

Structural and Stratigraphic Controls on the Geothermal System Near Paisley, Oregon

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Keywords

Basin and Range, Brothers Fault Zone, Southeast Oregon, transfer zone, permeability, geothermal, Oregon

ABSTRACT

Geothermal resources in southeast Oregon are predominantly similar to those further to the south in Nevada and can be classified as Basin and Range geothermal systems. Work done on the geothermal system near Paisley, Oregon exemplifies the relationship between regional and local structure as it controls thermal fluid movement. Neogene tectonism has produced the Basin and Range and the Brothers Fault Zone. Paisley, Oregon lies at a unique location where these individual tectonic provinces coalesce to produce an extremely high geothermal resource potential. Thermal upwelling and production in the Paisley Geothermal System is controlled by the Paisley Hills Fault where it lies in a structural transfer zone evidenced by overlapping en echelon geometry with the Winter Ridge Fault. This structural setting has produced the necessary permeability to allow for the concentrated flow of thermal fluids.

Introduction

The northern Basin and Range is host to a large number of known and unknown geothermal resources (Muffler et al., 1978; Williams et al, 2008). The majority of research has been focused in California, Utah, and Nevada. Considerable insight into geothermal systems in these areas has been elucidated by detailed geologic, geochemical, and geophysical studies. However, little work has been done on known and potential geothermal resources in Oregon. One main goal of this project was to characterize the Paisley resource, and to then provide a conceptual model into which geothermal resources of southeast Oregon could be placed.

The Paisley resource was initially discovered in the 1960's by a local rancher while drilling an irrigation well. During the drilling of this well, water of nearly 115 °C was discovered. Around 2011, Surprise Valley Electrification Corporation, which serves as

the local power cooperative, initiated drilling of three geothermal wells with support from the U.S. Department of Energy, to drive a small power generation system aiming to produce 3 Megawatts of electricity. The Paisley resource serves as a real-world example of how low enthalpy geothermal systems can be utilized with collaboration between both the public and private sectors.

Geologic Setting

The convergence of several geologic provinces in southern Oregon produces a complex geologic setting. Here, the northwestern most margin of the Basin and Range Province meets the Cascades and High Lava Plains provinces (Fig. 1). However, because these provinces do not terminate against one another *sensu stricto* but overlap in their spatial extent, a complex pattern of geologic structures exists, producing high geothermal resource potential through the creation of secondary permeability and increased heat flow.

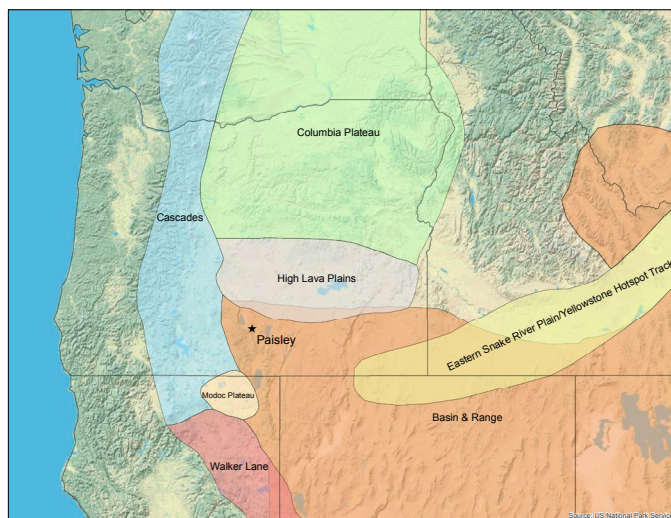


Figure 1. Map showing tectonic provinces adjacent to Paisley, Oregon. The complex geology at Paisley is controlled by the coalescence of several tectonic provinces.

The rocks in Paisley record a complex geologic history spanning back to the Eocene (Appling, 1950; Muntzert, 1969; Walker and MacLeod, 1991; White and Robinson, 1992). The predominant volcanic center in the Pacific Northwest during the Eocene was the Challis Volcanic center located in central Idaho, stretching northward into Canada (Fig. 2). Volcanism began to migrate westwards in the late-Eocene, probably associated with the accretion of Siletzia. At this time, volcanism across Oregon was diffuse and is evidenced by the Clarno Formation. During the Oligocene, volcanism became more localized in western Oregon, creating the volcanic centers that produced the abundant tuffs of the John Day Formation in central Oregon.

The Miocene (20 Ma to 5 Ma) is the most important time period for both the Great Basin and southeast Oregon with respect to geothermal resource development. The High Cascades, which developed in the late-Miocene, form the western edge of the study area. Volcanic centers associated with the High Cascades are located only ~72 km west of Paisley and could therefore play a potential role in geothermal systems of southern Oregon (Walker and MacLeod, 1991). Voluminous outpourings of basalt magma occurred in eastern Oregon and Washington and are evidenced by the Steens and Columbia River Basalts, respectively. The development of the northern Basin and Range Province provides the main control on the development of geothermal systems in the region. A distinct package of bimodal basalt and rhyolite lavas defines magmatism on the High Lava Plains of Oregon. The silicic volcanics of the High Lava Plains young to the northwest, terminating at Newberry Caldera (e.g., MacLeod et al., 1975). The Brothers Fault Zone is important to the existence of geothermal resources in southeastern Oregon. The coexistence of faulting associated with the Brothers

Regional Heat Flow near Paisley, Oregon

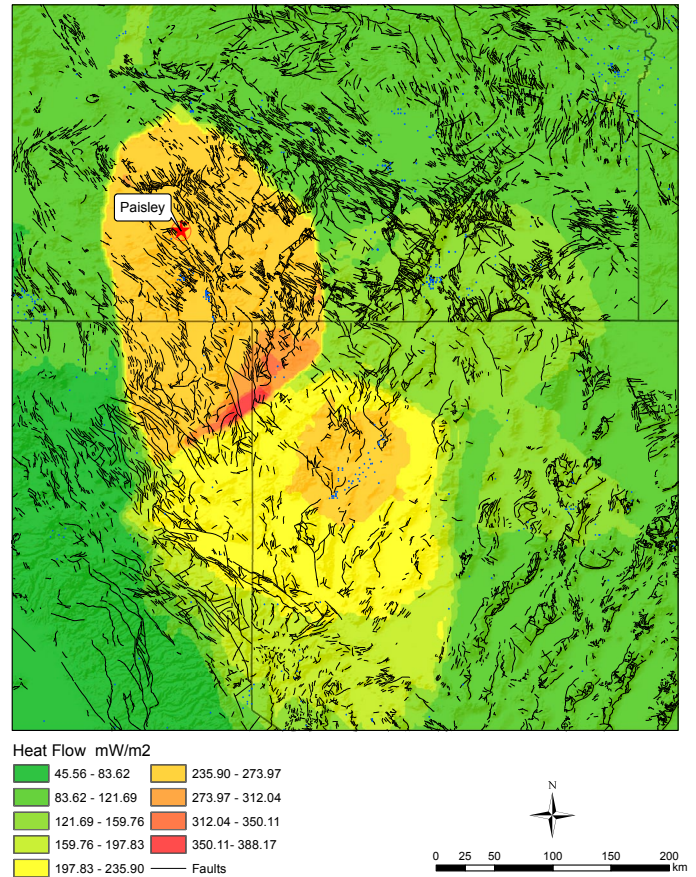


Figure 3. Heat flow in the western United States. Data taken from the University of North Dakota Heat Flow Database. Heat flow surface created by spherical Kriging of wellbore heat flow data.

Fault Zone with pre-existing structures of the Basin and Range provide the structural controls for fluid flow in geothermal systems of southeast Oregon.

Northern Basin and Range

The northern Basin and Range, with its characteristic high heat flow, magmatism and faulting is widely recognized as the single most important tectonic development that led to the creation of geothermal resources within the Great Basin and in southeast Oregon (Fig. 3).

Basin and Range deformation is characterized by a mixture of block faulting along listric normal faults which terminate at a lower detachment fault and traditional horst and graben structures. Within the northern Basin and Range, changes in fault block dip-direction oscillates from east-west, with fault-bounded basins and ranges separated by transfer or accommodation zones, which usually exhibit strike-slip motion parallel to the extension direction (Stewart, 1978,

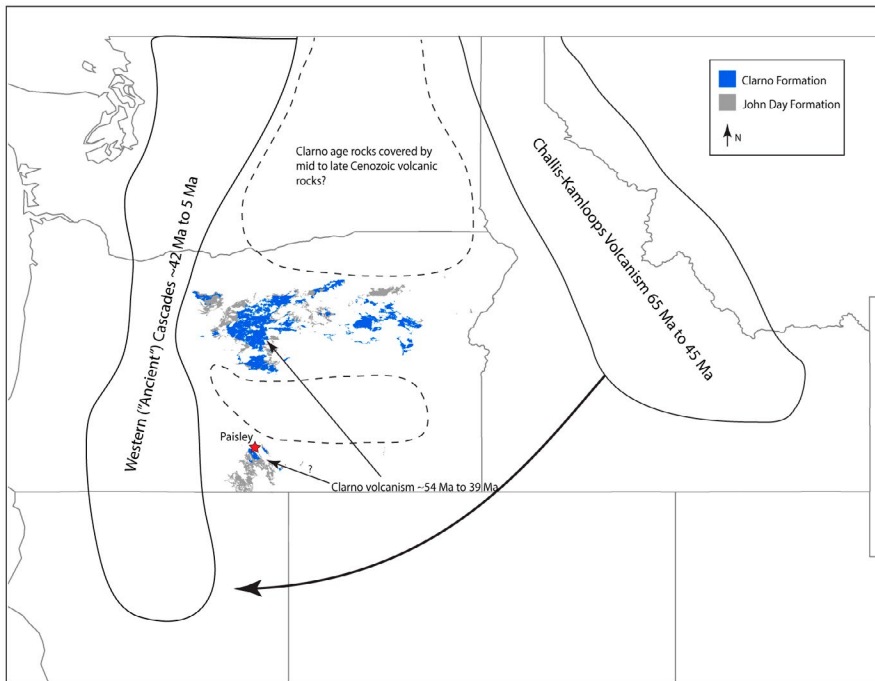


Figure 2. Map showing regional tectonic setting of the Eocene Clarno and Oligocene John Day Formations. The Clarno Formation of central Oregon represents an intermediate stage in volcanism between the Challis-Kamloops and Western Cascade episodes. Position of the Challis-Kamloops volcanic center modified from Dickinson (2006). Geographic extent of Clarno and John Day Formations taken from the digitized version of the Oregon statewide geologic map of Walker and MacLeod (1991) and is available as an ArcGIS layer from the USGS.

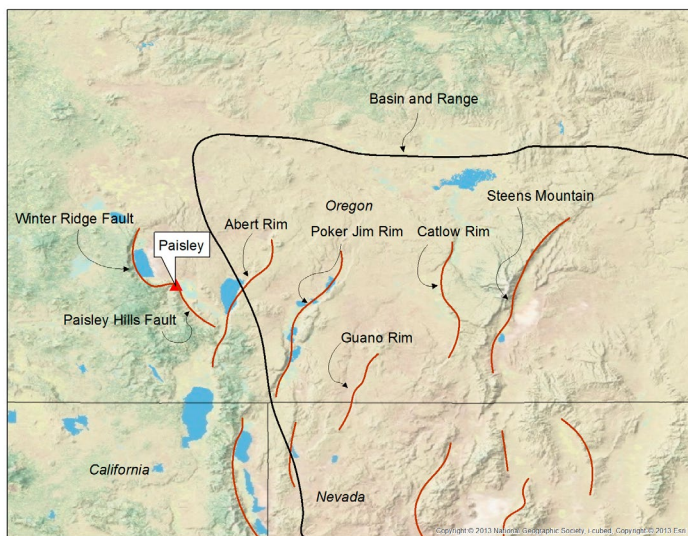


Figure 4. Map showing some of the major Basin and Range faults in southeast Oregon.

1980; Faulds and Varga, 1998).

Early workers included southeast Oregon as part of the Basin and Range province (e.g., Donath, 1962; Donath and Kuo, 1962; Lawrence, 1976). Recent work (e.g., Jordan et al., 2004; Scarberry et al., 2010; Egger and Miller, 2011) have confirmed this notion, placing southeast Oregon as part of the northwestern-most Basin and Range Province. Extension initiated in southeast Oregon perhaps in the late-Miocene earliest-Pliocene, which is much younger than that of the rest of the northern Basin and Range (~16 to 6 Ma). Scarberry et al. (2010) has dated the initiation of faulting on the Abert Rim Fault (Fig. 4) in southern Oregon to have begun <7.5 Ma based on minimum age requirements from cross-cutting relationships. Similarly, Pezzopane and Weldon (1993) determined that the Winter Ridge fault initiated ~6.5 m.y. ago (Fig. 4).

Brothers Fault Zone

A zone of northwest striking faults in the High Lava Plains of Oregon characterizes the Brothers Fault Zone. Donath (1962), Lawrence (1976), and Pezzopane and Weldon (1993) believed these faults to have dominantly strike-slip motion. However, in more recent literature (e.g., Jordan et al., 2004; Trench et al., 2012) it has been suggested that these faults have normal displacement. The controversy is beyond the scope of this paper but it is important to note that geothermal favorability increases in areas where Basin and Range structures terminate, or coexist with, structures of the Brothers Fault Zone. The geothermal resource potential increases in these areas because of complex fault geometries that arise, creating numerous pathways for both infiltrating meteoric water and also for rising thermal water (e.g., Faulds et al., 2006).

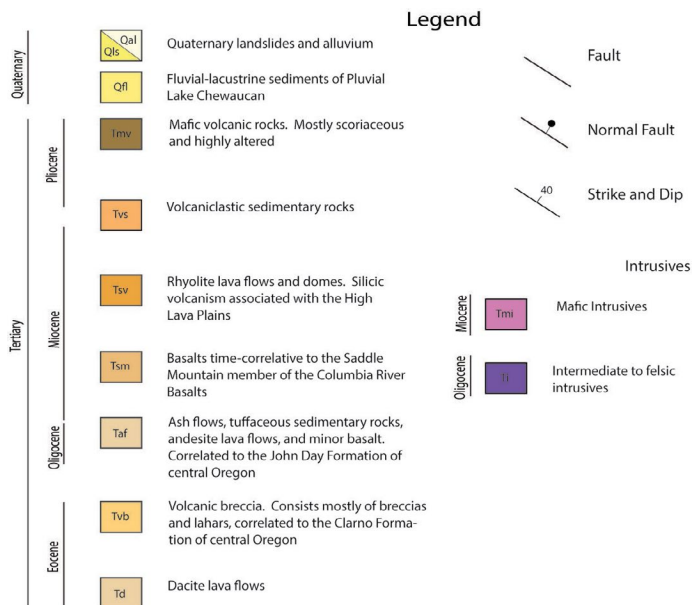


Figure 5a. Legend for Geologic map below.

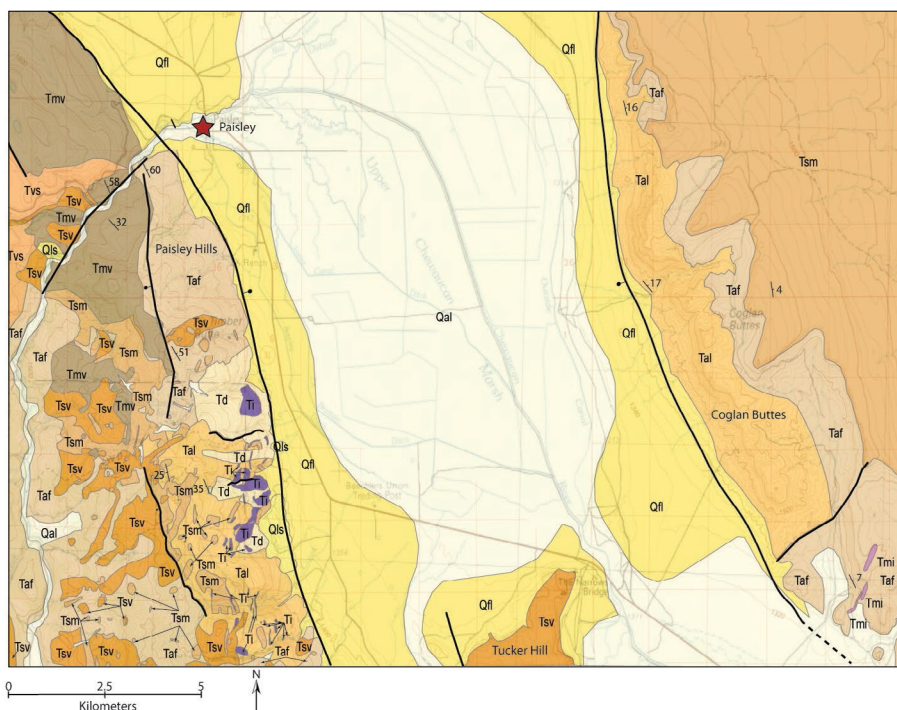


Figure 5. Geologic map of the Paisley area. This map was created by mapping done by the lead author and by the compilation of local and regional maps by Muntzert (1969) and Walker and MacLeod (1991), respectively.

Stratigraphic and Structural Framework at Paisley, Oregon

Detailed geologic mapping in the Paisley area has revealed a complex succession of Tertiary rocks spanning from the Eocene(?) to Present (Fig. 5). The oldest rocks exposed in the area are dacite and andesitic volcanic breccias of Eocene(?) age. The andesitic rocks are interpreted to be the southern extent of Clarno-type rocks typically found in central Oregon (Rogers

and Novitsky-Evans, 1977; Bestland et al., 1999; White and Robinson, 1992). Lying stratigraphically above the Eocene age rocks is a sequence of bimodal basalt/dacite-rhyolite flows and tuffs of Oligocene age. These rocks have been correlated with the John Day Formation of central Oregon based on a K/Ar age of 33.6 ± 1.5 Ma from a biotite grain taken from a quartz monzonite intrusive (Munzert, 1969; Walker, 1963; Walker and MacLeod, 1991). The contact between the lower Clarno type rocks and the upper John Day type rocks is unconformable. These formations represent local basement rock, where they are exposed in both the Paisley Hills and Coglan Buttes (Fig. 5). Lying unconformably above the John Day age rocks in both the Paisley Hills and Coglan Buttes are numerous basalt flows, correlated regionally with either the Umatilla or Wilber Creek Members of the Saddle Mountains Basalt, which is part of the Columbia River-Steens episode of basaltic magmatism (Walker and MacLeod, 1991). Younger, late-Miocene-Pliocene bimodal basalt and rhyolite rocks follow the eruption of the Saddle Mountains Basalts. These bimodal rocks are interpreted to be products of volcanism associated with the High Lava Plains. MacLeod et al. (1975) dated a local rhyolite volcanic center (Tucker Hill, Fig. 5) at 7.42 ± 0.19 Ma via K/Ar.

Rocks of pre-Pliocene age have apparently been folded into low amplitude anticlines and synclines (Peterson and McIntyre, 1970). Adjacent to Paisley, a northwest trending anticline has been identified by Peterson and McIntyre (1970), the axis of which is a line connecting Silver Lake, Summer Lake, and Goose Lake, Oregon. This is evidenced in the Paisley Hills by rocks that are dipping 45° NE. It remains unclear if the apparent folding of these rocks is related to an older regional compressive event, young tectonic stresses, or even by the emplacement of local volcanic centers. Munzert (1969) interpreted the tilting of units in the Paisley Hills with the emplacement of plutonic quartz monzonite, diorite, and granodiorite. However, this hypothesis does not explain the tilting of units younger than these intrusives. Subsequent tilting in the Paisley Hills and in the Coglan Buttes is therefore associated with rotations due to normal faulting.

Two main sets of normal faults occur in the Paisley area; northwest trending faults, which have the highest frequency ($\sim 307^\circ$) and have less offset relative to the lower frequency, northeast trending ($\sim 030^\circ$) set of faults. The NW striking faults have been interpreted to be part of the Brothers Fault Zone, and as it was mentioned above, is a series of normal faults which forms the northern boundary of the Basin and Range Province (Lawrence, 1976; Trench et al., 2012). Northeast striking faults such as Winter Ridge, Slide Mountain, and Abert Rim, were probably created by the northwestward expansion of the Basin and Range into southeast Oregon (Scarberry et al., 2010). The Paisley Hills fault and Coglan fault create a graben defining the southern portion of Summer Lake Basin (Fig. 5). The orientation of these faults is problematic. All Basin and Range faults of southeastern Oregon are oriented N-NNE; however, The Paisley Hills, Coglan, and southern part of the Winter Ridge faults are all orientated NW, yet have similar ages of initiation as N-NNE trending normal faults related to the Basin and Range. A detailed discussion of this issue

is beyond the scope of this paper yet is an interesting problem which requires further attention.

In the Paisley region, thermal fluid flow is controlled by a structural transfer zone on the western side of Summer Lake Basin. Two en echelon normal faults just north of Paisley are possibly separated by an individual or complex series of sinistral strike-slip faults, referred to here as the Paisley Transfer Zone. The two en echelon normal faults involved in this transfer zone are the Paisley Hills fault and the Winter Ridge fault to the north (Fig. 6). Both of these faults have been shown to display dip-slip motion, with this motion continuing into the Quaternary (Pezzopane and Weldon, 1993; Badger and Watters, 2004). Transfer zones typically contain a set of faults parallel or oblique to the extension direction; these faults accommodate strain between two en echelon normal faults (Faulds and Varga, 1998). In the Paisley Transfer zone, the transfer fault appears to be a normal fault, even though it separates two en echelon normal faults. Because of the large topographic features created by these faults, they clearly have dip-slip motion, but how a dip-slip fault accommodates strain between two en echelon normal faults is problematic.

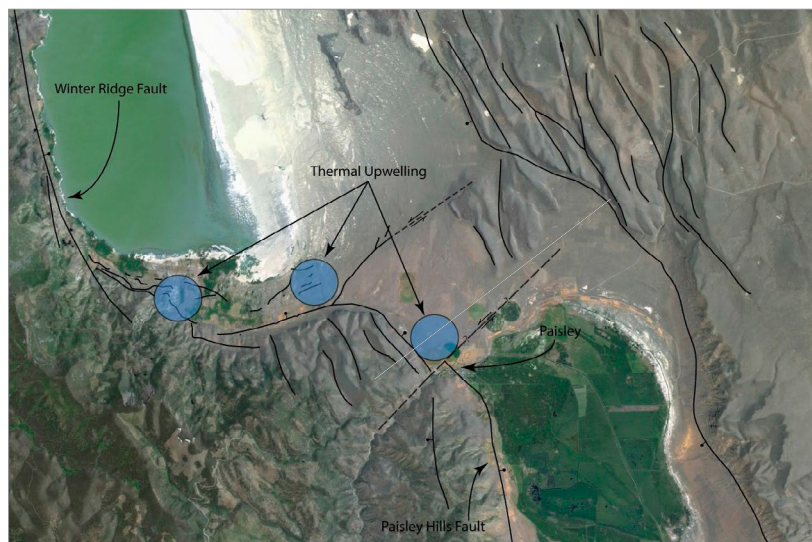


Figure 6. Structural map of the Paisley area showing the en echelon character of the Winter Ridge Fault and the Paisley Hills Fault. The geometry has created a structural transfer zone where the strain is transferred from the Paisley Hills Fault to the Winter Ridge Fault, or vice versa. Known locations of thermal water are delineated by the blue circles. The zones of upwelling are located near areas of fault intersections, terminations, or fault bends. The western and central zones of upwelling are identified by extensive fossil hydrothermal alteration of bedrock and warm wells, respectively. The eastern zone of upwelling has been identified by three wells with water exceeding 100°C . White line is the line of section in Figure 7.

One possibility is that this transfer fault is potentially younger than the Winter Ridge and Paisley Hills faults, which may have once been one linear structure, and the current geometry is now the result of a change to oblique motion in NW trending faults across central Oregon (Pezzopane and Weldon, 1993). Another possibility is that relative displacement rates on the Winter Ridge and Paisley Hills faults are different, thus a transfer fault is created to accommodate this differential motion. Regardless of how it was created, the transfer system is extremely important for localizing the rise of thermal fluids in the Paisley geothermal system and has important implications for other geothermal resources in southeast Oregon.

Discussion

The Paisley geothermal system shares many similarities to other structurally-controlled geothermal systems of the Basin and Range. That is, high regional heat flow in southeastern Oregon combined with complex Neogene faulting allows for the deep circulation of meteoric water. This water then becomes heated by the high ambient geothermal gradient and rises in high permeability areas (i.e., faults, fault zones). In the Paisley geothermal system, water enters the ground from topographically high areas southwest of Paisley (Fig. 7). The water descends further into the ground along bedding planes, which dip to the northeast. The water becomes heated by an elevated geothermal gradient (evidenced by high regional heat flow values, Fig. 3) and eventually reaches the Paisley Hills fault. Because of its decreased density, the thermal water rises along the Paisley Hills fault into the shallow subsurface (~350 m) where it is then penetrated by three boreholes drilled by Surprise Valley Electrification Corporation. The locations of thermal water upwelling seem to at least be coincident with areas of fault intersections (Fig. 6). The rocks in which the thermal water is produced are basalts probably of late- Miocene-Pliocene age, and therefore those related to the High Lava Plains. Permeability in these rocks is created from complex faulting and associated fracturing during the creation of the Paisley Transfer Zone.

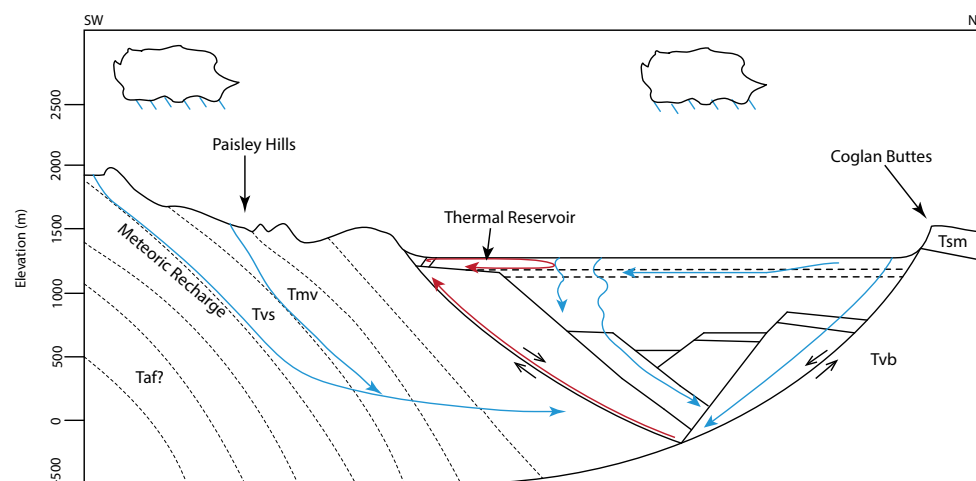


Figure 7. Conceptual model for the Paisley Geothermal System. Line of section for this figure can be seen in Figure 6. See text for discussion.

Paisley is a great example of the potential for geothermal resources in southeast Oregon. High heat flow coupled with complex faulting is the predominant late-Neogene tectonic feature of this area. Also, areas where Basin and Range normal faults meet or overlap with the Brothers Fault Zone have a high geothermal resource potential. In addition to continued extension since ~10 Ma, late-Neogene (10 Ma-Present) magmatism in southeast Oregon also has created a high geothermal resource potential for magmatically-controlled geothermal systems. This is especially true on the High Lava Plains where silicic magmatism <3 Ma is abundant. Further exploration for new resources along with synthesis of existing data is now necessary to elucidate the role each of these processes play on the existence, and hence location of, geothermal resources in southeast Oregon.

Acknowledgements

The authors wish to thank Surprise Valley Electrification Corporation for their support and for partial funding for this project. We would also like to thank the Colahan's of Paisley for allowing us access to their land for field work. The majority of this work is excerpted from the first author's M.S. Thesis and would therefore like to thank everyone at Boise State University who helped make this manuscript a possibility.

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