Structures Controlling Geothermal Circulation Identified Through Gravity and Magnetic Transects, Surprise Valley, California, Northwestern Great Basin

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ABSTRACT

Combined geological and geophysical investigations are used to characterize intra-basin and basin-bounding faults, constrain basin geometry, study fault interactions, and ultimately to identify areas favorable to hydrothermal flow in the geothermal system in Surprise Valley, California. We utilize high-resolution gravity and ground-magnetometer data collected along several detailed transects within Surprise Valley to identify intra-basin structures. Our data show two types of structures whose magnetic signatures differ markedly: N-S-trending normal faults and NW-SE-trending fracture zones that accommodate little offset. The geothermal system is concentrated at the intersections of these two contrasting structural trends, implying that the fracture system facilitating hydrothermal flow to hot springs in Surprise Valley is more complex than typically envisioned for Basin and Range extensional geothermal systems. Our results suggest that there are potentially many pathways for fluid flow, offering new targets for geothermal exploration.

Introduction

Surprise Valley of northeastern California is the westernmost graben of the Basin and Range province (Figure 1, inset). The valley marks a major tectonic transition between the relatively un-extended volcanic Modoc Plateau and a region of 10-15% extension to the east. In addition, it sits just north of the Walker Lane, which accommodates up to 20% of dextral slip associated with Pacific-North American plate interactions (Hammond and Thatcher, 2004), and just south of the Cascades back-arc that is undergoing extension and clock-wise rotation (Figure 1, inset) (Wells and Muffler, 1990).

On the western margin of the valley, the east-dipping Surprise Valley Fault separates the valley from the Warner Mountains and may accommodate over 7 km of normal slip (Figure 1) (Egger et al., in review). On the eastern margin of the valley, a west-dipping normal fault has exhumed the Hays Canyon Range (Figure 1). Between the major range-front faults is a set of northwest-trending structures referred to as the Lake City Fault Zone (LCFZ), a ½-km wide zone of low-relief alluvial scarps and photo lineaments that crosses the subdued topographic high separating the Upper and Middle Lakes (Figure 1, overleaf) (Hedel, 1984). This network of scarps appears to connect the eastern and western basin-bounding faults. The close correspondence of this feature with most hot springs in the valley suggests it plays a key role in hydrothermal circulation (Figure 1).

No large historic earthquakes have occurred in Surprise Valley, but small events have been felt since settlement in the early 1850's, and as recently as 1958 (Hedel, 1984). Despite this relative quiescence, fault scarps in surficial deposits indicate that ruptures have occurred repeatedly in the Quaternary (Hedel, 1984). Additional support for Holocene faulting is provided by recent trenching of the Surprise Valley fault near Cedarville that exposed ~7 ka ash deposits correlated to the eruption of Mt. Mazama in the hangingwall block that provide a minimum offset and uplift rate across the fault of ~1 mm/yr (Personius et al., 2007).

The relationship between the range-front faults and the LCFZ, including their relative roles in basin evolution and their exact controls on the geothermal system, is poorly understood. Our ongoing work to better constrain the character of these two fault systems is critical to understanding basin development and the valley's geothermal system.

Geothermal Resources

Thermal springs issue from eight areas within Surprise Valley (Figure 1): Boyd Warm Spring (BWS), Fort Bidwell Hot Springs (FBHS), Lake City Hot Springs (LCHS), Leonards Hot Springs (LHS), Menlo Baths (MB), Seyferth Hot Springs (SHS), Squaw Baths Hot Springs (SB), and Surprise Valley Mineral Wells (SVMW). All but one (Surprise Valley Mineral Wells) lie near the margins of the basin, slightly offset from the main range-front faults (Figure 1). These locations suggest that the Surprise Valley

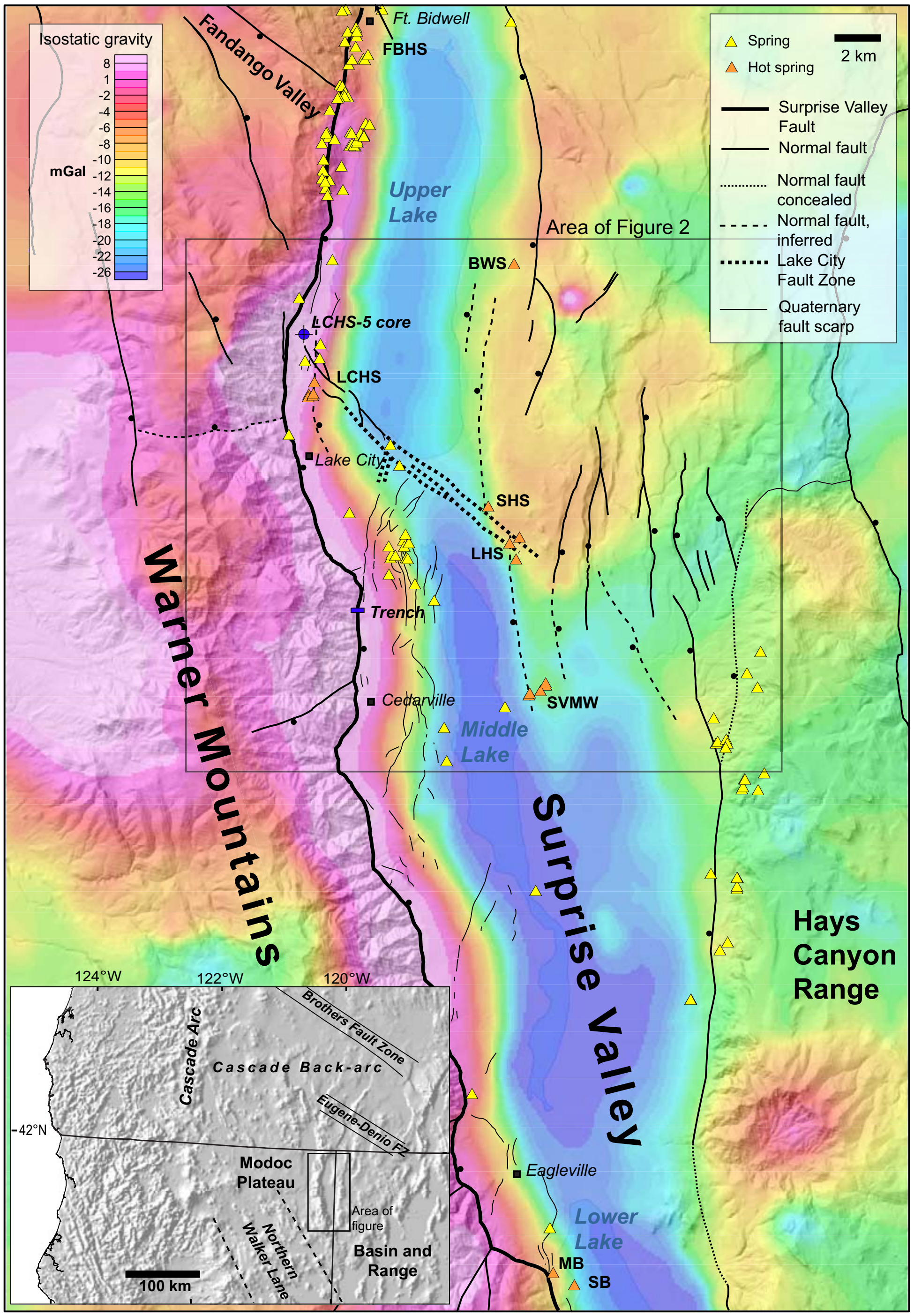

Figure 1. Isostatic gravity map draped over shaded-relief of Surprise Valley and surrounding regions. BWS, Boyd Warm Spring; FBHS, Fort Bidwell Hot Springs; LCHS, Lake City Hot Springs; LCFZ, Lake City fault zone; LHS, Leonards Hot Springs; MB, Menlo Baths; SB, Squaw Baths Hot Springs; SHS, Seifert Hot Springs; SVMW, Surprise Valley Mineral Wells. Inset shows a regional index of the northwestern Basin and Range province.

system is typical of other extensional geothermal systems in the Basin and Range, which arise from deep circulation of meteoric water along major normal faults. Although the close proximity of several of the hot springs to young silicic volcanic outcrops led Duffield and Fournier (1974) to suggest that they may be related to residual heat associated with Tertiary magma chambers, this possibility seems remote given the fact that the youngest nearby volcanic units are 3.8 Ma (Carmichael et al., 2006). Instead, it seems that Surprise Valley, like Dixie Valley and other Basin and Range extensional systems that exhibit higher-than-average crustal heatflow, are driven by a deep-crustal, non-magmatic heat source.

Five of the hot springs (FBHS, LCHS, SVMW, SHS, MB) have been the subjects of geothermal exploration, which began following a mud volcano eruption at Lake City in 1951 (White, 1955), one of the largest recorded in North America in the past century. The phreatic event ejected mud, rocks, and steam as high as 1500 m above the vents, and spurred exploratory drilling near Lake City and elsewhere in the valley throughout the 1970s. The Lake City field, consisting of a north-south elongate zone of nearly 2.5 km with near-boiling hot springs and hydrothermal siliceous deposits is the most extensively studied. It has been the site of numerous shallow temperature gradient holes, and several shallow-to-deep wells, including a deep (1047 m, core OH-1) core-hole yielding temperatures in excess of 163 ºC (Benoit et al., 2004). Alteration at the deepest levels in the cores is indicative of temperatures in excess of 250 ºC. Given these estimated reservoir temperatures, present technology would allow for development for electrical generation in addition to use for residential and public heating, agriculture, and other commercial purposes. Results from the most recent investigations indicate that Surprise Valley is one of the highest potential geothermal prospects in the state (Benoit et al., 2004). Nonetheless, the resource remains largely untapped.

The Lake City Fault Zone

A primary focus of this study is the Lake City Fault Zone (LCFZ), which sits in a complex area between the Upper and Middle Lakes where the range-front fault to the south terminates in the valley and another, overlapping fault segment begins (Figure 1). The LCFZ is a zone of permeability for flow of geothermal fluids as evidenced primarily by the occurrence of hot springs at the intersections of the LCFZ with basin-bounding structures (Figure 1). The depth and extent of that permeability enhancement has not been resolved, however – although springs along the LCFZ at Seyferth, Leonards, Surprise, and Lake City have similar water chemistries, their isotopic signatures differ and it appears unlikely that they are connected at depth (Mariner et al., 1978). In addition, the LCFZ corresponds with 1) a mapped area of hazardous groundwater, characterized by high concentrations of boron, fluoride, sodium and sulfate, 2) small gravity and magnetic anomalies that suggest mineralization (occurring at shallow depths in basin sediments) possibly associated with hydrothermal fluids and 3) a southeast-trending zone of microseismicity (Hedel, 1981).

Despite its obvious importance to the geothermal system, the origin of the LCFZ and its role in accommodating strain remain unclear, as does the depth of penetration into the crust. Significantly, it parallels a widespread structural trend that includes the Brothers and Eugene-Denio fault zones in Oregon (Figure 1, inset). These diffuse, small-offset fracture systems are associated with NW-directed extension and clockwise rotation in the Cascade back-arc. Is the LCFZ a local manifestation of this trend that has been utilized by geothermal fluids for deep circulation? Does it accommodate dextral deformation across the northwestern margin of the Basin and Range? Or is it an accommodation zone that does not reflect regional strain, but partitions a zone of greater extension to the south from lesser extension to the north? Resolving the depth and structural significance of the LCFZ should help to address these questions and guide further geothermal exploration in Surprise Valley.

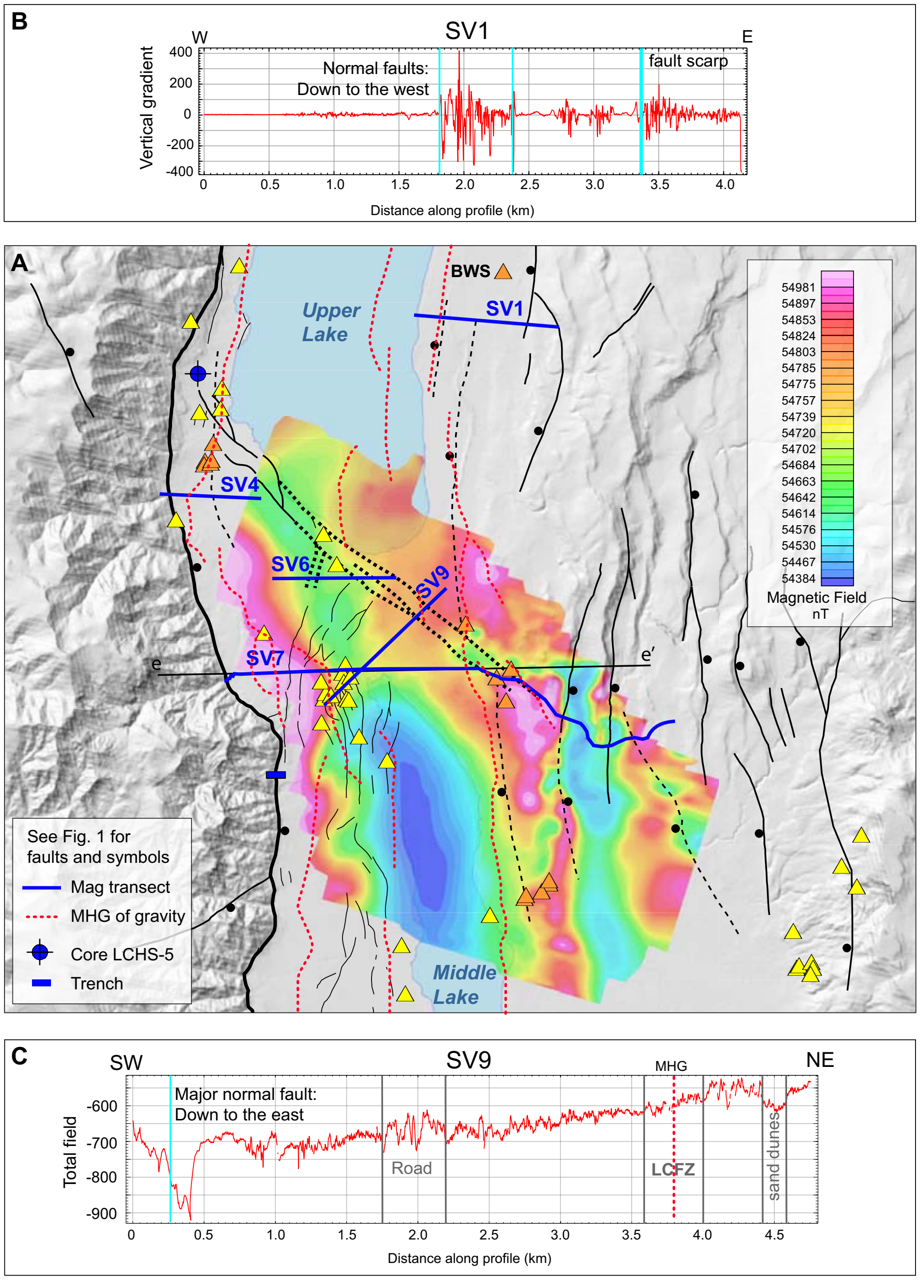

Figure 2. A. Magnetic map draped over shaded-relief topography of the study area, including maximum horizontal gradients (MHG) from gravity. Magnetic highs appear as reds and pinks and lows as blue. Faults are mapped on the basis of geology and geophysics and include Holocene fault scarps within the basin (after Hedel, 1984). Same legend for faults and springs as in Figure 1. **B.** Magnetic profile SV1 and **C.** Magnetic profile SV9, both collected by foot-traverse and annotated with faults and other features. Light blue lines indicate normal faults inferred from magnetic profiles; thicker blue line in SV1 corresponds with a mapped fault scarp.

Potential Field Data

In the present study, we use potential field mapping and profiles to identify intra-basin faults and fractures in Surprise Valley in order to assess different tectonic models for basin development and evaluate which features influence the hydrothermal system. Data employed in this study include a gravity compilation with 793 new gravity stations collected regionally and along detailed profiles across Surprise Valley, a detailed aeromagnetic survey of the LCFZ area, a truck-towed magnetometer profile, and several ground-magnetometer transects (Ponce et al., in prep). Gravity and magnetic maps were used to identify the extents of regional anomaly sources and to trace inferred faults, fractures and contacts (Figures 1, 2). In addition, maximum horizontal gradients (MHG) were calculated to help define modeled body edges (Figure 2). The MHG tend to lie over the edges of bodies with near vertical boundaries and highlight abrupt lateral changes in density or magnetization, thus representing either faults or buried contacts (Cordell and McCafferty, 1989; Grauch and Cordell, 1987).

We collected several detailed gravity and magnetic transects crossing the valley floor for identifying intra-basin structures (Figure 2A, blue lines). We present here two of those transects that highlight the nature of the intra-basin faults: SV1, which is perpendicular to the basin-bounding faults and near Boyd Warm Spring, and SV9, oblique to the major faults but perpendicular to the LCFZ (Figure 2). Profile SV1 (Figure 2B) crosses mapped Quaternary normal fault scarps and extends 1 km into the playa (Figure 2A). This magnetic profile displays several major amplitude changes and one of them coincides with a mapped Quaternary fault scarp whose offset might be as large as several tens of meters (Figure 2B, thick blue line). We propose that other similar amplitude changes in the profile not associated with Quaternary scarps may reflect the presence of faults with similar offset at depth buried beneath lake sediments (Figure 2B, thin blue lines). The westernmost of these also coincides with an MHG in gravity (Figure 2A). The existence of buried faults that are not associated with exposed scarps is confirmed by the presence of the Boyd Warm Springs (BWS in Figure 2) whose location projects near one of those inferred faults.

Profile SV9 also displays a significant magnetic gradient and an MHG in gravity on its southwestern end where it crosses a series of mapped Quaternary fault scarps and springs (Figure 2C, blue line; Figure 2A). This magnetic profile also crossed the LCFZ where it shows a distinct change in character (amplitude and wavelength) with respect to the adjacent regions (Figure 2C, gray lines), as has been previously noted (Griscom and Conradi, 1976). This change in character likely results from alteration in the fault zone due to near-surface circulation of hydrothermal fluids. SV9 also crosses an MHG in gravity within the LCFZ (Figure 2A). This MHG is less continuous than the MHG on the western end of the profile and it coincides with a gentle westward slope in the magnetic profile (Figure 2C). Taken together, these features suggest a westward-dipping basalt flow within the LCFZ rather than a normal fault.

Discussion

The magnetic transects reveal two significant features that help constrain the structural setting of Surprise Valley: first, they highlight intra-basin faults which accommodate significant offset but have little to no surface expression, and second, they confirm previous work suggesting that the Lake City Fault Zone differs in character and offset from other intra-basin faults that accommodate normal offset. The potential field data presented here were also used with high-resolution seismic reflection data to create a geophysical model (Egger et al., in review) along a regional cross-section (e-e', Figure 1). The results of this modeling suggest that the basin-bounding Surprise Valley Fault could be cut at depth by the intra-basin N-S-trending, steeply dipping normal faults described in this study. In contrast, our preliminary modeling along profile SV9 suggests that the LCFZ accommodates little if any vertical offset.

As noted earlier, the majority of all springs are located along these intra-basin faults, while the majority of hot springs are located at the intersection of the LCFZ with these intra-basin faults (Figure 1). Clearly, this interaction is a key factor controlling hydrothermal fluid flow in the Surprise Valley geothermal system. This is not surprising – local deviations in stress leading to concentrated dilation, for example, would be the most favorable mechanism to maintaining open pathways for fluid flow – but suggests that the plumbing system is more complex than deep circulation along a single normal fault. Other structures within the region parallel the trend of the LCFZ, including Fandango Valley (Figure 1), which projects towards Boyd Warm Springs, but a structure similar to the LCFZ has not yet been identified there.

Similar structures have been identified in Dixie Valley (Parry et al., 1991; Smith et al., 2001), providing a potential analog for Surprise Valley. There, structures that cut obliquely across the basin are similarly associated with the geothermal system, coincide with embayments in the range-front, and have apparently controlled the segmentation and trend of the range-front fault (Smith et al., 2001). Historic seismicity in Dixie Valley has made defining the origin and role of these structures more straightforward. Johnson and Hulen (2002) interpret these features within the valley as pre-existing structures that accommodated later transtensional motion and rotation of blocks in the mid-Tertiary (Hudson and Geissman, 1987).

What is the tectonic setting of these interacting fault systems in Surprise Valley, and what can it tell us about the geothermal system? Based on this study, it appears that the LCFZ accommodates little vertical offset, suggesting two interpretations. First, the LCFZ might be a zone of diffuse, shallow fractures that accommodates very little strain, which would imply shallow penetration into the crust for these features and suggests that they provide a lateral conduit for geothermal fluids rather than serving as the main system that allows deep circulation of fluids. Second, the LCFZ might represent a vertical fault system accommodating strike-slip motion, implying deep crustal penetration and associated deep fluid flow. In this case, the topographic ridge between Upper and Middle Lakes may result from compression along the LCFZ due to a small component of N-S-oriented, right-lateral strike-slip motion (Figure 2). In fact, recently published GPS data suggest the possibility of right-lateral strike-slip motion in this portion of the Basin and Range (Hammond and Thatcher, 2005), but the structures that accommodate this motion have not been identified and the wide distribution of data points leave these data open to interpretation (Egger et al., in review). If the LCFZ indeed locally accommodates this right-lateral motion, then the abrupt intersection with the basin-bounding faults would suggest that the offset is not significant. The lack of a similar topographic high in the valley near the projection of Fandango Valley towards Boyd Warm Springs may also support the idea of a shallow fracture zone more strongly than strike-slip motion.

Conclusions

Combined geological and geophysical investigations have helped define a complex fault system within the Surprise Valley, including several concealed structures east of the main range front, interpreted as the currently active set of normal faults, that could represent potentially important conduits for circulation of thermal waters. The importance of the Lake City Fault Zone, which cuts obliquely across the valley, in controlling the geothermal system is confirmed in this study. We believe this may reflect a pervasive regional fabric that has not significantly influenced structural development of the valley but does influence current geothermal activity, since virtually all of the valley's hot springs are associated with these obliquely-trending fault sets.

This network of interacting fault sets presents a more complex plumbing system than has previously been proposed for Surprise Valley, and we suggest that these characteristics may be common to many geothermal systems in the Basin and Range. Although this complexity can complicate exploration, it suggests there are additional unexplored resource targets and detailed structural mapping is critical to predicting these target areas.

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