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3D geophysical and hydrologic characterization of geothermal systems in Warner Valley, Oregon USA

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ABSTRACT

Warner Valley in southern Oregon (USA) hosts a geothermal system characterized by several thermal springs and siliceous sinter mounds. Crump geyser, that issued from a well soon after being drilled in 1959 on the west side of the valley, underwent frequent eruptions of boiling water. These manifestations prompted several geological, geochemical, and geophysical investigations of the valley's geothermal resources. The present work focuses on 3D potential field modeling, incorporating a diverse range of datasets, aimed at characterizing the structural setting of the natural hydrothermal system around Crump geyser.

Warner Valley forms a narrow north-south trending extensional basin that developed as an asymmetric graben in a tectonically complex region situated in the northwest corner of the Basin and Range Province. The regional geology consists predominantly of interbedded Neogene sediments and Neogene to Paleogene volcanics that have been faulted by a series of obliquely oriented NW and NNE-trending extensional faults. The large contrast in rock properties (density, magnetic susceptibility, and magnetic remanence) between the basin sediments and volcanic rocks renders 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 result in distinct gravity and magnetic anomalies.

We performed high-resolution gravity and ground magnetic surveys locally around Crump Geyser, as well as regionally, to constrain basin geometry, characterize intra-basin faults that are obscured by basin fill, and study fault interactions. Furthermore, this work is aimed at identifying areas favorable to hydrothermal flow that will help guide further exploration of the area's geothermal system. We also performed rock-property measurements on samples from several stratigraphic sections in the region, as well as on two ~1000m cores recently drilled near Crump Geyser to constrain model properties.

Our modeling efforts began with a series of intersecting 2D profile models across the area that extend through existing wells and integrate information from: recent local-scale geologic mapping, seismic and airborne magnetic surveys, well cuttings and core, borehole geophysical logs, and rock property measurements to correlate subsurface and outcrop stratigraphies.

We built in mapped contacts and fault interpretations into the models, and incorporated surfaces from seismic interpretations, which provided useful subsurface control on some structures. Further control on these structures and constraints on additional structures were determined from the potential field data. Maximum horizontal gradients of magnetic (pseudogravity) and gravity (isostatic) grids were used to constrain the lateral extent of faults and contacts, and we used tilt derivative calculations to estimate the depth to magnetic source solutions, which provided initial estimates of depth-to-magnetic basement.

We exported horizons from the 2D models to build 3D surfaces for import to the initial 3D model. We developed the 3D model through a series of forward manipulations, and structural and property inversion steps. Property inversions began with average rock properties and were permitted to vary within the range of measurements determined from rock property samples. In addition, we integrated results from 3D voxel-based magnetic vector inversions to aid in modeling the vector magnetization of strongly magnetic volcanic units whose magnetizations are not well constrained by outcrop rock property measurements. Combined, these methods provide better control on subsurface stratigraphy and structure to guide exploration drilling and hydrologic models.

Mapping and modeling results reveal buried intra-basin structures that intersect the range front at Crump Geyser. We suggest these fault intersections, as well as the geometry of the basin, are important for promoting permeability and facilitating hydrothermal flow within the Crump Geyser geothermal system. To test this, we perform preliminary heat and groundwater flow simulations to evaluate our conceptual model of reservoir location, heat accumulation, and hydrothermal fluid delivery via structurally controlled outflow zones deduced from the potential field results.

1. INTRODUCTION

1.1 Geology, structure and tectonics

Warner Valley forms a narrow north-south trending extensional basin (6.5-8km x 95km) in southern Oregon. It is situated in a tectonically complex region of the Cascadia back-arc (fig. 1) where east-west basin and range extension fades out northward into the gently warped High Lava Plains. Deformation across this region has been attributed to a combination of SE-to-NW expansion of the basin and range (Scarberry et al., 2010) and northward propagation of the Walker Lane shear zone.

The southern Warner Valley 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 on the major range front fault along the west Warner Rim at the western edge of the basin. While the overall orientation of the valley is NNE-trending, 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.

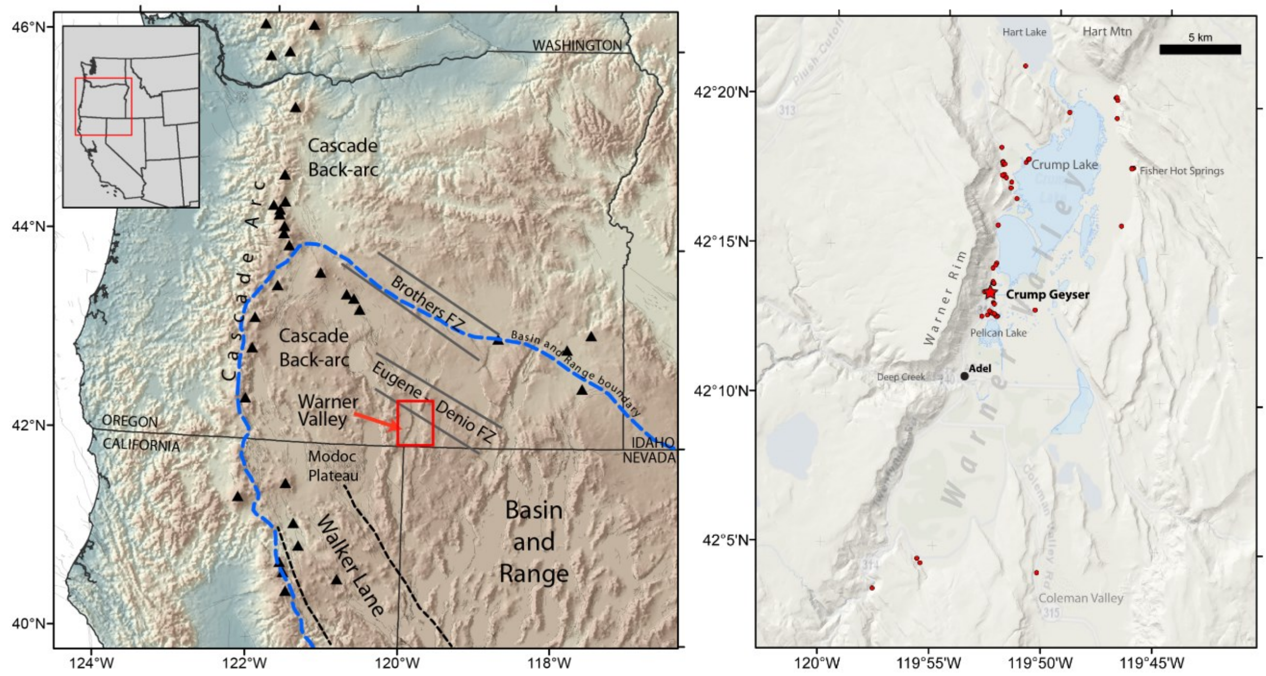

Figure 1) Regional index maps showing location of Warner Valley. (Left) Color shaded relief of the Pacific Northwest showing various physiographic and volcano-tectonic features. (Right) Shaded relief of Warner Valley in south-central Oregon showing physiographic features and hot springs.

The West Warner range front 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 NNE 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 also 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 range front, north of the town of Adel. This historical seismicity indicates the region is tectonically active and suggests the range front fault system is a zone favorable to fracturing that may provide important pathways for fluid flow associated with the valley's hydrothermal system.

In addition to the NNE-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 were offset by later NS dextral shear. Scarberry et al. (2010) suggests 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 structural development of Warner Valley (Craven, 1991).

In the present study area, the western Warner escarpment 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 range front and extending into the basin (Walker and Repenning, 1965). This is due to the steep slopes, variable density and strength of interbedded 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 along the Warner 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 renders potential field (gravity and magnetic) methods particularly well-suited to resolving subsurface geologic structures such as faults that juxtapose contrasting rock types. The present study, was conducted to characterize the regional geologic framework of the Warner Valley geothermal area, and to identify key structures that may play a role in controlling hydrothermal fluid flows in the area around Crump Geyser.

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 region 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, Sass et al., 2005). 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 range front 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 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 range front 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. POTENTIAL FIELD DATA

Geophysical methods allow imaging of subsurface geologic bodies and structures and are useful in geothermal exploration, to the degree that structures or contacts controlling fluid flow 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 field geophysics, 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.

2.1 Gravity

Gravity maps were produced from a collection of new (~1000 stations) and existing data (Glen et al., 2015). New gravity data were collected to improve regional coverage in areas of sparse control and provide detailed coverage along in the area of Crump Geyser (fig. 2). Gravity data were reduced using standard gravity reduction methods (Dobrin and Savit, 1988; Blakely, 1995, Glen et al., 2015). These data were then gridded using minimum curvature algorithms to produce the gravity maps shown in this report. The resulting map (figs. 2, 3) reflects anomalies that arise from variations in density in the subsurface and can aid in identifying faults and contacts.

A large gravity gradient along the west edge of the valley is associated with the range front 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 locations of dense mafic volcanic rocks (fig. 2) in the shallow subsurface. In contrast, gravity lows typically reflect locations of 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 this basin narrows and shallows to the north towards the Crump Geyser region (fig. 2). 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.

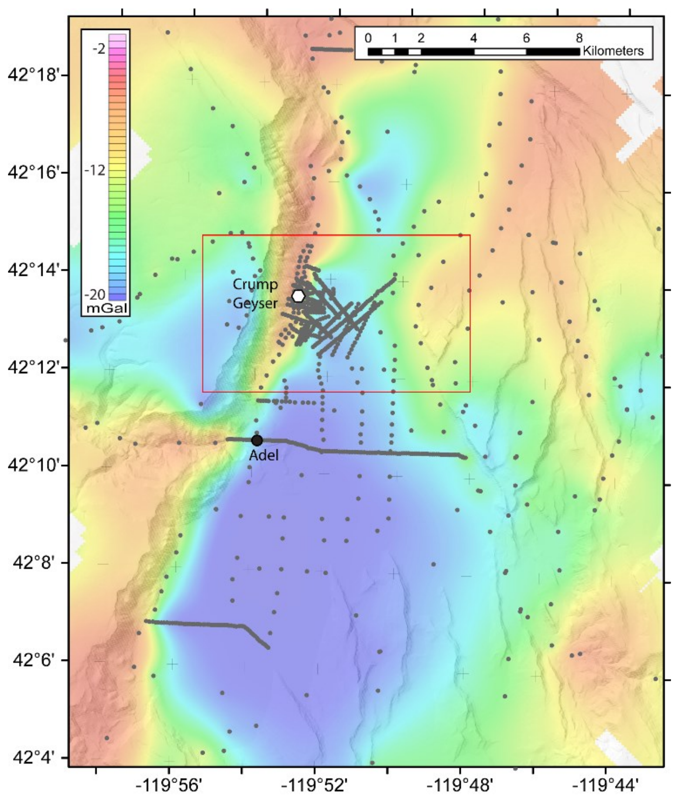

Figure 2. Isostatic gravity map of Warner Valley and surrounding region, showing gravity stations (grey dots), extent of 3D potential field model (red rectangle), and location of Crump Geyser (white pentagon).

2.2 Magnetics

The magnetic map (fig. 3) for the study area, derived from a high resolution airborne survey (Glen et al., 2015), 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. Shallower magnetic bodies produce anomalies that have higher amplitudes, shorter wavelengths, and sharper gradients along their boundaries. In addition, a regional aeromagnetic survey, flown with a constant flight elevation of ~2.1 km above sea level and a flight line spacing of ~l.6 km (Plouff and Conradi, 1975; Plouff, 2006), was used to control the regional field beyond the extent of the high resolution survey.

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.

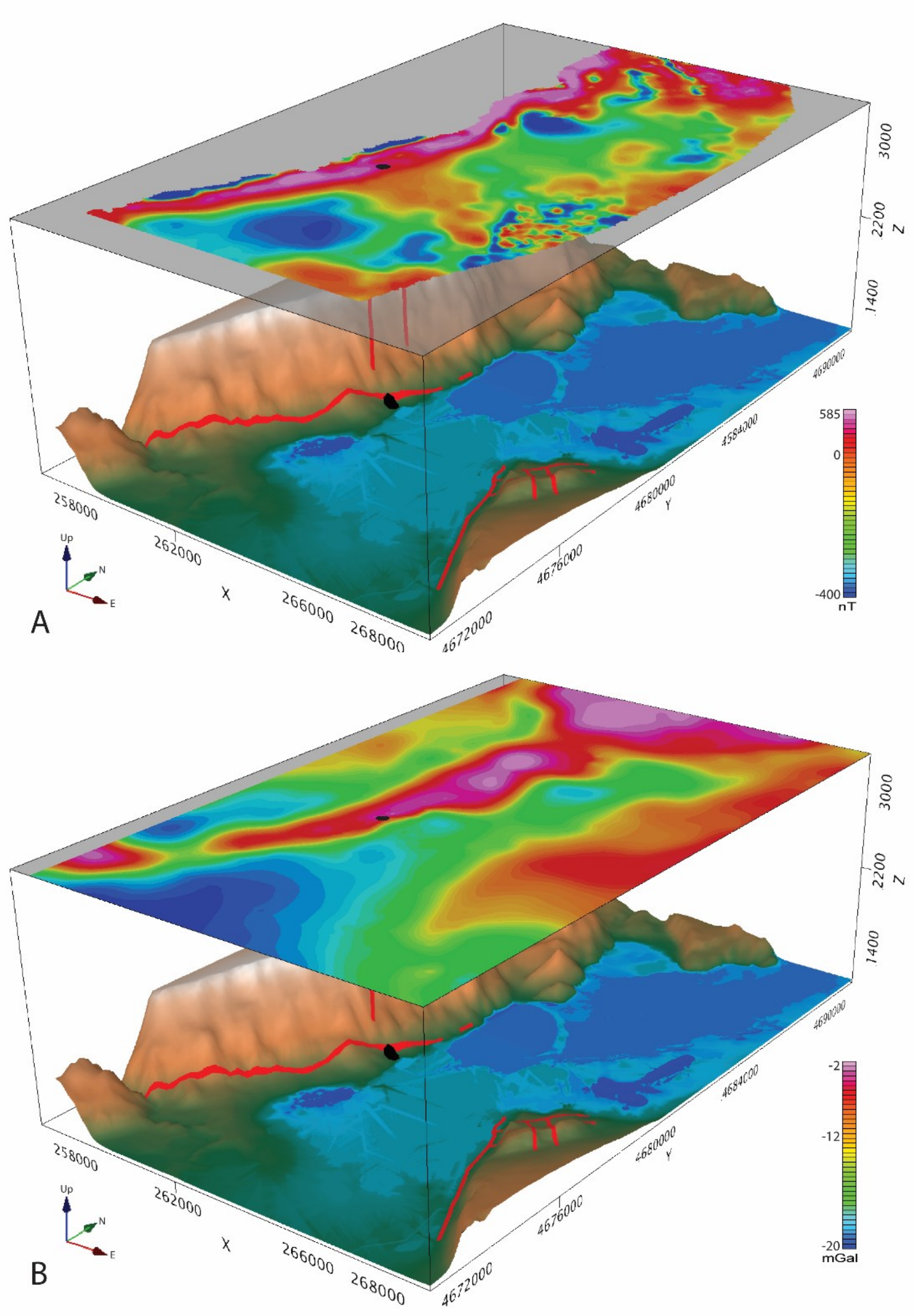

Figure 3: View of study area (looking northwest) showing color shaded relief of topography and grids of A) magnetic field, and B) isostatic gravity. Faults, shown in red, are draped on the topographic surface. Crump Geyser is identified by a black circle on topographic surface and potential field maps.

Prominent magnetic highs and lows in the study area (figs. 3,4) 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 sedimentary rocks.

The magnetic map reveals pervasive NW and NE-trending magnetic fabrics that resemble the range front faults bounding the valley, and the regional fault sets seen in surrounding ranges. 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. 3), reflecting exposed, strongly magnetic, volcanic rocks.

Several moderate amplitude magnetic highs occurring within the basin (e.g., dashed-outlined area in figure 4) are interpreted as relatively shallow fault-bounded structural blocks (consisting of the same general stratigraphy as the surrounding ranges - strongly magnetic volcanics and interbedded 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).

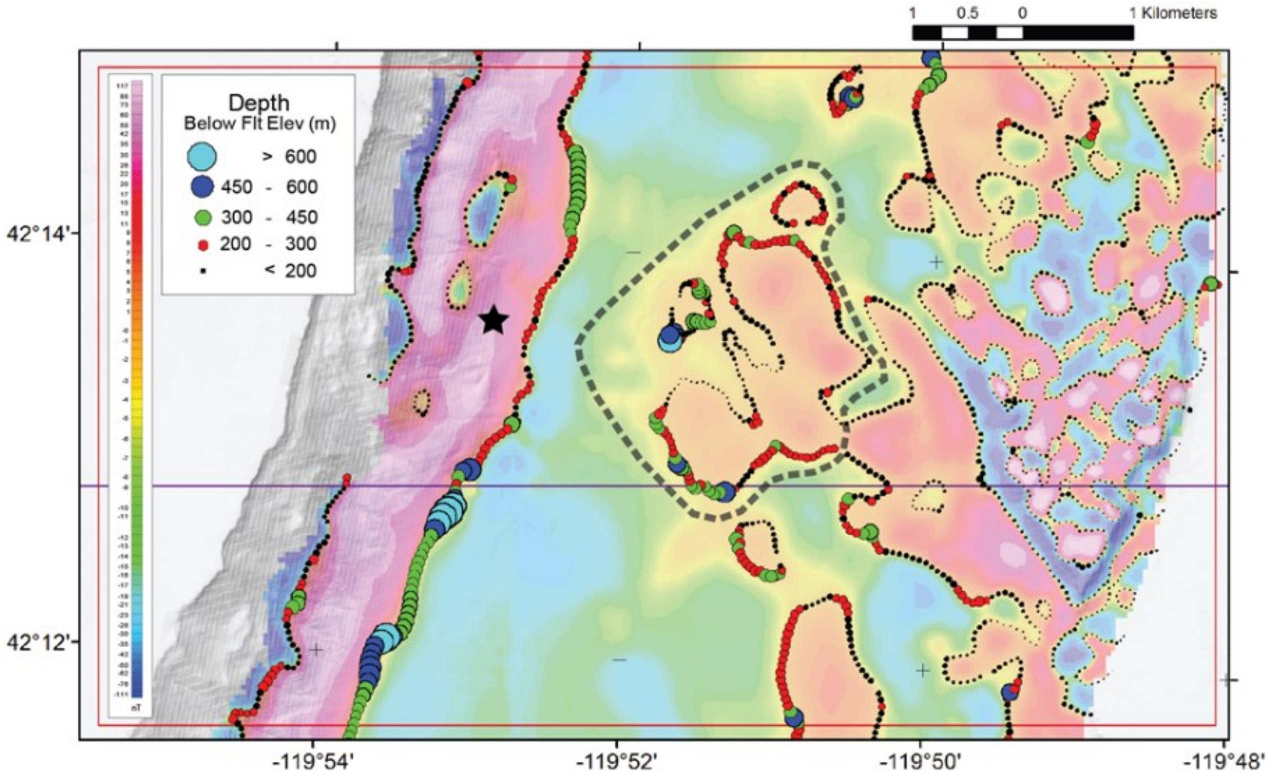

Figure 4) Residual reduced to pole magnetic field of the 3D model area. This map highlights buried source anomalies such as the inferred intra-basin block (outlined with a thick grey dashed line). The map also shows tilt derivative solutions that estimate depth to magnetic sources. The results reveal the range front fault on the west side of Warner Valley, the triangular shape of the magnetic sources impinging on the Valley from the east, and the increasing depth of those magnetic sources from east to west. The red rectangle shows the extent of the 3D model area. The purple line indicates the location of the Suneson profile shown inf figure 6. Crump Geyser is shown by the large black star.

3. MODELING CONSTRAINTS

3.1 Rock properties

Because gravity and magnetic field anomalies reflect variations in the density and magnetic properties of subsurface rocks, constraining these parameters is essential to deriving relevant potential field modeling results. Density (dry bulk, grain and saturated bulk densities) and magnetic property (susceptibility, remanence) measurements were performed on hand samples, paleomagnetic cores, and drill cores (CG35-34 and CG38-34 drilled by ORMAT in 2011 to depths of 3400' and 3100', respectively) taken from the study area.

Average grain density of rocks in the region generally 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 when strongly magnetic volcanic rocks are present, as they are throughout the present study area. For this reason, we have also performed magnetic remanence measurements on paleomagnetic cores and on drill core samples (Note that drill core samples yielded Koenigsberger ratios and magnetic inclination from which polarity was interpreted).

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 in-house national database (unpublished data, D. Ponce, USGS, 2010) consisting of over 19,000 measurements.

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.

3.2 Other constraints

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), 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').

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 NGP in 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 range front 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 through 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.

3.3 Filtering and derivative methods

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.

3.3.1 Boundary analysis

Maximum horizontal gradients (MHG; Blakely and Simpson, 1986) of gravity and pseudogravity grids 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.

3.3.2 Depth to source estimates

We used the Tilt Derivative method (Verduzco et al., 2004; Salem et al., 2010) to estimate depth to magnetic source from the aeromagnetic survey conducted over the valley (Glen et al., 2015). This technique maps the contacts between magnetic source bodies and estimates the depth to those contacts below the flight elevation. The Tilt Derivative solutions (fig. 4) constrain the range front fault on the west side of Warner Valley, outline the triangular shaped fault block impinging on the valley from the east, and reveal the increasing depth of buried magnetic sources from east to west.

4. THREE-DIMENSIONAL MODEL CONSTRUCTION

Two-dimensional potential field models were constructed along several intersecting 2D profiles (locations shown in figure 5) 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.

4.1 Two-dimensional profiles

We developed 2D forward potential field models along twelve profiles (fig. 5). 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, or to aid in constraining the 3D model (e.g., the four EW-oriented profiles). Subsurface geology was approximated by horizontal tabular prisms, or blocks, that varied in the ± Y directions (commonly referred to as 2¾D modeling).

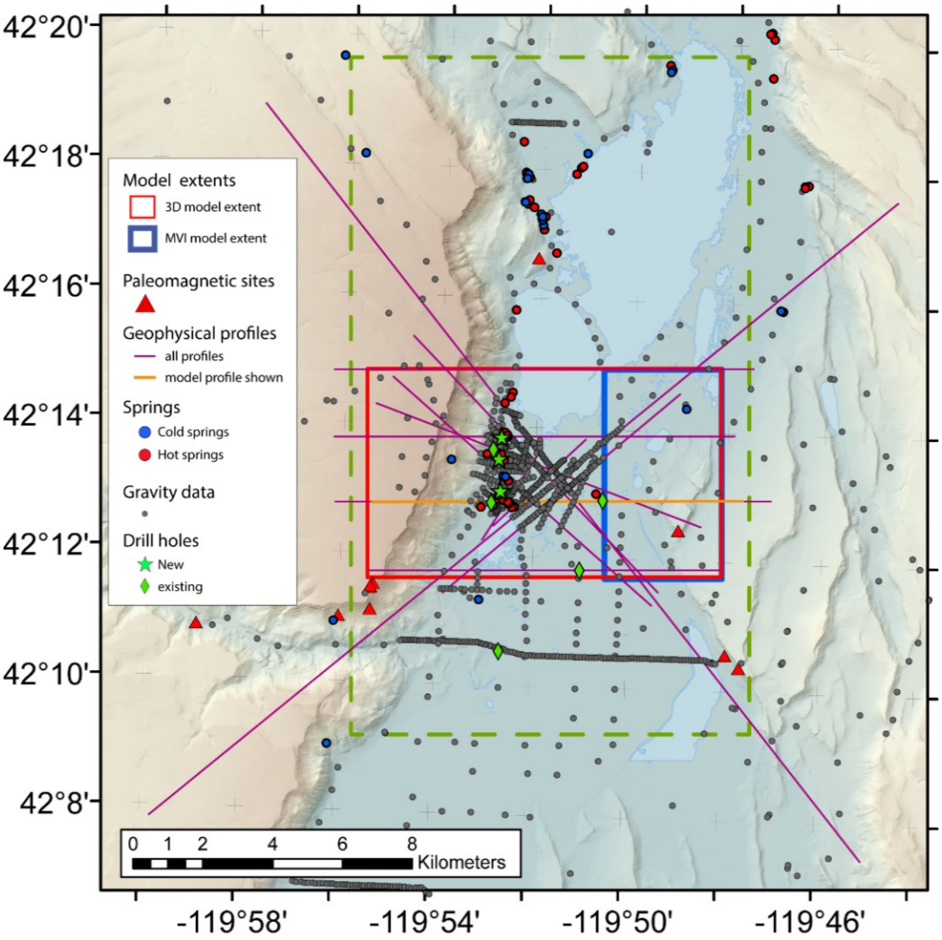

Figure 5A: Regional index map showing data coverage, 2D model profile locations, and extent of 3D and MVI models. Dashed green polygon shows the area of figure 3.

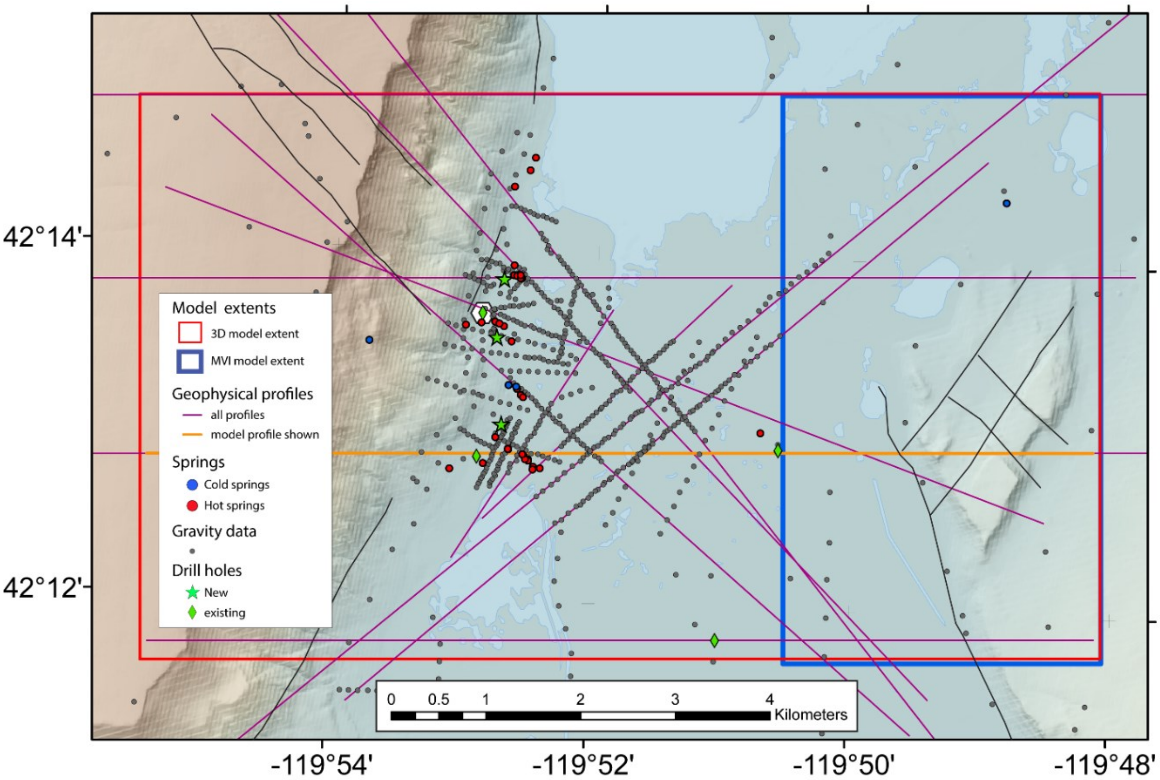

Figure 5B: Local index map of the study area. Mapped faults are shown as black lines. The location of Crump Geyser is shown by a white pentagon. The location of the 2D profile model (figure 6) is shown by an orange line.

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 the modeled 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. An example of one of these models along the Suneson profile is shown in figure 6.

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.

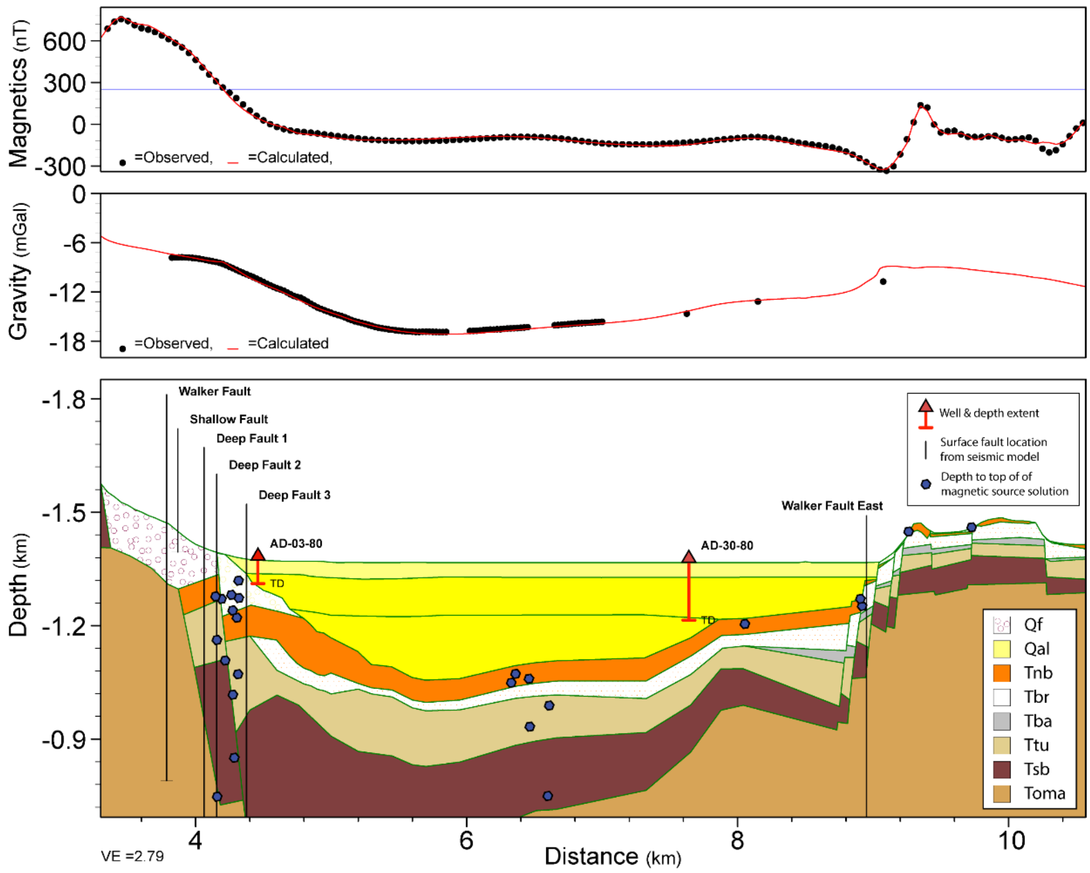

Figure 6: Two-dimensional potential field model along the Suneson profile (location shown by orange line in figure 5). The top two panels show observed (black circles) and calculated model (red line) anomalies for magnetic and gravity fields. The lower panel shows the potential field model with individual model bodies colored by rock unit. Also shown are, wells (AD03-80, AD-30-80), faults interpreted from the seismic survey (labeled), and depth to top of magnetic source solutions (blue circles) estimated from the Tilt Derivative method that were used to help guide the magnetic modeling process (displayed are solutions from a 675 meter wide polygon centered on the profile).

4.2 Three-Dimensional Modeling

Below we describe 3D potential field models we developed of the Crump Geyser geothermal area (fig. 7) using a series of forward manipulations and structural and property inversion steps, as well as 3D voxel-based magnetic vector inversions.

4.2.1 Forward model

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., figs. 5, 6). 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 pyroclastic 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.

The deep crustal structure of the model is poorly constrained, 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, the deepest portions of the model extend only to depths of 2 km, with most of the model complexity occurring in the shallow-level crust. 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. The model results for depths to the alluvium-volcanic interface are consistent with those projected from the closest deep wells, and regional depths-to-volcanic basement are consistent with those inferred from the seismic profiles (estimated depths of the deepest basin fill east of Crump Geyser are on the order of 300 m).

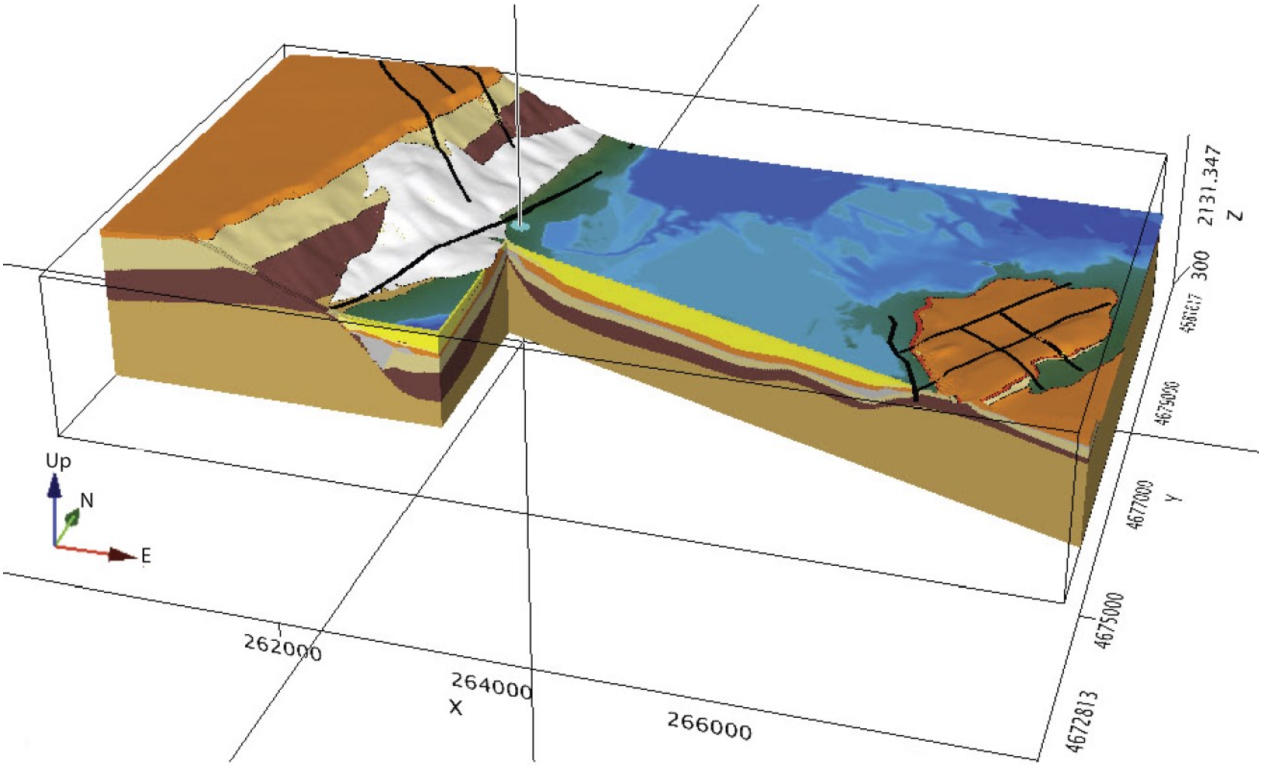

Figure 7: Cutaway view of 3D model (looking north northwest) showing model rock units colored by lithology (see figure 6 for legend and text for unit descriptions). Faults are shown in black. Vertical crosshair is centered on Crump Geyser.

4.2.2 Three-dimensional voxel-based inversion

We also performed 3D voxel-based magnetic vector inversions (fig. 8) to aid in modeling the vector magnetization of strongly magnetic volcanic units whose magnetizations are not well constrained by outcrop rock property measurements. By integrating these results with the forward 3D model, we provide better control on subsurface stratigraphy and structure to guide exploration drilling and hydrologic models.

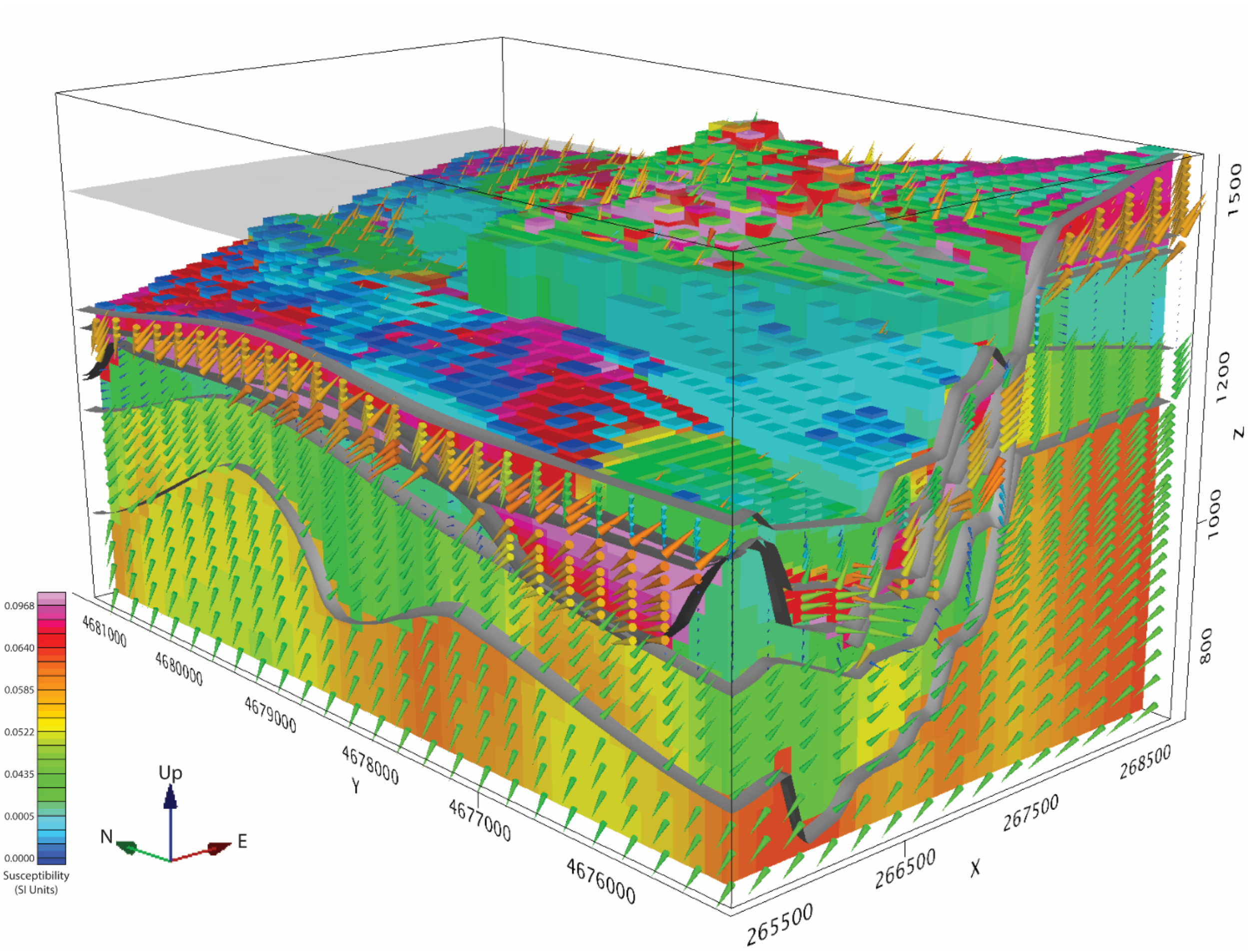

Figure 8: View (looking northeast) of 3D voxel magnetic vector inversion model. 3D magnetization amplitude distribution resulting from Magnetization Vector Inversion (MVI) in VOXI of the observed magnetic anomaly. Cones represent the magnetization vector direction and amplitude (scaled to length and color). The tops of model units are shown in grey. The topographic surface is shown in semi-transparent grey.

5. CONCEPTUAL MODELS

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. 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 (the zone of heat accumulation), suggest pathways the geothermal fluids take from deeper crustal levels to the surface, explain why up-flow 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.

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 up-dip through permeable horizons within the volcanic stratigraphy where they eventually intersect the main range front fault. Both scenarios (closed or open-basin circulation) predict focused up-flow along the primary NNE-trending range front 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 in a third well (see figure 5 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 range front 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 up-flow 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 range front, localizing stress and promoting fracturing and permeability around Crump Geyser that would provide a pathway for deep hydrothermal fluids to reach the surface.

The intra-basin 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 (fig. 9). The deepest part of the basin, revealed by a prominent gravity low (located 10 km south of Crump Geyser, fig. 2), may represent one deep 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, precipitation-driven recharge becomes thermal fluids at depth that then 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.

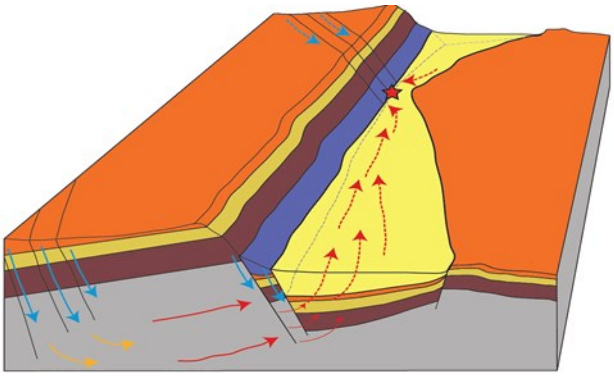

Figure 9: Cartoon illustrating our conceptual model of the Crump Geyser geothermal system (view looking north). In this model, recharge occurs in highlands to the west, where meteoric waters migrate to depth along deep-seated fracture zones. The main range front fault system, and the set of NW-trending faults to the northwest of Crump, may also act as conduits for deep circulation. Additional recharge may involve infiltration through basin sediments. Up-flow within more permeable strata circulate water into Warner Valley. The reservoir consists of fluids residing in the volcanic basement and blanketed by a thick section of thermally insulating sediments. The shape of the basement/sediment interface (that shallows and narrows towards Crump Geyser) may guide flow northwards where they intersect the structures around Crump that provides a path to the surface.

6. HYDROLOGIC FLOW MODEL

Using the proposed geothermal reservoir geometry, the range of heat flows required to explain the geothermometer value of 150°C and the measured Geyser temperature of 122°C can be estimated. Two possible conditions exist at the Geyser: the hydrothermal flow path is nearly in steady state, or the system is still responding to the episodic generation of permeability that controls spring discharge location.

To evaluate the steady-state possibility, preliminary simulations of temperature along groundwater flow paths through the geothermal reservoir to Crump Geyser are made using the steady-state analytic tool of Burns et al. (2016). This tool, which accounts for the widths and depths of flow paths, requires that heat flow be sufficient to heat water in the reservoir to 150°C, and that flow paths be sufficiently shallow to cool the water to 122°C at the Geyser. Conductive cooling of water from 150°C to 122°C downgradient from the reservoir is physically reasonable given the uncertainty in depth of this flow path, but heating within the reservoir requires higher than expected heat flows (>400 mW/m^2), requiring a local heat source such as a magmatic intrusion (fig. 10).

It is also conceivable that water in the reservoir was stagnant until faults formed a connected pathway from recharge areas, through the reservoir, and to the Geyser. Under this condition, the reservoir is heated by conduction only, and the 150°C temperature is a result of the natural thermal gradient. Assuming the system is in equilibrium before flow occurs, effective thermal conductivities of the overlying strata in the range 1.0-1.6 W/m/°C correspond with heat flows in the range 140-220 W/m^2. Once permeability is initiated, hydrothermal water must travel to the Geyser, heating rock along the way. In this case, the 122°C Geyser temperature could be on the rising limb of temperatures (i.e., the Geyser will continue to heat as the reservoir water moves out), or on the falling limb of temperatures (i.e., the slug of hot water from the reservoir has moved past, and now we are approaching a new steady-state at temperatures lower than 122°C). Using the time of travel of a thermal signal (Burns et al., 2017), the rising limb temperature of 122°C will occur in tens to hundreds of years after initiation of permeability, depending on the geometry of the flow path. These preliminary models help us refine testable hypotheses. Future efforts will explore alternative models and put bounds on the range of parameters likely to account for the hydrogeologic characteristic of the Crump Geyser geothermal system. This, and more detailed 3D fluid flow simulations should help better resolve the provenance of groundwater recharge that feeds discharge zones.

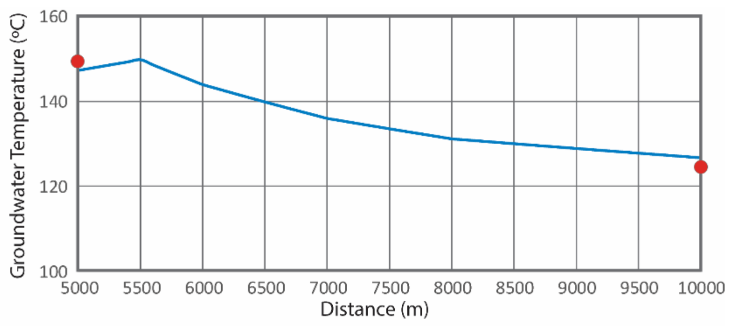

Figure 10: Simulated temperature for Warner Valley based on a minimum hydrologic path involving a relatively short recharge path and the principal range front fault zone. Red points at left and right indicate estimated reservoir temperature and well temperature at Crump Geyser, respectively (following method of Burns et al., 2016).

7. 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 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.

The proximity of Crump Geyser to the range front together with geochemical data from spring and well waters suggest that lake brines, circulating down through the basin and returning along the main range front fault, are a likely source 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 intra-basin 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 intra-basin 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 range front, 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. The potential field mapping and 3D models lend valuable constraints on likely fluid pathways. A simple hydrologic model based on insights from the potential field studies, that assumes reasonable model input parameters (basal heat flow, groundwater flow, thermal conductivity, hydraulic head, and land surface temperature), is capable of accounting for the measured hydrothermal discharge data. Future efforts will involve more extensive modeling aimed at distinguishing between alternative conceptual models for hydrothermal fluid flow associated with the Crump geothermal system.

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