1 **Quantitative structural-geological exploration of fault-controlled geothermal systems – a**
2 **case study from the Basin-and-Range Province, Nevada (USA)**

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13 **Keywords**

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16
17 **Abstract**

18 Fluid-bearing fracture zones are typically the focus of geothermal exploration as preferential
19 targets for production wells. The ability of fractures to channel fluids is commonly affected by
20 the current stress field. In this study, a three-dimensional structural-geological model of the
21 Brady's geothermal system (Basin-and-Range Province, USA) was developed. We
22 demonstrate that by incorporating slip- and dilation tendencies as a function of the stress field
23 and fault geometry, our 3D-model can efficiently contribute to the identification of favorable
24 drilling targets.

1 Introduction

1.1 Background

The Brady's geothermal system is located approximately 80 km northeast of Reno (Fig. 1) in the western part of the Basin-and-Range Province in Nevada (USA). Utilization of the geothermal reservoir started in 1978 with direct use by a vegetable dehydration plant (Lund, 1994), and a double-flash geothermal power plant with an installed capacity of 26.1 MWe has been in operation since 1992 (Nevada Division of Minerals, 2012; Ettinger and Brugmann, 1992).

Figure 1: Local sketch map of the Brady's geothermal system illustrating the boundaries of the surveyed area for the applied methods. Geological cross sections (A-D) are shown in Fig. 3. The area of the 3D model is outlined by the gray dashed line. SBF: Southern Brady's fault; NBF: Northern Brady's fault; BFSO: Brady's fault step over; Coordinate System: NAD 1983 UTM Zone 11N.

1.2 Regional tectonic and structural setting

The Basin-and-Range Province is characterized by ongoing, W-E to WNW-ESE extension of the lithospheric crust, which began in some areas as early as the Oligocene (~29-30 Ma),

43 peaked in many areas in the middle Miocene, and has continued to the Quaternary throughout
44 much of the region (Eaton, 1982, 1984; McQuarrie and Wernicke, 2005; Fosdick and Colgan,
45 2008). The normal faulting that resulted from this extension produced an alternating pattern of
46 parallel elongated mountain ridges and basins and induced approximately N- to NNE-striking
47 fault zones (Faulds et al., 2003; Jolie et al., 2012).

48 Convection-dominated geothermal systems of the Basin-and-Range Province belong to the
49 category of fault-controlled geothermal systems, where permeability and fluid flow is
50 dominated by dilational faults and fractures (Faulds et al., 2006). According to Coolbaugh et
51 al. (2002), the Basin-and-Range Province is dominated by two major types of geothermal
52 systems – extensional amagmatic and magmatic geothermal systems. The Brady’s geothermal
53 field belongs to the category of extensional amagmatic geothermal systems (Moeck, 2014).
54 Many amagmatic geothermal systems of the Basin-and-Range Province are thought to be
55 blind or hidden, this is, characterized by relative lack of surface manifestations (e.g., hot
56 springs or fumaroles) and weak or ambiguous geophysical and geochemical signatures. In this
57 context, geophysical investigations including magnetotellurics, gravimetry and seismic
58 reflection surveys, have been conducted in the Basin-and-Range Province with variable
59 success. For instance, the success of 2D seismic reflection has proved limited due to seismic
60 signal scattering (Martini et al., 2005). Resistivity surveys have proved equally challenging to
61 interpret in a range of prospected areas (Cumming, 2009).

63 **1.3 Geological framework of the Brady’s geothermal field**

64 The Brady’s geothermal system is one of the three independent geothermal systems of the Hot
65 Springs Mountains (Desert Peak and Desert Queen geothermal system). The stratigraphy of
66 the Brady’s geothermal field consists of a Mesozoic metamorphic and plutonic basement
67 covered with Cenozoic volcanic and sedimentary sequences. Geological understanding of
68 Brady’s has been gained by detailed 1:24,000 geological mapping (Faulds and Garside, 2003;
69 Faulds et al., 2012; Fig. 2), geophysical surface exploration (i.e., 2D seismic reflection
70 surveys, gravimetry) and drilling (Faulds and Garside, 2003; Hinz, unpublished data, 2011;
71 Queens, unpublished data, 2011). The known geothermal reservoir is located at a depth of
72 600-1,500 m below the surface and lies within the Oligocene ash-flow tuffs and Miocene lava
73 flow formations.

Figure 2: The simplified geological map (modified after Faulds and Garside, 2003; Faulds et al., 2012) provides a brief overview of the major stratigraphic units in the study area. SBF: Southern Brady's fault; NBF: Northern Brady's fault; BFSO: Brady's fault step over; Coordinate System: NAD 1983 UTM Zone 11N.

A major feature of the Brady's geothermal system is the Brady's major fault zone, a ~10 km long, NNE-striking fault zone, which dips 60°-80° to the NW as determined by surface exposures of faults and 2D seismic reflection surveys (Rudisill, 1978; Faulds et al., 2010a). In the immediate vicinity of the Brady's geothermal power plant is the ~600 m wide Brady's fault step over (or relay ramp, cf., Larsen, 1988), mapped in detail by Faulds and Garside (2003) and Faulds et al. (2012). The Brady's fault step over consists of multiple minor *en échelon* faults (small left steps) that connect the major overlapping fault segments (Faulds et al., 2006, 2010b), and concentrates active geothermal surface manifestations over a ~200-300 m broad area, including fumaroles, seasonally dried out mud pools, warm and steaming grounds, hydrothermal alteration zones, and calcareous sinter deposits (but no hot springs). Production wells target primarily this part of the Brady's fault zone at a depth of 600-1,500 m b.s.l. where highest production rates are obtained (Fig. 6B-D; Davatzes et al., 2013). Elevated permeabilities in the hanging wall of the Brady's fault zone have suggested the possibility of lateral stratigraphic units acting as a potential reservoir (Faulds et al., 2006). Static temperature logs from Brady's (Shevenell et al., 2012) indicate a convection-dominated geothermal system, yet, the extent and recharge mechanisms are not comprehensively understood (Benoit et al., 1982; Coolbaugh et al., 2007; Faulds et al., 2010a). Local recharges

to the geothermal system are assumed to be minimal due to the arid climate of the region (Welch and Preissler, 1986).

1.4 Objectives of the study

In this study, a three-dimensional structural-geological model of the Brady's geothermal system is presented and combined with detailed fault stress modeling in order to investigate the relationship of faulting and fluid flow. Models are validated against field data, including location of geothermal surface manifestations (Faulds and Garside, 2003; Faulds et al., 2012); tracer tests conducted in production wells, which are used as indicators of directional flow at a field wide scale (Davatzen et al., 2013); and subsidence as a result of pressure drawdown in the reservoir (Oppliger et al., 2005). Favorability of faults to promote fluid flow was quantified by computing slip- and dilation tendency analysis. These quantifications can be useful for EGS (enhanced geothermal system) stimulation experiments (Krieger and Sponsler, 2002), such as those planned for well 15-12 (Fig. 1), which encountered temperatures in excess of 200°C but low permeability (Lutz et al., 2011). Similar approaches have been applied to other geothermal sites (e.g., Moeck et al., 2009).

2 METHODS

2.1 Three-dimensional geological modeling

2.1.1 Data sources

Geological mapping and associated geological cross sections of the Brady's geothermal field (Faulds and Garside, 2003; Faulds et al., 2012) provided the major input data set for the development of the 3D structural-geological model. Four geological cross sections were developed (Fig. 3), based on mapped surface faults and formation boundaries (Fig. 2), interpretation of two 2D seismic reflection profiles (total length ~6,000 m) (profiles from Queen, unpublished data, 2011), gravity data (Faulds and Garside, 2003; Muir and Queen, unpublished data, 2011), and analysis of drill cuttings and cores from 19 wells drilled to depths ranging from 227 m to 2,145 m (Hinz and Faulds, unpublished data, 2011; Jolie et al., 2012). The cross sections were constructed perpendicular to the main structures and strike WNW to NW and reach to a depth of 1,000 m below sea level (b.s.l.) from an average

topographic elevation of 1,400 m above sea level (a.s.l.; Jolie et al., 2012), with a spacing between adjacent cross sections ranging from 700 m to 1,300 m.

2.1.2 Modeling approach

The 3D model of the Brady's geothermal field was developed with the 3D modeling software earthVision 8.0.1 (developed by Dynamic Graphics, Inc.). The adopted dimensions of the geological model were $7.2 \times 8.3 \times 3.0$ km, with the base of the model located at a depth of 1,000 m b.s.l. (same vertical extent as cross sections) within the Mesozoic basement.

Figure 3: Geological cross sections A-D. The cross sections show color-coded fault lines (fault 3 in red, fault 4 in blue, fault 5 in green), which are used for an exemplary 3D fault plane development (see Fig. 4A-C). The acronyms for the geological horizons are defined in Table 2. The Brady's fault zone is located on the western limb of the extensional syncline.

The 3D structural-geological model of the Brady's geothermal system was developed in two steps: 1) fault model and 2) stratigraphic model. Primary inputs for the fault model included fault traces on cross sections and surface maps, which were digitized, georeferenced and edited, and then grouped into three different hierarchical fault classes according to fault length, fault plane area, cross-cutting relationships, and fault sequence criteria (e.g., synthetic and antithetic faults). Faults were then modeled in hierarchical order, from high to low hierarchy. The developed 3D fault model provides the basis for the fault stress analysis and the fault stress model (Jolie et al., 2012). For the stratigraphic model, a spatial resolution of 28

× 28 m was adopted for the horizon layers. For the most efficient construction of the stratigraphic sections, horizons were imported stepwise from the bottom-up (Jolie et al., 2012). Calibration of each horizon with borehole data was carried out within each fault block (Jolie et al., 2012). Constructing and editing the stratigraphic horizons perpendicular to the major strike direction was found to be most efficient in honoring fault displacements and facilitating control on the modeling (Jolie et al., 2012). More details on fault and stratigraphic modeling of the Brady's system as implemented here can be found in Jolie et al. (2012).

Figure 4: A) Fault trace map with color-coded fault lineaments (fault 3 in red, fault 4 in blue, fault 5 in green) used for an exemplary 3D fault plane development. SBF: Southern Brady's fault; NBF: Northern Brady's fault; BFSO: Brady's fault step over; VDP: vegetable dehydration plant; BPP: Brady's power plant; B) Merged and imported fault data extracted from four geological cross sections (Fig. 3) and the fault trace map (Fig. 4A); C) Constructed fault planes based on data points illustrated in Fig. 4B; Coordinate System: NAD 1983 UTM Zone 11N (Fig. 4A-C).

2.2 Stress field and structural analysis

2.2.1 Stress inversion

Field-based analysis of fault slip data in areas of active faulting can provide a first estimate of the regional stress field by stress inversion techniques based on the relationship of stress and strain (Angelier, 1984; Angelier, 1990; Zoback, 2010). It is assumed that observed surface faults represent failure planes in the current stress field and that the resolved stress regime from exposed faults is also acting at reservoir depths (cf., Frizzell and Zoback, 1987). Assuming measured striae in faults occur parallel to the maximum shear stress acting on the fault plane, and the stress state has remained relatively uniform over time (Angelier et al., 1982), principal stress orientations σ_1 , σ_2 and σ_3 are back-calculated for each individual fault

plane and averaged for the whole stress field with the PBT-axes method (P (pressure) $\approx \sigma_1$, B (intermediate) $\approx \sigma_2$, T (tension) $\approx \sigma_3$) (Turner, 1953; Sperner et al., 1993). This calculation can be automated with specialized software (in this study *tectonics FP* software was used). Within the Brady's geothermal field no suitable surface outcrops of faults were available for stress field analysis. Instead, 37 measurements of kinematic indicators on fault surfaces from the Desert Peak and Desert Queen areas were selected for stress field analysis assuming a similar principal stress orientation between all geothermal fields. Studied kinematic indicators included striations, Riedel shears and rough facets acquired through the detailed geologic mapping (Faulds and Garside, 2003; Faulds et al., 2012).

In order to verify that stress inversions provide a reasonable approximation of the present-day stress field, results from stress inversion can be compared with independent stress field data including focal mechanisms of earthquakes, borehole breakouts and tensile-induced fractures, and/or the world stress map (cf., Frizzell and Zoback, 1987; Moeck et al., 2009). In tectonically active areas with relatively young geological history, good agreement among stress indicators of different sites is expected. Indications of more than one stress field can be a sign of a combination of present-day and paleo-stress fields (Lacombe et al., 1992).

2.2.2 Estimation of in-situ stress ratios

Applying Anderson's theory of faulting (Anderson, 1951) the stress ratios for σ_1 and σ_3 can be determined for the three principal stress regimes (NF – normal faulting, SS – strike slip, RF – reverse faulting) by the empirical approach (Eq. 1) after Jaeger et al. (2007). The concept of limiting stress ratios is based on the assumption that stresses in the crust are in frictional equilibrium and limited by the frictional strength of rocks according to Eq. 1 (Pěška and Zoback, 1995). Since the friction coefficients of faults are not known for the Brady's geothermal system, the friction coefficients of rocks are used instead to infer fault properties (see Morris et al., 1996). Therefore, the variety of possible rock strength, ranging from weak to strong rock strength (Lutz et al., 2011), was studied. Other fault mineralogical characteristics (e.g., healed faults, fault gouge,) or fracture density (Hoek-Brown parameter) are not known. Instead, the Mohr-Coulomb failure criterion is applied and faults are considered as cohesionless. The calculated horizontal stress ratios are normalized to the vertical stress σ_v of a given depth and can be illustrated by stress polygons. The specific value of $\sigma_{h,min}$ can be directly measured during drilling by means of leak-off tests or minifrac tests (e.g., Zoback, 2010).

Equation 1

$$\frac{\sigma_1 - P_p}{\sigma_3 - P_p} = \left((\sqrt{\mu^2 + 1}) + \mu \right)^2 \quad / \quad P_p = \frac{P_p}{\sigma_v}$$

P_p - pore fluid pressure normalized to σ_v ; μ - friction coefficient of rocks

The range of variation of minimum and maximum horizontal stresses at a given depth (i.e., σ_v), as dictated by Eq. 1, can be illustrated graphically by use of stress polygons (Moos and Zoback, 1990) for different tectonic regimes. The friction coefficients of rocks have been investigated by Byerlee (1978) under different normal stress conditions. For normal stresses $\sigma_n < 200$ MPa (depth < 6 km) Byerlee (1978) found an empiric correlation (Byerlee's law), which is the basis to define the shear failure. Applying the stress ratio information from the stress inversion, the stress ratio R can be calculated (Eq. 2; Carey-Gailhardis and Mercier, 1987).

Equation 2

$$R = \frac{\sigma_2 - \sigma_1}{\sigma_3 - \sigma_1}$$

2.2.3 Slip- and dilation tendency

A number of studies have shown that critically stressed faults ($T_s \geq \mu_s$) and faults with a dilational tendency represent favorable zones for fluid flow (e.g., Barton et al., 1995, 1997; Ferrill and Morris, 2003; Gudmundsson et al., 2002) and could therefore mark preferential target zones for geothermal production wells. Both tendencies were analyzed in this study using Brady's stress field data. The developed 3D fault model provides the basis for the fault stress model (Jolie et al., 2012). Fault zones were assessed according to their orientation within the current stress field. The derived principal stresses σ_1 , σ_2 and σ_3 of a given depth are projected to all fault planes with constant magnitudes and orientations, neglecting local stress field variations. The slip tendency is quantified as follows (Eq. 3; Morris et al., 1996):

Equation 3

$$T_s = \frac{\tau}{\sigma_n} \geq \mu_s$$

μ_s - critical friction coefficient of rocks; τ - shear stress; σ_n - normal stress

Eq. 3 indicates that the slip tendency depends on the ratio of shear stress to normal stress resolved on a surface, in relation to the friction coefficient of rocks. The normal and shear

stress can be calculated on a fault plane of any orientation if the magnitudes and directions of the principal stresses are known. The graphical representation of normal and shear stress is the Mohr circle. The higher the normal stress on a fault plane, the lower the tendency to slip. Increased pore fluid pressure results in lower normal stresses and higher slip tendencies. The dilation tendency (Eq. 4) is a normalized relative measure of the likelihood of a fault to dilate (Ferrill et al., 1999). Eq. 4 reveals that fracture planes perpendicular to σ_3 have the highest dilation tendency in a given stress field.

Equation 4
$$T_d = \frac{\sigma_1 - \sigma_n}{\sigma_1 - \sigma_3}$$

3 RESULTS AND DISCUSSION

3.1 Three-dimensional geological modeling

The 3D structural-geological model of the Brady's geothermal system comprises 61 discrete fault planes (Fig. 5), 71 fault blocks with tilt angles of up to 35°, and eight geological units (Fig. 6; Table 1; Jolie et al., 2012). Faults mainly strike NNE to NE and dip 45° to 80° NW and SE (Jolie et al., 2012). The Brady's fault step over is located in the central part of the model (Fig. 1).

Figure 5: The 3D fault model consists of a set of 61 NNE- to NE-striking fault planes. The fault planes are bounded by the Mesozoic basement and the digital elevation model. Coordinate System: NAD 1983 UTM Zone 11N.

Figure 6: Development stages of the 3D model (view to NE). Displacements are illustrated according to the developed fault model (Fig. 5). A) Mesozoic basement (granites, metamorphic rocks); B) Oligocene ash-flow tuffs; C) Early Miocene: lacustrine sediments intercalated with basalt, andesite, dacite, and rhyolite flows; D) Early to Middle Miocene: andesite-dacite lavas; E) Middle to late Miocene: generally aphanitic basalt flows and breccia; F) Late Miocene: lacustrine sediments (diatomite, siltstone, minor limestone and sandstone); G) Late Miocene-Pliocene: sandstone, conglomerate and tuffaceous sediments; H) Quaternary: alluvial fan deposits and Lake Lahontan lacustrine deposits of up to 75 m in thickness, draped with the DEM of the study area (from green/basin to red/mountain range); Coordinate System: NAD 1983 UTM Zone 11N.

272 **Table 1: Simplified stratigraphy of the 3D structural-geological model (Fig. 6; Faults and Garside, 2003;**
273 **Faults et al., 2012).**

Age	Model color code	Model ID (acc. to Fig. 6)	Main lithology (max. thickness)	Grouped with
Quaternary		H	Alluvial fan deposits and Lake Lahonton lacustrine deposits (Qf) (< 75 m)	Disturbed areas (anthropogenic); <u>Geothermal features:</u> Colluvium, mud, silicified sand, older silicification; Qsi – Sinter deposits; occurrence in the vicinity of the Brady's geothermal power plant and along NNE-striking fault zones
Late Miocene-Pliocene		G	Sandstone, conglomerate, and tuffaceous sediments (Tsy) (< 350 m)	
Late Miocene		F	Lacustrine sediments (diatomite, siltstone, minor limestone and sandstone) (Tsl) (< 420 m)	Interlayering of Tls – Limestone, commonly with abundant tufa, forms two separate sequences in some areas, complex interfingering with other units and between cross sections
Middle to late Miocene		E	Older, generally aphanitic basalt flows and breccia (Tbo) (< 830 m)	<u>Interlayering of following units:</u> Tlr – Rhyolite lavas and lesser tuffs, two intervals; Tabo – Altered aphanitic basalt flows and breccia (possibly due to geothermal alteration); Tpd – Porphyritic dacite to rhyodacite flows and domes; Tsl – Lacustrine sediments (diatomite, siltstone, minor limestone and sandstone) (Late Miocene); Tbai – Basaltic andesite intrusions, irregular sill-like body; Tbi – Basalt dikes, observed in cores/cuttings and by field mapping
Early to middle Miocene		D	Andesite-dacite lavas (Tda) (< 660 m)	
Early Miocene		C	Older lacustrine sediments intercalated with basalt, andesite, dacite, and rhyolite flows (Tslo) (< 80 m)	
Oligocene		B	Ash-flow tuffs (Trt) (< 660 m)	
Mesozoic		A	Granites and metamorphic rocks, undivided (Mzu)	

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275 3.2 Stress field analysis

276 The determined principal stresses based on fault slip data from the neighboring Desert Peak
277 and Desert Queen areas indicate that σ_1 , σ_2 and σ_3 form distinct clusters without obvious
278 indications of paleo stress fields (Fig. 8B). The orientation of the inverted stress axes
279 (azimuth/plunge) are $\sigma_1 \approx P$ (pressure) = $242^\circ/77^\circ$ for the maximum principal stress, $\sigma_2 \approx B$
280 (intermediate) = $024^\circ/10^\circ$ for the intermediate principal stress and $\sigma_3 \approx T$ (tension) = $116^\circ/08^\circ$
281 for the minimum principal stress as shown in the PBT plot (Fig. 8B). The stress field is
282 slightly tilted, with σ_2 and σ_3 nearly horizontal and σ_1 nearly vertical, corresponding to a
283 normal stress regime ($\sigma_v > \sigma_{H,max} = \sigma_2 > \sigma_{h,min} = \sigma_3$) with some strike slip effects. The misfit

angle between calculated and measured shear stress vectors, as a measure for the homogeneity of the stress field, is low (Fig. 8C). More than 75% of the fault-slip data fit in the calculated stress regime, indicating a relatively homogenous data set. The optimal shear angle to induce the observed slip for all mapped faults in the calculated stress field is 35° . The stress ratio R (Eq. 2) based on the stress inversion of fault slip data from surface measurements is $R = 0.53$ (Fig. 8D).

The principal stress orientations from inverted surface data (Desert Peak and Queen) are in agreement with stress analysis of Desert Peak's borehole breakouts by Davatzes (pers. comm., 2011) and focal mechanisms (Ichinose et al., 1998, 2014), but not in agreement with Brady's stress orientations ($\sigma_{H,max}$) from borehole breakouts (well 15-12). This highlights the occurrence of stress field variations over relatively small distances. As a consequence, only data from well 15-12 was used as an indicator of the Brady's stress field and for fault stress modeling.

Figure 7: Principal stress orientation (azimuth/plunge) based on borehole data and stress inversion of surface measurements in the Hot Springs Mountains (Davatzes, pers. comm., 2011; Hickman and Davatzes, 2010; Robertson-Tait et al., 2004; Zemach et al., 2010).

Figure 8: Results of the stress field analysis. A) Angelier plot (after Angelier, 1979) of fault planes. Slip vectors point in the relative slip direction of the hanging wall. The error of slip sense to shear stress is less than 1° for individual planes; B) PBT plot ($\sigma_1 = P$ (pressure), $\sigma_2 = B$ (intermediate), $\sigma_3 = T$ (tension)): Inverted stress axes based on kinematic indicators of mapped faults (calculated with tectonics FP software) and their confidence level CL (in %); C) Fluctuation histogram: Misfit angle between calculated and measured shear stress vector as an indicator of the homogeneity of the data set; D) Normal faulting stress regime (stress ratio $R = 0.53$) illustrated by Mohr circles. In the hybrid stress regime σ_2 approaches the value of σ_1 and R approaches 0.

In order to characterize the Brady's present in-situ stress conditions by the concept of limiting stress ratios, three scenarios have been calculated for friction coefficients representing weak ($\mu = 0.56$; Scenario I; Lutz et al., 2011), average ($\mu = 0.85$; Scenario II; after Byerlee, 1978) and strong rock strength ($\mu = 0.98$; Scenario III; Lutz et al., 2011). For reference, these values are within the range of friction coefficients reported for Desert Peak ($\mu = 0.65$ - 0.96 ; Lutz et al., 2010). Fault zones are treated with uniform properties and individual rock mechanical properties of encountered stratigraphic horizons are not considered. Stress magnitudes and stress ratios, including upper boundary for the magnitude of $\sigma_{H,max}$, are given in Table 2, for each rock strength scenario and for both normal faulting (NF) and hybrid normal/strike-slip (NS) stress regimes. Ratios of possible horizontal stresses normalized to vertical stress are graphically shown in the stress polygon plot for scenario II (Fig. 9). All stress calculations refer to a depth of 1,463 m where well stimulation is planned. Based on the average lithostatic

gradient of 27.1 kPa/m (Davatzes, pers. comm., 2011), $\sigma_v = 39.5$ MPa is obtained at 1,463 m. Formation fluid pressure P_p measured in borehole 15-12 is 13.2 MPa (hydrostatic gradient of 9.0 kPa/m) and indicates a static water level 120 m below ground level, assuming an average fluid density of 1,000 kg/m³. Taking pore pressure into account for the normal faulting regime (scenario II) the effective vertical stress is $\sigma_{v,eff} = 26.3$ MPa, $\sigma_{H,max,eff} = 19.5$ MPa and $\sigma_{h,min} = 12.4$ MPa.

Figure 9: Stress polygon showing stress ratios at a depth of 1,463 m under scenario II (friction coefficient $\mu = 0.85$). * after Davatzes (pers. comm., 2011); ** after Byerlee (1978); The determined stress ratios are labeled in red. NF: Normal faulting; SS: Strike slip faulting; RF: Reverse faulting.

Table 2: Absolute stress magnitudes calculated at a depth of 1,463 m, where injection tests were carried out (production zone) under three different friction coefficients (Scenario I-III; after *Byerlee, 1978 and **Lutz et al., 2011). Stress magnitudes are given in MPa. R – stress ratio.

Tensor	Azimuth	Plunge	Stress magnitudes - Scenario I: $\mu = 0.56$ (weak rock strength)**		Stress magnitudes - Scenario II: $\mu = 0.85$ (average rock strength)*		Stress magnitudes - Scenario III: $\mu = 0.98$ (strong rock strength)**	
			NF R = 0.5	NS R $\approx$ 0	NF R = 0.49	NS R $\approx$ 0	NF R = 0.50	NS R $\approx$ 0
σ_1	000°	90°	39.5 (= σ_v)	39.5 (= σ_v)	39.5 (= σ_v)	39.5 (= σ_v)	39.5 (= σ_v)	39.5 (= σ_v)
σ_2	007°	0°	30.8 (= $0.78\sigma_v$)	39.5 (= σ_v)	29.4 (= $0.74\sigma_v$)	39.5 (= σ_v)	28.8 (= $0.73\sigma_v$)	39.5 (= σ_v)
σ_3	097°	0°	22.1 (= $0.56\sigma_v$)	22.1 (= $0.56\sigma_v$)	18.7 (= $0.47\sigma_v$)	18.7 (= $0.47\sigma_v$)	17.8 (= $0.45\sigma_v$)	17.8 (= $0.45\sigma_v$)

3.3 Slip- and dilation tendency analysis

Slip- and dilation tendencies have been calculated for the entire model domain and are assessed in detail 1) within the step over of the Brady's fault zone (Fig. 10A and B) where abundant geothermal surface manifestations occur, and 2) along fault zones intersected by the stimulation well 15-12 (Fig. 10A and C).

Figure 4: A) The map highlights the Brady's fault step over (BFSO, marked in red) and the target area for the reservoir stimulation along the Southern Brady's fault (SBF, marked in red). For each area three major faults have been selected from the fault trace map (from Faulds and Garside, 2003; Faulds et al., 2012) for fault stress modeling (BFSO: faults 8, 11, 12; SBF: faults 12, 18, 20). NBF: Northern Brady's fault; BPP: Brady's geothermal power plant; VDP: Vegetable dehydration plant; Coordinate System: NAD 1983 UTM Zone 11N; B) 3D fault model with faults along the BFSO in the vicinity of the geothermal power plant. View from top down parallel to fault dip. C) The stimulation well 15-12 intersects five major fault planes, three of which are intersected within the reservoir (faults 12, 18, 20).

Figures 11A and 12A illustrate slip- and dilation tendency values along a set of 12 representative major fault zones within the entire model domain for a normal faulting regime according to Table 2 (Scenario II). The calculated slip- and dilation tendencies show a relatively heterogeneous pattern on single fault planes (Fig. 13), illustrating the effect of geometrical irregularities of fault zones. Only a few faults from a complex fault pattern trigger

flow of geothermal fluids and control the location of the geothermal resource (Faulds et al., 2004, 2006). Even along single fault zones only individual fault segments may enable fluid flow (Faulds et al., 2004, 2006).

The rose diagrams (Fig. 11B, 12B) illustrate the major strike directions of all 61 fault zones with their maximum slip- and dilation tendency values (color-coded) by considering only optimally oriented dip angles. Stereo plots have been compiled (Fig. 11C, 12C) illustrating the actual slip- and dilation tendency values (gray dots) for different fault segments of the Brady's fault step over (fault 8, 10, 11, 12, 18, 20). The red areas in the stereo plot represent maximum slip tendencies with T_S -values ≤ 0.38 (Fig. 11C) and maximum dilation tendencies with T_D -values ≤ 1.0 (Fig. 12C).

Fig. 11: A) Slip tendency for selected faults of the Brady's geothermal system. Other fault zones are indicated by their surface fault traces using dotted lines. The purple lines have been used for the stereo plot (see C). B) The rose diagram illustrates the maximum slip tendencies that fault zones could have for each strike azimuth bin. C) Stereo plot with slip tendency values from selected fault surfaces (see purple lines in A). Slip tendency greater than 0.35 is outlined by the two red ellipses. D) The plot shows the main geothermal surface manifestations and the central area affected by subsidence at 20 mm interval contour lines (from Oppliger et al., 2005).

Fig. 12: A) Dilation tendency for selected faults of the Brady's geothermal system. Other fault zones are indicated by their surface fault traces using dotted lines. The purple lines have been used for the stereo plot (see C). B) The rose diagram illustrates the maximum dilation tendencies that fault zones could have for each strike azimuth bin. C) Stereo plot with dilation tendency values from selected fault surfaces (see purple lines in A). Dilation tendency greater than 0.8 is outlined by a red ellipse. D) The plot shows the main geothermal surface manifestations and the central area affected by subsidence at 20 mm interval contour lines (from Oppliger et al., 2005).

The maximum slip tendency in the Brady's fault step over occurs on NNE-oriented ($007 \pm 2^\circ$) faults with a dip azimuth of $277 \pm 2^\circ$ and dip angles of $55-56^\circ$ (Fig. 11B and 11C). High slip tendencies (> 0.35) occur along N- to NE-oriented fault zones with dip angles in the range from $43-66^\circ$ and dip azimuths from W to NW (see red ellipses in stereo plot Fig. 11C). Considering friction coefficients within the given range ($\mu = 0.56-0.98$; Lutz et al., 2011), no critically stressed (i.e., close to slip) faults can be identified in the fault slip model with slip tendencies $T_s \leq 0.38 < \mu_s$ – neither nearby the stimulation well nor in the step over of the Brady's fault zone. In order to obtain critically stressed faults, the normal stress acting on a fault plane has to be reduced, e.g., by increasing fluid pressure due to injection. Maximum dilation tendency of $T_d=1.0$ also occurs along NNE-oriented ($007 \pm 2^\circ$) fault segments in the Brady's fault step over, but at steeper dip angles of $89-90^\circ$ to the WNW ($277 \pm 2^\circ$) (Fig. 12B and 12C). Dilation tendency is increased (> 0.8) along steeply dipping ($64-90^\circ$), N- to NE-

oriented fault zones with dip azimuths from W to NW (see stereo plot Fig. 12C). In contrast to slip tendency, dilation tendency reaches increased T_s -values ≥ 0.8 , which indicates that some faults are close to dilate. Generally spoken, the red areas in the stereo plots indicate maximum slip- and dilation tendencies, but this does not necessarily imply that the faults are close to slip or dilation. The spatial distribution of slip- and dilation tendency, rather than absolute values, is of primary interest in the structural analysis.

The 3D and stereo plot representation of slip- and dilation tendencies help visualize the favorable orientations for fluid flow within the Brady's fault step over. Though, the dominant structural trend is NE $\sim 026^\circ$ (see 11B, 12B), major geothermal surface manifestations (Fig. 11D, 12D) correlate spatially with N- to NNE-oriented ($\sim 007^\circ$), steeply westwards dipping fault zones (dip angles $63\text{-}72^\circ$) with dilation tendencies of 0.8-0.9 and slip tendencies of 0.3-0.35. The position of production wells and region of subsidence as an indicator of production-related effects (Oppliger and Coolbaugh, 2004) are shown in Fig. 11D and 12D. Microearthquake data (MEQ) could be evaluated for analysis of the 3D fault model, however, Davatzes et al. (2013) have shown that MEQ activity seems not to correspond to the permeable fractures. Based on the 3D fault model, the results of the stress inversion and the slip- and dilation tendency analysis applied herein, a fault intersection/tip density analysis was conducted by Siler and Faulds (2013), which may be a reasonable addition to the fault stress analysis. This method enables to focus on the interaction of fault density and fault stress conditions.

Well 15-12 intersects five interpreted major fault planes (Fig. 10C; faults 8, 10, 12, 18, 20). Slip- and dilation tendencies are presented in detail at three selected fault planes intersected by well 15-12 (faults 12, 18, 20) for the normal faulting stress regime of scenario II (average rock strength). Calculated slip tendency values range from 0.23-0.38 along selected fault planes (Fig. 13), which seems to be far from critical stress conditions.

Figure 53: Slip tendency, dilation tendency of selected fault planes intersected by stimulation well 15-12, based on scenario II (Fig. 9). The parameters of the inverted stress axes and stress ratios have been set according to scenario II (Table 2).

It is predicted that a fluid pressure increase of ~16 MPa would be required for scenario II (average friction coefficient $\mu = 0.85$; after Byerlee, 1978) to induce fault reactivation along fault planes 12, 18 and 20, assuming an optimal orientation of fault planes (30° – 45°) relative to σ_1 (Fig. 14). Considering intact strong rocks, additional fluid pressure would be required to hydraulically connect fault zones.

Figure 64: Mohr-Coulomb diagram with failure envelope of average reservoir rocks to show the effect of increasing pore fluid pressure (s – measure of fracture density; m – analogous to frictional strength of rock; m and s are empirical material constants; UCS – uniaxial compressive strength of intact rock; ΔP_p – fluid pressure increase).

4 CONCLUSION

A combined approach of 3D geological modeling, stress field analysis and fault stress modeling was applied to the Brady's geothermal field to characterize its tectonic and structural setting. This combination allows prediction and visualization of preferential fluid pathways and can be a relevant tool for the design of drilling strategies (e.g., production/reinjection wells, EGS stimulations). The applied methodology is expected to be effective in tectonically active regions such as the Basin-and-Range Province where stress indicators at the surface reflect the stress field in the subsurface. This study extended to neighboring areas of Desert Peak and Desert Queen, where local surface-based fault slip data and borehole data demonstrate slight variations in the stress field among neighboring geothermal systems.

Based on the structural analysis, faults within the Brady's geothermal reservoir were found to be primarily dominated by a high dilational trend, rather than a high slip tendency, indicating critically stressed faults.

The results of the study encourage adopting this technique on a routine basis to the management of developed geothermal fields and geothermal exploration, especially in fault-controlled systems.

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