

Geologic and Geophysical Analysis of the Desert Peak-Brady Geothermal Fields: Structural Controls on Geothermal Reservoirs in the Humboldt Structural Zone

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ABSTRACT

We propose to expand an ongoing investigation of the geologic and geophysical character of the Desert Peak-Brady geothermal fields in the Hot Springs Mountains of western Nevada. Two power plants and one vegetable dehydration plant currently operate in this field. The ongoing (*Phase-I*) investigations involve detailed geologic mapping and structural analysis of faults and folds along a narrow transect between the Brady and Desert Peak fields, a gravity survey, and GIS compilation of geologic and well data. The proposed Phase II seeks to 1) expand the detailed mapping and structural analysis to include remaining parts of the northern Hot Springs Mountains, 2) acquire a greater density of gravity stations across several critical profiles, 3) conduct a micro-earthquake (MEQ) study, and 4) continue the GIS compilation. Radiometric dating, geochemical analyses, and paleomagnetic investigations will complement the geologic work. The mapping and structural analysis will better define the Tertiary stratigraphy and structure, thus elucidating the 3D strain field, subsurface framework, and structural and stratigraphic controls on geothermal reservoirs. The enhanced gravity survey will facilitate detailed modeling of several profiles critical to understanding producing fields and sites of future development (EGS site). The MEQ study will reveal the subsurface geometry of faults and fractures that channel fluids and define the present-day stress field. The ultimate goal of this study is to develop a comprehensive 3D model of a major geothermal field within the Humboldt structural zone of northern Nevada, a broad region of NE-striking faults and high heat flow that contains many of the geothermal fields in the Great Basin (Steamboat, Dixie Valley, Desert Peak-Brady). Such a model may facilitate exploration and/or enhancement of geothermal resources elsewhere within the Humboldt zone.

INTRODUCTION

A broad region of high heat flow, the Battle Mountain heat flow high, covers much of northern Nevada and includes an ENE-trending zone of ENE- to NE-striking faults extending from near Reno to Carlin (Fig. 1). This zone of faulting and high heat flow has been referred to as the Humboldt structural zone (HSZ) (Rowan and Wetlaufer, 1981). Most of the major geothermal fields in northern Nevada, including Steamboat, Brady's, Desert Peak, Rye Patch, Dixie Valley, and Beowawe, occur along NE-striking faults in the HSZ. The abundance of producing geothermal fields and regional extent of the heat flow anomaly indicate high potential of discovering additional geothermal reservoirs in this region.

From west to east, major ENE- to NE-striking faults in the HSZ include the Olinghouse fault, faults bounding the Smoke Creek and Black Rock Deserts, faults along the northern margin of the Carson Sink, Stillwater fault in Dixie Valley, Midas fault, and Malpais fault near Beowawe. Most of these faults accommodate left-lateral and/or normal slip. Normal slip is related to WNW-oriented extension in the Basin and Range (Thatcher et al., 1999). In the Walker Lane, some ENE-striking faults also serve as extensional transfer zones between right-stepping, NW-striking dextral faults (Oldow et al., 1994). However, seismological data (Ichinose et al., 1998) and Quaternary studies (dePolo et al., 1997; Sanders and Slemmons, 1979; Briggs et al., 2000) indicate recent left-lateral motion on ENE-striking faults.

Despite the economic significance of the HSZ, few detailed investigations have been conducted on the Cenozoic stratigraphic and structural framework of the region. Although major contributions have recently been made (e.g. McNitt, 1990; Blackwell et al., 1999, 2002; Caskey and Wesnousky, 2000; Trevor and Wesnousky, 2001; Blewitt et al., 2002; Johnson and Hulen, 2002), the temporal and spatial relationships between various structural features in the HSZ and how individual faults, stratigraphic units, or sets of structures control fluid pathways and geothermal resources are generally poorly understood.

We propose to continue and enhance an integrated structural, geophysical, and geochronologic investigation of the Desert Peak-Brady geothermal fields in the Hot Springs Mountains of western Nevada. Of the developed geothermal fields, some of the best exposures of faults and folds occur in the Desert Peak-Brady fields. Consequently, comprehensive analysis of this area has significant potential for characterizing both the structural setting (strain and stress fields) and structural controls on geothermal reservoirs within the HSZ. Our proposed research complements an ongoing EGS (Enhanced Geothermal Systems) study of the Desert Peak area by ORMAT and GeothermEX (Schochet et al., 2002; Nathwani and Creed, 2002) and builds on our completed work in the area (Faulds et al., 2002).

HOT SPRINGS MOUNTAINS

The Desert Peak-Brady geothermal fields lie in the Hot Springs Mountains of western Nevada, ~80 km east-northeast of Reno (Fig. 1). The fields occur along or near a major ENE-striking fault zone that extends from near Fernley to Lovelock and bounds the Carson Sink on the north. Two power plants and one vegetable dehydration plant currently operate in the field. The Brady power and dehydration plants are located at Brady's Hot Springs just south of I-80 along the NE-striking Brady fault. The smaller Desert Peak power plant taps a *blind* geothermal reservoir ~5 km (3 miles) southeast of Brady's Hot Springs. Available aqueous chemistry and isothermal maps suggest that the Brady and Desert Peak fields are associated with essentially independent thermal plumes (Benoit et al., 1982).

The Hot Springs Mountains are composed of Tertiary volcanic and sedimentary rocks that rest directly on Mesozoic metamorphic and granitic basement. NNE-striking faults dissect the range. In addition, the Tertiary rocks (some of which are less than 9 Ma) are deformed into closely spaced NNE-trending folds. As a result of its relatively low elevation (~4,000 to 5,300 feet) and sparse vegetation, the Desert Peak-Brady fields are relatively well exposed. Benoit et al. (1982) compiled isothermal maps, a near-surface thermal aquifer map, Bouguer gravity map (Desert Peak area only), and a generalized geologic map of the area. They concluded that the Desert Peak geothermal reservoir resides in pre-Tertiary rocks and further speculated that some mechanism other than Tertiary high-angle faulting localizes the heat, although such faults locally tap the reservoirs. However, the boundaries of the geothermal reservoirs in both the Brady's Hot Springs and Desert Peak areas remain poorly defined, which poses problems for further development of the field.

PROPOSED RESEARCH

We propose a comprehensive geologic and geophysical analysis of the northern Hot Springs Mountains that builds on our ongoing study (Phase I) and complements the EGS study east of the Desert Peak plant. The Phase I study involved detailed mapping of a narrow 3.5 km wide transect between the Brady and Desert Peak fields, structural analysis of faults and folds, a new gravity survey, and GIS compilation of existing geologic and geophysical data. We now seek funding to 1) expand the detailed mapping to include remaining parts of the northern Hot Springs Mountains, 2) conduct more thorough stratigraphic and structural analyses, 3) acquire additional gravity data, 4) carry out a micro-earthquake study, and 5) continue the GIS compilation. Although the Phase I study has better defined the stratigraphic and structural framework of the Hot Springs Mountains and elucidated controls on geothermal aquifers, the narrowness of its scope has precluded full assessment of the geothermal fields.

Several problems have confronted geothermal operations in the Desert Peak-Brady fields. These include short residence times for fluids between recharge and intake wells and excessive draw-down in existing wells induced by nearby production (Benoit, pers. comm., 2003). Such problems indicate a high level of fluid transmissivity. Known faults, such as the NNE-striking Brady fault, account for some of this high transmissivity. However, high transmissivity has also been documented across and within the hanging wall of the Brady fault, suggesting that stratigraphic units or obscure cross faults also channelize fluids. A more comprehensive geologic and geophysical study of the northern Hot Springs Mountains and incorporation of the large amounts of subsurface data (Benoit et al., 1982; NBMG well data files) has significant potential for addressing these problems while also unraveling the fundamental stratigraphic and structural controls of two major geothermal fields within the HSZ.

Geologic Studies. The geologic investigations will involve 1) detailed geologic mapping (1:24,000 scale) of remaining parts of the northern Hot Spring Mountains (~80 km²), 2) more comprehensive assessment of the Tertiary stratigraphy, 3) further analysis of the geometry, kinematics, and origin of faults and folds, 4) a paleomagnetic investigation, and 5) additional ⁴⁰Ar/³⁹Ar dating and geochemical analyses of key units. The primary goals of this work are to a) delineate the late Cenozoic 3D strain field in the area, b) elucidate the relations between faults, stratigraphic features, and geothermal reservoirs, c) better define the overall extent of these reservoirs, and d) define the late Miocene to recent stress field.

Additional detailed mapping is warranted to better define the stratigraphic and structural framework of the Hot Springs Mountains. Because the volcanic and lacustrine strata are characterized by abrupt pinchouts and lateral facies variations, it is not clear whether the stratigraphy defined in the relatively narrow, initial transect of mapping is representative, making correlations with drill-core difficult. Also, a full understanding of the 3D structural framework requires better coverage in the along-strike dimension such that the geometry of fault systems and kinematic linkages between the many overlapping en echelon faults can be adequately defined. For example, the Brady geothermal field appears to be associated with a left-stepping, NNE-striking WNW-dipping normal-fault system, whereas the Desert Peak field may be localized near the horse tailing northern end of a similarly oriented normal fault zone. However, bedrock exposures in the direct vicinity of both fields are obscured by Quaternary cover. The best exposures of Tertiary strata in the region lie just to the north of our completed transect within the proposed map area.

Critical features in the proposed map area include: 1) numerous well-exposed en echelon faults and related folds, including structures similar to those that may exist in the subsurface of the Desert Peak and Brady fields; 2) the apparent northern tip of the Rhyolite Ridge fault zone, which may play a role in localizing the thermal reservoir in the Desert Peak field; 3) a possible transfer or accommodation zone (cf. Faulds and Varga, 1998) linking the oppositely dipping Rhyolite Ridge and Desert Queen faults; 4) the apparent northern terminus, in the Desert Queen area, of the horst block that occupies much of the EGS site; and 5) exposures of granitic basement and overlying hydrothermally altered Oligocene ash-flow tuffs, also in the Desert Queen area. Extensive argillic and sericitic alteration of Oligocene tuffs in the Desert Queen area may have formed at relatively shallow depths since late Miocene time. Because the geothermal aquifer in the *blind* Desert Peak field is localized near the basement-Tertiary contact, detailed mapping, structural analysis of faults and joints, and studies of vein character and mineralogy in the

Desert Queen area may provide important insight into subsurface relations in the Desert Peak field and adjoining EGS site. The Desert Queen area may represent a fossil hydrothermal system similar to present conditions in the Desert Peak field. Detailed mapping to the north of the completed transect is therefore critical for developing exposed analogues for both the Desert Peak and Brady fields, as well as better defining the Tertiary stratigraphy, 3D strain field, and regional stress orientations.

Geochronologic and geochemical data ($^{40}\text{Ar}/^{39}\text{Ar}$ and tephrochronology) will facilitate stratigraphic correlations and aid in estimating offset across faults. Both exposed volcanic units and samples from drill core will be dated. A large tephrochronologic data base from directly north of the Hot Springs Mountains (Stewart and Perkins, 1999) will also be integrated into our study. Also, $^{40}\text{Ar}/^{39}\text{Ar}$ dating of alteration minerals in the Desert Queen area will be useful in understanding the hydrothermal history of the range.

Exposed fault surfaces, which are relatively common in the Hot Spring Mountains, will continue to be scrutinized for sense of slip. Slip sense will be determined through combined analysis of stratigraphic separation, fault striae (slickenlines), and brittle kinematic indicators (e.g. Riedel shears and rough facets; Angelier et al., 1985). The kinematics of individual fault sets will then be deduced employing methods developed by Marrett and Allmendinger (1990). From this analysis, we will infer principal shortening and extension axes for each fault set and assess the degree of kinematic compatibility of various fault sets. In addition, the geometry and possible origins of folds will be further evaluated, particularly their temporal and spatial relationship with major faults.

We will also examine cuttings and drill core, with emphasis on correlating lithologic logs with exposed stratigraphic sections. Drill cuttings are available at NBMG from production and injection wells drilled in the past 20 years. Additionally, some core is available from Ormat. Certain well samples will be radiometrically dated and analyzed chemically and petrographically.

A paleomagnetic study of Tertiary volcanic rocks is also proposed. Approximately 25 sites (8-10 samples/site) will be drilled in mafic lava flows and ash-flow tuffs. The paleomagnetic data will facilitate regional correlations of the tuffs and document the magnitude of vertical-axis rotation in the Hot Springs Mountains. If the area has experienced significant rotation since the late Miocene, stress orientations determined from fault-slip data may differ appreciably from current orientations. Because the NNE-striking normal faults in the Hot Springs Mountains are roughly orthogonal to the present-day least principal stress, we suspect that vertical-axis rotations are negligible. The paleomagnetic study will test this hypothesis. To average out short-term variations in the geomagnetic field (paleosecular variation, McFadden and McElhinney, 1984), multiple mafic flows will be sampled from 3 localities. Vertical-axis rotations will be assessed by comparing tilt-corrected directions with expected Miocene field directions calculated from established paleomagnetic poles (e.g. Mankinen et al., 1987; Berggren et al., 1995).

The detailed mapping and stratigraphic and structural analyses will address several key questions and hypotheses. These include: 1) Do sets of cross faults and/or permeable stratigraphic horizons channelize fluids in the Brady and Desert Peak fields? 2) Do the northern Hot Springs Mountains contain exposed analogues of inferred subsurface structures in the Desert Peak and Brady fields? 3) Is there a relationship between the geometry and kinematic evolution of faults and location of the geothermal plumes? 4) Has the area undergone significant vertical-axis rotation since late Miocene time?

Dr. James Faulds and Larry Garside at NBMG will undertake the geologic investigations, with assistance from one or more students. Faulds is a structural geologist who has over 15 years of experience in analyzing complex structural relations in the Basin and Range through detailed mapping, structural analysis, paleomagnetic investigations, and $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Garside is an economic geologist who has over 30 years of experience in mapping and studies of energy resources (including geothermal) and hydrothermal mineral deposits in the Great Basin. Garside will be on sabbatical during Year-1 of this project but will assist Faulds in Year-2, particularly with mapping of alteration zones in the Desert Queen area. Under Faulds' supervision, one graduate student and 1-2 undergraduates will assist in the acquisition and processing of the geologic data, including conducting mineral separates for radiogenic dating and processing paleomagnetic samples. This work may become part of a senior thesis and/or masters thesis. **Gravity Study.** Gravity investigations of geothermal fields commonly elucidate the underlying geologic structure that might otherwise require extensive drilling (e.g. Blackwell et al., 1999). At Desert Peak-

Brady, our completed gravity survey has proven valuable for projecting structural and stratigraphic data into the subsurface, thereby better defining the structural controls on the geothermal systems. Delineating patterns of pre-Tertiary basement depths are particularly important, considering that pre-Tertiary rocks host the *blind* Desert Peak reservoir and the base of the Tertiary section serves as an effective cap for this reservoir. Our gravity results are also helping to refine our regional-scale structural concepts.

In Phase I, ~90% of all gravity stations (440) were focused on exploring ~200 km² in the Brady and Desert Peak geothermal fields (~2 stations/km²). Within this area, producing and prospective geothermal reservoirs (~30 km²) were sampled at ~5 stations/km². The completed gravity work has 1) delimited a 3 km long narrow basement horst associated with the Brady fault and indicated its possible lateral extent, and 2) clarified the geometry of the basement horst-complex in the Desert Peak and adjacent EGS study areas. Our work also identified errors in a 1979 Phillips gravity survey in the Desert Peak and EGS areas that obscured basement structure. We collected 43 additional stations to replace the questionable data.

We propose to expand the gravity investigation toward the northeast with the objectives of tracing the Brady fault and constraining the configuration of the Tertiary-basement contact near the Desert Queen fault, particularly near the fossil hydrothermal system in the Desert Queen Mine area. The new gravity data (170 stations) will cover ~80 km², with an average density of 2 stations/km².

The new gravity measurements will be integrated with the completed study and used to extend the pre-Tertiary bedrock depth interpretations. Dr. Gary Oppliger will collect and analyze the gravity data using a LaCoste and Romberg gravimeter and Geosoft-Xcelleration. Control will be provided by Trimble geodetic grade GPS surveying with elevations to +/- 15 cm. A digital elevation model will be used to implement full terrain corrections. The Bouguer gravity anomaly data will be analyzed using Fourier transform-based potential field processing tools with emphasis on identification of fault-block edges as expressed in horizontal gravity gradients. The expanded gravity-derived model will be synthesized with the expanded geologic study to evaluate critical profiles and produce maps of subsurface faults and bedrock relief. A 3D model of the gravity-inferred bedrock surface will be produced and superimposed on the geologic map, thus providing a structural framework from which to analyze thermal aquifers.

Micro-Earthquake Study. Shallow seismicity has been correlated with zones of fractured and permeable rock through which geothermal fluids can migrate in substantial volume. Location of these micro-earthquakes (MEQ) can be used to reveal and constrain the location of faults and permeable subsurface fractures. Fractures with production potential can be imaged if currently producing MEQ's. Work done at the Steamboat and Lake City geothermal fields have shown that most MEQ recordings can be correlated to production and injection. Changes in pore pressures within the geothermal reservoir due to production and injection activity cause a change in the stress regime. This, in turn, can trigger MEQ's causing the permeable faults and fractures to be illuminated. Thus, recording and locating these MEQ's can help map the subsurface permeability prior to drilling, leading to reduced exploration and development costs and also to enhanced resource management. Furthermore, detailed focal mechanism studies of MEQ's may reveal the current stress regime affecting the geothermal reservoir.

An MEQ survey is proposed for the Desert Peak-Brady geothermal fields. The pattern of MEQ events will be utilized to discern the subsurface geometry of faults and fractures that channel fluids. Depending on the quality and magnitude of recorded events, an attempt will be made to derive focal mechanisms, which will elucidate the present-day stress field in the geothermal fields. The recent success of an MEQ study at Steamboat (Optim LLC, 2001), where rock types are similar to those in the Hot Springs Mountains, suggests that useful MEQ data will be obtained from the Desert Peak and Brady fields.

The survey will employ 12 Model 72A-07 seismometers from Reftek. The array will be deployed to provide MEQ seismic data to maximum depths of ~8,000 ft. The duration of deployment will be six months. The recording parameters will be adjusted based on the number and magnitude of MEQ's, as well as noise level. Accuracy of MEQ locations is typically ~50 m or less. Phase arrivals (S- and P-waves) from MEQ records will be hand picked and re-checked for timing accuracy. This includes all earthquakes distant to the geothermal property recorded during deployment. The P and S-wave phase arrivals will be formatted for input to FASTHYPO, a standard least-squares location routine. Depending on the quality of the MEQ's, focal mechanisms will also be derived for recorded events.

GIS Work. The proposed geologic and geophysical studies will be added to the Hot Springs Mountains GIS database. Most of the existing geologic, gravity, and well data (lith logs and temperature data from 104 wells) was digitized during Phase I. In addition to the proposed geologic and geophysical work, data from ~25 additional wells will be incorporated into the database. Collectively, these data sets will provide a large body of subsurface data in digital format for the Desert Peak-Brady area and permit comprehensive 3D modeling of the fields. The GIS lab at NBMG is equipped with the latest computer hardware and GIS software that allows 2D and 3D modeling and analysis of earth resource systems. The lab utilizes ArcView, IDRISI, ENVI, Arc/Info, Log Plot, Surpac, and image processing software.

RESULTS AND RELEVANCE

The proposed research holds great promise for enhancing our understanding of geothermal reservoirs in the Great Basin and may therefore facilitate future exploration and development of these resources. The major goals of this project are to 1) characterize the linkages between thermal reservoirs and individual structural and stratigraphic features, 2) better define the boundaries of the geothermal reservoirs in the Desert Peak and Brady fields, and 3) elucidate the late Cenozoic 3D strain and stress fields in the HSZ. The Desert Peak geothermal field may ultimately be utilized as a prototype for the identification of blind resources elsewhere in the Great Basin, particularly within the HSZ. This project is directly relevant to nearly all *applied research areas* in the Great Basin Center for Geothermal Energy Program, including 1) inventory of existing geothermal resources in GIS context (Part 1A), 2) geologic mapping and fault characterization (1B), and 3) assessment of controls of reservoir boundaries (2B).

SCHEDULE AND DELIVERABLES

Geologic Studies: 1) Detailed geologic map and cross sections of the entire northern Hot Springs Mountains (final by 12/04). 2) Compilation of geometry and kinematics of faults and folds (preliminary 9/03; final 11/04). 3) Integration of geochronologic and geochemical data with stratigraphic columns and geologic map (preliminary 9/03; final 12/04). 4) Completion of paleomagnetic study (12/2004).

Gravity Study: 1) Final processed complete Bouguer anomaly map (contours and color shaded-relief in GIS form by 12/03). 2) Expanded map of surface and subsurface faults and bedrock relief (preliminary 1/2004; final 3/04). 3) Expanded 3D computer model of gravity inferred bedrock surface (3/04).

GIS Work: 1) Digitization of additional well data (12/03). 2) Digitization of new geologic map (12/04). 3) 3D subsurface model of northern Hot Springs Mountains, including fence diagrams (12/04).

MEQ Study: 1) Digital copy of MEQ events and P- and S-wave phase arrival information (6/04). 2) Final velocity model (8/04). 3) MEQ hypocentral locations (8/04). 4) Depth and cross-sections of MEQ hypocenters (8/04). 5) Focal mechanisms (12/04). 6) Report of results and interpretation (12/04).

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