Text and references accompanying Nevada Bureau of Mines and Geology Open-File Report 16-7

Preliminary Geologic Map of the Truckee Range, Black Warrior Geothermal Area, Washoe and Churchill Counties, Nevada

by

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INTRODUCTION

The Black Warrior geothermal system lies 20 km east of the southern end of Pyramid Lake in the Truckee Range of northwestern Nevada (figure 1). It is an amagmatic blind geothermal system, lacking hydrothermal surface manifestations (no fumaroles, hot springs, sinter deposits, or high temperature alteration) and also lacks recent (<5 Ma) volcanism. The system was discovered through temperature gradient drilling (100–600 m depth) by Phillips Petroleum Company in the 1980s (Sass et al., 1999). The Black Warrior area, synonymous with the North Valley prospect, exhibits a maximum observed temperature of ~128°C at 552 m surrounded by elevated temperature gradients (figure 2). Also, a weak shallow anomaly was observed with a 2-m temperature survey circa 2009 (Kratt, personal communication).

The 1:24,000-scale geologic map of the Black Warrior geothermal area showcases the results of detailed stratigraphic and structural analyses. The map focuses on the Truckee Range in northwestern Nevada and covers portions of four adjoining 7.5' quadrangles: Black Warrior Peak, Russell Peak, Nixon, and Juniper Peak (figure 1). The detailed map was produced to evaluate the structural controls of the Black Warrior geothermal system and overall geothermal potential of the area (Sadowski and Faulds, 2015; Sadowski, 2016).

Geologic mapping of surficial and bedrock lithologies identified faults and stratigraphic relationships between successive and interfingering Tertiary volcanic sequences that nonconformably overlie Mesozoic plutonic and metamorphic basement (figure 3). Middle Miocene basaltic andesites, dacites, tuffs, sandstones and conglomerates are widespread throughout the study area, whereas outcrops of Mesozoic basement rocks are limited. Mesozoic basement rocks include Cretaceous granodiorite, hornfels, and skarn, as well as Late Triassic to Middle Jurassic meta-siltstone, quartzite, carbonate (dolomite and marble), phyllite, and schist. Quaternary alluvial fans reside in low-lying areas adjacent to and within the Truckee Range.

The structural framework is dominated by gently to moderately east-tilted fault blocks bound by moderately to steeply west-dipping, north-northeast-striking normal faults (figure 4). The fault blocks consist of highly deformed and metamorphosed Mesozoic rocks and faulted and tilted Oligocene-Miocene volcanic rocks. Inversion of fault kinematic data and regional relations indicate a NW-trending extension direction (300–310°). Major extension began ~12 Ma and has continued into the present, as evidenced by Quaternary fault scarps.

Major strands of the west-dipping normal fault system terminate and step in the vicinity of the thermal anomaly. The fault pattern suggests two possible structural settings for the Black Warrior geothermal system: (1) a fault termination of the southeastern range-front fault (Little Valley fault) with accompanying ~2 km wide horse-tailing producing an area with abundant closely spaced faults and high fracture permeability; and/or (2) a ~3–5 km wide fault step-over between two major west-dipping normal faults (Little Valley and Black Warrior faults), whereby many closely spaced minor faults produce a zone of high fracture permeability. Thus, the Black Warrior thermal anomaly appears to reside in a hybrid structural setting in which the faults are favorably oriented for dilation in the local stress field. These structurally complex characteristics are advantageous for geothermal activity (e.g., Faulds et al., 2013) and suggest that Black Warrior may host a viable geothermal system with suitable permeability at depth. However, additional exploration is recommended to better define the system and select drilling sites. Ultimately, the structural relationships at Black Warrior may help to guide exploration efforts for other blind geothermal systems in the Great Basin region and other extensional settings.

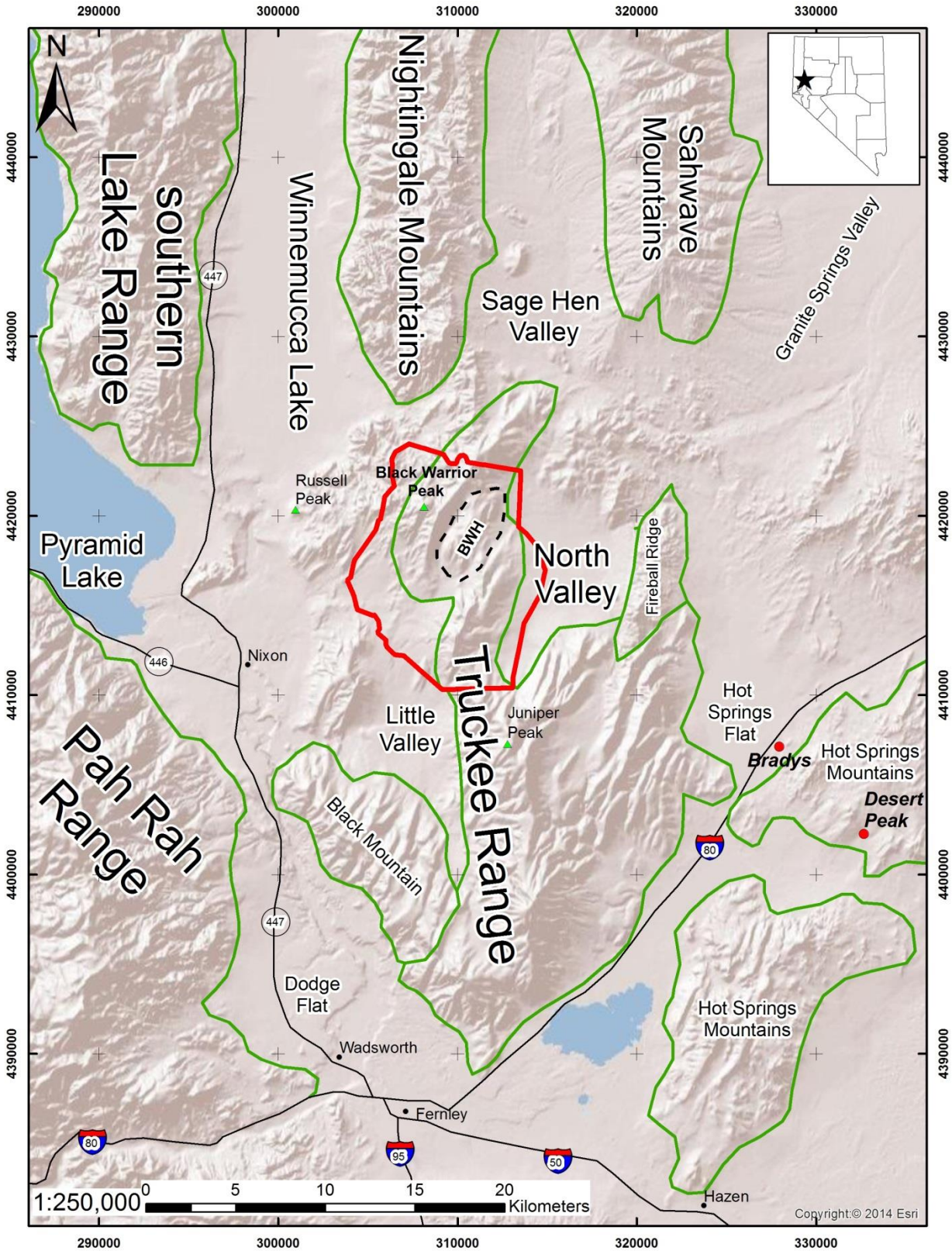

Figure 1. Location map for Black Warrior study area. Geographic features (towns and roads) and physiographic features (ranges, peaks, and valleys) are labeled and outlined in green on a digital elevation model (DEM) hillshade. Red outline marks the boundary of the Black Warrior study area. The thermal anomaly area is centered on the "Black Warrior Hills" (BWH, black dashed outline) approximately 20 km northwest of the power-producing geothermal systems in the northern Hot Springs Mountains (red dots).

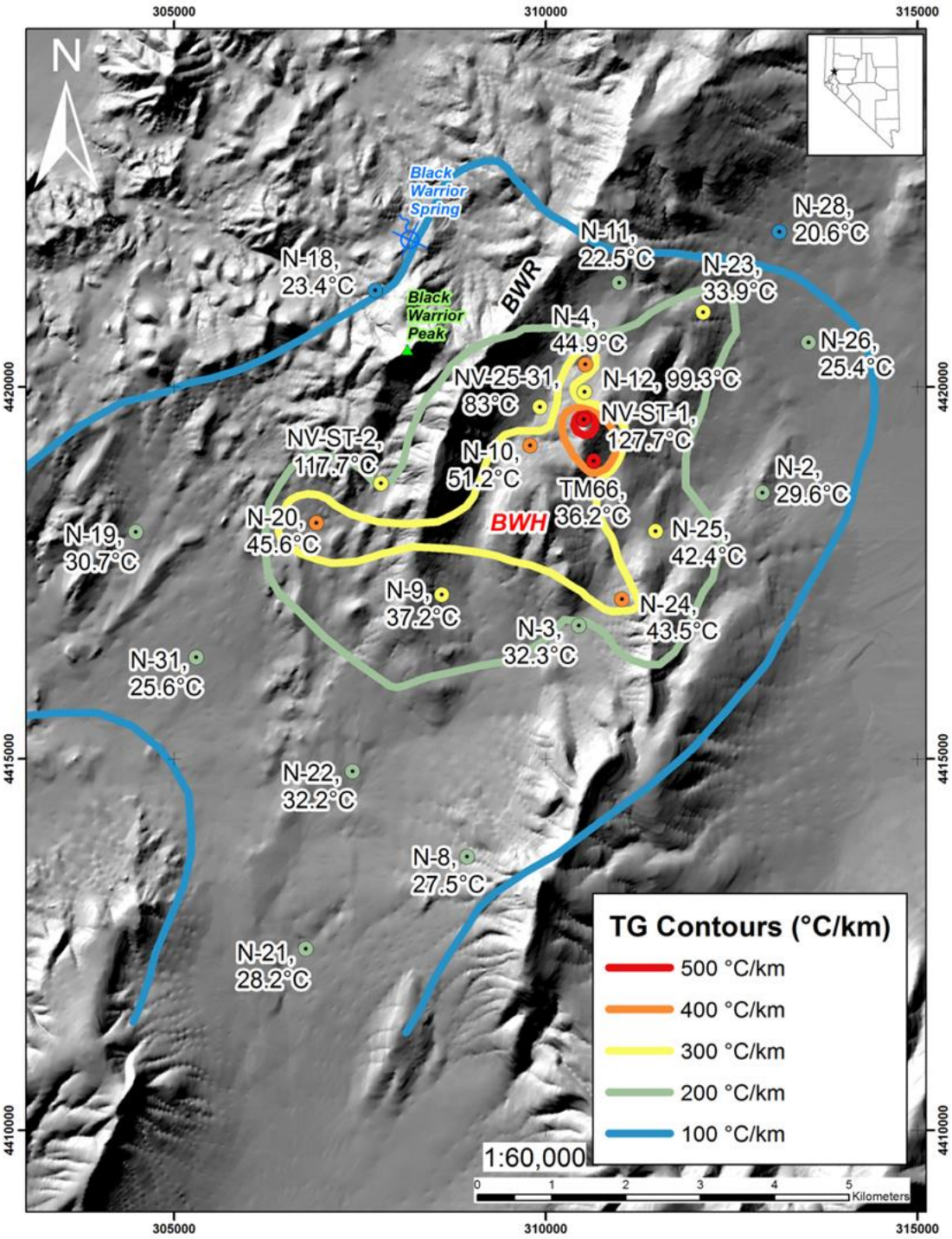

Figure 2. Thermal anomaly map of the "Black Warrior Hills" (BWH) according to temperature gradient holes. Temperature gradients (TG) contoured by hand at 100°C/km interval. TG holes and NV-25-31 well (circles) are colored coded by temperature gradient but labeled with maximum temperature (°C). Approximate center of the thermal anomaly is located at NV-ST-1, where maximum temperature and temperature gradient were recorded at ~550 m depth. Black Warrior Spring is dry and located north and northwest of Black Warrior Peak and "Black Warrior Ridge" (BWR), respectively.

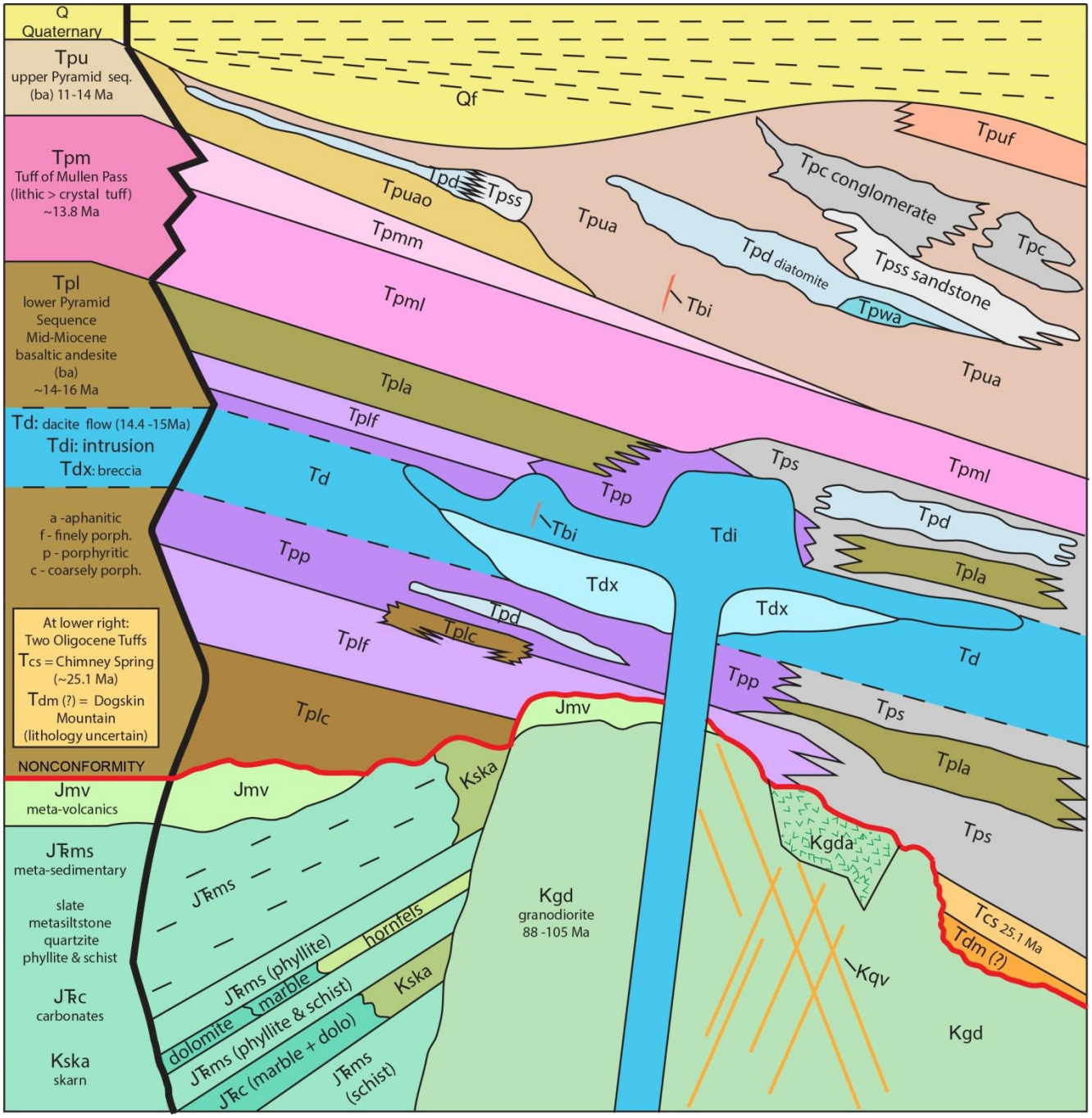

Figure 3. Stratigraphy of the Black Warrior study area from west to east (left to right). Lithologies grouped into stratigraphic units of Black Warrior are shown along sidebar (left of thick black line). The Oligocene-Miocene nonconformity (thick red line) and interfingering relationships of the Pyramid sequence are shown to the right of the sidebar.

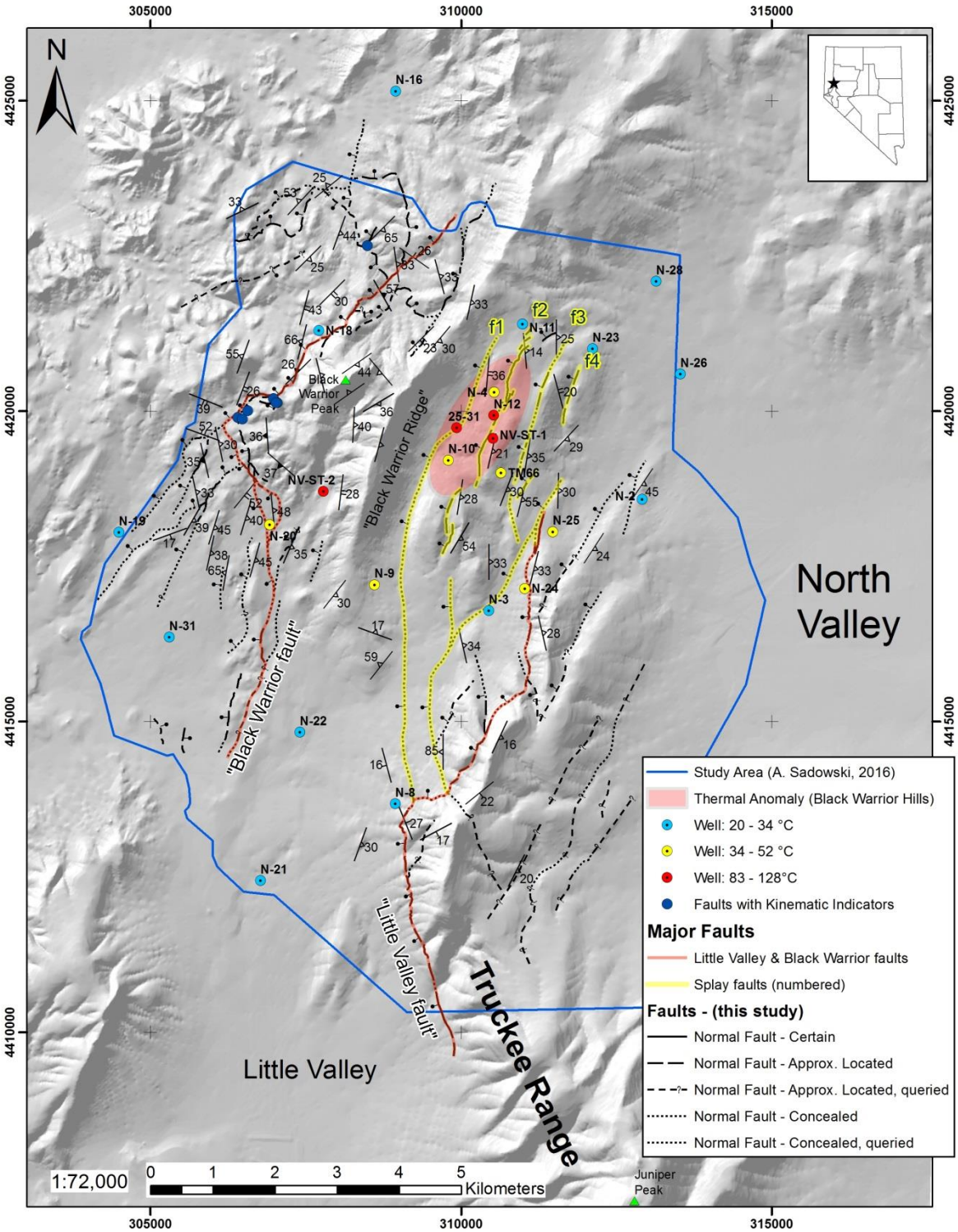

Figure 4. Structural map with major faults (red) and localities of fault kinematic data (solid blue circles) of Black Warrior study area. Map shows a broad left-step between two major fault zones (Little Valley and Black Warrior faults). Within the step-over, several splay faults (yellow) are linked to the northern termination of "Little Valley fault" and encompass the approximate center of the thermal anomaly (red oval).

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DESCRIPTION OF MAP UNITS

Quaternary Deposits

Qfa Active channels and minor terraces (latest Holocene) Recently to annually active alluvium restricted to valley bottoms and tributaries. Unconsolidated subangular, arkosic > lithic (?) sand and gravels in channels. 1 to 3 m thick.

Qfe Eolian deposits and sand sheets of North Valley (Pleistocene to Holocene) White to light tan, medium- to fine-grained sand in low basins of North Valley in easternmost study area. Thickness is less than a few meters.

Qfy Youngest alluvial-fan deposits (Holocene) Well-developed alluvial fan morphology incised by most active alluvial channels (Qfa), with poorly developed bar-and-swale morphology. Less than 5 m thick.

Qslm Lacustrine deposits of the upper Sehoo Alloformation (late Pleistocene) Moderately sorted, fine- to medium-grained, light-colored sands and gravels from Lake Lahontan below the Upper Sehoo highstand (1332 m elevation) (Bell et al., 2005a, b). Shorelines are preserved adjacent to intermediate alluvial-fan surfaces (Qfi) but are broken by young (Qfy) and active (Qfa) alluvium. The unit is <10 m thick.

Qfi Intermediate alluvial-fan deposits (late Pleistocene to early Holocene) Moderately incised surfaces with well-developed bar-and-swale morphology. 5 to 10 m thick.

Qls Landslides (Pleistocene to Holocene) Slope-failure derived unconsolidated debris, consisting of poorly sorted, matrix-supported cobble- to boulder-size clasts of Pyramid sequence volcanic rocks in pebble and sand matrix. Common on the west sides of high slopes on Black Warrior Ridge and Truckee Range with unrecognizable headwall escarpments.

Qc Colluvium and talus (Pleistocene to Holocene) Poorly sorted, matrix- to clast-supported, angular to subangular cobbles. Commonly subangular cobbles and boulders of basaltic andesite along steep slopes and ridges of the Truckee Range and near the Black Warrior Hills thermal anomaly area. Moderately vegetated with sage and grasses. The unit thickness is up to 15 m based on drilling logs from temperature gradient holes.

QTfo Oldest alluvial-fan deposits (Pliocene to Pleistocene) Highly incised, smooth surfaces with well-developed soils. Less than 20 m thick.

Cenozoic Volcanic and Sedimentary Rocks of the Pyramid Sequence

Tv Volcanic rocks (Miocene) Undivided Tertiary volcanic rocks, including but not limited to the middle Miocene Pyramid sequence rocks as described below.

Upper Pyramid Sequence (middle Miocene, 11–14 Ma)

Tbi Aphanitic basaltic dikes (middle Miocene) Medium to dark gray, weathering light to medium brown, basaltic dikes forming highly resistant outcrops that exhibit subvertical flow foliation. 1–5 m wide dikes intrude dacite and upper Pyramid sequence units in only two locations in the study area. Exposed dike lengths are <300 m. The unit is aphanitic with very sparse phenocrysts (total phenocrysts 2–3%), including plagioclase (1–2%, <1 mm long), lesser olivine (1%, <2 mm, equant), and clinopyroxene (<1%, 0.5 mm, equant, subhedral), with interstitial pine green chlorite (<0.1 mm, blebby, globular) in a maroon-gray groundmass with a felty to trachytic texture. Glomerocrysts are rare.

Tpu Volcanic rocks of the upper Pyramid sequence (middle Miocene) Undivided basaltic andesite as described below.

> **Tpuf Finely porphyritic basaltic andesite (middle Miocene)** Medium to dark gray, weathering light to medium brown, highly resistant basaltic andesite lava flows forming cliffs in the eastern part of the map area in the Truckee Range. The unit is finely porphyritic with distinct, 2–4 mm glomerocrysts in a felty groundmass of 0.05–0.5 mm long tabular plagioclase microlites. Total phenocrysts (5–18%) include plagioclase (andesine-labradorite; ~3–12%, 1–2 mm long) and mafic minerals (total: 2–6%), including olivine (<4%, <1 mm, equant) that is moderately to strongly altered to iddingsite, and minor-trace, forest-green clinopyroxene (augite; <1–2%, <1–2 mm, equant). Clinopyroxene can be as large as 4.5 mm long and is more common where total phenocryst percentages are lower and glomerocrysts are sparse to absent. The unit is approximately 65 m thick.
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> **Tpua Aphanitic basaltic andesite (middle Miocene)** Medium to dark purplish gray, weathering very dark brown, variably vesiculated, and locally columnar jointed basaltic andesite flows. An amorphous silica coating on weathered surfaces is common and abundant locally on highly elevated outcrops. The unit is aphanitic with very sparse phenocrysts of plagioclase (oligoclase-andesine?; 1%, <1–2 mm long), pyroxene (<0.1 mm, equant), and lesser olivine (0.2–0.8 mm), which is weakly to strongly altered to iddingsite. The groundmass is felty

to trachytic and largely consists of 0.1–0.5 mm long plagioclase microlites. Size of vesicles ranges from <5 mm to <5 cm. The unit thickness is constrained between >> 100 m to 500+ m.

Alteration/weathering note for Tpua: Groundmass is also commonly lighter gray, where fine, "yellow flecks," "yellow streaks," and "yellow dots" likely composed of clays give the groundmass a variably lighter color. This lightens the macroscopic rock subtly from un-"altered" purplish medium-dark gray groundmass to progressively more "altered" light gray to yellowish gray and pale greenish-yellowish gray (weak to strong "alteration"). These "altered" flows have well-developed flow foliation and 2 to 6 cm partings. These outcrops commonly underlie and interfinger with unaltered aphanitic basaltic andesites (Tpua), especially in the Black Warrior Hills thermal anomaly area and are proximal to faults. It is not clear if hydrothermal alteration or weathering is responsible for modifying the plagioclase groundmass. ^{40}Ar-^{39}Ar radiometric dating of a groundmass concentrate yielded an age of 11.12±.21 Ma for this unit.

Tpuao Olivine-rich aphanitic basaltic andesite (middle Miocene) Gray, weathering reddish-brown, basaltic andesite flows exhibiting well-developed flow foliation with common platy entablature or columnar colonnade. The unit is aphanitic with sparse phenocrysts (total phenocrysts: <5%) of olivine (2–3%, 0.2–1.0 mm, equant, anhedral) and lesser plagioclase (1–2%, 0.5–1 mm long laths) in a very dark greenish-gray to medium-brown groundmass. Matrix consists of finer moderately oriented plagioclase microlites (0.05–0.5 mm long), pyroxene, and opaque minerals. Olivine is strongly altered to iddingsite giving the weathered surface a distinctive, reddish-brown color with <1 mm, black and red dots that contrast with its dark-greenish-gray fresh surface. The unit is approximately 65 m thick.

Sedimentary Rocks

Tps Sedimentary rocks of the upper Pyramid Sequence (middle Miocene) Undivided conglomerate, sandstone, diatomite, and water-lain ash as described below (cross section only).

Tpc Volcaniclastic conglomerate (middle Miocene) Moderately indurated, massive, light-gray to tan, poorly sorted, matrix-supported conglomerate, with 5- to 20-cm long clasts of subrounded to subangular aphanitic volcanic rock in a fine- to medium-grained matrix. The unit interfingers with volcaniclastic sandstone (Tpss), aphanitic basaltic andesite (Tpua), and olivine-rich basaltic andesite (Tpuao). May have originated as debris flows on subaerial or sublacustrine alluvial fans. The unit is 80–140 m thick.

Tpss Volcaniclastic sandstone (middle Miocene) Light-gray to yellowish-light-brown sandstone forming cliffs in the southern part of the map area on the western flanks of the Truckee Range, but also forming slopes near faults in central and northern parts of the study area. The unit is generally laminated (< 1 cm) to thinly bedded (<10 cm) with subrounded, medium- to very coarse-grained sands (0.25 to 2.0 mm) and gravels (2 to 10 mm) of dark- to medium-brown aphanitic volcanic rocks. The unit also exhibits normal grading (fining upward) with uncommon cross-bedding. This unit may have originated as either fluvial or alluvial-fan deposits. The unit is 30–110 m thick.

Tpd Diatomite (middle Miocene) White, thinly laminated (<3 mm), fissile, nonresistant diatomite forming chalky slopes with discontinuous lenses of pebbly sandstone and water-lain ash. The unit is soft and rarely crops out but is marked by a colluvial veneer of white chips. Diatomaceous sediments were likely deposited in small, shallow lakes. The diatomite unit is 20–50 m thick.

Tpwa Water-lain ash (middle Miocene) Light-gray to light-tan, thinly bedded (1–10 cm) water-lain ash is interbedded with the diatomite. The unit crops out less commonly than the diatomite and was only observed at two locations in the study area, where both locations were in contact with diatomite. Compared to the diatomite, the water-lain ash is more resistant and forms subtle low outcrops (<0.5 m high). The unit has abundant glass shards. The water-lain ash unit is less than 2 m thick.

Tuff of Mullen Pass (middle Miocene, ~13.8 Ma)

Tpm Tuff of Mullen Pass (middle Miocene) Undivided lower and middle cooling units of the tuff of Mullen Pass as described below (cross section only).

Tpmm Middle cooling unit of Tuff of Mullen Pass (middle Miocene) White-light gray to light-tan, poorly welded vitric ash-flow tuff generally forming slopes with less common ledges (1–5 m high); lower portions are massive and lack layering, whereas upper portion is weakly layered. The unit is distinctly pumice-rich (10–20% of total rock) with lesser lithic fragments and phenocrysts. Poorly sorted clasts of pumice commonly fine-upward (from 3.5 cm upward to 5.0 mm). Medium-gray to reddish-brown subrounded to subangular lithic fragments (< 1.0 mm to 4.5 cm long) include porphyritic dacite (Td) and aphanitic basaltic andesite of the lower Pyramid sequence (Tpla). The

dacitic lithic fragments are porphyritic (total phenocrysts: ~10–15%) containing hornblende (6–9%, 1–2 mm) and plagioclase (4–6%, <1 mm) phenocrysts. Phenocrysts in the tuff (total: 8–15%) are anhedral to subhedral and consist of plagioclase (5–8%, <1 mm), hornblende (2–6%, <1 mm long), and clinopyroxene (<1%, <0.5 mm). The unit ranges from approximately 80 to 120 m thick, and is approximately 98 m thick in cross section. Plagioclase yielded an ^{40}Ar-^{39}Ar radiometric date of 13.98±0.03 Ma for this unit.

Tpml Lower cooling unit of Tuff of Mullen Pass (middle Miocene) Tan to medium-light brown, densely welded, vitric ash-flow tuff forming weakly developed columnar-jointed cliffs with an orangish-brown to medium-gray basal vitrophyre with black, variably porphyritic fiamme that fine-upward (from round, 10 cm long obsidian fragments upward to <3 cm long fiamme). Phenocrysts in fiamme consist of white to cloudy 0.5-to 2-mm-long plagioclase. Above the basal vitrophyre, where black fiamme are absent, the unit exhibits a distinct and well-developed texture of light-gray to dark-brown, compaction foliation with partings spaced from <1 mm to <10 cm ("wispy" to "blebby"). Other foliation features include compressed vesicles that exhibit minor vapor-phase alteration. The lower member contains <10% pumice with lesser lithic fragments and phenocrysts. Medium-gray lithic fragments of volcanic rock (Tpl) are angular to subangular, rarely subrounded, and contain sparse phenocrysts (<3%, mostly ~1 mm plagioclase with trace hornblende). Phenocrysts in the tuff (total: <4%) mostly consist of plagioclase (<2 mm, euhedral to anhedral laths) and hornblende (<<1%, <0.5 mm, euhedral) in a very fine (<10 μm) glassy groundmass with a felty to trachytic texture. The unit ranges from approximately 60 to 115 m thick, and is approximately 73 m thick in cross section.

Dacite (middle Miocene, ~14–15 Ma?)

Td and Tdi Porphyritic dacite flow and intrusion (middle Miocene) Purplish-gray weathering dark-reddish brown to medium-brown, craggy dacite flow and intrusive units, both commonly exhibiting platy, well-developed flow foliation (1–10 cm thick partings). Flow (Td) and intrusion (Tdi) subunits are compositionally identical but geometrically distinct in outcrop pattern, and both weather to a "nubbly" character. Fresh surfaces exhibit groundmass colors that vary widely from light-bluish gray to purplish-gray to purplish-pink. Phenocrysts (total: 15–25%) include plagioclase (oligoclase-andesine?; 8–18%, 2–6 mm long laths), biotite (1–4%, <1 mm), and sparse hornblende (<2%, 1–3 mm) in a groundmass of plagioclase microlites exhibiting a trachytic texture. Pumice and quartz are absent. Altered rims are present along mafic grain boundaries (from vapor-phase crystallization, mild hydrothermal alteration, or possibly deuteric alteration). Dacites form a flow-dome complex with thicknesses <200 m, including underlying vapor-phased altered, block-and-ash flow (Tdx). Plagioclase yielded an ^{40}Ar-^{39}Ar date of 15.29±0.06 Ma for unit Td.

Tdx Dacite block-and-ash flow (middle Miocene) Light-purplish-gray to purplish-white, friable dacitic outcrops are less resistant than closely associated, consistently overlying porphyritic dacite (Td and Tdi). The unit has a tuffaceous matrix, contains matrix-supported, flow-banded boulders (<1 m diameter) of porphyritic dacite, and is common beneath ledges of dacite (Td). Phenocrysts of the boulders and matrix (Total phenocrysts: ~10%) include plagioclase (1–2%, ~1 mm), hornblende (1–2%, 3–10 mm long), and black to coppery biotite (<1%, ~1 mm). ~5% of the phenocrysts are highly weathered, leaving a pock-marked appearance on weathered surfaces.

Lower Pyramid Sequence (middle Miocene, 14–16 Ma)

Tpl Volcanic rocks of the lower Pyramid sequence (middle Miocene) Undivided basaltic andesite as described below.

Tpp Porphyritic basaltic andesite (middle Miocene) Dark-gray, greenish-brown, light to medium greenish-gray, and light-reddish to purplish-gray, weathering medium-brown to medium-gray, rubbly basaltic andesite lava flows, commonly exhibiting extensive oxidation. The unit also contains rare, 1–3 cm wide rosettes of secondary, white quartz south of Black Warrior Peak in the central map area. Plagioclase phenocryst size, shape, and grouping density produce a distinct texture akin to dry instant oatmeal flakes ("oats texture"). Phenocrysts (total: 20–30%) include cloudy to clear plagioclase (oligoclase-andesine?, ~25%, 1–5 mm long, euhedral laths), olivine (1–2%, <0.5 mm), which is pervasively altered to iddingsite, and very sparse black biotite (<1%, <1 mm) in felty groundmass of plagioclase microlites (<50 μm to 0.1 mm) with abundant globular opaques (<0.1 mm). Plagioclase is commonly replaced by clays (moderately to strong alteration of plagioclase feldspars). Zeolites (thomsonite, heulandite?) are very common and partially to completely fill small vugs (<1 mm). The unit is <65 m thick.

Tpla Aphanitic to finely porphyritic basaltic andesite (middle Miocene) Medium gray to dark greenish gray, weathering medium to dark brown, basaltic andesite lavas forming low outcrops and cliffs with uncommon columnar joints. The unit is aphanitic to finely porphyritic (total phenocrysts: 5–15%), consisting dominantly of plagioclase (<1 mm long laths, rarely as long as 3 mm) with minor to trace

olivine (<<1%, 0.4–1.0 mm, equant, moderately altered to iddingsite) and trace clinopyroxene (<<1%, <1 mm) in a felty to sub-trachytic groundmass of plagioclase microlites (<<0.1 mm). This unit is less porphyritic than Tplf. The unit is approximately 100 m thick.

Tplf Finely porphyritic to aphanitic basaltic andesite (middle Miocene) Light-pinkish-purple to light-greenish-gray to medium to dark gray, weathering to maroon and brown, basaltic andesite lavas generally forming low outcrops, with less common cliffs (1–4 m tall) that lack columnar joints. The unit commonly has platy flow foliation, lacks abundant vesicles, and contains associated autobreccias. The unit is sparsely to finely porphyritic (total phenocrysts: 10–27%) containing clear plagioclase (oligoclase-andesine?; ~5–25%, 1–3 mm, laths) with fewer dark-green clinopyroxene (augite; 1–3%, <0.4 mm, trace as large as 2 mm, equant, subhedral), orthopyroxene (2–4%, <0.2 mm, equant, subhedral), and olivine (~5-10%, <0.4 mm equant) in a felty to sub-trachytic groundmass of plagioclase microlites (<0.1 mm). The unit is more porphyritic than Tpla. The unit is extensive and approximately 100–200 m thick.

Tplc Coarsely porphyritic basaltic andesite (middle Miocene) Very dark-gray to dark-greenish-brown, basaltic andesite lavas that form resistant outcrops and cliffs (0.5–5 m tall) exhibiting well-developed flow foliation. The unit is not extensive and only crops out in the northwestern part of the study area. Distinctive, translucent, dime-size plagioclase (<1.5 cm diameter, hexagonal-like) oriented in a trachytic texture characterize the unit. The unit is coarsely porphyritic, and phenocrysts (total: 30–40%) include plagioclase (20–25%, 3–15 mm long, euhedral laths), clinopyroxene (augite to aegirine-augite; <6%, <1 mm long), olivine (5–10%, 0.5 to 1 mm subhedral equant granular), which is moderately altered to iddingsite (<0.2 mm anhedral, honey brown, micro-globs), opaques (<5%, <0.4 mm euhedral equant cubes to subhedral granular crystals), and rare, zeolite (thomsonite or natrolite?) or secondary chalcedony (<<1%, <1 mm) in a felty to sub-trachytic groundmass of plagioclase microlites (<0.5 mm long). The unit is <20 m thick. ^{40}Ar-^{39}Ar dating of ground mass concentrate yielded a date of 15.54±0.03 Ma for this unit.

Oligocene Ash-Flow Tuffs

Ttu Ash-flow tuff (Oligocene) Undivided ash-flow tuffs, including but not limited to the tuffs of Chimney Spring and Dogskin Mountain as described below.

Tcs Tuff of Chimney Spring (late Oligocene) Pink to light-reddish gray, moderately to poorly welded, ash-flow tuff forming low-lying outcrops with poorly developed and rare compaction foliation. The unit crops out with the underlying tuff of Dogskin Mountain in a single drainage on the western flank of the Truckee Range near the Little Valley fault. Phenocrysts (Total: 20–35%) include clear and adularescent sanidine (10–20%, 1–2 mm long, subhedral, equant), distinctive smoky quartz (10–20%, 1–2 mm, anhedral), biotite (<1%, 1–2 mm, subhedral), clear plagioclase (<0.5%, 1 mm, equant), and clinopyroxene (augite?; <<0.5%, <0.3 mm, euhedral). The groundmass exhibits a glassy, fan- to sheaf-like volcanic glass texture (microspherulites?) with axialitic devitrification on edges and spherulitic growth around phenocrysts. The unit is 25.11±0.07 Ma (Faulds et al., 2003; Henry et al., 2004; Henry and Faulds, 2010). The unit is 40–50 m thick.

Tdm (?) Tuff of Dogskin Mountain (?) (late Oligocene) Light-yellowish to pinkish-gray, poorly welded, ash-flow tuff with weak compaction foliation (1–4 mm long pumice) and trace lithic fragments (<1% of total rock, <4 mm). The unit crops out with the overlying tuff of Chimney Spring in a single drainage on the western flank of the Truckee Range abutting the Little Valley fault. The unit is pumice-, plagioclase-, and biotite-rich compared to the tuff of Chimney Spring. Phenocrysts (total: 20–30%) include plagioclase (10–18%, <2 mm, equant, angular to subangular, anhedral), biotite (<2–6%, 1–4 mm, subhedral, black >> coppery), sanidine (<3%, 0.5–1.0 mm, equant, non-adularescent), and hornblende (<2%, <2 mm, bladed). Phenocrysts are fractured and weakly altered to clays in a glassy groundmass exhibiting felty and eutaxitic textures. This tuff is possibly silicified near Little Valley fault. Identity of the tuff is uncertain, but if it is the tuff of Dogskin Mountain, the unit is 29.21±0.10 Ma (Henry et al., 2004). The unit is <60 m thick.

Mesozoic Basement Rocks

Mzu Mesozoic basement rocks (Triassic to Cretaceous) Undivided intrusions, metavolcanic, and metasedimentary rocks, including but not limited to granodiorite, meta-basalt to meta-andesite, carbonate, slate, meta-siltstone, quartzite, and phyllite-schist as described below (cross section only).

Contact Metamorphic Rocks Related to Intrusion

Kska and Khf Skarn and hornfels (Cretaceous) Resistant metamorphic rocks forming waist-high outcrops that weather to brownish red gravels. These units are

hosted within the carbonate unit (JŦc) and reside proximal to intrusive contacts with granodiorite (Kgd). Relict foliation is subtle. Grain size and color distinguish skarn from hornfels lithologies. Skarn (Kska) is coarse grained (<1.5 mm) and dark brown to deep reddish brown, whereas hornfels (Khf) is fine grained (<0.5 mm) and yellowish-greenish brown. Deep brown to brownish red garnet (andradite-grossularite?) decreases in size toward the hornfels. Other minerals include dark green to light greenish yellow clinopyroxene (likely Fe-rich salite/hedenbergite in skarns, and Fe-poor varieties in hornfels), apple-green vesuvianite (i.e. idocrase), and white rhombohedral-euhedral calcite. Scheelite, a tungsten-bearing mineral, was not confirmed. The unit thickness is irregular and dependent on the thickness of the carbonate host rock.

Mesozoic Intrusive Rocks

Kgd Granodiorite (and/or quartz monzodiorite?) (Cretaceous) Light to medium gray (mesocratic), coarse-grained (1–3 mm) intrusions, including granodiorite (and/or quartz monzodiorite) that forms large, rounded outcrops with high relief (<10 m). The unit contains multiple joint sets, but primary magmatic foliation was not observed. The unit weathers to tan, fine- to medium-grained sand (0.125–0.5 mm), grusy medium brown to tan gravels (<1.5 cm), and large, rounded boulders (<5 m) on hilltops and ridge flanks. The unit is extensive in the central-northwestern part of the study area and has dimensions 4 km long (north-northeast to south-southwest) by 1 km wide (east to west), with smaller satellite intrusions through older Mesozoic lithologies. The granodiorite (and/or quartz monzodiorite) is phaneritic and equigranular consisting of, in decreasing order of abundance, plagioclase (oligoclase-andesine?; 60–80%, <3 mm, subhedral > euhedral), potassium feldspar (microcline + orthoclase ± anorthoclase?; 20–40%, <1.5 mm, anhedral), quartz (10–30%, ~1 mm, anhedral to subhedral, subequant), biotite (~50–75% of mafic minerals, <2 mm, tabular, weakly to moderately chloritized), hornblende (~25–50% of mafic minerals, <1.5 mm, subhedral, weakly chloritized), and accessory minerals, including (<1 mm) clinopyroxene (augite ± aegirine?), orthopyroxene (hypersthene), titanite, and opaque minerals (pyrite and sulfides?). Minor replacement of feldspars by clays (kaolinite ± smectite (montmorillonite?)) is common. The unit thickness is poorly constrained but exceeds 1000 m.

Kgda Altered (?) granodiorite or leucocratic Enclaves (Cretaceous?) Light to medium gray, massive, resistant outcrops that are irregularly distributed within Mesozoic lithologies, particularly the granodiorite, and are proximal to faults. The unit is equigranular with abundant, coarse-grained (1–5 mm) quartz and feldspars, as well as sparse "pin-head" pyrite (<1.5%, <1 mm), which is commonly weathered to goethite. The unit has distinct empty phenocryst sites (1–4 mm). The unit locally displays texturally destructive phyllic alteration (quartz-sericite-pyrite). The unit may represent leucocratic enclaves or pegmatite related to the pluton. Age and cause of alteration are unknown and possibly related to emplacement of the intrusion or recent epithermal activity.

Veining in pluton

Kqv Quartz veins in granodiorite (Cretaceous?) Large (20 cm to 100 cm wide), steeply dipping, white quartz veins with alteration envelopes containing abundant clays, common iron oxide (goethite, hematite, and jarosite), trace pyrite (<0.5 mm), and rare copper oxide (chrysocolla?). Mine shafts, adits, and workings are present near these veins. Age of these veins is unknown and may be related to emplacement of Kgd.

Metamorphic Rocks: Metavolcanic and Metasedimentary Rocks

Jmv Metavolcanic rocks (Jurassic?) Dark greenish gray, rocks weathering to clusters of rounded boulders (<0.5 m) on greenish hilltops of moderate topography. The unit only crops out in the northwestern part of the study area, but outcrops are rare, so float was mapped where observed. The unit is aphanitic to porphyritic. Where porphyritic (total phenocrysts: ~10–30%), phenocrysts, in order of decreasing abundance, include milky white plagioclase (35% of phenocrysts, 0.3–2.0 mm), clinopyroxene (augite?) (25% of phenocrysts, <4 mm, equant), and blebby opaque minerals (<0.15 mm) in a strongly altered groundmass of clays (<0.25 μm) exhibiting a felty texture. Abundant chlorite and clays comprise the remaining phenocryst percentage (~40%). Pervasive chlorite possibly derives from low grade metamorphism (possibly sub-greenstone). Presence of large pyroxene crystals and argillically altered groundmass distinguishes this unit from metasedimentary rocks (JŦms). Parent lithology could be aphanitic andesite to diorite and/or coarsely porphyritic, pyroxene-plagioclase basalt to andesite. The unit thickness is unconstrained (>50 m), because the base of the section is not exposed in the study area and flow foliations were not observed.

JŦms Metasedimentary rocks of the Nightingale sequence, undivided – slate, meta-siltstone, argillite, quartzite, phyllite, and schist Resistant outcrops of several metamorphic rock types are interbedded among gently sloping, greenish hills of moderate relief. Slates and meta-siltstones are most common followed by cryptocrystalline quartzites, phyllites, and least common schists. All rock types are not fossiliferous and very weakly metamorphosed (very low to low grade metamorphism). Establishing marker horizons for a single rock type is

difficult in the study area, and therefore these units are undivided. Slates and quartzites preserve kinematic indicators on fault surfaces. The Nightingale sequence correlates with the Auld Lang Syne Group of north-central Nevada (Burke and Silberling, 1973). The unit thickness is unconstrained, because the base of the section is not exposed in the study area, but may be upwards of 500 m.

Slate, meta-siltstone to argillite Very dark gray to medium-light gray, metasedimentary outcrops are laminated (1 cm) to thickly bedded (>30 cm), very fine-grained, variably calcareous, and show subtle metamorphic sheen. Darker outcrops commonly weather to 1–3 cm wide, 5–10 cm long talus chips with orange- to dark brown-staining (informally, "tiger-stripe" weathering) due to oxidizing pyrite (<2%, <0.5 mm, metallic yellow). Other outcrops weather to piles of platy stone similar to weathered outcrops of platy volcanic flows. The unit exhibits moderately foliated microstructures with preferred orientation of grains producing crenulation cleavage with poorly developed (faint porphyroblasts), mica-deficient S-C fabrics. The unit contains abundant (~50%) fine-grained (<0.4 mm) opaque minerals (equant, cubic pyrite + unknown equant and blebby opaque mineral(s)). Translucent minerals include extremely fine-grained deformed quartz (~50%, <15 μm), which constitutes the metamorphic texture, sparse to very minor fine-grained mica (<0.1 mm, muscovite?), minor clays (<0.35 μm, talc?), and rare carbonate (<0.3 mm). The protoliths of these rock types were siltstone, shale, or mudstone.

Near faults, the unit is a black to dark gray cataclastite with 1 to 30 mm angular metasedimentary clasts that are clast-supported and carbonate-cemented in a jig-saw breccia, particularly along Black Warrior fault.

Quartzite? White to bluish gray quartzite is cryptocrystalline with no visible grains, and it can be confused with the altered granodiorite unit (Kgda), which is leucocratic but equigranular with conspicuous crystals (especially trace biotite). Microstructure foliations are weak (to absent). The unit dominantly consists of quartz (>95%, <0.1 mm, less commonly 0.2 to 0.4 mm, equant and subhedral). Quartz grain boundaries are irregular and non-distinct (fuzzy, not sharp). Accessory minerals include: minor to trace clusters of muscovite (0.5 mm) and clusters of shreddy biotite (0.1 mm, non-magmatic, possibly hydrothermal or diagenetic), with trace relict plagioclase (<5%, <1.0 mm, anhedral to subhedral, subrounded), which are replaced with clays. Also present are trace subhedral opaque minerals (pyrite?), minor clays, and a yellowish-brown, very fine-grained, shreddy-wispy mineral (very fine biotite, limonite, or hematite (?)). The protolith was probably clastic siltstone to fine-grained sandstone.

Phyllite Light brown to medium-gray phyllite crops out and exhibits good planar metamorphic foliation, but is not highly schistose and lacks porphyroblasts. The unit is intermediate between slate and schist (see schist below).

Schist Greenish gray, brownish gray, to bluish gray sheets exhibit well-developed schistosity.

JTRc Carbonates – dolomite and marble Tan dolomite and medium to dark bluish gray marble (recrystallized limestone) form low outcrops among metasedimentary lithologies of the Nightingale sequence in the western and northern parts of the study area. Resistant, medium-grained (0.25–1.00 mm) dolomite exhibits a sandy weathered appearance and forms massive to bedded outcrops. Coarse-grained (1–2 mm) marble is commonly a foliated, highly friable, granular rock with <20 cm elongate mineralized pods of white <1 cm long rhombohedral calcite. Along the southwestern contact with the granodiorite intrusion, this unit has been metasomatized to skarn or hornfels. The unit is approximately 500 m thick.

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REFERENCES

Bell, J.W., House, P.K., and Briggs, R.W., 2005a, Geologic map of the Nixon area, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 152, scale 1:24,000.

Bell, J.W., Garside, L.J. and House, P.K., 2005b, Geologic map of the Wadsworth quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 153, scale 1:24,000.

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: U.S. Geological Survey Bulletin 1394-E, 14 p.

Faulds, J. E., dePolo, C. M., and Henry, C. D., 2003, Preliminary geologic map of the Sutcliffe quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Open-File Report, 03-17, scale 1:24,000.

Faulds, J.E., Hinz, N.H., Dering, G.M., Drew, D.L., 2013, The hybrid model—the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 37, p. 3–10.

Henry, C. D., Faulds, J. E., dePolo, C. M., and Davis, D. A., 2004, Geologic map of the Dogskin Mountain quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 148, scale 1:24,000, 13p.

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.

Sadowski, A. J., and Faulds, J. E., 2015, Structural controls of the Black Warrior blind geothermal system, Washoe-Churchill counties, Truckee Range, northwestern Nevada, USA: Geothermal Resources Council Transactions, v. 39, 8 p.

Sadowski, A. J., 2016, Structural controls of the Black Warrior blind geothermal system, Washoe-Churchill counties, Truckee Range, northwestern Nevada, USA [M.S. Thesis]: University of Nevada, Reno, scale 1:24,000, 144 p.

Sass, J. H., Priest, S. S., Blanton, A. J., Sackett, P. C., Welch, S. L., and Walters, M. A., 1999, Geothermal industry temperature profiles from the Great Basin: U.S. Geological Survey Open-File Report 99-425, online version 1.0.

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