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A GEOTHERMAL EXPLORATION STRATEGY USING HIGH RESOLUTION AEROMAGNETIC SURVEYS FOR THE BASIN-AND-RANGE PROVINCE

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ABSTRACT

Basin-and-range geothermal resources are typically fault-controlled, deep-circulation systems. They commonly occur beneath thick sequences of Tertiary and Quaternary basin-fill sediments which hinder understanding of fault geometries and faulting patterns. Recent experience at Dixie Valley and survey of the literature for other systems suggest a low-cost and rapid exploration strategy for establishing basin geometries, patterns of Quaternary faulting in and beneath basin-fill sediments, and rationale to select locations for other geophysical surveys and drilling. The strategy involves standard geologic and geophysical techniques but includes early deployment of high-resolution aeromagnetic surveys to establish intra-basin fault patterns. This provides reliable information to focus deployment of more detailed and expensive geophysical surveys, and to site exploration wells. In addition, high-resolution aeromagnetic surveys can provide previously unavailable insight into the structural setting of established geothermal fields.

INTRODUCTION

Recent investigations at Dixie Valley provide the basis to put forward a geothermal exploration strategy for untested areas in the basin-and-range province. The Dixie Valley experience included assembly and synthesis of published regional mapping and geophysical surveys (Thompson et al., 1967; Whitney, 1980; Plank, 1997) along with geologic mapping and aerial photograph interpretation (Smith et al., 2001) which provided a basic structural concept for the area. Also, studies focused on the subsurface configuration of the geothermal system (Benoit, 1999; Blackwell et al, 1999; Blackwell et al., 2000) and on the paleoseismicity of the Stillwater fault (Bell and Katzer, 1987; Wallace and Whitney, 1984; Caskey et al., 1996, 2000) help to develop a structural and tectonic context for this deep circulation system.

Notwithstanding the geophysical surveys, geologic mapping, and well logs available for the Dixie Valley area, the grasp of the faulting patterns in and below the basin-fill sediments was not complete. Therefore a high resolution aeromagnetic survey was designed and conducted (Grauch, 2002; Smith et al., 2002). This survey (Figure 1) showed that fault patterns in Dixie Valley are well defined by high-resolution aeromag, just as in the Albuquerque Basin (Grauch, 2001; Grauch et al., 2001) where the method is used effectively to augment surface mapping of intra-basin faults. High-resolution aeromagnetic surveys can be used effectively to optimize geothermal exploration in common geologic settings in the Basin and Range province.

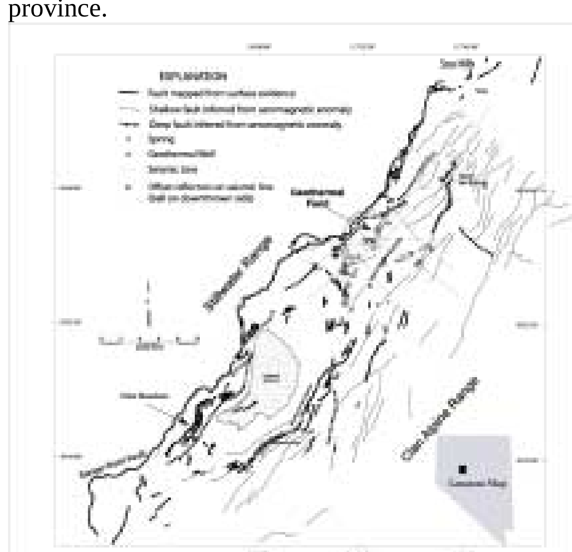

Fig. 1. The intra-basin fault pattern at Dixie Valley defined by geologic mapping, high-resolution aeromag, drilling, and seismic reflection profiles. Note that the fault pattern recognized from geologic mapping (solid lines) is greatly augmented by faults recognized by the high-resolution aeromag survey (dotted lines). The producing geothermal field is located where intra-basin fault systems merge, and where a prominent NW-trending lineament seen in satellite imagery crosses the valley.

CONTRIBUTION OF HIGH-RESOLUTION AEROMAGNETIC SURVEYS

Details of the acquisition and processing of high-resolution aeromagnetic surveys are presented in Grauch (2001), Grauch et al. (2001), and Smith et al., 2002). Basically, flight lines are sufficiently close spaced (150-200m) and instrument heights are sufficiently low (100-150m) to allow detection and areal correlation of low-amplitude, short-wavelength anomalies. Under these conditions, anomalies caused by vertical offsets of sediment layers of differing magnetic properties within ~500m of the surface are revealed. This makes the method especially useful for detecting late Quaternary faulting in basins which are continually and rapidly resurfaced by alluvial and playa sediments from adjacent, actively rising mountain ranges. An important advantage of high-resolution aeromagnetics over other techniques is the uniform areal coverage that provides an understanding of the complete pattern of intra-basin faulting (Figure 1). Even though some faults can usually be recognized at the surface by geologic mapping, the rapid rate of sedimentation assures that most surface evidence will be quickly buried. Some can be recognized in the subsurface by displaced reflectors on seismic reflection sections, but the limited areal coverage and expense of such surveys leave many faults undetected and the areal fault pattern ambiguous.

Because faults in the upper 0.5 km of the basin-fill sediments grow upwards through the sediments with each surface-rupturing earthquake event in the basin, the high-resolution aeromag results provide an understanding of the attitudes and spatial arrangement of active faults in potential reservoir rocks beneath the sediments. Knowledge of the fault pattern is important because there is considerable evidence that enhanced geothermal circulation occurs in zones where fault systems merge (Smith et al., 2002; Figure 1), intersect (Zoback, 1979; Sibbett, 1983; Richers et al., 1991; Jones et al., 2002), and/or lie in optimal orientations for slip (Barton et al., 1998; Hickman et al., 1998).

Shallow faults identified by high-resolution aeromag data also seem to reflect faithfully the positions of faults at depth. In Dixie Valley (Smith et al., 2002) and the Albuquerque basin (Grauch 2001; Grauch et al., 2001), the surface expression of faults as indicated by geologic mapping is areally coincident with their shallow expression as indicated by high-resolution aeromagnetic surveys, suggesting steeply dipping to vertical faults. At Dixie Valley (Smith et al., 2001, 2002) both surface and shallow expressions are areally coincident with the deep expression as indicated by seismic reflection surveys, suggesting a nearly vertical dip extending to the base of the valley-fill sediments. At Rye Patch, Beowawe, and Railroad Valley, there is also strong seismic reflection and drilling evidence of steeply dipping intra-basin and range-bounding faults (Ehni, 2001; Sibbett, 1983; Duey, 1983; Liberty et al., 1994).

A DIXIE VALLEY EXPLORATION MODEL

As others have shown (Benoit and Butler, 1983) geothermal systems in the Basin and Range province occur in a wide variety of geologic settings. Although the relative importance of various geologic, structural, and tectonic features in localizing geothermal systems not always clear, it is still valuable to have a conceptual model or models in mind to guide exploration activities. Dixie Valley is sometimes portrayed as a “typical” example of a deep circulation system in the basin and range, and it is one for which extensive geophysical (including high-resolution aeromag) and geologic information exists. Whether it is typical or not, it is at least a prime example or epitome of other systems that we would like to discover, and a conceptual model based on Dixie Valley can be put forth. It consists of several essential elements that are relevant to development of an exploration strategy.

1. Permeability is controlled by major basin-bounding fault systems (Benoit, 1999).
2. The fault system dips steeply and consists of multiple faults (Blackwell et al., 1999, 2000).
3. Most of the structural relief is accommodated by a buried fault(s) outboard of the exposed range-front fault (Blackwell et al., 1999, 2000).
4. Thick Tertiary and Quaternary basin-fill sediments mask the structural relationships and make siting of wells difficult.
5. The basin-fill sediments record a history of growth faulting, and evidence of young faulting at and near the surface helps to define the intra-basin fault patterns in the underlying bedrock (Smith et al., 2001, 2002).
6. The fault system is active, with evidence of late Quaternary earthquakes (Caskey et al., 2000).
7. Water in the geothermal system is old (isotopic evidence suggests late Pleistocene age) and may have infiltrated from pluvial lakes to depths of ~10 km in order to attain observed temperatures.
8. Much or all near-surface evidence of geothermal systems may be masked by shallow, cold aquifers.
9. Merging or intersecting faults may control the location of exploitable geothermal systems.

This model demonstrates the importance of structure and fault geometry in genesis of geothermal systems, and therefore, in the development of exploration strategies in the basin and range.

Other known geothermal systems in the Basin and Range province that seem to represent some variation on the theme of the Dixie Valley model are Railroad

Valley and Rye Patch (Figures 2 and 3). Although unique in numerous ways, they both have thick basin-fill sediment/volcanic sequences above the faulted basement host-rocks. In both cases, a definitive pattern of intra-basin faulting would be very helpful for focusing detailed geophysical surveys and siting exploration wells.

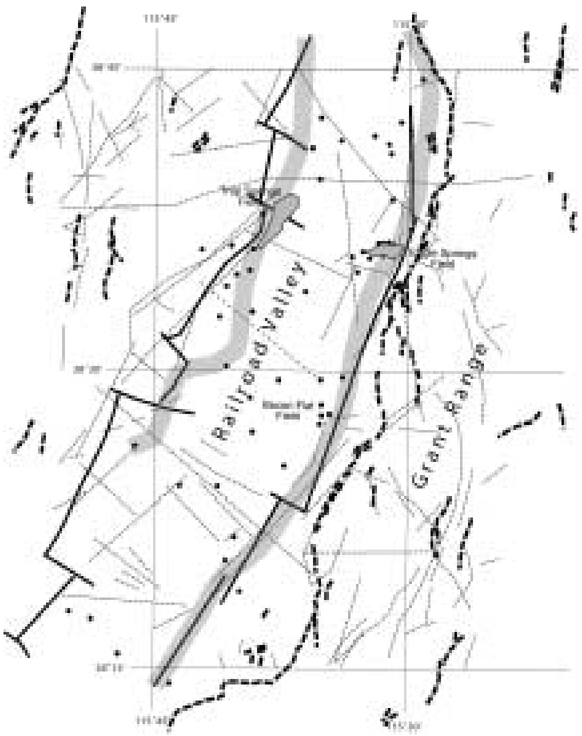

Fig. 2. Railroad Valley. A continuous system of Quaternary faults (heavy dashed lines) define the exposed range-front fault system. Maximum gravity gradient (broad gray lines) outline the deepest portion of the basin and show that most structural offset lies basin-ward of exposed range-front faults. Heavy solid lines are faults interpreted from geophysics and well logs (Duey, 1983). Light dashed lines are lineaments from air photo and satellite imagery (Richers et al., 1991). Dots are locations of oil wells.

OTHER EXPLORATION MODELS

Some of the known geothermal systems in the basin and range seem to be variations on the Dixie Valley theme. Beowawe occurs on a range-front fault system but the range is small and the "basin" is very shallow, and Bradys and Desert Peak occur in faulted Tertiary and pre-Tertiary rocks without development of large structural relief. Other systems such as Soda Lake, Steamboat Springs, and Roosevelt have the added complexity of young volcanism and potential magmatic heat sources.

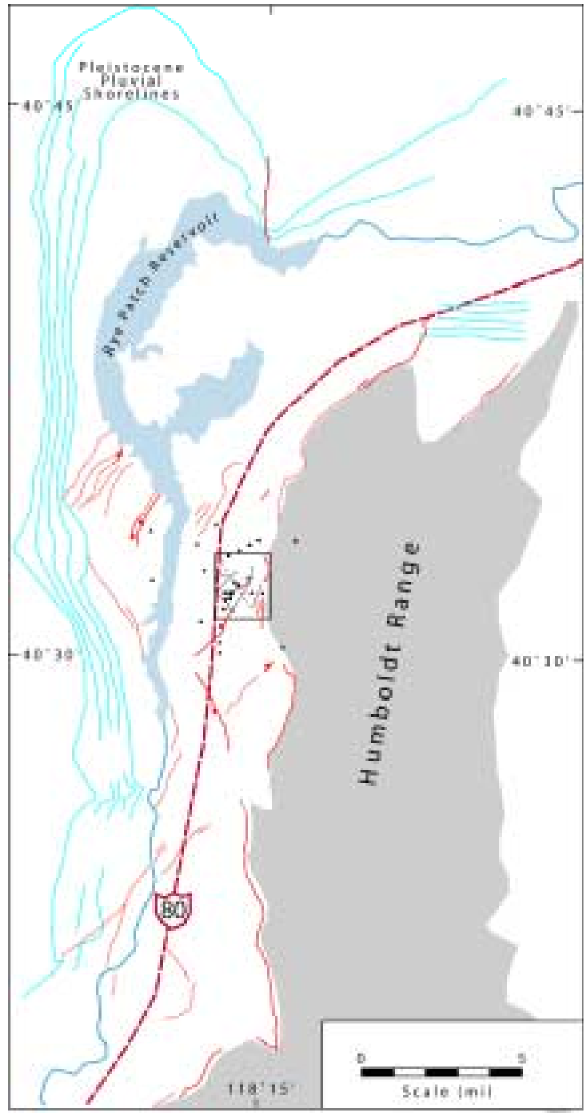

Fig. 3. Rye Patch Reservoir. Late Quaternary range-front faults (red lines) along the west edge of the Humboldt Range bound the basin-fill sediments. Faults interpreted from air photos (this study) shown in red solid and dotted lines. Shoreline features show high stands of pluvial lakes. Rectangle shows area of detailed geophysical surveys and drilling (black circles and triangles).

EXPLORATION STRATEGY FOR UNTESTED AREAS

The Basin and Range province has numerous basins with little or no previous geothermal exploration, but with geophysical, geologic, and surface geothermal expressions conducive to occurrence of exploitable geothermal resources. For expanding geothermal exploration into these areas, early deployment of high-resolution aeromag would help to provide a knowledge of intra-basin fault patterns that is not attainable by other methods. Such knowledge would guide further explorations activities with greater confidence and effectiveness than has been possible until now.

An effective exploration strategy in this case would include initial screening using existing geologic, geophysical, and geochemical data to select promising basins for further exploration assessment. This would be followed by an assessment of fault patterns in the basin by geologic mapping using aerial photograph and remote-sensing interpretation, and field investigations. Acquisition and processing of high-resolution aeromagnetic data simultaneously with geologic mapping would serve several purposes. First it would be a useful geologic mapping tool for connecting and extending isolated exposures of faults, for confirmation of ambiguous surface evidence of faults, and for showing areas to look for fault evidence on the ground (Grauch 2001;Grauch et al., 2001). The step of comparison of geologic mapping results with the high-resolution aeromagnetic data is important. It provides independent evidence that short-wavelength linear anomalies are generated by fault offsets, increasing the confidence that linear anomalies without surface evidence can be interpreted as faults. Second, it would round out the intra-basin fault pattern by revealing buried faults that have no surface expression. And third, it would augment the interpretation of large aeromagnetic anomalies related to lithologic variations in bedrock. For instance, the high-resolution aeromagnetic survey of Dixie Valley provided more detailed shapes of the same large anomalies mapped in earlier, coarser surveys; anomalies that are related to distribution of mafic rock bodies beneath the sediment fill (Smith et al., 2002).

As the exploration activities continue, other techniques can the be brought to bear. Detailed gravity surveys can help to establish overall basin geometry and positions of major range-bounding faults that might be buried beneath the basin-fill. Correlation of intra-basin fault positions, orientations, and patterns to other data, such as thermal features, temperature anomalies, bedrock geology, any existing well information, geochemistry, hydrology, late Quaternary geomorphic features, major lineaments identified from remote-sensing imagery, and regional stress orientations can then be used to design detailed geophysical surveys (seismic reflection, electrical, electro-magnetic) and assess various locations for exploration wells.

SOME EXPLORATION SCENARIOS AT KNOWN GEOTHERMAL FIELDS

The high-resolution aeromagnetic survey of Dixie Valley was a test of the method in a basin known to contain a productive geothermal field. Previous success with the method in the Albuquerque basin (Grauch, 2001 and Grauch et al., 2001) prompted a test in a different setting. The main differences between the Dixie Valley and the Albuquerque Basin settings are the steep range-front, narrower and deeper basin, and presence of extremely magnetic rock bodies in the bedrock basement at Dixie Valley. These difference required that the acquisition at Dixie Valley be done by helicopter instead of fixed-wing aircraft, and that additional processing steps were required to separate the short-wavelength linear anomalies from the longer-wavelength, large magnitude anomalies related to bedrock sources (Smith et al, 2002). Results of the survey were successful despite these adjustments. It revealed the pattern of faulting in the basin with a clarity not possible in other ways, showed that the producing geothermal field lies in an area of merging of two fault systems, and showed another area of the basin with similar merging of fault systems (Smith et al., 2002).

Application of the method in other areas of known geothermal systems will provide the much-needed structural framework on which to base additional local exploration. Some examples are given to illustrate the potential usefulness of the method.

Railroad Valley, a basin in which both petroleum and geothermal systems reside (Hulen et al., 2994), has received extensive geophysical and drilling activity, yet the intra-basin structural framework is still uncertain. Gravity for the region (Blank, 1993) shows that, like Dixie Valley, the bulk of the structural relief is accommodated by faults that lie buried beneath the valley-fill sediments outboard of the exposed range-front fault system (Figure 2). The locations of major displacements of the top of basement in the valley, based on drilling and seismic data (Duey, 1983), are shown on Figure 2, and agree remarkably well with the steepest gravity gradients. Several interpretations have been made of lineaments within the basin from air photographs and remote sensing imagery (Richers et al., 1991; Levandowski et al., 1993), and one (Richers) is shown on Figure 2. Differences between these interpretations are significant and point to the need for a definitive elucidation, which could be provided by a combination of geologic mapping and a high-resolution aeromagnetic survey. The fault pattern revealed could then the used in conjunction with other information to select sites for geothermal exploration wells. As an example, most of the existing wells are located near the oil fields in the northern and eastern parts of the basin, but the highest geothermal gradients lie south-southwest of 38° 30’ and 115° 45’ (Duey, 1983) where only one well has been drilled. Several interpreted fault intersections also lie in this area, and refinement of the faulting patterns in this area could reveal promising sites for exploration wells or additional detailed geophysical surveys.

Exploration at Rye Patch would also benefit from a knowledge of definitive fault patterns (Figure 3) to help place the known geothermal system in a more regional context. Interpretation of Quaternary geomorphic features on high altitude aerial photographs provides a suggestion of intersecting NE- and NW-trending faults in the valley-fill sediments. Combining those interpreted faults with ones interpreted from seismic reflection and drilling suggests that the known geothermal system is centered on one such fault intersection. However other similar intersections lie to the south, and if that interpretation is confirmed or modified by a high-resolution aeromagnetic survey, then additional exploration targets would be revealed. Most of the exploration activity (detailed geophysical surveys and drilling) have been focused in the area of the known geothermal system (rectangle in Figure 3) (Teplow, 1999; Gitto et al., 2002). A broader look at the structure of the basin could provide additional insight into siting wells at the known system and reveal new targets within the basin.

The Soda Lake geothermal system lies in Carson Sink, far from basin-bounding faults. It is very different from systems discussed previously because it is associated with very young basaltic volcanism, possibly fed by a shallow NE-trending dike extending through Soda Lake and Upsal Hogback (Benoit and Butler, 1983). The geothermal system lies between the lake and the hogback and several possibilities exist for the localization at that position. A high-resolution aeromagnetic survey would be extremely valuable to assess this area for at least two reasons. First, the basin is large and deep and geomorphically active. Both alluvial, playa, and eolian activity constantly remodel the surface so that surface evidence of faulting is ephemeral. In spite of this, several Quaternary faults have been mapped in the basin, so many active faults are likely to be present and most of them have no surface expression. Second, any basaltic dikes in the basin that extend into the sediment fill would be easily detected and mapped by the survey, and the aeromagnetic expression would be different from that associated with faults in the sediments. So the potential exists to map the distribution of faults and basalt dikes in the subsurface, and to assess the relationship of the known geothermal system to those distributions. This could clarify the factors localizing the known system and provide additional targets within the basin.

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