The Geothermal Information System GeotIS

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ABSTRACT

The Leibniz Institute for Applied Geophysics (LIAG) runs GeotIS, an internet-based information system on geothermal resources in Germany. The user-interface of GeotIS is available in English and German and can be accessed free of charge with a standard web browser. The development of the system was accomplished in close collaboration with partners from 2006 to 2009. Since then, the LIAG has been continuously maintaining and improving the system. GeotIS shows the potentials and the installations of deep geothermal use in Germany. It consists of two independent modules:

The module *Geothermal Potentials* offers a compilation of data and information about deep aquifers in Germany for possible geothermal use. Extent, depth and temperature of relevant geologic formations are presented for those regions of Germany most relevant to geothermal exploration. Surface and subsurface temperatures are provided where a sufficient amount of data is given. Both, temperature and geologic data have been compiled to state-of-the-art 3D-models to improve our understanding of subsurface conditions. Maps of formation permeability are available as part of the information system for many regions of geothermal interest. Furthermore, data such as the locations of wells or seismic profiles can be displayed.

The module *Geothermal Installations* provides an overview of geothermal power plants, heating stations and spas in Germany that are in operation or under construction. For each installation, details such as installed capacity or mean power production are provided. From 2011 on, energy statistics are presented on an annual basis.

GeotIS has become an advanced tool for the site assessment and the planning of geothermal installations in Germany. Basically, it is a digital, almost scale-independent and always up-to-date version of a geothermal atlas. Current knowledge and most recent results are provided and can be visualised in a convenient manner. Despite the amount of incorporated data, GeotIS cannot replace local feasibility studies.

1. INTRODUCTION

There are many areas in Germany where deep geothermal energy is available as an environmentally friendly alternative to fossil fuels as a source of power and heat. Far more geothermal resources exist than are currently used. When it comes to utilising this energy, deep boreholes must be drilled into suitable subsurface reservoirs. Geothermal power and heat generation is only cost-effective if sufficiently high water temperatures and flow rates are found.

The primary objective of the German geothermal information system GeotIS is to make a contribution to improving the quality of geothermal-plant project-planning by providing preliminary figures on these crucial parameters (Schulz et al. 2007, Agemar et al. 2007). Data from thousands of boreholes drilled by the oil and gas industry in Germany has hardly ever been published for commercial reasons. Using this valuable data can help to better estimate the exploration risk for deep boreholes and increase the chances of success for geothermal energy projects.

Only a geographical information system can satisfy the demand for spatial geological and geophysical data that is always up to date. Therefore, GeotIS is a dynamic system that includes the latest findings and results, and is continuously expanded. Like a virtual geothermal atlas, GeotIS makes these data available in a generalised form. This helps interested parties such as planners, investors, public authorities and insurance companies carry out a basic assessment of a site. However, concrete, location-specific prospectivity analyses still remains the brief of local feasibility studies.

GeotIS provides fast and free access via the Internet with any standard browser (http://www.geotis.de). It consists of two modules. The module *Geothermal Installations* is online since 2008 and gives information on geothermal plants, heat stations and spas. For each installation, details such as installed capacity or mean power production are provided. The module *Geothermal Potentials* is online since 2009 and provides geological and geophysical data important to geothermal resource assessment. The web-interface of GeotIS is available in English and German and also hosts many documents related to geothermal energy in Germany.

2. GEOLOGY

The system focuses on deep aquifers suitable for geothermal exploitation. Thus, it is restricted to hydrothermal resources. Other areas of deep geothermal energy, like for instance petrothermal systems, will be considered for future developments of GeotIS.

The most important regions for hydrothermal exploitation in Germany are the North German Basin, the Upper Rhine Graben, and the South German Molasse Basin (Fig. 1). Stratigraphic units relevant for geothermal energy use in these three regions that are covered by GeotIS are listed in table 1.

Table 1: Regions and stratigraphies of high hydrothermal interest in Germany.

Region	Stratigraphy / Formation
North German Basin	Lias-Rhaetian aquifer complex
	Middle Bunter
	Lower Cretaceous
	Dogger
	Keuper
Upper Rhine Graben	Upper Muschelkalk
	Bunter
	Hauptrogenstein
	Rotliegend
South German Molasse Basin	Upper Jurassic (Malm)

Figure 1: Map of areas with potential for hydrothermal resources in Germany.

The Mesozoic deposits of the North German Basin consist of siltstones, sandstones, clays, carbonates, and evaporites. Sandstone aquifers most suitable for the direct use of geothermal energy are confined to the Permian and Mesozoic stratigraphic column: Rotliegend, Middle Bunter, Keuper, the Lias-Rhaetian Aquifer Complex, Dogger, and Lower Cretaceous (Katzung et al., 1992; Feldrappe et al., 2008). They are generally 2 to 3 km thick and have sunk to depths of 4 km and more in the basin center (Baldschuhn et al., 1996; Katzung et al., 1992). Locally, much higher thicknesses and greater depths occur as a result of tectonic movements. In the Glückstadt Graben in Schleswig-Holstein for instance, the Triassic sediments are 3.5 to 6.5 km thick (Maystrenko et al., 2006). Salt tectonics cause great lateral depth and thickness variations over relatively short distances, and contribute to the uncertainty of any structural model. Therefore, the geothermal potential of individual aquifers varies strongly at a local scale.

The Upper Rhine Graben is part of a large rift system which traverses the north-western European plate (e.g. Villemin et al., 1986). The graben is 30 to 40 km wide and runs from Basel, Switzerland, to Frankfurt, Germany. The structure was formed during the Tertiary about 45-60 Ma. It is interpreted as a doming of the crust-mantle boundary due to magmatic intrusions at 80-100 km depth. The stress induced by folding and thermo-mechanical effects have given rise to extensional tectonics with a maximum vertical offset of 4.8 km. Three Mesozoic aquifers and one Permian aquifer are of primary interest for the exploitation of geothermal energy for direct use: the Triassic Upper Muschelkalk, the Bunter, the Hauptrogenstein formation and the Rotliegend (Haenel and Staroste, 1988). The base of the Upper Muschelkalk reaches depths of more than 4 km, whereas the base of the Bunter reaches depths of more than 5km.

The Molasse Basin in southern Germany is an asymmetrical foreland basin of the alpine mountain belt which was filled during the uplift of the Alps (Lemcke, 1988). It extends over more than 300 km from Switzerland in the southwest to Austria in the east. The basin is mainly filled by Tertiary sediments overlying Cretaceous, Upper Jurassic and Triassic sediments. The sedimentary layers of the Upper Jurassic (Malm) primarily consist of carbonate rocks, namely small-pored white limestones as well as fine-to-coarse grained dolomites. The dolomites are characterised by a predominantly good porosity caused by the dolomitization of limestone (e. g. Wolfgramm et al. 2007). Over and above matrix porosity, fluid pathways have been created by karstification, most notably in the northern part of the basin. The Malm aquifer is one of the most important geothermal energy reservoirs in Central Europe due to its high productivity and presence beneath almost the whole Molasse Basin (e. g. Fritzer et al., 2010). South of the Danube, the Malm aquifer dips from north to south and reaches depths of more than 5 km along the northern margin of the Alps.

To make a statement about the hydrothermal resources at a certain location the properties of the deep aquifer have to be estimated as precisely as possible: subsurface temperatures as well as thickness and hydraulic properties of an aquifer are the determining factors for the exploration risk. Thus, they constitute an important part of the geothermal information system GeotIS.

3. GEOTHERMAL POTENTIALS

The data to be incorporated in the information system is derived from a very wide range of data sources, and therefore has to be standardised and analysed to assess its quality. Temperature data and hydraulic parameters required for predicting exploration risk are data measured in deep boreholes.

Besides data from oil and gas exploration, GeotIS also benefited from data exchange with the national geological surveys in Germany as well as with geological surveys in neighbouring countries. The French Bureau de Recherches Géologiques et Minières (BRGM) has provided archive documents from boreholes in the French part of the Upper Rhine Graben for further investigations through the Department of Environment of the Regional Council Freiburg of the State of Baden-Württemberg. A similar exchange of data is taking place with Switzerland for south-western Germany. Additional subsurface temperature data of deep boreholes have been obtained from France, the Netherlands and Switzerland.

3.1 Stratigraphic data

Information on the occurrence and depth level of stratigraphic units with major aquifers relies on the development of specialised subsurface models. The starting point for the modelling of the eastern part of the North German Basin was a collection of geothermal maps of NE Germany which are available at a scale of 1:200,000 (e.g. Gesellschaft für Umwelt- und Wirtschaftsgeologie 1992, Zentrales Geologisches Institut 1988-1990). These maps provide information on the occurrence and base level of Mesozoic horizons relevant for geothermal exploitation. In order to use this material, maps of five stratigraphic units have been carefully digitised and vectorised by the geological survey of Mecklenburg-Vorpommern (LUNG). The digital maps have been checked and reworked using the ArcGIS software package. The reworked data have been converted into triangulated surfaces using the Gocad software package. Geological profiles of wells were used for regional correction and the construction of top level surfaces.

A similar procedure has been applied for the construction of triangulated surfaces for NW Germany. Here, the 3D models have been built on the basis of well profiles, the geothermal resource maps of Beutler et al. (1994), and, to a minor degree, the geological 3D models of the geological survey of Lower Saxony (LBEG) which are based on the maps of Baldschuhn et al. (1996).

The Bavarian Molasse Basin has been modelled very similarly on the basis of a map at a scale of 1:500,000 which is part of the "Bayerischer Geothermieatlas" (Fritzer et al. 2010). This model has been extended to the west on the basis of the geological map Bodensee-Oberschwaben (Bertleff et al. 2005) from the geological survey of Baden-Württemberg. The complete 3D model represents the top level of the Malm aquifer. In the eastern part, the Purbeck formation (above Malm) is also included.

A geothermal resource assessment on the basis of a new structural 3D model of Hesse has been the result of a close collaboration of the geological survey of Hesse (HLUG) with the Institute of Applied Geosciences at the University of Darmstadt, initiated in 2008 (Arndt 2012, Bär 2012). This 3D model also includes the northern most part of the Upper Rhine Graben and has been integrated in GeotIS recently.

The integration of all above mentioned 3D models involves the transformation to orthogonal 2½D grids with a resolution of 100 m and the storage in a binary format in the GeotIS database.

3.2 Well data

The most accurate data available on the deep subsurface originate from approximately 30,000 wells. The largest proportion, approximately 27,000 wells, is related to the oil and gas exploration. The remaining wells were drilled for other purposes, e.g. geothermal energy, drinking water, thermal water or mining.

The main source of information on deep boreholes and their geological profiles is the Hydrocarbon Information System (FIS KW) created by LBEG (Brauner 2003). It currently contains approximately 22,000 geological profiles from approximately 11,000 deep wells in Germany. The most important data source for the area covered by the new German federal states is the "Hauptspeicher Bohrungsdaten" (a borehole database). It is managed by Gaz de France and incorporates all the hydrocarbon wells drilled in the former German Democratic Republic (GDR). It provides data on approximately 2,500 wells with approximately 2,000 geological profiles and large amounts of core analysis data. Data on non-hydrocarbon deep wells can be found in databases operated by the state geological surveys.

In order to use well data from different sources with varying structures and processing levels, comprehensive data conversions towards standardised formats are essential. These conversions include among others the calculation of true vertical depths from measured depths, the implementation of a hierarchical data structure for geological profiles, coordinate transformations and the application of the so-called ATS key of the German oil and gas industry as the final key for the description of stratigraphic sequences as well as for lithologic and tectonic details (Brauner et al. 2001).

3.3 Hydraulic data

Porosity and permeability data from core analyses provide important input for determining the hydraulic properties of geologic formations. The distribution of the core samples naturally reflects the geographical as well as the stratigraphic interests of oil and gas exploration. Most data on core samples is available for the North German Basin. Standardisation of the data is relatively uncomplicated because data sets contain the information catalogued in similar structures. However, correct correlation – necessary for interpretation – between sample analyses and cores, and cores and specific boreholes, was possible in the case of the GDR data after a great deal of intensive revision, only.

Test data constitute another important source of hydraulic data. Transmissivity estimates derived from hydraulic tests provide reliable evidence on the suitability of stratigraphic formations as aquifers. The transmissivity is equal to an integration of the hydraulic conductivities across the aquifer thickness perpendicular to the flow paths.

3.4 Temperature data

The mean increase in temperature with depth is generally around 3K per 100 m. Local deviations from this trend may occur due to high thermal conduction inside salt domes, due to varying thermal conductivity in the sedimentary column or as a result of groundwater movements.

The LIAG runs the Geophysical Information System (Kühne et al. 2003) which contains log data and single values from a range of geophysical methods, primarily within Germany. Subsurface temperature information from approximately 9,500 wells constitutes a geothermal subsystem within the system (Schulz and Werner, 1989). Equilibrium temperature logs and reservoir temperatures are considered to be optimal data which require no corrections. Because of the regular monitoring of production wells over many years, reservoir temperatures are available in time series; the fluctuation in these temperatures is mainly less than 1 K. Bottom-hole temperature data (BHT) are also stored in the geothermal subsystem. These BHT values are recorded in almost all industrial boreholes at the deepest point of the well immediately after drilling has stopped. BHTs are frequently measured at different depths during the drilling operation, resulting in two or more BHT-values per well. The temperature field around a borehole is usually disturbed by mud circulation related to the drilling process. A number of methods to extrapolate the undisturbed temperature have therefore been developed based on various assumptions about the cooling effect of the circulating mud and the thermal behaviour of the borehole and the surrounding rock. A review of existing correction methods can be found in Hermanrud et al. (1990). The choice of the most appropriate correction method depends on the availability of data such as the circulation period, the elapsed time after the end of drilling, the number of subsequent measurements, and the well radii. Despite such corrections, these results still have errors of up to ± 8 to 10 K (Hermanrud et al., 1990; Förster, 2001), and are therefore much less accurate than undisturbed temperature logs. The best correction results can be obtained for BHTs if a time series of two or more measurements is available.

Surface temperatures have been approximated from 30 year averages of air temperatures 2 m above ground. Most data was obtained from the state meteorological service of Germany (DWD, 2010). Additional data for neighbouring countries was used to cover regions along the German border. Altogether, data from 675 German locations and from 37 locations in neighbouring countries have been compiled.

The surface temperature distribution has been interpolated using kriging. The kriging was performed on a grid of 1 km by 1 km resolution (Agemar et al. 2012). Since the air temperature decreases with altitude, it was necessary to deduct this temperature gradient from the data beforehand and add it back to the final kriging estimate. The necessary elevation data were extracted from the in-house digital terrain model. In order to account for climate change during 1961-1990 and 2001-2010, a location independent value of 0.9 K (DWD, 2011) was added.

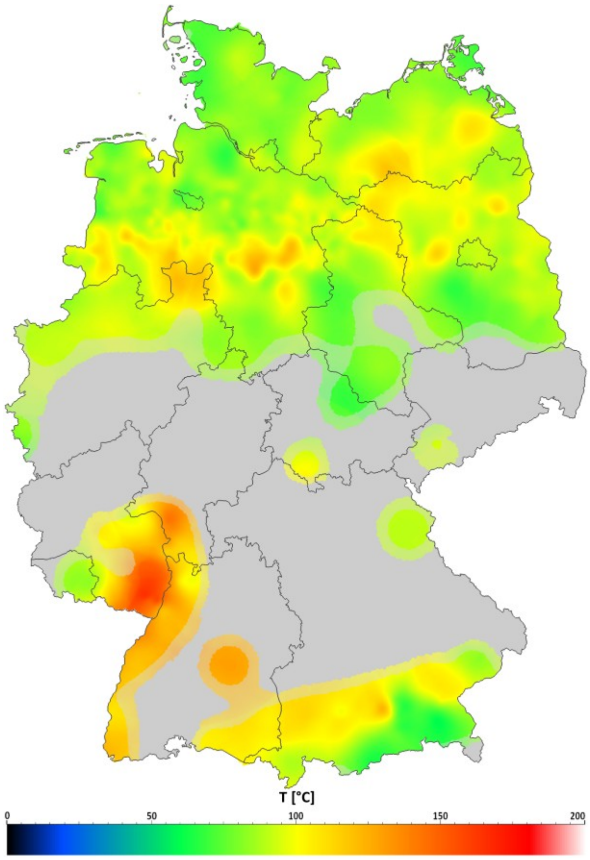

Figure 2: Map of the temperature at 2500 m b.s.l. - the grey zones indicate lack of data

The subsurface temperature distribution has been spatially interpolated using universal kriging in a 3D-space reaching from ground level down to 5,000 m below mean sea level (Agemar et al. 2012). The 3D grid of the kriging estimates is orthogonal and the vertical axis is zero at sea level, not at ground level. The lateral and vertical grid resolutions are 2000 m and 100 m, respectively. As an example, the temperature distribution at 2500 m below sea level has been extracted out of this 3D subsurface temperature model and is shown in Fig. 2.

The primary advantage of kriging is the application of customised interpolation parameters for an unbiased estimate of the subsurface temperature distribution. Another advantage is,that kriging also gives an estimate of the uncertainty of the temperature prediction and thus provides a local probability interval of the temperature estimate. The geostatistical analyses and the kriging estimation of subsurface temperatures were performed using the Gocad software package.

3.5 GIS interface of *Geothermal Potentials*

The module *Geothermal Potentials* gives a regional overview of geological layers that look promising for geothermal exploration. The system provides information on the location of boreholes and seismic profiles and salt structures. Structural 3D models are available for northern Germany and for the Molasse Basin in southern Germany. GeotIS provides an interactive display of the depth and temperature of the relevant layers and large-scale fault structures. In addition, geological cross-sections can be drawn between any two points. The temperature below ground can be shown via contour lines and colour spectrums on cross-sections and horizontal sections. All cross-sections and maps can be exported and printed as a PDF file.

Regarding the Upper Rhine Graben, only a minor portion is covered by a structural 3D model. As an alternative, details on the geological setting are presented in longitudinal and transversal cross-sections which are available at intervals of approximately10 km as static graphics. Most of these cross-sections have been contributed by the Department of Environment, Regional Council Freiburg. Some further static cross-sections in the north have been provided by the geological survey of Hesse (HLUG) and the Institute of Applied Geosciences at the University of Darmstadt (Arndt 2012, Bär 2012).

For NE Germany, facies maps provide information on the overall thickness of the most important aquifers for geothermal energy.

GeotIS also presents maps of the hydraulic conductivity for sediment layers in the eastern part of the North German Basin which have been developed on the basis of test and core sample data. Another map presented in GeotIS shows the hydraulic conductivity of the Upper Jurassic Malm aquifer beneath the Molasse Basin and is based on hydraulic tests, only (Birner et al. 2012).

4. GEOTHERMAL INSTALLATIONS

The module *Geothermal Installations* offers information on geothermal power plants, heating stations and spas in Germany that are in operation or where construction is in progress. At present, geothermal installations produce 730 GWh/a of heat and 25 GWh/a of electricity in Germany.

4.1 Data of geothermal projects

For each installation, records of installed capacity and mean power production are available. The records are based on a table which was elaborated by the "Deep Geothermal Energy" working group of the national/federal panel of state geological surveys (Bund/Länder-Ausschuss Bodenforschung, BLA-GEO) (Pester et al. 2007). This table has been revised and updated since then and contains now all available data on geothermal installations in Germany that are being operated or under construction. From 2011 on, energy statistics are presented on an annual basis.

4.2 GIS interface of *Geothermal Installations*

The internet presentation is based on an interactive map which allows a comfortable navigation. A wide range of research tools is being offered, e.g. to search for a specific location. An information frame shows the most important parameters of selected installations (name, use, temperature, flow rate, depth, and production data) combined in a table. By clicking on a single installation a complete overview is being given including all available information on that geothermal plant such as coordinates, aquifers, installed geothermal output, provided energy, references, and links. All statistic data about geothermal energy can either be displayed for Germany, a certain federal state or for any selected area. Operating data and maps can be exported and printed as a PDF file.

5. OUTLOOK

The LIAG will continue to maintain and expand the geothermal information system GeotIS. The temperature models and exploration prognoses will be improved and the development and inclusion of further 3D models will continue. In the medium term, the LIAG also aims to investigate the suitability of deep faults as geothermal reservoirs in Germany.

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