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THE DEVELOPMENT OF A 3D STRUCTURAL-GEOLOGICAL MODEL AS PART OF THE GEOTHERMAL EXPLORATION STRATEGY – A CASE STUDY FROM THE BRADY'S GEOTHERMAL SYSTEM, NEVADA, USA

Egbert Jolie[1], James Faulds[2], Inga Moeck[1]

[1]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[2]Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada, 89557, USA
e-mail: jolie@gfz-potsdam.de

ABSTRACT

In the framework of geothermal exploration campaigns 3D structural-geological modeling plays an important role in the understanding of geothermal systems. The focus for the Brady's geothermal system located in the Basin and Range province is on the identification of structural controls on fluid flow and permeability anisotropy. In addition to 3D structural-geological modeling, the applied exploration strategy also includes stress field analysis and surface geochemical surveys.
We have used 1) detailed geological maps, 2) borehole data, 3) processed 2D seismic and gravity data, and 4) a digital elevation model as input parameters of the 3D model. Based on these data, four representative cross sections have been developed as a major input for a preliminary 3D geological model. Well logs are used to verify the stratigraphic structure between the cross sections. The major strike direction of the faults is NNE. Normal faulting is the dominant stress regime. Dip angles range from 45° to 80°. The 3D model consists of eight geological units. The Mesozoic basement consists of granites and metamorphic rocks. Above, a sequence of Tertiary ash-flow tuffs, lacustrine sediments, and lava flows of different composition has been encountered.

3D structural models populated with geomechanical and stress data can help to delineate between dilational and shear zone both being prone for channeling fluids.
In a later stage, stress data derived from fault plane analysis shall be integrated into the 3D structural-geological model applying the slip and dilation tendency technique to estimate hydraulically active fault zones. These results shall be verified by surface gas measurements to understand the impact of individual faults on fluid flow.

GEOLOGICAL SETTING

The Basin and Range-province is characterized by E-W to WNW-ESE extensional motion of the lithospheric crust, which began in the Paleogene about 29-30 Ma ago and reached main extension in the middle Miocene (Eaton, 1982; Eaton, 1984; Fosdick and Colgan, 2010; McQuarrie and Wernicke, 2005). Due to the extension, an alternating pattern of parallel elongated mountain ridges and desert basins formed, which increased its original width since the Oligocene between 100 % and 200 % and resulted in crustal thinning (Proffett, 1977, Velasco et al., 2010, Eaton, 1984). The extension resulted in approximately N to NNE-striking fault zones. Various geothermal surface manifestations along normal faults give evidence to the existence of hydrothermal systems. In this study we focus on the Brady's geothermal field, which occurs along a normal fault and appears to be amagmatic. It is located at the in the Basin and Range province (Nevada, USA) approximately 80 km northeast of Reno (Faulds et al, 2010).

FIELD MAPPING

The entire area around the Desert Peak and Brady's geothermal systems has been mapped in detail at 1:24,000s scale (Faulds and Garside, 2003; Faulds et al., 2010, unpublished data). Together with well logs and the results of geophysical surveys, the geological map provides a major input dataset for the development of geological cross sections from which the 3D structural-geological model can be derived.

DEVELOPMENT OF CROSS SECTIONS

Four cross sections have been developed, based on mapped surface faults and rock units, 2D seismic reflection data, gravity data, and re-interpreted drill cuttings and core from wells in the study area (Faulds, unpublished data). Faults and horizons have been attributed in each cross section, which allows

the later merging of data points from the same fault plane or horizon. The cross sections are constructed to a depth of 1,000 m bsl, which forms the basis of the model.

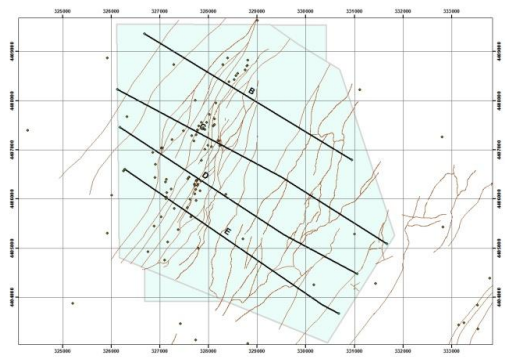

Figure 1: Study area with fault traces (red), well locations, and developed cross sections (B, C, D, E).

METHODS

The development of the 3D structural-geological model has been completed in two steps. First, a fault model has been calculated, which is followed by the development of a horizon model. The model has a size of 7.2x8.3x3.0 km. Its base lies within the Mesozoic basement.

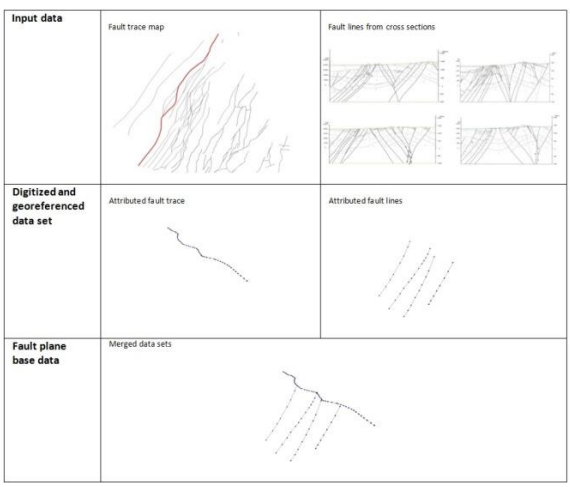

Figure 2: Process of data preparation for the development of a 3D structural model. The entire model is based on four geological cross sections and a geological map.

Fault modeling

In total, 61 fault planes have been implemented into the model. This required the consistent attribution of each fault in each cross section. The cross sections have been digitized, georeferenced, and edited before the modeling workflow started. The structural model includes only fault planes and no horizons. The location of geothermal surface manifestations helps to identify the structural controls of fluid circulation. Control points between the cross sections help to constrain the fault plane computation. The workflow consists of four different stages: 1) definition of model information, 2) stepwise implementation of fault sets, 3) fault tree building (hierarchy model), and 4) fault modeling.

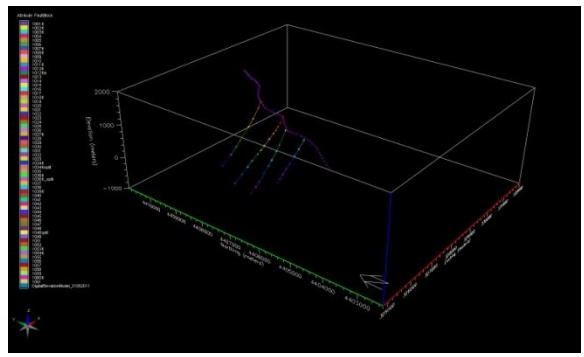

Figure 3: Development of a fault plane I: Input data from four geological cross sections and the fault trace map.

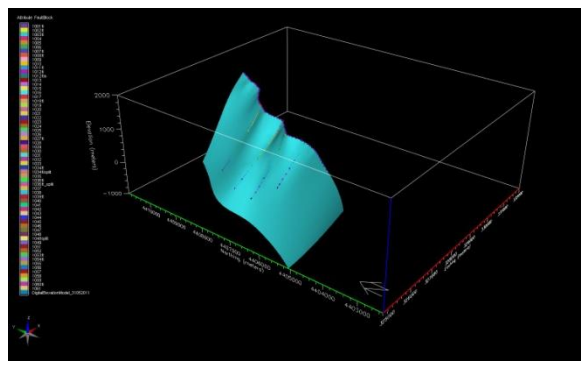

Figure 4: Development of a fault plane II: Computed fault plane, based on the input data from Fig. 4.

The implementation of faults has been accomplished in a stepwise approach. Faults have been separated into three different classes and priorities according to their length, fault plane surface, and hierarchy. Each fault has been classified in the hierarchy system. The hierarchy has been created according to the developed cross sections. Faults with the highest priority have been implemented first, as they will have the strongest effects on the model design. The second fault set was modeled according to the given hierarchy of set 1. Set 3 is the final fault set, which contains minor fault planes associated with faults of set 1&2. The separation of huge fault sets with complex interactions into different sets appeared to be a very successful approach. The majority of the faults have been implemented as “dying faults”; only

a few faults cross the entire model. The selected gridding method for the fault planes is a 2D minimum tension gridding algorithm with trend control (DGI, 2009).

The fault model will provide the basis for the stress field analysis. Each fault plane can be assessed according to their orientation within the present stress field. The stress field analysis includes the stress inversion from surface measurements of fault slip data, and the slip and dilation tendency analysis after Morris et al. (1996).

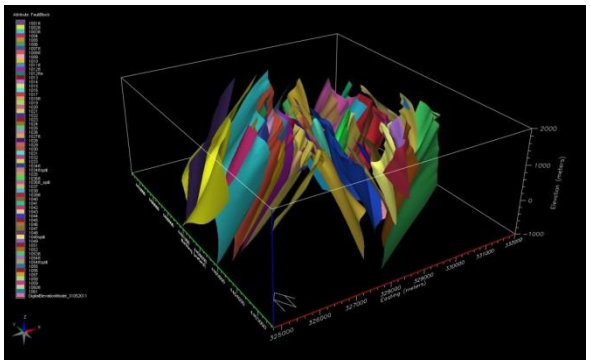

Figure 5: Final fault model with 61 fault planes. The dominant strike direction of the fault system is NNE (~N30E).

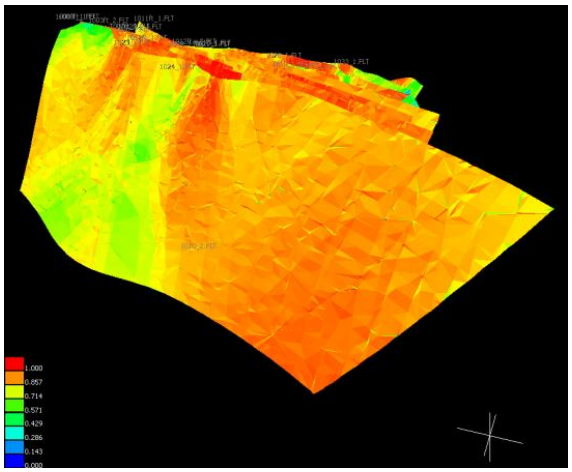

Figure 6: Results of the dilation tendency analysis on selected fault planes within the Brady's geothermal system. Yellow to red colors indicate an increased tendency of faults to dilate.

Horizon modeling

The process of 3D structural-geological modeling, also referred to as 3D mapping (Moeck et al., 2010), includes the import of stratigraphic horizons. Their assembly is arranged according to the developed fault model. 3D structural-geological modeling provides information at each point of the model within the defined z-range. The uncertainty of models can be reduced by the calibration with borehole data. However, the most accurate models with highest resolution can only be achieved by using additional information such as high definition 3D seismic reflection data.

For the Brady's model a simplification of the geological succession was necessary due to heterogeneous volcanic units. The horizons of the cross sections are digitized in the same manner as the fault planes. Each horizon was consistently attributed throughout all cross sections. For the correct display of the geological succession, horizons are imported stepwise bottom-up. This allows maximum control on the interpolation of each horizon. The calibration of all horizons was carried out for each fault block. It is suggested to conduct the editing perpendicular to the major strike direction. This method allows the maximum control on the correct modeling of structural displacements. Once the interpolation of a horizon has been successfully performed, the data points of the overlying horizon are imported and interpolated in the same manner.

At this stage eight different geological units have been integrated into the presented model.

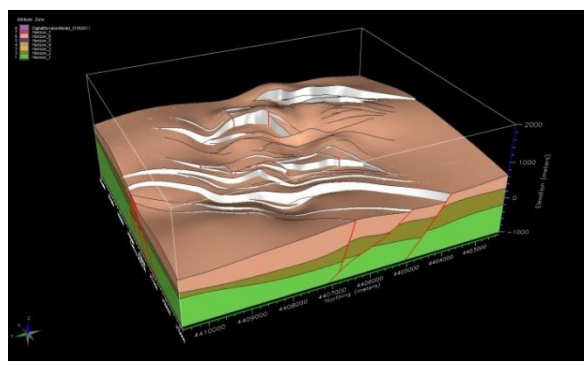

Figure 7: Horizon model of the Brady's geothermal system. The top horizon represents the early to late Miocene.

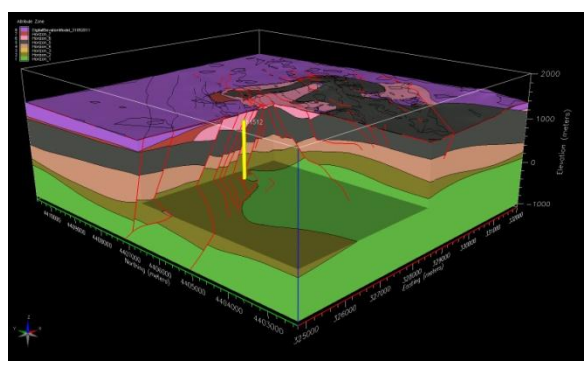

Figure 8: 3D geological model with the proposed stimulation well 15-12.

RESULTS

The 3D structural-geological model of the Brady's geothermal system comprises 61 fault planes and

eight geological units. Due to the complex fault pattern, the model consists of 71 large fault blocks. This compartmentalization has effects on the hydraulic conductivity, as it can isolate or connect production or re-injection wells from each other. The dip angles of the faults vary from 45° to 80°. The major strike direction is NNE. The known geothermal reservoir is located at a depth of 600-1,500 m below surface and lies within the Oligocene ash-flow tuffs and Miocene lava flows. Production wells target the NNE-striking Brady's fault, which has a dip range from 70°-80°. The Brady's fault occurs on the western limb of an extensional syncline. Some of the encountered stratigraphic units could also contribute to the reservoir in addition to the faults. The 3D model for the Brady's area achieved in this study will help to guide the proposed stimulation in Well 15-12 in terms of enhancing understanding of the subsurface faults and major stratigraphic packages that lie between the well and the known geothermal reservoir to the north.

OUTLOOK

3D mapping and stress field analysis should be a standard approach in geothermal exploration. It improves the interpretability of already existing data sets. Much of the data can be derived through non-invasive surface methods, which is beneficial especially in the first stages of exploration campaigns, where minimal information is available. The results can be used as a basis for any further exploration work (e.g. dynamic modeling).

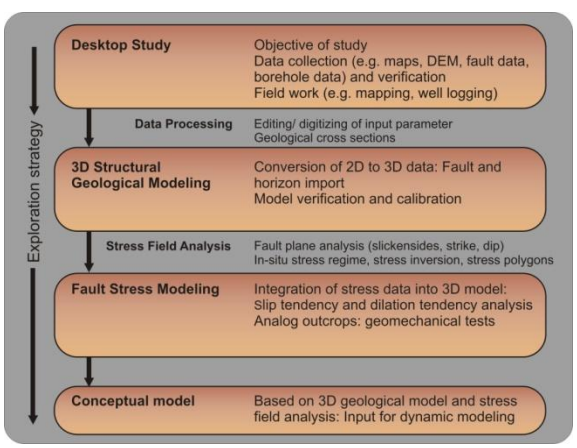

Figure 9: Work stages of the applied exploration approach.

However, both methods cannot qualify and quantify the presence of geothermal fluids in the inferred reservoir. At that stage the degree of uncertainty still has to be reduced. This can only be reached by additional surveys, which will assist in the verification of the results.

Geochemical surveys

Other helpful methods to verify and improve the accuracy of the 3D model are, for example, geochemical surveys. For that reason, diffuse degassing measurements are planned to be applied at the Brady's geothermal system to actually confirm where potential pathways of geothermal fluids are present at depth and if results match with the modeled fault system. This approach seems to be promising as the Brady System is an active geothermal system, where various gas emanations (e.g. CO_2) are likely to occur with high effluxes.
Integration with the results of 3D modeling and stress field analysis would improve this exploration technique. The method of diffuse degassing measurements has already been used for various purposes worldwide, such as volcanic hazard analysis and volcano monitoring (Hernandez, 2001; Fridriksson, 2006).

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