Electrical Resistivity and Self-Potential Surveys Blue Mountain Geothermal Area, Nevada

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ABSTRACT

Self-potential and electrical resistivity surveys have been completed at the Blue Mountain geothermal area to search for the source of thermal fluids discovered during drilling for mineral exploration, and to help characterize the geothermal resource. Two large SP anomalies are associated with the artesian thermal area and the area of highest temperatures observed in drill holes. Two similar anomalies were mapped 1 to 3 km to the south and west over valley fill. Electrical resistivity and induced polarization profiles define deep, low-resistivity zones which may serve as conduits for, or the upper portions of, the geothermal reservoir. Self-potential and induced polarization anomalies also correspond to the main known occurrence of gold-silver which is associated with pyrite mineralization.

Introduction

The Blue Mountain geothermal area occurs on the western flank of Blue Mountain about 35 km west of Winnemucca, Nevada . The geothermal resource was discovered by Nassau Gold Limited during shallow drilling for mineral exploration (Parr and Percival, 1991). The thermal fluids are associated with subeconomic gold mineralization which occurs in a thick sequence of Triassic metasediments assigned to the Grass Valley and Raspberry formations (Wilden, 1964). Gold mineralization and associated alteration, and the present day hydrothermal system, appear to be localized by north-northeast trending faults which are cut by multiple north-trending Basin and Range faults along the west flank of Blue Mountain. The area geology is described in detail by Wilden (1964) and the geothermal resource by Parr and Percival (1991) and Fairbank and Ross (1999).

The importance of the geothermal resource was recognized by Blue Mountain Power Company (BMPC) and a subsidiary, Noramex Corporation, obtained geothermal leases in 1993 and 1994 to evaluate the resource. BMPC was awarded a Contract with the Department of Energy, Office of Geothermal Technology (DOE-OGT) for cost-shared drilling in 1996, and the Energy & Geoscience Institute (EGI), University of Utah initiated geophysical studies under a Cooperative Research Agreement with BMPC (Fairbank and Ross, 1999). The self-potential (SP) and electrical resistivity studies described here are part of this Agreement.

Self-Potential (SP) Survey

EGI decided to complete SP surveys at Blue Mountain because the area had not been systematically explored for the geothermal resource, and SP had proved to be a cost-effective method for locating geothermal upflow and outflow zones in the Basin and Range and Rio Grande Rift geothermal environments (Ross *et al.*, 1991; Ross *et al.*, 1995). EGI had also been conducting SP field studies to characterize the expression of a number of geothermal systems as part of a DOE-OGT exploration technique development program. Most of the survey work was completed from mid-April to mid-June 1996, with some survey fill-in and repeat lines for verification two years later, in May 1998. Survey conditions were nearly ideal, with good near-surface moisture conditions which reduced survey noise, for much of the survey. The completed survey includes more than 44.3 line-km (145,480 line-ft) of SP profiles and covers 11 km^2 (4.5 mi^2). The survey was conducted using a high-impedance digital voltmeter and copper sulfate porous-pot electrodes connected by a spooled 1290 m light weight single-conductor copper wire. A basic radial or "spoke" survey technique was used as described by Ross *et al.* (1991). The basic station spacing of 200 ft. (60 m) was reduced to 100 ft. (30 m) in areas of high SP gradients and certain tie-in areas. Repeat traverses after a period of a few days, and after a period of two years, generally showed excellent agreement in the amplitude and position of the anomalies traversed.

The SP contour map (Figure 1) shows differences in millivolts (mV) with respect to Base Station #1 located west of the access road and near the southwest corner of Sec. 14, in the central part of the survey area. An evaluation of SP values and gradients in the northern and southeastern areas of the survey, away from obvious anomalies, suggest the 0 contour is within

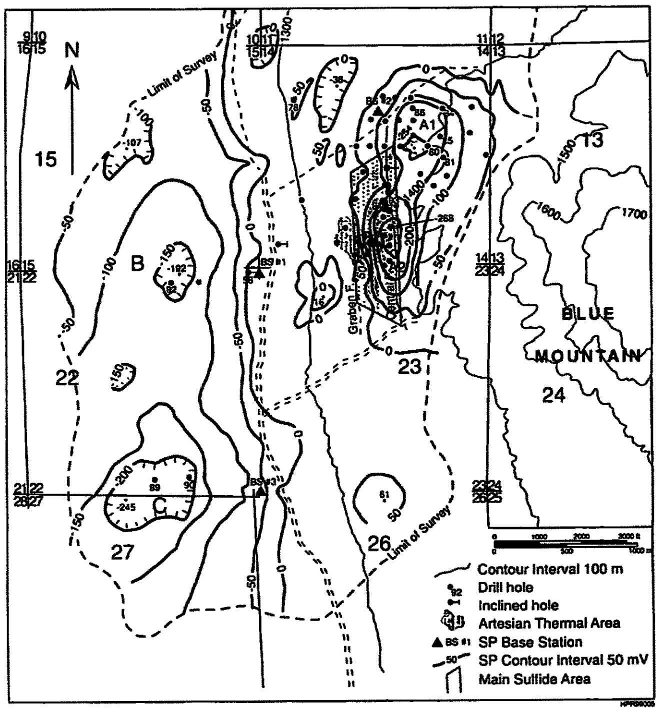

Figure 1. Self-potential survey, Blue Mountain geothermal area, Humboldt County, Nevada. The artesian thermal fluids and main mineralized body are likely sources for Anomalies A1, A2.

20 mV of the local natural potential background. Figure 1 documents four major SP minima of -268, -254, -245 and -192 mV and several broad maxima of 30 to 61 mV, some of which may be dipolar highs of the minima. A long linear gradient of 50 to 100 mV, positive to the east, trends northerly along the access road between the range block to the east and the valley fill to the west. This trend may reflect resistivity changes across the north-trending faults.

SP anomaly A1 (-254 mV) is associated with the highest observed temperatures and temperature gradients, and SP minimum A2 (-268 mV) occurs just east of the artesian thermal area (Fairbank and Ross, 1999). While it is tempting to attribute the anomalies to rising thermal fluids, the entire anomaly corresponds closely to the sulfide mineralization (1-10 weight percent pyrite) with which the gold mineralization is associated. Simple depth estimates of 50-100 m correspond to the depths of both the sulfide mineralization and the thermal fluids as indicated by drilling (Fairbank and Ross, 1999). The anomaly amplitudes are larger than many hydrothermal anomalies (60-150 mV) but comparable to the Beowawe, NV, SP minimum of about -250 mV reported by DeMoully and Corwin (1980). Anomalies A1, A2 are likely due to both factors.

SP anomalies B and C occur west of the range front faults on sands and alluvium and have similar amplitudes and extent as A1. Drilling subsequent to the SP survey indicated anomalous temperatures and temperature gradients, and minor sulfides in bedrock in BM-89, -90, -92 (Fairbank and Ross, 1999). An electrical resistivity survey (discussed later) suggests thermal fluids and sulfide mineralization may also contribute to these SP anomalies. Rule-of-thumb depth estimates (linear extent of steep gradient) indicate depths of 100-200 m for these anomalies.

Electrical Resistivity Surveys

Most geothermal systems are characterized by low electrical resistivity because of the associated conductive alteration minerals and thermal fluids. Mapping this property in the subsurface is an important and cost-effective part of most geothermal exploration programs. Two electrical resistivity surveys have been completed at Blue Mountain. In 1988 Chester Lide and Associates conducted an induced polarization (IP)/resistivity survey as part of a precious metals exploration program. The survey consisted of four profiles, spaced 300 m apart and oriented N40°W, and one profile to the south and adjacent to the main grid in a N50°W direction (Figure 2). All profiles were centered in Section 14 which includes the northern part of the thermal anomaly (Fairbank and Ross, 1999). Lide and Associates used the dipole-dipole array (favored for mineral and geothermal exploration) with 500 ft (150 m) dipoles, and recorded separations n=1-7. These profiles will be referred to as LA-1 through LA-5.

Profiles LA-1 through LA-5 were located on the west flank of Blue Mountain at elevations of 1300-1500 m (Figure 2). A review of the psuedosection data shows high resistivities (100-1040 ohm-m) on shallow separations (n=1-3) are generally associated with outcropping metasediments. Larger separations and the western parts of all the lines show lower apparent

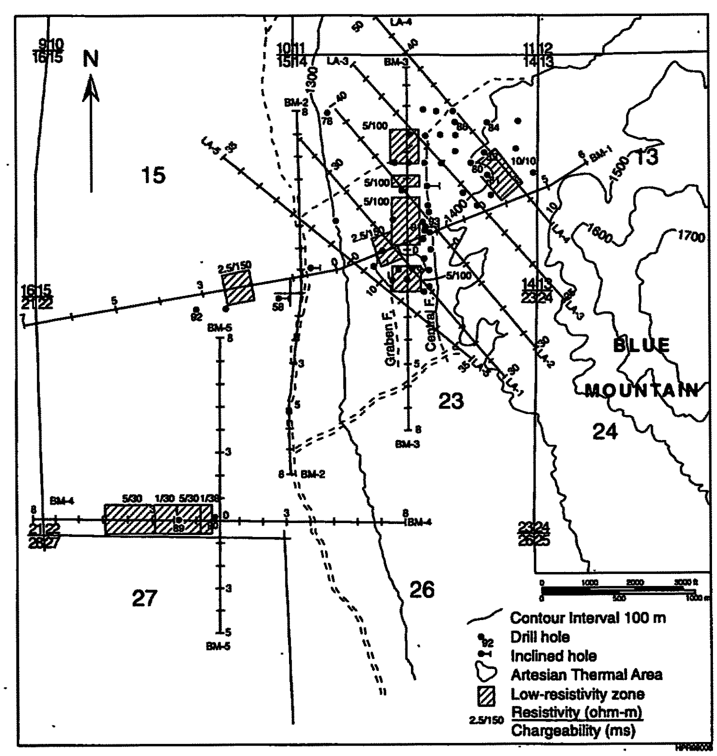

Figure 2. Resistivity/IP line locations, and low-resistivity areas determined by numerical modeling of Lines LA-4, BM-1, -3, -4. Compare with locations of the artesian thermal area and main sulfide body on Figure 1.

resistivities, typically 10 to 20 ohm-m. Although LA-4 crosses some of the warmest drill holes, and LA-1 crosses the artesian thermal area (ATA), no obvious pattern of low resistivities suggestive of the geothermal system is apparent in the data.

A second resistivity survey was completed in June 1998 by the Energy & Geoscience Institute (EGI), University of Utah and a contractor, Consolidated Geophysical Surveys (CGS). This survey included one profile of 1000 ft (300 m) dipoles and four profiles of 500 ft (150 m) dipoles and was intended to search for indications of the geothermal system. Induced polarization (IP) was recorded for profiles BM-1,-3,-4, and -5 to help identify the cause of SP anomalies believed to be related to the thermal system. Low signal strengths and high noise levels resulted in incomplete IP data for larger separations on profiles BM-1 and BM-3. The locations and orientations of all survey profiles are shown on Figure 2.

Line BM-1 (300 m dipoles) was sited to traverse SP anomalies A2 and B, the artesian thermal area (ATA), and to explore to depths of about 600 m. Low apparent resistivities (4-10 ohm-m) are associated with the ATA and areas to the west. Lines BM-2, -3, -4, and -5 all recorded observed resistivities below 10 ohm-m or a pattern suggestive of lower resistivities at depth. Apparent resistivity and Chargeability (*M*; milliseconds, ms) data for lines BM-1 (300 m dipoles) and BM-4 (150 m dipoles) are shown in standard psuedosection format in Figure 3. Both profiles show higher resistivities near surface (n=1,2) and lower values at depth. The induced polarization (*M*) is generally low (<20 ms) near surface but increases to highly anomalous values (>35 ms) to the east and at depth.

Interpretation of Resistivity Data

EGI employed CGS to complete numerical modeling of selected resistivity/IP profiles and used these results and other model results to infer less precise interpretations of the other resistivity profiles. CGS used a revised version of IP2D (Rijo, 1977; Killpack and Hohman, 1979) for interactive forward modeling of the observed resistivity data. Satisfactory fits to the observed data were obtained for all critical profiles, and sensitivity tests were completed to determine the accuracy of the final models.

BM-1 (300 m dipoles) trends E-NE across an artesian thermal area known from drilling and uphill across considerable topography on the east side. Preliminary modeling indicated a substantial topographic effect so subsequent modeling was completed using a good representation of the topographic surface. After completing a good fit to the resistivity data, the successful resistivity units were subdivided and assigned intrinsic chargeability (*M*) values to arrive at a satisfactory fit to the observed *M* data. The successful resistivity model and chargeability values are shown in Figure 4. Generally low resistivity (ρ; 10 ohm-m) and moderate *M* (20 ms) are present west of Sta. 1E with a deep (300 m), narrow zone of very low resistivity (2.5 ohm-m) and very high *M* (150 ms) at Sta. 2 to 2.5 W. At Sta. 1-2 E, a near-surface zone of M/ρ=60/10 corresponds to sulfide mineralization and artesian thermal fluids. The high *M* and low ρ suggest an apparent 7 weight percent sulfides. Lesser *M* values and higher ρ continue to the east beneath the rough topography and surface rocks. Beneath the high-sulfide, near-surface zone, at a depth of about 300 m (1000 ft), is a near-vertical body of high *M* and very low ρ (150 ms/2.5 ohm-m) at Sta. 1-1.5 E. The high resistivity contrast and good fit between computed and observed data insist on the presence of this body. This is interpreted as a mineralized zone with thermal fluids, beneath areas reached by the present drilling. The

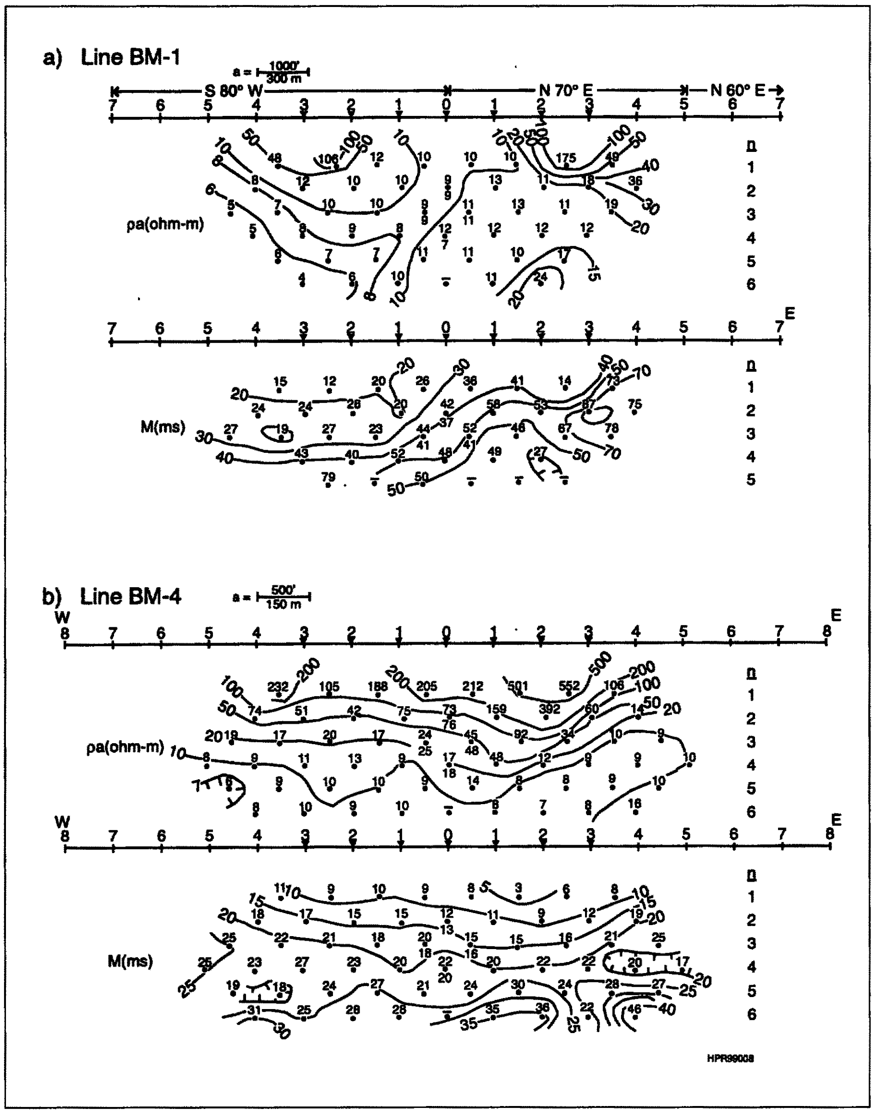

Figure 3. Observed apparent resistivity and induced polarization psuedosections: a) Line BM-1; and b) Line BM-4.

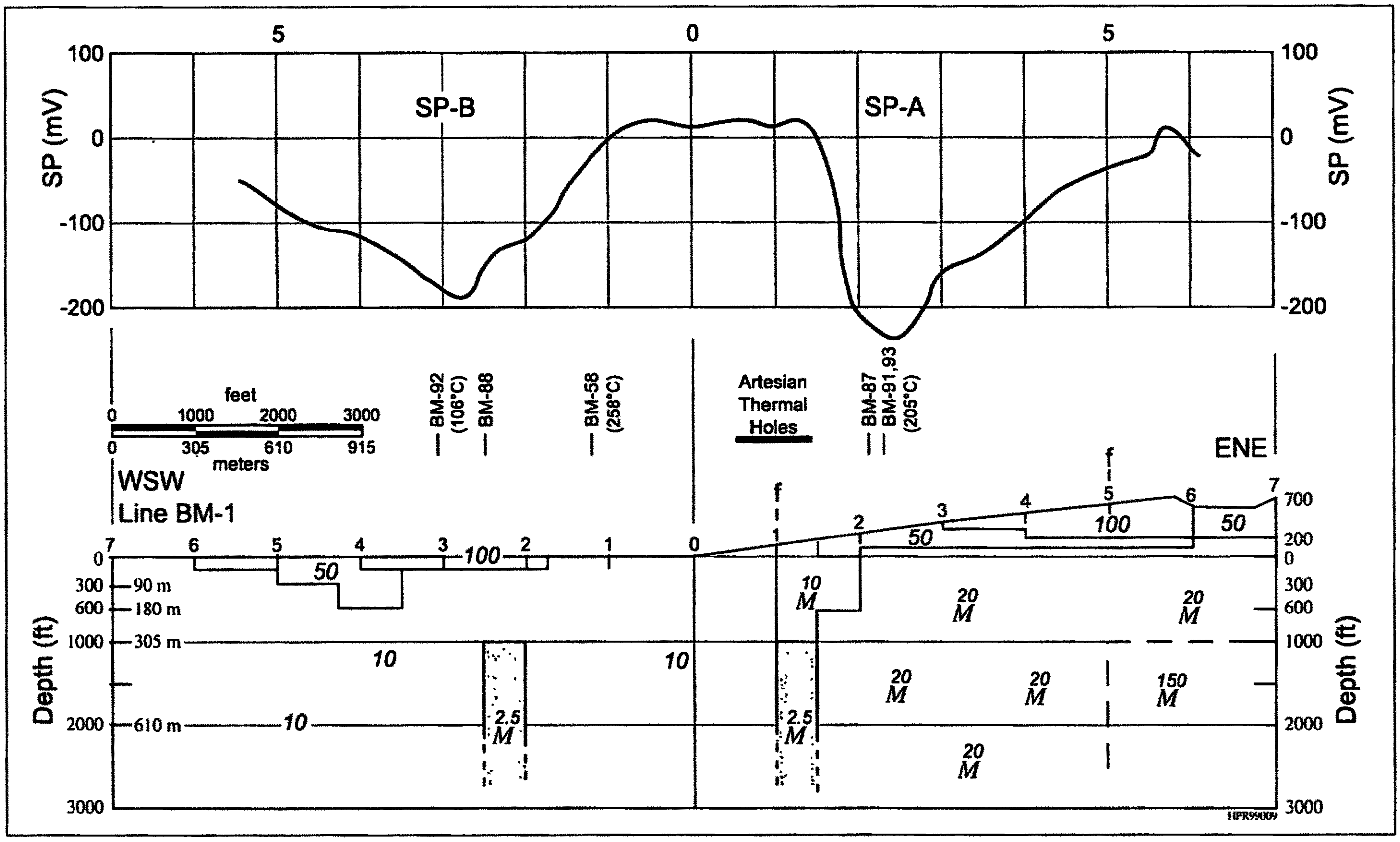

Figure 4. Numerical model for electrical resistivity line BM-1 (1000 ft. dipoles). Numbers in geometric bodies are intrinsic resistivities (ohm-m). *M* indicates chargeability greater than 50 milliseconds (ms). Self-potential profile corresponding to the resistivity line is shown above. The locations of nearby drill holes and the area of artesian thermal drill holes are also shown. Temperatures shown for BM-58, -92, -93 are linearly extrapolated to 500 m depths from 132, 215, and 108 m depths, respectively.

zone may be localized by the north-trending Graben Fault and West Fault, at intersections with northeast-trending faults.

Line BM-2 was oriented north-south along the dirt access road and sought to detect any low-resistivity outflow plumes from structures in the range. It recorded quite uniform low resistivities (8-12 ohm-m) west of the main drilled area, and did detect one area of 5 ohm-m resistivities between Sta. 5-7 south. Line BM-3 trends along the flank of the range and crossed Line BM-1 near the deep low-resistivity zone. The successful numerical model shows several low-resistivity, high chargeability (5 ohm-m, 100 ms) bodies at depths of 100 to 200 m (Figure 2).

Line BM-4 (Figure 3) was completed to provide resistivity and IP data for SP anomaly C and to compare with temperature studies of BM089 and BM090. The successful model shows a broad area of low resistivity (1-5 ohm-m) at depths of 200-300 m, roughly coincident with the SP minimum. The model suggests a separate fluid upflow zone and sulfides as the source of the SP anomaly. This may be a different fluid conduit to the main reservoir or a secondary thermal reservoir. BM-5, perpendicular to BM-4 with a common center, recorded a simplified "layered" appearing resistivity structure with higher (155-383 ohm-m) near-surface values which decrease to less than 10 ohm-m at depth. The low-resistivity area may really be lateral to the profile (just west of the line) and deeper as mapped by line BM-4 and the SP survey.

The 1988 IP/resistivity survey by Chester Lide and Associates was designed to map sulfide distributions as part of the precious metals exploration effort. Lines LA-1, -2, -3, -4 (Figure 2) map variable and often high resistivities (50-1040 ohm-m) to the east and at shallow depths (0-150 m). High chargeability values (20-60 ms) are associated with these high resistivities. Line LA-5 recorded relatively low and uniform apparent resistivities (10-20 ohm-m) and only low-moderate chargeabilities. Line LA-4 was numerically modeled to better determine the resistivity structure near several drill holes with higher temperatures (Fairbank and Ross, 1999). The successful model includes a 10 ohm-m body from Sta. 0 to Sta 10 W, 100-200 m deep, which extends to depth. This low- resistivity body corresponds to the higher temperatures in BM-80, -81, -85 but the resistivity is higher than the low-resistivity bodies modeled for lines BM-1, -3, -4. The source area for thermal fluids may be too deep for direct detection by the 150 m (500 ft) dipole line in this area.

Discussion

A self-potential (SP) survey has mapped four large negative anomalies, and the largest is spatially associated with an artesian thermal area and sulfide mineralization. Limited drill testing of the two SP anomalies 1-3 km to the south and west has revealed anomalous temperatures and minor sulfides in bedrock. Numerical modeling of dipole-dipole resistivity data indicates low-resistivity and high chargeability bodies associated with all SP anomalies (i.e. Figure 4). A deep (300 m) low-resistivity body mapped by BM-1 is closely associated with the artesian thermal area and may be the expression of a hydrothermal reservoir at depth. A low-resistivity body near BM080,-081, -086 may be associated with thermal conduits at similar depths. If the hydrothermal reservoir is present at depths greater than 500 m, there may be good reason to project temperature gradients to these depths, and reservoir temperatures of 150°C to 250°C may be present (Fairbank and Ross, 1999).

The coincidence of high chargeability and low resistivity with the SP anomalies indicates sulfide mineralization and alteration minerals are part of the SP sources. The joint occurrence of thermal fluids and older mineralization clearly indicates a major fault/fracture system which has been reactivated to permit thermal fluids to flow from depth to the near-surface. The hydrothermal system has not yet been tested to depth and the extent of the thermal area is favorable for the occurrence of an economic geothermal system. Low-resistivity bodies at depth which were modeled on Lines BM-1 and LA-4 occur near high-temperature gradients, and these are good drilling targets for intermediate-depth geothermal tests.

Acknowledgments

Financial support for this study was provided by the U.S. Department of Energy under DOE/ID Contract No. DE-AC07-95ID13274 to EGI. Such support does not constitute an endorsement by the U.S. Department of Energy of the views expressed in this publication. BMPC has provided previously unpublished geophysical and geologic information to contribute to this study.

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