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A New Approach to Estimating the Geothermal Potential of Faults in Germany

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ABSTRACT

Tectonic processes are an important control in the deformation of rocks and the formation of faults. The properties of the resulting fractures reflect the relationship between the mechanical properties of the rocks involved and the stress field within which the fracturing occurs. The flux that can be obtained from highly fractured rocks is generally much greater than that which can be obtained from matrix rocks.

Currently, geothermal energy exploration in Germany focuses on deep aquifers. Faults are not yet considered as primary geothermal targets. However, in the Upper Rhine Graben area and in the South German Molasse Basin, project developers frequently try to intersect fault zones during drilling in order to gain access to a larger part of the reservoir. Depending on interconnectedness, aperture, and dimensions, fault zones may promote flow rates and make a geothermal resource economic. Furthermore, in some locations with high geothermal potential, upwelling of deep groundwater is connected to faults. Characterizing faults in a way that adequately allows predictions to be made about transmissivity is difficult. Knowledge of the fault history and geometry is a first step for the estimation of the geothermal potential of a fault system. Rough estimates can be made by setting boundary values for thermal and hydraulic properties of fault zones.

The Leibniz Institute for Applied Geophysics (LIAG) operates GeotIS (http://www.geotis.de), an internet-based information system on geothermal resources. This information system provides data on deep sedimentary rocks suitable for geothermal energy exploitation. Currently, GeotIS contains only simplified and incomplete information on faults. The first objective of our project is therefore the compilation of data on hydraulic properties, size and the geometry of deep reaching faults. Another major objective is to enhance the functionality of GeotIS to enable the storage and retrieval of more sophisticated geometries and hydraulic data.

1. INTRODUCTION

Germany uses its low enthalpy hydrothermal resources predominantly for balneological applications, space and district heating, but also for power production. In recent years, geothermal energy utilisation has been growing rapidly, especially in southern Germany. From 2003 to 2013, the annual production of geothermal district heating stations increased from 60 to 530 GWh. In the same time, the annual power production increased from 0 to 36 GWh. Most geothermal facilities in operation rely on deep aquifers and use deep boreholes to produce hot water. There are also a few hot springs in Germany which are used for balneological applications like for example in the city of Aachen where over 30 hot springs with water temperatures of up to about 70 °C can be found along two lineaments. Another example can be found in the city of Wiesbaden where the Kochbrunnen (in English: boil fountain) is one of several hot springs located on a SW-NE oriented line with a water temperature of 66 °C. These artesian springs can be attributed to deep reaching faults (Breddin 1963, Pommerening 1993, Michels 1954). Faults or fault zones can be considered as a special type of geothermal reservoirs. They promise a high geothermal potential (Jung et al. 2002) due to the fact that faults can represent connections to hot rock bodies and deep aquifers. Depending on interconnectedness, aperture, and dimensions, fault zones may substantially increase achievable flow rates for geothermal facilities. Thus, they might even establish pathways for deep groundwater to migrate to shallower depths. Frequently, projects in the Molasse Basin (geographically the area between the river Danube and the Alps) or the Upper Rhine Graben pursue the objective to construct wellbores intersecting fault planes by means of directional drilling, like for instance the injection well of the geothermal plant in Unterhaching near Munich (Bavaria). It is assumed that faults and fault zones have a higher geothermal potential than deep aquifers in Germany (Jung et al. 2002). The geothermal exploitation of faults and fault zones could therefore substantially lower the demand of fossil fuels, in particular for heating. However, utilising faults and fault zones for geothermal energy production requires a good understanding of the complex nature of such reservoirs including the geological setting and the hydraulic and thermal properties. Our new approach to estimating the geothermal potential of faults in Germany is based on spatial matching of comprehensive data compilations. The objective of our project is to find regional cross-correlations between proven or assumed geothermal potentials and relevant geophysical and geological attributes. The results will be fed into the geothermal information system GeotIS. The overall objective is to minimise exploration risk of geothermal projects in Germany.

2. METHODS AND DATA

In order to precisely estimate the geothermal potential of faults and fault zones in Germany it is crucial to know the temperature, the permeability, and the dimensions of reservoirs comprised of faults. While geostatistical temperature estimates usually match real subsurface temperatures quite well, it is not possible to derive the hydraulic properties of one fault from other faults in the vicinity. Even the same fault may exhibit diverging permeability. Furthermore, there is very little known on the extent and permeability of deep reaching fault zones in Germany. Therefore, it is necessary to include secondary information as well. The spatial cross-correlation of secondary data with primary data may help to identify locations for new geothermal projects.

Important information for this study comes from a former project, the “Geothermal Atlas” , which was carried out by the LIAG and the BGR (Federal Institute for Geosciences and Natural Resources) with the objective to find out where geothermal energy exploitation and carbon capture and storage (CCS) may compete for the same areas in Germany (Suchi et al. 2014). This atlas consists of a detailed report and four maps on scale of 1:1 000 000 showing areas of proven or assumed geothermal potential and areas interesting for further CCS investigations.

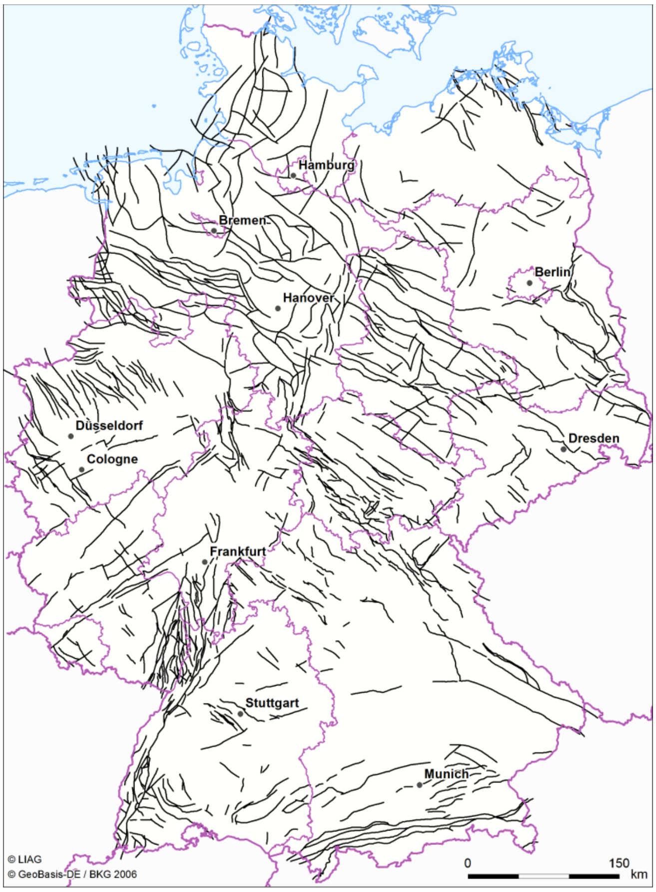

Figure 1: Major faults and fault zones in Germany.

Within the framework of the project "Geothermal Atlas" cartographic data of deep seated faults were collated and compiled for Germany resulting in a map with 916 lineaments (Fig. 1). Faults within a distance of 5 km were merged and labelled as fault systems within ESRI's software package ArcGIS®. Hence, this distance represents the maximum geographical resolution. To get further information of the characteristics of faults and faults zones, a map of geothermal facilities has been combined with the compiled faults map. Initially no differentiation was made between the different kinds of geothermal facilities. In this way geothermal sites located at faults within a given radius could be determined easily. About 60 % of the geothermal sites are less than 5 km away from faults. Faults which are related to existing geothermal sites are most suitable for further investigations. The estimation of the geothermal potential of faults can be refined by adding more information, for instance the recent local stress field given by the World Stress Map Project (Heidbach et al, 2008). Most of the faults predominantly strike in NW-SE, NNE-SSW and W-E direction. A beneficial orientation of faults to the prevailing stress field enhances the probability of a higher transmissibility. Unfortunately, there is little information about the stress regime of the deep subsurface (up to 5000 m depth) which is of interest for geothermal projects. As a further source of information several hundred publications have been compiled and catalogued in a bibliographic database and linked to particular map segments or single faults. Here, one can find more detailed information about age, activity, hydraulic properties, and orientation of faults or fault systems to enhance the probability of success for geothermal projects.

More secondary information will be obtained from specialised information systems and databases. The Leibniz Institute for Applied Geophysics operates two public information systems, which hold data relevant for geothermal exploration. The Geophysics Information System (http://www.fis-geophysik.de) provides subsurface data sets and allows querying, visualization and interpretation of measurements from various geophysical methods (Kühne et al. 2003). The system can be accessed through a web interface and provides all features typical for a geographic information system and data centre. The Geothermal Information System GeotIS (http://www.geotis.de) is the second web-based information system ran by the LIAG (Agemar et al., 2014a). It offers geological, hydrogeological, and geophysical information and data about the deep subsurface. The system supports 3D stratigraphic investigations by means of stratigraphic maps, freely oriented vertical sections, and horizontal sections. To this day GeotIS only offers little information on faults and fault zones. So far, faults are usually represented as vertical planes in GeotIS, because original maps give little or no information about the dip of a fault. The only exception here is the stratigraphic 3D model of Hesse (Arndt 2012; Bär et al. 2011), which contains realistic fault planes with dip derived from seismic data.

The database of GeotIS also holds data on 30 000 wells, including 11 000 with temperature measurements. The temperature data has been regionalised with the 3D universal kriging method with no anisotropic preferences (Agemar et al. 2012). 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 kriging estimate. The temperature data is stored in a database as an orthogonal 3D grid with a lateral spacing of 2 km and a vertical spacing of 0.1 km. The vertical axis is set to zero at mean sea level and the grid extent reaches from ground level down to 5000 m below mean sea level (mbsl). Temperature estimates can be retrieved for stratigraphic and plane surfaces. GeotIS also gives information on geothermal power plants, heating stations, and spas (Agemar et al., 2014b). It offers a record for each installation, including location coordinates, tapped aquifers, installed capacity, annual power and heat production, and many more. These records are annually updated and contain all available data on deep geothermal installations in Germany. GeotIS can be seen as the digital variant of a geothermal atlas which is almost independent of scales and always available in its most actual edition. It is used by project planners to estimate the regional potential of hydrothermal resources in Germany.

A simple approach for estimating the geothermal potential is based on the amount of heat stored in deep rocks and fluids which can be accessed with current drilling technology. Jung et al. (2002) estimated the overall geothermal potential of Germany including petrothermal and hydrothermal resources. They emphasized that the geothermal exploitation of deep fault structures could make a noticeable contribution to the German energy production. A summary of the results for the public and the Parliament of the Federal Republic of Germany (TAB-study) is provided by Paschen et al. (2003). The assessment of the geothermal potential of faults provided by Jung et al. (2002) consists of two parts: the estimation of the heat in place and the calculation of the recovery factor. The recovery factor describes how much of the heat in place could be withdrawn for power and/or heat production. Various concepts for the determination of the recovery factor can be found in the literature, for instance in Bodvarsson (1974), Nathenson (1975) and Muffler and Cataldi (1978) to name a few.

Jung et al. (2002) defines the heat in place as

$$E_{th} = c_R \cdot \rho_R \cdot V \cdot (T_R - T_S) \tag{1}$$

where c_R = 840 J/(kg·K) (specific heat capacity), ρ_R = 2600 kg/m^3 (density), and V is the rock volume in m³. Variation of the parameters shows that the temperatures of the rocks (T_R) dominate the equation. The surface temperature (T_S = 10 °C) is constant. Due to the complexity of specifying a recovery factor, the first aim is to improve the estimation of the heat in place with the help of the GeotIS database.

For this reason, the GeotIS temperature model and the map of deep faults (Fig. 1) are used to improve the heat in place calculation. Jung et al. (2002) used four T_G values starting in 3000 m depth with the geothermal gradient (30 K/km) as the arithmetic average of the temperatures on top and down of a block of rock with the vertical extent of 1000 m plus 10 °C surface temperature. In the new calculation of the heat in place, the temperatures are determined with the help of the 3D temperature model and fault lines. The 916 faults (cp. Fig. 1) are represented as regularly spaced nodes linked with line segments. Subsurface temperatures are provided as temperature-depth profiles for each node along the fault line. The temperature-depth profiles have a vertical resolution of 100 m (Fig. 2). An individual cell volume with the height h = 100 m and a distance d = (d_1 + d_2)/2 has been calculated for every temperature value. The thickness t is fixed to 337 m which relates to the thermally affected width after 100 years of operation. For every single cell, the heat in place was calculated with the parameters used by Jung et al. (2002). Finally, the heat in place values were summed up in four blocks of rock with 1000 m vertical extent, starting in 3000 m to 7000 m depth.

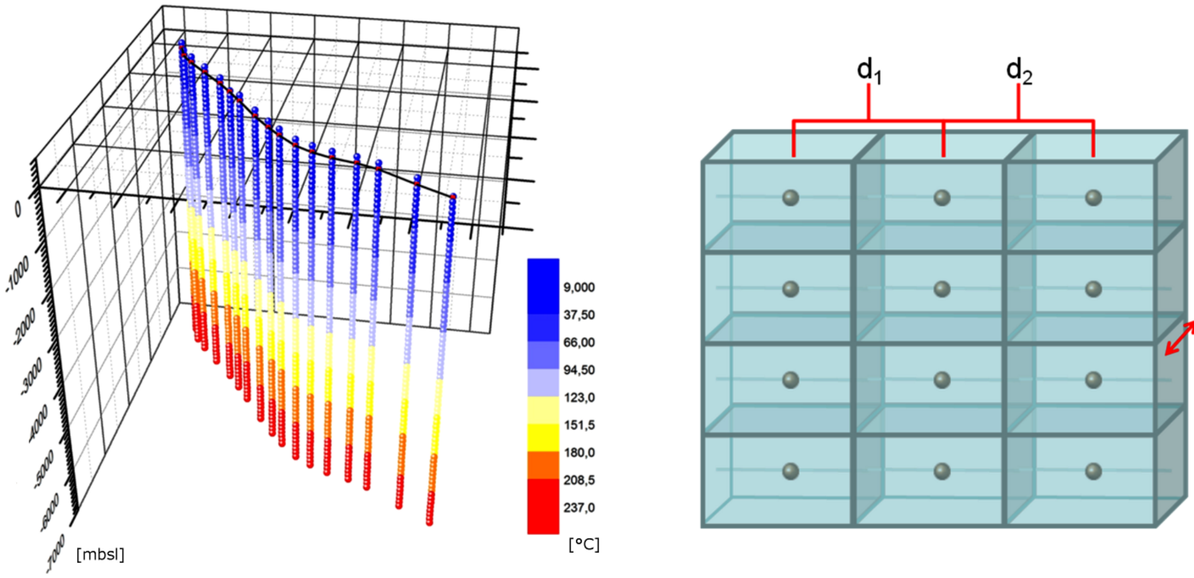

Figure 2: Left: Subsurface temperatures for a deep reaching fault. Right:Volume model for the temperatures. d1 and d2 are the distances between temperature points, h is the height of a volume cell (h =100m) and t the thickness (t = 337m).

3. RESULTS

The estimates of the heat in place along faults are shown in Table 1. The new estimate of the geothermal potential of the fault network is 11.4 ZJ compared to 8.7 ZJ reported in the TAB-study (Paschen et al. 2003). The difference is mainly due to the larger estimate of the fault network size. Jung et al. (2002) assumed the total length of all deep seated faults in Germany to be 19 600 km.

Our estimate of the total length is based on the new map (Fig. 1) and amounts to 24 365 km. The application of the 3D temperature model changes significantly the heat in place estimates for individual faults but does not alter much the total heat in place estimate for the overall German fault network. The calculated recoverable heat energy is slightly higher when using the 3D temperature model from GeotIS because of higher heat in place values and the positive effect of higher temperatures on the recovery factor.

Table 1: Heat in place estimates for the German fault network according to the method of Jung et al. (2002).

	Heat in Place [ZJ]*		
Calculation Details	original TAB-study	based on a new fault map and a geothermal gradient of 30 K/km	based on a new fault map and a new 3D temperature model
Total Length of Faults [km]	19 600	24 365	24 365
Depth Interval [km]:			
3 – 4	1.5	1.9	2.0
4 – 5	2.0	2.4	2.6
5 – 6	2.4	3.0	3.1
6 – 7	2.8	3.5	3.7
Total Heat Energy:	**8.7**	**10.8**	**11.4**
Recoverable Heat Energy:	**0.43**	**0.54**	**0.61**

*) 1 ZJ = 10^{21} J

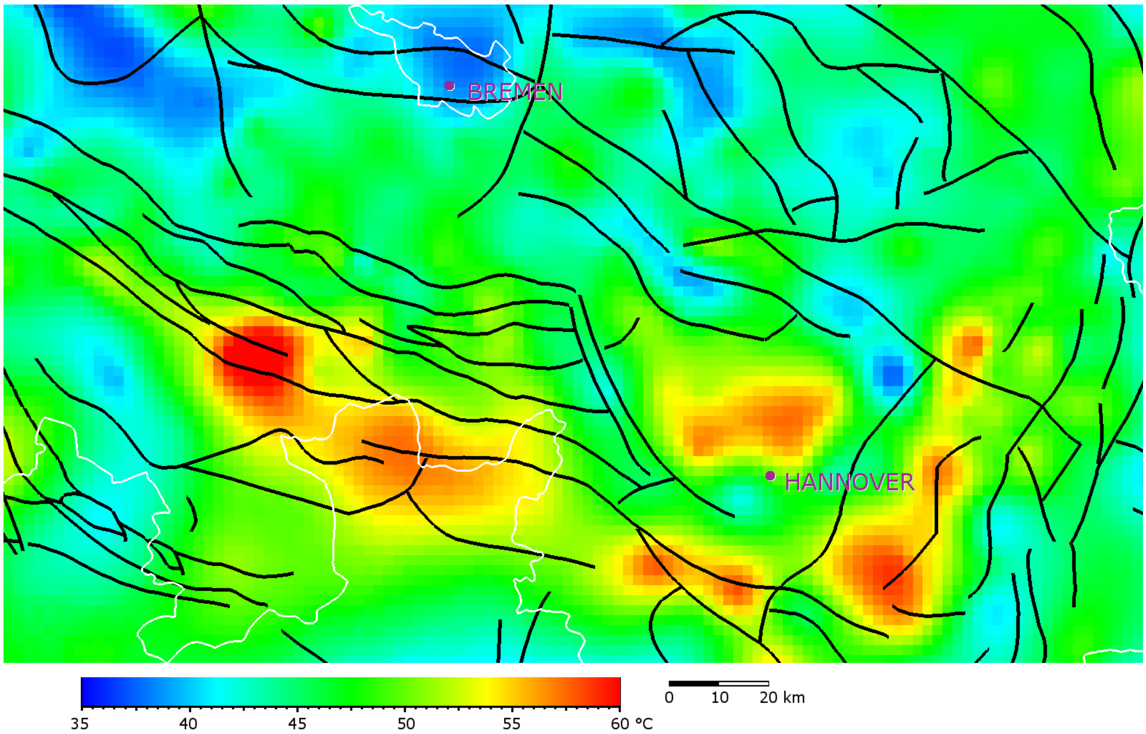

Figure 3: Subsurface temperature at 1000 mbsl and deep reaching faults and fault zones in the southern part of Lower Saxony. Blue colours represent normal temperature-depth gradients. Green, yellow and red colours mark positive temperature anomalies.

Faults and fault zones may also influence the local groundwater flow regime. Some subsurface temperature anomalies in Germany are related to convective heat-transport mechanisms. In order to differentiate between heat-transport by convection and by conduction, it is necessary to calculate the geothermal gradient in absence of any fluid flow. This can be done if the thermal conductivities and heat-production rates within the sediment column are known. Residual temperature anomalies can be obtained by removing the conduction related portion of the geothermal gradient. Rühaak et al. (2010) showed that these temperature anomalies with respect to thermal conduction can be used to track convection of deep groundwater along fault zones in the south German Molasse Basin. Pribnow and Schellschmid (2000) used temperature logs from deep boreholes in the Upper Rhine Graben to identify the impact of faults on the groundwater flow regime and the re-distribution of heat in the upper crust. This concept of using subsurface temperature as a tracer for groundwater flow in fault zones could be adopted for other regions in Germany, too. Figure 3 shows a cluster of positive temperature anomalies at a depth of 1000 mbsl at the south-western border of the North German Basin (Lower Saxony). Some anomalies seem to be located along major faults with a SE–NW strike. Upper Jurassic or Lower Cretaceous aquifers may have a leakage along fractured rocks typically found at fault zones. Other anomalies are clearly not related to faults but can be explained with the thermal properties of the sediment fillings, like for instance in the area north of Hannover. Further research is needed to clarify the origin of thermal anomalies close to deep reaching faults.

4. VISUALISATION IN GEOTIS

It has been mentioned before that the geothermal information system GeotIS is an important source of data relevant for this project. The LIAG continuously updates software and hardware components of the system and implements new features. Furthermore, the LIAG is permanently looking for new data records and 3D models ready to enter into the system. As a matter of course, we are planning to incorporate the results described in section 3 into GeotIS. New structural 3D models with detailed information on fault networks are to be included as well. Currently, 3D models developed with Paradigm's software suite GOCAD/SKUA are preferred due to established workflows.

Recently, we revised the visualisation software of GeotIS in order to show the dip of faults on interactive cross sections. At the moment, this visualisation technique is limited to normal faults and strike-slip faults because the actual data format used by GeotIS cannot handle multiple z-values. The stratigraphic horizons are stored as orthogonal 2½D-grids, which means that the position of each point is defined by its surface coordinates and a depth. This data format is basically the GeotIS equivalent to the 2DGRID of GOCAD/SKUA. Information on faults is stored in ESRI's shape file format. These polylines represent the intersection of fault planes with the top or base of stratigraphic units. Faults are usually visualised as vertical planes in GeotIS because most structural 3D models are based on maps which give little or no information about the dip of a fault. The only exception here is the stratigraphic 3D model of Hesse (Arndt 2012; Bär et al. 2011), which contains triangulated fault planes with dip derived from seismic data. The visualisation of reverse and thrust faults requires the implementation of a data format capable of handling multiple z-values. It would be advantageous to use a grid that holds both, stratigraphic layers and fault planes. The grid should follow the fault geometry. No displacements should be represented as stair-steps. On the other hand, GeotIS requires fast data access and efficient visualisation algorithms to keep response times low for users. The choice of the data format has implications for the overall performance of the system. At present, we are planning to test stratigraphic grids and orthogonal 3D grids with an internal octree structure.

Orthogonal 3D grids consist of box-shaped cells with the edges spaced in a fixed manner. The GOCAD/SKUA software suite realizes orthogonal 3D grids as Voxet objects. Voxets are cell-centered, meaning that properties are assigned to the centre of cells. At present, orthogonal 3D grids are used in GeotIS to store subsurface temperature and associated kriging variance data. The representation of stratigraphic data of adequate resolution with orthogonal 3D grids requires a huge amount of memory and increases computing time. This problem could be solved by applying an octree algorithm (Jackins & Tanimoto 1980) where 2^3 (or 4^3, or 8^3, . . .) adjacent cells representing the same stratigraphic unit are merged to one super cell. The same technique is applied recursively to 8 adjacent super cells etc., resulting in an octal tree structure (Fig. 3). The idea is basically to reduce grid resolution where it is not necessary. This procedure reduces memory usage and enables faster visualisation. Faults, however, need to be stored separately as triangulated surfaces because orthogonal grids do not hold information on fault geometry.

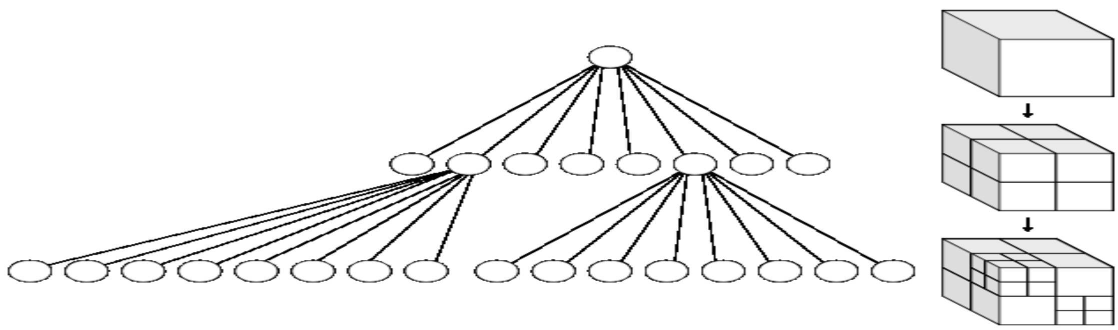

Figure 4: Diagram of octree data representation (adapted from Wikipedia, accessed: 05/26/2014).

Stratigraphic grids (SGrid objects in GOCAD/SKUA) are flexible 3D grids that can be fitted between two boundary horizons to model a formation or stratigraphic unit (Fig. 4). Stratigraphic grids are commonly used for reservoir models or flow simulations. The cells are hexahedrons and properties can be stored at the cell centre or at the edges of the cells, depending on the grid type. These grids can also contain faults, which are assigned to single cell faces. Thus, the grid follows fault geometry without any stair-steps. However, the creation of X- or Y-shaped faults may be difficult if too many cells have to be squeezed between converging fault planes.

5. DISCUSSION

The estimation of the geothermal potential of faults and fault zones remains difficult, mainly due to a lack of reliable transmissibility data. The approach of Jung et al. (2002) assumes permeable faults and fault zones everywhere although most likely only a tiny fraction of the fault network might fulfil this requirement. Furthermore, the recovery factors applied are based on a rather simple theoretical model. Thus, the values for recoverable heat energy in Table 1 merely represent upper limits. It is also important to note that the approach of Jung et al. (2002) relies on the concept of combined heat and power. However, the construction of district heating networks is limited to densely populated areas due to appreciable transmission loss on long distances.

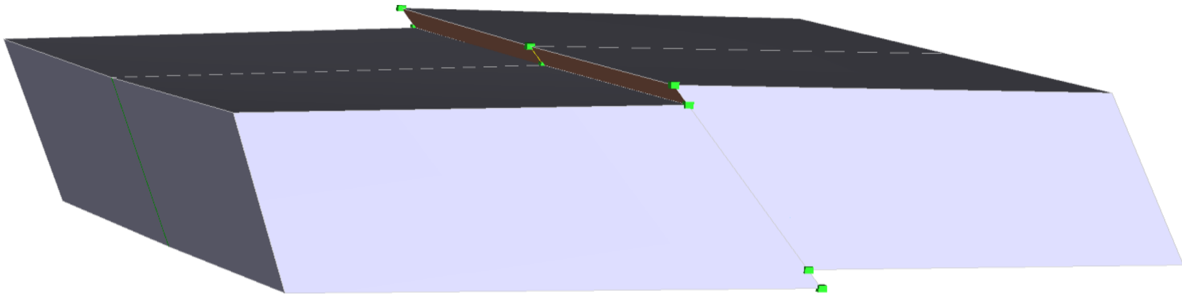

Figure 5: Example for a stratigraphic grid. Green cubes mark the contact to a fault plane.

A detailed analysis of individual faults on the basis of extensive cross-correlation of existing data sets might help to identify new research targets. A closer look at subsurface temperature anomalies and geologic settings could improve the estimation of the geothermal potential of individual faults and fault zones. Finally, all structural information and data sets on faults should be published with the geothermal information system GeotIS (http://www.geotis.de). Currently, GeotIS only provides simplified and incomplete information on faults. Further development is needed to enhance the functionality and to enable the storage and retrieval of more sophisticated fault geometries and transmissibility values.

REFERENCES

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

Agemar, T., Alten, J.-A., Ganz, B., Kuder, J., Kühne, K., Schumacher, S. and Schulz, R.: The Geothermal Information System for Germany – GeotIS. – *Z. dt. Ges. Geowiss.*, **165**(2), (2014a), 9-32. [in press]

Agemar, T., Weber, J. and Schulz, R.: Deep geothermal energy production in Germany. – *Energies*, special issue: Geothermal Energy: Delivering on the Global Potential, **7**, (2014b)**.** [accepted]

Arndt, D.: Geologische Strukturmodellierung von Hessen zur Bestimmung von Geopotenzialen. Thesis, Technical University of Darmstadt, Darmstadt, 199 p.

Baer, K., Arndt, D., Fritsche, J.-G., Goetz, A. E., Kracht, M., Hoppe, A., Sass, I.: 3D-Modellierung der tiefengeothermischen Potenziale von Hessen – Eingangsdaten und Potenzialausweisung. – *Z. dt. Ges. Geowiss.*, **162**/4, (2011), 371-388

Bodvarsson, G.: Geothermal Resource Energetics. – *Geothermics*, **3**, (1974), 83-92.

Breddin, H.: Neue Erkenntnisse zur Geologie der Aachener Thermalquellen. *Geol. Mitt.,* 1, (1963), 221-238.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B.: The World Stress Map database release 2008. – DOI: 10.1594/GFZ.WSM.Rel2008, (2008).

Jackins, C. L. & Tanimoto, S. L.: Oct-trees and their use in representing three-dimensional objects. – *Computer Graphics and Image Processing*, **14**(3), (1980), 249–270.

Jung, R., Röhling, S., Ochmann, N., Rogge, S., Schellschmidt, R., Schulz, R. and Thielemann, T.: Abschätzung des Technischen Potenzials der geothermischen Stromerzeugung und der geothermischen Kraft-Wärmekopplung (KWK) in Deutschland. Gutachten im Auftrag des Deutschen Bundestag, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, (2002).

Kühne, K., Maul, A.-A. and Gorling, L.: Aufbau eines Fachinformationssystems Geophysik. – *Z. Angew. Geol.*, 2, (2003), 48-53.

Michels, F.: Zur Geologie der Wiesbadener Mineralquellen. *Z. dt. geol. Ges.,* 106, (1958), 113 - 117.

Muffler, P. and Cataldi, R.: Methods for Regional Assessment of Geothermal Resources. – *Geothermics*, **3**, (1978), 53-89.

Nathenson, M.: Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas. US. Geol. Survey Open-File Report. 75-525, (1975), 38 p.

Paschen, H., Oertel, D. and Grünewald, R.: Möglichkeiten geothermischer Stromerzeugung in Deutschland. Arbeitsbericht Nr. 84, Büro für Technikfolgenabschätzung beim Deutschen Bundestag (TAB), (2003), Berlin.

Pribnow, D.F.C. and Schellschmidt, R.: Thermal tracking of upper crustal fluid flow in the Rhine Graben. – *Geophys. Res. Lett.*, **27**, (2000), 1957–1961.

Pommerening, J.: Hydrogeologie, Hydrogeochemie und Genese der Aachener Thermalquellen. *Mitteilungen zur Ingenieurgeologie und Hydrogeologie* 50, (1993), 168 p.

Rühaak, W., Rath, V. and Clauser, C.: Detecting thermal anomalies within the Molasse Basin, southern Germany. – *Hydrogeol. J.*, **18** (8), (2010), 1897–1915.

Suchi, E., Dittmann, J., Knopf, S. Müller, C. and Schulz, R.: Geothermal Atlas to visualise potential conflicts of interest between CO_2 storage (CCS) and deep geothermal energy in Germany. – *Z. dt. Ges. Geowiss.*, (2014) [accepted].