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Assessing Structural Controls on Geothermal Fluids from a Three-dimensional Geophysical Model of Warner Valley, Oregon USA

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ABSTRACT

Warner Valley in southern Oregon (USA) is the site of a geothermal system that hosts several hotsprings in addition to Crump geyser – a geysering well that soon after being drilled in 1959 underwent frequent eruptions of boiling water. This, and thermochemical studies that estimate reservoir temperatures of 150°C, have prompted ongoing geological and geophysical investigations.

Warner Valley is situated in a tectonically complex region in the northwest corner of the Great Basin - a basin and range province characterized by east-west extension. The regional geology consists predominantly of Neogene volcanics that have been faulted by a series of obliquely oriented NW and NNE-trending extensional faults. The valley forms an asymmetric graben, with the NNE-trending range front fault along the west Warner escarpement exposing over 600m of section.

Warner Valley seems to be similar to other extensional geothermal systems in the Great Basin, which arise from deep circulation of meteoric water along major normal faults. This is evident in the proximity of Crump Geyser to the principal rangefront fault. Localization of surface hydrothermal features and patterns of borehole temperatures and flow suggest that secondary fault interactions may play a role in controlling geothermal fluids along the rangefront, but their presence within the basin is obscured by the basin fill.

The large contrast in properties (density and magnetic susceptibility) between the basin sediments and volcanic rocks render potential field methods (gravity and magnetics) particularly well-suited to mapping and modeling subsurface geologic structures such as faults that juxtapose contrasting rock types and lead to distinct gravity and magnetic anomalies.

We have performed geophysical studies in Warner Valley and surrounding regions, collecting high-resolution gravity and ground magnetic data along several detailed transects around Crump Geyser as well as regionally to characterize intra-basin and basin-bounding faults, constrain basin geometry, study fault interactions, identify areas favorable to hydrothermal flow, and ultimately to guide exploration of the area's geothermal system.

We have also performed density, magnetic susceptibility, and magnetic remanence measurements on samples from several stratigraphic sections in the hills surround the valley as well as on two ~1000m cores recently drilled near Crump Geyser. We are using these rock-property measurements, along with borehole geophysical logs, to correlate subsurface and outcrop stratigraphies.

These data, along with recent 1:24,000-scale geologic mapping and newly-acquired seismic and airborne magnetic surveys, place critical constraints on 2D and 3D potential field models we are developing of the subsurface around Crump Geyser. Our results reveal buried intra-basin structures that intersect the rangefront at Crump Geyser that we suggest are principally responsible for promoting permeability and facilitating hydrothermal flow within the Crump Geyser geothermal system.

1. INTRODUCTION

1.1 Geologic Setting

Warner Valley forms a narrow north-south trending extensional basin (6.5-8km x 95km) in southcentral Oregon, about 50km east of the town of Lakeview, OR along Highway 140. It is situated in a tectonically complex region in the northwest corner of the Basin and Range province (fig. 1) where east-west extension, typical throughout northern Nevada, fades out northward into the gently warped High Lava Plains. The extension across this region of the Cascadia back-arc has been described as a response to northward propagation of the Walker Lane shear zone, the SE-to-NW expansion of basin and range (Scarberry et al., 2010), and also attributed to deformation in the wake of a northward migrating, clockwise rotating Oregon coastal block (Wells and Simpson, 2001).

The southern Warner Valley, which spans ~30km (from ~12km south of the town of Adel to Hart Mountain), has been faulted by a series of obliquely oriented NW and NNE-trending faults (Walker and Repenning, 1965). This part of the valley represents an asymmetric, nearly half-graben formed by extension which is largely accommodated by slip along the major range front fault along the west Warner Rim at the western edge of the basin. The overall orientation of the valley is NNE trending, but the valley appears to consist of two laterally offset, left-stepping sub-basins. A third and more pronounced step occurs to the north between Crump and Hart Lakes. Several exposed structural blocks at the margins of the valley have sharply defined edges reflecting both NW and

NNE regional fault trends. Several similar structural blocks likely occur within deeper parts of the basin, but are now buried under basin fill.

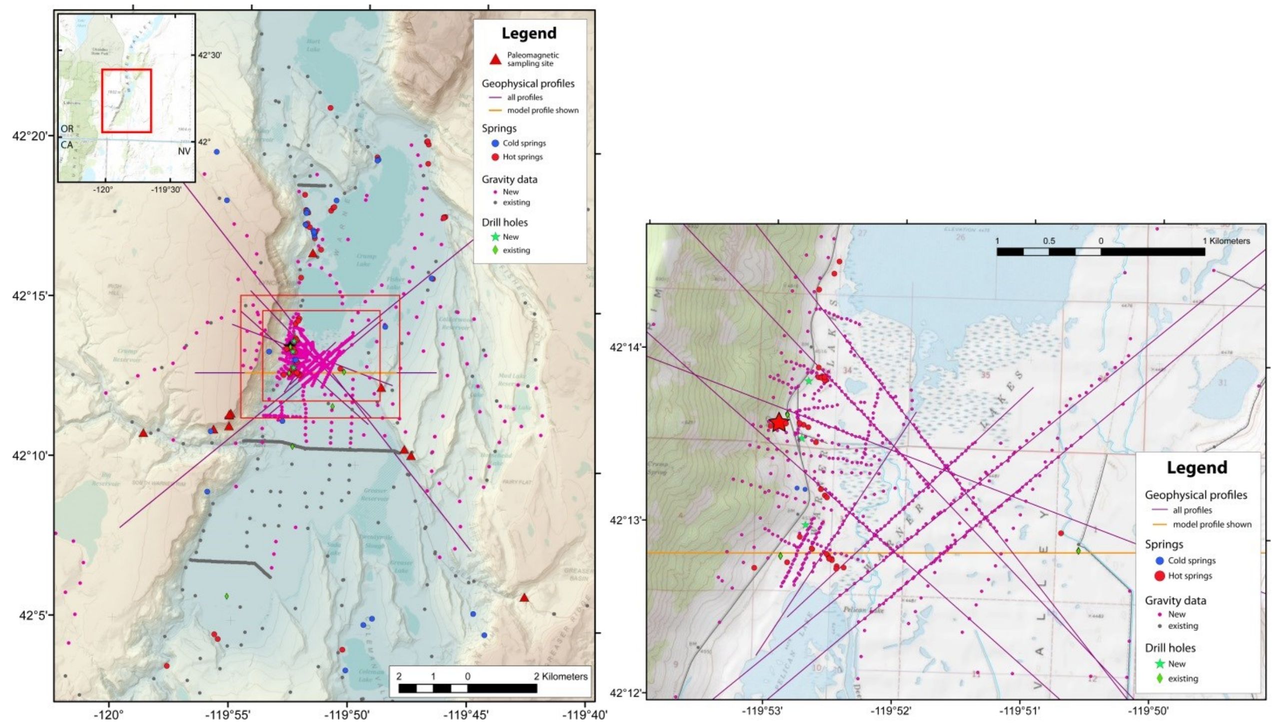

Figure 1a) Regional index map of Warner Valley and surrounding region, south-central Oregon showing physiographic features, locations of 2D profiles used to construct the 3D model (purple lines), gravity stations (circles; grey-existing, pink-new), sampled paleomagnetic localities (red triangles), wells (green symbols; diamonds-existing, stars-new), and springs (large circles; hot-red, cold-blue). Location of 2D model in figure 4 is indicated by the orange line. Red boxes outline the areas shown in subsequent figures. 1b) Local index map of the Crump Geyser area showing gravity stations taken along several detailed profiles located between Pelican and Crump Lakes. Star indicates location of Crump Geyser. See caption for figure 1a for a description of other features. Extent of area shown is indicated by small red box on figure 1a.

The West Warner rangefront fault, which exposes over 600m of Tertiary mafic lavas, tuffs, and tuffaceous sediments on the west side of the valley (Peterson, 1959; Walker and Repenning, 1965; Dooley, 2010), is the most prominent of a set of north-northeast trending basin and range faults in the area that initiated in the late Miocene to early Pliocene. Slickens exposed along this fault at Deep Creek near the town of Adel indicate normal dip slip motion along the fault which is dipping 70°SE (Couch and Johnson, 1968; Casteel, 2010). This is consistent with high angle normal dip-slip motion on a north-oriented fault plane determined from focal mechanisms associated with a seismic swarm that struck the southern Warner Valley in 1968 (Patton, 1985; Wong and Bott, 1995). The focal mechanism plane is consistent with the trend of aftershocks following the swarm (Schaff, 1976). The largest of the earthquakes was an estimated 5.1 magnitude event occurring along the western rangefront north of the town of Adel. Shaking, which led to rockslides and damaged buildings in Adel, was felt 30 miles away in the town of Lakeview, OR.

In addition to the N-NE-trending faults, a set of densely-spaced NW-trending normal faults, that form part of the Eugene-Denio fault zone (a ~75km-wide zone of en echelon normal faults), is also present. One of these faults (striking N40°W, dipping 75°S) near the base of Hart Mountain at the north end of Warner Valley, shows slickens indicating oblique dextral motion (Casteel, 2010). According to Craven (1991) both sets were active in the mid-late Miocene and reactivated during subsequent development of Warner Valley, and offset by later NS shear. Scarberry et al. (2010) suggest that NW-trending structures formed primarily as dilational fractures at the tips of NNE-trending faults, and played an important role in localizing volcanism throughout the NW Basin and Range. NS-trending faults in the southeast Warner Valley and adjacent Coleman Valley, that are typical of those to the south and east in the Basin and Range, do not show evidence of being active prior to development of the Warner Valley (Craven, 1991).

In the vicinity of Crump Geyser, the western Warner escarpment (exposing over 600m of stratigraphy) is characterized by four primary volcanic and volcaniclastic sedimentary units: 1) Pliocene and Miocene HAOT basalts (Tb) that cap the plateau above the escarpment, 2) Pliocene and Miocene pyroclastic rocks and pyroclastic sediments (Ttu), 3) mid-Miocene Steens Basalts (Tsb) and, 4) Miocene to Oligocene trachyandesite (Toma). A significantly compressed section containing these same units (with the addition of a Miocene basaltic andesite (Tba) unit that lies between Ttu and Tsb) is found in the hills bounding the basin to the east in escarpments that expose less than 200m of section (unit designations after Dooley, 2010). This general stratigraphy also occurs within the basin but is now covered with Quaternary alluvium.

Quaternary deposits, occurring within the basin and along its margins, consist primarily of landslide deposits, fluvial sediments, and lacustrine deposits. The range fronts are mantled by talus that covers the lower extents of stratigraphy. Landslide deposits are also common throughout the area. Several have been identified along the base of the west Warner rangefront and extending into the basin (Walker and Repenning, 1965). This is due to the steep slopes, variable density and strength of interbeded flows and tuffs, and active faulting and seismicity. Landslides occurring near Crump Geyser may have been influenced by prominent NW-trending faults seen along the plateau at Lynchs Rim that project into this area.

Lacustrine deposits filling the basin are related to ancient pluvial Lake Warner. In the southern Warner Valley basin, hydrologic well logs reveal sedimentary fill reaching depths of ~250m (Sammel and Craig, 1981). Plouff (2006) estimated maximum sediment thickness to be at least 820m roughly 10km south of Crump Geyser, based on regional gravity data (assuming a density contrast of 0.5g/cc between alluvium and the Tertiary volcanics). In the vicinity of the area modeled in this study, sediment thicknesses from nearby well logs indicate depths to the volcanic-alluvium interface of ~250m. This is consistent with our modeling and with our interpretations of available seismic data.

The large contrast in properties (density and magnetic susceptibility) between the basin sediments, pyroclastic rocks and lava flows render potential field (gravity and magnetic) methods particularly well-suited to resolving subsurface geologic structures such as faults that juxtapose contrasting rock types and lead to distinct gravity and magnetic anomalies. The present study, which involves potential field mapping and modeling, was conducted to study intra-basin crustal structures as an aid to understanding the regional geologic framework of the Warner Valley geothermal area, and in particular the area around Crump Geyser, and to identify structures that may play a role in controlling hydrothermal fluids associated with the Crump geothermal system.

1.2 Geothermal Resources

The southern Warner Valley is the site of a geothermal system with potential for commercial power generation that is characterized by several thermal springs and siliceous sinter mounds. As a result, the regions has been the subject of early (Sammel and Craig, 1981; Plouff, 1975; Gregory and Martinez, 1975; Plouff and Conradi, 1975) and more recent (Plouff, 2006; Hantelmann, 2006; Casteel, 2010) geological and geophysical investigations.

Sammel and Craig (1981) identified at least 20 thermal springs in the area (fig. 1), noting that many of the springs appear to be closely related to faults and fault intersections. The focus of much of the research on the valley's resources has been the Crump Geyser area, a site where many of these springs occur, and a region characterized as an anomalously electrically conductive region (~2x3km wide; Gregory and Martinez, 1975; Hantelmann, 2006).

The Crump Geyser Known Geothermal Resource Area was designated in 1971 by the USGS as one of seven KGRAs in the state of Oregon (Godwin, 1971). The resource was named after Crump Geyser, a 1684ft exploratory geothermal well drilled in 1959 that erupted a > 150ft column of steam and boiling water a couple of days after the well was abandoned (Peterson, 1959). A year later, the geyser ceased to erupt after vandals had plugged the well with rocks and cement. Shortly following this, an older well drilled on the Crump property had undergone sporadic eruptions that continued through the 1970s. Following this, the geyser ceased to erupt naturally but, up until the mid-1990s, the landowners were able to cause eruptions by simply drawing up a bucket they had submerged in the well (Birkby, 2002).

Hot springs around the Crump geyser area display temperatures ranging from 38-56°C and are often associated with siliceous and calcareous sinter mounds (Hantelmann, 2006; Casteel, 2010). The overall distribution of these springs is in a NE trend, though locally the springs appear to align in places along NW-trends, suggesting that both rangefront parallel faulting as well as a secondary NW-trend of fractures may play a role in guiding geothermal fluids to the surface.

Thermochemical studies of geothermal spring waters in the Crump geyser area that estimate reservoir temperatures of 150°C (Molling, 2006). Temperature measurements made in the Crump geyser well during drilling, before it was abandoned, yielded a maximum temperature of 122°C at 200m depth (with a reversal of temperatures below this depth). Measurements made at a second Crump Geyser well yielded a maximum temperature of 122°C at a depth of 12m and showed nearly isothermal temperatures below that to the bottom of the hole at 21m.

The Warner Valley geothermal area seems to be similar to other extensional geothermal systems in the Basin and Range, which arise from deep circulation of meteoric water along major normal faults. This is evident in the proximity of the Crump Geyser to the principal rangefront fault along the Warner Rim. It is unclear, however, whether Warner Valley, like other Basin and Range extensional systems is driven by a deep-crustal, non-magmatic heat source. While it is possible that the Warner Valley geothermal system is related to residual heat associated with Tertiary magma chambers, this possibility seems remote given the youngest volcanic units in the area are the 5-10Ma basalts (Tb) that cap the ranges on both sides of the valley. Geochemical similarities between sampled geothermal fluids and surface waters suggest the geothermal waters may originate from saline lake fluids, however they do not preclude a deep magmatic source.

2. ROCK PROPERTY MEASUREMENTS

Because gravity and magnetic field anomalies reflect variations in the density and magnetic properties of the underlying bedrock, constraining these parameters is essential to deriving relevant potential field modeling results. Density (dry bulk, grain and saturated bulk densities) and magnetic susceptibility measurements were performed on hand samples, paleomagnetic cores, and drill cores taken from the study area.

In general, average grain density of rocks in the region increases from sedimentary, and felsic- to intermediate-igneous rocks, to mafic igneous rocks, consistent with general trends (Olhoeft and Johnson, 1989). Magnetic susceptibilities are low for sedimentary; moderate for felsic extrusive rocks, and highest for mafic volcanic rocks that generally contain more abundant strongly magnetic minerals (note that the magnetization of a rock depends primarily on its content of magnetic minerals such as magnetite; Carmichael, 1982).

Magnetic remanence can also be an important factor in controlling magnetic anomalies, particularly in strongly magnetic volcanic rocks like are found throughout the present study area. For this reason, we have also performed magnetic remanence measurements on paleomagnetic cores and on drill core samples.

This collection of field and laboratory measurements spans all of the major rock units found in the study area and expressed in the potential field models. Model rock properties are based on a combination of these samples and outcrop measurements taken from the study area, as well as data on similar lithologies derived from an national database (unpublished data, D. Ponce, USGS, 2010) consisting of over 17,000 measurements.

Outcrop susceptibility measurements were made using a handheld GF Instruments SM20 susceptibility meter. Typically 12 or more measurements were made over a large (5-10m) extent of the outcrop. Susceptibilities of paleomagnetic samples (including both those drilled from outcrops and from drill cores) were performed using Bartington MS2 and MS3 meters equipped with MS2B sensors.

Density and susceptibility measurements were made on whole core segments from two cores CG35-34 and CG38-34 drilled by ORMAT in 2011 to depths of 3400' and 3100', respectively. Magnetic susceptibilities of drill core segments were measured using an MS3 sensor and passing core segments through an MS2C (80cm diameter) coil.

In general, magnetic susceptibility values ranged from 1-2E-2 SI, for mafic volcanics, to ~1E-3 for tuffaceous units. Saturated bulk densities ranged from ~2.7-2.8g/cc, for mafic volcanics, to ~2.3-2.4g/cc for tuffaceous units. Koenigsberger values for lava flows ranged from 3 to 20.

2.1 Paleomagnetic samples

We collected 157 (2.5cm diameter) cores using a gasoline powered portable drill sampled from outcrops at 31 sites spanning 7 localities and all of the major units present in the study area and represented in the potential field models. We also made use of data reported by Mankinen et al. (1985, 1987) and Watkins and Larson (1966) as well as unpublished data (E. Mankinen, 2012) pertaining to the Steens basalts. In general, at least 6 (but typically 8) samples were taken from each site (a site being a single unit -- e.g., flow or pyroclastic unit) and oriented with magnetic and/or sun compasses. In the absence of sun compass readings, declination corrections were based on either site or section mean corrections, or on the International Geomagnetic Reference Field (IGRF). In the laboratory, cores were cut into 2.5cm long (11cc) specimens.

We sampled drillcore at both the Marine Geology Repository at the College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis and at the rock preparation laboratory at the US Geological Survey (USGS) in Menlo Park, CA using a water-cooled drill presses mounted with a 1in diameter diamond bit. Samples were drilled with their long axes oriented perpendicular to the axis of the drill core. In the laboratory, samples were cut into 2.5cm long specimens (yielding 2 specimens per sample).

Sample magnetizations were measured on a 2G cryogenic magnetometer housed in the shielded room at the USGS Paleomagnetism Laboratory. We applied stepwise alternating field (AF) to samples to determine characteristic and overprint components of magnetization. Prior to each thermal step, susceptibility measurements were typically performed in order to identify changes in the rock magnetic characteristics with temperature. AF demagnetizations were performed with a 2-axis AF demagnetizer. We determined characteristic components of magnetization using least squares principal component analysis (Kirschvink, 1980), and mean flow directions by applying Fisher statistics (Fisher, 1953) and great-circle analysis. Great-circle analysis was particularly useful for obtaining site mean directions in cases where lightning was a problem.

Complete stepwise AF demagnetization (involving 18-27 steps) was applied to at least three samples from each flow, and complete stepwise thermal demagnetization (involving 13-15 steps) to at least one sample per flow. We determined sample directions by applying a least squares linear fit to points on the vector demagnetization plots, or great circle analysis in cases where the characteristic component was not isolated or was poorly resolved. Site mean directions were determined by applying Fisher, great circle, or mixed (line and great circle) statistics to sample directions and great circle fits.

Magnetic remanence measurements were made on 143 and 162 samples extracted from drill cores CG35-34 and CG38-34 drill cores, respectively. Because the drill cores were rotary drilled, azimuthal orientations (and hence declinations) were not recovered. As a result of the loss of declination control, polarity is determined from the inclination data. Primary directions indicate that at least 11 and 8 magnetized zones are represented within the CG38-34 and CG35-34 drill cores, respectively. Based on inclination statistics the mean inclination for normally magnetized samples from CG35-34 is 50°±4.8 (n=78, k=11.7) and for reversely magnetized samples is 40.2°±5.9 (n=58, k=11.2). The shallower than expected inclinations (note the expected geocentric axial dipole field inclination is 61°) can be attributed to the fact that we made no attempt to omit samples reflecting extremely shallow transitional inclinations, and to borehole deviations which amounted to ~5 degrees. In addition, differences between normal and reverse inclinations may be due to unremoved normal overprints that would tend to preferentially shallow reversely magnetized samples resulting in the shallow reverse mean inclination.

3. AUXILARY DATA

Important constraints for the potential field modeling came from several auxiliary sources that included, regional geologic mapping, seismic data from a survey contracted by Nevada Geothermal Power Company (NGP), and borehole and core logs from wells CG35-34 and CG38-34, and a third borehole from which no core was taken (CG34-3, drilled to a depth of 4976'; CG well locations are plotted as green stars in figure 1b).

Geologic mapping of contacts in the ranges bounding the valley were used to constrain unit thicknesses (Walker and Repenning, 1965; Suneson, 1981; Dooley, 2010). Modifications to these contacts were made through detailed comparisons with aerial imagery and the processed maps of the high resolution magnetic survey that proved useful in highlighting unit boundaries.

A high resolution 2D seismic reflection survey was performed for NGPin 2010 consisting of 7 lines that cross the study area in the vicinity of Crump Geyser. The seismic interpretation resulted in identification of 6 seismic horizons and several faults that were correlated between lines. Due to the lack of relevant borehole data that could provide seismic velocity data at the time the interpretations were made, regional data from a nearby valley were used to perform time-to-depth conversions. The lack of calibrated velocity data from the study area, however, limits the ability to evaluate the seismic results and to correlate seismic sections to borehole logs and cores.

Boreholes were correlated based on borehole- and core-logs as well as measurements performed on core samples. These correlations were challenging due to the fact that all three holes were drilled in close proximity to the rangefront near Crump Geyser, located 1-2km west of the center of the modeled area. The lack of core from hole CG34-3, and casing that extended to thru the upper 2500ft, hampered efforts to reliably correlate this hole to the other two. In addition, it is difficult to rely on the lithologic interpretations from this hole based on cuttings, particularly due to the presence of a large landslide in this area that may constitute a significant part of the uppermost stratigraphy in this hole (as well as the other two). Correlation between the two cores is aided by geophysical measurements performed on the cores for density, magnetic susceptibility, and magnetic remanence.

4 POTENTIAL FIELDS

Geophysical methods allow imaging of subsurface geologic bodies and structures and are useful in geothermal exploration to the degree that structures or contacts controlling fluids are associated with density and/or magnetic contrasts that will generate anomalies useful for mapping and modeling. Variations in gravity and magnetic fields occur due to lateral contrasts in rock density and magnetic properties (magnetic susceptibility and remanent magnetization). Rock-property contrasts may occur within a rock unit, (e.g., lateral facies changes), across geologic structures (faults or folds), or at contacts with other rock units. The geometry and depth to sources, the character of the geomagnetic field, and the rock properties of sources all determine the character of a source's potential field anomaly. Despite the complexity and non-uniqueness of potential fields, gravity and magnetic data can be effectively used to resolve the geometry and origin of sources, particularly when combined with other geologic constraints.

Potential field methods are useful in geothermal resource exploration because they often highlight structures (fault or fracture zones, or geologic contacts) that may play a role in guiding geothermal fluids in the subsurface. In Warner Valley, the physical properties of mafic volcanic rocks contrast strongly with the surrounding tuffaceous and sedimentary rocks to produce prominent gravity and magnetic anomalies. In addition, geothermal activity may lead to characteristic changes in the density and rock-magnetic properties, producing gravity and magnetic anomalies that can be used to successfully map hydrothermal deposits and alteration of the country rock. We use detailed potential field data, integrated with geologic, paleomagnetic, drill core, and borehole data to understand the structure and character of the Warner Valley.

4.1 Gravity

A total of 971 new gravity data were collected for this project to improve regional coverage in areas of sparse control and provide detailed coverage (30-100m station spacing) along a series of profile lines in the area of Crump Geyser (fig. 1). This included several stations obtained around the lake edges, along the west Warner escarpment, and in the hills east of the valley. In addition, we collected several stations located on islands within Crump Lake that we accessed by boat. These fill large holes in the gravity station coverage and help to critically constrain the gravity in those portions of the study area. Nonetheless, significant holes still remain over Crump and Pelican lakes and across the west Warner escarpment and Warner plateau.

The majority of regional stations were accessed by car, while difficult-to-access stations around the lake edge were reached using All-Terrain-Vehicles (ATV). Detailed profile data were obtained on foot. Due to the wet ground conditions in swampy areas around the lakes, we sometimes employed the use of a tripod on which the gravity meter was placed during measurements.

In order to produce a gravity map reflecting lateral variations in density in the crust, raw gravity measurements were reduced using standard gravity reduction methods (Dobrin and Savit, 1988; Blakely, 1995) that correct for: (a) the tidal effects of the moon and sun; (b) instrument-drift due to drift in the instrument's spring; (c) variations of the Earth's gravity with latitude; (d) , variations in gravity due to elevation relative to sea level; (e) the attraction of material between the station and sea level; (f) the effect of the Earth's curvature; (g) the effect of topography (applied to a radial distance of 167 km around the station); and (h) long-wavelength variations in the gravity field related to the compensation of topographic loads.

New gravity data were combined with pre-existing gravity data. Pre-existing gravity data from the surrounding areas were compiled from a variety of sources (Ponce et al., 2009; Plouff, 2006; Pan-American Center for Earth and Environmental Studies - PACES, 2009), edited, and re-reduced. Data were then gridded using minimum curvature algorithms to produce the gravity maps shown in this report. The resulting map (fig. 2) reflects anomalies that arise from variations in density in the subsurface and can aid in identifying faults and contacts.

4.2 Magnetics

The magnetic map (fig. 3) for the model area was derived from a high resolution airborne survey flown for the NGP in 2010 using an ultra-light aircraft. The survey was flown with an average terrain clearance of 123m along NS-oriented lines spaced 100m apart, and along EW-oriented tie lines spaced 400m apart.

The magnetic map reveals variations in the magnetic field that arise from contrasting magnetic properties of rocks, such as variations in remanent magnetization or the amount and type of magnetic minerals. The shallower the depth of a body, the higher the amplitude, the shorter the wavelength, and the sharper the gradients of its magnetic anomaly.

Although crustal fields depend on both induced and remanent crustal magnetization, remanence is often ignored because in many cases its magnitude is negligible or because its direction lies close to the induced field direction. Remanence however, may have a significant effect, particularly in the case of strongly magnetic units such as mafic and ultramafic rocks like many of the basalts and basaltic andesites that occur throughout the study area.

We also collected extensive ground magnetic data (using several different platforms) to obtain high resolution data over near surface faults and contacts that may not be resolved by aeromagnetic data. Ground magnetic data were taken on foot along the gravity profile lines. ATV-magnetometer systems (Athens et al., 2011) were deployed to collect data along roads and levees, and a boat-borne magnetometer system was used to collect data on Crump Lake.

4.3 Potential field processing

In processing the magnetic and gravity data, we applied a variety of derivative and filtering methods that aid in interpretation by helping to delineate structures and to constrain their geometry (features such as intra-basin or basin-bounding faults or contacts).

Difference or residual maps are useful for emphasizing surface and near-surface sources. They are produced by upward-continuing the observed anomalies and subtracting the result from the original grid. This effectively removes the contribution of deeper sources. Matched bandpass filtering methods (Syberg, 1972; Phillips, 2001) applied to the frequency spectrum of potential field data can be used to isolate anomalies arising from different crustal levels, provided that the depths of anomaly sources are sufficiently distinct.

Reduced-to-pole and pseudogravity (or magnetic potential) transformations (Blakely, 1995) are useful for simplifying magnetic anomalies by centering them over their sources. The pseudogravity transformation is applied to magnetic data in order to isolate broad magnetic features that are often masked by high-amplitude shallow magnetic sources. The pseudogravity transform converts a magnetic anomaly into one that would be observed if the magnetic distribution of the body were replaced by an identical density distribution. Although there are significant assumptions that can limit the effectiveness of this method, it can be useful because it significantly simplifies the interpretation of magnetic sources.

Maximum horizontal gradients (MHG; Blakely and Simpson, 1986) of gravity and pseudogravity reflect abrupt lateral changes in the density or magnetization of the underlying rocks, and tend to lie over the edges of bodies with near vertical boundaries. They are therefore useful for estimating the extent of buried sources (Grauch and Cordell, 1987; Cordell and McCafferty, 1989), and to define the boundaries of geophysical domains, and internal domain structures. Geophysical domains are defined in part with the MHG method, but also with other filtering and derivative methods that aid in highlighting the regional structural grain. Regions with a consistent anomaly trend, amplitude, or frequency content are defined as distinct geophysical domains, and assumed to represent discrete crustal blocks with similar physical properties or sources.

We have also applied a tilt derivative method (Salem et al., 2007) to estimate the depth to magnetic sources. This method can be used to determine source depths (assuming sources have vertical contacts) from contours of the magnetic tilt angle, which is a normalized derivative based on the ratio of the vertical and horizontal derivatives of the reduced-to-pole field.

5. GEOPHYSICAL MAPS

A large gravity gradient along the west edge of the valley is associated with the rangefront fault at the west Warner escarpment that juxtaposes low-density valley fill with dense volcanic rocks in the footwall block. Gravity highs in the study area (occurring along the west Warner range, over the low hills between Crump and Hart lakes, and east of Crump Lake) reflect dense mafic volcanic rocks (fig. 2). In contrast, gravity lows reflect low density sedimentary or tuffaceous rocks that are found within the Warner Valley basin. A prominent gravity low (10-15 mGal), occurring in the southern Warner Valley and centered on a region 2-3km south of the town of Adel, was interpreted by Plouff (2006) as reflecting a thick (up to ~820m) section of basin sediments. New detailed gravity data collected within the study area suggests the basin narrows and shallows to the north towards Crump Geyser region (fig. 2b). Another less pronounced low occurs to the north over Crump Lake that similarly suggests a shallowing and narrowing of the basin southwards. This produces an hourglass-like shape to the valley floor that tapers in the vicinity of Crump Geyser.

Prominent magnetic highs and lows in in the study area (fig. 3) reflect strongly magnetic mafic volcanic rocks that outcrop or occur in the shallow subsurface. Moderate highs reflect moderately magnetic rocks (such as tuffs) or buried mafic volcanic rocks within the basin. Moderate magnetic lows occurring within the basin typically reflect weakly magnetic, low density sedimentary rocks.

The magnetic map reveals pervasive NW and NE-trending magnetic fabrics that resemble the regional fault sets seen in surrounding ranges and characterizing the rangefront faults bounding the valley. High amplitude, short wavelength anomalies are observed over hills east of Crump Geyser (triangular shaped structural block) and between Crump and Hart Lakes (northern portion of the aeromagnetic survey; fig. 3a), reflecting exposed, strongly magnetic, volcanic rocks.

Several moderate amplitude magnetic highs occurring within the basin (e.g., dashed-outlined area in figure 3b) are interpreted as relatively shallow fault-bounded structural blocks (consisting of the same general stratigraphy as the surrounding ranges - strongly magnetic volcanics and interbeded tuffs) buried beneath Quaternary lacustrine sediments. These blocks are similar in size to the triangular-shaped structural block east of Crump geyser, and appear to be bound by the dominant regional fault sets (NW and NE-trending).

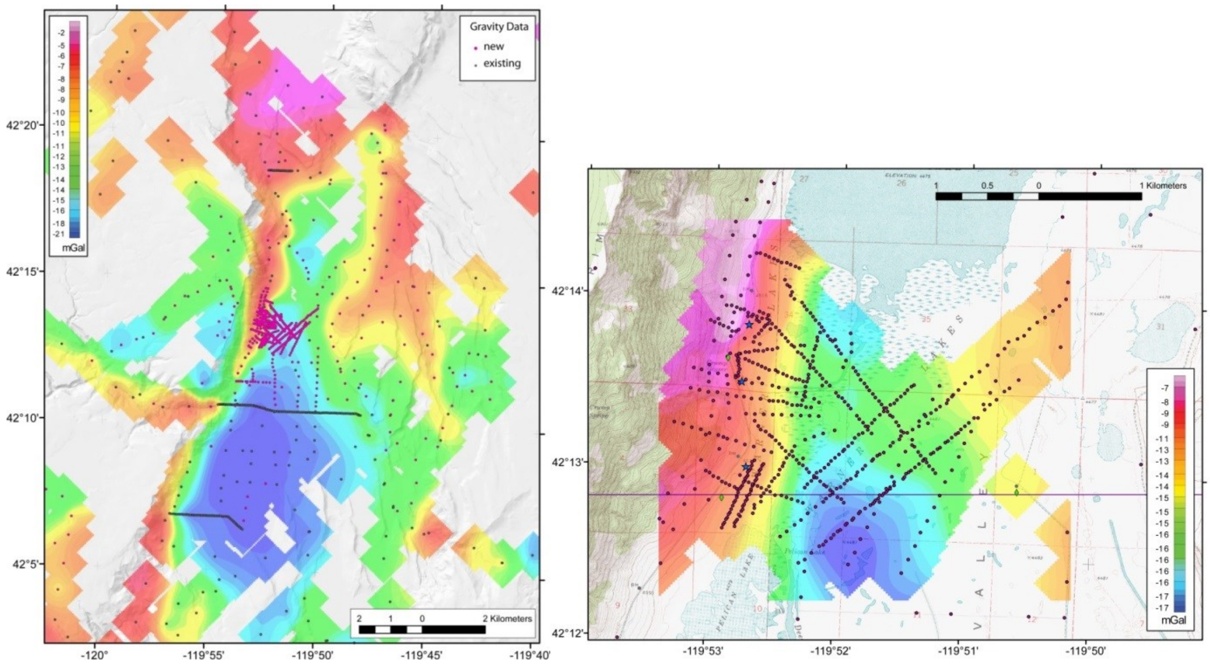

Figure 2a) Regional isostatic gravity map of Warner Valley and surrounding region, south-central Oregon showing existing (grey symbols) and new (pink symbols) gravity stations. Extent of area shown is the same as in figure 1a. 2b) Isostatic gravity map of the Crump Geyser area (same area shown in figure 1b). Note that the gravity grid is poorly constrained in areas to the north and southeast where there is a lack of data. See caption for figure 1a for a description of other features.

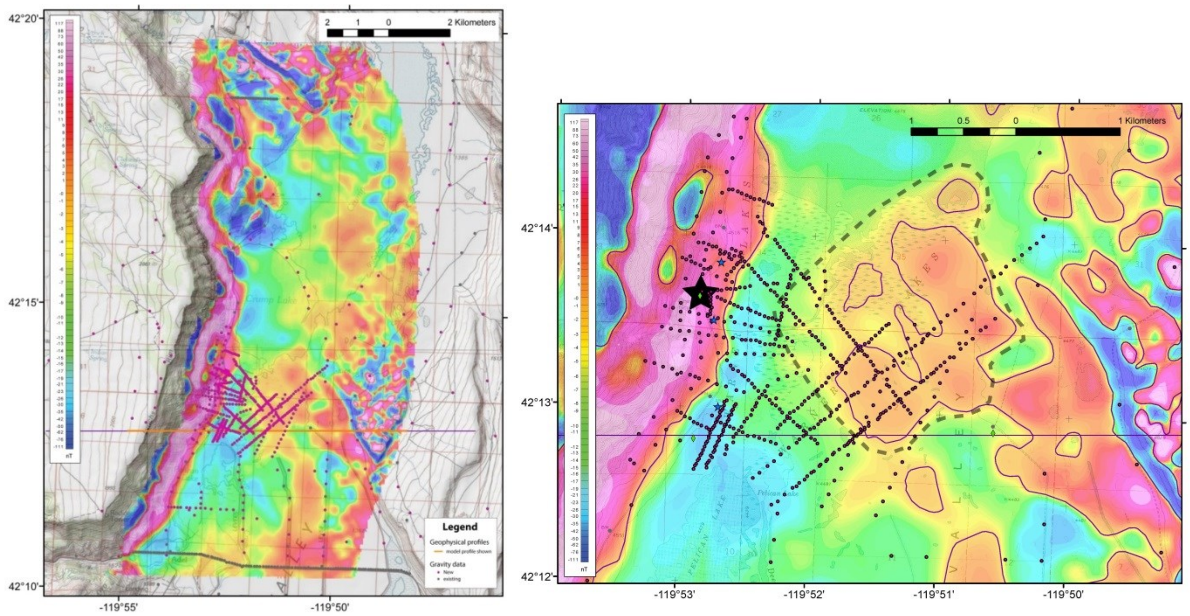

Figure 3a) Residual reduced to pole magnetic field of the high-resolution ultralight aeromagnetic survey of the southern Warner Valley. Gravity stations are shown for reference to other maps. Extent of area shown is indicated by large red box on figure 1a. 3b) Residual reduced to pole magnetic field map of the Crump Geyser area. See caption for figure 1a for a description of other features. Crump Geyser is shown by the large black star. The residual map highlights shallow-sourced anomalies such as the intra-basin block inferred here and outlined with a dashed line.

6. PROFILES AND MODELING

Two-dimensional potential field models were constructed along several intersecting 2D profiles (locations shown in figure 1) across the study area, that were chosen based on key structures inferred from both gravity and aeromagnetic data. These 2D models were then used as the initial input to build the 3D model.

6.1 2D Models

The 2D profiles were selected to 1) include the highest density of gravity data, 2) coincide with seismic profiles and drill holes, and 3) run roughly perpendicular to the strike of geologic units or structures of interest (fig. 1). Subsurface geology was approximated by horizontal tabular prisms or blocks that varied in the ± Y directions (commonly referred to as 2¾D modeling).

The surface extents of model blocks were constrained to be consistent in size, shape and orientation with mapped geologic units. The subsurface geometries of the model bodies were determined through a series of forward and inverse calculations (whereby density and magnetic properties of 2D bodies were adjusted iteratively) to match model anomalies with observed anomalies within the limits imposed by surface geology, rock property data, and maximum horizontal gradients (MHG) that are useful for estimating the horizontal extent of buried sources.

Forward modeling of this type (Talwani et al., 1959; Blakely and Connard, 1989) can critically constrain viable structural models, especially when combined with geologic (bedrock, drilling) and other geophysical data. Seismic horizons were imported into the model and used to constrain the general trend of subsurface units in the vicinity of the seismic survey. Structural boundaries were interpreted from MHGs of gravity and magnetic data, and tilt derivative solutions were used to guide depth to the top of magnetic sources.

Although potential field models are relatively effective at constraining the depth to the top of an anomaly's source, or the location and dip of its edges, they are relatively insensitive to the depth of a source's base, and therefore characterize the shallow and deeper crust with different degrees of detail. In addition, potential field forward models are critically dependent on the modeling assumptions inherent in the simplification of complex geology by discrete geometric blocks. Because of the inherently 3D structure of this area, 3D modeling is required to adequately characterize the geometry of the structure and surrounding features.

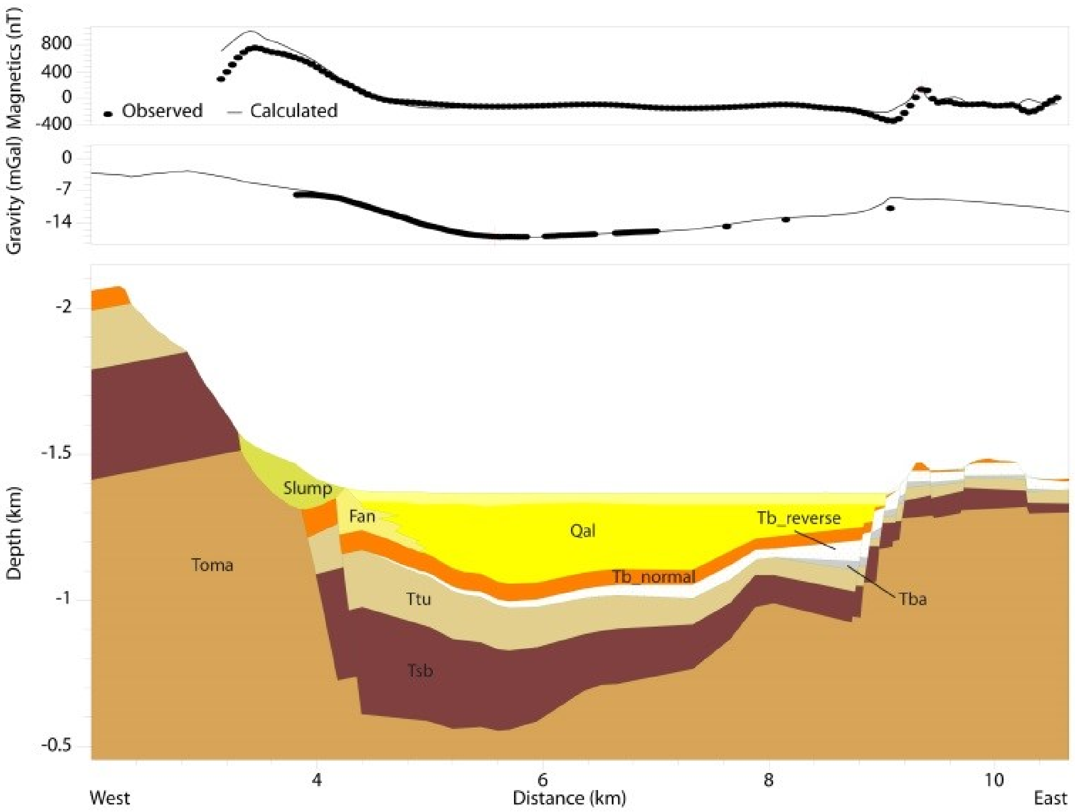

Figure 4) Two-dimensional potential field model (see figure 1 for profile location). The top and middle panels show observed (black circles) and model (black line) anomalies for magnetic and gravity fields, respectively. The lower panel shows the potential field model with individual model bodies colored by rock unit. . Location shown on Figure 1b.

6.2 3D Model

We are presently developing a 3D potential field model of the Crump Geyser geothermal area (fig. 5). The first step towards constructing the 3D model involved exporting surfaces defined as the top or bottom surfaces of layers from our 2D profile models (e.g., fig. 4). This required simplifying the geology, resulting in some features in the 2D models not being represented in the 3D model.

The exported 2D surfaces, together with outcrop constraints, were gridded, within a model area of 6x10km, to produce a set of 9 grid layers from which the 3D model was initially constructed. Once all the layers were in place, the 3D model was then modified through a series of forward and inverse steps to minimize the error between observed and calculated anomalies.

In developing model layers, we followed the unit designations of Dooley (2010), but have excluded some minor units that are only expressed south of the modeled area. We have also split Dooley's unit Tb into two parts based on magnetic remanence measurements that indicate the formation spans normal and reverse polarity chrons. In the model, each surface (layer) represents the top of a particular unit. These include (from top to bottom in model order): Slump material on the west side of the valley (equivalent to the topographic surface), Quaternary fan and talus deposits (Qf), Quaternary lacustrine deposits (Qal), normally magnetized Pliocene and Miocene basalts (Tbn), reversely magnetized Pliocene and Miocene basalts (Tbr), Miocene basaltic andesites (Tba), Pliocene and Miocene pyroclasic rocks (Ttu), mid-Miocene Steens basalts (Tsb), Miocene to Oligocene trachyandesites (Toma). Herein, we will refer interchangeably to units and the model layers that represent their tops. We note that this order was imposed largely for modeling convenience and does not imply the actual stratigraphic order of units.

Upcoming field work to collect additional data in the basin, surrounding ranges, and on Crump and Pelican Lakes (using a hovercraft and sea-borne gravity meter) will help to better constrain the 3D model where there is little to no existing data coverage. Despite the preliminary nature and ongoing development of the 3D model, the model results yield depths to the alluvium-volcanic interface consistent with that projected from the closest deep wells, and regional depths-to-volcanic basement consistent with that inferred from seismic profiles (estimated depths of the deepest basin fill east of Crump Geyser are on the order of 300 m).

The deep crustal structure of the model is poorly constrained, however, due to the fact that most of the area in the eastern Cascades, High Lava Plains, and northwest Basin and Range is extensively covered by relatively undissected Tertiary volcanics that effectively conceal pre-Tertiary stratigraphy and crystalline basement. As a result, most of the complexity in the model occurs in the shallow-level crust with only the deepest portions extending to depths of 2 km. Despite this lack of detail in the deeper extents, the model is capable of accounting for much of the observed anomalies because it is more sensitive to shallow crustal sources.

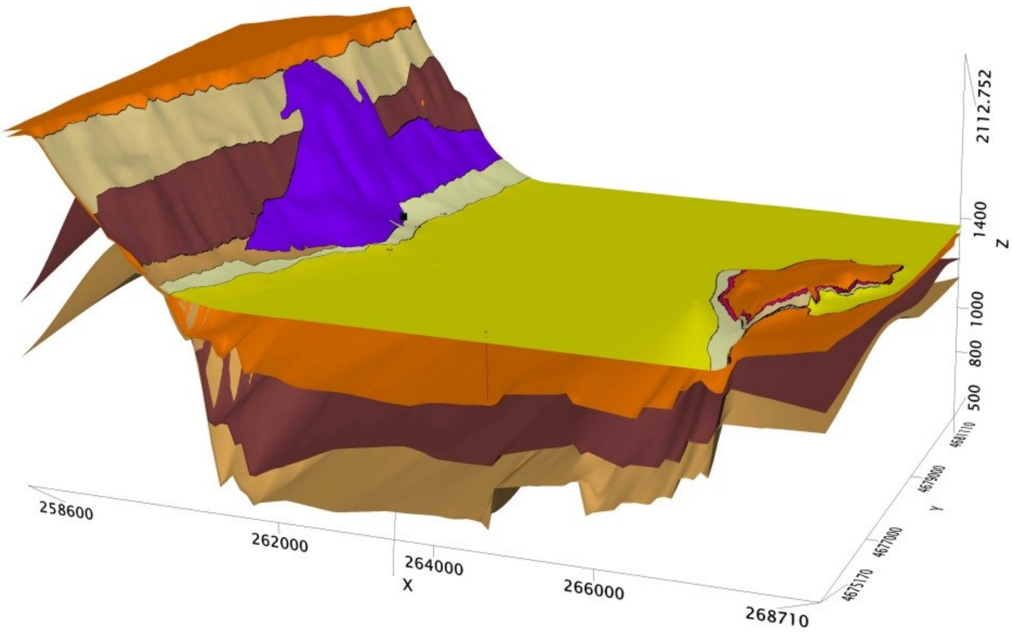

Figure 5) view (looking northwest) of 3D model showing tops of unit layers as colored surfaces (Slump material - purple, Quaternary deposits - yellow, Pliocene and Miocene basalts - red, Miocene basaltic andesites - grey, Pliocene and Miocene pyroclasic rocks – light tan, mid-Miocene Steens basalts - brown, Miocene to Oligocene trachyandesites – dark tan). Black dot indicates location of Crump Geyser.

7. DISCUSSION

Existing geologic, geochemical, and geophysical data suggest that the Crump Geyser area in the southern Warner Valley is an active geothermal field that has the potential for power production. The presence of numerous hotsprings, as well as a local electrical conductivity anomaly around the Crump area (revealed by resistivity and magnetotelluric studies that show a ~2x3km wide region immediately around Crump Geyser; Gregory and Martinez, 1975; Hantelmann, 2006), indicate the presence of shallow warm saline geothermal fluids.

These indications highlight Crump as an important site of geothermal fluid flow in the shallow subsurface but do not: identify possible sources of the deep geothermal reservoir, suggest pathways the geothermal fluids take from deeper crustal levels to the surface, explain why upflow is confined to a relatively narrow (2-3 km long) zone along the fault, or reveal much about the longevity of the system around Crump. New geophysical data lend insight into the geothermal system that is relevant to addressing these issues.

High-resolution ground and airborne magnetic data reveal that the Crump area is characterized by a northeast-trending magnetic low immediately east of the rangefront (fig. 3) and largely coinciding with mapped hotsprings and sinter mounds. Lows like this can result from hydrothermal alteration whereby thermal fluids, interacting with the host rock, result in changes of rock chemistry and mineralogy. A striking example of this is documented by studies of hydrothermal areas in Yellowstone National Park (Finn and Morgan, 2002; Bouligand et al., 2014), show hydrothermal areas are often characterized by pronounced magnetic lows resulting from hydrothermal alteration that destroys magnetic minerals such as magnetite by transforming them into weakly magnetic minerals such as hematite, goethite, montmorillonite, and pyrite.

If the cause for the low is indeed due to alteration then the geothermal system in this area must have been active sufficiently long enough that hydrothermal fluids could effectively alter a large enough volume of the substratum (to a significant degree) that the low would be discernable. This would suggest that the present geothermal activity in the Crump area is not simply a recent manifestation, or transient (e.g., following an historic slip even similar to the seismic swarm that occurred in the 1950's). Future efforts, to perform more detailed analyses of the magnetic data to may allow for estimating the volume of subsurface alteration (e.g., following the methods of Bouligand et al., 2014) associated with shallow thermal fluid circulation around Crump, while other aspects of the potential field data help to infer the source of reservoir fluids and the deeper pathways of geothermal fluid flow.

Various models have been proposed for the source and circulation of thermal fluids. Geochemical data from spring and well waters suggest that recharge of the geothermal reservoir may originate from saline lake fluids migrating down through the basin sediments to reach the underlying basement (Casteel, 2010). It is possible however that the geochemical data may be explained by thermal fluids having come in contact with a magmatic source, in which case recharge would not require a saline source but could come from the local groundwater originating at high elevations in the west Warner Range.

An alternative to closed basin circulation was proposed by Casteel (2010) who suggested geothermal fluids may originate beneath the Warner Range and migrate updip through permeable horizons within the volcanic stratigraphy where they eventually intersect the main rangefront fault. Both scenarios (closed or open-basin circulation) predict focused upflow along the primary NNE-trending rangefront fault, but they do not account for why the fluids are locally restricted to the region around Crump Geyser.

In addition, these models cannot account easily for borehole temperature data that show consistent reservoir temperatures (250-260°F) in near-surface outflow and at >3000ft along the range front fault in two recently drilled deep core wells, but only shallow outflow only in a third well (see fig. 1 for new well locations). If the source of geothermal fluids was simply stratigraphic, we would expect a more extensive deep temperature anomaly along the range front wherever it intersects the permeable layers conducting the geothermal fluids. We suggest that the localization of hydrothermal features and patterns of borehole temperatures and flow are likely the result of enhanced permeability at the intersection of intrabasin structures with the rangefront fault.

If geothermal fluids originate from circulation within the footwall block (as suggested by Casteel, 2010), it is possible that NW-trending faults observed along the plateau of the west Warner Rim may be responsible for directing the fluids towards the Crump area. An alternative explanation would be needed to account for the focused upflow of thermal fluids if circulation was restricted to within the basin. In this case, intrabasin structures would need to be called on since it is unlikely that the NW-trending faults on plateau extend into the basin. Detailed gravity and magnetic data collected in the vicinity of Crump Geyser offer clues to why shallow circulation of thermal fluids is localized around Crump, and where the deeper fluids originate.

Potential field data provide information on the shape of the basin and reveal basin structures that likely play a critical role in influencing intrabasin fluid flow. High-resolution gravity data indicate the southern Warner Valley basin forms an hourglass–shape that pinches and shallows towards Crump Geyser. The cause for the narrowing of the basin is revealed by magnetic data that indicate the presence of a buried crustal block occurring in the basin immediately east of Crump Geyser, and bound by NE and NW-trending faults. This rhombic-shaped block is oriented such that its corner points towards the Crump area, constricting the basin in this part of the valley. Trans-tension across this region could cause this intrabasin block to rotate and impinge on the footwall of the west Warner rangefront, localizing stress and promoting fracturing and permeability around Crump Geyser that would provide a pathway for deep hydrothermal fluids to reach the surface.

The intrabasin block may be related to structural accommodation associated with the transition between the two laterally offset sub-basins. While the southern Warner valley has a general NNE trend, it appears to consist of two laterally offset, left-stepping sub-basins, with Crump (and the intrabasin block) occurring at the transition between the two basins (note that a third and more pronounced step occurs to the north between Crump and Hart Lakes). This resembles what may be an oblique synthetic accommodation zone (e.g., Faulds and Varga, 1998) that cuts northwest across the valley, and accommodates differences in strain distribution occurring to the north and south of Crump, between the two sub-basins. If so, this could account for the localization of shallow fluid flow around Crump Geyser by leading to fracturing and faulting that would provide pathways for mid-level thermal fluids to reach the surface.

Deeper circulation, on the other hand, may result from a more regional control of basin geometry on fluid flow. The deepest part of the basin, revealed by a prominent gravity low (located 10 km south of Crump Geyser), may represent one source of fluids that feed the hot springs in the Crump area. Fluids residing in the volcanic basement and blanketed by a thick section of thermally insulating sediments may be influenced by the shape of the basement/sediment interface (that shallows and narrows towards Crump Geyser). In this scenario, thermal fluids driven by buoyancy, would flow from the deep basin northwards upslope through the basement and along the sediment-basement interface until they intersect the permeable zone around Crump that provides a path to the surface.

8. CONCLUSIONS

The Crump Geyser geothermal area in southern Warner Valley is located in a tectonically complex region in the northwest basin and range, as manifest by several interacting obliquely-trending fault sets that occur throughout the valley and surrounding ranges. We set out to perform combined geological and geophysical investigations to map and model the basin and buried intra-basin structures to better understand the geothermal field, the source of geothermal fluids, and the factors controlling subsurface fluid flow.

High-resolution ground and airborne magnetic data reveal a magnetic low largely coinciding with mapped hotsprings and sinter mounds around Crump geyser that may result from hydrothermal alteration imposed by fluids migrating along rangefront-parallel, intra-basin faults related to Tertiary-to recent basin extension, with intersections of northwest-trending fractures possibly focusing fluid flow locally. If so, the geothermal system in this area must have been active for a sufficient amount of time to alter a significant portion of the substratum, indicating that the present geothermal activity in the Crump area is not simply a recent manifestation.

The proximity of Crump Geyser to the rangefront together with geochemical data from spring and well waters suggest that lake brines, circulating down through the basin and returning along the main rangefront fault, are a likely course of the thermal fluids. Potential field data provide new detail into the shape of the basin and reveal basin structures that likely play a critical role in influencing intrabasin fluid flow.

Regional gravity data define a deep basin located 10 km south of Crump Geyser that may represent a reservoir of the geothermal fluids residing within the volcanic basement and insulated by a ~1 km thick blanket of intrabasin sediments. High-resolution gravity data indicate that the basin pinches and shallows at Crump Geyser. One possible scenario is that the thermal fluids, controlled by the shape of the basement/sediment interface, are funneled from south to north towards Crump Geyser where they intersect a permeable zone around springs that transmit fluids to the surface.

The cause for the narrowing of the basin is revealed by magnetic data that indicate the presence of a buried crustal block occurring in the basin immediately east of Crump Geyser. The block is oriented such that its corner points towards the Crump area, constricting the basin in this part of the valley. Trans-tension across this region may be causing the block to rotate and impinge on the footwall of the west Warner rangefront, localizing stress and promoting fracturing and permeability around Crump Geyser necessary for deep hydrothermal fluids within the volcanic substratum to reach the surface.

The complex network of interacting faults that occur throughout the southern Warner Valley presents significant challenges to deciphering what structures are important to the plumbing of geothermal fluids. In tectonically active, complex areas where Quaternary alluvium conceals key features, geophysical mapping is critical to providing insight into these structures. Our present efforts build a fully-3D stress model of the area is helping to better characterize the structural setting of the Crump Geyser geothermal area and identify favorable pathways for fluid flow and the deep circulation of fluids.

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