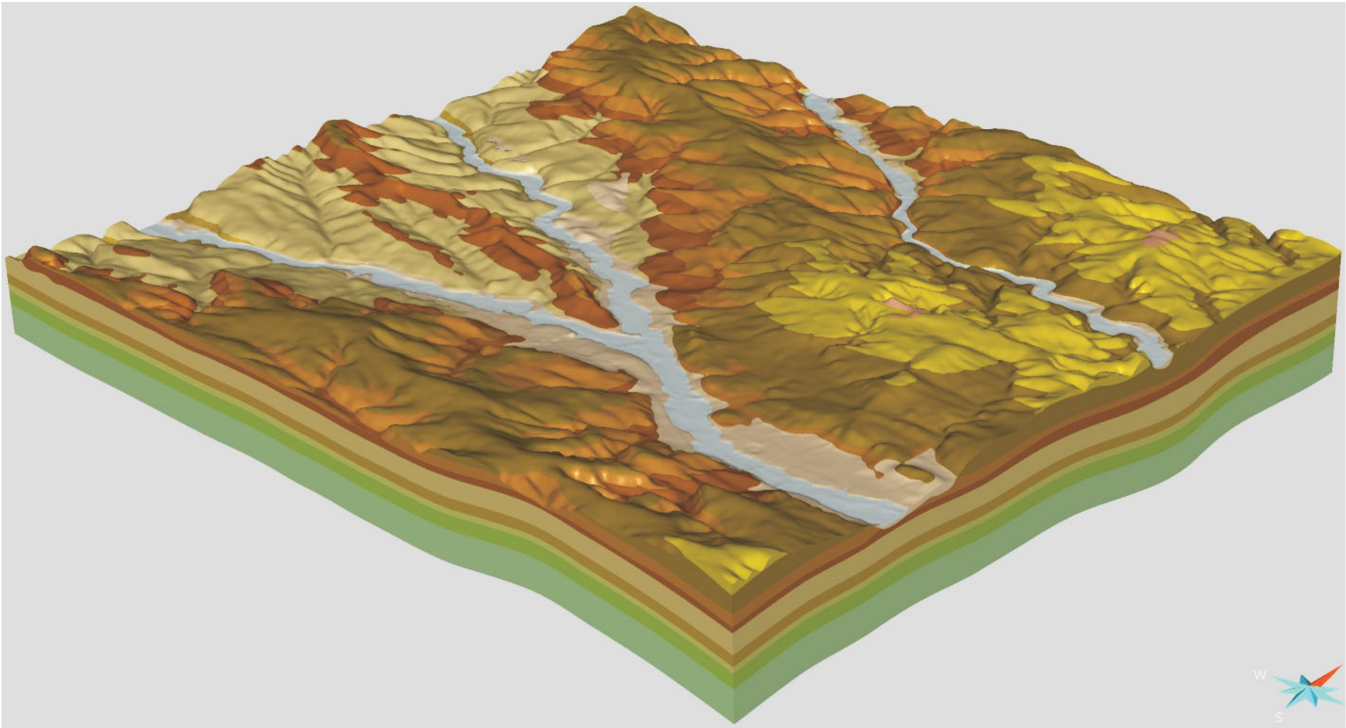

Figure 3. 1:25,000 scale map grid Burgebrach tile (part of Bamberg focal area) as an example for a LOD3 geological model. In addition to 11 lithostratigraphic units of the Keuper group (upper part of the Germanic Trias) Pleistocene fluvial terraces and Holocene valley fill are differentiated. Detailed structural modelling revealed that the faults inferred in bordering areas are just flexures of the strata.

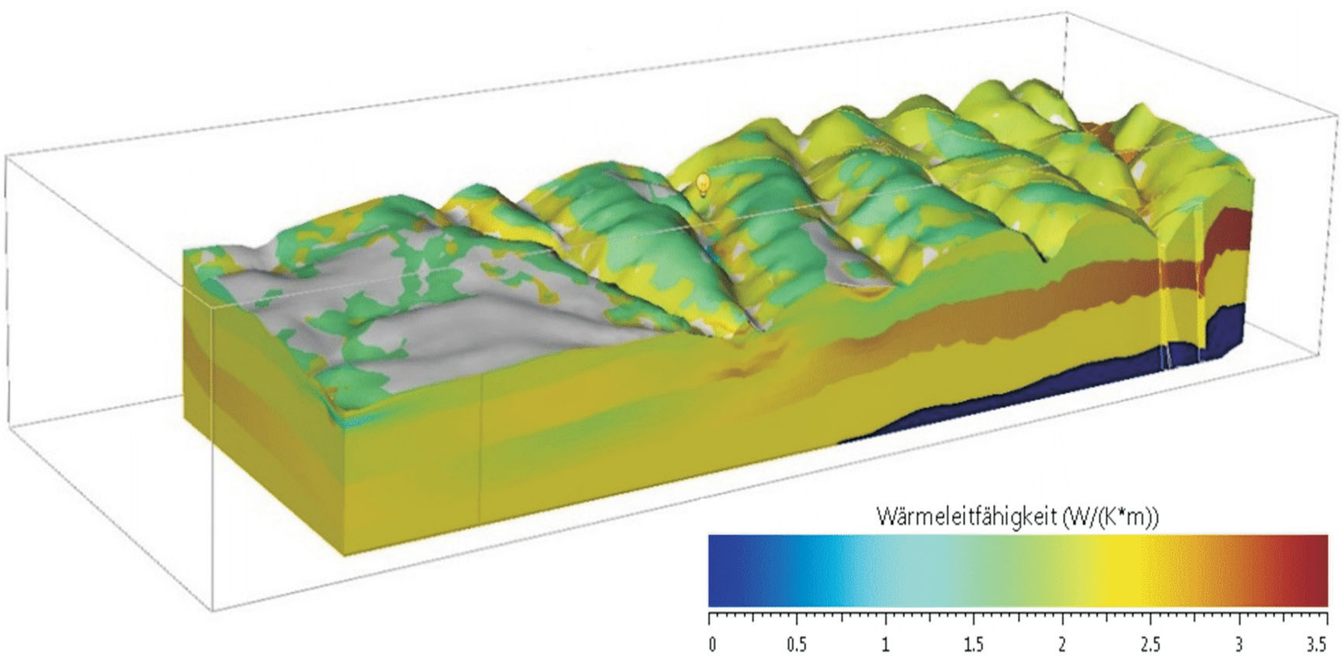

Figure 4. Example of a LOD3 model application: Cut-out of the Schweinfurt 1:25,000 scale geological model parameterized with the rock specific heat conductivity. Such heat conductivity distribution models are the basis for assessing the downhole heat exchanger efficiency with regard to rock specific properties as provided in http://www.umweltatlas.bayern.de/mapapps/resources/apps/lfu_angewandte_geologie_ftz/.

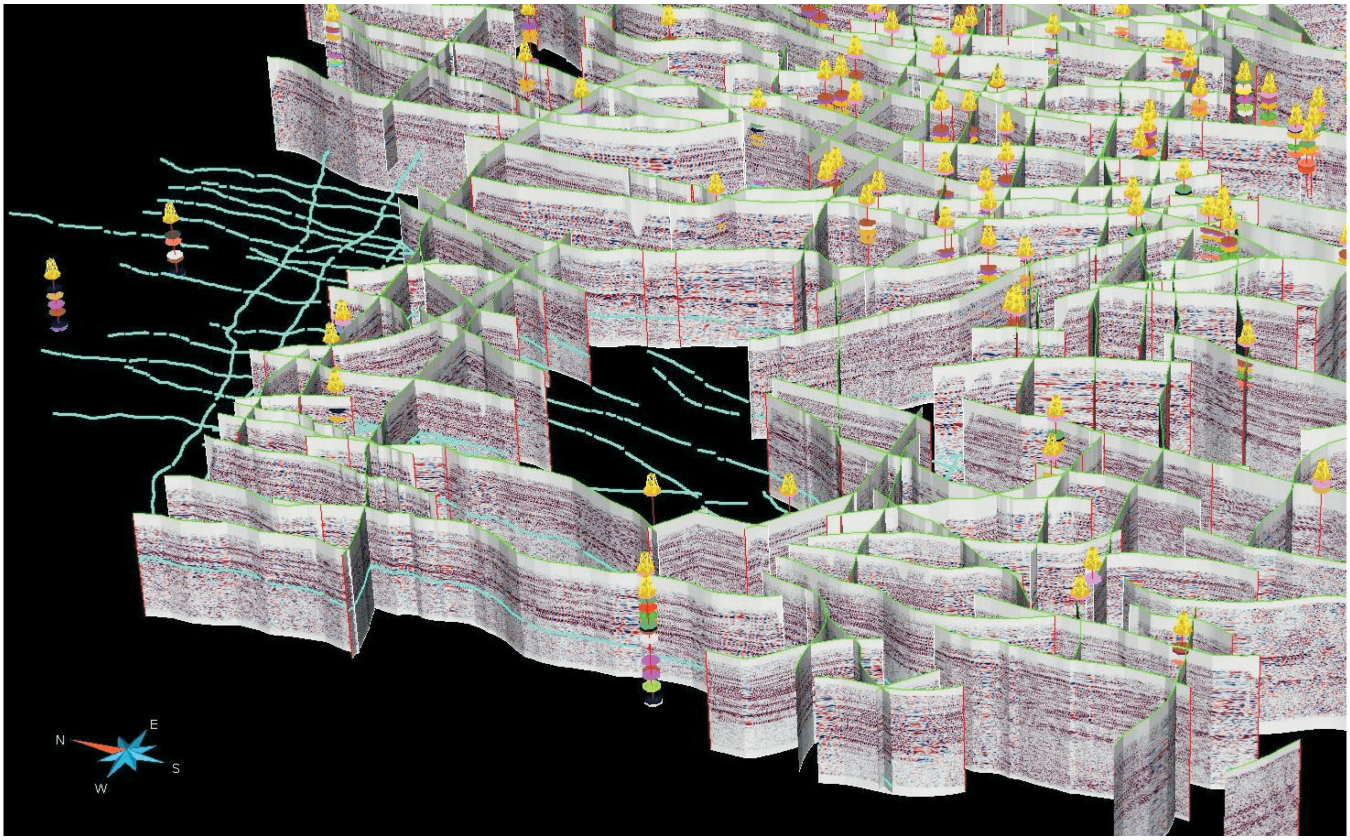

Figure 5. Screenshot of the larger Munich area GoCAD° scene while GeoMol model preparation featuring an exceptionally dense seismic network and borehole information. Borehole markers were used to derive regionalized depth constraints for areas with no significant seismic signature or without stratigraphic control and to overall calibrate the scene. The cyan lines trace the top of the Upper Jurassic hydrothermal aquifer, one of the principal target horizons of modelling (from GeoMol Team 2015).

Project Report (GeoMol Team 2015, http://www.geomol.eu/report/).

Undoubtedly successful with respect to knowledge exchange and fine tuning of methods and workflows – from baseline data processing, specifically seismic interpretation, to distributed organized model delivery (GeoMol Team 2015) – the project had to exclude "Niederbayern" (cf. Figure 2) due to the limitations of the Alpine Space Cooperation Area and revealed fundamental constraints with respect to cross-border lithostratigraphic harmonization. Nevertheless, for the Bavarian territory it delivered two detailed cross-border harmonized geomodels of pilot areas (GeoMol West and GeoMol Ost in Figure 2) and a downscaled framework model of (almost) the entire Molasse Basin, roughly 1,000 km in length, from Grenoble in France to Vienna in Austria.

Methodologies approved in and lessons learned from the GeoMol project are the guidelines for the current efforts that finally include the preparation of an all-encompassing geomodel of the Bavarian Molasse Basin and its connected terrains. This endeavor interlaces two projects: the Survey-internal project Infra3D and HotLime, one of 15 projects under the umbrella of GeoERA (**E**uropean **R**esearch **A**rea on Applied **Geo**sciences, http://geoera.eu/) that has received funding from the European Union's Horizon 2020 research and innovation programme.

Infra3D started in 2015 and is geared towards further systemization of 3D modelling processes and setting up an IT- and geoinformation infrastructure that supports data integration and model documentation. (Infra3D's data integration efforts are further discussed in the "Data" section below.) Implementation and evaluation of these processes is most suitable controlled in real case testbeds featuring a wide range of baseline data and different approaches of integration of downhole data with seismic data. Consequently, the revision and aggregation of the Molasse Basin has been chosen for Infra3D testbed. With this, Infra3D comprises topics that comply with the objectives and scope that have been prioritized in the GeoERA call, specifically the Geo-energy and

All tradenames (/ ®) in this paper are marked with a postposed °. This use of tradenames is for descriptive purposes only and does not imply endorsement.

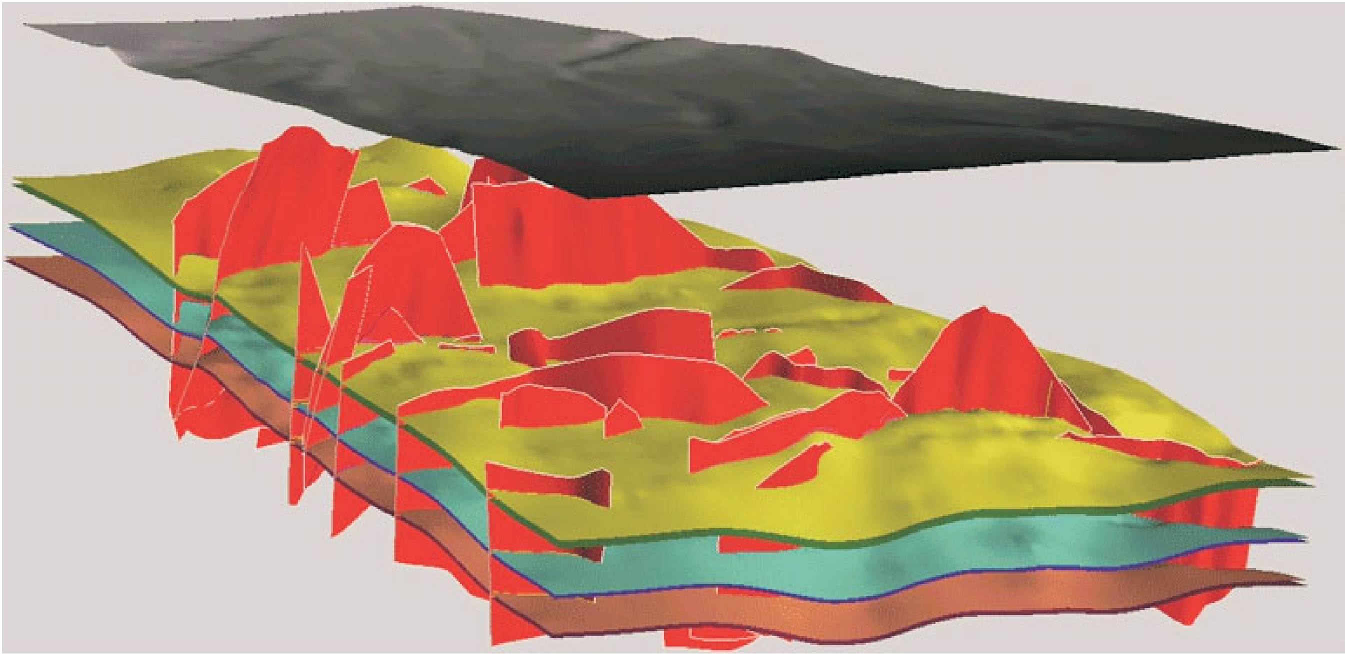

Figure 6. 2,000 km^2 tile of GeoMol Ost pilot area model, vertical extension ca. 5,400 m, view from SW. Depicted are six Mesozoic layer surfaces of the south dipping footwall sedimentary sequence and the fault network reflecting the complex tectonic evolution of the basin. Tertiary units are omitted for clarity. Modelling blind faults was a principal objective of GeoMol as these intrinsically control resources through forming hydrothermal fluids conduits, structural traps and reservoir compartmentalizing offsets.

Information Platform Themes. Thus it appeared obvious to propose the relevant parts of present work of the Survey as contributions in-kind to GeoERA projects and put it in a wider European context.

Core of the 3D modelling activities of the Survey in GeoERA is the HotLime project (http://geoera.eu/projects/hotlime6/), geared towards identifying the generic structural controls of hydrothermal plays in deep carbonate formations, through the comparison of geological situations in 10 case study areas across Europe. Similar to GeoMol but in a larger area including also the outcrop and subcrop (recharge area) of the Upper Jurassic hydrothermal aquifer, the capture of the structural inventory is the gist of the German-Austrian Molasse Basin cross-border study area (red outline in Figure 2). In HotLime, running from July 2018 to June 2021, all existing geo-models within the HotLime areal coverage are refined, extended to close the gaps, supplemented with missing areas and finally intertwined to form a single harmonized model. To this end an improved velocity model for time-depth conversation is applied. Model integration also includes segments where new approaches have been tested in areas with an inadequate coverage of seismic and downhole data, like the LOD2 model "Niederbayern" (Figure 7), prepared within the generic scope of the BAB (Subsurface Atlas of Bavaria) project.

For all deeper parts of the basin seismic data are the pivot for modelling both, layers and blind faults. Deep downhole data is used to calibrate the scene. Combining both, the modelling workflow requires switching repeatedly between time and depth domain. Thus, special emphasis is placed on the refinement of the velocity model quality by utilizing a layer-specific 3D property modelling workflow that responds to lateral changes in rock characteristics and yet velocities in a mostly automatized way. This update and refinement exploits methodologies developed by the Italian GeoMol Partners rounded up in the Vel-IO 3D tool (Maesano and D'Ambrogi 2017).

The spatial outcomes of all HotLime case studies will feed into the GeoERA Information Platform EGDI (http://www.europe-geology.eu/), supplemented with the HotLime knowledge base and project vocabulary as part of the Semantic Web. Likewise, the fault network modelled and parameterized will feed into the European fault database, a principal delivery of the GeoERA project HIKE (http://geoera.eu/projects/hike2/).

Resources Allocated to 3D Modelling Activities

All active 3D modelling is implemented by project staff contracted on a maximum 8-years basis. At present the 3D-modelling team consists of 5 geologists (see Acknowledgement) and permanently employed coordinators only marginally involved in routine modelling. The resulting volatility in human resources is one of the driving forces for the efforts to make

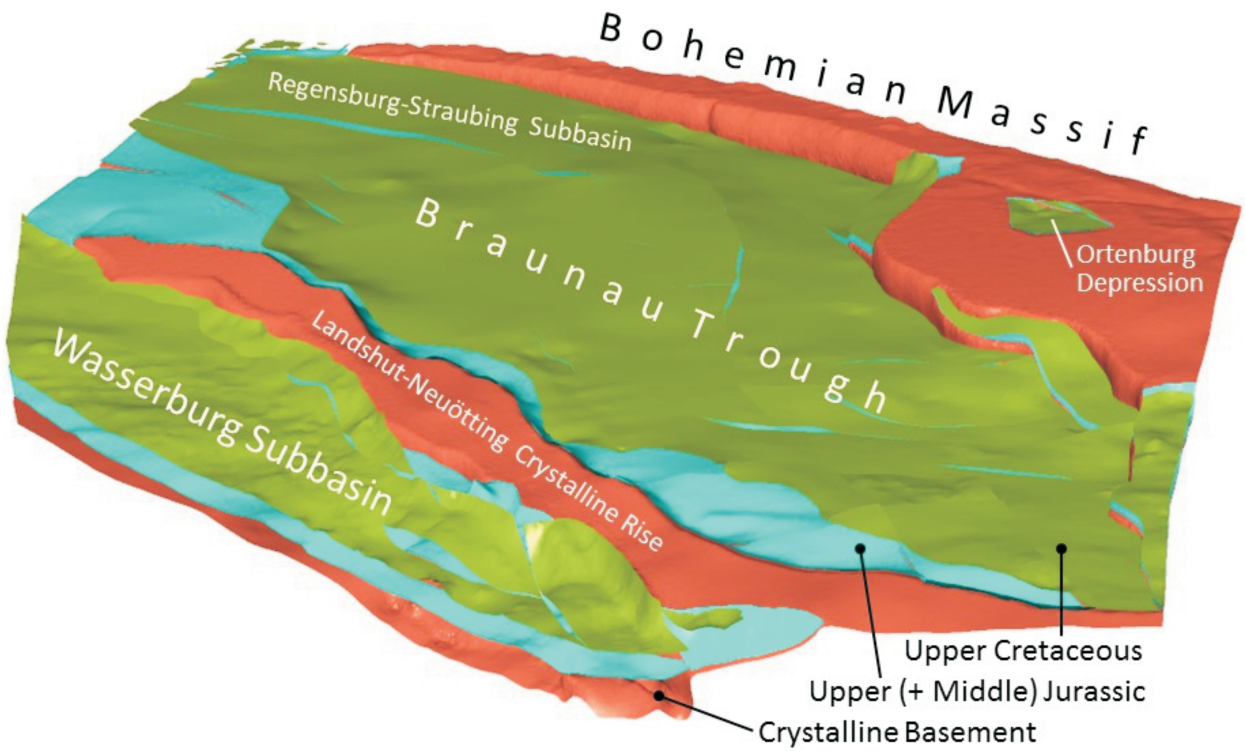

Figure 7: Preliminary LOD2 geological model Niederbayern (for outline see Figure 2) presently under revision and refinement (view from SW, Tertiary layers omitted for clarity). Due to the lack of hydrocarbon prospectivity and a low geothermal potential few seismic surveys have been carried out in the southern (deeper) part of this shallow to medium-deep portion of the Molasse Basin only. Hence, a Bouguer gravity residual anomalies map was used to accentuate the structure of the pre-Mesozoic basement and the >2,000 m throw fault system along the edge of the Bohemian Massif basement complex (cf. Figure 1).

the Survey's 3D geo-models sustainable through preserving the implicit knowledge and experience of the modellers in detailed model documentations.

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 on crystalline basement and the Alpine Orogen to the south (Figure 1). Four structural domains can be distinguished: the Alps, the Molasse Basin, the Scarpland (Cuesta Region) and the crystalline basement terrain. 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 fill, the Subalpine or Folded Molasse (Figure 8).

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 8), and form the uppermost escarpment of the Scarpland revealing increasingly older strata towards the northwest.

The lowermost cuesta forming sequence, Buntsandstein, rests upon non-metamorphic Permian sediments in post-Variscan troughs or directly overlays older medium-grade to high-grade metamorphic rocks associated with plutonic rocks, both formed during the Variscan orogenesis. This crystalline basement crops out in the very northwest of Bavaria and along its eastern border, partly covered by low-grade metamorphic rocks of Paleozoic age (Figure 1).

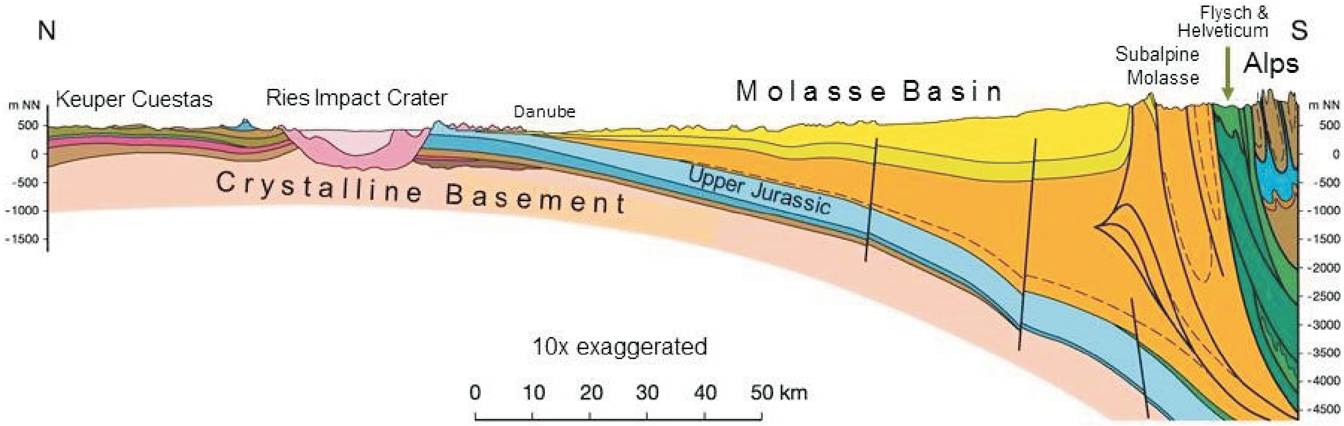

Figure 8. Geological section across the southern Cuesta Region, the Alpine Foreland and the Pre-Alps in western Bavaria (from Doppler et al. 2004, modified; color coding refers to the legend of Figure 1). The south-dipping Upper Jurassic karstified carbonate rocks forming the footwall of the Molasse Basin feature the most prolific geothermal aquifer in Central Europe thus being a principal target of 3D geological modelling. See text for details.

Data (Type, Abundance, Availability, Confidentiality Issues, Integration)

In Germany the federal law on geological resources (Lagerstättengesetz) enacts the reporting obligation for all geological findings towards the authorised GSO in order to support their mandate to gather, store and evaluate information on the subsurface. This statutory duty for data provision covers borehole data (since recently feasible through digital notification and report) as well as seismic surveys. At present index and downhole data of roughly 228,000 boreholes (about 950 deeper than 1,000 m), 1,770 seismic lines (overall length 12,230 km) of that 1185 in SEG-Y format, and 30 3D-seismic surveys in SEG-Y (overall coverage 3,550 km^2) are stored in the data repositories of the Survey. Auxiliary data for larger-scale structural models are gravity, magnetics and electromagnetics data from state-wide airborne geophysical surveys.

The vast majority of the seismic and deep borehole data comes from exploration and production (E&P) activities mainly for oil and gas, of late increasingly for deep geothermal. These data are subject to business interests and are thus classified confidential or commercial. A framework agreement with the E&P association allows us to utilize the data for interpretation and generic modelling, but no primary data may be displayed in detail nor may disclosed models be suitable for back-engineering. This imposes special requirements on the disclosure of 3D geological models and their mode of distribution.

Datasets of both, borehole index and downhole data and the digital repository for geophysical data are consolidated in the central database (BIS) of the Survey and are on the way to be supported by controlled vocabularies for lithological, stratigraphic and structural terminology. Virtually all the Survey's paper records had been scanned and most legacy data had been geo-registered. The retrieval and subsequent use of all these data is aided by data indices and associated metadata. Streamlining the linkup and synchronisation of this data thus facilitating their use and intertwining with the implicit knowledge in the scientists' brain, to produce re-useable hence sustainable 3D geological models, is the objective Infra3D project. Infra3D aims at the upgrade and extension of technical infrastructure assisting in semi-automated model development and update. Besides BIS and MIS (metadata database), the GST° (Geosciences in Space and Time, https://www.giga-infosystems.com/products) framework is the pivotal pillar of the Survey's 3D infrastructure (Figure 9).

To support the automation of the processes, certain custom programming features are developed, based on international standards for information exchange and data description. Their main purpose is to check, correct and improve the consistency of the underground data. The programming features include the development of ArcGIS° Python toolboxes, of a custom Python° library and standalone scripts. The GST° API Python module GSTPy provides capabilities to enhance the data processing. Since Infra3D is oriented to open source technologies Eclipse° is used as an integrated development environment. All programming modules are stored in Git code repository, SmartGit° is used as a graphical Git° client. Additionally an ETL-Process for data synchronization via FME platform is developed.

Examples of applications in automated model documentation and controlled vocabulary integration are addressed in the chapter "Current Challenges" and "Lessons Learned" sections.

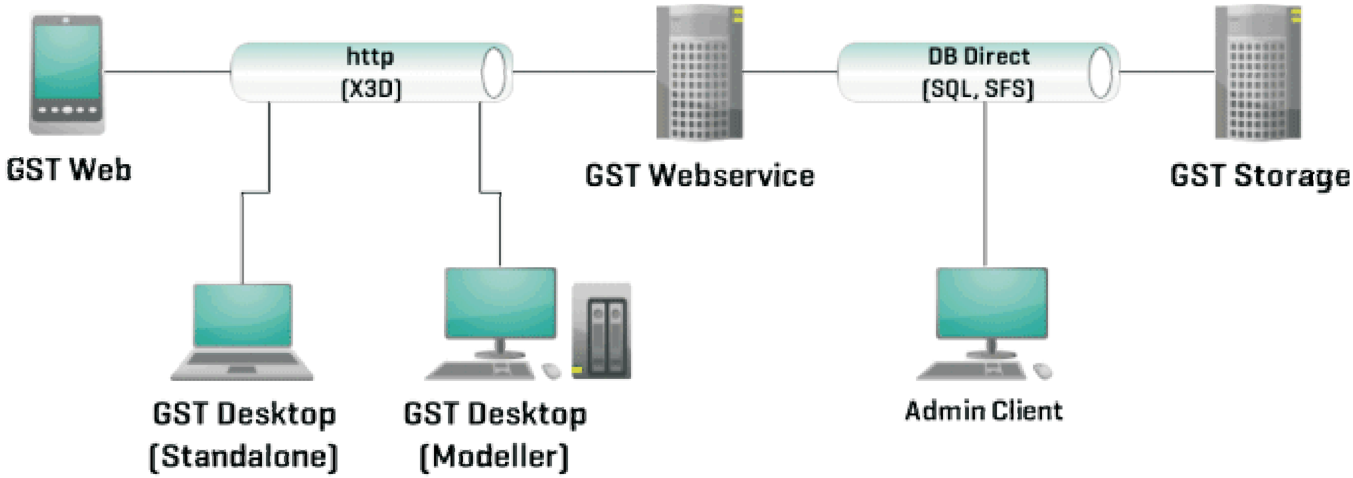

Figure 9. GST° provides collaborative environment for software independent storage, administration and visualization of spatial data. The GST° DesktopClient assists modellers in organizing 3D geo-models. GST° WebClient, a Web 2.0 application, forms the back end component which allows presenting the open source models of GST°Storage in web-based 3D browser-analyst (as exemplified in Figure 10). Beyond visualizing 2D and 3D geometries the browser analyst is capable to display corresponding baseline data objects retrieved on the fly (for data privacy internal version only). Figure courtesy of GiGa infosystem.

3D Modelling Approach

Confined to static modelling 3D model building at the Survey is based on the SKUA-GoCAD° software package, applied to implicit as well as explicit techniques at all scales and levels of detail. This software proved to be capable of regional stratigraphic modelling the majority of geological terrains encountered in Bavaria at acceptable productivity rates and capable of dynamic revision when new data or interpretive insight becomes available.

We learned that there is no universal best practice applicable to all geological regions or project settings. With scarce baseline data, modelling is driven by geological concepts and implicit knowledge guided by the modeller and the software's algorithms. In contrast, when baseline data is sufficiently available and expert knowledge is on-hand explicit modelling is the means of choice, particularly based on geological cross sections. In practice, both extremes and all facets in between may occur in the same modelling area. In any case, modelling is controlled by the field geologist's expertise and modelling results feed back into the "hard" baseline data, manifested in repeated revision and re-evaluation especially of the stratigraphic interpretation of downhole data, but also for improving the conceptual model. In the long term, 3D geological models will be the datum for calibrating all new spatial data and geological evolution concepts.

Clients

In line with the statutory mandate to counsel the Bavarian public authorities on geoscience issues principle clients of the Survey are planners, regulators and decision makers of the public sector. However, these stakeholders require justiciable "frozen-state" information and only rarely have capability to interpret basic geoscience data, let alone to evaluate the merits of 3-dimensional interpretations, in short: they desire "solutions, not data" (Turner and D'Agnese 2009). Accordingly, these clients are served by 2D or 2.5D information derived from 3D geological models rather than by the full 3D information itself.

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 Survey to unveil "the hidden landscape beneath their feet" by providing straightforward insight into the subsurface. To this end a public access 3D explorer (Figure 10) was implemented for visualization and query of down-scaled 3D geo-models at a restricted zoom-in range.

The 3D browser-analyst for exploring open source models is based on GSTWeb° technology (https://www.giga-infosystems.com/products). It allows for spinning the model and exploded views as well as to toggle surfaces and faults, to slice through the model, to generate arbitrary cross-section and virtual drill holes, and to drape geospatial information from other WMSs. With the next release of GST° it will also be able to depict volumes grids.

The disclosure of 3D geo-models for further processing is limited to stake-

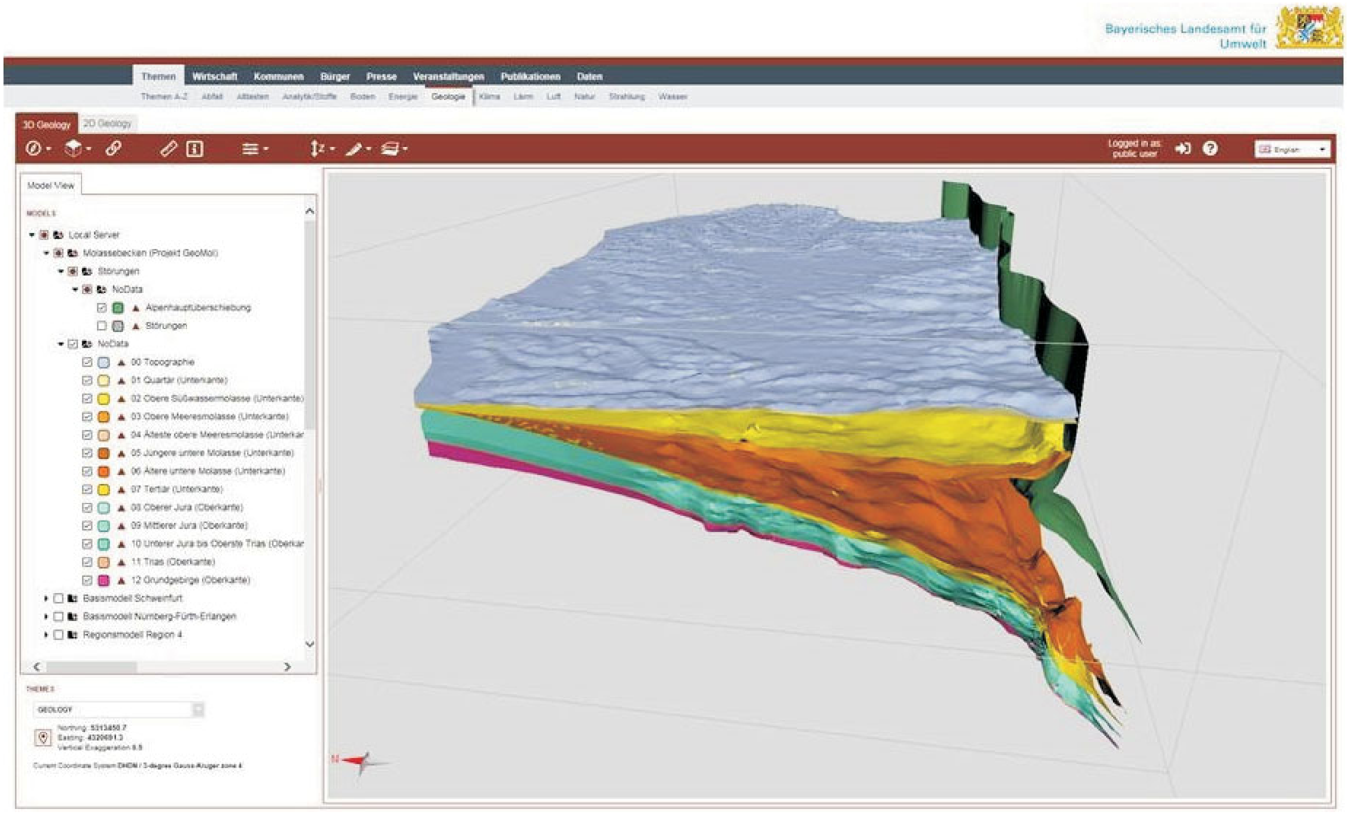

Figure 10: Screen dump of LfU's 3D explorer (https://www.3dportal.lfu.bayern.de/webgui/gui2.php) portraying the eastern portion of the Bavarian Molasse Basin of the GeoMol framework model. Fault planes (except for the Alpine orogenic front wedge in dark green) and the topographic overlay are disabled for clarity.

holders from academia and research institutions for further evaluation, parameterization and thus valorization of the models, and to GSOs of neighboring territories for cross-border adjustment and trans-regional investigations. In all cases, to comply with the statutory provisions on data privacy, the 3D geo-model is made available only upon request and in recognition of the case specific terms of use. One recent example is the collaboration with the Leibnitz Institute for Applied Geophysics (LIAG): The framework model of the Bavarian Molasse Basin has been deployed for the assessment of the main fluid and heat transport processes for a better understanding of thermal anomalies induced by gravity-driven groundwater flow and the long-term effect of Pleistocene glaciation (Schintgen et al. 2019). This negative temperature anomaly (cf. Figure 11) affecting the Upper Jurassic hydrothermal aquifer is a major constraint for the further boost of deep geothermal energy production in the Bavarian Molasse Basin.

Recent Case Studies Showcasing Application of 3D Work

As the Alps and the terrains of exposed crystalline basement are not covered by 3D models so far, there is no truly statewide case study application of 3D modelling results. However, the available models of the Molasse Basin and the Scarpland are shared for various thematic applications of different supra-regional coverage.

Implemented by LIAG, the Molasse Basin framework model was exploited to model the temperature distribution at the top of the Upper Jurassic hydrothermal aquifer in a cross-border approach including the Baden-Wuerttemberg, Bavaria and Upper Austria territories (Figure 11).

LfU's web-based information system "Umweltatlas" (http://www.umweltatlas.bayern.de) features various maps on the appropriateness and efficacy of downhole heat exchange including a map on the depth-related rock specific heat capacity. Presently building on flat-rate value 2.5D information it will incrementally be refined by tiles of parameterized LOD3 models as depicted in Figure 4.

Current Challenges (Organization, Technological, Conceptual)

Over the course of augmentation, revision, and upgrade of the 3D geo-models as described above we identified the increasing importance to improve our geo-information infrastructure towards supporting integrated data storage and facilitating knowledge sharing. One of the principal issues to achieve the latter is making

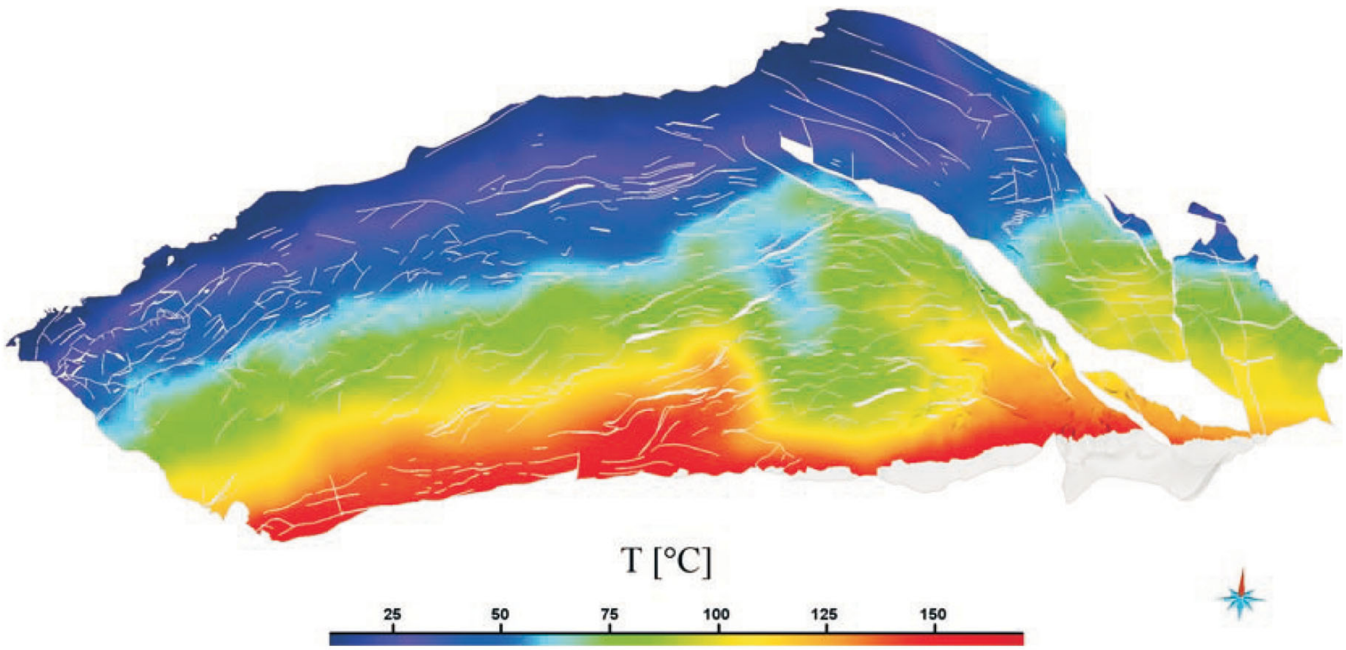

Figure 11: Temperature distribution in the Molasse Basin at the top of the south dipping Upper Jurassic, based on 3D structural models of the states of Baden-Wuerttemberg, Bavaria and Upper Austria and the 3D temperature model of LIAG (from Agemar and Tribbensee 2018). The white gaps represent the Landshut-Neuötting Crystalline Rise aka "Zentrale Schwellenzone" bare of Upper Jurassic and the fault tears in the Upper Jurassic surface. The south-trending bluish to green bulge indicates a marked negative temperature anomaly of unresolved origin, possibly a long-term effect of Pleistocene glaciation.

our models and associated data sets FAIR – Findable, Accessible, Interoperable, and Re-usable (Wilkinson et al. 2016), exploiting the functionalities of the Semantic Web.

Findable: The key for making information findable is discovery metadata. Well established for 2D geographic information and services, ISO 19115 provides information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data. This standard is not yet adjusted to 3D geo-models. It lacks an input option for the key information clients might search for, the lithostratigraphic units modelled as the gist of 3D geological models. ISO 19115, though, allows the indication of multiple keywords thus making possible an approach as outlined in Kondrová and Diepolder (2018), by tagging all modelled geological formations in *KeywordTypeCode:stratum*. However, such keywords are just empty shells if not underpinned by a controlled vocabulary that glosses synonyms and similar concepts as well.

This approach, initially conceptualized by the German SGD 3D modelling work group, has been recognized by the OCG and is proposed for interoperability tests within the OGC/CGI-IUGS GeoScience DWG (http://www.opengeospatial.org/projects/groups/geosciencedwg).

Accessible: ISO 19115 provides various data items describing the mode and constraints for distribution. Open disclosure geo-models can be furnished with a *dataSetURI* for direct retrieval via web services, and *distributionFormat* to ensure beforehand that the client has available the suitable equipment for model exploitation. Models being subject to data privacy, as stated in *accessConstraints* and *useLimitations* can be made available upon request via the *distributorContact*, in recognition of the case specific terms of use.

Interoperable: Technical interoperability among the German SGD, e.g. for cross-border harmonization, is not an issue as all SGD are utilizing (among others) the SKUA-GoCAD° software package. File-based model transfer, however, is outdated since GST° Storage (https://giga-infosystems.com, cf. Diepolder 2011b) has become a quasi-standard for model storage and exchange at the SGD. GST° also allows the frictionless exchange with other software packages like MOVE° or Petrel°.

Unlike technical interoperability, content-related interoperability, the cross-border fit of the model layers, can only be achieved by harmonization of the lithostratigraphic subdivision at the very beginning of the modelling process. As one of the principal lessons learned from GeoMol project, the approach to tackle this challenge is discussed in the following chapter.

Re-usable: Model documentation and versioning is the crucial pre-requisite to make 3D-geo-models re-usable. With fluctuating staffing it is also essential to preserve the implicit knowledge of the model builder and to keep track of the modelling process applied and the data used, thus facilitating future model updates. Recently, each model prepared or revised at the Survey is described in standardized digital templates stored in the Geo3D database. By database exports this formalized records can be compiled for various publication formats or can be re-used in other data bases. All relevant information is supported by controlled vocabularies for lithological, stratigraphic and structural terminology. In addition to formalized records, the model documentation (Figure 12) also admits free text for an unconstrained, individual appraisal of the modelling process and the conceptual background.

Lessons Learned

Cross-border harmonization of the lithostratigraphy and correlation with seismic reflectors, in order to achieve content-related interoperability among cross-border models, was the most underestimated issue during the implementation of GeoMol. Lithostratigraphic subdivisions are standards with limited areal validity evolved from regional approaches reflecting regional peculiarities and are subject to semantic changes in historical evolution of terms. Full standardization of such geological interpretation terminologies is virtually impossible as pluralism of terms is fact-based, well-established and has been used in geoscientific publications over decades (Kondrová and Diepolder 2018). Furthermore, in geology, semantics defines the delimitation of units, e.g. depth of strata. Thus, shifts in lithostratigraphic subdivisions often require realigning, or even re-surveying of geological units.

Rather than attempting to harmonize lithostratigraphic concepts, the Survey's present approach is to elucidate the differences by contrasting juxtaposition of these concepts. Lithostratigraphic concepts collated in a general legend and linked to external classification schemes, using the standard relations (same as, broad match, etc.) of semantic triples in the Resource Description Framework (RDF) data model allow for the straightforward comparison of the geological interpretation terminologies. Embedded in a Semantic Web exploiting the functionalities of the Simple Knowledge Organization System (SKOS) and using unique web addresses (URIs), such controlled vocabularies can be related to other web resources like code lists of established definitions and standards thus constituting a comprehensive web-based thesaurus of geoscientific concepts like the advanced GBA-Thesaurus (Hörfarter and Schiegl 2016, http://resource.geolba.ac.at/). The Survey's general legend now is used for tagging discovery metadata, the formalization of model documentations, etc. As soon as the SKOS modelling is fully implemented the unique ID of the concepts will be converted into an URI and uploaded to a registry, thereby integrated into the Linked Open Data Semantic Web serving both, the SGD lithostratigraphic concepts thesauri network in the

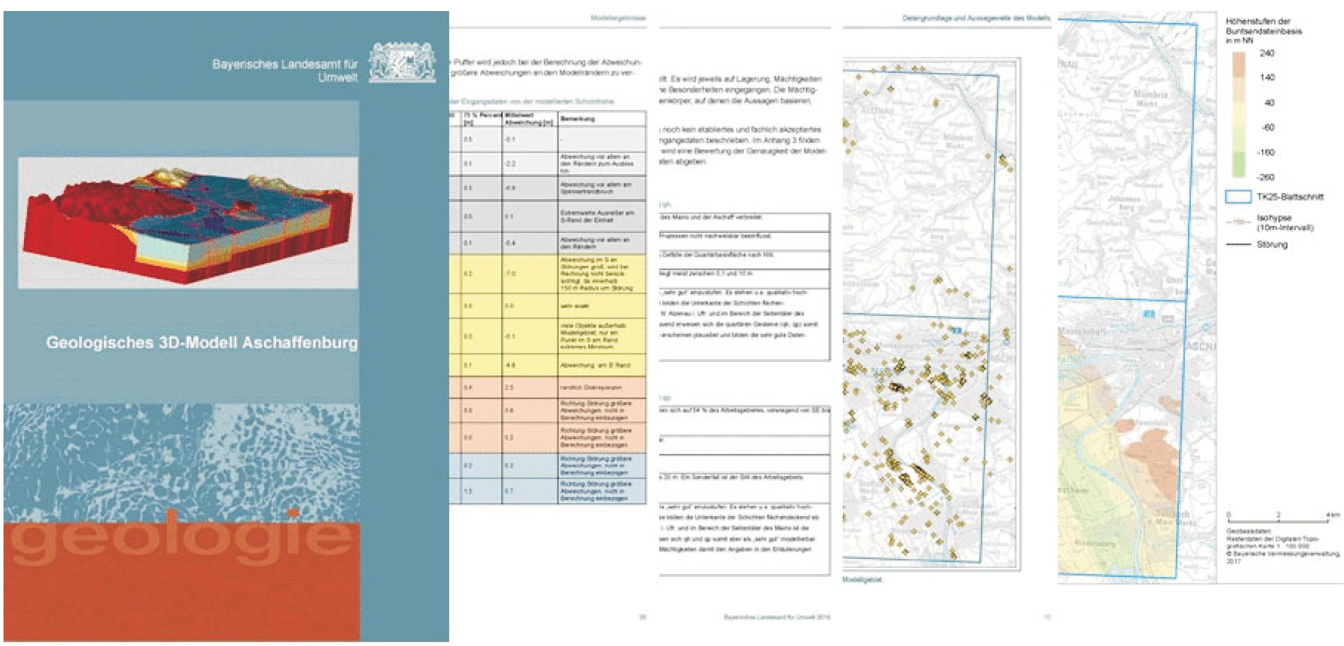

Figure 12: Example of the print copy of standardized model documentation. Tables and annexes are featuring mandatory information directly integrated from the GEO3D database using templates in a machine-readable format based on CGI Geoscience Vocabularies (http://resource.geosciml.org/def/voc/) and other standard code lists. The documentation's annex comprises thematic 2D extracts (maps, contour line plans) derived from the geo-model described including information to assess uncertainty like data density distribution maps for all modelled units.

making and the GeoERA project vocabularies as part of a comprehensive knowledge base.

Next Steps

Next steps planned at the Survey are to continue and complete the present plans as set out above. Sparse staffing levels do currently not allow for ambitious new plans and rather we try to disburden our modellers from secondary work by fully automating data handling processes. Likewise, it is not our ambition to single-handedly deal with all advancements in 3D geological modelling. To mitigate shortcomings caused by sparse staffing we rather further on promote knowledge sharing through inter-SGD and transnational exchange as spearheaded by the Survey for more than a decade. However, despite the tacit appreciation of the mutual benefits of such collaboration, succession planning to secure the continuity of the SGD task group on 3D modelling and its international involvements, now, as the chair is approaching retirement, is a challenging task.

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