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STRUCTURAL ASSESSMENT AND 3D GEOLOGICAL MODELING OF THE BRADY'S GEOTHERMAL AREA, CHURCHILL COUNTY (NEVADA, USA): A PRELIMINARY REPORT

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ABSTRACT

The northwestern Great Basin (NGB) in the western USA hosts abundant, generally amagmatic geothermal activity. Significant geothermal exploration is ongoing, but controls on fluid flow in the geothermal systems are generally poorly understood. To elucidate the controls on fluid flow, we are conducting a detailed structural assessment and 3D modeling study of the Brady’s geothermal field ~80 km east-northeast of Reno, Nevada. It has an estimated reservoir temperature of 175-205°C at 1- 2 km depth and supports a combined flash and binary geothermal power plant with a total electrical generation capacity of 16-17 MWe. The surface expression of the Brady’s system is a 4-km-long, NNE-trending zone of extensive sinter, warm ground, fumaroles, and mud pots along the Brady’s fault, which is part of a complex en echelon normal fault system locally with Quaternary scarps.

Optimized utilization of this mature geothermal field necessitates a detailed 3D understanding of the complex fault system and its impact on channeling fluids. Over the past decades, abundant wells and detailed geophysical surveys have been generated and provide extensive subsurface data, which can be used for 3D geological modeling. Our structural assessment therefore combines detailed geological field mapping, fault plane analysis, stress inversion, 3D structural geological modeling and stress modeling to contribute to concepts for EGS development. The structural 3D geological model will be validated by well and seismic data. The discrete fracture surfaces will be populated with geomechanical parameters and stress data derived from the surface and subsurface. The fault pattern will also be characterized in terms of slip and dilation tendency. The results are not only important for better understanding permeability anisotropy in the geothermal reservoir but also for estimating the fault reactivation potential, which is crucial for EGS development at Brady’s well 15-12. Our integration of detailed field studies, stress modeling, and 3D structural modeling may be valuable for geothermal development where cost-effective exploration strategies are needed.

INTRODUCTION

The northwestern Great Basin contains abundant geothermal fields (Fig. 1), many with subsurface temperatures approaching or exceeding 200°C. Most of these geothermal systems occur along complex, recently active normal fault systems (e.g., Faulds et al., 2004, 2006a) that accommodate the deep circulation of fluids in a region of high heat flow. The lack of recent volcanism suggests that upper crustal magmatism is generally not a heat source for most of the geothermal activity in this region.

Because faults are the primary control on geothermal activity, it is important to understand their geometry and kinematics and which fault patterns or fault segments are most favorable for geothermal activity. Knowledge of such structures would facilitate exploratory drilling in known, but as yet undeveloped fields, expansion in producing fields, identification of possible blind (or hidden) geothermal resources, and selection of the best sites for EGS development.

Full characterization of individual sites requires, however, a full three-dimensional (3D) perspective of the geothermal system and associated fault zone. Our approach is to combine detailed geologic mapping with structural analysis and geophysical investigations, such that all available geologic and geophysical data are incorporated into a conceptual 3D model.

For the development of this approach, we are analyzing the Brady’s geothermal field in western Nevada, which has been utilized for power generation since the early 1990’s. Brady’s is a high enthalpy geothermal system slated for EGS development. EGS development of mature or high enthalpy fields can be practical due to the lower risk of drilling into cooler parts of the reservoir (drilling technology exists for 150-180°C temperature from the oil&gas industry) and due to the use of existing logging tools for characterization (logging tools have generally a temperature limit of 150-180°C). However, increasing productivity with EGS treatments, such as hydraulic stimulations, also requires a detailed understanding of fault and fracture systems within the current stress field.

In this paper, we describe our ongoing structural assessment and planned 3D geological modeling of the Brady's geothermal field. We are developing a 3D geological model for fault stress modeling and will employ slip tendency analysis to assess the reactivation potential of faults with varying orientations, a critical aspect for any EGS experiment. We first review the geological setting at Brady's and then discuss in greater detail our methodology.

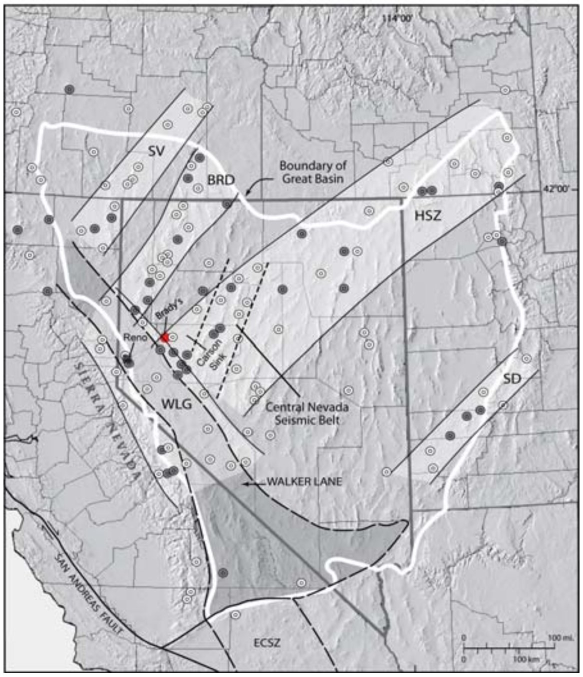

Figure 1: *Geothermal belts in the Great Basin (from Faulds et al., 2004). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. White circles are geothermal systems with maximum temperatures of 100-160^{o}C; grey circles have maximum temperatures >160^{o}C. The Brady's system is a high temperature system shown by the red circle. ECSZ, eastern California shear zone.*

GEOLOGY OF THE BRADY'S AREA

The Brady's geothermal field lies in the northern Hot Springs Mountains ~80 km east-northeast of Reno, Nevada, along the northern margin of the Carson Sink (Fig. 1). The Hot Springs Mountains are dominated by thick (>2 km) sections of highly faulted Miocene (~15 to 7.5 Ma) volcanic and sedimentary rocks resting on Oligocene ash-flow tuffs and/or Mesozoic plutonic-metamorphic basement (Stewart and Perkins, 1999; Faulds et al., 2003; Faulds and Garside, 2003). The region is fragmented into multiple NNE-trending fault blocks, which are bounded by numerous en echelon, overlapping NNE-striking normal faults. Miocene sections are generally much thicker in the hanging walls of major normal fault zones, indicating syntectonic deposition (Faulds and Garside, 2003). Tilt-fanning in growth-fault basins demonstrates that the main pulse of extension in the region occurred ~13 to 8 Ma (Faulds et al., 2006b), but several fault scarps indicate significant ongoing Quaternary extension (e.g., Trevor and Wesnousky, 2001). The NNE-striking, WNW-dipping Brady's fault zone, which bounds much of the northern Hot Springs Mountains on the northwest and Hot Springs Flat basin on the southeast, is the main controlling fault zone in the Brady's geothermal field. Kinematic data indicate essentially dip-slip normal displacement on the NNE-striking faults.

Brady's Geothermal Field

The Brady's geothermal field has an estimated reservoir temperature of 175-205°C at 1- 2 km depth (Benoit et al., 1982) and supports a combined flash and binary geothermal power plant with a total electrical generation capacity of 16-17 MWe. The power plant has been in operation for nearly 20 years. The ongoing EGS project is targeting well 15-12 in the southern part of the field (Fig. 2).

The surface expression of the Brady's geothermal system is a 4-km-long, NNE-trending zone of extensive sinter, warm ground, fumaroles (Figs. 2 and 3), and mud pots along the Brady's fault, which is part of a complex en echelon normal fault system locally with Quaternary scarps. The main production wells at Brady's appear to penetrate the down-plunge projection of a small left step in a major splay of the Brady's fault zone (Figs. 2 and 3; Faulds et al., 2006a). The NNE-striking Brady's fault is orthogonal to the regional WNW-trending extension direction and is thus favorably oriented for fluid flow. Multiple fault strands in the step-over presumably provide subvertical conduits of high fracture density that enhance fluid flow and may facilitate the rise of a deep-seated thermal plume.

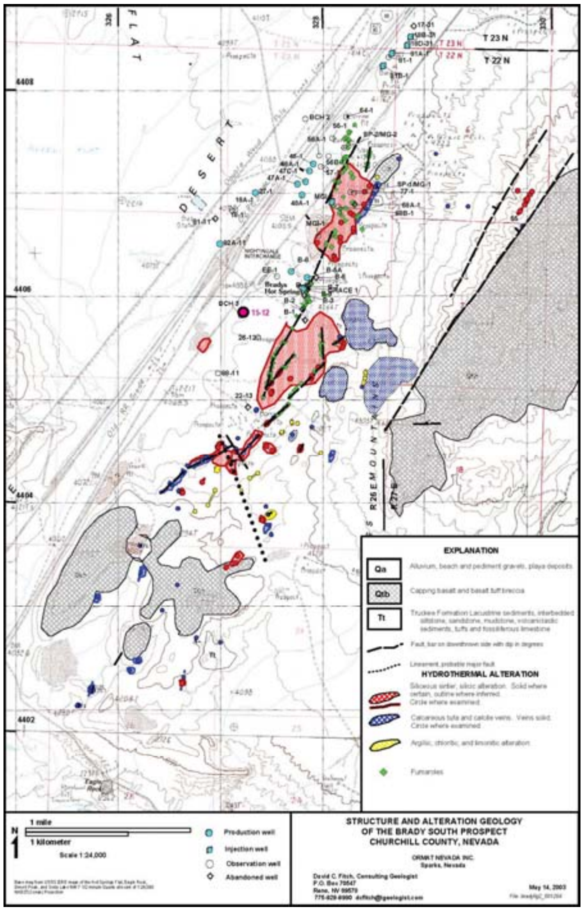

Figure 2: Well locations, faults, and surface thermal features, Brady's Hot Springs geothermal project. The EGS project is utilizing well 15-12 shown by the large purple circle in west-central part of the map.

Several problems have confronted geothermal operations in the Brady's field. These include short residence times for fluids between recharge and intake wells and excessive draw-down in existing wells induced by nearby production. Such problems indicate a high level of fluid transmissivity. Known faults, such as the NNE-striking Brady's fault, account for some of this high transmissivity. However, high transmissivity has also been documented across and within the hanging wall of the Brady's fault, suggesting that stratigraphic units or obscure cross faults also channelize fluids. Drilling over the past 15 years has yet to be integrated into a comprehensive structural model of the field. Thus, detailed geologic and geophysical studies of the northern Hot Springs Mountains together with incorporation of existing subsurface data (Benoit et al., 1982; NBMG well data files) has significant potential for assessing the Brady's field and enhancing production in the field utilizing EGS technologies.

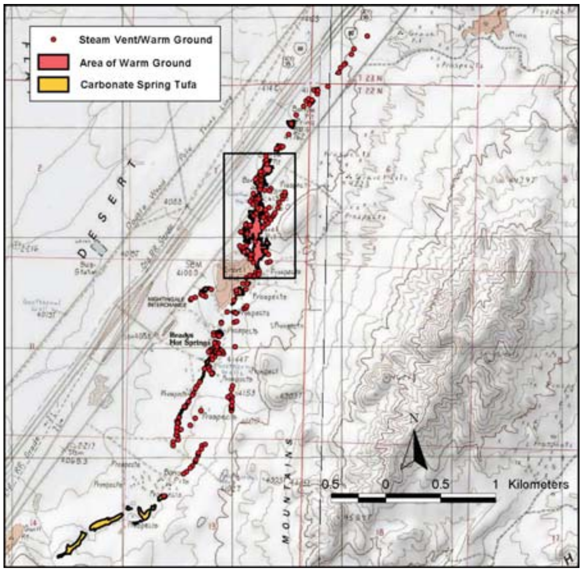

Figure 3: Brady's field, surface geothermal features (adapted from Coolbaugh et al., 2004). The Brady's system is marked by a linear zone of hot springs, fumaroles, warm ground, and sinter along the WNW-dipping, NNE-striking Brady's fault zone. The main production wells are located as much as ~1 km to the west of a small left step in the fault zone (encompassed by black box) and presumably penetrate the down-plunge projection of a highly fractured step-over at depth.

WORK PLAN AND METHODOLOGIES

We are conducting a detailed structural and 3D modeling study of the Brady's geothermal area to characterize the fluid flow and better define the extent and character of the geothermal reservoir. This project involves 1) detailed field studies; 2) structural analysis of fault zones; and 3) geomechanical 3D modeling incorporating available subsurface and surface geologic and geophysical data. Figure 4 shows the planned work flow for the project. The geological and geomechanical modeling will establish the 3D structural framework of the Brady's area, determine which faults have accommodated dilation and are more likely to channel fluids, and ultimately facilitate development of detailed models of the geothermal system.

The field-based structural investigations involve 1) detailed geologic mapping (1:12,000 scale) in the Brady's area; 2) measuring joints in silicified Lake Lahontan sands; 3) correlation of surface stratigraphy with well logs; 4) analysis of fault geometries and kinematics; and 5) isotopic dating and/or tephrochronology of critical units. The detailed mapping and structural analysis will constrain the geometry of controlling faults. The kinematics will be determined from geometric patterns at the macroscopic and mesoscopic scale and examination of exposed fault surfaces. Slip sense will be gleaned from such surfaces through analysis of kinematic indicators (e.g., Riedel shears, Angelier et al., 1985; Petit, 1987).

Fault slip data will provide input for stress inversion, which yields principal strain and stress axes for each fault set (e.g., Marrett and Allmendinger, 1990; Angelier, 1994). Fault sets will be grouped in stress field populations utilizing the P-/T method. In addition, youthful (<12,000 years old) joint sets from Quaternary silicified sands will be measured to determine the general orientations of stresses, although joints cannot provide information on the magnitudes of these stresses. The fault slip and joint data will permit slip and dilation tendency analysis, incorporating different failure modes under the conditions of mechanical stratigraphy within the current stress field. Applied software will include Tectonics FP (University of Innsbruck) and 3DStress (Midland Valley). As a result of these analyses, we will determine which faults and which fault intersections are most dilational and therefore likely to channel geothermal fluids. This work will be integrated with previously completed studies of surficial geothermal features (e.g., sinter and fumaroles) and available geophysical data.

The 3D modeling based analysis will extrapolate the acquired knowledge from surface geology to subsurface structures with a focus on stress conditions along faults and related preferential fluid pathways at depth. The modeling procedures will involve: 1) integration of available geologic and geophysical data into a preliminary 3D structural model; 2) stress field determination based on available data (fault slip data inversion, borehole breakout analysis, frictional constraints) and, 3) slip and dilation tendency analysis of faults incorporating different failure modes and man-made modifications of stress state through injection and production (e.g., Moeck et al., 2009). The geomechanical analysis is based on the extended Mohr-Coloumb failure criterion incorporating Hoek-Bown rock strength parameters (Jaeger et al., 2007) and slip tendency analysis, as described by Ferrill and Morris (2003). Applied software will include 3DStress (Midland Valley) and EarthVision (Dynamic Graphics Inc.). As a result of these modeling studies, potential fluid pathways will be delineated in 3D model space by specification of dilational or critically stressed fault segments.

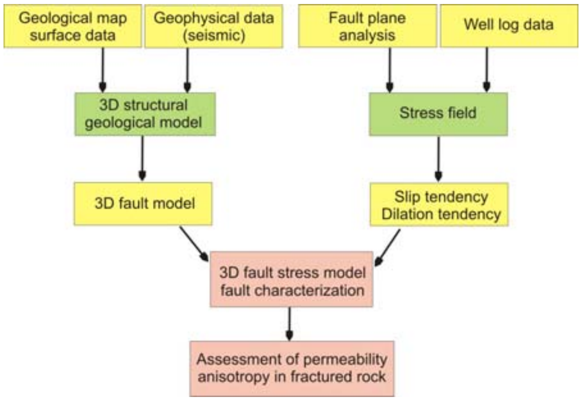

Figure 4: Workflow to develop a 3D fault stress model as basis for assessment of permeability anisotropy and fractured rock.

GOALS AND IMPLICATIONS

From the structural studies, our main goals are to generate the following:

- Detailed geologic map of Brady's area in ArcGIS format that will serve as critical data base for this and future studies.
- Compilation of structural data (fault geometries and kinematics) from Brady's area.
- Stress field determinations from a) fault kinematic data and b) joints in late Pleistocene silicified sands.
- Integration of well data with local stratigraphy.

In addition, the 3D Modeling will produce:

- A conceptual 3D model of the Brady's area.
- Subsurface geometries of faults.
- Ability to generate cross sections of any orientation in the 3D model.
- Stress modeling to determine favorable fluid pathways near the surface and at depth, also under modified stress conditions.
- Geomechanics: Slip and dilation tendency on various fault orientations.
- Integration of well data (logs and temperature) into 3D model.
- Geosteering: 3D model that will serve as basis for selecting and defining future well sites and paths.

An optimized utilization of the mature Brady's geothermal field clearly necessitates a detailed 3D understanding of the complex fault system and its impact on channeling fluids. Over the past decades at Brady's, abundant wells and detailed geophysical surveys have been generated and provide extensive subsurface data. Thus, the area is conducive to 3D geological modeling.

Our comprehensive structural assessment combines detailed geological mapping, fault plane analysis, stress inversion, 3D structural geological modeling and stress modeling to contribute to concepts for EGS development, including characterizing fault patterns in terms of slip and dilation tendency. The results will not only be important for better understanding permeability anisotropy in the geothermal reservoir but also for estimating the fault reactivation potential, which is crucial for EGS development when high injection rates induce additional fluid pathways. Furthermore, our integration of detailed field studies, stress modeling, and 3D structural modeling may be valuable for geothermal development in a variety of settings where cost-effective exploration strategies are needed.

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