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Structural Controls of Three Blind Geothermal Resources at the Hawthorne Ammunition Depot, West-Central Nevada

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ABSTRACT

In cooperation with the U.S. Navy Geothermal Program Office, we have undertaken a multidisciplinary investigation to identify geothermal resources and select new drill target areas for future exploration at the Hawthorne Ammunition Depot (HAD). The HAD straddles the southern part of the Walker Lake basin, extending east into the northwestern Garfield Hills and west into the south-central part of the Wassuk Range. The northwestern Garfield Hills are composed mostly of Mesozoic metamorphic basement with lesser granitic plutons overlain by Cenozoic volcanic and sedimentary rocks. Cenozoic rocks are cut by a system of NW-striking dextral faults and NE-striking sinistral faults, and locally contain gentle ENE-trending folds. A complex westward-deepening half-graben separates the Wassuk Range from the Garfield Hills. In contrast to the Garfield Hills, the Wassuk Range is composed mostly of Mesozoic granite with minor metamorphic rocks or Cenozoic rocks. The Wassuk Range front fault zone bifurcates into two major strands west of the town of Hawthorne. Based on geophysical, field, and well data, the NW-striking, east-dipping Wassuk Range front fault strands dip of 30° to 55°, with an average of ~45°. The NE-striking range-front segment at Cat Creek dips ~65° SE. Fault slip data from the range-front within the step-over indicate a NW-SE (azimuth 127°) extension direction.

Temperature and geochemistry data indicate three blind geothermal systems (no surface hot springs) within the HAD. All three geothermal systems follow steeply dipping, NE-striking faults, consistent with slip and dilation tendency analysis indicating that NE-striking, 70° NW- and SE-dipping fault planes have the highest tendency to slip and dilate. One system (A) parallels the Wassuk Range front adjacent to where the range-front fault zone bifurcates with a major right step in the active part of the fault zone. A second system (B) resides along the northwest margin of the Garfield Hills at the south end of a pull-apart. The third system (C) resides ~7 km north-northeast of the city of Hawthorne where tufa mounds form a linear outcrop along part of the Hawthorne fault zone and the northwest corner of the pull-apart. Cation geothermometers for geothermal systems A and C range 90-180°C and 90-137°C, respectively, while geothermometry for system B has not been established. Our primary recommendation for drilling is the highly faulted, down-plunge projection of the right step between faults A and B in the western part of the basin near Cat Creek.

Introduction

Previous studies have demonstrated that faults are the primary control on geothermal systems in the western Great Basin (Faulds et al., 2004, 2006, this volume; Faulds and Melosh, 2008; Hinz et al., 2008; Vice et al., 2007). In cooperation with the U.S. Navy Geothermal Program Office, we have undertaken a multidisciplinary investigation to develop a structural model from which to identify and evaluate geothermal resources and select new drill

Figure 1. A) Faults of the Walker Lane (modified from Stewart, 1988) on shaded elevation model (modified slightly from Faulds et al., 2005). CD, Carson domain; PLD, Pyramid Lake domain, WLD, Walker Lake domain. B) Physiographic map of the Hawthorne Ammunition Depot (HAD).
target areas for future exploration at the Hawthorne Army Depot (HAD) in the southern part of Walker Lake basin, Mineral County, western Nevada (Figure 1). Developing the structural model involved integrating detailed geologic and geophysical studies within the context of the regional tectonic framework to delineate the local structural and stratigraphic framework of the HAD. We then evaluate the spatial distribution of geothermal anomalies and mapped locations of possible surface manifestations of geothermal activity relative to the structural model to correlate specific fault zones with respective geothermal resources. A final step involves slip tendency analysis of these faults to identify the most dilatant parts as drill target areas for further exploration.

Nearly 500 km² were mapped in 1:24,000 scale detail (Figure 2). In addition, regional reconnaissance mapping of faults and major stratigraphic packages surrounding the HAD linked findings within the HAD to the regional setting. Faults and folds were analyzed to constrain the kinematic evolution of the HAD area and evaluate the local strain and stress fields. Well cuttings were examined to correlate down-hole lithologic units and evaluate the local strain and stress fields. Well cuttings were examined to correlate down-hole lithologic units with geologic map units and geophysical anomalies, indentify faults, and evaluate the degree and type of alteration (Lamb et al., this volume). Geophysical data sources include a new gravity study (Shoffner et al., this volume), a reinterpretation of existing 3D seismic data (Kell et al., this volume), and geophysical well logs. Temperature data includes existing well data reevaluated by Penfield et al. (this volume) and a new 2-m temperature survey reported by Kratt et al. (this volume) and geochemistry data includes existing well data, also reevaluated by Penfield et al. (this volume). Local strain and stress fields were determined from fault slip data subsequently used for slip and dilatation tendency analysis (Moeck et al., this volume). A digital 3D geologic model was constructed for the Hawthorne area in order to quantify fault geometries and select drill targets (Moeck et al., this volume). This paper summarizes the stratigraphic and structural framework of the HAD and discusses both the structural model for geothermal activity and reasoning for selection of drill targets.

**Stratigraphic Framework**

In the HAD area Neogene volcanic and sedimentary deposits rest unconformably on Mesozoic basement (Figure 2). The composition of the Mesozoic basement contrasts greatly across the HAD. The northwestern Garfield Hills are composed mostly of Mesozoic metamorphic rocks with one granitic pluton identified. In contrast to the Garfield Hills, granitic plutons dominate over metamorphic rocks.
basin fill sediments. Approximate age distinctions of these units were based on lithologic correlation with the Neogene stratigraphy defined in the central Wassuk Range north of Walker Lake (Stockli et al., 2002; Surpless et al., 2002). The only surface manifestations possibly related to geothermal activity were observed in the form of massive tufa heads and colonies related to paleo-springs. Exposures up to 8 m-thick of tufa were mapped coincident with Holocene fault scarps within the south-central part of Walker Lake basin northeast of the town of Hawthorne (Figure 2).

**Structural Framework**

The Walker Lake basin is a complex half-graben, bound on the west by the Wassuk Range front fault system and defined to the east by a broad, gently west-dipping ramp, cut locally by west-dipping antithetic faults. Within the map area, the Wassuk Range front fault bifurcates into two major strands from the Lucky Boy Mine area to the mouth of Cat Creek (faults A and B, Figure 2). Based on field evidence, well data, and 3D seismic data, the major NW-striking strands of the range-front fault system dip ~30° to 55° NE, whereas the NE-striking part of fault A at the mouth of Cat Creek dips ~65° SE. The overlap area between faults A and B is cut by numerous N- to NE-striking, east- and west-dipping normal faults with ~45-65° dips. At the south end of the basin, the ~20 km-long NW-striking dextral Willow Springs fault (informally named in this paper) splays from the Wassuk Range front near the Lucky Boy Mine area and connects with other strike-slip and normal faults at the west edge of the Garfield Hills. The Walker Lake basin half-graben is cut by multiple N- to NW-striking E- and W-dipping normal faults, including the newly identified Hawthorne fault zone that extends NNE from the step-over region of the range-front to a N-striking, W-dipping antithetic fault system coincident with the west side of the Gillis Range (Bell and Hinz, this volume). Displacement along these normal faults within the basin ranges up to 0.5 km. Tilt of Neogene strata filling the basin are not well constrained. Several west-tilted fault blocks identified in the 3D seismic data dip gently 15° west with a decrease in dip up section. Dips range from 5 to 20° W in un-folded, late Miocene basaltic andesite that project into the basin along the west edge of the Garfield Hills.

The Garfield Hills are cut by a system of kinematically linked NW-striking dextral faults and NE-striking sinistral-oblique faults. The Pamlico strike-slip fault (informally named in this paper) splays from the Wassuk Range front near the Lucky Boy Mine area and connects with other strike-slip and normal faults at the west edge of the Garfield Hills. Another steep gravity gradient that probably marks a NE-striking, NW-dipping fault bounds the NW end of the Garfield Hills. No exposures of this fault zone were identified at well sites. This NE-striking dextral fault bounds the NW end of the Garfield Hills. Another steep gravity gradient that probably marks a NE-striking, NW-dipping fault bounds the NW end of the Garfield Hills. No exposures of this fault zone were identified at well sites.

**Geothermal Anomalies**

Three thermal anomalies were distinguished within the HAD based on integrated analyses of maximum well temperatures, Na-K-Ca geothermometry, well temperature gradients, total dissolved solids (TDS), and a 2-m temperature survey (Figures 3A-E; Kratt et al. and Penfield et al., both this volume). Anomaly A (labeled in Figure 3E) corresponds to a 7-km long region paralleling the Wassuk Range front from near wells HWAAD #2 and 3 north toward the right step in Fault A at Cat Creek (Figure 2). Cation geothermometry ranges from ~90° C in the north to ~180° C at the south end. Total dissolved solids (Figures 3D) also indicate higher temperatures at the southern end of this anomaly, whereas well temperature gradients and maximum well temperatures increase to the north (Figures 3A, C). Catchment runoff from Cat Creek may mask the cation geothermometry and concentrations of total dissolved solids for north end of anomaly A (Penfield et al., this volume).

Anomaly B is defined by a broad 2-m temperature anomaly ringing the northwestern margin of the Garfield Hills and contains the maximum observed 2-m-deep temperature within the HAD at the northern terminus of the Garfield Hills. Well data only overlaps with the western edge of anomaly B as defined by 2-m temperatures; however one well along the Pamlico fault on the west side of the Garfield Hills reaches 61° C. Two wells located between anomaly A and B record cation geothermometry of ~120-130° C.

Anomaly C surrounds tufa outcrops 6-7 km north-northeast of Hawthorne and has cation geothermometers ranging from ~90-137° C. Well temperatures and temperature gradients define a north-trending anomaly 5 km-wide by 2 km-long to the west of the tufa outcrops (Figures 2B, D). Total dissolved solids and the 2 m-shallow temperature survey both exhibit broad anomalies surrounding the tufa deposits but are open-ended to the north and/ or northeast due to the limited spatial extent of data points.
Discussion and Conclusion

Based on the geologic, geophysical, temperature, and geochemical investigations, we suggest that three blind geothermal systems reside within the HAD, each controlled by distinct structures including a right step in the Wassuk Range front fault system and a complex pull-apart in the southeastern Walker Lake basin (Figures 2, 3). All three geothermal systems follow steeply dipping, NE-striking faults, consistent with slip and dilation tendency analysis indicating that NE-striking, 70° NW- and SE-dipping fault planes have the highest tendency to slip and dilate. Anomaly A parallels the Wassuk Range front adjacent to where the range-front fault zone bifurcates with a major right step in the most recently active part of the fault zone. We suggest that the higher fracture density associated with the abundant NE-striking faults between faults A and B and the right step in the normal-dextral Wassuk Range front fault have collectively induced dilation and facilitated deep circulation of fluids. Anomaly B resides at the northwest terminus of the Garfield Hills at the south end of an inferred pull-apart, whereby deep circulation is enhanced along a steeply N-dipping, ENE-striking normal fault transferring strain between the Pamlico fault and the unnamed NW-striking strike-slip fault along the southwest flank of the Gillis Range. Additional enhanced dilation at fault intersections between the Pamlico fault and ENE-striking sinistral-oblique faults accounts for broad anomaly wrapping around the northwest margin of the Garfield Hills. Anomaly C resides north of the city of Hawthorne, where tufa mounds form an NNE-trending lineament along part of the Hawthorne fault zone (Figure 3F). The NW-striking Pamlico fault merges with Hawthorne fault zone near the south end of the tufa lineament, transferring strain into the NE-striking faults defining the northwest corner of a pull-apart. Deep circulation of fluids is facilitated along the steeply dipping NE-striking Hawthorne fault zone and at intersections with the Pamlico fault.

Our primary recommendation for drilling (Target A) is the highly faulted, down-plunge projection of the right step between faults A and B in the western part of the basin near Cat Creek at the north end of anomaly A (Figures 3, 4). This segment of Fault A is oriented perpendicular to the regional extension direction, has relatively high Holocene slip rate relative to entire Wassuk Range front fault, and exhibits a major damage zone in the footwall which could act as an excellent reservoir.
Figure 4. Simplified structure map of the HAD area showing primary faults and proposed drill target areas. Faults highlighted in red have been active in the Quaternary. HFZ, Hawthorne fault zone; PF, Pamlico fault; WSF, Willow Springs fault. Fault strands A and B of the Wassuk Range front fault system are also shown in Figure 2 and described in the text.

rock. Moeck et al. (this volume) produced a digital 3D model of Target area A, providing quantitative data for placement of exploration wells. Target area B corresponds to the down-dip projection of the NW-dipping, NE-striking fault at the northern terminus of the Garfield Hills, below and to the north of the pronounced 2℃ temperature anomaly, where brittle metamorphic rock and possible buried plutonic rocks may provide a viable reservoir. Target area B also overlaps with the intersection of this NE-striking fault with the Pamlico fault, where cross-cutting fractures may enhance permeability. Target area C corresponds to the down-dip projection of several NW-dipping, NE-striking strands of the Hawthorne fault zone adjacent to the tufa deposits. Target area C also includes the intersection of the Pamlico fault with the Hawthorne fault zone, where cross-cutting fractures may enhance permeability. Overall, we rate target areas B and C as secondary priorities for exploration relative to target area A (Figures 3, 4). Quaternary fault scarps were not identified for any of the structures related to Anomaly B. Although Holocene fault scarps are associated with anomaly C, suitable reservoir rock is probably buried at least 1.5 km-deep in Walker Lake basin (Shoffner et al., this volume).

In summary, these findings are consistent with previous studies demonstrating that specific segments of fault zones are the primary control on geothermal systems in the western Great Basin (Faulds et al., 2004, 2006, this volume; Faulds and Melosh, 2008; Hinz et al., 2008; Vice et al., 2007). The geothermal resources in the eastern part of HAD are structurally controlled by strike-slip faulting in the Walker Lane, whereas the geothermal resources along the Wassuk Range front in the western part of the HAD are controlled by oblique-slip (normal-dextral) range-front faulting.

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