Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

A Preliminary Conceptual Model for the Blue Mountain Geothermal System, Humboldt County, Nevada

John Casteel, Rogel Trazona, Glenn Melosh, Kim Niggemann and Brian Fairbank

Nevada Geothermal Power Inc. 900-409 Granville St. Vancouver, BC V6C1T2

jcasteel@nevadageothermal.com

Keywords: Blue Mountain, geothermal, reservoir, model, structure, geochemistry, lithology.

ABSTRACT

Geothermal exploration at Blue Mountain in northern Nevada has proven the presence of a viable resource, leading to the development of a 49.5 MWe-gross binary power plant. Surface mapping has documented extensive faulting, fossil hot springs, and significant hydrothermal alteration along the western Blue Mountain range front. Drilling and testing of thermal gradient wells, slim holes and full-size (12.25" diameter) wells for production and injection provide direct observations of the lithologic, thermal, geochemical, and permeable character of the reservoir. Subsurface geophysical investigations are providing less direct observations of the system that are unavailable from drilling data.

The resource is classified as a hot liquid-saturated convective system circulating neutral-pH, dilute alkali-Cl waters, with low to moderate contents of non-condensible gases. The reservoir is hosted within a fault and fracture network and fluids are circulated along a predominant NE-trending range front fault zone. The resource is an artesian reservoir at or below an elevation of ~1100 feet, which is calculated to be equilibrating to ~250°C at depth. Fluids produced for power generation are oversaturated with respect to silica causing a potential for scaling, however, this can be mitigated effectively by chemical inhibition. The risk of calcite deposition occurs only through adiabatic cooling and will not be problematic in the operation of the binary power plant.

1. INTRODUCTION

Blue Mountain is located within the Basin and Range province, approximately 25 miles west of Winnemucca in northern Nevada (Figure 1). The geothermal field underlying Blue Mountain and portions of Desert Valley to the west is a blind system with no current hydrothermal activity at the surface. The geothermal potential here was first recognized through shallow mineral exploration drill holes, which has subsequently led to full size production and injection wells. Concurrent development of a 49.5 MWe-gross binary power plant is scheduled to begin operation in 2009. The information presented herein is a partial assessment of pertinent data from Blue Mountain summarized into a preliminary working model, which is used to conceptualize the resource as a complete and integrated system to aide in well targeting, resource management and to better understand geothermal systems in Nevada and elsewhere.

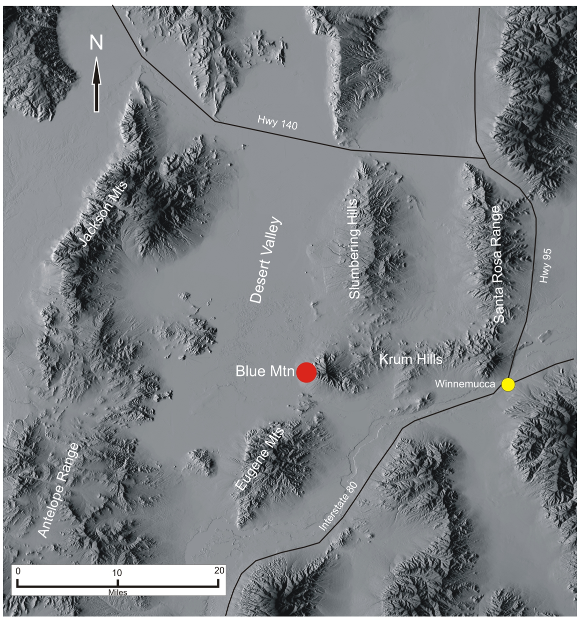

Figure 1: Regional shaded relief map showing location of Blue Mountain and surrounding features.

2. GEOLOGY

Blue Mountain is underlain by metapelitic rocks including slate, phyllite, varying grades of metasiltstone and metasandstone, quartzites and lesser carbonates (Wyld, 2002). These rocks have undergone at least two major phases of deformation and igneous intrusive episodes; one felsic intrusive episode in the late Cretaceous, and intrusion of mafic dikes in the late Tertiary (Wyld, 2002). There is a predominant northeast trend and northwest dip to the structural fabric that is pervasive throughout Blue Mountain and which strongly reflects its past deformation history, and offers insight into the current extensional regime and distribution of the hydrothermal system.

2.1 Surface Indications

Taken at a broad view, rocks exposed along the range front and western tip of Blue Mountain clearly reflect their past depositional, deformational and erosional history. On a finer scale, evidence for prolonged hydrothermal activity is present in numerous locations along the range front including extensive silicic and argillic alteration and brecciation, abundant quartz veining, and fossil hot spring deposits (Szybinski, 2004). The majority of these features are located along the northwestern flank and westernmost extent of the range. Their distribution correlates well with certain aspects of the thermal anomaly, and at least partially reflects the magnitude and aerial extent of the reservoir as it has been discovered through exploratory drilling.

2.2 Subsurface Lithologic Findings

A combination of shallow mineral exploration and thermal gradient boreholes, intermediate depth exploration slim holes, and deeper, full size (12.25” diameter) production wells (Figure 2), provide direct observations of the complete lithologic section from overburden to reservoir host rock across much of the field. An idealized lithologic section is summarized in the following sections.

Formation progresses with increasing depth from unconsolidated sands, silts and gravels into moderately consolidated alluvial fill. In southerly portions of the field, drilling has encountered discrete zones of strongly cemented and hydrothermally altered silicic breccia, often characterized by capacious voids. This unit is believed to represent past boiling horizons of the current hydrothermal system, although at much shallower depths than it exists today. At greater depths, largely in metasedimentary and intrusive bedrock, a capacious void zone has been identified that is laterally prevalent, similar to the shallower silicic zones. It is hypothesized that distribution of the silicic zones is directly linked to the underlying fault and fracture network, but there is not enough data to predict the spatial distribution of voids within the zone. The connection between the deeper and shallower void zones is uncertain. In portions of the field where boreholes have not encountered any shallow silicic void zones, it is common to drill through increasingly competent metasedimentary bedrock until the primary reservoir is reached.

The section of bedrock immediately overlying the reservoir typically contains a significant portion of argillic-altered rocks, with the total clay content reaching 100% of cutting returns in some places. Clay portions eventually decreases to 0% as silicic alteration increases along with rock competency. Evidence of micro-fracturing, brecciation, and quartz veining become more prevalent with increasing proximity to faults or permeable regions in the reservoir.

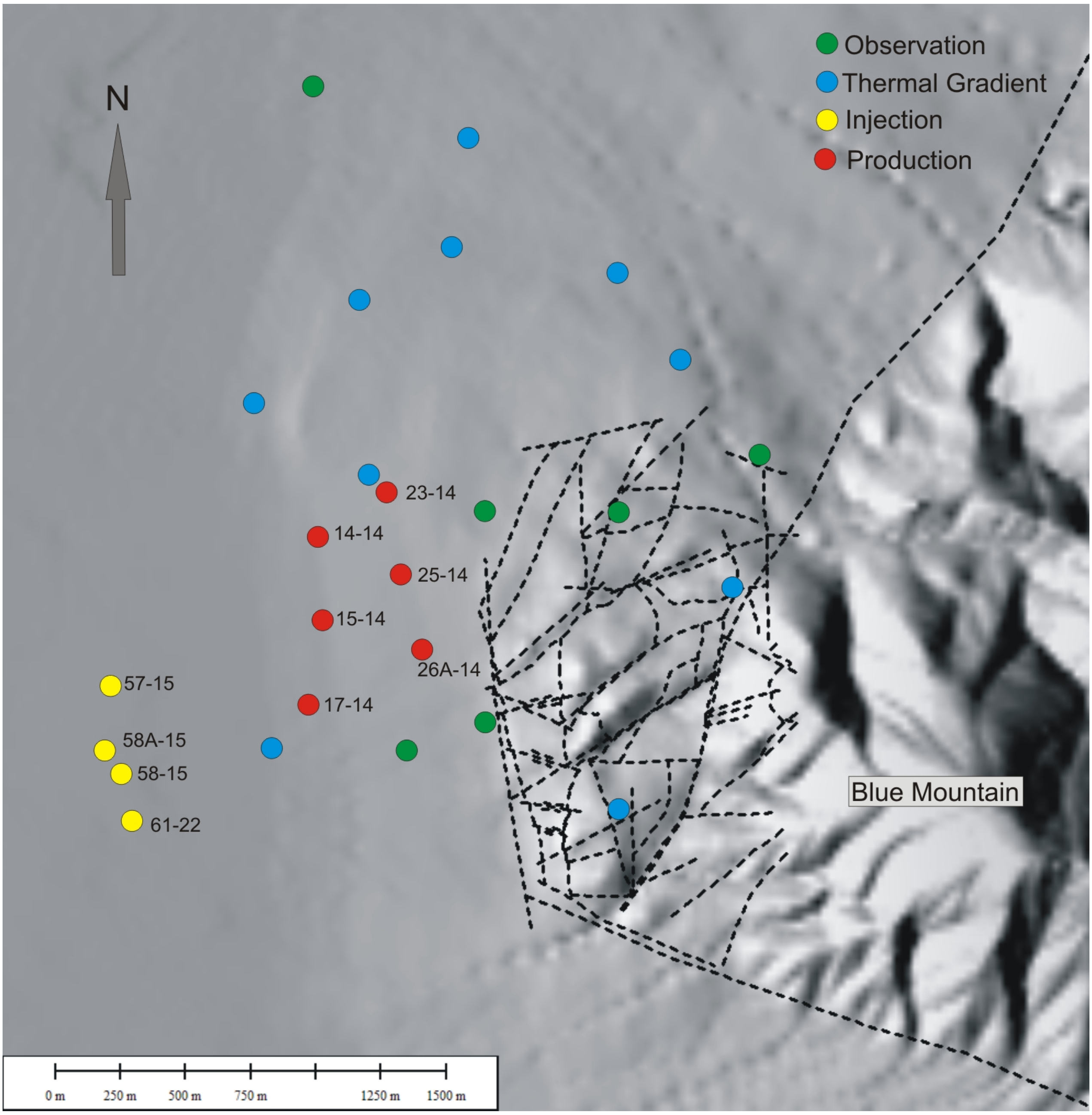

Figure 2: Map of Blue Mountain showing faults and well locations. Wells being utilized for the power plant are labeled.

Methylene-blue clay analyses reinforced by XRD and clay separation studies on drill cuttings has preliminarily shown the existence of smectitite/illite clay transitions, representing a reservoir cap within overlying altered formations.

Reservoir permeability does not appear to be directly controlled by lithology, however because the dominant lithology is metasedimentary there is a strong correlation; the majority of well entries and known permeable zones are encountered within metasedimentary rocks with the exception of one deep entry in diorite. Because total circulation is typically lost in the main zones, there is some uncertainty as to what is the true formation. It is possible that permeable zones are occurring at, or very near, the contacts between the intrusive bodies and the host metasedimentary rocks. As is discussed below, there is a strong case favoring a permeability model where faults and fractures provide the most numerous and significant fluid pathways.

3. FAULTS

3.1 Surface Mapping

Fault mapping at Blue Mountain demonstrates three predominant fault orientations of NW, NS and NE (Szybinski, 2004) (Figure 2). As is more fully detailed by Faulds (2007), the prominent NE fault system likely accommodates the bulk of the current deformation at Blue Mountain, and consequently is probably the primary cause or source of permeable rock hosting the hydrothermal system. Furthermore, a combination of small pull-aparts along the main NE trend, combined with the confluence of the NE and NW trending faults, has created a local zone of dilation and extension, resulting in a region of highly fractured rocks (Faulds, 2007). In this case, faults trending approximately NS may fit best into the current model as ancillary piedmont faults existing only in the relatively shallow hanging wall of the predominant NE trending fault zone. As is discussed below, on the basis of the current model, it is less likely that NS faults account for the deep permeability patterns. However, due to the fact that they do exist, are fairly pronounced at the surface, it is probable that the NS faults have a strong influence on shallow permeability patterns.

3.2 Drilling Results and Borehole Analysis

The current understanding of faulting at Blue Mountain is largely known from drilling results, which has provided a unique perspective of the 3D distribution of known permeability. Correlation of well entries and mapping of known permeable zones throughout the entire well set have defined multiple sub planar features, interpreted as strands of the range front fault system. Although multiple fault configurations can be generated by mapping different combinations of entries, the best fit define NE trending and NW dipping features, with orientations that strongly agree with structural trends at the surface (N10-30E, 45-55W). These findings support a fault model where gross permeability distribution throughout the system is dominated by NE trending faults, while subsidiary piedmont faults may be important structures for providing system-wide connectivity among the dominant faults.

A preliminary analysis of borehole televiewer image logs completed on wells 26A-14 and 44-14 demonstrates that the western range front of Blue Mountain contains fracture orientations which vary in strike between NNW-SSE and NNE-SSW, and dip both to the east and to the west. These results are in agreement with, and indicate that structural relationships from surface mapping may be extrapolated to reasonable depths in the field. However, none of the mapped fractures have yet been directly correlated with the known production zones in either of the two wells.

Despite recent drilling success and improvements in the fault model, it is clear that the system is more complex than is currently understood or modeled. Additional fault configurations, and possibly non-fault related permeability solutions need consideration. More work is needed to further understand the finer scale geometries of the fault system and how they specifically relate to fault permeability at a level of precision useful for well targeting.

4. RESERVOIR FLUID CHARACTERIZATION AND UTILIZATION

The discharge testing of six production wells and three (3) injection wells proved the presence of a convective hot brine resource that is upflowing along the WSW flank of the reservoir. The output, injectability, and brine and gas chemistry were also characterized during the testing of these wells.

The production testing indicated the viability of the fluid for direct commercial electrical generation. The production wells that will be linked into the brine gathering system have enthalpy values ranging from 325 - 350 BTU/lbm, and maximum reservoir temperatures ranging from 371 - 387ºF. It appears that there are about 44 MW-electrical (MWe) net presently available which will be pumped at a rate of approximately 15,000 gpm from the wells to a binary heat exchanger (Lovekin, 2008; Stacey, 2009(a); Stacey, 2009(b); Stacey, 2009(c)).

Injection testing of two deep injection wells and one shallow injection well demonstrated high injectivity potential. The two deep wells (> 5600 feet depth) demonstrated that they had maximum temperatures ranging from 410 - 416ºF, and enthalpies ranging from 361 - 375 BTU/lbm. The shallow injection well drilled to 1554 feet had a maximum temperature of 165ºF, and an enthalpy of 134 BTU/lbm (Stacey, 2008).

Flow testing also provided for the chemistry of the reservoir to be characterized. The geothermal system is classified as a hot brine geothermal convective system, with neutral-pH, dilute alkaline-Cl waters (Fig. 3), and moderate amounts of gases. The initial conditions of the reservoir are saturated liquid with Cl_{res} content ranging from 2000-2200 ppm, SiO_{res} = 400 - 430 ppm, Cl/B = 160 - 170 weight/weight (w/w) that when flashed would yield non-condensable gases of <3% w/w (Table 1) (Trazona, 2008).

Table 1: Reservoir chemistry, solubility index and NCG.

Parameters	Reservoir Chemistry
Aquifer Steam Fraction	0
B, mg/kg	12.7
SiO_2, mg/kg	400-430
Na, mg/kg	1340-1350
K, mg/kg	160-170
Mg, mg/kg	0.25-.45
Ca, mg/kg	18
F, mg/kg	4
Cl, mg/kg	2000-2200
SO_4, mg/kg	60-90
HCO_3, mg/kg	130-140
Log Q/K (calcite)	< 0
SSI	1.5-1.7 @ 158 ºF
NCG	< 3% weight/weight

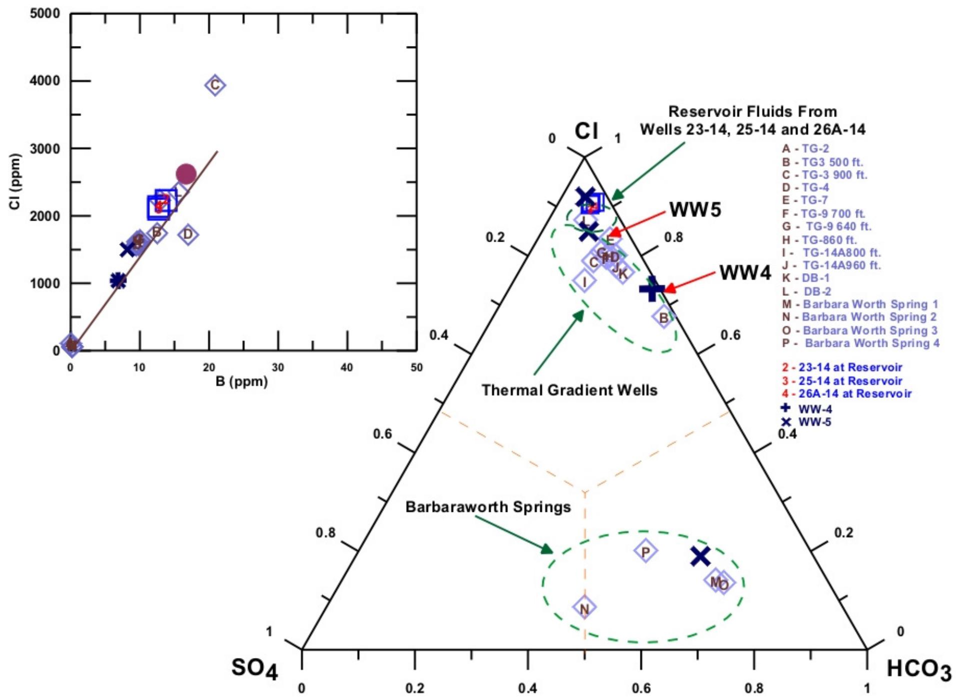

Figure 3: Ternary plot of Cl-SO_4-HCO_3 indicated that production fluids are classified as neutral-pH dilute alkaline-Cl water. Reservoir fluids showing Cl/B ranging from 160-170 w/w indicate homogeneity of the reservoir fluids.

The water and gas geothermometers which are given in Table 2, show that most of the geothermometers predict temperatures greater than 200ºC are possible for neutral-Cl waters. The parent fluid predicted by a NaKMg ternary Giggenbach plot is about 250ºC (Fig 4). The predicted temperature from quartz geothermometer (T-Qtz) in well 58 - 15 is about 213°C which is usually seen in upflowing wells equilibrating with the said mineral. A Fisher-Tropsch diagram predicted reservoir fluid at saturated liquid conditions with temperatures 230 - 240ºC (Fig. 4), and the T-H_2/Ar, and TH_2 values agreed closely to the wellbore temperatures actually recorded (Trazona, 2008).

The fluid type of the reservoir is benign, making it commercially viable. The reservoir is initially unsaturated with respect to calcite and silica. As the fluid conductively cools, log Q/K of calcite (< 0) shows a reverse solubility remaining in solution, while silica has a silica saturation index (SSI) increase to 1.5 - 1.7 at 158ºF (Table 1). An anti-scalant compound injected upstream of the heat exchanger should mitigate concerns of silica deposition (Trazona, 2008).

Table 2: Range for water and gas geothermometers.

Water Geothermometer, °C		Gas Geothermometer, °C	
Chalcedony	202-207	N&A (1984) THC	207-212
Quartz (no steam loss)	234-238	N&A (1984) TSC	247-250
Quartz (max steam loss)	211-215	A&G (1985) TCO_2	278-281
Na/K, Fournier	236-238	A&G (1985) TH_2S	270-273
Na/K, Arnorrson, 25-250°C	234-237	A&G (1985) T (H_2S/H_2)	252-260
K^2/Mg, Giggenbach (1988)	208-219	A&G (1985) T CO_2/H_2	256
Na/K, Giggenbach (1988)	250-252	SA (1998) T CO_2	278-282
Na-K-Ca	237-238	SA (1998) T H_2S	215-218
Na-K-Ca (Mg Corr)	222-232	SA (1998) T H_2	182-186
Anhydrite	221-234	SA (1998) T CO_2/N_2	270
		SA (1998) T H_2/Ar	180-182
		SA (1998) T (H_2S/Ar)	215-217
		G (1991) TH_2/Ar	192-195
		G (1991) T CH_4/CO_2	280

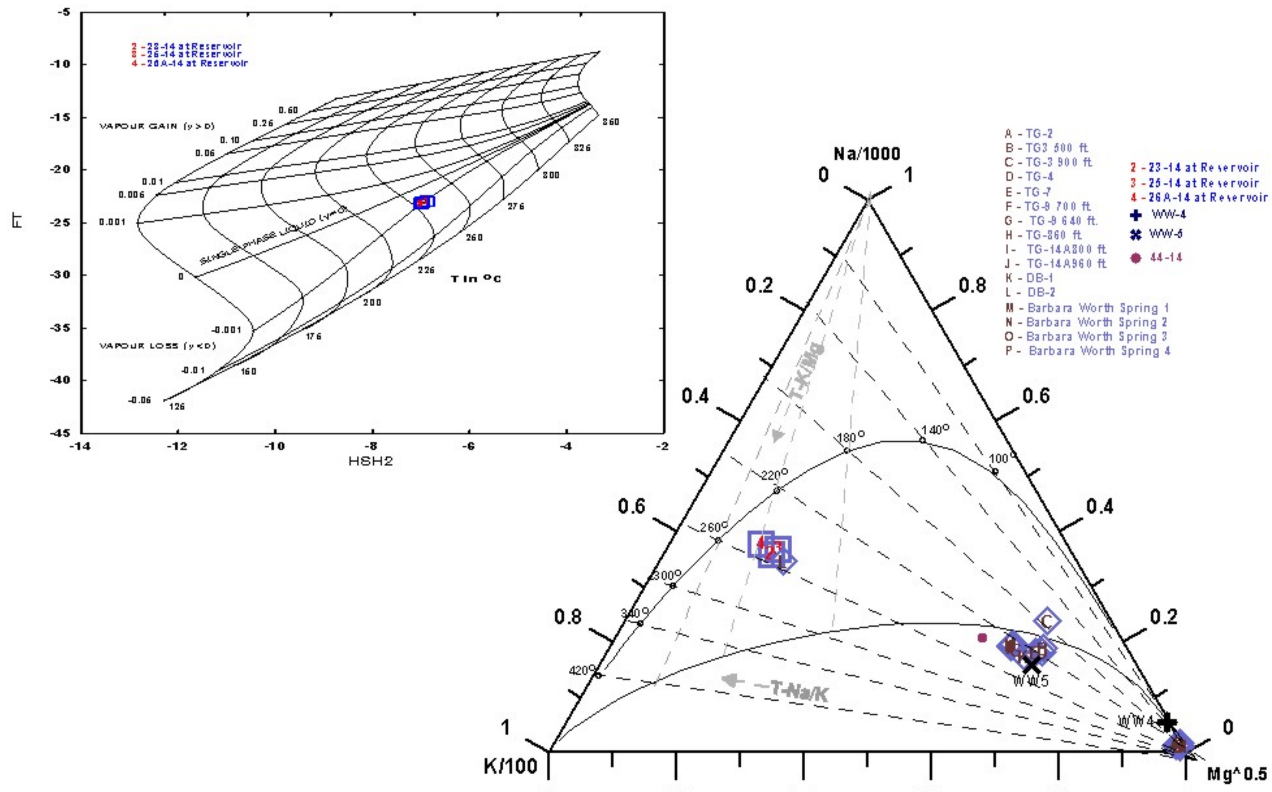

Figure 4: Giggenbach ternary plot of NaKMg predicted reservoir temperatures for T-Na/K = 250ºC, and T-K/Mg = 240ºC. Fisher-Tropsch: Pyrite/Hematite reactions showed fluid to be saturated liquid with temperature equilibrating at 230 - 240ºC.

5. PRELIMINARY CONCEPTUAL MODEL

The combined datasets that have so far been collected at Blue Mountain provide the framework for a preliminary conceptual model of the geothermal system. This model is principally based on drilling results and focuses on fluid characteristics, lithology and three-dimensional permeability mapping while incorporating limited supporting geophysical results.

The deep and intermediate depth core of the reservoir is hosted within silicic and argillic altered metasedimentary and intrusive formations. Characteristics of the known permeability indicate that it is structurally dominated by a fault and fracture network accommodating the regional WNW extensional stress field. 3D permeability mapping from drilling results suggest that fluids are primarily circulated along a predominant NE-trending range front fault zone with variably trending subsidiary piedmont faults providing local interconnectivity between major splays. Based on fluid geochemistry, it has been hypothesized that a small component of reservoir fluid eventually rises through shallow fractures into variably altered sediments, where it eventually mixes with the regional ground water aquifer. However, preliminary reservoir testing indicates that there is no pressure communication between the producing reservoir and the groundwater aquifer, which might indicate that high TDS values may be sourced locally as the ground water migrates through altered sediments in the shallow silicic and argillic zones resultant from ancient hydrothermal systems.

The resource is classified as a hot liquid-saturated convective system circulating neutral-pH, dilute alkali-Cl waters, with low to moderate contents of NCG in an artesian reservoir below an elevation of ~1100 feet, which is calculated to be equilibrating to ~250°C at an unknown depth. Fluids produced for power generation will have a low potential for SiO_2 scaling when mitigated effectively by chemical inhibition. The risk of calcite deposition occurs only through adiabatic cooling and will not be problematic in the operation of the binary power plant.

REFERENCES

Faulds, J.E.: A Preliminary Structural Model for the Blue Mountain Geothermal Field, Humboldt County, Nevada, *unpublished report for Nevada Geothermal Power* (2007).

Lovekin, J.: Blue Mountain - Well 25-14 Flow Test, *unpublished report for Nevada Geothermal Power*, (2008).

Moore, J.N.: A Petrographic Investigation of Nevada Geothermal Power well NGP 58-15, *unpublished report for Nevada Geothermal Power*, (2008).

Stacey, R.: Blue Mountain - Well 15-14 Flow Test, *unpublished report for Nevada Geothermal Power*, (2009(a)).

Stacey, R.: Blue Mountain - Well 14-14 Flow Test, *unpublished report for Nevada Geothermal Power*, (2009(b)).

Stacey, R.: Blue Mountain - Well 17-14 Flow Test, *unpublished report for Nevada Geothermal Power*, (2009(c)).

Stacey, R.: Blue Mountain - Well 58-15 Flow Test, *unpublished report for Nevada Geothermal Power*, (2008).

Szybinski, Z.A.: Structural Setting of the Blue Mountain Geothermal Project Area, Humboldt County, Nevada, *unpublished report for Noramex Corp*, (2004).

Trazona, R.,: The Geochemistry of Wells 23-14, 25-14, 26A-14, *unpublished report for Nevada Geothermal Power*, (2008).

Wyld, S. J.: Structural evolution of a Mesozoic backarc fold-and-thrust belt in the U.S. Cordillera: New evidence from northern Nevada, *Department of Geology*, *University of Georgia*, Athens, Georgia 30602, USA (2002).