Exploration and Development Techniques for Basin and Range Geothermal Systems: Examples From Dixie Valley, Nevada

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Introduction

As a result of recent drilling, the Dixie Valley geothermal system is now interpreted to be associated with a normal fault zone consisting of several steeply dipping major strands instead of a single master fault with splays (Benoit, 1999; Blackwell, *et. al.*, 1999, 2000). A cross section is shown in Figure 1. We have revisited the available exploration data in the light of this new understanding. The objective of this paper is to summarize the exploration data in order to see what techniques work the best and should be used in the exploration for, and evaluation of, Basin and Range geothermal systems of the Dixie Valley type. This paper will focus on gravity and seismic data in conjunction with the drilling results. New aeromagnetic data are described by Smith, *et. al.* (2002).

An index map to the geothermal field is shown in Figure 2 and the line of the structure section in Figure 1 is shown. Drilling has shown that the range front fault is not responsible for the valley displacement. There is at least a second major fault zone (referred to as a piedmont fault), typically about 1-2 km away from the range front, that often carries most of the valley displacement. All of the current production in Dixie Valley comes from wells drilled into the piedmont fault zone and none of the current production or injection wells penetrate the range-bounding fault. The implications of this new model are that a large zone rather than a single fault forms the reservoir, that there is open porosity even in parts of the fault system that are not directly connected to the surface, and that the faults are very steep (on the order of 75°+). Thus directional drilling is the best way to explore in the systems.

The Dixie Valley Producing field (DVPF) has been described by Benoit (1992, 1999). This portion of the field was developed between 1979 and 1988 and for the last 14 years about 60 MW of electrical power has been produced by Oxbow Power (since 2000 by Caithness). The field consists of two groups of production wells in sections 33 and 7 (Figure 2, overleaf), with injection wells in between (section 5) and to the south (section 18 and Lamb Ranch). The DVPF has the highest temperatures (248°C) found in the province in a nonmagmatic system. Temperatures reach 285°C in well 36-14 immediately south of the DVPF. Wells outside the field include two hot wells located several km to the southwest. Wells 66-21 (218°C) and 45-14, (195°C) both have above regional temperatures and have a few lpm of artesian flow. Temperatures in the northernmost well, 76-28 (Tmax of 162°C at 2350 m), and well 62-21 in the middle of the valley (Tmax of 184°C at 3318 m) appear to approach

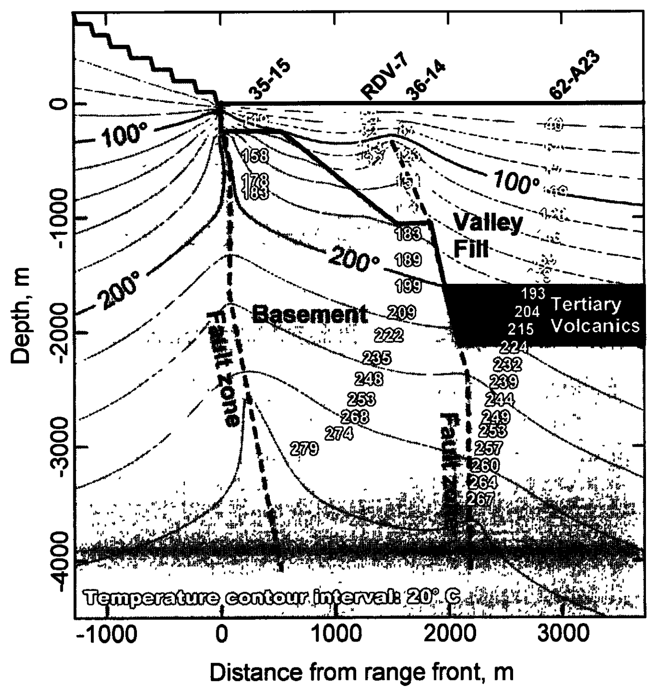

Figure 1. Structure and thermal cross section of the DVPP area (Blackwell, *et. al.*, 2000).

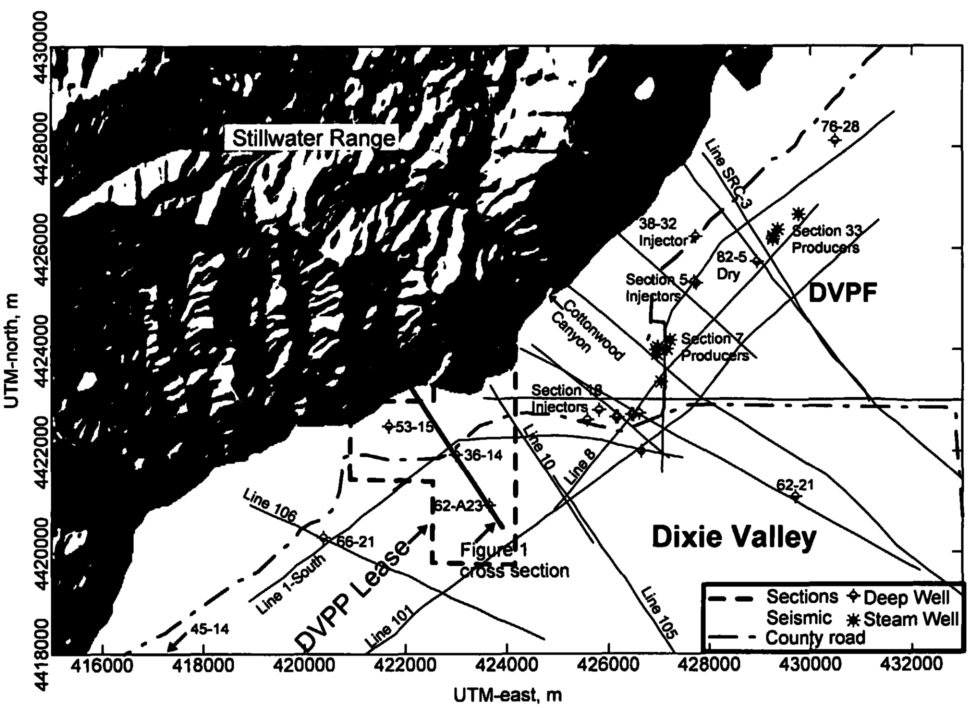

Figure 2. Index Map of the Dixie Valley geothermal field. DVPF is the Dixie Valley Producing Field area.

background conditions (see Williams, *et. al.*, 1997 for temperature-depth curves for several wells).

The models of the range bounding fault within the Dixie Valley geothermal field span the gamut from low angle or listric (Plank, *et. al.*, 1999) to typical "high" angles (50 to 60°, e.g. Okaya and Thompson, 1985; Benoit, 1992). In spite of the large amount of drilling into the fault zone the production and injection wells are all about the same distance from the range/valley contact and produce from about the same depth. As a result the dip of the structures associated with the production is constrained by drilling information only between depths of 2.5 and 3 km. Consequently, the working model of the system was a single fault dipping at about 54° with small synthetic and antithetic faults in the deep valley in the hanging wall of the major fault. This 54° dip was based on the assumption that the fault encountered in the producing wells connects to the range/valley topographic contact. This result seemed to be consistent with abundant seismic reflection data and other information (e.g. Okaya and Thompson, 1985).

Exploration Data and Interpretation

There are several generations of exploration data that can be compared. The original exploration focus on the area was by Southland Royalty and Sun. They centered their activities along the range front between the Stillwater Range and Dixie Valley from the Dixie Comstock area to the Senator fumaroles. Much of the Southland Royalty data was made public in the Industry Coupled DOE program of the early 1980's. Included were seismic, gravity, and aeromagnetic data. The maps were generally at a scale of 1"= 1 mile.

Sun also collected a variety of geophysical data including gravity, aeromagnetic, electrical, and seismic reflection data. The initial Sun discovery wells (Lamb Ranch #1,2,3) were drilled on private land and this had a large impact on the locations and the subsequent follow-up drilling. Seismic reflection data played a part in the selection of the targets.

Following Sun, a number of companies were active in the area, but generally confined their activities to production drilling. Wells drilled, including those that expanded the producing area to section 7, discovered the producing area in section 33 and defined the apparent north end of the field (76-28). Following the acquisition of the field by Oxbow a number of production and injection wells were drilled in the areas of section 7 and section 33. There was no other significant drilling activity until 1993/94 when DVPP (Caithness and Florida Power and Light) drilled the 62-23, 62A-23, and 36-14 wells in an area between the Lamb Ranch wells, and the Southland Royalty 66-21 well and proved the existence there of high temperatures and fluid flow (Figure 1 and 2).

Seismic Results

A wide variety of seismic exploration techniques have been applied in Dixie Valley. Early studies included refraction profiles widely distributed in the valley (Thompson, *et. al.*, 1967). During the exploration phase of the late 1970's and early 1980's many kilometers of conventional seismic reflection surveys were collected using dynamite sources. The lines available are shown on Figure 2. An influential early interpretation of one of these profiles (SRC-3) was published by Okaya and Thompson (1985). There was later reprocessing of the seismic reflection data in 1993/94 and 1998/99. In the 1993/94 study several lines (106, part of 101, 10 and 105, Unpublished, Caithness Report, 1994) were conventionally migrated. In the later study (Lettis, *et. al.*, 1998) Kirchof migration techniques were applied to a number of the lines in the northern part of the system. The seismic lines have been successful in showing generalized structure in the valley, but are not very useful for illuminating the fault style details important for exploration because of the difficult setting.

To illustrate the effects seen on the various profiles, Line 10/105, the SE-NW line that runs between the Lamb Ranch wells and the DVPP wells, is discussed in this section. The lines

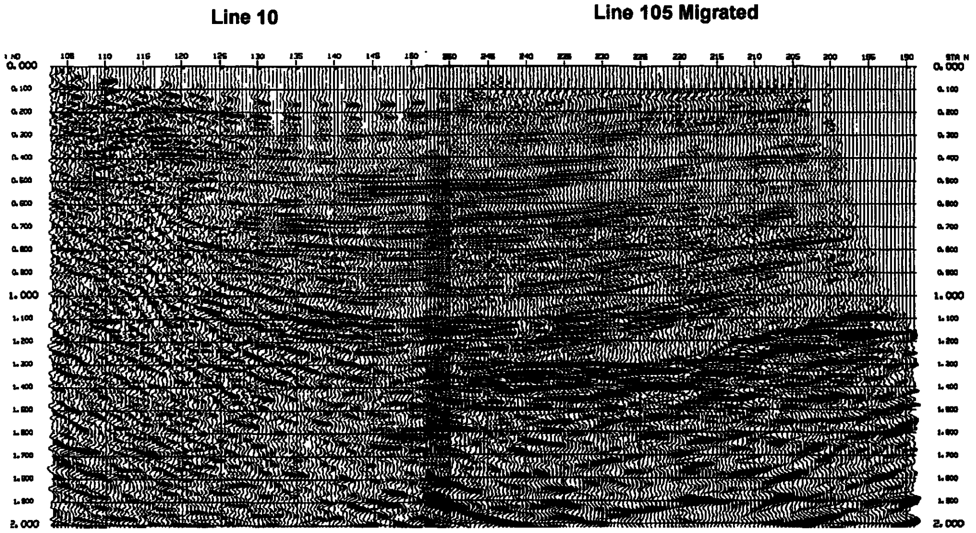

Figure 3. Seismic reflection lines 10/105 combined.

have been combined because both are short and cover complementary areas. The reason to use them as examples is that both migrated and unmigrated versions of the lines are available. These lines also cross the SRC-1S and 101 NE-SW lines so that the inferences from the lines can be directly correlated with other parts of the data set. The merged migrated lines are shown in Figure 3. An interpreted summary line drawing of this profile converted to depth is shown overlaid on a structural model in Figure 4.

The most prominent feature of the migrated lines is the presence of a clearly imaged valley fill. The thickness of the valley is greatest between SP's 145 and 245. The prominent reflector at about 1.1 seconds two way travel time (TWTT) is interpreted to be the top of the Tertiary basalt (see Okaya and Thompson, 1985). The basalt is close to the basement based on the Lamb Ranch wells and the section 18 wells immediately to the northeast (Benoit, 1992). The second prominent reflector along the eastern part of the sections at 1.3 s (west) to 1.1 s (east) is interpreted to be the top of basement reflector. Although the data quality is poor, it shows reflectors as shallow as 0.16 seconds, but generally between 0.2 and 0.3 seconds.

A major feature of the section is the termination of most of the valley reflectors at about SP 120 on Line 10. West of this point there are coherent reflectors above about 0.4 s only. The reflection section SRC-3 described by Okaya and Thompson (1985) is about 4 km northeast along the range front. It closely resembles these sections. Okaya and Thompson (1985) interpreted the similar western end of SRC-3 to represent loss of reflection coherency due to coarse alluvial fill. They furthermore thought that they saw signals from the range bounding fault dipping at about 54° in the data.

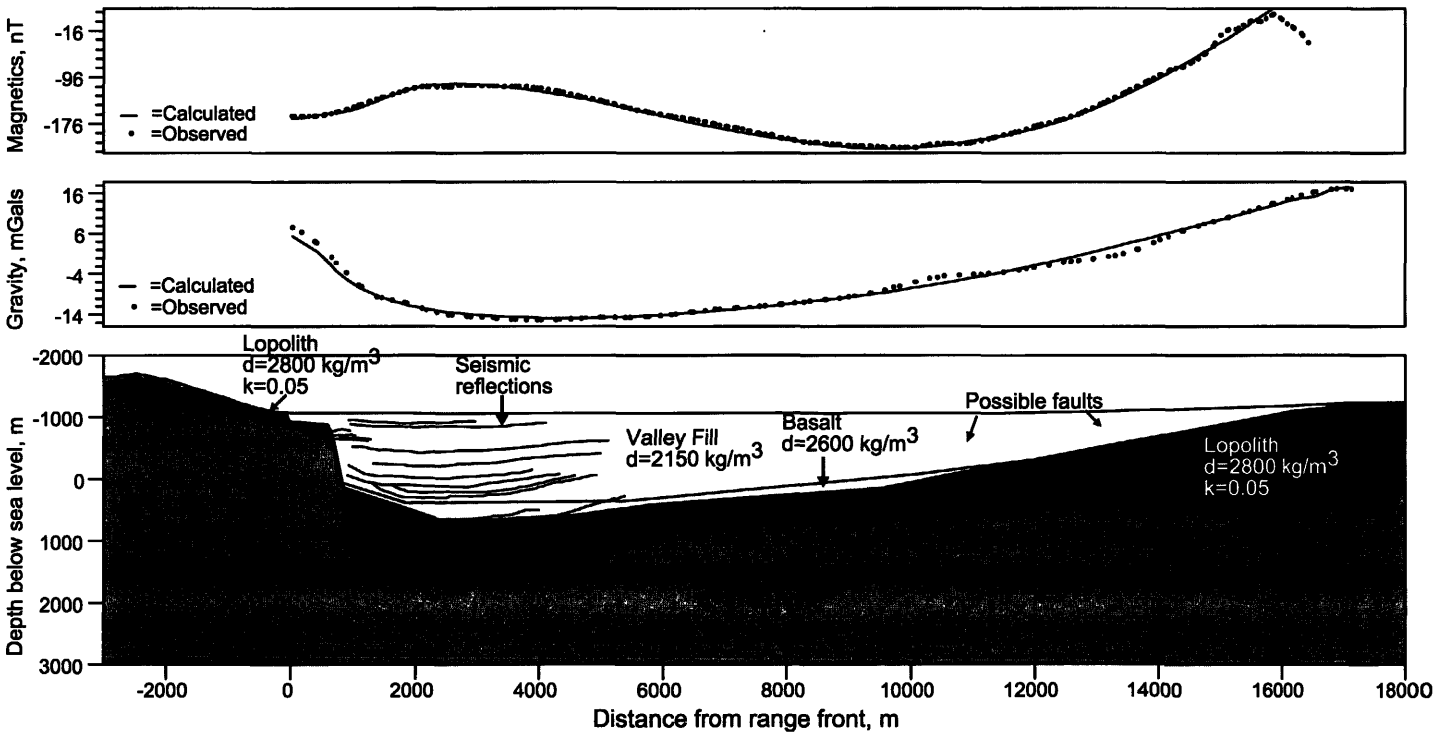

Figure 4. Depth section for seismic reflection lines 10/105 superimposed on gravity and magnetic cross sections.

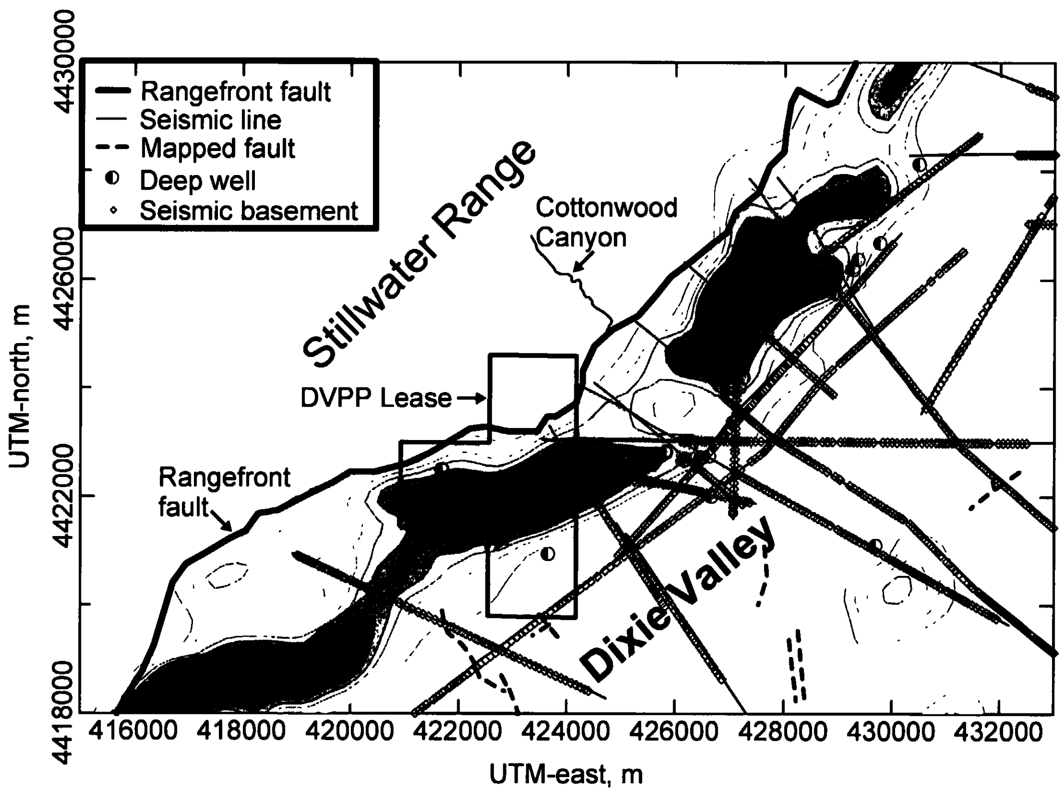

Figure 5. Comparison of location of steepest gravity gradients, mapped faults from air photos, and seismic reflection terminations for the area of the geothermal field. The diamonds on the seismic lines represent basement picks.

Similar terminations of reflector packages are present on most of the NW-SE trending seismic lines. The positions along the seismic lines where basement reflections could be identified are shown in Figure 5 by the diamonds along the lines. Also shown on Figure 5 is the calculated gradient of the residual Bouguer gravity field. It is clear that the seismic reflection termination points and the maxima of the residual gravity gradient coincide. This coincidence implies that the situation shown for sections 10/105 is true for the area of the producing field as well as the DVPP area, i.e. the piedmont fault is located by both the gravity and seismic data in the same place. Geologic mapping from air photos shows that there are often fault scarps and small grabens at the surface over the gravity gradient maxima (Smith, *et. al.*, 2001). On at least one of the seismic sections, 106 to the south, a large, deeply buried antithetic graben is imaged along the piedmont fault.

A simple example of the correlation of the gravity anomaly and the gravity gradient is shown for the 10/105 cross section data in Figure 6. Two generic models that satisfy the gravity anomaly and the gravity gradient pattern are shown. The peak of the gravity gradient is approximately coincident with the position of the main valley-bounding fault where it starts to displace the basement against valley fill.

A version of the lines 10/105 is shown converted to depth in Figure 4. The depth conversion was made using a velocity versus depth relationship based on sonic well logs and matches the lithology section as drilled in the deep wells near the seismic lines. In converting from two way travel time (TWTT) to depth we have used a conversation in the valley fill of 0.5 s ~ 500 m, 1.0 s ~ 1.2 to 1.4 km, and 1.2 s ~ 1.5 to 1.8 km.

Problems with Seismic Data

There are several problems with the seismic reflection data that are available and some problems that are endemic to the technique. The sections generally have not been migrated using modern techniques. The reflection technique does not deal well with steep structures and in the real case the faults generally have very steep dips. There are strong lateral and vertical velocity variations that complicate the interpretation. There are numerous examples of out-of-plane reflections on the sections as well because of the 3-dimensional velocity configuration.

The most enigmatic feature of the sections is the noise in the vicinity of the Lamb Ranch injection wells and the section 7 production wells. This "noise" is particularly clear on the Lines 8 and SRC-1N. This area is enigmatic since the drill data from the wells does not indicate anything anomalous about the valley in this area. One possibility is that the noise is due to side swipes from a buried fault scarp along the piedmont fault just to the northwest of the line. Another possibility is an area of pull up because of induration or alteration of the valley fill due to some unknown cause, maybe silicification.

Gravity Data

A detailed gravity compilation for this area of Dixie Valley was described by Blackwell, *et. al.*, (1999). These data were used to generate residual maps of the field area. A detailed interpretation of the section along the seismic lines 10/105 is shown in Figure 4. This section includes an interpretation of both gravity and magnetic data. A single density contrast of -0.55 gm/cc was used for the valley fill relative to basement and a positive density contrast of +.10 gm/cc for the lopolith relative to the basement.

Magnetic Studies

Aeromagnetic surveys were carried out by both Sun and Southland Royalty in the late 1970's and early 1980's. More

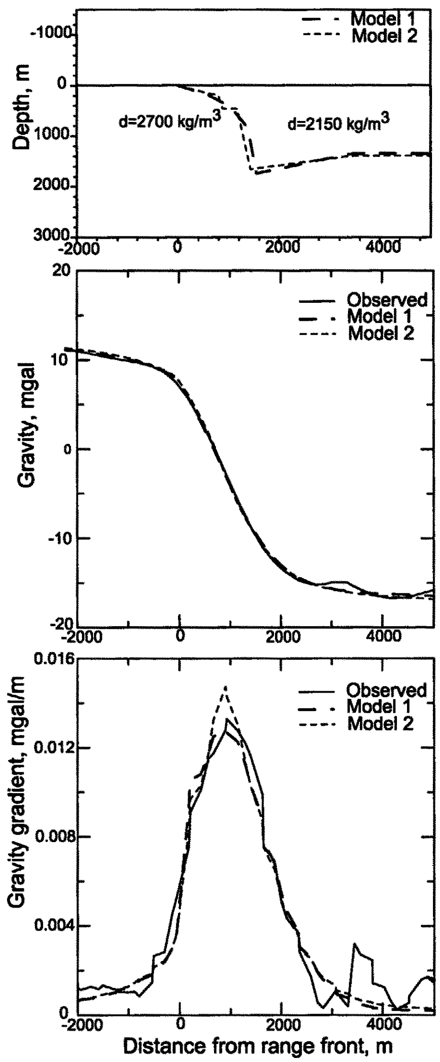

Figure 6. Example gravity gradients from example range front structures.

recently in early 2002 a high-resolution low-altitude aeromagnetic study was carried out (Smith, *et. al.*, 2002) based on success in imaging shallow expressions of intrabasin faults in the Albuquerque Basin (Grauch, *et. al.*, 2001). That survey is described by Smith, *et. al.* (2002). It was very successful in locating faulting trends along the east side of the valley, but was less successful along the deeper west side.

Interpretation

Both the gravity and the magnetic data on the profile along seismic lines 10/105 are shown in Figure 4. The total field aeromagnetic data from a 1979 survey flown at an elevation of 5500 ft (1676 m) are shown. There is an excellent correlation on the regional scale between the two sets of data. Areas of high gravity along the east side of Dixie Valley correspond to the areas of positive magnetic field strength. Both of these in general, correspond to areas probably underlain by the Jurassic Humboldt lopolith (see Smith, 1968). For example, there are two generally circular areas in Dixie Valley where the contours of the residual gravity field follow the contours of the magnetic field and both are clearly related to lopolith bodies that are mostly buried. Therefore, the mafic rocks of the lopolith are both dense and magnetic. Weaker positive magnetic anomalies, not so clearly related to gravity, are located along the west side of the valley. The magnetic anomalies on both sides of the valley are on the section shown in Figure 4. Only the lopolith was assumed to be magnetic in modeling the section.

Discussion

The drilling described by Blackwell, *et. al.,* (2000) in the DVPP area to the south, the drilling in section 18, and the gravity interpretation show that the point where the reflectors end on Figure 3 is the location of the piedmont fault. The fault there has about 0.6 s of displacement as shown on Figure 4. In these areas the range bounding fault and the piedmont fault dip at an angle of greater than 80° and carry fluid at temperatures of 240-285°C. Most of the rest of the sections perpendicular to the range valley contact show clear valley reflectors to a certain point and then have no clear reflections from there to the range end of the line. Both gravity and drilling show that the "alluvial fan" of Okaya and Thompson (1985) is actually a shallow basement block in between a piedmont fault and the range front fault.

Given the present understanding of the Dixie Valley field, what might be the optimum approach to developing the field? The results described above show that there is no magic bullet. The seismic reflection data are very useful and can be site specific when a profile is in the right place, but are sparse, very difficult to interpret correctly, and expensive to collect. The velocity values used are uncertain even though there are several sonic logs for the wells. A VSP, Vertical Seismic Profile, survey would significantly improve the precision of the interpretation. The gravity data are not as site specific as the seismic, but put the major parts of the structure in their proper location and places vital constraints on the possible interpretations of the seismic data. The high resolution aeromagnetic technique was very successful along the east side of the valley, but less along the geothermally important west side. Detailed correlation will be investigated when the high resolution data are available. The magnetic results will also vary from area to area depending on the local rock types more than in the other techniques. Nonetheless important information on the style of the faulting is contained in the data. Geologic mapping from air photos in some places clearly located the structures in the valley and hence is very site specific. None of the techniques was very successful in determining the strike of the fracturing and faulting between the piedmont and range front faults in a useful way. This is a problem since a large volume of reservoir is included in this area. The single most useful data set might be a high resolution 3-d or closely space 2-d seismic survey focused on the depth range of 500 to 1500 m and covering the piedmont area. We are investigating the design and costs of such a survey to help resolve the uncertainties in the structure of the piedmont/range zone.

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