# Transnational Geo-potential Assessment Serving the Sustainable Management of Geothermal Energy and Resources Efficiency – the Project GeoMol

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**ABSTRACT**

Boosting the use of deep geothermal energy and fostering resource efficiency require a sound, three-dimensional geological knowledge of the deep subsurface as the scaffolding for planning and management. This information allows prioritization and helps avoid mutual interferences with other subsurface utilizations also at cross-border scale; it gives planners, licensing authorities and project developers a holistic, transnationally harmonized three-dimensional assessment regarding all geo-potentials and the intrinsic (geogenic) constraints for their use. GeoMol's transnational approach, as performed in the Foreland Basins of the European Alps, provides consistent and seamless geological information based on harmonized fundamental data and common methods. To ensure the project's outcomes also benefit users beyond the geological community, they are converted into ready-to-use information, customized to the users' requirements as revealed in a stakeholder survey. Thus, different channels for information distribution are provided, including a web-based geo data infrastructure for multidimensional subsurface data; in compliance with the data policy of the project's member states, a 3D-explorer and a map server were set up to assist governments, planners, and industry to manage the geothermal potential in an integrated and sustainable manner.

## 1. INTRODUCTION

The Alpine Foreland Basins – the northern Molasse Basin and the southern Po Basin (Fig. 1) – feature a unique geological inventory which can contribute substantially to meet Europe's ambitious targets for carbon emission reduction. Due to their geological evolution, these more than 5000 m deep sedimentary basins along the northern and southern fringes of the Alpine mountain range offer abundant deep geothermal potential, storage capacity to attenuate intermittency of weather dependent wind and solar fuels, and space for underground storage of gas or $CO_2$.
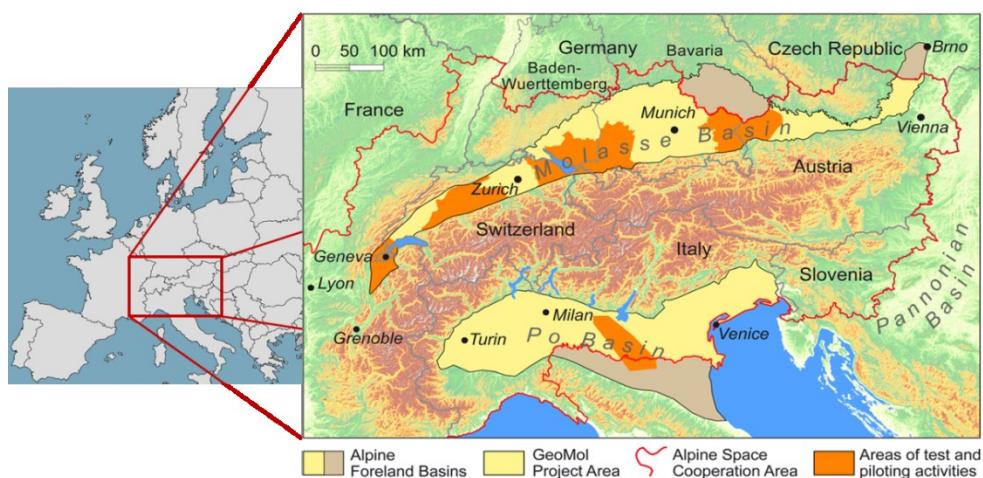


**Figure 1: Outline map of the Alpine Foreland Basins, the GeoMol project area ($\approx$ 90,000 km$^2$), the Alpine Space funding scheme's eligible area and the GeoMol test and pilot areas for a more detailed geo-potential assessment.**

Among the deep geo-potentials of the Alpine Foreland Basins, geothermal energy is by far the most important and most widely deployed. Solely exploited for balneological use until the 1990s, it has become increasingly important for energy generation over the last decade. Due to especially favorable conditions with respect to geology, and the high exploitation of the utilization potentials for district heating in densely build-up areas, the Greater Munich area at present features 15 deep geothermal installations for district heating or combined heat and power generation in operation or running-in tests (Fig. 2), providing a total 150 MW$_t$ heat exchanger capacity. Beyond the present focus on the Molasse Basin, in eastern Bavaria further installations for hydrothermal energy generation are under development or in planning stages all over the Alpine Foreland Basins, with major projects in Upper Austria, St. Gallen and Geneva in Switzerland, and Peschiera del Garda and Ferrara in Italy.

Geothermal exploration and development is an acknowledged high-risk investment. This applies in particular to the low enthalpy system of the Alpine Foreland Basins, where tapping suitable temperatures in the hydrothermal aquifer system requires drilling depths of more than 3000 m. Varying hydraulic characteristics of the geothermal reservoir further increase the development risk as the actual local performance of hydrogeothermal installations strongly depends on the natural flow conditions in the deep aquifer system and the specific discharge.

Gas storage is another focus of subsurface utilization in the Alpine Foreland Basins – to safeguard the security of supply and balance the seasonal swing in gas demand, as well as to allow that renewable energy, such as wind and solar, to become base-load capable energy sources within the next decade. To attenuate weather dependent intermittency, there is a strong need to convert renewable electricity into hydrogen or methane and inject and store this in gas networks and underground.
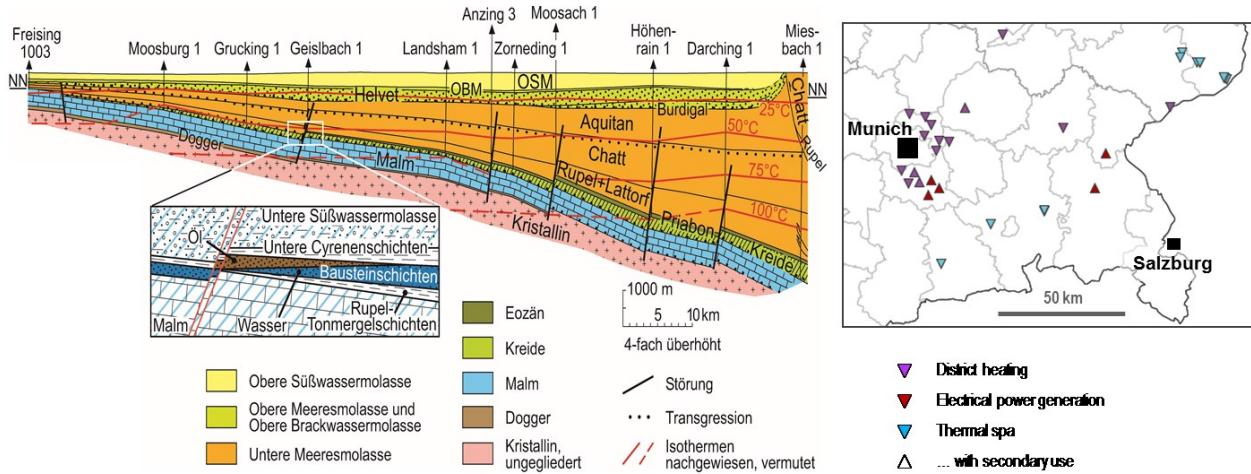


**Figure 2: N–S geological cross-section of the northern Foreland Basin (Molasse Basin) east of Munich (from Diepolder and Schulz 2011, after Lemcke 1988) exemplifying two types of geo-potentials: Temperatures up to more than 150°C in the south dipping Upper Jurassic (Malm) karstified limestone aquifer and a typical setting of a hydrocarbon structural trap in the western Bavarian Molasse Basin as a possible target for underground gas storage. *Right:* Sketch map of geothermal installations in operation or running-in test in the eastern Bavarian Molasse Basin as of May 2014 (GeotIS 2014).**

Exploiting the subsurface potentials of the Alpine Foreland Basins for the improved use of renewable sources, as well as fostering energy efficiency requires the consideration of existing uses such as oil and gas licenses and groundwater rights; one must regard the mutual interferences as well as areas at risk. Thus, an adequate comprehensive understanding of the deep subsurface is a pre-requisite for the sustainable management and efficient use of geo-potentials, reducing the financial risks of development measures, avoiding usage conflicts and delineating no-go areas due to geological risks. Coherent information on the structures and features of the subsurface also serves improved underground spatial planning, and enables a changeover from the currently practiced unlimited depth licensing (one allocated use only per license area) to a vertically zoned licensing allowing multipurpose use. Geo-potential assessment must, therefore, principally be based on a sound, unbiased and holistic three-dimensional evaluation of the geological fundamentals utilizing advanced 3D modelling techniques.

The reach of impact for many geo-potential utilizations is much larger than the respective license areas, and as with geology in general, does not respect political boundaries. The sustainable management and impact assessment of exploiting subsurface potentials, thus, requires a supra-regional approach which must be guided by geological structures rather than by administrative units.

To comply with these fundamental principles for sustainable action within the scope of the GeoMol project, data on the geological structures and features of the Molasse and Po Basins have been gathered and analyzed in order to serve transnational planning and decision making. The project is also aimed at raising the societal awareness about geo-potentials and the subsurface as a finite resource. GeoMol provides consistent three-dimensional subsurface information based on coherent evaluation methods and concerted criteria and guidelines. Enhancing the common knowledge of the subsurface in the Alpine Foreland Basins will further stimulate homemade, decentralized green energy by exploiting geothermal potentials and using subsurface storage capacities for solar and wind fuels thus contributing to low-carbon economy and ensuring the security of energy supply. GeoMol will also improve the spatial understanding of the basins' structures and thus will support the evaluation of potentially active faults especially in the Po Basin.

## 2. DATA PREPARATION AND HARMONIZATION

A major challenge in 3D modeling at great depths is the availability of data with an adequate distribution and resolution to address issues properly. Several 3D geological models on or comprising parts of the Molasse Basin have been built over the last years (e.g. Rupf and Nitsch 2008, Pamer and Diepolder 2010, Sommaruga et al. 2012), but the merger of existing 3D geological models by just filling the gaps in between is not feasible. They are made for different purposes and address distinct issues, and are based on different primary data originating from multiple sources with various dates of origin. Thus, preparing coherent 3D information imperatively requires harmonization from the very beginning of the model-building process, applying consistent methods and common parameters.

Base data for GeoMol's 3D geological models are seismic data, scattered and clustered borehole evidence and the conceptual models of the basin evolution. By far the largest data pool is the seismic sections network and, lately, 3D seismic surveys (Fig. 3). More than 28,000 km seismic lines have been selected as the basis for structural 3D modeling, to interconnect existing spatial information in its true spatial relation, and to integrate cross-sections of earlier syntheses implicating the concepts and tacit knowledge of decades of geological expertise. Where available, e.g. at the Seismic Atlas of the Swiss Molasse Basin (Sommaruga

et al. 2012), the base data of recent syntheses have been re-processed in compliance with GeoMol's best practice workflows to achieve trans-border consistent results.
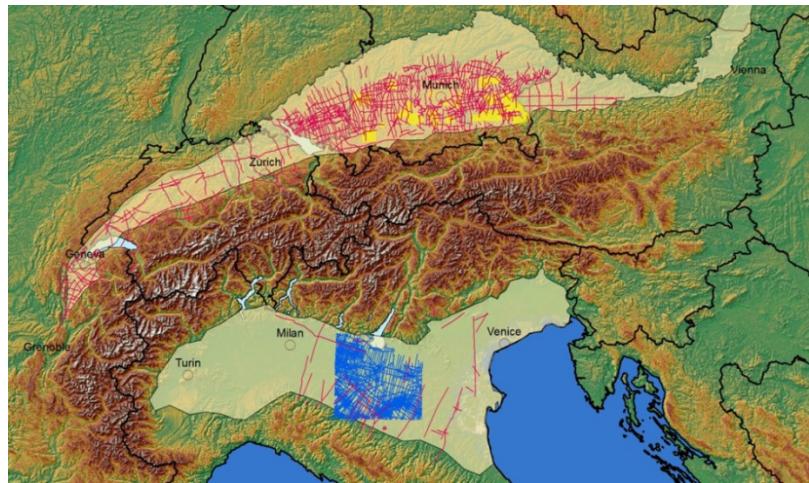


**Figure 3: Seismic 2D-sections (red lines), 3D-seismic projects (yellow) available for interpretation in the Foreland basins. Additional seismic sections for the Po Basin Pilot Area and surroundings (blue lines) have been made accessible for in-house inspection at the ENI S.p.A. archives. The highly imbalanced distribution of these fundamental data due to the differing legal framework in the partner states is a major obstacle in transnational harmonization and in providing a cross-border coherent level of detail.**

Originating from multiple sources and various dates of origin, the seismic data is subject to heterogeneous interpretations which have gone through several paradigm shifts over the last decades. Thus, as with preceding projects (e.g. Rupf et al. 2012), it is imperative to standardize the data with regards to technical parameters and content prior to further analysis, exploiting the technical advances in seismic processing. An effort has been made to adjust all lines to the same seismic reference level, amplitude and step of signal processing to avoid mismatching at intersections and at the country borders (Capar et al. 2013). After applying the whole sequence of processing steps from scanned paper plots to filtered post-stack migrated SEG-Y files, structural features can be identified more precisely and certain seismic pattern can be used in sedimentary facies interpretation (Fig. 4). Both features are critical parameters for the existence of geo-potentials: the fault network determines the rock mass permeability and the occurrence of structural traps, facies distribution controls the hydraulic conductivity of the aquifers.
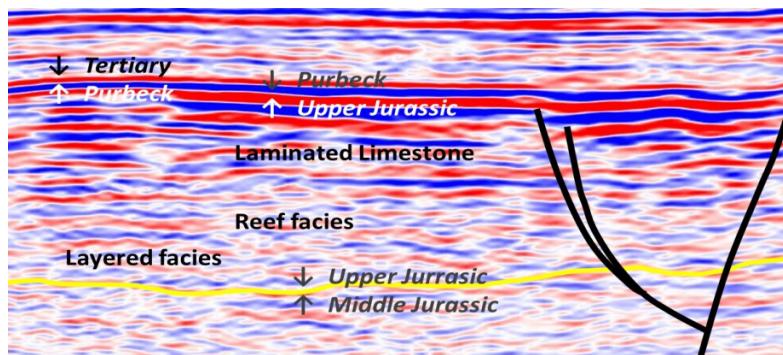


**Figure 4: Example of seismic pattern which can be attributed to the facies distribution in the Upper Jurassic hydrothermal aquifer of the Bavarian Molasse Basin.**

To improve the accuracy and reach of correlating lithologies and their seismic signature, several synthetic seismograms based on drill hole measurements have been generated and parallelized with the stratigraphy of the borehole evidence. An effort was made to record in detail all units deemed distinctly identifiable, as well as their range of variation, to eventually provide a catalogue of characteristic seismic signatures for all model units of the entire northern Molasse Basin.

The stratigraphic subdivision of the Alpine Foreland Basins, however, has evolved from regional approaches and reflects the complex basin evolution, featuring sedimentary cycles which vary in space and time. Grown historically from different schools of thought, differing nomenclatures and subdivisions on the detailed scale are used. Thus, working cross-border also requires a semantic harmonization and the alignment of stratigraphic peculiarities to allow the correlation of a uniform lithostratigraphic column with the prominent seismic reflectors traceable over the entire basins. A harmonized lithostratigraphy also serves uniform model building between and beyond the seismic reflectors, e.g. by using regionalized thickness constraints derived from borehole information.

As many data sets used in 3D modeling are classified data, access restrictions require that all model building may be implemented at the legally mandated regional or national GSO only. For a transnational project this means a maximum of coordination from the very beginning of the data preparation and the 3D modeling processes. GeoMol's 3D modeling procedure consists of several workflows adjusted to the specific needs of each partner, depending on the 3D modeling software used, and if modeled in time or

depth domain (Rupf et al. 2013, Maesano et al. 2014). If modeled in time-domain, refinement of layer surfaces was done by borehole data re-converted into time-domain (Fig. 4), based on check shot data available for many hydrocarbon exploration drillings. Regionalized velocity models for time-depth conversion were applied at a late stage of modeling only, to facilitate later model refinement by additional seismic sections where needed.

Seismic interpretation as well as all 3D modeling based on seismic data was performed and stored in time domain to facilitate later integration of new data. For all information rendered in depth domain such as borehole data (Fig. 5) or geological cross-sections velocity models had to be applied for integration. Thus, several regional velocity models for time-depth conversation were developed. These take into account the regional differences in rock composition and were adopted according to the territorial scope. Depending on the base data available, over 270 boreholes with primary velocity data and 4,300 locations comprising more than 70,000 individual secondary stack velocities have been used for a single dynamically updatable velocity model, deploying geostatistical workflows for velocity interpolation. Cross-check with depth data added even velocity constraints that were re-introduced into the velocity modeling workflow in order to calibrate the model. The transformation of the velocity model into a density model constrained by borehole logs is envisaged.
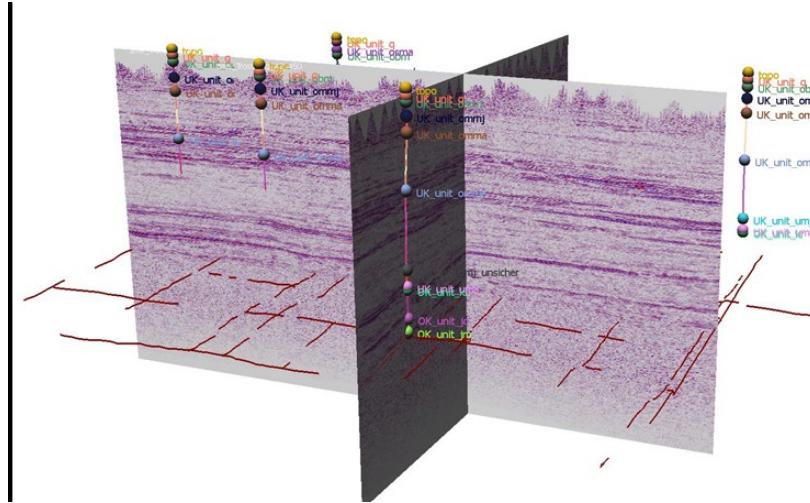


**Figure 5: Calibration of interconnected seismic sections using borehole markers re-converted into time-domain. The red lines mark traces of the base of the Upper Jurassic (Malm) geothermal aquifer as picked from seismic sections (from Diepolder et al. 2014).**

The trans-border accuracy of fit of base data, the evolving 3D geological models and their intermediary products were verified by periodic check-up of all adjacent sub-territories during the whole modeling process. Since the deployment of the first modules of GeoMol's data exchange system GST (Geo Sciences in Space and Time, cf. chapter 4), the necessary transformation of country-specific coordinate systems for this cross-check runs real-time, adapting the partners' reference system on the fly, and no longer requires the cumbersome bilateral file exchange.

## 3. 3D MODELING, GEO-POTENTIAL ASSESSMENT AND NO-GO AREA DISERNMENT

Many of the geo-potentials in the tilted sedimentary sequences of Alpine Foreland Basins are bound to structural features such as fault traps or anticline traps (Fig. 2). Fault and fracture networks, as arrays of increased permeability, have significant effects on the productivity and economic viability of hydrogeothermal developments. They can significantly impact drilling, resource operations and potential recovery. Fault and fracture networks also control the compartmentalization of reservoir rocks for underground storage and the sealing characteristics of cap rocks, and are thus crucial for storage security.

On the other hand, seismogenetic structures like the Apennine buried orogenic fronts are the source of geological hazards – as recently evidenced by the May 2012 seismic sequence in the Po Basin. Even though epicenters of stronger earthquakes are located at depths far beyond the reach of human impact, any major utilization of subsurface potentials must consider the possible seismic risk. Thus, structural features of the deep subsurface also define no-go areas, and may be a strong limiting factor for the utilization of geo-potentials. The spatial characterization of potential active faults was the prime objective of GeoMol's 3D modeling in the Po Basin (Maesano et al. 2014), supporting further studies for seismic hazard assessment as performed by D'Ambrogi and Congi (2010).

Summarizing the chief purpose of 3D model building within the scope of Geomol, it can be outlined as the three-dimensional analysis of the structural setup and characterization of the foreland basins' fault networks.

Information on the structural setup, however, is just one aspect in assisting more detailed regional and local assessments of geo-potentials and the improved estimate of the capacity and the effectiveness of the resource stocks. Therefore, the volumes of the 3D models' rock sequences were populated with regionalized physical properties compiled from databases of the partners and beyond: the temperature distribution at depth, and the bulk permeability of the reservoir and barrier rocks at a regional scale.

Even though geothermal energy is by far the most important and most widely used geo-potential in the Alpine Foreland Basins, until recently, generally available but non-verifiable assessments have been applied in spatial temperature modeling. Thus, an effort has been made to improve the temperature model, applying more sophisticated geo-statistical methods and a reworked correction of bottom-hole-temperatures (BHT) based on a comprehensive revision of the primary data.

A validation of the different graphical and numerical BHT correction methods has been performed, comparing the undisturbed bore logs with calculated formation temperatures using different correction methods. The sensitivity analysis implemented in areas with a high data density revealed the downtime of circulation as the pivotal parameter for BHT correction, and allowed the definition of a verified threshold for use of data. Accordingly, an improved 3D temperature model was built, applying only the most reliable formation temperatures. This toilsome but verifiable approach (Casper and Zosseder, in prep.) also enables a classification with respect to the presented temperatures, specifying the range of uncertainties depending on data quality and the used correction method – an issue highly demanded especially by project planners and underwriters.

Further parameters essential for geo-potential assessments, which cannot be regionalized due to lack of data availability, will be addressed in GeoMol's best practice manuals and workflows. Geared to the geological situation of the Alpine Foreland Basins, but generalized for the use in other deep basins as well, these guidelines are designed as a basic planning tool to serve the administration and decision makers. The deliverables of GeoMol are not designed to permit the scoping and economic validation of individual projects for geo-potential utilization.

As discussed, core of the project GeoMol (and additional model building beyond the project area) is a structural 3D subsurface model of the principal units for the entire Northern Molasse Basin, covering almost 55,000 km$^2$, providing the framework to slot into all aligned existing and emerging models in their true spatial setting. Detailed models in the five pilot areas (cf. Fig. 1) have been built to cover specific questions of subsurface use and/or to identify seismogenetic structures (as a principal constraint for geo-potential utilization), and to provide the three-dimensional framework for subsequent (numerical) modeling beyond the project.

The 3D geological models set up consist of up to 13 litho-stratigraphic units ranging from the Cenozoic basin fill down to Mesozoic and late Paleozoic sedimentary rocks and the crystalline basement (Fig. 6).
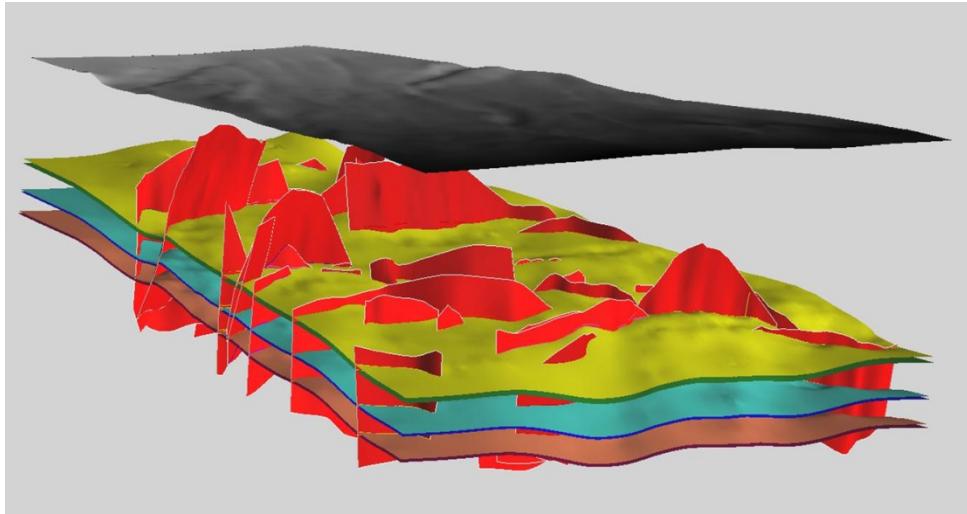


**Figure 6: A 2,000 km$^2$ clip of the preliminary framework model down to more than 5,000 m, located in eastern Bavaria, view from SW, showing six pre-Tertiary layer surfaces of the south dipping sedimentary sequence and a fault network reflecting the complex tectonic evolution of the basin. The Tertiary units are omitted for clarity.**

## 4. 3D DATA DISTRIBUTION AND INFORMATION CHANNELS

The increasing relevance of geological information for policy and economy at transnational level has recently been recognized by the European Commission, who called for the availability as well as comparability of data/information related to reserves and resources in the EU Member States (EU 2013, van der Krogt et al. 2014). GeoMol's transnational approach responds to that, providing consistent and seamless geological information based on harmonized fundamental data and agreed methodologies. However, no adequate tool existed at GeoMol's outset to distribute the multi-dimensional information of a transnational project facing diverse data policy, data base systems and software solutions.

### 4.1 The Infrastructure for Multi-dimensional Geo Data

In recent years, open standards describing 2D spatial data have been developed and implemented in different software systems, including environments for 2D spatial data (Gietzel et al. 2014). Despite these data exchange, information systems and web access tools, at the start of GeoMol the 3D geological community still lacked the ability to exchange 3D geo data efficiently across the diverse systems (cf. Diepolder 2011). Thus, to set up and deliver seamless 3D geological information, a key issue of GeoMol was to provide a software independent infrastructure for multi-dimensional geo data. This structure would comply with both the data policy of the project's member states and the EU's request for harmonized geological information to support policy and economy at transnational level. The software development chosen to accomplish this is called GST, **G**eo Sciences in **S**pace and **T**ime (Gabriel et al. 2011). Developed initially for the ProMine project at the TU Bergakademie Freiberg, it was extended, refined and customized to the project partner's proprietary IT environments incrementally.

Major technical characteristics and principal features of GST have been described previously (Diepolder 2011, Gabriel et al. 2011). The fundamental object-relational data model has lately been published in detail (Le et al. 2013).

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In summary, GST's objective is to give access to, visualize and organize geo-objects using open standards, aimed at the generation of geomodels which will use thematic geo-information gathered at various scales to store and visualize the key spatial, geological, geophysical and geochemical parameters. A major concern is the management of large models, e.g. GeoMol's framework model(s), and the ability of 3D tiling into spatially restricted models with refined resolution, i.e. models of GeoMol's pilot areas. The object-relational data model allows an easy integration of existing metadata models into the newly developed 3D environment.
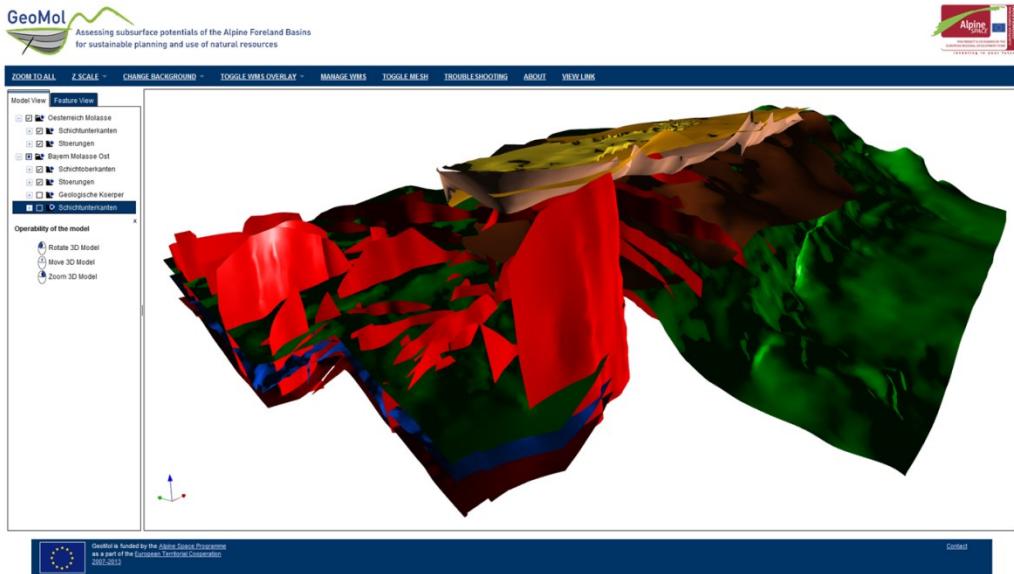


**Figure 7: GeoMol's web-based 3D viewer showcasing two preliminary 3D geological models of the cross-border Upper Bavaria – Upper Austria area (screen dump of the beta version as of 15/05/2014). The two 3D models displayed are stored separately at the legally mandated GSOs and merged on the fly via the web.**

GST is the core of GeoMol's web-based collaborative environment designed to serve the GSOs concerned and the scientific community. Common users spaces have been installed providing a central access point to manage locally stored data at each of the project partners IT site. This distributed-organized system allows data storage of the live system locally, sharing only cleared portions of the data (Fig. 7), thus adhering to national regulations on geo data access. GST also allows for a dynamic generation of virtual drilling profiles and cross sections of the stored models. As this enables the deduction of classified borehole data, a role based log is implemented, giving full access to the live system only for legally mandated or licensed bodies. The GST based developments of GeoMol will also be an important contribution to the future pan-**E**uropean **G**eological **D**ata **I**nfrastructure as prepared recently by the EGDI scoping study (http://www.egdi-scope.eu/) and summarized in van der Krogt et al. 2014.

**4.2 Further Information Channels**

It is generally acknowledged that 3D models provide the best information to tackle geological and environmental issues. However, the stakeholder analysis implemented within the objective of GeoMol clearly revealed that only a very small minority of potential users have the facilities and capability required to directly exploit 3D models. The majority of stakeholders strongly prefer 2D information derived from 3D models, such as digital maps implementable into GIS projects. To make sure that GeoMol's outputs also benefit users beyond the geological community and academia, they are converted into ready-to-use information customized to the needs of the users. Thus, two further channels for information distribution are provided, (1) to serve the administration and decision makers, and (2) to raise the awareness of the general public and to provide educational material.

GeoMol incorporates a variety of stakeholders and advisors from different areas of expertise to assist in the appropriate design of its products. To satisfy the users' demand for ready-to-use 2D products, an interactive web mapping application will be implemented, where project results can be searched, spatially visualized and queried, also allowing for the dynamic generation of vertical and horizontal geological sections. The GST techniques implemented for 3D model visualization also allow data support for common 2D web services like traditional Web-GIS, thus it is integrated into GeoMol's map applications. In addition, web mapping services (WMS) will provide a metadata catalogue for information on the availability of spatial data, on the access to these services and the restrictions of use. This metadata database has to comply with both the requirements of the EU directive INSPIRE and national spatial data infrastructures and data policies.

To meet the societal needs for information and the citizen's concerns about the impact of geo-potential utilizations, GeoMol's website www.geomol.eu provides detailed textual information and a 3D viewer. This GST-based interactive visualization tool is continuously extended and improved to enable the general public to eventually slice through, explode and virtually pierce through the subsurface of the Alpine Foreland Basins. In order to comply with data protection regulations, only a scaled down overview 3D framework model will be showcased. First modules of this online query tool have been deployed and tested successfully and are now available for WebGL enabled web browsers via a tab on GeoMol's website. Further modules and tools will be implemented incrementally. The functionalities of the interactive 3D visualization tool will be fully available by the finalization of GeoMol project in June 2015.

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