

Structural Controls of the Tuscarora Geothermal Field Elko County, Nevada

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Keywords

Nevada, Basin and Range, Tuscarora, Elko County, normal faults, accommodation zone, step over, Independence Mountains, Bull Run Mountains

ABSTRACT

Tuscarora is an amagmatic geothermal system located ~90 km northwest of Elko, Nevada, in the northern part of the Basin and Range province ~15 km southeast of the Snake River Plain. Detailed geologic mapping, structural analysis, and well data, have been integrated to identify the structural controls of the Tuscarora geothermal system. The structural framework of the geothermal field is defined by NNW- to NNE-striking normal faults that are approximately orthogonal to the present extension direction. Boiling springs, fumaroles, and siliceous sinter emanate from a single NNE-striking, west-dipping normal fault. Normal faults west of these hydrothermal features mostly dip steeply east, whereas normal faults east of the springs primarily dip west. Thus, the springs, fumaroles, and sinter straddle a zone of interaction between fault sets that dip toward each other, classified as a strike-parallel antithetic accommodation zone. Faults within the study area are mostly discontinuous along strike with offsets of tens to hundreds of meters, whereas the adjacent range-bounding fault systems of the Bull Run and Independence Mountains accommodate several kilometers of displacement. The geothermal field lies within a broad step over between the southward terminating Bull Run fault zone and the northward terminating Independence Mountains fault zone. Neither of these major fault zones is known to host high temperature geothermal systems. The northeastern Basin and Range currently hosts several known high temperature geothermal systems, which cumulatively produce <27 MW of electricity. Characterization of the structural controls at Tuscarora will benefit further development and exploration of geothermal resources in this tectonically distinct subprovince of the Basin and Range.

Introduction

The Tuscarora geothermal field resides in northeast Nevada within the north-central part of the Basin and Range province. There is a dearth of detailed studies characterizing the structural and stratigraphic framework of geothermal systems in north-central Basin and Range. Detailed (1:24,000 scale) structural studies of several high temperature geothermal systems in the northwest Great Basin have been completed in recent years (e.g. Faulds et al., 2006; 2010; Vice et al., 2007; Vice, 2008; Hinz et al., 2010, 2011; Rhodes et al., 2010; Rhodes, 2011), and several more are underway. In contrast, only two high temperature systems in the north-central Great Basin have been mapped in any detail (see Struhsacker, 1980; Sibbett, 1982). Despite four decades of sporadic geothermal exploration, the structural settings of high temperature geothermal systems in the north-central Basin and Range remain poorly understood.

Within normal and oblique-slip fault systems, steeply-dipping, breccia-dominated faults oriented approximately orthogonal to the least principal stress direction have been shown to host most high temperature geothermal systems (Faulds et al., 2004, 2006, 2011). Structural settings that host active geothermal systems in the Basin and Range province described by Faulds et al. (2011) include 1) step-overs and relay ramps linking normal faults, 2) intersections of normal, strike-slip, and/or oblique-slip faults, 3) fault terminations where individual faults break into multiple interacting fault splays, 4) displacement transfer zones between strike-slip faults and normal faults, 5) apices of major normal faults, 6) pull-apart zones within strike-slip fault systems, and 7) accommodation zones where belts of oppositely dipping normal faults intermesh.

Many high temperature geothermal systems in the Great Basin are characterized by more than one favorable structural setting. For example, the 130° C geothermal system at Gerlach in northwestern Nevada lies at the intersection of a major northwest-striking oblique slip fault and a major north-striking normal fault (Faulds et al., 2006). Both of these fault zones terminate southward and break into multiple splays. The complex fault intersection formed

by these two horsetailing fault zones promotes hydrothermal circulation in densely fractured rock. Thus, the structural setting of the Gerlach geothermal system is characterized by two fault terminations which overlap, forming a complex fault intersection. Commonly, geothermal systems characterized by more than one favorable structural setting exhibit both a regional and local control.

Tectonic Setting

The north-central Basin and Range is a tectonically distinct subprovince of the Basin and Range characterized by relatively low strain rates (Payne et al., 2012; Hammond et al., 2011; Bennett et al., 2003) and sparse historic seismicity (Ramelli and dePolo, 2011). The present day topography is defined by widely spaced, steeply dipping Quaternary normal faults that bound north-trending ranges on at least one side and cut shallower dipping Tertiary normal faults (Henry and Colgan, 2011). The region is actively extending,

as evidenced by the 6.0 M February 28th Wells Earthquake on a blind normal fault (Smith et al., 2011). However, regional studies of Quaternary deformation in the northern Basin and Range suggest that, at present, this region accommodates relatively minor east-west-directed extension (Hammond and Thatcher, 2004; Wesnousky, 2005). The north-central Basin and Range is a relatively aseismic region with a Holocene strain rate of $2.8 \pm 0.2 \text{ mm yr}^{-1}$ oriented $N84^\circ \pm 5^\circ W$ (Bennett et al., 2003) with respect to stable North America. Cumulatively, the Basin and Range accommodates $\sim 11 \text{ mm yr}^{-1}$ of strain oriented $N47^\circ \pm 1^\circ W$ between the Sierra Nevada microplate and the Colorado Plateau with deformation concentrated at the eastern and western margins of the province.

Tuscarora lies within this relatively quiescent part of the Basin and Range but also resides within the Humboldt structural zone, which is defined by a region of ENE-striking discontinuous sinistral normal faults and physiographic lineaments 150–200 km wide, extending more than 800 km from the Carson Sink to southeast Idaho (Rowan and Wetlaufer, 1981; Faulds et al., 2004). The Humboldt geothermal belt is an ENE-trending belt of moderate to high temperature geothermal systems within the Humboldt structural zone, including (from SW to NE) Brady's/Desert Peak, Dixie Valley, Rye Patch, Beowawe, Tuscarora, and Raft River (Figure 1).

Tuscarora Geothermal Field

The geothermal surface expression and associated hydrothermal alteration of the Tuscarora geothermal field occur on a NNE trend in the vicinity of Hot Sulphur Springs. A broad silica sinter terrace $\sim 1000 \text{ m}$ long and $\sim 35 \text{ m}$ wide is perched 10 m above active hot springs. Boiling springs and fumaroles are tightly clustered 400 m NNE of the sinter terrace, actively precipitating travertine, sinter, and sulfur. Minor hydrous silica veining and veinlets cut Miocene lava flows proximal to the hot springs. Isolated patches of silica-cemented alluvium are observed along fault traces subparallel to the Hot Creek drainage.

Geothermal Exploration

From 1978 to 1981 AMAX Exploration Corporation mounted a geothermal exploration effort, funded in part by the U.S. Department of Energy (DOE) Geothermal Reservoir Assessment Case Study program. The exploration project included geologic mapping, water and soil geochemistry, a variety of geophysical surveys, and a multi-phase drill program (Pilkington, 1981). As part of the AMAX-DOE contract, a geologic map of $\sim 210 \text{ km}^2$ surrounding the Tuscarora geothermal prospect was produced and published

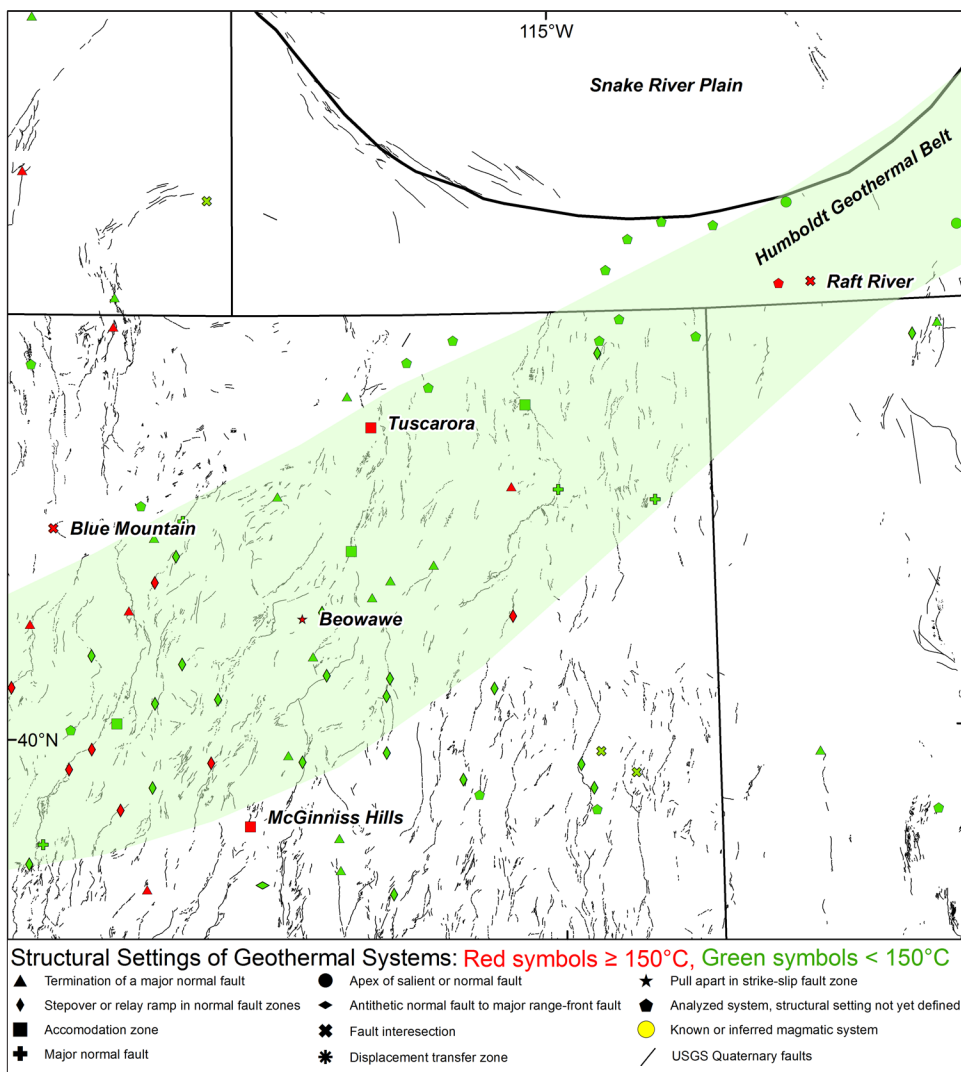


Figure 1. Known geothermal systems in the northeastern part of the Basin and Range province. Labeled geothermal fields have power plants currently in production or under development. The Humboldt geothermal belt is an ENE-trending belt of moderate to high temperature geothermal systems that lie within the Humboldt structural zone, including (from SW to NE) Brady's/Desert Peak, Dixie Valley, Rye Patch, Beowawe, Tuscarora, and Raft River. (Faulds et al., 2004).

(Sibbett, 1982). The exploration drilling program included 32 temperature gradient holes and a 1663 m (5456 ft) deep test well, which achieved a maximum temperature of 107 °C during flow tests. However, drilling was hampered by lost circulation zones and swelling clays. Severe caving problems in the deep test well prevented identification of a discrete production zone.

Exploration activity resumed at Tuscarora in 2003 under the Federal Geothermal Resource Exploration and Definition program (GRED III). Earth Power Resources LLC explored Tuscarora with drilling, geologic mapping, and seismic reflection surveys (Goranson and van de Kamp, 2007). Improved drilling technologies and a refined geologic model allowed for successful completion of several test wells with a maximum temperature of 170 °C reached at depth of 899 m (2950 ft) (Goranson, 2005).

Ormat Technologies announced acquisition of the Tuscarora project in 2010 and completed construction the first power plant at Tuscarora in December, 2011. Ormat geologists gathered and analyzed borehole image logs of the existing hot wells to determine the orientation of open fractures controlling geothermal fluid flow. Three successful production wells were drilled by targeting the projection of a NNE-striking open fracture.

Stratigraphic Framework

A Tertiary section consisting of Tertiary volcanic rocks and a single volcanic-derived sedimentary unit nonconformably overlies deformed Paleozoic sedimentary basement. Quaternary alluvium onlaps gently south dipping Tertiary strata at the south end of the geothermal field. Thin alluvial deposits mantle bedrock of the narrow Hot Creek drainage in the geothermal area.

The basement is composed of two allochthonous marine sedimentary packages, which crop out in the ranges adjacent to the geothermal area and are intersected by drill holes within the geothermal field. The older and structurally lower package is Ordovician quartzite and siltstone of the Valmy Formation. Thrust over the Valmy Formation is a one km thick sequence of Devonian-Permian argillite, siltstone, and minor carbonate-cemented sandstone of the Schoonover Formation (Miller et al., 1984).

Tertiary volcanic and sedimentary rocks can be separated into two age groups:

1) A complex group of genetically related Eocene volcanic rocks erupted during a brief period of intense andesitic to rhyolitic magmatism from 40.0-39.3 Ma, forming the Tuscarora volcanic field (Henry et al., 1999). Eruptive centers are mapped in the northern Tuscarora Mountains directly west and south of the study area and likely extend into the Tuscarora geothermal field. Rocks of the Tuscarora volcanic field found within the study area include andesite and dacite flows, compositionally equivalent intrusions, and rhyolitic lithic tuff. Overlying igneous rocks of the Tuscarora volcanic field are poorly indurated tuffaceous siltstones, sandstones, and pebble conglomerate lenses, regionally correlative with the Elko Formation (Coats, 1987).

2) A Miocene rhyolite flow overlies Eocene tuffaceous sedimentary rocks, forming a slight (<10°) angular unconformity. This distinct flow has been regionally correlated with the Jarbidge rhyolite, yielding an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 16.15 ± 0.02 Ma (Henry et al., 2011). Locally, this resistant flow is conformably overlain by erosional remnants of porphyritic glassy flows of intermediate composition.

Structural Framework

The Tuscarora geothermal field lies within a broad zone of structural interaction, where three regional-scale extensional fault systems come together. These fault systems are: 1) Independence Valley fault zone; 2) Bull Run Mountains (BRM) fault zone; and 3) northeast-striking sinistral-normal faults within the Humboldt structural zone (Figure 2).

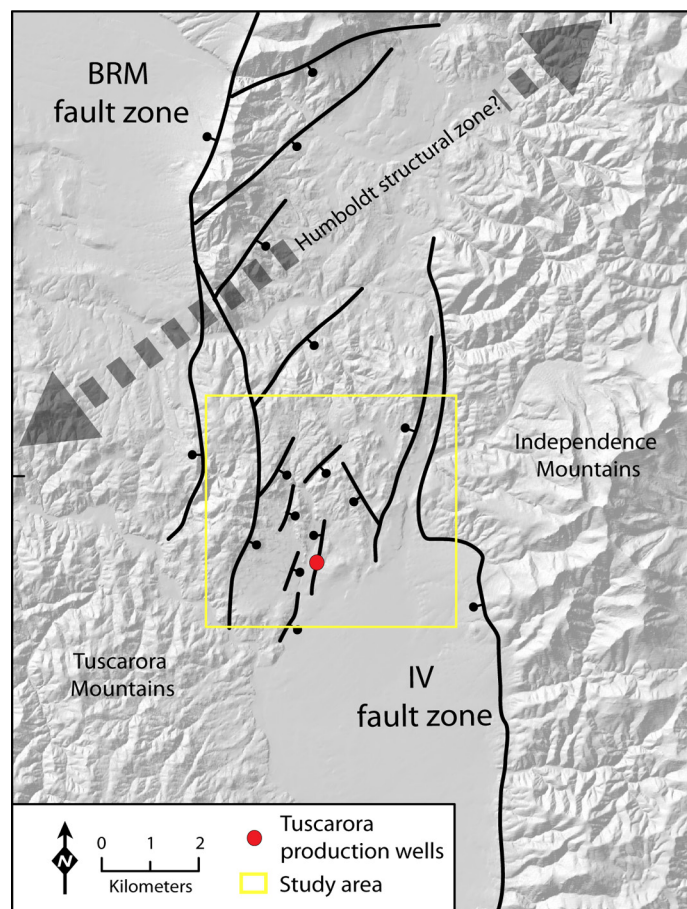


Figure 2. Schematic map of major faults involving Tertiary and younger rocks near the Tuscarora geothermal field: 1) eastern Independence Valley (IV) fault zone 2) Bull Run Mountains (BRM) fault zone 3) northeast-striking sinistral-normal faults that strike roughly parallel to faults and lineaments of the Humboldt structural zone. Faults are approximately located from Coats (1987), the USGS Quaternary Fault and Fold Database, and detailed geologic mapping.

The BRM fault zone dips west and terminates southward, splaying into a series of smaller east- and west-dipping faults with diminishing offset and topographic relief toward the south. At the latitude of the geothermal area, oppositely dipping fault splays of the BRM fault zone form a prominent horst block exposing Eocene welded tuff. The east side of the horst block is bounded by a steeply east-dipping normal fault. This fault zone is demarcated along strike by hydrothermally-altered and pervasively silicified fault breccia, which crops out locally over ~4 km along the fault trace. The age of this silicified zone is unknown but must be younger than ~39 Ma and could possibly be associated with the active geothermal system or to Eocene caldera-related hydrothermal circulation.

The Independence Valley fault zone also dips west but terminates northward. At the latitude of the geothermal area, the Independence Valley fault zone juxtaposes Miocene lava flows against Paleozoic basement with a minimum offset of ~2000 meters. South along strike, the Independence Valley fault zone defines the eastern boundary of Independence Valley and crosses well developed alluvial fans at the base of the Independence Mountains. The Independence Valley is a composite down-to-the-east half graben, controlled by the west-dipping Independence Valley fault zone.

The northward-terminating Independence Valley fault zone overlaps the southward-terminating BRM fault system for ~15 km of strike length. Within this overlap zone, the footwall of the BRM is the hanging wall of the Independence Valley fault zone, forming a relay ramp that dips south into Independence Valley. The relay ramp is dissected by a myriad of discontinuous normal faults with offsets of tens to hundreds of meters. Detailed geologic mapping reveals a somewhat systematic distribution of small-offset faults, which strike NNW to NNE and dip both east and west (Figure 3). Fault-bounded blocks capped by Miocene rhyolite flows tilt south, east, and west between 5° and ~35° toward these normal faults. The geothermal field lies at the hinge line of a strike-parallel anticlinal accommodation zone, where a series of west-dipping faults overlap with east-dipping faults. Tilt-block domains resulting from this pattern of faulting form a subtle extensional anticline that trends orthogonal to extension direction and roughly parallel to fault strike. The accommodation zone is bounded on the east by the west-dipping Independence Valley fault zone and bounded on the west by an east-dipping splay of the southward terminating BRM fault zone (Figure 2).

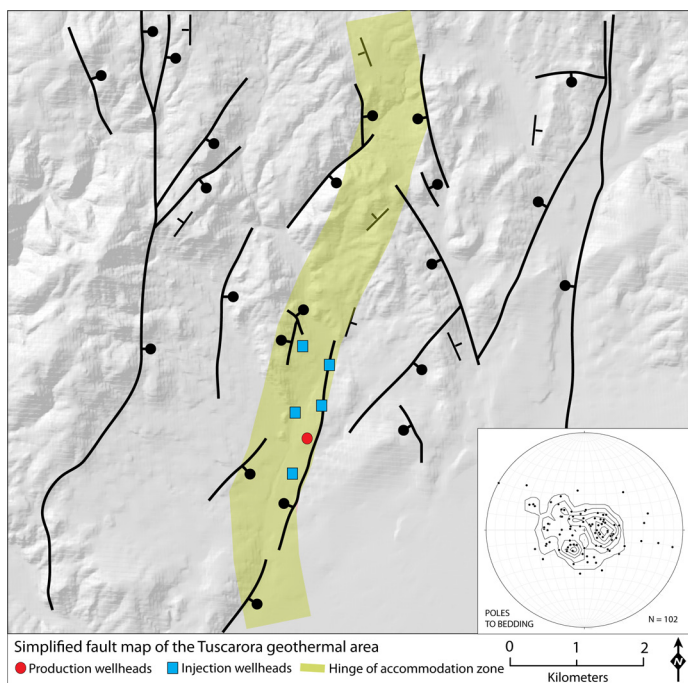


Figure 3. Simplified preliminary structural map of the Tuscarora geothermal area showing primary dip domains, which form an extensional anticline that defines the accommodation zone between east- and west-tilted domains. Inset shows equal-area stereographic projection of poles to bedding planes. Clusters of poles reflect tilting of strata towards ~NNE-striking normal faults which dip both east and west.

Discussion

Together, the BRM and Independence Valley fault zones form a semi-continuous system of west-dipping normal faults, kinematically linked by a broad left step over and relay ramp (Figure 2). The pattern of faulting within the step over is diffuse, and most individual faults are discontinuous along strike, exhibiting relatively minor offsets. The absence of geothermal activity along large-offset faults within the BRM-Independence Valley fault system and localization in the hinge zone of an anticlinal accommodation zone may be attributable to differing fault zone architectures. Fault planes with large magnitude offsets develop a fault core consisting of clay gouge, whereas fault planes with small offsets tend to be fracture-dominated (Caine et al., 1996). Gouge zones act as barriers to fluid flow across a fault, whereas brecciated zones promote fluid flow. At Tuscarora, the oppositely dipping normal fault sets that locally control the geothermal upwelling have small offsets and are likely breccia-dominated. Fault intersections formed by oppositely dipping, small offset normal faults in the hinge zone of the accommodation zone are more likely to be permeable and can therefore serve as favorable sub-vertical conduits for fluid flow. In contrast, the adjacent range-bounding fault zones have offsets of several kilometers, and thus are more likely to be gouge-dominant and inhibit fluid flow.

Accommodation zones are relatively common structural components of extended terranes that transfer strain between oppositely dipping fault sets via a network of subsidiary normal faults (Faulds and Varga, 1998). The recognition of accommodation zones as favorable structural settings for geothermal systems is a useful exploration tool for development of drilling targets in extensional terranes, as well as for developing geologic models of known geothermal fields. Tuscarora is one of several high temperature Great Basin geothermal fields currently in production or development and classified as an accommodation zone. Others include Brady's, Salt Wells, and McGinness Hills (Faulds et al., 2011). The detailed work at Tuscarora highlights the importance of accommodation zones in controlling geothermal activity in some areas, but also provides critical information on what portions of an accommodation zone are most conducive for such activity. In this case, the hinge zone of the anticlinal accommodation zone facilitates upflow presumably because of the increased density of faulting and greater abundance of fault interactions. This type of information can ultimately help to reduce the risks of targeting the locations of geothermal wells in such settings.

Conclusion

Preliminary interpretations of detailed geologic mapping, integrated with well and regional geologic data, have revealed that the Tuscarora geothermal field is characterized by two structural settings: 1) a broad left step over in a major normal fault system, and 2) an anticlinal accommodation zone, which occupies the relay ramp formed by the step over. The distribution of hot wells at Tuscarora suggests that the geothermal system is restricted to the complex intersection of steeply dipping faults along the hinge zone of the accommodation zone. At depth, oppositely dipping normal fault sets intersect in this area and have produced

significant breccia in Paleozoic siliciclastic rocks, generating the necessary permeability to host the geothermal system.

Further interpretation of the structural setting at Tuscarora will benefit from compilation of geologic mapping in a GIS, integration of geologic mapping with geophysical surveys, structural analysis of fault kinematics and local stress conditions, and generation of geologic cross sections through the geothermal field.

Acknowledgments

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