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SEISMIC AND MAGNETO-TELLURIC IMAGING FOR GEOTHERMAL EXPLORATION AT JEMEZ PUEBLO IN NEW MEXICO

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ABSTRACT

A shallow geothermal reservoir in the Pueblo of Jemez in New Mexico may indicate a commercial-scale geothermal energy potential in the area. To explore the geothermal resource at Jemez Pueblo, seismic surveys are conducted along three lines for the purpose of imaging complex subsurface structures near the Indian Springs fault zone. A 3-D magneto-telluric (MT) survey is also carried out in the same area. Seismic and MT imaging can provide complementary information to reveal detailed geologic formation properties around the fault zones. The high-resolution seismic images will be used together with MT images, geologic mapping, and hydrogeochemistry, to explore the geothermal resource at Jemez Pueblo, and to determine whether a commercial-scale geothermal resource exists for power generation or direct use applications after drilling and well testing.

INTRODUCTION

The Pueblo of Jemez is located on the southwestern margin of the Jemez Mountains in north-central New Mexico, USA. The most prominent feature in the area is the Valles Caldera, one of the most intensively studied volcanic terrains in the world. Jemez Pueblo is located at approximately 22 miles southwest of the Valles Caldera. There are many hot springs on the west and southwest edge of the Valles Caldera and down San Diego Canyon.

Most previous research on the geothermal system in the Valles Caldera area focused on the southwestern margin of the caldera itself (Figure 1), including the Sulfur Springs area, Fenton Hill, Soda Dam, San Diego Canyon, and Jemez Springs (Goff and Grigsby, 1981; Goff et al., 1988). Fenton Hill was the test site for the Hot Dry Rock Project in the late 1970s and early 1990s. Jemez Springs is the site of commercial hot springs with temperatures up to 72°C.

A shallow geothermal reservoir is located at Indian Springs on the east bank of the Jemez River, approximately one mile south of the main village of Jemez Pueblo. A 240-foot deep well was drilled in 1991 at the Indian Springs fault zone to test for the geothermal reservoir (Figure 2). The well is located right next to the Jemez River, and produces water of 136°F and a flow of 150 gallons per minute (Witcher, et al. 1992; Witcher, 2004).

The Indian Springs is the southernmost hot spring discharge on the southwestern flank of the Jemez Mountains and is thought to represent the distal portion of the hydrothermal outflow plume from the Valles Caldera (Trainer, 1984; Goff et al, 1988). The

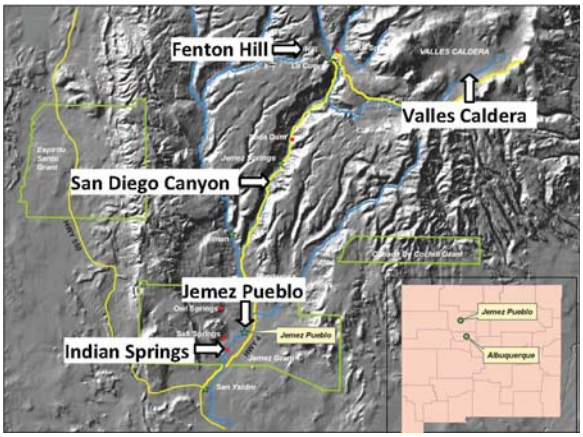


Figure 1. A map showing locations of Vales Caldera, Fenton Hill, and the Pueblo of Jemez.

Figure 2: A 240-foot deep well drilled at the Indian Springs fault zone in 1991 produces water of 136°F and a flow of 150 gallons per minute.

hot springs located along San Diego Canyon are associated with the Jemez fault.

The anticipated geothermal reservoir in the Indian Springs area may be located deeper than 3000 feet. However, the detailed subsurface geologic structures of the Indian Springs area are mostly unknown. The Indian Springs area consists of many steep faults. It is critically important to understand the subsurface geologic structures and image these faults because these faults may dominate the flow paths of the hot water, or confine the boundaries of the geothermal reservoir.

To explore the potential geothermal resources at the Pueblo of Jemez, a 3-D magneto-telluric (MT) survey was conducted in November, 2010. Following the MT survey, seismic surveys were carried out along three lines in the same area in December, 2010. We describe the field data acquisitions at the Pueblo of Jemez, and present results of poststack time migration of the seismic data and inversions of MT data. Seismic and MT imaging reveals many new faults in addition to those faults determined by previous geologic studies. We demonstrate that seismic and MT images can provide complementary information of subsurface geologic structures and properties, and are very useful tools for exploration of geothermal resource at the Pueblo of Jemez.

SEISMIC IMAGING

The geologic studies indicate that the faults in the Indian Springs fault zone are steep (Figure 3). These fault zones may have controlled the flow of (hot) water of the springs in the area. High-resolution imaging of these faults is essential to understand the potential geothermal system. Seismic migration imaging can reveal detailed subsurface structures, and is the primary tool for oil/gas exploration. It uses

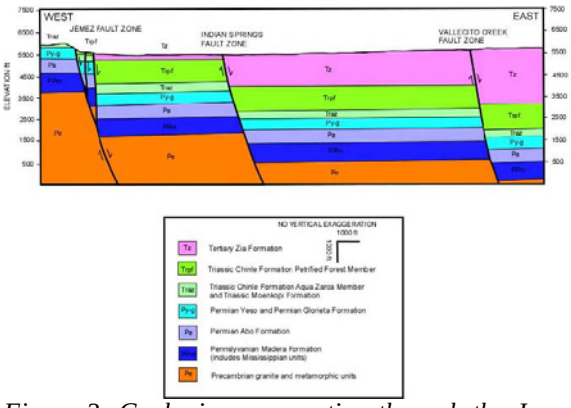


Figure 3: Geologic cross section through the Jemez fault, Indian Springs fault, and Vallecito Creek fault zones. Cross section is an eastward continuation of cross section A-A' in Woodward and Ruetschilling (1976). (From Witcher, 2004)

active seismic reflection data to obtain three-dimensional subsurface images showing where changes in elastic properties (impedances) of geologic formations occur.

To obtain high-resolution images of subsurface geologic structures of the potential target geothermal reservoir at the Pueblo of Jemez, active seismic reflection surveys were conducted along three lines as depicted in Figure 4 in December, 2010. Lines 1 and 2 were designed to be nearly perpendicular to the Indian Springs fault zone in order to image the fault. Line 3 was along mostly the North-South direction in order to verify previous geologic studies that the geologic formations in the area are dipping toward the South. Seismic data were acquired using an accelerated weight-drop seismic source (Figure 5) and a static geophone array covering the entire lines.

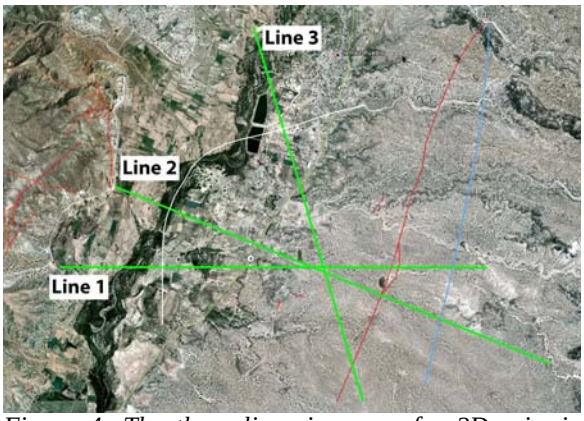


Figure 4: The three lines in green for 2D seismic reflection surveys at the Pueblo of Jemez. The white curved line is the Indian Springs Fault zone, and the light blue line is the Vallecito Creek fault zone, according to previous geologic studies of the fault system in the area.

Figure 5: An AXIS™ accelerated weight-drop seismic source.

The spatial intervals of the sources and receivers are both 50 ft.

Poststack time migration was performed using 80% of stacking velocity values for seismic data acquired along the three seismic lines in Figure 4, and the migration results are shown in Figure 6. Figure 6 shows excellent images up to 1 second of two-way time, which corresponds to the depth of approximately 6000 ft. Using a vibroseis source may be able to acquire seismic reflection data from the geologic formations deeper than 6000 ft at the Pueblo of Jemez area.

The image profiles along Lines 1 and 2 in Figure 6 show that the geologic structures along these two lines are mostly dipping towards the West. The image profile of Line 3 in Figure 6 confirms that the geologic formations at the Pueblo of Jemez are dipping toward the South.

Figure 7 is the preliminary interpretation of poststack time migration results in Figure 6. It shows that the profiles along the three lines in Figure 4 intersect with several other faults in addition to the Indian Springs fault zone and the Vallecito Creek fault zone.

Prestack depth migration can provide the depth profiles along each line in Figure 4, and therefore, it can give direct depth information of subsurface geologic formations and spatial orientations of the faults in Figure 7. We are conducting prestack depth migration of seismic data acquired at Jemez Pueblo.

Seismic imaging can provide high-resolution images of subsurface geologic structures. On the other hand, magneto-telluric imaging is highly sensitive to electrically conductive formations, and can supply useful, complementary information of geothermal reservoirs even though its image resolution is lower than seismic imaging.

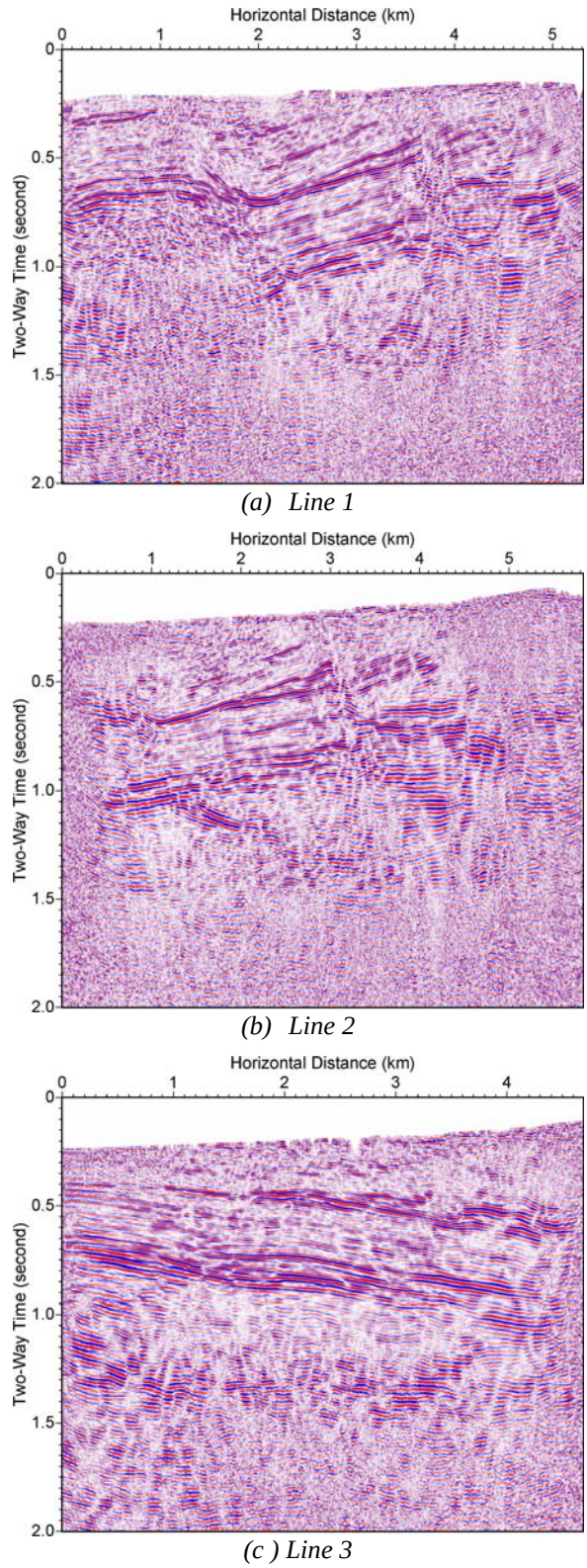
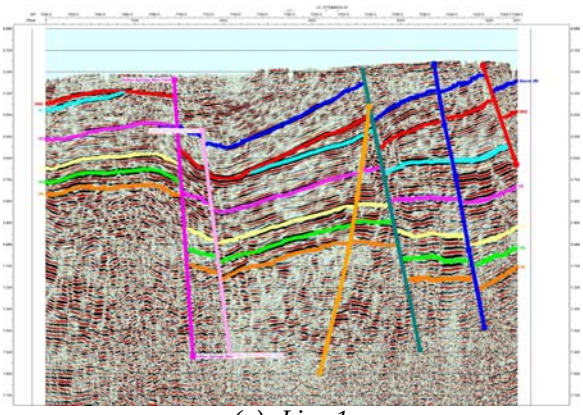
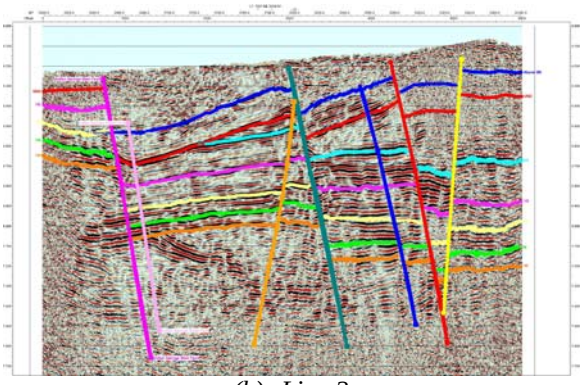


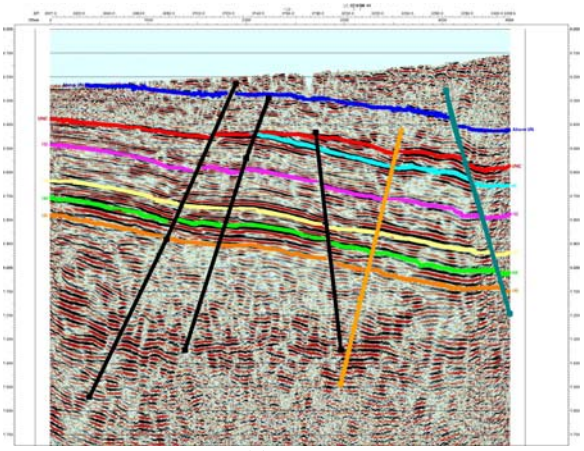
Figure 6. Poststack time migration images along Lines 1, 2, and 3 in Figure 4.



(a) Line 1



(b) Line 2



(c) Line 3

Figure 7: Preliminary interpretation of poststack time migration of seismic data along Lines 1, 2 and 3 showing each line intersects with several fault zones.

MAGNETO-TELLURIC IMAGING

For magneto-telluric (MT) imaging at the Pueblo of Jemez, we conducted 137 broadband MT (BMT) station observations resulting in 129 BMT 1-D inversions, 1 BMT 3-D rendering from 1-D data (1.5-D inversion), 13 BMT 2-D inversions (profiles), 1 BMT 3-D rendering from 2-D data (2.5-D inversion), and 6 unconstrained BMT 3-D inversions (Figure 8). We also conducted 25 long-period MT (LMT) station observations with 24 LMT 1-D inversions and 14 LMT 2-D inversion profiles (Figure 9). A total of 162 MT stations (both BMT and LMT) were used for observation, and 153 of them were used for inversion. The receiver frequency range for LMT stations is 100 Hz to 0.0001 Hz and the frequency range for BMT is 1000 Hz to 0.001 Hz.

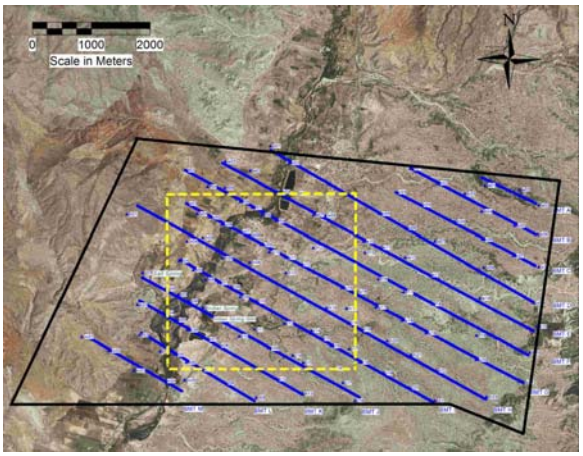


Figure 8: Configuration of BMT observations at the Pueblo of Jemez. Black polygon represents the extended survey area, the yellow rectangle represents the original survey area, and the blue lines represent the BMT profile.

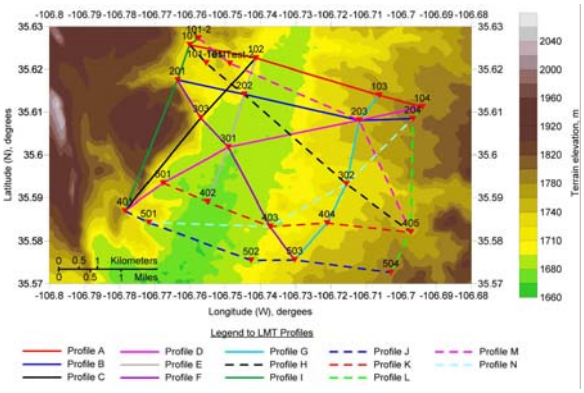


Figure 9: LMT profiles provide additional structural confirmation and information.

Occam 2-D mathematical inversions were performed along each BMT profile in order to derive a model that represents or fits the data. This modeling allows for a geological interpretation of the geophysical data (Figure 10).

The procedure proposed by Pedersen and Engels (2005) was used for all 2-D inversions. This involves inverting for the apparent resistivity and phase of the determinant of the impedance tensor. The resulting

inversion models were generally obtained at the fourth iteration with an RMS error of 1.

The inversion models show the distribution of electrical resistivity in the subsurface. The resistivity varies from below 10 Ohm-m to several hundreds of Ohm-m or higher. It is not uncommon for the distribution of resistivity within the Earth to vary by several orders of magnitude. Presenting the resistivity on a log base 10 scale is therefore usually helpful.

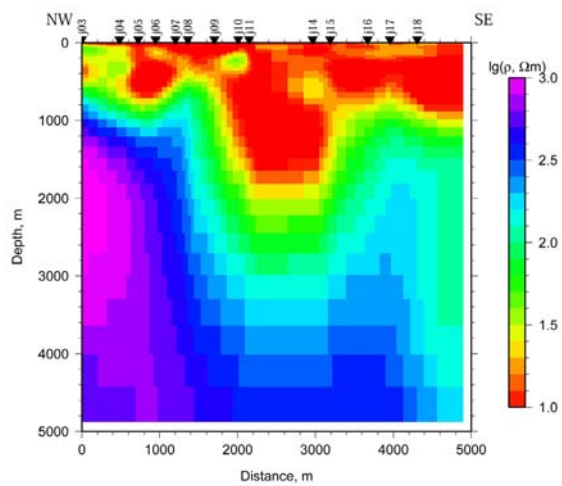


Figure 10: BMT profile J showing a highly conductive zone reaching at least 2000 m deep and confirming the steep and deep fault structures visible in the seismic as well.

The rock resistivity depends on porosity and brine (salt water) content. The regions in red in Figure 10 represent the geologic formations with a resistivity of 10 Ohm-m or less. This is a good indicator for brine in the rock matrix of a geothermal reservoir or clays and geothermally altered "cap" rock. Due to resolution limitations, the depth of this low resistivity area along profile J might reach well beyond 2000 m – a good potential drilling target. The steep blue and purple structures representing typical basin, basalts and granites appear to be correlating well with the preliminary seismic interpretation (Figure 7). The 2-D LMT inversions indicate a very deep heat source sitting below the Pueblo of Jemez (Figure 11). The unconformity time structure map in Figure 12 provides a new interpretation of the fault systems in the area of the Pueblo of Jemez.

CONCLUSIONS

Preliminary results of the first exploration of the deep geothermal reservoir at the Pueblo of Jemez using active-seismic reflection imaging reveals many fault zones that were unknown before. The magneto-telluric imaging indicates potential permeable structures and large regions with high conductivity. Integration of seismic and MT imaging with geologic and hydrogeochemical information will provide guidelines for placing exploration wells.

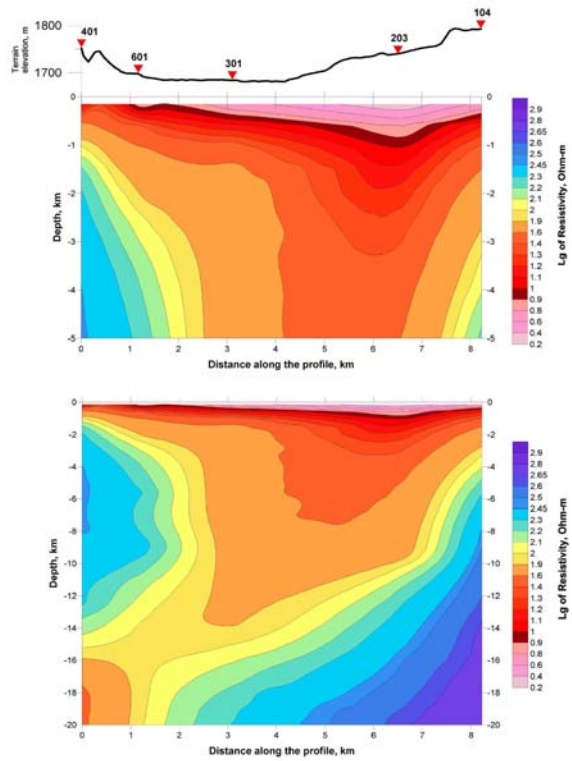


Figure 11: The LMT profile D indicates that the Pueblo of Jemez may be on the top of a deep heat anomaly.

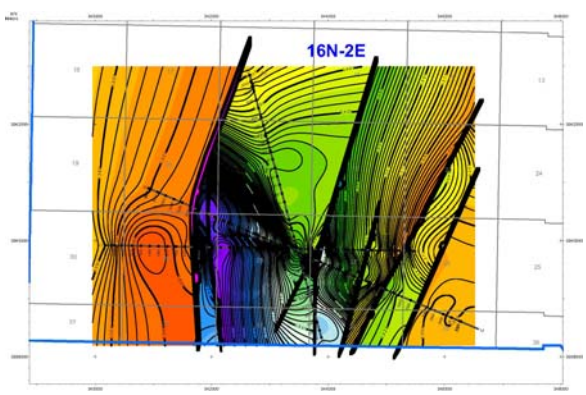


Figure 12: The unconformity time structure map displaying an updated interpretation of the fault systems in the area of the Pueblo of Jemez.

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