Evolution of the Northwest Basin and Range Province: Implications for Geothermal Exploration in Southeast Oregon

Kyle A. Makovsky[1], Silvio Pezzopane[2], Lynn Culp[3], Leland "Roy" Mink[4], Daniel Hand[5], Daniel Silveria[3], Erin Colahan[6], Mark Douglas[6], Kim Johnson[7]

[1]Boise State University, Department of Geosciences, Boise ID
[2]Paisley OR
[3]Surprise Valley Electrification Corp., Alturas CA
[4]U. S. Geothermal Inc., Boise ID
[5]Sustainable Engineering, Puyallup WA
[6]Colahan Enterprises Inc., Paisley OR
[7]Spatial Dynamics Inc., Boise ID

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ABSTRACT

Volcanism along the northwest margin of the Basin and Range province started in the early Eocene, and after a short hiatus, reinitiated in the late Oligocene (28 Ma) to early Miocene and continued through the mid Miocene (17 Ma). This second volcanic event is thought to have been the result of hinge rollback of the shallowly subducting Farallon plate in the Oligocene. After volcanism ceased, tectonic extension offset these early-mid Cenozoic units, with extension in this locality occurring at a younger age than the central and southern Basin and Range province. Two main trends in fault orientation have developed due to this extension, with the dominant trend striking NE-SW and dip-slip as the main kinematic feature. Minor faults trending NW-SE also occur and most likely accommodate strain with oblique-slip to strike-slip motion. These two trends may play a key role in the surface manifestation of geothermal anomalies in southeast Oregon.

The structural framework of this area provides a unique view into young extensional terranes, where high angle normal faults and crustal blocks dominate. The combination of volcanism followed by regional extension has led to numerous geothermal anomalies in southern Oregon. Geologic mapping near Paisley, Oregon has indicated that Cenozoic, mostly Oligocene and Miocene, ash-flow tuffs, dacite to rhyolite lava flows, and other volcaniclastic rocks are the major lithologies of the region. Most of these rocks are potentially excellent reservoirs due to the highly fractured nature of welded tuffs and lava flows and the unconsolidated nature of ash flow deposits. Mapping has also indicated that faults created during mid-Miocene extension have offset volcanic strata of late Oligocene-early Miocene age.

2 meter survey data also shows high heat flow near the surface, ranging from 55-80 °F. The range and temporal change in the 2 m data suggests there is a flux of heat flow in the subsurface. A preliminary Complete Bouguer Gravity Anomaly map has also been created for the study area. A range of +18 to +23 mgals has been observed, with higher gravity values attributed to denser bedrock, adjacent to unconsolidated basin fill. This study was aimed at identifying the orientation of a range front fault that could play a major role in transport of hot fluids. Geothermometry using the Na/K

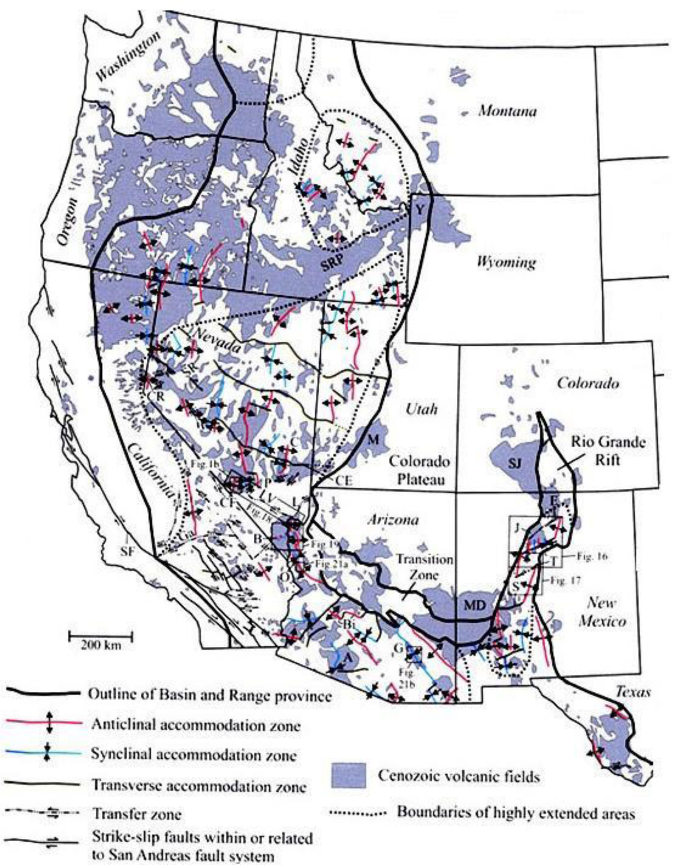

Figure 1. Location of field area outlined in red circle. Areas in gray are major Cenozoic volcanic centers and bold black line is the geographic extent of the Basin and Range Province. Red and or Blue lines indicate areas of Anticlinal and Synclinal accommodation zones, respectively. From Faulds and Varga (1998).

and K/Mg Giggenbach methods has shown that for several wells in the Paisley area, temperatures could range between 95-127 °C. Preliminary stable isotope data of water from the potential production well shows that it may be from meteoric sources, with mean δD and $\delta^{18}O$ values of -120.066 and -14.307 (n=3), respectively.

Geologic Setting

Paisley, Oregon resides in Summer Lake Basin in southern Oregon and is bounded on either side by normal faults, with the Paisley Hills to the west and the Coglan Hills to the east.

Geologically, Paisley resides in the northwestern most extent of the Basin and Range province (Figure 1). In this area, voluminous latest Miocene to Pliocene volcanic rocks consist of dacite to rhyolite ash flow tuffs and basalt flows which were emplaced in an arc-related volcanic province (McKee et al 1983; Bacon, 1990; Jordan, 2002). Work done by previous authors (Naeser et al 1980; Cater 1982; McKee et al, 1983; Draper 1991; Macdonald et al, 1992; Streck and Grunder, 1997; Jordan et al 2002; Jordan et al 2004; Carmichael et al, 2006) has shown that the geochemistry of the volcanic rocks near the Paisley area have an arc signature. Figure 2 is a compilation of data from these authors, arranged in Harker diagrams to best illustrate the bimodality of late Tertiary volcanism. Magmatic arc volcanic rocks often have a calc-alkaline signature, which could be the result of partial melting of oceanic crust and/or from contamination of continental crust as the magma is rising (Winter, 2001). The fractionation process is most likely responsible for the high silica and low Fe and Mg content of these

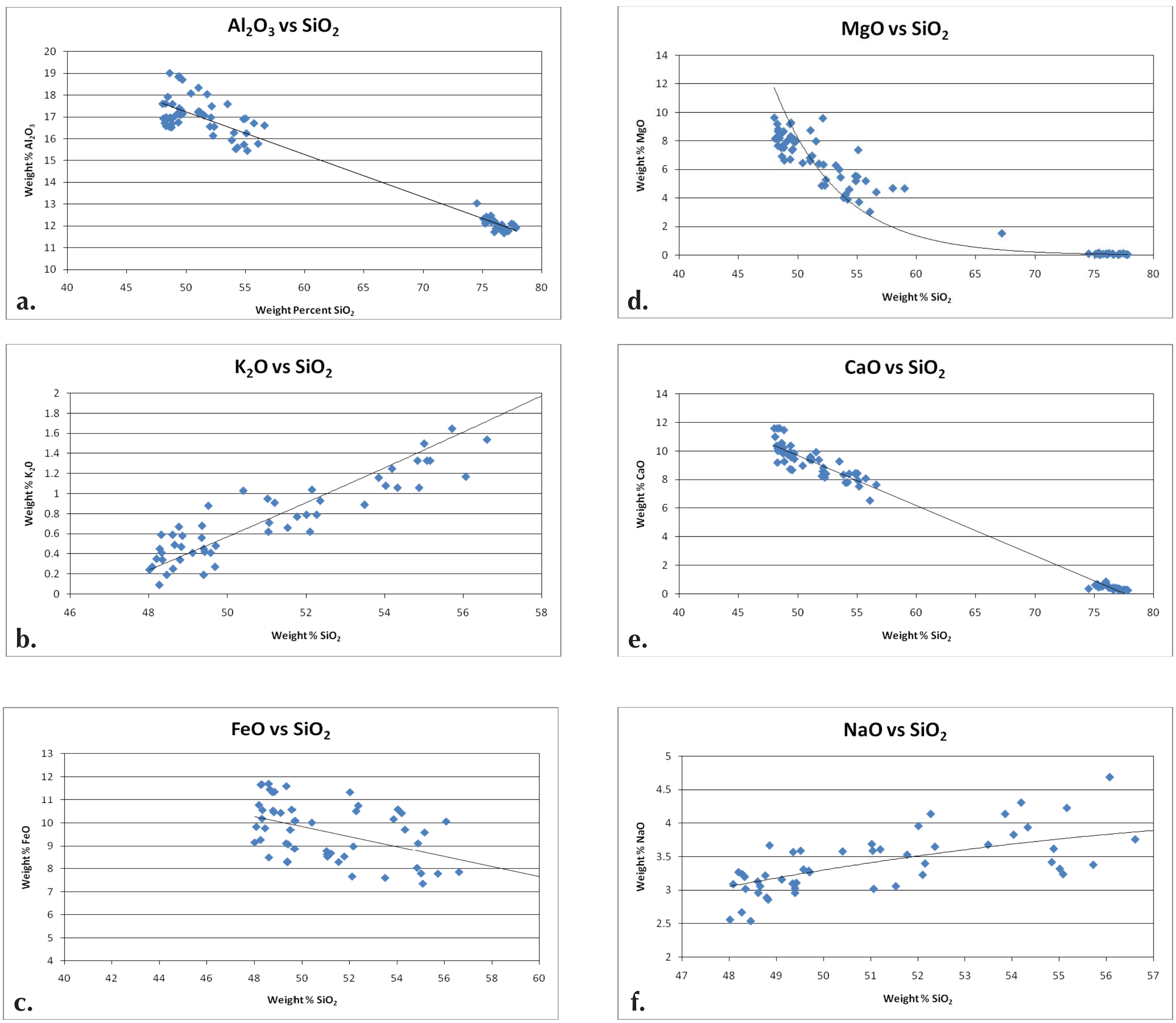

Figure 2. Values of major oxide concentrations of volcanic rocks near Paisley. Notice the bimodal behavior present in figures a, d, and e. These diagrams suggest that fractionation of uprising magmas is the main process acting on these magmas. Data from NAVDAT, references herein.

volcanic flows. The High Alumina Olivine Tholeiites (HAOT) described by Bacon (1989) indicates that these basalts are more primitive and are similar to intraoceanic arc volcanic rocks.

Most units mapped near Paisley shows signs of hydrothermal alteration, with many of these volcanic units having large crystals of calcite within the matrix and in some cases constituting the vein fill. Giggenbach (1988) stated that calcite is a common mineral precipitated by hydrothermal waters that have a magmatic source and interact with calcium rich rocks. A large volume of rocks in the Paisley area contain plagioclase as main or accessory minerals, and due to the high volume of calcite crystallization, this mineral assemblage suggests rock-fluid interaction. Another common alteration mineral present in these units are pistachio green minerals that are present as amygdules.

High angle normal faults and tilted crustal blocks are the dominant structural feature in southern Oregon. There are two main orientations to these faults, those striking northeast-southwest have the most vertical offset compared to faults trending northwest-southeast, which have little relative offset (Pezzopane and Weldon 1993). This area has been referred to as an anticlinal accommodation zone by Faulds and Varga (1998) (see figure 1). According to Faulds and Varga (1998) an accommodation zone consists of a set of faults that transfer strain between zones of en echelon faults, with these zones separating areas of oppositely dipping, overlapping normal faults. This type of kinematic feature is important because it creates extensively faulted terranes which in turn generate highly permeable reservoirs. The high degree of faulting coupled with recent volcanism has made southern Oregon a prime location for geothermal prospects.

In the Paisley Hills, volcanic units dip to the northeast (Figure 3), which is consistent with domino style half graben formation due to extension (Bott, 1997). The dip of these beds could allow for easy infiltration of meteoric water that is replenishing the aquifer.

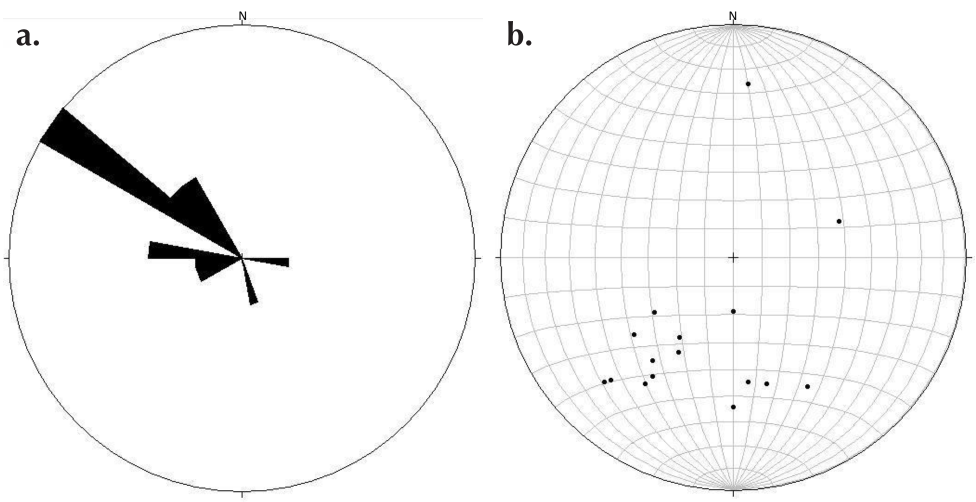

Figure 3. Rose Diagram showing strikes of planes, it is apparent that most of the beds are striking NW (n=16, figure a). Figure b is showing the poles to the planes in figure a, which indicates a dominant dip direction of northeast for these beds.

Methods and Results

Correctly exploiting a geothermal resource requires a sound conceptual model. At the Paisley site, geologic, geochemical, and geophysical methods were used to construct this conceptual model. The first step in this process was to identify faults by the use of aerial photographs and remote sensing techniques to recognize regional structural trends. This was carried out using Geographic Information Systems (GIS) software and is a fairly cheap and effective way to obtain very useful information. Linear features are identified by changes in tonal variations and in rock type. Figure 4 is a LANDSAT image and shows some results of this satellite image interpretation showing that Summer Lake Basin is bounded by northwest trending faults. The colored dots

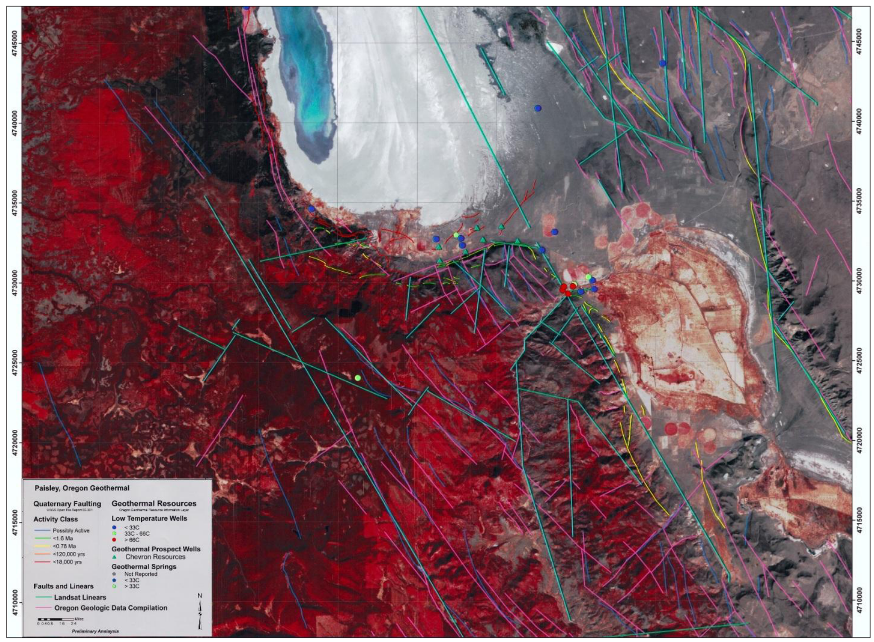

Figure 4. Result of linear identification of the Paisley area. See text for explanation. Image courtesy of Kim Johnson.

in the figure refer to thermal wells drilled in Summer Lake Basin. The area immediately around Paisley contains 4 wells that have a temperature greater than 66 °C and the hottest temperature recorded comes from the "Hot Well" at 112 °C.

The next phase was to field check the results of the reconnaissance mapping. Figure 5 is an approximately 1:24000 scale map of the area just southwest of Paisley. This area was chosen for further study because the beds are dipping northeast and would serve as a useful analog to the reservoir rocks found in the Hot Well. Most of the mapped units are welded and non welded dacitic to andesitic ash flow tuffs and basalt flows. The tuffs range in color from white, gray to dark gray, and some of the andesitic tuffs contain phenocrysts of biotite and sanidine (?), possibly making them trachyandesitic. Some basalt units in this area show signs of hydrothermal alteration, evidenced by small inclusions of opal in the matrix quartz. Palagonitized textures can also be seen in some of the basalt units further up in the stratigraphic section, which suggests interaction with water upon their emplacement.

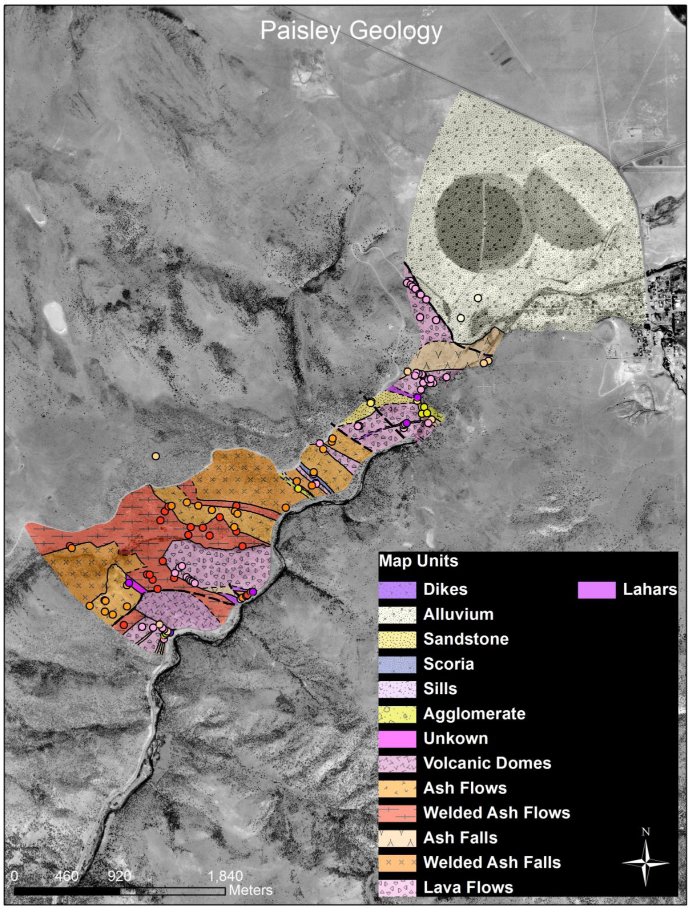

Figure 5. Preliminary Geologic map of the paisley area. Most geologic units are volcanic in nature and sedimentary units are interpreted to be derived from local sources. The dominant rock types consist of welded and non welded rhyolitic ash and basalt flows. The dots on the map are locations where samples were taken and solid black lines correlate to contacts between geologic units. Refer to figure 1 for regional location.

2 meter surveys are an important and cost-effective way to characterize the shallow subsurface heat flow (Sladek et al, 2007; Kratt et al, 2008). The depth of 2 meters is chosen because anything shallower than 1 meter is prone to daily temperature fluctuations (Sladek et al 2007; Elachi, 1987). A depth of 2 meters is to a lesser degree prone to seasonal temperature fluctuations (Sladek et al 2007) but deep enough to be sensitive to geothermal heat. A grid was set up in order to best characterize the subsurface heat flow, which is demonstrated in figure 6. Figure 7 shows the subsurface temperature readings on November 24, 2009 and a graph from selected points from July 15-September 9, 2010. It is interesting to note that in the contour of November 24, there is a low temperature halo around the outline of the irrigation pivot, which could be the result of thermal cooling due to irrigation activities by evapotranspiration of the alfalfa crop (Pezzopane et al, unpublished report). One interpretation offered by Pezzopane et al (unpublished report) is that there is a plume of warmer temperature water uprising in a trough that trends north-northeast towards highway 31. Also of interest in the graph is the decrease in temperature on August 10, which could be attributed to a precipitation event. A more detailed explanation of the 2 meter survey conducted in Paisley can be found in an unpublished report by Pezzopane et al.

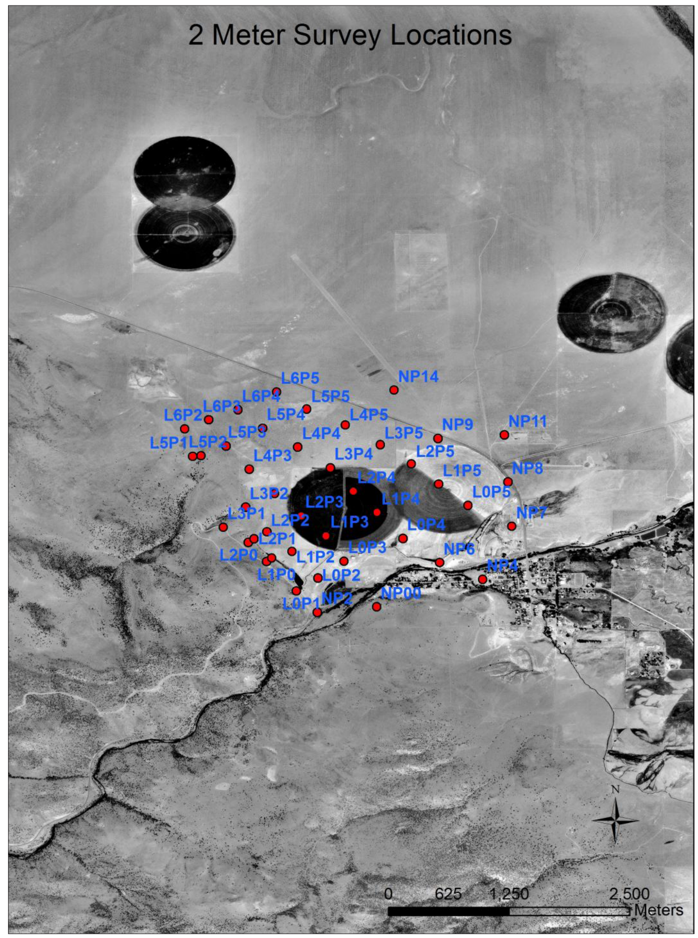

Figure 6. Locations of 2 meter survey points. Labels on blue dots are names of 2 meter stations. Survey area is located just west of the town of Paisley. Refer to Figure 1 for regional location.

Geochemical analysis has been done on ten wells in the Paisley area. Temperatures were calculated using the methods derived in Giggenbach (1988), Fournier (1989), Giggenbach (1991), and described in Powell and Cumming (2010). Figure 8 is a ternary diagram of Cl-SO_4-HCO_3. The Hot Well was sampled at three different times and from this diagram one can deduce that the Hot Well and Corky's Well (CW) lie in the realm of volcanic waters. According to Powell and Cumming (2010), waters that lie within this region could have come from a geothermal reservoir, which is consistent with the fact that they are the two hottest wells of the ten sampled. All other wells reside in the HCO_3 section of the diagram, suggesting they come from peripheral waters. Powell and Cumming (2010) suggest

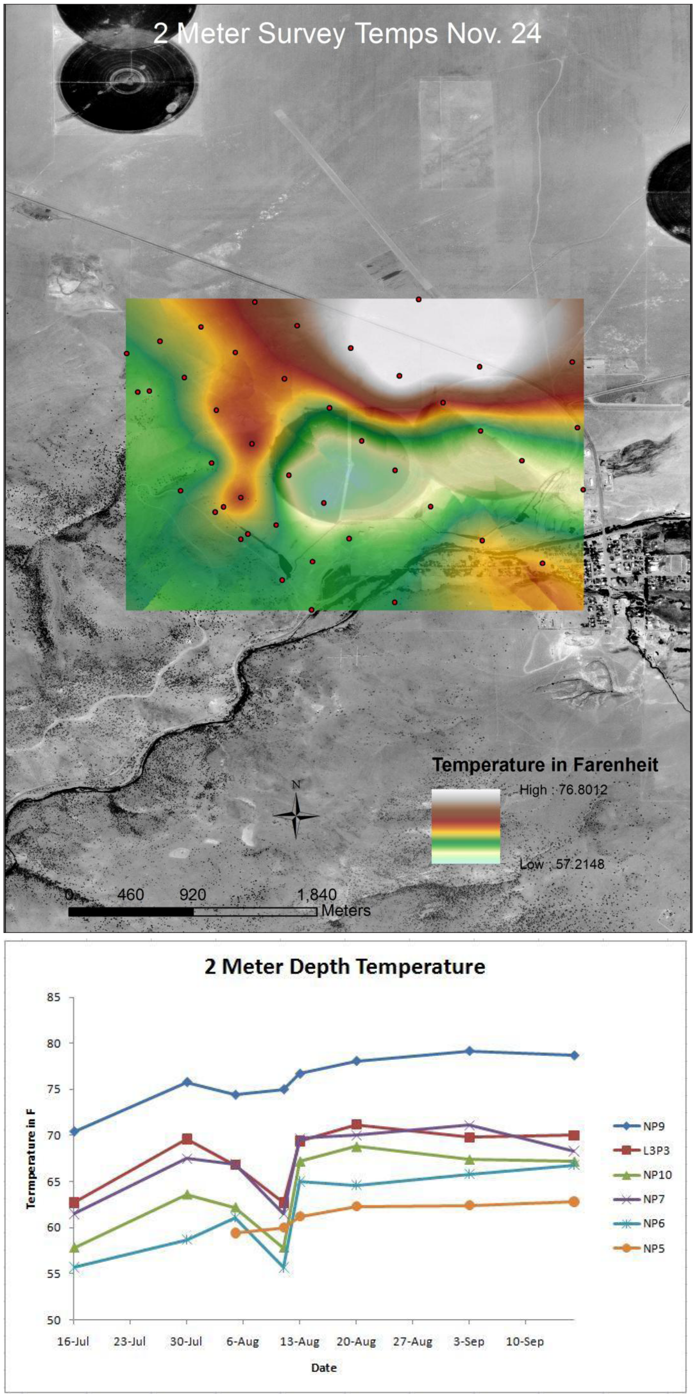

Figure 7. Figure on top is a contour created using the kriging method that shows temperature at 2 meters. Note the decrease in temperature around the irrigation pivot. The graph is a plot showing temperatures at 2 meters for selected points, refer to figure 5 for point locations.

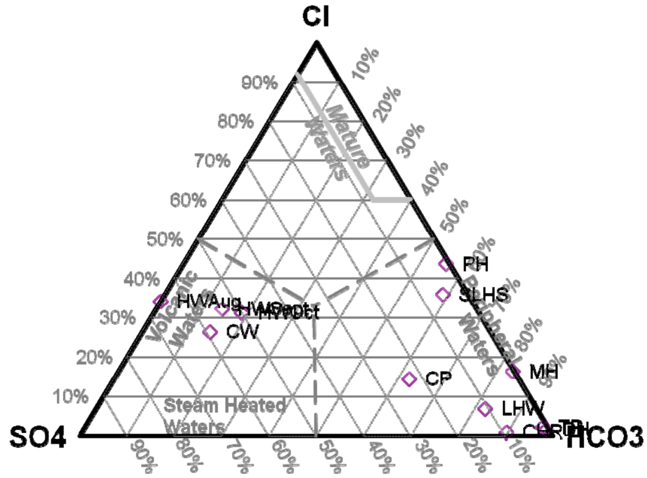

Figure 8. Ternary diagram for Cl-SO_4-HCO_3. The Hot Well and Corky's Well lie within a region interpreted to be associated with magmatic waters (Giggenbach 1988).

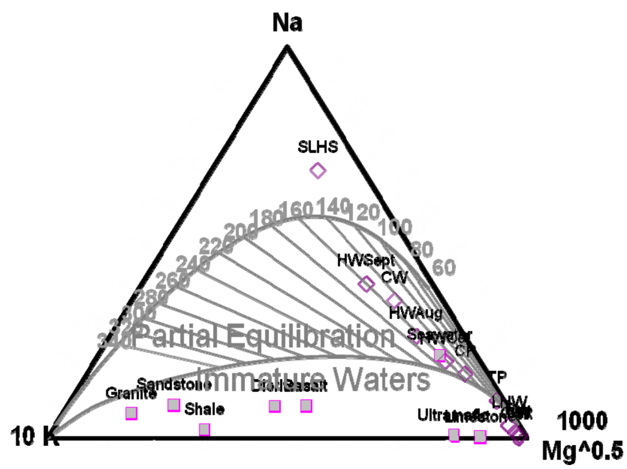

Figure 9. Ternary diagram of Na-K-Mg geothermometer. Refer to text for explanation.

that waters that lie in this part of the diagram could have been heated by a geothermal aquifer.

Figure 9 is a ternary diagram of Na-Mg-K and is considered to be the most commonly used geothermometry plot (Powell and Cumming, 2010). From this diagram one can observe that temperatures for the Hot Well range from 160-166 °C, which is higher than measured temperatures of 112 °C at the bottom of the borehole.

Preliminary stable isotope analysis of hydrogen and oxygen has also been done on the Hot Well. 3 samples were run at Boise State University and are plotted in figure 10 (Powell and Cumming 2010). It is interesting to note that although the Cl-SO_4-HCO_3 diagram suggests this water is interacting with volcanic rocks, the data lies nowhere near the mixing line toward andesitic waters on the isotope figure. The three points plotted in figure 10 lie to the right of the meteoric water line, which is due to the fact that they are depleted in deuterium and enriched in ^{18}O and suggests that there may indeed be, to a lesser degree, water-rock interaction within this reservoir. This could be interpreted as water that is interacting with the reservoir rock but is not in situ long enough to have a strong "andesitic water" signature.

The use of gravity surveys to explore for buried faults has proved to be very useful (Sugihara et al 2002; de Castro et al 2008; Gimenez et al 2009; Meiyin and Bin 2010), with faults shown to display a gravitational anomaly because of the effects faults have on bedrock, i.e. the creation of fault breccias. These breccias are relatively less dense than the surrounding bedrock, which lowers the measured gravity reading.

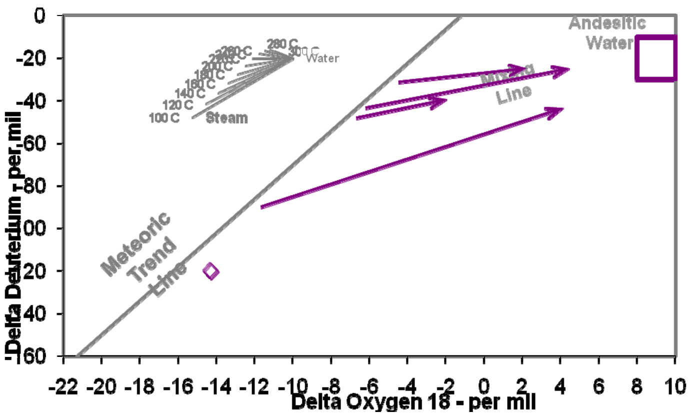

Figure 10. $\delta^{18}O$ vs δD plot showing meteoric water line. Figure adopted after Henley et al (1984) and taken from Powell and Cumming (2010).

Four basic things need to be calculated to obtain the Complete Bouguer Anomaly, and a detailed account of the data reduction process can be found in an unpublished report for Surprise Valley Electrification by Makovsky and Pezzopane. The equations used to reduce the raw gravity data can be found in Holom and Oldow (2007). MATLAB was used to do all the calculations including the terrain correction. The terrain correction takes into account the terrain of the surrounding area, as they can affect the gravity of a point up to 50 km away (Shaun Finn, pers. com., 2011). This correction was prepared by using 10 meter resolution and 30 meter resolution Digital Elevation Models. Figure 11 is the result of the gravity survey conducted at Paisley. Our preliminary interpretation of this data is that the low gravity anomaly is attributed to the hot channel that trends north-northeast identified by the 2 meter survey.

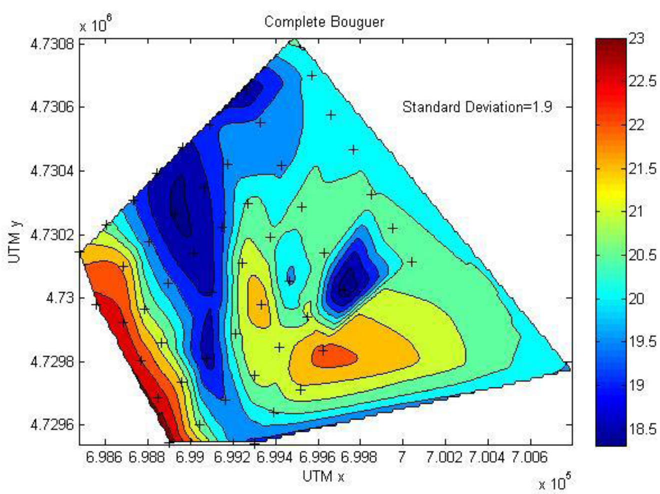

Figure 11. Complete Bouguer Anomaly Map of the Paisley area. High gravity areas in southwest part of map are interpreted as the exposure of denser bedrock adjacent to less dense basin fill, offset by a normal fault. The results of this survey match very well to the conceptual geologic model. Refer to figure 6 for approximate location of gravity survey, as some gravity stations coincide with 2 meter stations. Values are in milligals.

Discussion

The northwest margin of the Basin and Range tectonic province is a geologically complicated area that has many interesting structural and magmatic trends. High to low angle (75-50°) normal faults are the main structural feature and accommodate up 300 meters of vertical offset in the 7 Ma Rattlesnake Tuff near the Paisley area (Scarberry et al, 2010). These normal faults are the expression of the northwestward migration of the Basin and Range Province in the late Tertiary. Two dominant trends persist, with the majority of strain accommodated on NE-SW trending faults. The other trend, which is nearly normal to the main trend direction, could be explained by the accommodation zones of Faulds and Varga (1998). These zones are characterized by en echelon faults, which separate zones of oppositely dipping fault blocks.

Magmatism has also persisted in the northwest basin and range since at least the Mid Miocene (Colgan et al 2006). This magmatism has been shown in the literature to be mostly of a bimodal nature (figure 2). The tectonic implications for this bimodality are controversial and are beyond the scope of this paper. What is important is that the volcanism in this area is young enough to have left behind remnant heat. It is also important because the chemistry of these rocks can be used in conjunction with fluid geochemistry to ascertain a relationship of interaction between the two. Further work and more samples are needed to prove or disprove a relationship between these interactions.

The combination of geologic mapping and the gravity survey have proven to shed important light on the range front fault in Paisley. Although it seems obvious that there should be a fault at the range front, no surficial expression is evident. Geologic mapping provided orientations of faults that run parallel to the range front. This allowed for a confident assumption that there is a fault at the range front and combined with the results of the gravity survey, it is apparent that there is indeed a structural feature at the range front, which has major implications for the placement of the new production well.

The combination of tectonic setting, structural, and magmatic evolution all play a key role in the distribution of geothermal resources in southern Oregon. The goal of this project was to take a site where there is a known geothermal resource and find cost effective techniques that provide useful information about the resource. Most of the results in this paper are preliminary but when finished, promise to shed light on important issues with geothermal resource exploration.

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