PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2013
SGP-TR-198

Correlation of Geothermal Springs with Sub-Surface Fault Terminations Revealed by High-Resolution, UAV-Acquired Magnetic Data

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ABSTRACT

There is widespread agreement that geothermal springs in extensional geothermal systems are concentrated at fault tips and in fault interaction zones where porosity and permeability are dynamically maintained (Curewitz and Karson, 1997; Faulds et al., 2010). Making these spatial correlations typically involves geological and geophysical studies in order to map structures and their relationship to springs at the surface. Geophysical studies include gravity and magnetic surveys, which are useful for identifying buried, intra-basin structures, especially in areas where highly magnetic, dense mafic volcanic rocks are interbedded with, and faulted against less magnetic, less dense sedimentary rock.

High-resolution magnetic data can also be collected from the air in order to provide continuous coverage. Unmanned aerial systems (UAS) are well-suited for conducting these surveys as they can provide uniform, low-altitude, high-resolution coverage of an area without endangering crew. In addition, they are more easily adaptable to changes in flight plans as data are collected, and improve efficiency.

We have developed and tested a new system to collect magnetic data using small-platform UAS. We deployed this new system in Surprise Valley, CA, in September, 2012, on NASA's SIERRA UAS to perform a reconnaissance survey of the entire valley as well as detailed surveys in key transition zones. This survey has enabled us to trace magnetic anomalies seen in ground-based profiles along their length. Most prominent of these is an intra-basin magnetic high that we interpret as a buried, faulted mafic dike that runs a significant length of the valley. Though this feature lacks surface expression, it appears to control the location of geothermal springs. All of the major hot springs on the east side of the valley lie along the edge of the high, and more specifically, at structural transitions where the high undergoes steps, bends, or breaks. The close relationship between the springs and structure terminations revealed by this study is unprecedented. Collecting magnetic data via UAS represents a new capability in geothermal exploration of remote and dangerous areas that significantly enhances our ability to map the subsurface.

INTRODUCTION

Extensional geothermal systems such as those in the Basin and Range of the western US are characterized by moderate-to-high heat flow and hold significant potential for geothermal energy and hydrothermal-related mineral deposits. Evaluating these extensional geothermal systems depends on our ability to image subsurface structures and to determine how those structures control fluid flow. Understanding how these structures have evolved over geologic and shorter time scales lends insight into the lifecycle of a geothermal system and helps predict where resources are most likely to occur. This is particularly important for assessing the potential for systems controlled by blind structures.

In the present study, we use potential field methods to identify intra-basin faults and fractures, gain insight into the role these structures play in conducting geothermal fluids and controlling the locations of hot springs, and identify areas for future exploration with high geothermal potential.

SURPRISE VALLEY

Geology

Surprise Valley is situated between the relatively un-dissected Modoc Plateau to the west and the Basin and Range to the east (Fig. 1), forming the westernmost deep extensional graben of Basin and Range physiography. The valley also marks a major tectonic transition from north to south, as it sits immediately north of the Walker Lane, which accommodates up to 20% of dextral slip associated with Pacific-North American plate interactions, and just south of the low-strain High Lava Plains region (Hammond and Thatcher, 2004, 2005).

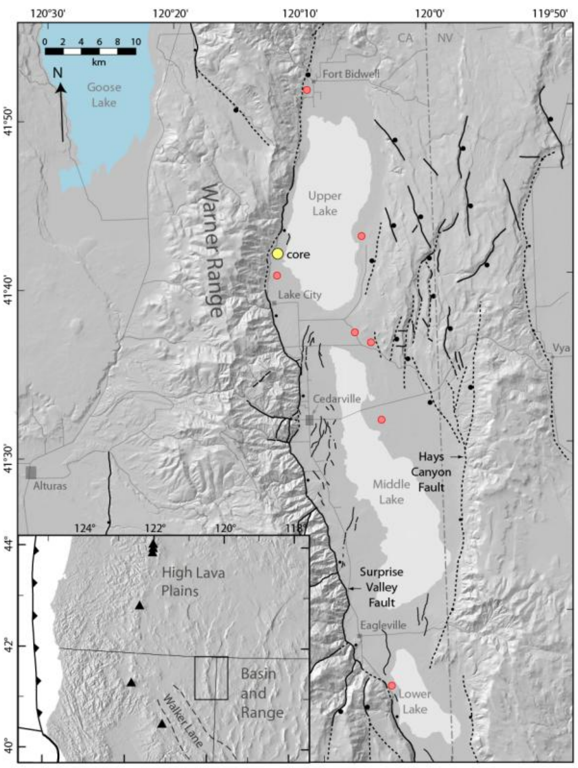

Figure 1: Index map of study area showing the location of normal faults and hot springs (red circles).

The western margin of the valley is marked by the east-dipping Surprise Valley fault (SVF) that has undergone ca. 8 km of dip-slip (Fig. 1) (Egger and Miller, 2011). Uplift and tilting has rotated the fault to shallow angles (25-35°) (Lerch et al., 2010). The southeastern margin of the valley is bound by the west-dipping Hays Canyon fault that has exhumed the Hays Canyon Range and creates a full graben (Fig. 1). The northeastern margin is marked by west-dipping basalts flows, however, and a series of faults with only minor offset, forming a half-graben (Fig. 1). An accommodation zone at approximately the latitude of Cedarville (Fig. 1) marks the transition between the full- and half-graben portions of the valley, and has the densest concentration of faults in the study area. Numerous Quaternary fault scarps (Bryant, 1990; Hedel, 1984) and recent trenching across the SVF (Personius et al., 2009) suggest the area is still actively extending, though the valley has not experienced any large historic earthquakes.

Geothermal Resources

Thermal springs in Surprise Valley occur throughout the valley, but most occur within the basin, and do not appear to be directly related to the main range-front faults (Fig. 1). Based on the presence of young silicic volcanic rocks on the eastern margin of the valley, Duffield and Fournier (1974) suggested that the geothermal system may be related to residual heat associated with Tertiary magma chambers, but recently published age data indicate that the youngest volcanic rocks are 3.8 Ma (Carmichael et al., 2006). While a magmatic source cannot be fully ruled out, it seems more likely that the geothermal fluids originate from deep crustal circulation of meteoric water, similar to other Basin and Range extensional systems that exhibit higher-than-average crustal heatflow (e.g. Kennedy and van Soest, 2006).

Exploration of the valley's geothermal resources began following a remarkable mud volcano eruption near Lake City (Fig. 1) in 1951 that ejected mud, rock, and steam as high as 1500 m into the air (White, 1955). Exploratory drilling occurred in the 1970s, mostly focused near Lake City, where near-boiling geothermal fluids and hydrothermal siliceous deposits occur at the surface, but did not result in any production. A renewed phase of interest began in 2004, when a set of deep core-holes (Fig. 1) were drilled at Lake City, revealing temperatures as high as 165 ºC at depths between 686 and 1036m, and the presence of alteration minerals at >1415m indicative of formation temperatures over 260 ºC (Benoit et al., 2005). These estimated reservoir temperatures would permit development for electrical generation in addition to direct use applications for municipal and residential heating as wells as agriculture and other commercial purposes.

POTENTIAL FIELD GEOPHYSICS

Potential field (gravity and magnetic) geophysical methods allow imaging of subsurface geologic bodies and structures. 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. In addition, fluids can precipitate hydrothermal deposits and alter the host rock that can significantly and characteristically modify the density and magnetic properties within fracture zones. 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 and geophysical constraints.

Potential field methods have proven particularly useful in areas like Surprise Valley where dense and magnetic volcanic rocks are interbedded with and faulted against less dense, less magnetic tuffs and tuffaceous sedimentary rocks to produce prominent gravity and magnetic anomalies (Egger et al., 2010; Glen et al., 2008). We have collected high-resolution magnetic data along several detailed profiles for mapping and detailed modeling of intra-basin structures using both ground-based and unmanned aerial systems.

Ground Based Studies

Magnetic field data are typically collected on foot by traversing across structures of interest. Employing this method allowed us to acquire several short profiles, which revealed the presence of some intra-basin structures (Stilson et al., 2008). But there were large gaps between widely spaced profiles that precluded our correlating features between lines, and determining the lateral extent of subsurface features.

The flat, broad playa surface afforded an ideal setting for deploying a mobile platform for rapidly collecting large amounts of data across the valley floor. This led to our developing two All-Terrain Vehicle (ATV)-based systems (Athens et al., 2011) that significantly augmented our coverage of the valley. Over a period of 3 seasons (~60 days), we collected a total of ~960 km of ground magnetic data (obtained on foot and with ATVs).

Results

The magnetic map of our ground-based data is shown in Figure 2. The data have been processed to remove dropouts, an IGRF field, and diurnal variations. Filtering was also applied to remove cultural noise, and a heading correction was applied to ATV-derived data to correct for magnetic fields arising from the ATV that depend on driving direction.

The wide range of anomaly wavelengths and amplitudes largely reflect varying depths to magnetic sources—the shallower the depth of a body, the higher the amplitude, the shorter the wavelength, and the sharper the gradients of its magnetic anomaly. As would be expected, exposed mafic volcanic rocks display prominent, high frequency magnetic anomalies, while the deepest parts of the basin containing thick sections of relatively weakly magnetic sediments and tuffs, correspond to a prominent long-wavelength magnetic low (Fig. 2). What is surprising, however, is a pronounced narrow magnetic high extending for several tens of kilometers across the upper and middle basins that reflects the presence of a prominent, buried, intra-basin structure with no surface expression. Based on its magnetic anomaly, the structure is surprisingly straight—much more so than the Surprise Valley fault—and apparently continuous. However, gaps in the ground data coverage, particularly around hot springs, precluded us from determining if the feature is segmented or represents a single through-going structure along its full length.

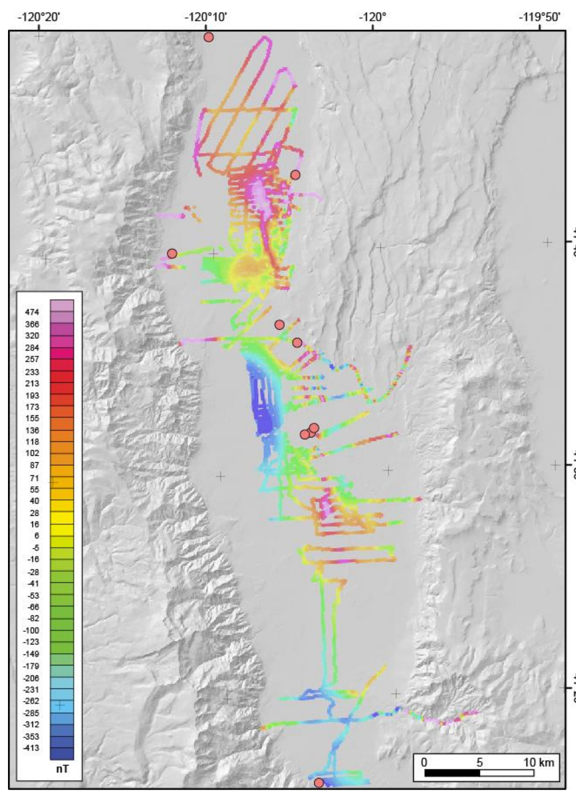

Figure 2: Magnetic residual map of ground magnetic data and hot springs.

The close correspondence of this intra-basin magnetic high with 3 of the 5 the major geothermal fields in the valley suggests it plays an important role in guiding hydrothermal fluids to the surface (Fig. 2), and thus it became a focus of our efforts. As crucial as the ground-based surveys were to discovering this feature, they are inherently limited in their spatial extent due to dense foliage, private lands, water, and dangerous conditions encountered around hot springs, where we are particularly interested in obtaining detailed data.

Unmanned Aerial Surveys

The limitations of ground-based surveys are typically overcome with commercial airborne surveys that can provide broad and uniform data coverage. High-resolution commercial surveys, however, are costly and relatively inflexible to the need to change survey specifications that may arise as data are collected. Unmanned aerial systems (UAS), however, offer a highly adaptable, efficient, and cost-effective alternative to commercial surveys. They are also ideal platforms for conducting airborne surveys that often require repetitive, low-altitude flight paths that can pose risks to a pilot and crew. Surprise Valley is particularly well-suited to UAS surveys due to its low population density, accessible airspace, municipal airport, and broad playa that allowed direct line-of-sight to the aircraft by ground observers and provided ample opportunity to safely land.

Figure 3: The SIERRA UAS in Surprise Valley.

Through collaboration between the USGS, NASA, Central Washington University, Carnegie Mellon University, and Geometrics, Inc., we have developed and tested a new system to collect magnetic data using small-platform unmanned aerial systems (UAS). The primary payload, a cesium magnetometer, is installed on the wingtip to situate it far from the fuselage that contains the most magnetic components of the aircraft. Testing served to assess, minimize, and correct for the magnetic signal of the system.

In September, 2012, we flew NASA's SIERRA UAS (Fig. 3) over a 3-day period (roughly 3½ hours of continuous flight per day), during which we collected over 1390 km of flight line data. After each flight, the data were corrected for diurnal variations (using data from a proton precession base station magnetometer that recorded at 1 min intervals), and compensated for heading errors that correct for induced, remanent, eddy current, and electrical current terms. Flight tests indicated that magnetic "noise" from the SIERRA platform was low, and can be effectively compensated to provide data comparable with high-resolution commercial methods.

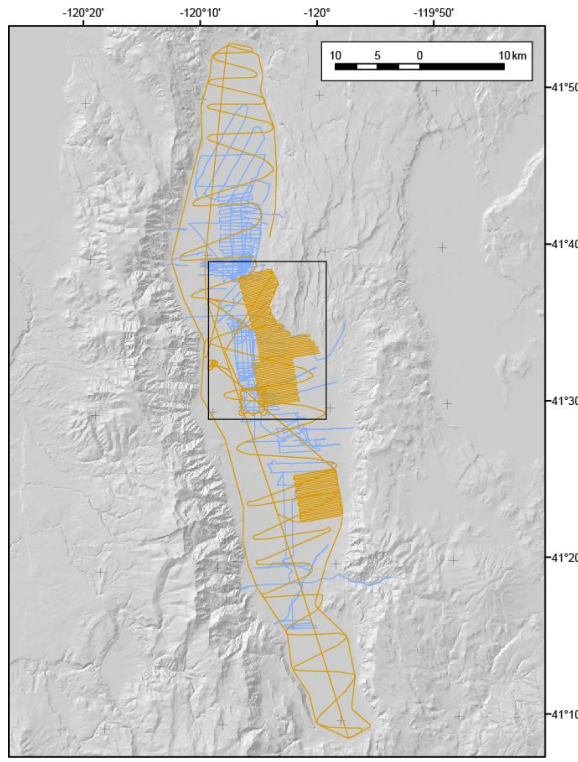

Figure 4: SIERRA flight lines (orange) and ground-based traverses (blue). Inset box corresponds to area of Figure 6.

The survey was restricted to the valley because the primary features of interest were in the basin, allowing us to maintain a nominal flight height of 150 m above ground. A reconnaissance survey of the entire valley was flown to map regional features and access previously unmapped areas (Fig. 4). In addition, we flew several small detailed surveys (0.2 km flight line spacing, ENE-flight lines direction) to map the intra-basin magnetic high around the hot springs where there were gaps in the ground-magnetic data (Fig. 4). Flight plans were drafted based on the previous day's results and uploaded each morning, allowing us to modify the survey as we analyzed and interpreted the data.

Results

The magnetic map of all of our data is shown in Figure 5. By combining a reconnaissance flight with tightly-spaced lines, we are able to map both the extent and detailed features of the intra-basin high, particularly near the hot springs. The magnetic high, while regionally quite linear, is locally discontinuous with splays, spurs, and segments that bend or abruptly terminate. The hot springs closely correspond to major breaks or bends in the anomaly, suggesting that the feature is integral to the plumbing of the hydrothermal system (Fig. 6). The level of detail afforded by these data also offers significant insight into the nature of the magnetic high.

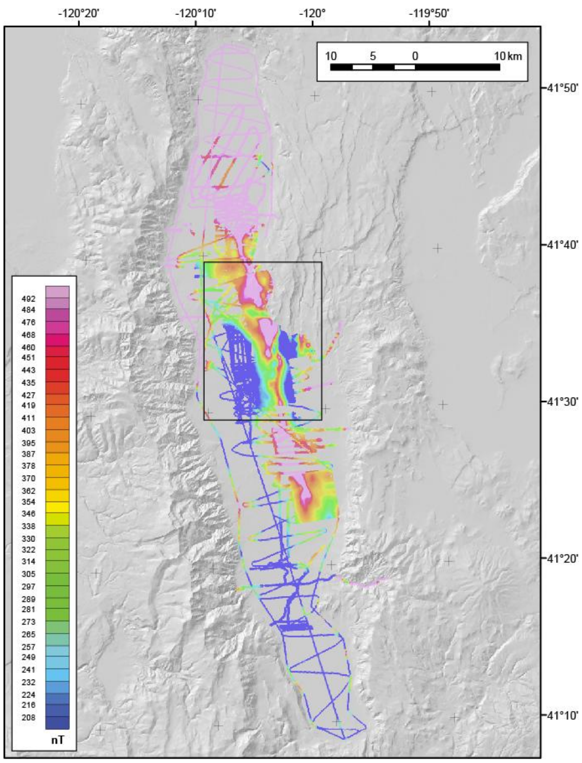

Figure 5: Magnetic residual map of combined *ground and UAS data. Ground data were upward continued to the height of the airborne survey (500ft). Inset box corresponds to area of Figure 6.*

DISCUSSION

Origin of the magnetic high

Our earlier efforts to understand the nature of the magnetic high were focused in the upper basin where we first observed it in foot-traversed magnetic data. Using a Betsey seisgun system, Fontiveros (2010) collected high-resolution reflection seismic data along a stretch of the intra-basin high that we identified as structurally simple (i.e., having 2D geometry, isolated from other magnetic sources). This system was able to image to depths of several hundred meters, sufficient to resolve a prominent basin structure coincident with the magnetic high. The seismic model of Fontiveros (2010) reveals a bright reflector that we interpret to be the top of the Pliocene basalts. The reflector is cut, tilted, and offset ~250 m by an east-dipping (~56°) normal fault.

A gravity model, based on the seismic results (to constrain structure and densities) reproduces, surprisingly well, gravity observed along the same profile (Athens, 2011). This simple faulted stratigraphy cannot account for the observed magnetic high, however. Instead, a joint gravity and magnetic model, consistent with the seismic reflection model and based on measured rock property data from units outcropping east of the profile, seem to require the presence of a tabular magnetic body aligned with the fault that we interpret to be a strongly magnetic mafic dike.

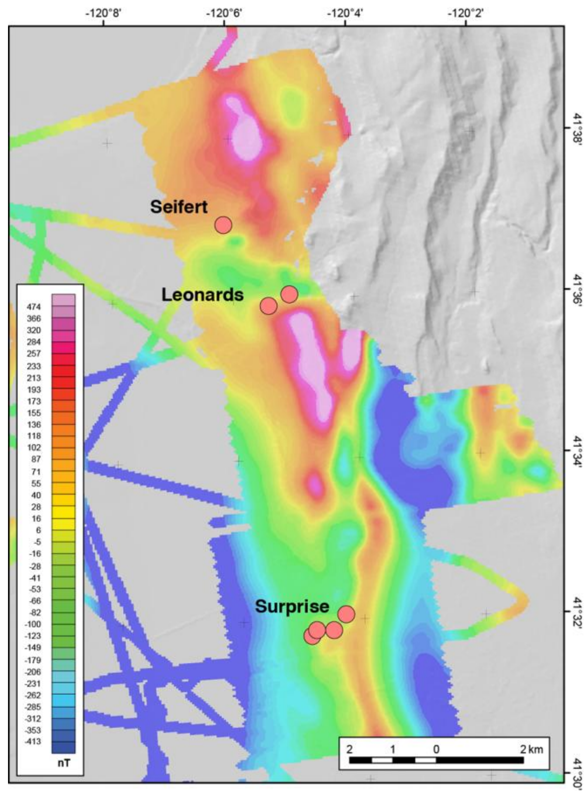

Figure 6: Detail of Figure 5 with hot springs (red circles).

However, the relatively shallow dip of the dike, where it has been modeled in the upper basin, is not consistent with the sub-vertical dips of dikes elsewhere in the area. This, and the close correspondence of the dike to the fault that is required by the model, suggests that the dike likely intersected and exploited a pre-existing fault. It is possible that intrusion of the dike also facilitated shearing along the fault (thus promoting syn-emplacement slip). In any case, it is likely that faulting continued subsequent to dike emplacement, because the potential field modeling appears to preclude the dike from extending to the top of the faulted block (Athens, 2011). The overlap in timing of magmatism and faulting suggests that this feature may have played an important role in basin development and the accommodation of extension.

Segmentation of the magnetic high

The detailed survey of the high in the middle basin reveals that the magnetic high is locally discontinuous, consisting of segments with splays and spurs that bend or abruptly terminate (Figs. 5, 6). Terminations of in-line segments such as between Seifert and Leonards hot springs (Fig. 6) appear as abrupt lows crossing the magnetic high. This may represent a primary structure that developed as the dike cut a pre-existing planar structure at a high angle. Alternatively, this feature could have formed if the dike was later disrupted by a structure that crossed it at a high angle. Mapping in the hills immediately east of the gap in the magnetic high reveals ESE-trending faults (Fig. 1) that may reflect the presence of a structurally-controlled paleovalley that was subsequently filled by reversely or weakly magnetic material, which could account for the magnetic low cutting the intra-basin high.

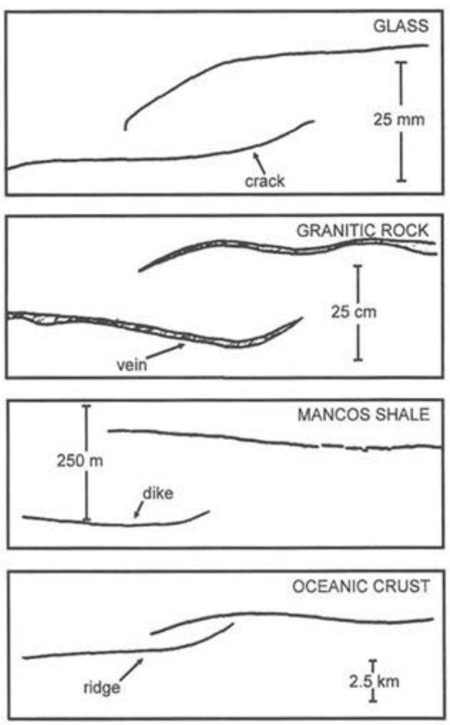

Figure 7: From Pollard and Aydin, 1984.

In contrast, overlapping segments between Leonards and Surprise Valley hot springs (Fig. 6) resemble en echelon fracturing or diking where two fault segments grow towards each other in response to local distortions of the stress field around crack tips (Fig. 7), a process that has been observed over a wide range of scales from microfractures to plate boundaries (Pollard and Aydin, 1984).

The shape of the magnetic anomaly and its resemblance to these models for fault growth and linkage provide additional evidence that faulting and dike intrusion were, in fact, contemporaneous.

En echelon fractures can form when a propagating dike undergoes a shear stress along it walls. If this was the cause for the en echelon feature along the intra-basin magnetic high, the relative offset of the anomaly segments would indicate right-lateral shear present at the time of dike emplacement (Miocene?). Existing GPS data (Hammond and Thatcher, 2007) could permit a small amount of right lateral shear across the valley, though data are sparse and cannot conclusively resolve a strike-slip deformation component. If transtension is occurring today, it is not being accommodated along the Surprise Valley fault, which has several prominent corrugations that would preclude oblique slip motion. Furthermore, evidence from trenching along the Surprise Valley fault (Personius et al, 2009) that document the last five surface ruptures over the past 18.2 ka do not reveal any oblique slip component. However, the relatively long and linear character of the intra-basin magnetic high suggests that it could more easily accommodate a minor shear component, and may have done so at the time the dikes were intruded.

Despite the evidence for a discontinuous and segmented dike near the surface, these segments may merge to form a single intrusion at depth, as its long and linear expression would suggest. If the source of the magnetic high is continuous at depth, and is faulted or fractured along its length, it may connect geothermal systems along the east side of the valley by accommodating lateral fluid flow.

Near the surface, discontinuities such as these segmented structures have the potential for promoting long-lived hydrothermal activity by creating stress perturbations around fault tips and interaction zones. These features maintain porosity and permeability in the surrounding rocks and sediments dynamically as strain accumulates, rather than kinematically through fault rupture (e.g. Curewitz and Karson, 1997; Faulds et al., 2010; Rowland and Sibson, 2004). Precipitation of hydrothermal minerals can rapidly decrease porosity and permeability, even along active faults (Rowland et al., 2008). Given the distribution of the hot springs in Surprise Valley and the lack of historic seismicity, we interpret these now-spectacularly imaged sub-surface features to be discontinuities that formed during dike intrusion (e.g., associated with Surprise

Valley hot springs), or possibly as secondary structures that developed after dike emplacement (e.g., associated with Leonards and Seifert hot springs) that promote dynamic permeability in a low-strain region.

CONCLUSIONS

We have performed potential field studies in Surprise Valley, CA, to map subsurface faults and fractures that may be controlling geothermal fluid circulation. As part of this work, we have applied a newly developed platform for collecting magnetic data using unmanned aerial systems (UAS). The high resolution airborne survey allowed us to obtain a uniform data coverage over areas inaccessible to ground surveys. This is an innovative use of UAS that has the potential to greatly increase the quality, quantity, and resolution of data collected while significantly reducing the costs and risks associated with manned surveys.

The surveys reveal >35 km-long linear, intra-basin magnetic high that we interpret as a buried dike that intruded along a fault, with contemporaneous motion and intrusion. A key outcome from the airborne survey was the development of a magnetic map at an unprecedented level of detail that allowed us to correlate several of the valley's major hot springs with local breaks and bends in the feature – a finding that could never have been substantiated by ground-based data. This result likely demonstrates that distortion of the stress field around structural discontinuities can stimulate permeability.

These data lend insight into the role of structures in controlling geothermal fluids and the locations of hot springs. It is expected that this will help identify areas for future exploration.

ACKNOWLEDGEMENTS

This work benefitted from a large number of individuals. We are particularly grateful to Ritchie Lee, Randy Berthold, Misha Tchernychev Geoff Phelps, Rick Kolyer, and Mark Sumich for their significant roles in this project. We are also grateful to Matt Fladeland, Bruce Storm, Phil Schuyler, Tom Lynn, Don Herlth, Munro Dearing, Brad Lobitz, George Tait, John Spritzer, Diana Strickley, Brent Ritzinger, Bruce Chuchel, Jay Bridgeman, Melissa Pandika, Ross Johnson, Kevin Denton, and Steve Patterson for their important contributions leading to the success of the SIERRA mission.

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