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Seismic Reflection Data and Conceptual Models for Geothermal Development in Nevada

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ABSTRACT

Seismic reflection data were collected in two geothermal areas in Nevada to support geologic structural models and geothermal well targeting. The data were integrated with surface mapping, well results, and other geophysical data in conceptual geologic models in both areas. Faults were interpreted from reflection data based on reflector offsets and apparent fault surface reflectors dipping away from the range front. Interpreted faults at Blue Mt., where several wells have been drilled, correlated with well entries. Subsequent well targeting based on the conceptual structural model at Blue Mt. resulted in an important step-out drilling success.

The data quality in reflection images with possible fault surface reflectors was reviewed because of the potential exploration value of the correlation of these reflectors with well entries. Data quality review at Blue Mt. showed that noise patterns dominate most of the reflection data. Consequently it appears that the interpreted fault surface reflectors are most likely related to coherent noise and that the observed well entry – fault correlations may be fortuitous.

The noise review experience from Blue Mt. has been integrated into more successful seismic interpretations elsewhere, including at the Pumpernickel Prospect. The application of reflection data in Basin and Range settings should consider noise issues at the design and interpretation stage, use quality assurance graphics to assess interpretation uncertainty, interpret the reflection data in the context of the refraction seismic velocity images, and apply skepticism to apparent fault reflectors dipping away from the range front.

The success of the step-out well targeting at Blue Mt. in spite of the failure of seismic reflection data to image the subsurface demonstrates the robust reliability of a conceptual model approach to geothermal exploration that emphasizes the consistent integration of multiple data sets.

1. INTRODUCTION

Although the application of the reflection seismic method to geothermal exploration has been the subject of extensive research for over 30 years, few drilling targets identified by reflection surveys have been validated by production wells (Nakagome et al. 1996; Gritto et al., 2003). Melosh (2008) reported a correlation of an apparent reflection seismic event with a permeable fault zone in a well at the Blue Mountain Geothermal Field (Blue Mt.) in the Basin and Range geological province. Further analyses subsequently done to characterize the uncertainty of this correlation led to a significant discounting of the reflection seismic evidence at Blue Mt. and a reassessment of the seismic results at other fields. The following review of the use of seismic reflection at Blue Mt. introduces a comparison of the results from Blue Mt. and the Pumpernickel Prospect, an analysis of the noise issues that led to the reassessment of the reflection seismic, and recommendations for interpreting these data in a geothermal context.

1.1 Pumpernickel Prospect

The Pumpernickel Valley geothermal project area is located about 35 km SE of the town of Winnemucca, within the structurally complex Winnemucca fold and thrust belt of north-central Nevada. The project area is cut by a series of range-parallel normal faults. Within the project area, abundant hot springs and seepages are present next to the range-front Pumpernickel Valley fault. The widespread hydration and alteration around the fault indicate that it focuses shallow fluid up-flow, whereas Piedmont Faults (faults that parallel the range front but are buried in sediments) bounding the nearby, down-dropped structural blocks may also host the deep reservoir.

1.2 Blue Mountain Geothermal Field

Blue Mt., located about 40 km west of Winnemucca, was a “blind” geothermal prospect with no surface thermal manifestations. Mineral exploration holes drilled in an area of intense silicification and alteration near Quaternary dikes revealed a 80°C aquifer in the 1990s. Fluid chemical indicators from this aquifer encouraged Nevada Geothermal Power to explore the geothermal potential of the area (e.g. Fairbank and Ross, 1999 and Ross et al, 1999). Exploration work included temperature gradient wells, fluid geochemistry, two DOE-funded slim holes, full-sized exploration wells, and the seismic reflection survey that is the subject of this paper.

Blue Mountain is a 185 to 190ºC dilute benign brine reservoir. Although the most prolific wells are located along Piedmont faults, the distributed fracture permeability in the system is also affected by the complex structural setting of the field. Young faulting at Blue Mt includes intersecting range front faults that strike NW, NS, and NE. The conceptual model suggests that geothermal fluids equilibrate at up to 250ºC at depth in NE-trending Piedmont faults located 400 to 2000 m toward the center of the basin from the surface trace of the range front. The upflow feeds an artesian reservoir at 190ºC in the fault zone and then leaks up into a widespread shallow 80ºC tabular aquifer at 100 to 300 m depth. Warm outflow mixes with meteoric water during flow out into the basin. This shallow aquifer provided the initial evidence of the commercial temperature system in mining core holes.

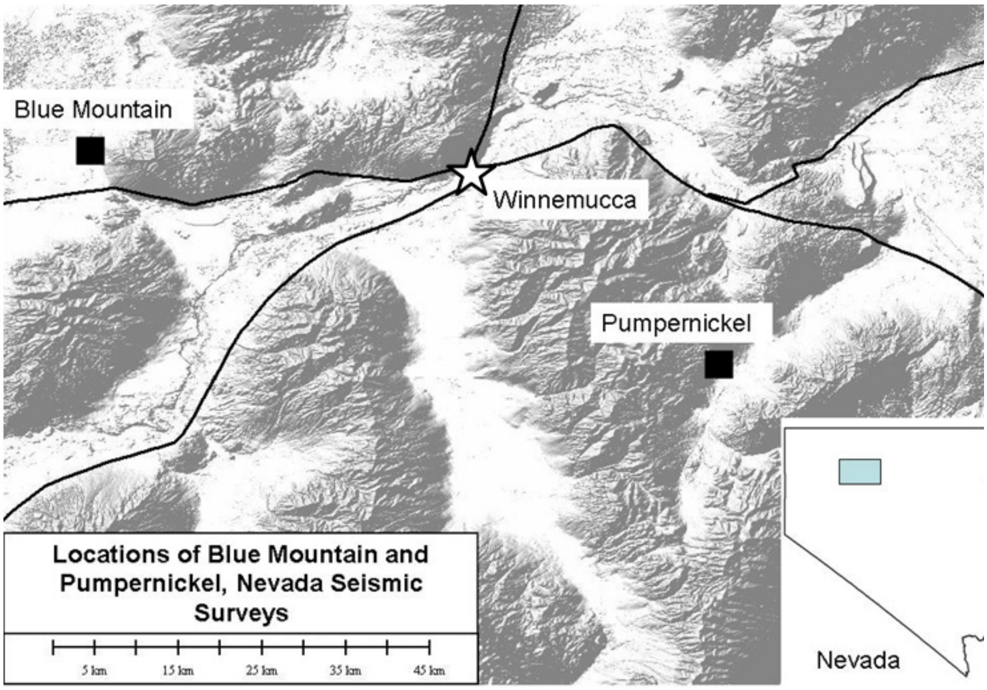

Figure 1: Location map for Blue Mountain Field and Pumpernickel Prospect.

3. EXPLORATION DATA INTERPRETATION

Seismic reflection and refraction data were collected and processed by Optim (2007a and 2007b) in the Pumpernickel Prospect and Blue Mt. Field. Both sets of images showed several possible fault surface reflectors dipping about 50º away from the range front as well as offsets of apparent reflectors in a broad range-front fault zone. Preliminary interpretations of the processed reflection images suggested that both areas had complex range front fault patterns with Piedmont faults that are offset a kilometer or more into the basin from the surface trace of the range-front fault.

The reflection data interpretation at Pumpernickel suggested that at least two Piedmont faults offset the basement up to 2 km east of the range front (Figure 2). In addition three or more possible fault surface reflections were identified in the processed data dipping about 50° to the east (basin-ward) below the range front. The Piedmont faults were based on the offset of multiple roughly parallel and horizontal reflectors that may be related to bedding surfaces. Both the Piedmont offsets and the dipping reflectors below the range front are of interest since they might provide geothermal drilling targets.

At Pumpernickel the reflection and refraction data were co-interpreted with 2.5D Bouguer gravity models and geologic mapping (Melosh et al, 2008). The gravity and refraction data confirm the occurrence of the offsets interpreted to be caused by Piedmont faults. The multiple reflectors dipping away from the range front are consistent with at least two range front fault traces mapped at and near the range front. Although detailed data is not available from the 962 m well drilled into the range front, it has been reported that the well encountered limited production at about 130°C. This well is currently leaking hot water and gas from the wellhead.

The apparent success of the reflection data collected at Pumpernickel to detail fault structures led to application of seismic reflection at Blue Mt.

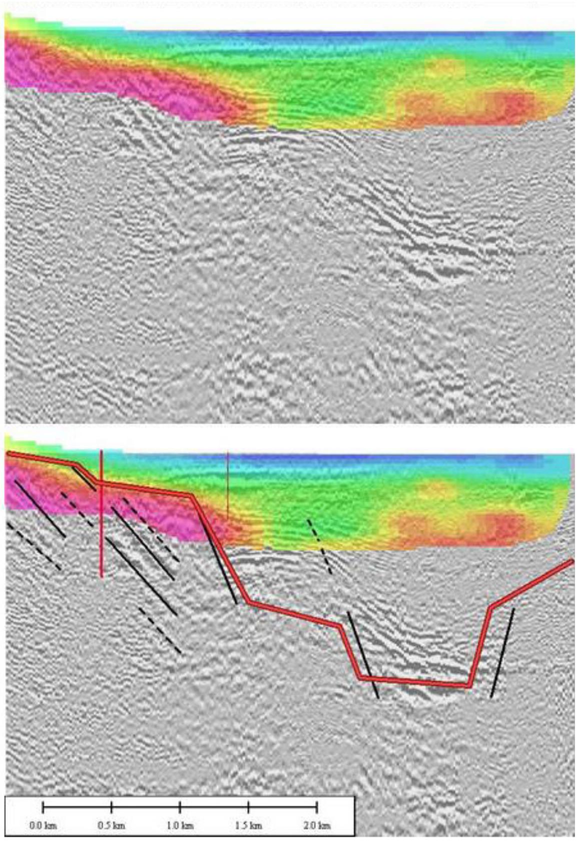

Figure 2: East-west seismic reflection image from Pumpernickel. The upper image shows the wiggle trace with refraction velocities in color. The lower image shows the basement interpreted from the gravity model and wells in red. Interpreted faults from offsets and apparent normal fault reflectors dipping away from the range front are in black. The image has no vertical exaggeration.

The Blue Mt. data (Figure 3) suggest a similarly broad pattern of range front and Piedmont faults. These data were also co-interpreted with gravity although the simplistic basin sediment - basement density model available at the time did not allow direct quantitative comparison of models for the two processed data sets. Co-interpretation in this case involved simple comparisons of fault locations and sense of offset between the two interpretations. Further confirmation of the structural model was derived from the refraction data, detailed geology based on extensive exposure at the range front, limited aeromagnetic data, and drilling results from five geothermal exploration and production wells. Confirmation of the dip of the faults was available from core fracture dip data that support an interpreted fault dip of about 50° to the west (basin-ward).

4. SEISMIC DATA QUALITY REVIEW

The potential suggested by the Blue Mt. seismic interpretation for imaging permeable reservoir fractures led to a detailed review of the Blue Mt seismic data to assess the uncertainty of the interpretation with respect to further targeting of well entries. The review process involved display of the original unfiltered data in shotpoint gather format to check signal quality. These images were then used to detect whether non-reflection seismic energy such as refracted and surface waves contaminated the seismic reflection interpretation.

The original seismic survey design by Optim (2007) was directed at high resolution of refraction arrivals for shallow velocity analysis and detecting reflections with high resolution at low cost. The preferred seismic source for good refraction analysis was single dynamite shots in shallow holes and this was also the lowest cost source, for example, in comparison to the vibrator array used at Pumpernickel. Unfortunately, shallow single shots tend to create large amplitude surface waves called ground roll that must be filtered, muted or attenuated by stacking reflection arrivals. In addition, much of the Blue Mt. survey area was covered with dunes and loose alluvium from the range front, a particularly difficult challenge for seismic reflection acquisition. It is usually met by the very expensive option of drilling multiple shots below the loose material, costing as much as $150,000/km. Besides poor penetration of reflections, such an environment also tends to create reverberations following the first break refraction arrivals. These arrivals must also be muted before proceeding with further processing. All these problems could be addressed if visible reflection energy is apparent in the field records.

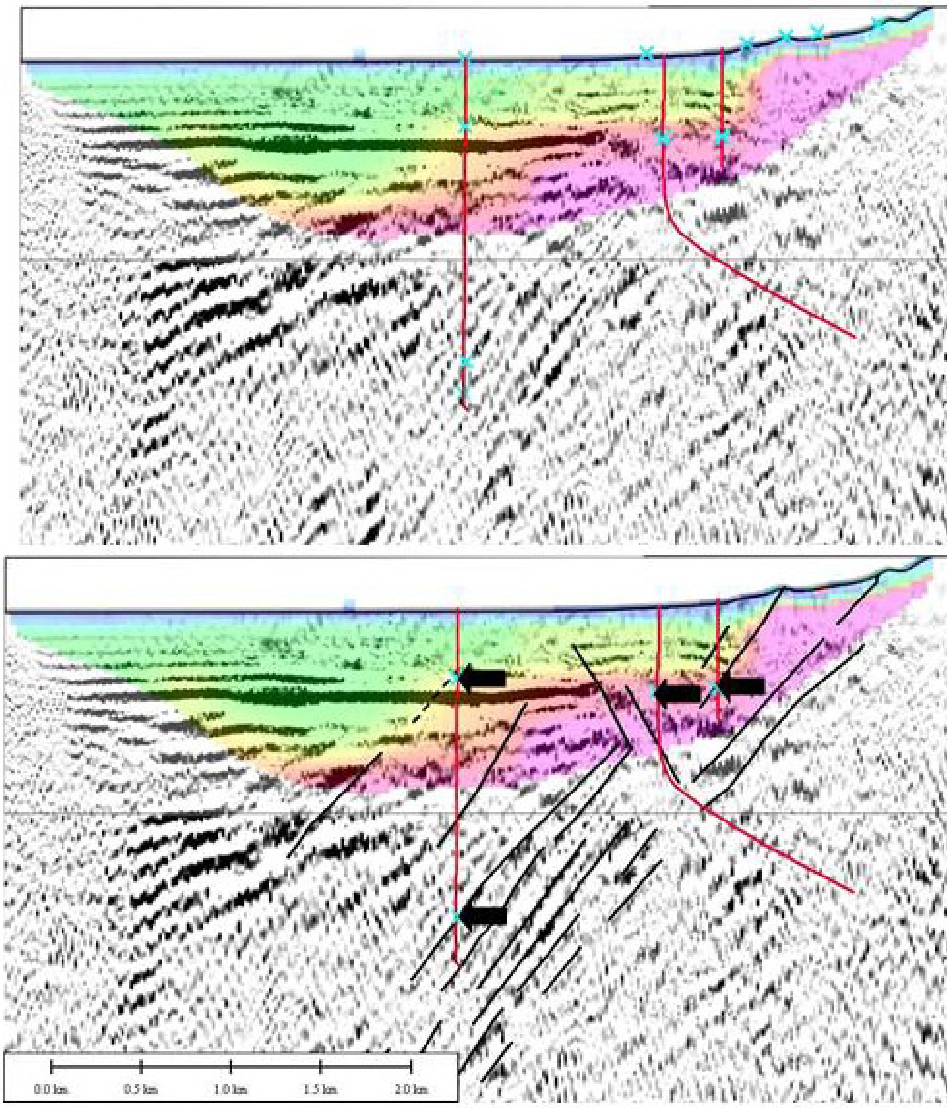

Figure 3: East-west seismic reflection image from Blue Mt. The upper image is a depth migrated section with refraction velocity in color. The lower image shows wells in red and entries marked with black arrows. The interpreted faults are based on offsets and apparent fault surface reflectors. The image has no vertical exaggeration.

The field seismic records at Blue Mt. had very little discernable reflection energy (Figure 5). All the coherent seismic arrivals generated by the seismic shots were not reflections, but instead appear to be ground roll, refraction first breaks and reverberation. In the context of a reflection processing, these types of energy are considered to be coherent noise that must be attenuated in the muting, filtering and stacking process or they will create erroneous arrivals. However, with little reflection energy available, these coherent noise sources leaked through to the more advanced imaging stages of the processing at Blue Mt. Likely examples are outlined in Figure 6. The arrival labeled “aliased ground roll” has a dominant frequency of 10 Hz, well below the typical reflection band of 20 to 70 Hz, but identical to the 10 Hz dominant frequency of the ground roll in Figure 5.

Review of the reflection images showed that the likely reflection arrival related to the contact between basin sediments and high velocity basement did not appear. Later drilling results have shown that a significant thickness of relatively soft clay-altered and presumably relatively low velocity rocks occur near the top of basement in some areas, however these rocks do not appear to be extensive enough to change the overall observation. In any case, reflection arrivals are not apparent where expected based on the more reliable refraction images.

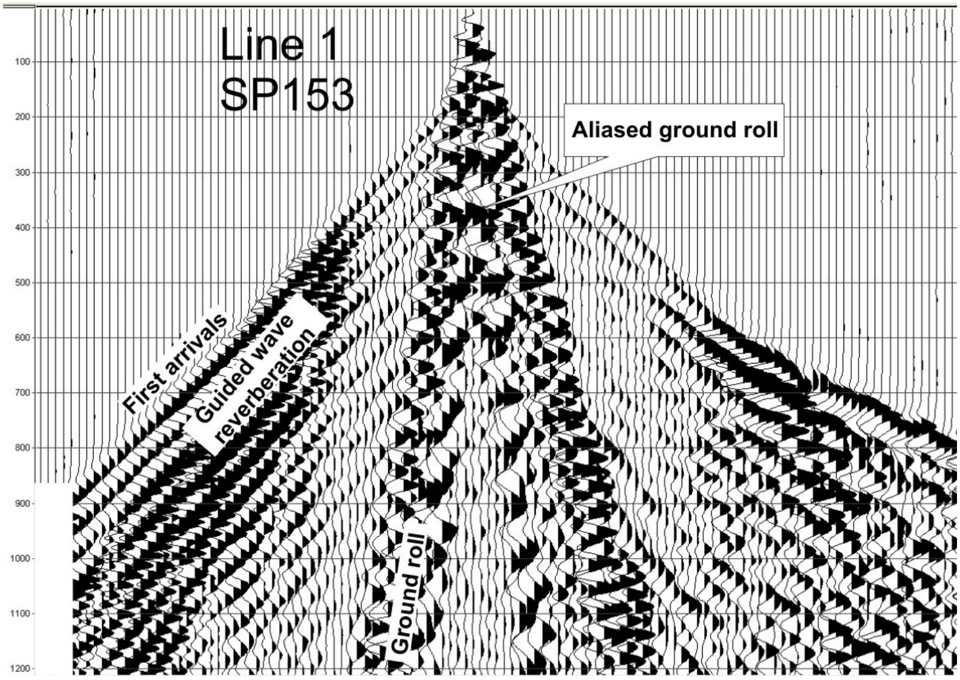

Figure 4: A shot gather field recording from the Blue Mt. seismic survey showing the ground roll, first breaks and the guided wave reverberation. No arrivals with the hyperbolic trend characteristic of reflections are apparent, although the gently dipping velocity contrast between the sediments and metamorphics should have created such a feature if any seismic reflections were detected.

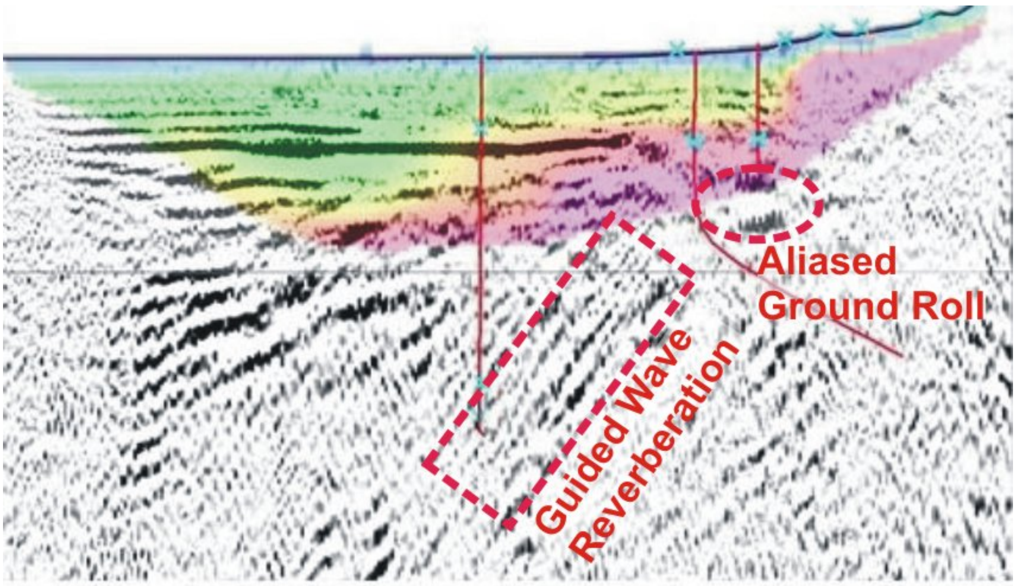

Figure 5: The seismic section from Figure 4 annotated in red with likely coherent noise of the type identified in Figure 4. No vertical exaggeration

In summary, the data quality review indicated that there were no valid reflectors in the data with sufficient amplitude to be reliably visible even in the filtered reflection data at shallow depth. Since the strong velocity contrast evident from the refraction data at the bottom of the basin sediments did not provide a reflection with appropriate frequency content it is unlikely that the mild contrasts possible within basement across a fault plane will be visible. More detailed and quantitative noise review have not been yet attempted and, as further information is gathered regarding the physical property variations within the basement metamorphic rocks, the reflection data can be tested against it.

Further tests of the reliability of the reflection seismic data set might include; 1) a review of edited shot gathers that were input to the pre-stack Kirchoff migration to check for leakage of non-reflection seismic arrivals into the reflection-specific processing, 2) a review of the Common Image Point (CIP) gathers that were summed to make the final stacked cross-sections to check for evidence that non-reflection arrivals are being stacked to make the final images; 3) analysis of the dip-corrected move-out velocity implied if the events tentatively identified as reverberation were actually reflections; and 4) reduced-travel-time shot gather analysis of the observed and computed first arrival picks used to derive the velocity images.

5. ROBUST CONCEPTUAL MODEL

Comparison of the geologic data and other geophysics with the reflection image allowed a consistent structural model to be defined that fit the data and what is now thought to be a noise image. The other data applied to the conceptual model included detailed surface geology, gravity, well entries, and aeromagnetic data. To some extent this demonstrates how a model that is not highly constrained can be adjusted to fit an appealing but invalid reflection image.

In spite of the questionable validity of features in the seismic reflection image, the structural model of the field was robust and was not significantly impacted by the realization that the reflection seismic data did not improve confidence in the model. This resulted from the integration of a variety of detailed data sets into a consistent conceptual interpretation. Once one component was shown to be un-reliable, it did strongly not affect the overall interpretation which eventually led to drilling success.

6. CONCLUSIONS

The reflection seismic interpretation at Blue Mountain was much less reliable than the results from the Pumpernickel Prospect. However, reliance on a resource conceptual model approach to well targeting and resource capacity assessment that ensured consistency with all available information minimized the negative impact of uncertainty in one data set. As a result, the application of noisy reflection seismic data in the interpretation had little effect on Nevada Geothermal Power's exploration program at Blue Mountain.

Moreover, the conceptual model approach allowed NGP to apply its reflection seismic experience at Blue Mountain to the assessment of uncertainty risk in the interpretation of the more reliable Pumpernickel reflection seismic data set. In this case the basic structural model is also thought to be still valid although the reliability of the apparent reflectors dipping away from the range front is questionable based on the analysis of similar features in the seismic reflection data at Blue Mt.

Finally, the initiation of the noise review of the seismic data was driven partly by a perception that the reflection result seemed too good to be true based on other attempts to image range front faults at depth and partly by the perception that the image looked funny to a relatively inexperienced eye. The learning in this case is to retain a healthy skepticism in spite of apparently successful results.

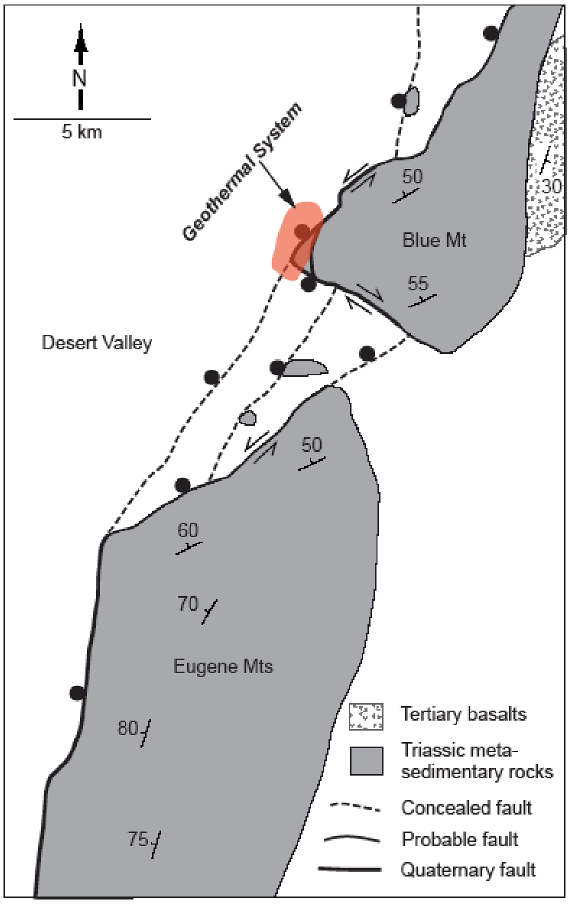

Figure 6: Preferred structural model for the Blue Mountain geothermal system (shown in red). The field occurs at the intersection of NE-striking, normal-sinistral and a WNW-striking normal-dextral fault zones. The intersection of the two faults generates a focused area of dilation along the west flank of Blue Mountain. Numerous fault intersections between fault strands produce a broad zone of highly fractured rock (Faulds and Melosh, 2008).

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