Integrated geophysical exploration of a known geothermal resource: Neal Hot Springs

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SUMMARY

We present integrated geophysical data to characterize a geothermal system at Neal Hot Springs in eastern Oregon. This system is currently being developed for geothermal energy production. The hot springs are in a region of complex and intersecting fault trends associated with two major extensional events, the Oregon-Idaho Graben and the Western Snake River Plain. The intersection of these two fault systems, coupled with high geothermal gradients from thin continental crust produces pathways for surface water and deep geothermal water interactions at Neal Hot Springs. New geologic mapping, geochemistry and several boreholes in the area suggest a steeply dipping 60° normal fault dips to the southwest to form a half-graben basin. This basin-bounding fault serves as the primary conduit for deep water circulation. Potential field, electrical, and seismic data characterize this major fault along with other smaller scale structures in the area. A self-potential survey indicates that water is upwelling in the fault plane, and suggests that the fault does provide the means for heated water to migrate to the surface. Electrical and magnetic surveys offer methods to locate hydrothermal waters near the surface by identifying areas affected by hydrothermal waters.

INTRODUCTION

Geothermal power production is a growing industry, but still plagued by high production costs. One reason for these high costs is the large risk in developing a field due to limited subsurface information (Barbier, 2002, Tester et al., 2006). Neal Hot Springs (NHS) is presently being developed into a geothermal energy resource by U.S. Geothermal Incorporated. We suggest that an integrated geophysical data acquisition campaign, involving numerous imaging techniques, is valuable for a geothermal energy project such as Neal Hot Springs. While geothermal targets are inherently challenging geologic conditions for many geophysical methods, we have found that the integration of numerous techniques provide useful subsurface information about Neal Hot Springs. This study uses geophysical data acquired at a 2011 geophysics field camp combined with prior and newly acquired geophysical and geologic data.

GEOLOGIC BACKGROUND

Neal Hot Springs is a structurally controlled thermal feature located in eastern Oregon. The geologic history of this area is dominated by late Cenozoic activity associated with the emplacement of volcanics from the Columbia River Flood Basalt Group (CRBG), and extension related to the Oregon- Idaho Graben (OIG) and Western Snake River Plain (WSRP). Multiple extensional events and emplacement of the CRBG have resulted in anomalously thin crust that provides a shallow regional heat source and high geothermal gradients (Bowen & Blackwell, 1975, Camp and Hanan, 2008, Eager et al., 2011, Wood & Clemens, 2000, Cummings et al., 2000).

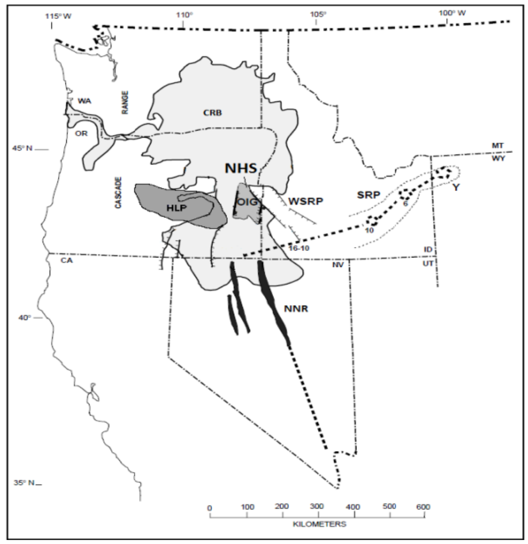

Figure 1: Regional map showing Neal Hot Springs (NHS) and its position relative to the Columbia River Flood Basalts(CRB),High Lava Plains (HLP), Western Snake River Plain (WSRP), Snake River Plain (SRP), Oregon-Idaho Graben (OIG), and Northern-Nevada Rift (NNR). The numbers indicate the age of rhyolitic magmatism along the SRP (revised from Cummings et al. 2000)

The CRBG is a collection of large Cenozoic flood basalts that cover portions of Washington, Oregon, Idaho, and Nevada (Figure 1; Cummings et al., 2000). The main phase of volcanism generated over 200,000 km^3 of lava between 16.6 and 15.0 Ma (Camp and Hanan, 2008). Basalt of the Malheur Gorge Sequence forms the oldest known stratigraphic unit at NHS and is considered the basement rock in the area.

Shortly after the CRBG eruptions, the Oregon-Idaho Graben initiated (Cummings et al., 2000). North-south trending faults with throws up to 1 km resulted from the

OIG event throughout a five million year extension. Syntectonic magmatism deposited rhyolitic to basaltic rocks. These volcanic units are intercalated with basin fill sediments, which makes for a complex and heterogeneous shallow subsurface at Neal Hot Springs and the surrounding area.

Extensional faulting related to the formation of the Western Snake River Plain initiated circa 11 Ma (Wood and Clemens, 2000). At Neal Hot Springs this faulting overprinted OIG structures with a northwest-southeast trending suite of faults and basins (Figure 2). The youngest faults in the area show latest Quaternary motion (Personius, 2002).

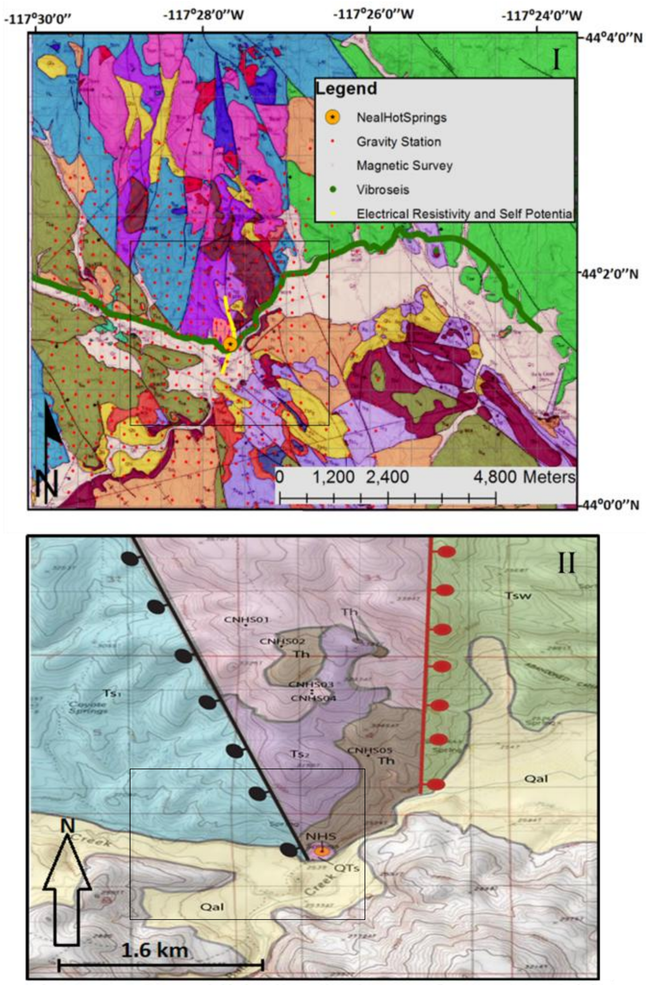

Figure 2: I- Unpublished geologic map from Evans with geophysical survey locations (1994). Note the complex surface geology and fault arrangements. The black square outlines the same area as the lower image.
II- New simplified geologic map based on geochemistry and surface mapping. Sample locations are noted on the map. The red fault is interpreted as being older and associated with the OIG while the younger black fault is associated with the WSRP.

GEOLOGIC MAPPING AND GEOCHEMISTRY

Any geophysical exploration benefits from a sound understanding of the geology of the survey area. In order gain a better understanding of the geology and structure immediately surrounding Neal Hot Springs, we performed detailed geologic mapping and geochemical fingerprinting in order to test large scale geologic mapping by J. Evans in 1994 (personal comm.).

New mapping suggested that prior geologic interpretations in the area had misidentified some volcanic units near NHS. This misinterpretation resulted in a complex interpretation of the surface geology. XRF whole rock geochemistry provides a revised interpretation that simplifies the geologic picture (Figure 2). The revised geologic interpretation is a horst and graben complex with units sitting in stratigraphic succession. This has significant implications for geophysical techniques and the hot springs controlling structure.

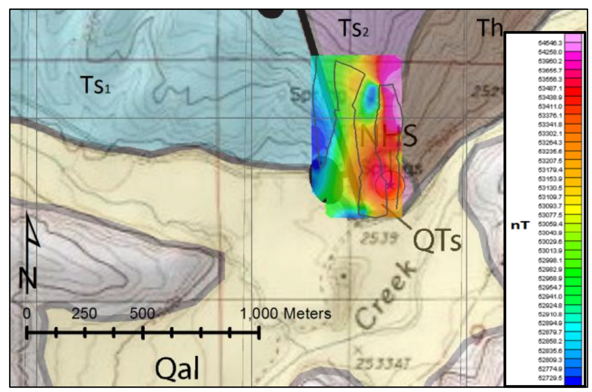

Figure 3: Total magnetic intensity grid over the surface expression of the hot springs. Notice the circular magnetic high coincident with NHS. The box in figure 2 is coincident with this map.

POTENTIAL FIELD SURVEYS

Large magnetic susceptibility contrasts between volcanic and sedimentary rocks allow magnetic surveys to identify subsurface geologic structures at NHS. We interpret a northwest-trending fault from a steep gradient in the magnetic field north of the NHS surface expression (Figure 3). An unexpected result of this survey is a small, circular magnetic high coincident with altered geothermal rocks and the surface expression of NHS. Normally one would expect to see a magnetic low at these locations due to oxygenation of magnetic minerals brought about by the presence of water (Allis, 1990). We will investigate this observation in future work with greater detail.

Gravity contrasts between dense volcanic rocks and less dense sediments allow us to map geologic structures using gravity data. We reduced new gravity data with a 2.20 $\frac{kg}{m^3}$ Bouguer slab and tied to absolute gravity at a nearby benchmark. The gravity data indicates a high density region flanked on both sides by lower densities (Figure 5). This high density region correlates with near-surface volcanic rocks, while less dense sediments account for the low density areas to the east and west. To locate the edges of steeply dipping density contrasts, the maxima of the horizontal gradients (HGM) were plotted (Blakely and Simpson, 1986; Blakely 1995). The mapped eastern basin bounding fault coincides with the HGM well which supports this interpretation. The western fault's overall trend agrees with the HGM, however the HGM suggest that a more complex arrangement of faults may be a better structural model.

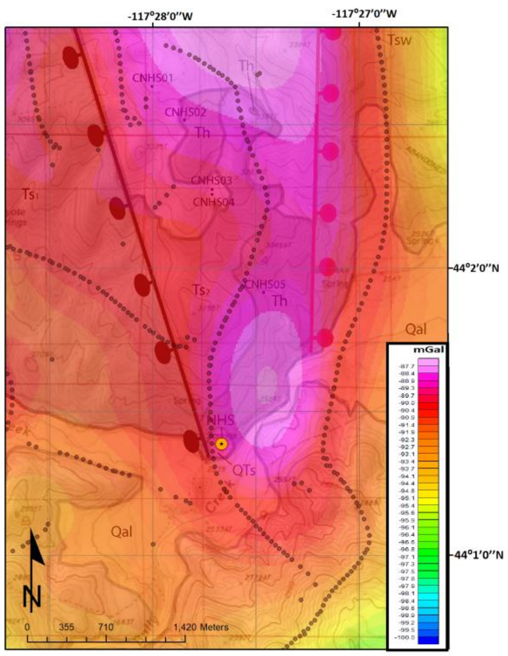

Figure 4: Complete Bouguer Anomaly overlain on the simplified geologic map. Horizontal gradient maximum (HGM) are plotted as the dark dots. The eastern mapped basin bounding fault coincides well with the HGM. The HGM on the western bounding fault suggests more complex fault geometry than one large basin forming fault.

ELECTRICAL RESISTIVITY AND SELF POTENTIAL

Contrasting resistivities between the differing rock types and subsurface fluids at NHS allow us to map geologic structure and hot springs location with electrical resistivity surveys (Figure 6). Movements of water carrying ions create measurable electric-potential anomalies at the surface. These anomalies allow us to map water movement in the shallow subsurface. A resistivity low and self-potential high locates the hot springs and indicate vertical water movement along the fault.

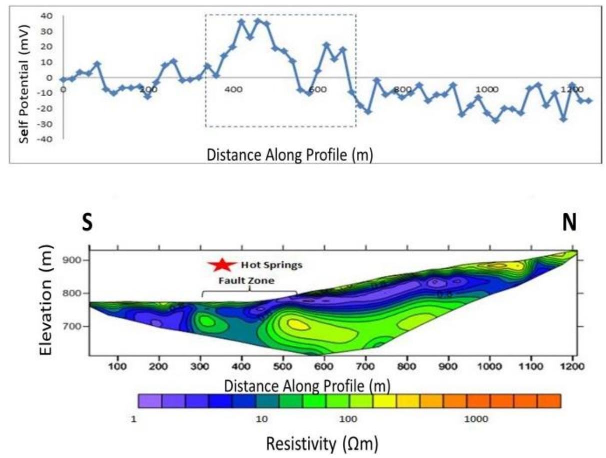

Figure 5: A resistivity low and self-potential positive anomaly locate the hot springs and indicate vertical water movement within a zone of <100m from the hot springs surface location

SEISMIC METHODS

Seismic velocity and density contrasts at NHS allowed seismic imaging at different scales to characterize major geologic boundaries. Two 20 ton Veritas vibroseis trucks along with a Sercel 120 channel recording system at a group spacing of 30 meters produced an image of the upper one km below NHS. From these data, we interpret a large normal fault and smaller subsidiary fault associated with the Oregon-Idaho graben that bound the basin east of the hot springs (Figure 7). A volcanic unit which is exposed at the surface is also imaged at depth. Due to limited offset during acquisition near NHS, shallow data was not recorded west of the hot springs.

The resolution of seismic surveys are limited by the frequency input of the seismic impulse. Large vibroseis trucks are limited to lower frequencies. We were able to input higher frequencies with a 50 kg hammer seismic source. This higher-resolution line was acquired with 96 active channels at a geophone spacing of 5 meters. The line helps to fill in the shallow subsurface missed with the vibroseis line. We interpret a fault associated with the WSRP (Figure 7) dipping at about 60 degrees to the southwest. This fault likely provides the conduit through which heated waters are brought to the surface at NHS. Interbedded sediments and volcanic rocks produce strong reflections in the shallow subsurface. One such seismic boundary is truncated at the fault intersection and constrains the fault dip. If we project the surface location of NHS to the termination of the strong reflection, a dip of roughly 60 degrees is found. This concurs with borehole observations. The dip of 15-20 degrees east of the reflector is consistent with surface dip measurements of overlying sediments.

CONCLUSIONS

Geophysical interpretations confirm large scale tectonic features at Neal Hot Springs. They also concur with surface observations, but more importantly, a joined interpretation of these data sets have resulted in subsurface information of value to the developers of this field. Two main fault trends associated with the OIG and WSRP intersect to produce conduits for geothermal waters to reach the surface. High geothermal gradients in the a rea relate to thin crust beneath the region and heat the water at Neal Hot Springs. Potential field, electrical, and seismic geophysical methods all located faults in the area, which ultimately control the location of hydrothermal waters. Electrical methods and potentially magnetic surveys provide a means to locate hydrothermal waters near the surface.

ACKNOWLEDGMENTS

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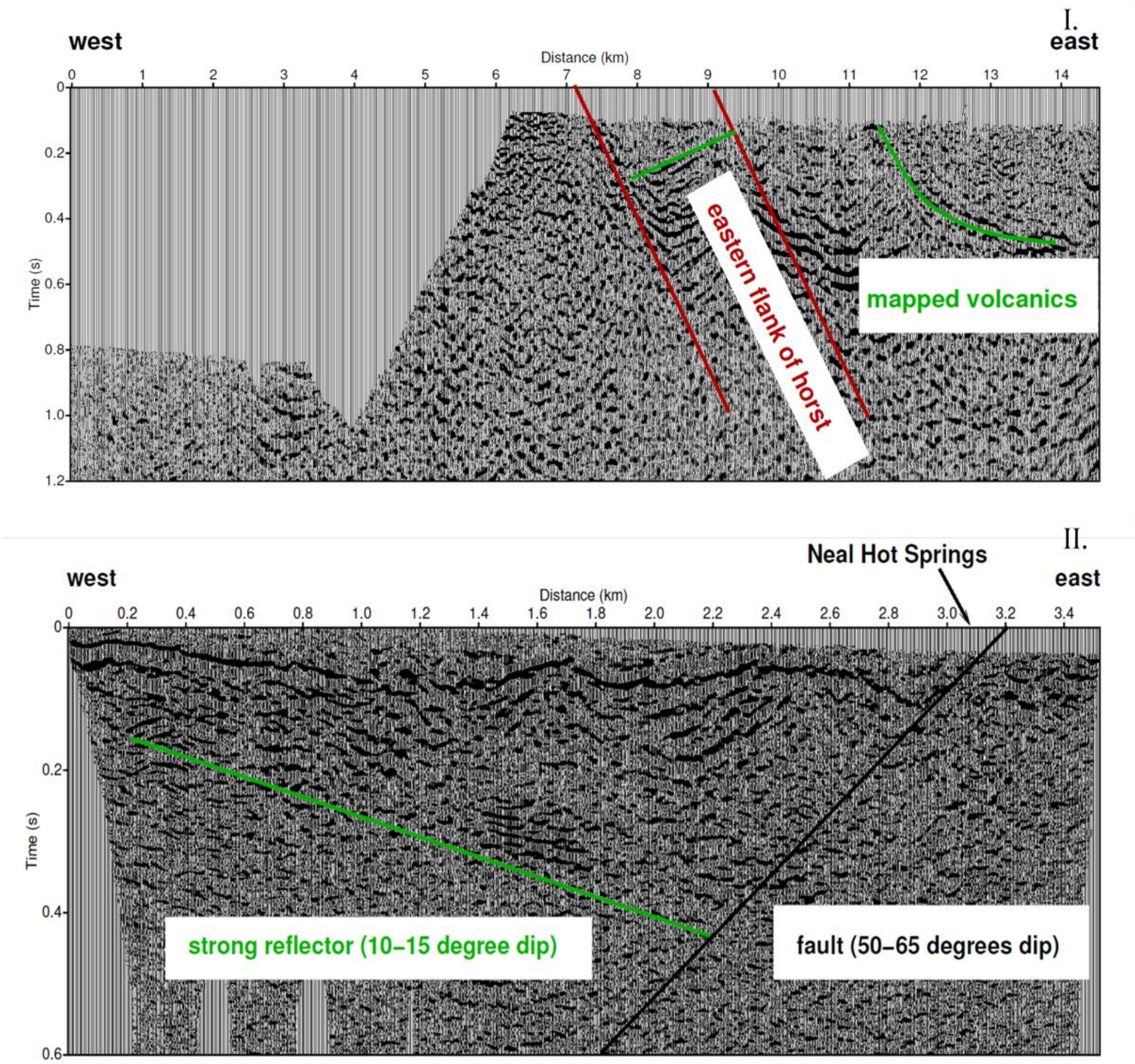

Figure 6:I- Vibroseis line showing a large normal fault and smaller subsidiary fault associated with the OIG. An exposed volcanic unit is imaged at depth as a reflector that plunges to the east.
II- Hammer seismic line that images a strong reflector terminating at a large southwesterly dipping fault associate with the WSRP. Shallow reflectors are interpreted as channel fill deposits.