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# Geology and Temperature Gradient Surveys Blue Mountain Geothermal Discovery, Humboldt County, Nevada

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## ABSTRACT

Triassic argillite and sandstone of the Grass Valley Formation and phyllitic mudstone of the overlying Raspberry Formation, also of Triassic age, host a blind geothermal system under exploration by Blue Mountain Power Company Inc. with assistance from the Energy & Geoscience Institute. Geologically young, steeply dipping, open fault sets, striking N50-60°E, N50-60°W, and N-S intersect in the geothermal zone providing deep permeability over a wide area. Extensive silicification and hydro brecciation accompanied explosive boiling in a hydrothermal system as it evolved 3-5 million years ago. Advanced argillic alteration resulted from steam heating and acid leaching above the former boiling zone. Ten temperature gradient holes, measured to a maximum depth of 132 meters and spread over an area 1.5 × 3 km, have gradients exceeding 300°C/km; of these, six exceed 400°C/km. Temperatures extrapolated to 500-meter depths exceed 200°C for nine of these holes. Two other holes in deep gravel on the west side of survey area had anomalous gradients of 85 and 142°C/km respectively. The results are highly encouraging for the development of a high-temperature, relatively shallow geothermal reservoir.

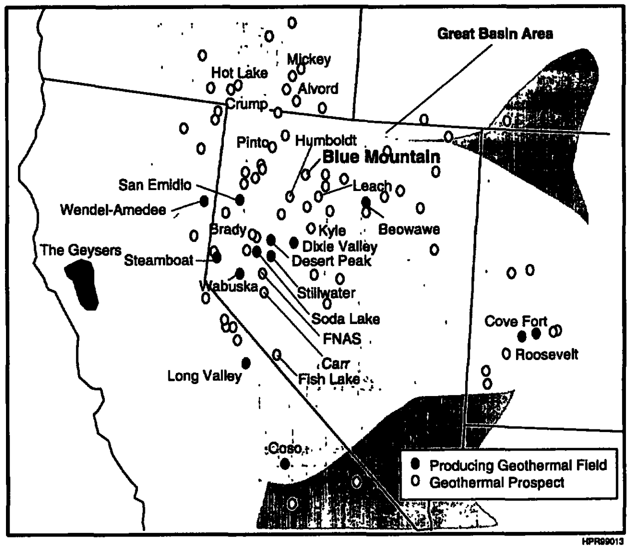


**Figure 1.** Location of Blue Mountain geothermal area, other geothermal prospects, and producing geothermal fields.

## Introduction

The Blue Mountain geothermal area is located on the west flank of Blue Mountain in Humboldt County, 35 kilometers west of Winnemucca, Nevada (Figure 1). The area is accessible year round from Winnemucca by a maintained gravel road. The project area is at 1300 meters (4300 feet) elevation above sea level. The terrain is flat in the west and central parts of the project, rising eastward in low steps to the base of Blue Mountain. The site is about 24 km from the Rose Creek Substation on the northern Nevada power grid.

The thermal anomaly was discovered by Nassau Ltd. during exploration drilling for precious metals; no hot springs or active thermal manifestations occur at surface. From 1982-1993, Nassau and partners including Billiton Minerals, Placer Dome, and Lac Minerals carried out a variety of exploration programs including geological mapping, seismic, magnetic and IP surveys, and drilling. A thermal anomaly was roughly outlined over an area 1000m × 1000m (Parr and Percival, 1991).

Blue Mountain Power Company Inc. (BMPC), through its subsidiary Noramex Corp., obtained geothermal leases in 1993 and 1994. Subsequently, geological and geophysical surveys were conducted and temperature gradients measured in 11 new holes to nominal depths of 125 m with scientific support from the Energy & Geoscience Institute (EGI), University of Utah. Self-potential (SP) and resistivity surveys conducted at Blue Mountain by EGI are described by Ross *et al.* (1999, this volume). This paper summarizes the geology of the project and the thermal studies completed to date.

## Geology

Descriptive geology is summarized from Percival *et al.* (1993), Booth (1994) and Sadlier-Brown (1998). Siliciclastic

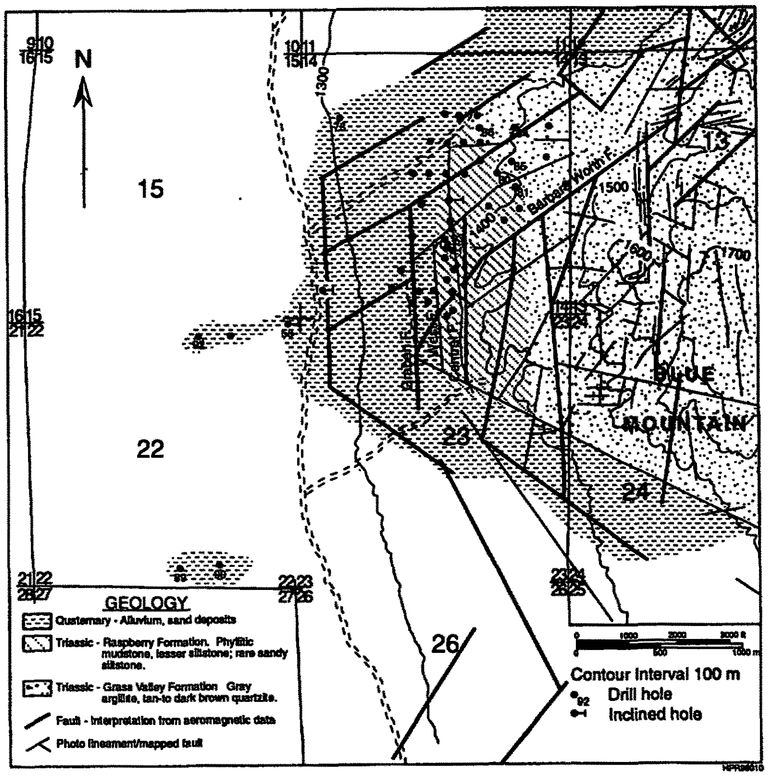


**Figure 2.** Geologic Map, Blue Mountain geothermal area. Faults/fractures were determined from mapped features, photo linears, and aeromagnetic discontinuities.

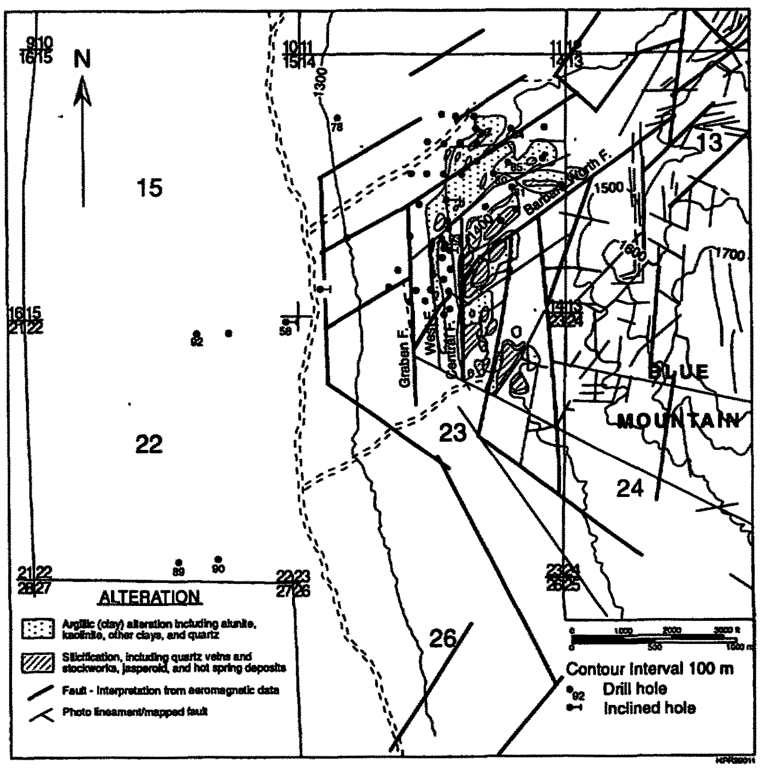


**Figure 3.** Alteration Map, Blue Mountain geothermal area. Note the relationship to mapped structures.

metasedimentary rocks of the Triassic Grass Valley and Raspberry formations underlie the Blue Mountain area (Figure 2). The Grass Valley Formation, exposed on the west slope of Blue Mountain, consists of grey to black, thin bedded, non-calcareous, carbonaceous platy argillite and intercalated, thin to thick, mature sandstone beds. Younger Raspberry Formation grey to grey-green, laminated, silty and locally sandy phyllitic mudstone forms a low bench at the base of Blue Mountain. White, unmineralized quartz veins crosscut both formations and are products of greenschist facies metamorphism along with chlorite and muscovite. The contact between the Grass Valley and overlying Raspberry Formations dips shallowly to the west.

Diabase dikes intrude the sedimentary rocks along steeply dipping north-trending structures and form a major dike swarm on the west flank of Blue Mountain. Variably altered, light grey, quartz-feldspar porphyry dikes have been intersected in numerous drill holes. Surface outcrops of the porphyry dikes are rare and where present are intensely altered. Alunite from a felsic dike outcrop yielded a K-Ar date of 3.9 Ma (Garside *et al.*, 1993). Alunite is associated with the gold mineralizing event at Blue Mountain and the age date from supergene mineralization probably represents a minimum age of hydrothermal activity associated with gold mineralization and paleo-hot springs.

Stratified lacustrine deposits of the Pleistocene Lake Lahontan sequence, younger pediment gravel and aeolian sand mask bedrock geology, structure and alteration features in the broad valley west of the known gold mineralization.

## Structure

Triassic rocks and the relatively young mineralized zones are dissected by three distinct, dipping, normal fault sets oriented N50-60°E, N50-60°W, and N-S respectively (Figures 2,3). Outcrops are cut by cleavage, joints and fracture sets oriented parallel to the major faults. NE trending and N-S trending faults are a major control for hydrothermal alteration and gold mineralization. The N-S fault set is the youngest, forming prominent scarp-bounded benches along the west flank of Blue Mountain. Generally, major NE faults have downdrops to the NW of 5-15 m; N-S faults, such as the Central, West and Graben Faults have downdrops of up to 50 m; and the NW trending fault along the base of Blue Mountain has a downdrop of at least 100m.

The gravel and lake sediment thickness increases rapidly in all directions from the base of the mountain; however, a bedrock high occurs at the location of hole 58, indicating a possible horst at this location.

## Alteration and Mineralization

Alteration is extensive throughout the area and is most intense along or at the intersection of faults and fault zones

(Figure 3). Alteration includes quartz veins and stockworks, intense silicification, chalcedonic and opaline silica hot spring deposits, moderate to advanced argillic alteration, alunite and quartz-alunite replacement and veining, and pervasive hematite formation especially in silica-altered rocks.

Jasperoidal silicified sedimentary rocks form resistant ridges and craggy outcrops along the range front fault zone; hydrothermal brecciation is common and voids are partially infilled by combinations of drusy quartz, barite, fluorite, calcite, and rare unoxidized pyrite. Argillic alteration occurs near the intersections of N-S and NE trending faults and is mostly restricted to the Raspberry Formation. Quartz, alunite, kaolinite and other clays occur in association with barite, sulphur, cinnabar and varying amounts of iron oxide minerals.

Hot spring deposits, comprised of reddish-brown opal, white to light grey siliceous sinter and banded chalcedonic veins, are common east of the Central and Barbara Worth Faults. These deposits contain clays, iron and manganese oxides and rare disseminated pyrite and secondary copper mineral coatings.

All hydrothermally altered rocks contain some anomalous amount of Au, Ag, As, Sb, Hg, Ba, F and Tl. The silicified rocks contain the highest gold-silver values with erratic trace element concentrations. Argillically altered rocks and hot spring deposits contain lower precious metal values and generally higher trace element concentrations.

The shallow-dipping contact between the Grass Valley (argillite and sandstone) and overlying Raspberry Formation (phyllitic mudstone) was the focus of hypogene mineralization. Silicification, brecciation, fracturing, voids and gold-silver mineralization are developed along the contact. A gold-silver zone of economic interest occurs in a large, tabular, silica-rich body, 6-20 meters thick and 60-100 m below the surface, lying between the Graben and Central Faults. The mineralization is generally unoxidized and contains 3-10% pyrite. Gold-bearing hydrothermal fluids are believed to have ascended along steep-dipping open feeder structures within the Grass Valley Formation. Upward mobility may have been impeded at the contact with the less permeable Raspberry Formation mudstone. Violent boiling occurred near the depth of the paleo-water table and the main gold-silica mineralized interval. Raspberry Formation rocks above the boiling zone are intensely clay altered from steam heating and acid leaching.

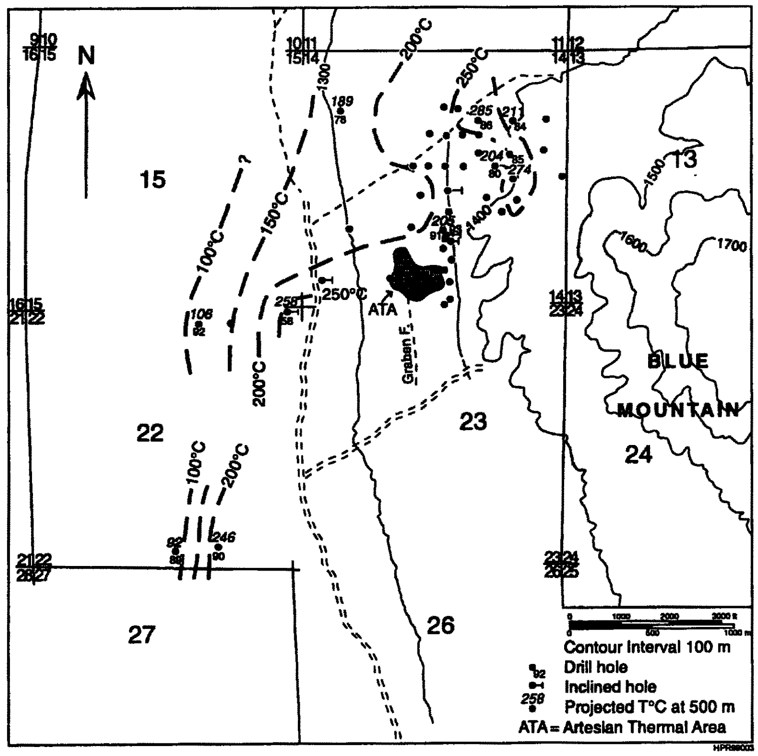


**Figure 4.** Drill holes for temperature studies, artesian thermal area, and projected temperature distribution at 500 m depth.

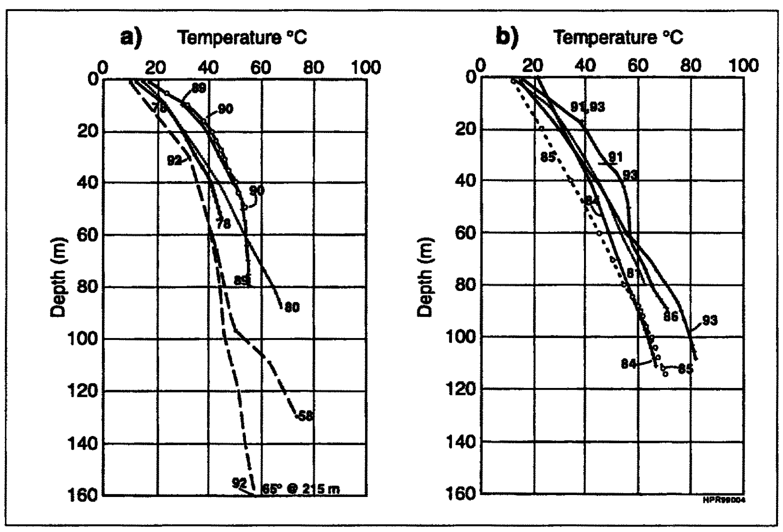


**Figure 5.** Temperature profiles for drill holes studied: a) Drill holes west of Graben Fault compared to BM-80; b) Drill holes at higher elevation, on bedrock.

## Drilling

Seventy-seven mineral exploration drill holes, 60-150 meters deep, were completed prior to Blue Mountain's geothermal involvement. Although little effort was made to record temperature information, anomalous temperatures and warm- to scalding waters were recorded in twenty-seven drill holes. Discussions with on site geologists support the belief that most of the holes encountered hot water. Five temperature measurements of return fluid in BM-58, an angled drill hole, defined an average temperature gradient of 420°C/km and a temperature of 73.9°C at 152 meters. Several holes defined an area of artesian thermal fluids (Figure 4) and many holes encountered voids and massive lost circulation zones associated with faults, hydro fracturing and brecciation.

BMPC's drilling was also directed toward mineral exploration, but eleven new holes were lined with PVC or iron pipe to enable accurate downhole temperature measurements. Liners were placed as far as possible down the holes but generally did not reach bottom due to blocking of fractured rock or caving of loose overburden in deep overburden areas. The BMPC holes are to northeast, northwest and southwest of previous thermal indications. All indicate high temperature gradients and fracture permeability, greatly increasing the size of the known geothermal system.

## Temperature Studies

The Energy & Geoscience Institute (EGI/UU) began detailed temperature logging of available mineral drill holes in 1996 as part of a DOE/OGT supported Cooperative Study Agreement with BMPC. Temperature measurements were made with EGI's N.P. Instruments high-precision (+/-0.01°C) thermistor probe and temperature logging equipment. Drill hole conditions, and convection within the hole may reduce the measurement accuracy to +/- 1°C. The available holes were logged in April and May 1996; March and May 1997; and May 1998. Most holes were logged on two different occasions, subject to hole condition and availability. Drill hole conditions included: open-hole; PVC pipe (sometimes twisted and ruptured); and iron pipe. Few holes retained water above 50 m depths, so these measurements were often made in air and are less accurate. Observations were made at 20, 10, and 5 m intervals above the water level and at intervals of 5 to 1 m below water level. Repeat measurements showed considerable variation from the surface to 30 m depth reflecting seasonal temperatures, but little change in temperature and temperature gradient (dT/dz) at depth. Figure 4 shows the drill holes logged in this study.

Table 1 summarizes the reliable temperature data for Blue Mountain. In all cases the maximum temperature was at the deepest measurement point, and this corresponded to total depth for only BM-58 and BM-81, because of hole obstructions or casing conditions. In BM-90 a maximum thermometer reading of 74°C recorded before the hole caved (R. Faulkner, personal communication) was much higher than the 53°C recorded with the logging system at 49.4 m. The highest observed temperature is 81.2° in BM-93 and all temperatures are anomalous even at depths as shallow as 34 m.

**Table 1.** Blue Mountain Geothermal Area, NV. Drill Hole Temperature Summary.

| Drill Hole | Depth (m) | Maximum T°C: T°C | Maximum T°C: Depth(m) | dT/dz °C/km | Projected Temperature: T°C@300m | Projected Temperature: T°C@500m |
|---|---|---|---|---|---|---|
| BM-58* | 132.0 | 73.9 | @ 132 | 500* | 157.9 | 258 |
| BM-78 | 152.4 | 44.83 | 54.0 | 321 | 24.3 | 189 |
| BM-80 | 102.0 | 67.78 | 90.0 | 344 | 136.7 | 204 |
| BM-81 | 80.0 | 62.29 | 80.0 | 436 | 168.9 | 274 |
| BM-84 | 138.7 | 66.48 | 110.0 | 370 | 137.3 | 211 |
| BM-85 | 126.5 | 70.06 | 114.0 | 443 | 153.5 | 242 |
| BM-86 | 99.1 | 69.82 | 89.0 | 485 | 179.4 | 285 |
| BM-89 | 126.5 | 55.60 | 79.9 | 85 | 74.4 | 92 |
| BM-90# | 167.6 | 52.99 | 49.4 | 431 | 160.1 | 246 |
| BM-91 | 88.4 | 49.93 | 34.6 | 738? | 246? | 393? |
| BM-92 | 243.8 | 65.11 | 215.0 | 142 | 77.7 | 106 |
| BM-93 | 125.0 | 81.19 | 107.9 | 313 | 142.2 | 205 |

* Maximum reading thermometer, 5 measurement depths.
# Maximum reading thermometer, 74°C at t.d. after drilling.

The temperature gradients in Table 1 are the best estimates of dT/dz determined for depth intervals of 8 to 95 m at the bottom of the logged intervals. The gradients vary greatly due to measurement depth and position in the geothermal system. Figure 5a records the temperature profiles for drill holes BM-58, -78, -89, -90, and -92, all located west of the Graben Fault in sands and valley fill deposits. The log for BM-80 (sited on bedrock in the northeast part of the area) is shown for comparison. Only BM-89 and BM-92 show much reduced dT/dz near total depth. The drill holes for temperature profiles in Figure 5b are all located on bedrock at higher elevations in the northeast part of the area. BM-91, -93 are inclined holes which cross the Central Fault. Most of these gradients at depth are in the 370-485°C/km range.

All gradients are anomalous (>50°C/km) and 10 exceed 300°C/km. Estimated temperatures for depths of 300 m and 500 m were projected from the temperatures at the base of the logged interval (Table 1) and 9 of the 12 projected temperatures exceed 200°C at a depth of 500 m. These temperatures, if present at reservoir depths, would be well-suited for the production of electric power. Temperature projections from shallow temperature profiles are speculative, but to date no temperature reversals have been observed. The need for intermediate-depth (300-600 m) temperature gradient holes to further evaluate the resource is apparent. Figure 4 shows the temperatures projected for 500 m depth in map view. Although speculative, this projection provides a common-depth summary of key temperature information in map form. The projected temperature contours reflect the structural control of north-trending range-front structures, and the northeast trend of structures inferred from aeromagnetic data and aerial photos.

Limited independent information regarding reservoir temperatures is available from geothermometry of three fluid samples collected from BM-90 in April 1997 by BMPC geologists. Dr. Joseph Moore (EGI/UU geologist) found the samples to be a relatively dilute geothermal water with a salinity of slightly more than 3000 ppm TDS. All samples gave consistent geothermometer temperatures: quartz (no steam loss) = 103-111°C; Mg corrected Na-K-Ca and Na/Li both indicated 112-119°C. Because BM-90 is located on the southern limit of the drilled area, more than 3 km from BM-78, -86, and 2 km from the artesian upflow area (BM-43, -44, -47, -48), BM -90 fluids may represent well-mixed fluids or a secondary reservoir rather than the main high-temperature reservoir. Electrical resistivity surveys (Ross *et al.*, 1999; this volume) suggest BM-90 may be located near a separate shallow reservoir. Fluid samples from other boreholes were contaminated and did not provide useful information.

## Reservoir Flow Model

Geothermal fluids have been heated by deep circulation of surface waters along a range fault zone oriented N50-60°E. A geothermal up-flow zone occurs at the intersection of the N50-60°E faults with a set of older range front faults trending

N50-60°W and younger N-S normal faults. Shallow drill holes have intersected thermal waters, locally hot enough to boil when penetrated by the drill hole, in N-S faults, for example the Central Fault, which is characterized by open cavities and hard, uncemented siliceous breccia. The geothermal system is not confined to a single fault, but rather is associated with a series of N50-60°E and N-S faults in zones 2500 to 3500 meters wide respectively.

## Summary

Geologic and temperature gradient studies indicate that structures which provided conduits for the hydrothermal system that deposited gold-silver mineralization 3-5 million years ago are also the conduits for the present-day geothermal system. Prior to obtaining the new temperature data, it was thought that the active geothermal system had moved westward from the mineralized area. It is now apparent that thermal activity is present both east and west of the Central Fault. The thermal anomaly, at least 1.5 × 3 km in aerial extent, is open in all directions.

The geothermal resource has only been tested to shallow depths, and intermediate-depth (500-600 m) holes are the necessary next step. The temperature studies suggest reservoir temperatures may exceed 200°C at reasonable (500-1000 m) production depths. Electrical resistivity surveys (Ross *et al.*, 1999) suggest that a low-resistivity body near BM-91 and BM-93 may be related to a deeper (> 500 m) geothermal reservoir. Two considerations make the Blue Mountain geothermal system promising, with respect to the 200°C temperatures extrapolation: (1) no temperature reversals or isothermal zones have yet been observed in those holes which have been logged; and (2) the relatively large extent of the resource, more than 3 km (NNE) × 1.5 km, as presently known by shallow temperature measurements. Resource temperatures of 200°C, with adequate flow from relatively shallow production wells located only 24 km from the transmission grid, may be an economic resource.

## Acknowledgments

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