Structural Controls of the Black Warrior Blind Geothermal System, Washoe-Churchill Counties, Truckee Range, Northwestern Nevada, USA

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ABSTRACT

The Black Warrior geothermal system lies 20 km east of the southern end of Pyramid Lake in the Truckee Range of northwestern Nevada on the Washoe-Churchill county line. It is an amagmatic blind geothermal system, as the region lacks recent (<5 Ma) volcanism and the system lacks hydrothermal surface manifestations (no fumaroles, hot springs, sinter deposits, or high temperature alteration). The system was discovered by shallow temperature gradient drilling (100-600 m, max temp: 128°C) by Phillips Petroleum Company in the 1980s and observed with a 2-m shallow temperature survey circa 2011.

The thermal anomaly resides in a structurally complex zone that has not been previously characterized. Detailed geologic mapping in the area has identified faults and stratigraphic relationships between successive and interfingering Tertiary volcanic sequences that nonconformably overlie Mesozoic plutonic and metamorphic basement. The structural framework is characterized by north-northeast-striking, moderately to steeply west-dipping normal faults that terminate and step in the vicinity of the thermal anomaly. This suggests two possible favorable structural settings: (1) a fault termination of the southeastern rangefront fault with accompanying horse-tail splaying producing an area with abundant closely spaced faults and high fracture permeability; and/or (2) a fault step-over in a broad left-step of the major normal faults, whereby many closely-spaced minor faults provide hard linkage and a zone of high fracture permeability. In either case, the study area lies in a favorable structural setting for geothermal activity and may host a robust geothermal system at depth.

Introduction

Geothermal energy is a clean renewable energy resource with minimal carbon emissions capable of generating tens to hundreds of megawatts of electricity depending on the available resource and its tectonic setting. As a baseload power source, it functions continuously regardless of weather conditions. Thus, geothermal energy has an advantage over other renewable energy resources.

Exploration for geothermal resources seeks to identify and characterize three critical components that comprise a *conventional geothermal system*: elevated temperature from a heat source, fluid as a heat transporter, and high permeability to constitute the reservoir. Ideally, a stable, high-temperature heat source with a large highly-permeable reservoir and abundant fluid characterizes a conventional geothermal resource capable of producing electricity.

On the first order, identifying a potential resource is accomplished typically via careful identification of hydrothermal surface features, followed by detailed geologic and geophysical analysis. These surface features can be divided into two groups: currently active (fluid) and previously active manifestations. The former group represents active circulation of hydrothermal fluids at surface elevations and includes fumaroles, boiling mud pots, hot springs and seeps, and steaming ground. Previously active manifestations represent relict hydrothermal fluid circulation either at depth or on the surface and involving precipitation of minerals from hot fluids, which can produce siliceous sinter terraces, travertine mounds, tufa towers, or hydrothermal alteration (e.g. advanced argillic). Anomalous vegetation patterns, caused by shallow but unexpressed hot fluids and/or gases can also serve as subtle indicators of active hydrothermal circulation.

In an *expressed geothermal system*, the relative abundance, type, temperature, and geochemistry of the surface manifestations aid in characterizing the robustness of a reservoir at depth. A *hidden geothermal system* lacks active, hydrothermal fluid manifestations of an expressed system but may have one or more of the previously active features, which may help assess potential temperatures at depth (Forson et al., 2014). Lastly, a *blind geothermal system* lacks all surface manifestations and has no active or previously active fluid features. A blind geothermal system is completely unexpressed at the surface, and other methods must be used to locate such systems. Without surface manifestations, it is a challenge to constrain the location of blind geothermal systems.

Detailed geologic mapping and structural analysis can identify and constrain favorable pathways that are capable of channeling fluids to the surface or serving as reservoirs at depth. Essentially, delineating the location and type of geologic structures aids in identifying the location of blind geothermal systems. Specific structures play critical roles in channeling hydrothermal upflow and generating permeability in reservoirs in both magmatic and amagmatic environments (Curewitz and Karson, 1997). In amagmatic geothermal systems of the Great Basin in western North America, intersecting networks of fractures and faults allow meteoric fluids to reach great depths, where they are heated, and subsequently either transported to the surface or trapped in geothermal reservoirs. Extensional-style geothermal systems in the Great Basin are generally fault-controlled (Faulds et al., 2004, 2011) and associated with Quaternary faults (Bell and Ramelli, 2007). In the Great Basin, the most favorable faults for geothermal activity are normal and oblique-slip normal faults that dip moderately to steeply and strike north-northeast (Faulds et al., 2004) orthogonal to the current west-northwest-trending extension direction (e.g. Zoback et al., 1981; Henry and Perkins, 2001; Whitehill, 2009).

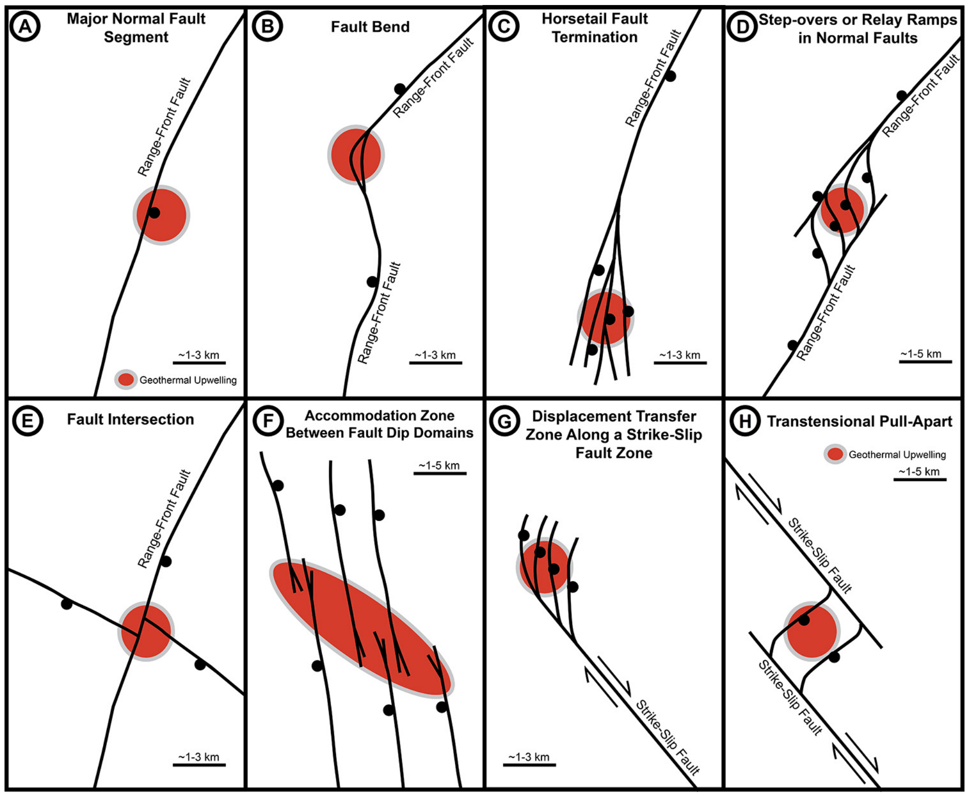
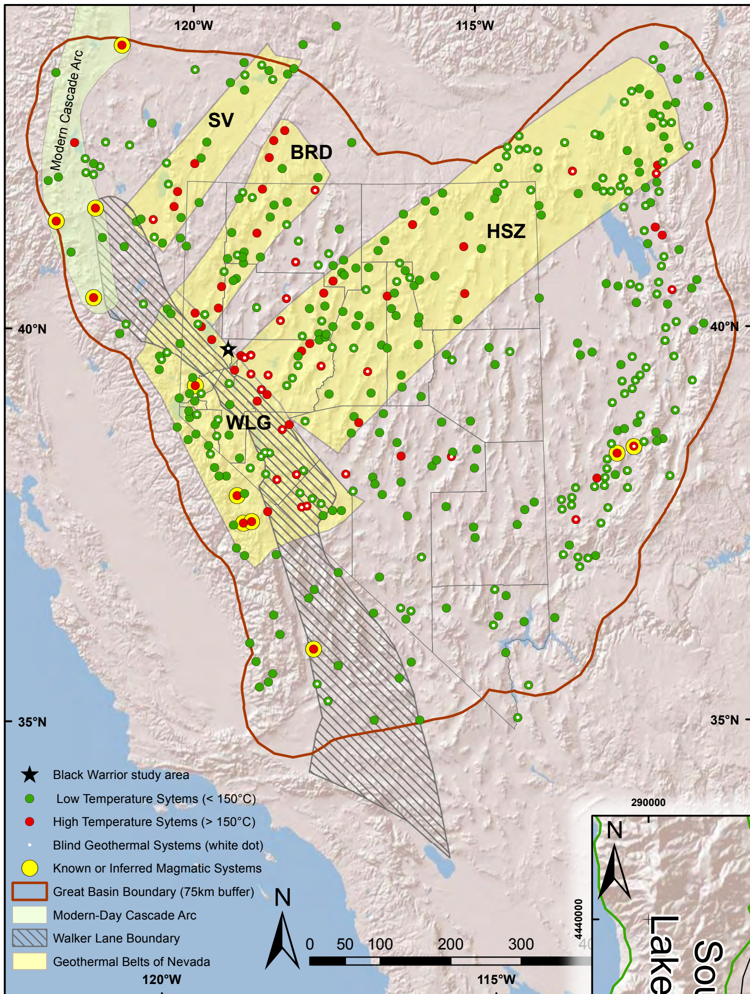


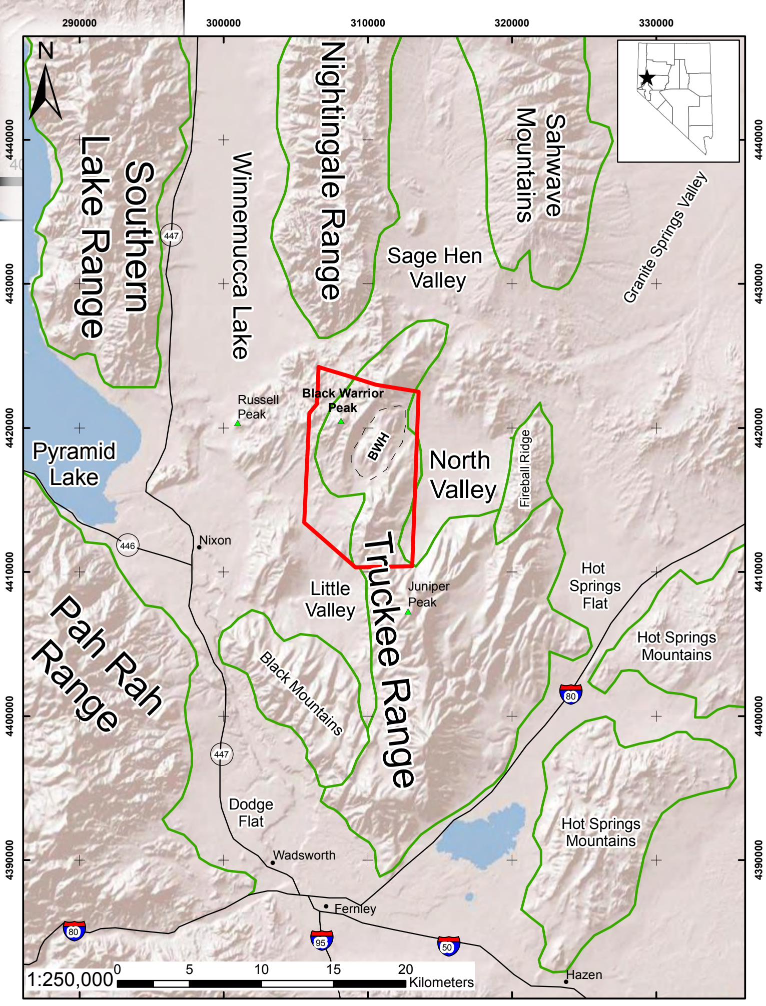
Figure 1. Examples of Structural Settings for Geothermal Systems (From Faulds and Hinz, 2015). Areas of potential upwelling of geothermal fluids are shaded in red. Fault balls are on down-dropped section. Favorable fault architectures include: A) major normal fault segments; B) subtle bends in a rangefront normal fault; C) terminations of major normal faults, whereby faults break up into multiple splays or horsetail; D) step-overs or relay ramps between two overlapping normal fault segments with multiple minor faults providing hard linkage between two major faults; E) dilational fault intersections between transversely-oriented, oblique-slip and normal faults; F) overlapping, oppositely dipping normal fault systems (accommodation zones) that generate multiple fault intersections in the subsurface, where tilt directions of fault blocks are opposite to the dip of the primary normal fault system; G) terminations of major strike-slip faults and their accompanying displacement transfer zone; H) transtensional pull apart zones (steps in strike-slip faults).

Fault architectures that characterize favorable structural settings of geothermal systems include the following: 1) discrete steps in normal fault zones, 2) intersections between normal faults and transversely oriented oblique-slip faults, 3) overlapping, oppositely dipping normal fault zones (i.e. accommodation zones), 4) terminations of major normal faults (or strike-slip faults) and the accompanying horse-tail splay of closely-spaced faults (in the case of strike-slip faults, displacement transfer zone), and 5) transtensional pull apart zones (Faulds et al., 2011) (Figure 1). These structurally-complex fault zones are physiographically manifested in the topography of an extensional terrain as a) major steps in rangefront faults (step-overs), b) interbasinal highs (accommodation zones) (cf. Faulds and Varga, 1998), c) mountain ranges consist-



← **Figure 2.** Regional map of geothermal systems (n=425) in the Great Basin region (adapted from Faulds et al., 2004, 2011, 2014). Map is centered on Nevada with counties outlined. Black star is the location of the Black Warrior study area (maximum downhole temperature: 128°C). Green circles are systems with maximum temperatures less than 150°C (n=353, ~83%); red circles have maximum temperatures ≥ 150°C (n=72, ~17%). Magmatic systems are yellow (n=11, ~2.5%), and blind systems (n=164, 38.5%) have a white dot. Abbreviations for geothermal belts: SV, Surprise Valley belt; BRD, Black Rock Desert belt; HSZ, Humboldt structural zone belt; WLG, Walker Lane geothermal belt. Maximum temperature is either the measured temperature or maximum geothermometry.

↓ **Figure 3.** Location Map for northwestern Nevada near the study area. Geographic features (towns & roads) and physiographic features (ranges, peaks, and valleys) are labeled and outlined on a digital elevation model (DEM) hillshade. Red outline marks the boundary of the Black Warrior study area. The thermal anomaly area, Black Warrior Hills (BWH), is delineated by the black dashed outline. A left-step in the Truckee Range is visible in the study area boundary (red outline) at 1:250,000 scale.



ing of relatively low, discontinuous ridges (fault termination splays & accommodation zones), and d) lateral terminations of mountain ranges (fault terminations) (Faulds et al., 2006, 2011).

Before geothermal energy can be utilized for electrical power generation, the location of the exploitable geothermal resource – in the form of active upflow of hydrothermal fluids – must be accurately determined. This is especially challenging for blind geothermal systems. Given their lack of surface manifestations, blind systems are more difficult to identify and assess, particularly without the aid of aqueous geochemistry to provide a geothermometer at depth.

The purpose of this paper is to characterize the structural setting (e.g. fault architecture) of the Black Warrior geothermal system, which is a blind system located ~65 km northeast of Reno, Nevada, in the Truckee Range in the western part of the Basin and Range province (Figures 2 and 3). A significant thermal anomaly has been documented at Black Warrior, but the structural setting and likely location for upwellings have not been well studied. This study is employing detailed geologic mapping, structural analysis, new detailed well logging, and synthesis of available geologic and geophysical data to establish a conceptual structural model for the geothermal system and ultimately facilitate geothermal development in the area.

Black Warrior/North Valley Geothermal System

The Black Warrior study area, also known as the North Valley geothermal prospect, was discovered by regional thermal gradient drilling by Phillips Petroleum Company in the late 1970s and early 1980s. Approximately 20 wells were drilled during this time period, most less than 100 m in depth, but two deeper stratigraphic test wells were drilled in 1982. The two stratigraphic wells, NV-ST-1 and NV-ST-2, reached depths of 552 m and 607 m, with maximum temperatures of 128°C and 118°C, respectively. Geothermal leases were subsequently acquired by Nevada Geothermal Power (NGP) Company. In 2011, NGP drilled a moderately deep well (445 m or 1460 ft) in the thermal anomaly area (NV 25-31), which yielded a temperature of 83°C at ~236 m. NGP also conducted a 2-m-deep shallow temperature survey. Eventually NGP became Alternative Earth Resources, Inc., and in August 2014 sold its leases to Ormat Technologies, Inc., the current owner of the Black Warrior-North Valley prospect. Ormat has since performed geophysical investigations on these leases.

Stratigraphic Framework

The stratigraphy of the Black Warrior study area is composed of Mesozoic metasedimentary and plutonic basement rocks, mid-Tertiary volcanic and sedimentary rocks, and Quaternary sediments, alluvium, and landslide deposits (Figure 4). The late Triassic to early Jurassic Nightingale sequence is the oldest package of rocks in the study area. The Nightingale sequence is composed of very fine- to fine-grained, low-grade metasedimentary rocks (variably metamorphosed from sub-greenschist to lower greenschist facies) that include argillite, mudstone, slate, phyllite, and quartzite (commonly meta-siltstone to meta-argillite) with local dolomite and marble (recrystallized carbonate), and sparse schist, hornfels, and scheelite-bearing skarn near intrusive bodies (Burke and Silberling, 1973; Willden, 1964; Bonham, 1969; Willden and Speed, 1973). These rocks were subsequently intruded by Jurassic (?) dioritic and late Cretaceous granitic plutons associated with the Sierra Nevada batholith (Van Buer et al., 2009; Van Buer, 2012). Heavily-jointed, equigranular granodiorite to quartz monzodiorite have not been dated in the study area but locally range from approximately 105 to 88 Ma (Van Buer and Miller, 2010). Basement rocks crop out in the central and western parts of the study area.

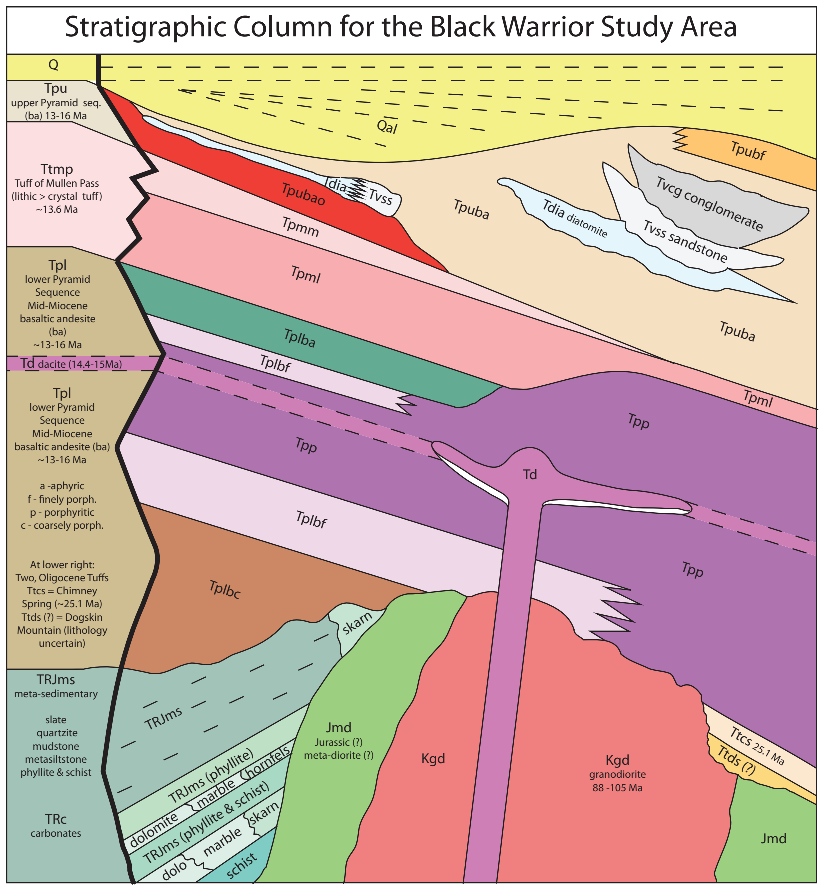


Figure 4. Stratigraphic column for the Black Warrior study area. Left column (without individual flows) shows simplified stratigraphy for the geologic map of Figure 6. Right section shows more schematic detail with common interfingering relationships in the volcanic stratigraphy. Naming scheme example: Tpubao = **T**ertiary-**P**yramid-**U**pper-**B**asaltic andesite- **A**phyric-**O**livine-rich. Tpubao is grouped into the upper Pyramid sequence basalts and basaltic andesites and is not illustrated in Figure 6. Oligocene tuffs of Chimney Spring and Dogskin Mountain (?) crop out only in the south-central map area. Tuff of Mullen Pass (Ttmp) serves as a local divider between upper and lower Pyramid sequence rocks. Dacite (Td) is a flow-dome complex that forms Black Warrior Peak. Volcaniclastic sandstones (Tvss) and conglomerates (Tvcg) are common in uppermost volcanic sections and in the eastern study area.

Cenozoic volcanic rocks nonconformably overlie Mesozoic basement rocks and dominate the area. Mid-Tertiary rocks fit broadly into two groups: sparse exposures of Oligocene ash-flow tuffs and common middle Miocene mafic to intermediate composition lava flows. Moderately to poorly welded late Oligocene ash-flow tuffs crop out in a single small drainage on the lower west flank of the Truckee Range in the southern portion of the study area. By contrast, the middle

Miocene lavas are extensive and crop out throughout the area. These volcanic rocks were produced from the ancestral Cascades arc from ca. 5 to 23 Ma (du Bray et al., 2014). The middle Miocene rocks are primarily part of the 13 to 16 Ma Pyramid sequence, which is composed of interfingering flows of basalt and basaltic andesite, dacite (flow-dome complex), and the tuff of Mullen Pass (strongly- and poorly-welded dacitic ash-flow tuff)), where the dacite and tuff separate the Pyramid sequence into upper and lower members. The lower member is commonly more porphyritic than the upper member. Additionally, the lower Pyramid sequence appears to thin eastward suggesting it may pinch out within the study area at depth. Diatomite with lenses of volcaniclastic sandstone and conglomerates also interfinger with lava flows and are more common in the upper Pyramid sequence. Lastly, Quaternary colluvium, alluvium fans, and landslides are common, particularly along the margins of the larger ridges.

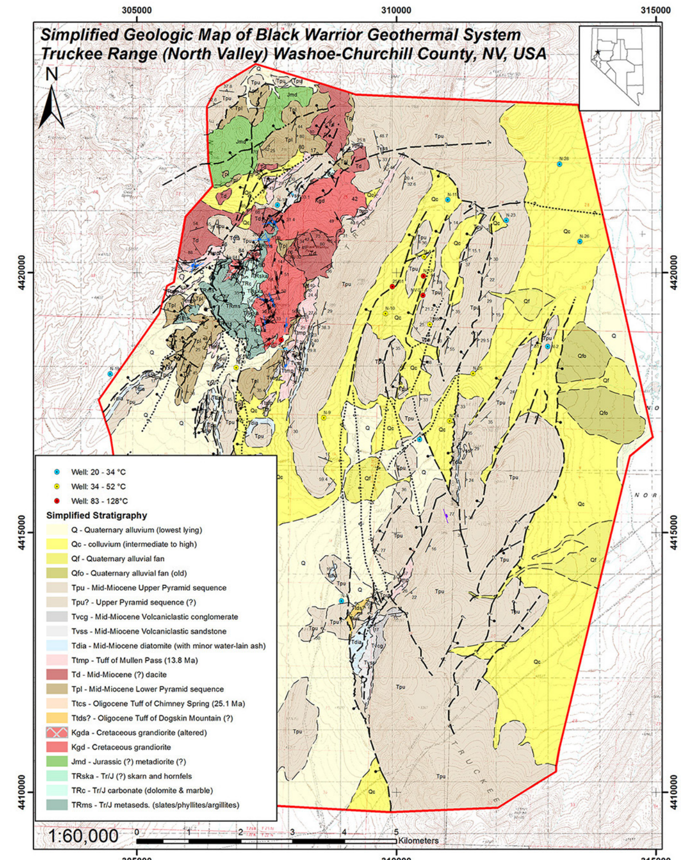


Figure 5. Geologic map of the Black Warrior study area, northern Truckee Range, Washoe-Churchill Counties, Nevada. Dashed faults are approximately located and queried (?) where uncertain or inferred. Dotted faults are concealed and similarly queried (?) where uncertain. For example, a queried concealed fault is the most uncertain fault type.

Structural Framework

The Black Warrior field area is characterized by a gently-to-moderately east-tilted fault blocks bounded largely by west-dipping normal faults. Most of the fault blocks are tilted ~20° to 35° east, with no obvious decrease in tilts up-section in the Pyramid sequence. Faults are generally not well exposed but appear to dip moderately to steeply. The faults generally cut Miocene strata, but Quaternary scarps are evident along the margins of all basins in the area (Figure 5). On the basis of regional relations (e.g., Trexler et al., 2000; Faulds et al., 2010), we infer that major extension began ~13 Ma, peaked ~13-9 Ma, and has continued episodically into the Quaternary since the late Miocene (e.g., Henry and Perkins, 2001; Colgan et al., 2006; Whitehill, 2009). Diffusion of dextral shear strain from the Walker Lane may have enhanced extension in the area since latest Miocene time (e.g., Faulds et al., 2005; Drakos, 2007).

The structural setting of the geothermal area appears to be characterized by a broad step over and associated relay ramp in the west-dipping normal fault system. The primary step over occurs between the Little Valley fault on the south, which bounds Little Valley on the east along the Truckee rangefront, and the Black Warrior fault on west, which bounds the crest of the Truckee Range and Black Warrior Peak on the west. Topographically, many of the faults blocks

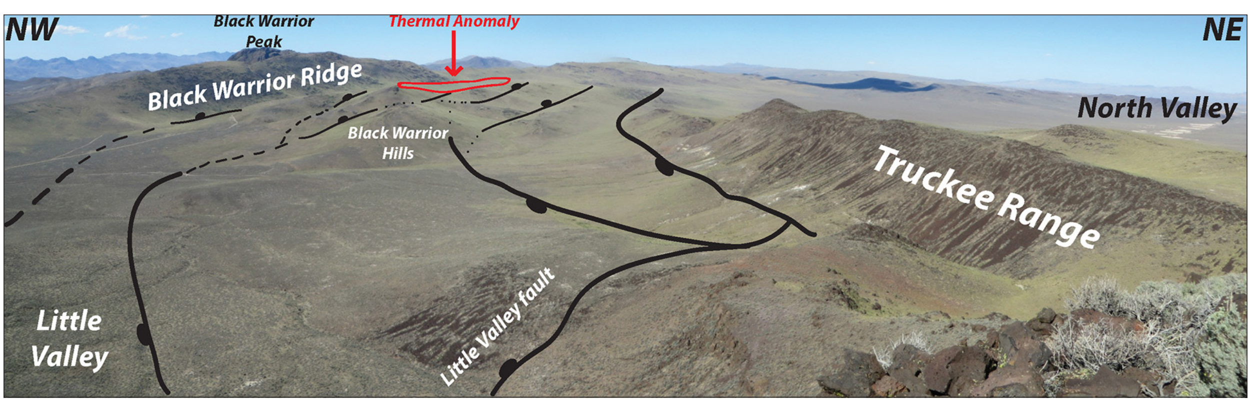


Figure 6. Photo taken from the Truckee Range looking north toward the thermal anomaly in the Black Warrior Hills. This perspective shows a simplified system of west-dipping normal faults, which correspond to the horse-tailing northward termination of the southeastern rangefront fault (Little Valley fault) and broad left step-over between the Little Valley fault (pictured) and Black Warrior fault (not pictured).

in the study area have a subtle southward slope, which probably reflects the relay ramp associated with the northward terminating Little Valley fault. It is noteworthy that this step over also appears to contain the horse-tailing northward termination of the Little Valley fault, which breaks into multiple splays in the vicinity of the thermal anomaly (Figure 6).

It is also important to note that paleotopography developed on the nonconformity (i.e., erosional surface) at the base of the Tertiary section is prevalent in the study area and generates stratigraphic discontinuities and relationships that can be misinterpreted as faults. This potential confusion is particularly evident in the narrow valley directly south of Black Warrior Peak, where the lower Pyramid sequence is largely missing against an apparent paleo-ridge consisting of Mesozoic basement. This relationship could be misinterpreted as an east-dipping normal fault that could influence the geothermal system. Significant paleotopography on this erosional surface has been well-documented in the region (e.g., Faulds et al., 2005; Henry and Faulds, 2010).

Well Temperature and Two-Meter Temperature Survey Data

Since 1982, twenty-four wells have been drilled at the Black Warrior-North Valley study area. All wells have temperature data and rudimentary driller logs. Twenty of the wells have depths less than 100 m. The other four wells – N-12, 25-31, NV-ST1, and NV-ST-2 – have respective total depths (and maximum temperatures) of ~300 m (99°C), 445 m (83°C), 551 m (128°C), and ~600 m (118°C). The two stratigraphic test (ST) wells were drilled in 1984 after the majority of the drilling in 1982-1983, and 25-31 was drilled much later in 2011 by NGP. Well 25-31 was the only well not drilled by Phillips Petroleum Company (Figures 7). Given the age of the drilling, reported locations for the earlier wells are approximate. Only the location of the youngest well, 25-31, is precise.

Examination of cuttings and logs reveals the subsurface lithologies and documents weak hydrothermal alteration in the study area. However, downhole rock samples are only available for well 25-31. Upper portions of well 25-31 down to depths of ~230 m (750 ft) correlate with aphyric basaltic andesite flows of the upper Pyramid sequence observed at the surface. Below that interval at intermediate depths of the well, returns are poorly preserved, coated in drilling muds, and mixed with cementing material. Logs indicate that this interval is composed of tuff, which may correlate with the tuff of Mullen Pass, but this is unclear judging by the poorly preserved samples. Lowest portions of the well (~300-445 m) show friable weakly propylitized ash or fine-grained, clastic sedimentary rock, possibly correlative with volcaniclastic units in the upper Pyramid sequence. Low temperature hydrothermal alteration is thus confirmed, but it is not clear which surface lithology correlates with the altered interval, given the mechanical reconstitution implicit in sample retrieval via rotary drilling. Partial and no returns were common in this well at lower intervals, suggesting loss circulation at depth. Also, observed at lower intervals are rock chips of basaltic andesite with <2 mm diameter vesicles and feldspar phenocrysts that are coated with or respectively replaced with banded silica; some of the chips appear to be coated with a thin veneer of microscopic calcium carbonate. Plagioclase phenocrysts are replaced with clay (montmorillonite >> chlorite, via TerraSpec, John Muntean personal communication). These mineralogical indicators, particularly amorphous silica, suggest higher temperatures at depth.

In 2010/2011 (?), a shallow, 2-m temperature survey was conducted. The data mimic background temperatures as observed from the earlier temperature gradient drilling, which further supports the location of the thermal anomaly. But, uncertainty surrounding the data collection may also suggest that seasonal temperature variations were observed by the survey rather than a thermal anomaly. Given the background temperature mimicry in the earlier survey and the extensive, hard cobble cover, additional shallow temperature surveys are not planned in our study.

Discussion & Conclusions

This study has constrained understanding of the primary structural controls of the Black Warrior geothermal system. This system consists of two favorable settings: (1) a fault termination of the Little Valley fault with accompanying horse-tail splaying producing an area with abundant closely spaced faults and high fracture permeability; and (2) a broad left-step in the major west-dipping normal fault system, whereby many closely-spaced minor faults provide hard linkage between the major faults and a zone of high fracture permeability (Figure 6 and 7). Additional damage zone areas formed via fault intersections with northwest-striking concealed “connecting” faults may locally enhance permeability and act as secondary and tertiary structural controls. Given the west-northwest-trending extension direction, these NNW-striking “connecting” faults likely exhibit oblique normal slip with a dextral component of motion. Multiple joint sets in the late Cretaceous granodiorite may also provide enhanced permeability and geothermal favorability at depth. If the lower Pyramid sequence pinches out toward the east within the geothermal field, these basement rocks would lie at shallower depths and would therefore play a more critical role in the structural controls on any geothermal reservoirs.

These structural controls have critical implications for future geothermal development at the prospect. First, they suggest locations of favorable production and injection (i.e., drill targets). In this way, Black Warrior may be analogous

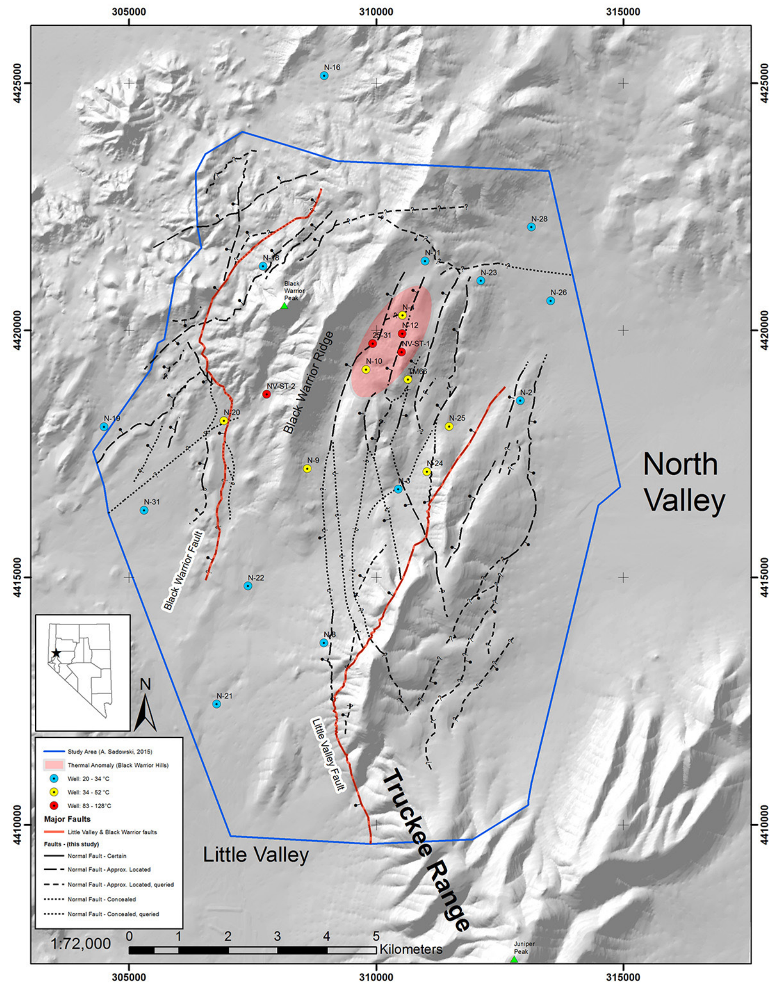


Figure 7. Simplified fault map of the Black Warrior study area. The thermal anomaly (red oval) is defined by temperature gradient drilling. This figure demonstrates a fault termination and associated horse-tail splaying of west-dipping faults into the thermal anomaly area, northward from Little Valley fault (red) that bounds the west side of the Truckee Range. Major north-northeast-striking faults east and west of Black Warrior Ridge (highlighted in red) may represent a broad step-over (Little Valley and Black Warrior faults, respectively).

to the Desert Peak geothermal system, a fault step-over in the Hot Springs Mountains (Faulds et al., 2010). Multiple fault spays at the northern end of the southeastern rangefront fault within this step-over may be the best production target in the Black Warrior field (Figure 7).

Explanation for the *blind-ness* of the geothermal system is uncertain, though multiple hypotheses are possible. In order from most probable to least, these hypotheses include: 1) the geothermal system is at high elevation, high enough to prevent upflow to the surface; 2) the local water table and the geothermal system are very deep; 3) the system is mostly dry; 4) faults are sealed in the shallow subsurface preventing upflow and formation of hot springs; and/or 5) the system has a clay cap. Inspection of the cuttings from the 25-31 well shows a lack of strong, pervasive argillic alteration suggesting the absence of a clay cap. Also, large zones of no returns at depth in that well imply that faults may be open and not sealed by gouge.

On-going work includes structural, geochronologic, geochemical, and petrographic analyses to better understand the stratigraphic and structural framework. These analyses will be integrated with available geophysical data to develop a more detailed conceptual model of the Black Warrior geothermal system. Ultimately, additional drill sites will be selected based on this conceptual model, and well testing will further constrain the locations of potential geothermal reservoirs.

Acknowledgments

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References

Allis, R., Moore, J., Blackett, B., Gwynn, M., Kirby, S., and Sprinkel, D., 2011, The potential for basin-centered geothermal resources in the Great Basin: Geothermal Resources Council Transactions, v. 35, p. 683-688

Bell, J. W., and Ramelli, A. R., 2007, Active faults and neotectonics at geothermal sites in the western Basin and Range: Preliminary results: Geothermal Resources Council Transactions, v. 31, p. 375-378.

Blackwell, D.D., P. Negraru, and M. Richards, 2007, Assessment of the enhanced geothermal system resource base of the United States: Natural Resources Research, doi:10:1007/s11053-007-9028-7.

Blackwell, D., Richards, M., Frone, Z., Batir, J., Ruzo, A., Dingwall, R., and Williams, M., 2011, Temperature-at-depth maps for the conterminous U.S. and geothermal resource estimates: Geothermal Resources Council Transactions, v. 35, p. 1545-1550.

Bonham, H. F. and Papke, K.G. 1969, Geology and mineral deposits of Washoe and Storey Counties, Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 70, 140 p.

Burke, D.B., and Silberling, N.J., 1973, The Auld Lang Syne Group, of Late Triassic and Jurassic(?) age, north-central Nevada: Contributions to Stratigraphy, United States Geological Survey Bulletin 1394-E.

Colgan, J. P., Dumitru, T. A., Reiners, P. W., Wooden, J. L., and Miller, E. L., 2006, Cenozoic tectonic evolution of the Basin and Range Province in northwestern Nevada. American Journal of Science, v. 306, no. 8, p. 616-654.

Curewitz, D., and Karson, J. A., 1997, Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction: Journal of Volcanology and Geothermal Research, v. 79, p. 149–168.

Drakos, P.S., 2007, Tertiary stratigraphy and structure of the southern Lake Range, northwest Nevada: Assessment of kinematic links between strike-slip and normal faults in the northern Walker Lane [M.S. thesis]: University of Nevada, Reno, 165 p.

Faulds, J. E., and Varga, R. J. 1998. The role of accommodation zones and transfer zones in the regional segmentation of extended terranes: Geological Society of America Special Paper 323, p. 1-46.

Faulds, J.E., Coolbaugh, M., Blewitt, G., and Henry, C.D., 2004, Why is Nevada in hot water? Structural controls and tectonic model of geothermal systems in the northwestern Great Basin: Geothermal Resources Council Transactions, v. 28, p. 649-654.

Faulds, J.E., Henry, C.D., and Hinz, N.H., 2005, Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific–North American plate boundary: Geology, v. 33, no. 6; p. 505-508, doi: 10.1130/G21274.1.

Faulds, J.E., Coolbaugh, M.F., Vice, G.S., and Edwards, M.L., 2006, Characrterizing structural controls of geothermal fields in the northwestern Great Basin: a progress report: Geothermal Resources Council Transactions, v. 30, p. 69-76.

Faulds, J.E., Coolbaugh, M.F., Benoit, D., Oppliger, G., Perkins, M., Moeck, I., and Drakos, P., 2010, Structural controls of geothermal activity in the northern Hot Springs Mountains, western Nevada: The tale of three geothermal systems (Brady's, Desert Perk, and Desert Queen): Geothermal Resources Council Transactions, v. 34, p. 675-683.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Cashman, P.H., Kratt, C., Dering, G., Edwards, J.,Mayhew, B., McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin, Western USA: Geothermal Resources Council Transactions, v. 35., p. 777-783.

Faulds, J.E., and Hinz, N.H., 2015, Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA: Proxies for discovering blind geothermal systems: Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April 2015, 6 p.

Forson, C., Faulds, J., Wannamaker, P,. 2014 Prospecting for a blind geothermal system utilizing geologic and geophysical data, Seven Troughs Range, northwestern Nevada: Geothermal Resources Council Transactions, v. 38, p. 369-376

Henry, C.D., and Perkins, M.E., 2001, Sierra Nevada–Basin and Range transition near Reno, Nevada: Two-stage development at 12 and 3 Ma: Geology, v. 29, p. 719–722.

Henry, C.D., and Faulds, J.E. 2010. Ash-flow tuffs in the Nine Hill, Nevada, paleovalley and implications for tectonism and volcanism of the western Great Basin, USA: Geosphere, v. 6, no. 4 p. 339-369.

Stager, H. K, and Tingley, J.V., 1988, Tungsten deposits in Nevada: Nevada Bureau of Mines and Geology Bulletin 105, 256 p.

Trexler, J.H., Cashman, P.H., Henry, C.D., Muntean, T., Schwartz, K., TenBrink, A., Faulds, J.E., Perkins, M., and Kelly, T., 2000, Neogene basins in western Nevada document the tectonic history of the Sierra Nevada–Basin and Range transition zone for the last 12 Ma, in Lageson, D.R., et al., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 97–116.

Van Buer, N.J., Miller, E.L., and Dumitru, T.A., 2009, Early Tertiary paleogeologic map of the northern Sierra Nevada batholith and the northwestern Basin and Range: Geology, v. 37, no. 4, p. 371-374.

Van Buer, N.J. and Miller, E. L., 2010, Sahwave batholith, NW Nevada: Cretaceous arc flare-up in a basinal terrane. Lithosphere, v. 2, no. 6, p. 423-446.

Van Buer, N., 2012, Preliminary geologic map of the Sahwave and Nightingale Ranges, Churchill, Pershing, and Washoe Counties, Nevada: Nevada Bureau of Mines and Geology Open-File Report 12-2, scale 1:62,500, 12 p.

Whitehill, C., 2009, Cenozoic evolution of the Shawave-Nightingale horst block, northwestern Basin and Range, Nevada, USA [Ph. D. thesis]: Stanford University, 179 p.

Willden, R. 1964, Geology and mineral deposits of Humboldt County Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 59, 154 p.

Willden, R. and Speed, R., 1974, Geology and mineral deposits of Churchill County Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 83, 95 p.

Zoback, M. L., Anderson, R. E., & Thompson, G. A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences, v. 300, p. 407-434.