Geologic Characterization of Pre-Tertiary Rocks at the Desert Peak East EGS Project Site, Churchill County, Nevada

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ABSTRACT

A DOE-Industry cost-shared project is underway at Desert Peak East, located within the Hot Springs Mountains, northwestern Churchill County, approximately 50 miles (80.5 km) northeast of Reno, Nevada. The potential reservoir under investigation is contained within pre-Tertiary metamorphic and granitic rocks with temperatures exceeding 400°F (204°C). The purpose of the geologic study is to determine the lateral and vertical extent of basement lithologies, and the character and mineralogy of natural fracturing in the rocks to identify suitable targets for hydrofracturing and stimulation in subsequent phases of this enhanced geothermal system (EGS) project.

Petrographic and X-ray diffraction studies of rock samples from deep drill hole DP 23-1 and core hole 35-13 TCH characterize the pre-Tertiary stratigraphic section in the project area as a sequence of weakly metamorphosed marine sediments, tephra deposits, and dioritic rocks that have been intruded by a younger two-mica granodiorite. The metamorphic pre-Tertiary sequence can be divided into two distinctive subunits based on differences in texture, metamorphic grade, and lithology. Subunit 1 (pT1) is composed of non-foliated pelites, mudstones and fine-grained tephra deposits that have undergone low-grade regional greenschist metamorphism. Subunit 2 (pT2) underlies pT1, and is composed of foliated phyllites and biotite and chlorite schists that are interlayered with mafic to intermediate composition intrusive rocks. Contact metamorphism and hornfelsic recrystallization of metasedimentary rocks in subunit pT2 has occurred near the contact with the younger granodiorite intrusive. The pre-Tertiary stratigraphy can be correlated across the project area between wells DP 23-1 and 35-13 TCH, a distance of 1.5 miles (2.4 km).

Several potential EGS target units have been identified. A laterally extensive but intensely altered and veined quartz monzodiorite unit with a thickness of more than 320 feet (98 m) is found at a depth of 5,060 feet (1,542 m) in well DP 23-1 and at 3,123 feet (951 m) in 35-13 TCH. A hornblende diorite with a thickness of about 220 feet is found at 6,800 feet (2,073 m) in DP 23-1. The younger granodiorite in DP 23-1 is at least 2,494 feet (760 m) thick and present at depths between 7,020 feet to TD at 9,641 feet (2,140 to 2,939 m). The uniform petrologic properties and the thickness of the granodiorite in well DP 23-1 indicate an excellent EGS target.

Introduction

The Desert Peak East Enhanced Geothermal System Project (DPEEP) is a DOE-Industry cost-shared site located within the Hot Springs Mountains, northwestern Churchill County, approximately 50 miles (80.5 km) northeast of Reno, Nevada. This study is part of DOE Contract DE-FC36-02ID14406, awarded to ORMAT Nevada, Inc. and its partner GeothermEx, Inc.

As defined by ORMAT (2002) and Schochet and others (2002), the DPEEP area is in Sections 13, 14 and 23, T22N and R27E, located between the Rhyolite Ridge Fault to the west and the Desert Queen Fault to the east (Figure 1, overleaf). The focus of the DPEEP research is the pre-Tertiary metamorphic and granitic rocks that have temperatures up to 400°F (204°C) in the study area.

In Phase I of the project, rock material from two drill holes within the DPEEP area was examined: deep test well DP 23-1; and core hole 35-15 TCH (Figure 1). In 1979, exploration well DP 23-1 was drilled to a depth of 9,641 feet (2,939 m). Core hole 35-15 TCH was core drilled to a depth of 4,230 feet (1,289 m) in 1992. A total of 52 thin sections were examined and 30 X-ray diffraction (XRD) analyses were completed on rock samples from these two wells (Lutz, 2003).

The availability and location of well DP 23-1 is crucial to the future planning of the DPEEP. It is near the center of the proposed project and is the focus of subsequent project phases involving hydraulic stimulation of potential reservoir units. Core hole 35-13 TCH is especially significant to understanding the geology of the area since it is the only core hole in the Hot Springs Mountains to encounter the entire Tertiary and much of the pre-Tertiary stratigraphic sequence.

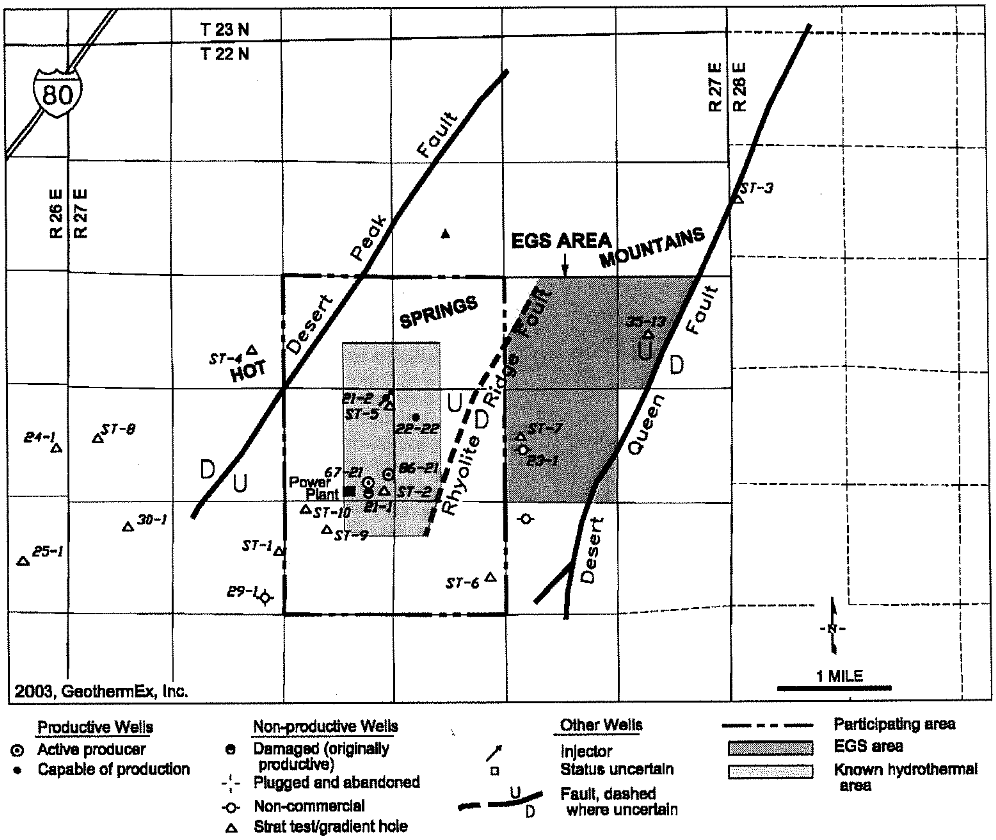

Figure 1. Well and fault location map, Desert Peak East EGS project site (faults from Benoit and others, 1982).

Geologic Framework of DPEEP

The Hot Springs Mountains rise to a maximum elevation of about 5,400 feet (1,646 m) above sea level and are composed primarily of Quaternary and Tertiary volcanic and metasedimentary rocks. Adjacent ranges consist of various Mesozoic sedimentary, volcanic and granitic rocks overlain by Tertiary volcanic formations similar to those found in the Hot Springs Mountains (Willden and Speed, 1974; Benoit and others, 1982). Extensive drilling in the Desert Peak geothermal area has shown that the Hot Springs Mountains are underlain by what appears to be equivalent pre-Tertiary metamorphic and granitic rocks exposed in the surrounding mountain ranges (Benoit and others, 1982). These crystalline rocks are the subject of the current EGS study.

The younger Tertiary formations were reviewed to correlate the regional stratigraphy across the DPEEP area but will not be discussed in this paper. A general stratigraphic column and brief description of the lithologies in the area near DP 23-1 are shown in Figure 2. From youngest to oldest, the Tertiary formations found in the area are as follows: Quaternary sediments; Pliocene-age Truckee and Desert Peak Formations; Miocene to Pliocene age Chloropagus Formation; and a probable Oligocene-age silicic volcanic sequence informally referred to as the "Rhyolite Unit" (Willden and Speed, 1974, Benoit and others, 1982).

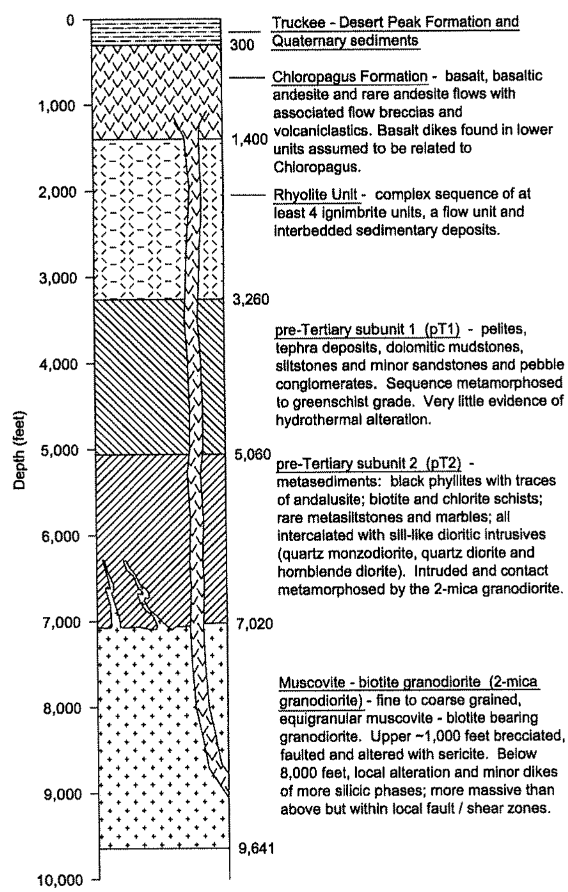

Figure 2. Generalized stratigraphic column of the Desert Peak East EGS site based on petrographic and mineralogic analyses of samples from well DP 23-1 and corehole 35-13 TCH.

Pre-Tertiary Stratigraphy

Three main stratigraphic units constitute the pre-Tertiary section in the DPEEP area, two packages of metamorphic rocks and an underlying intrusive body. A downhole plot of the lithologies, secondary and hydrothermal alteration minerals, and measured subsurface temperatures for well DP 23-1 is shown in Figure 3.

The pre-Tertiary metamorphic section in the Desert Peak East area can be divided into two subunits on the basis of distinctive lithologies, textural and mineralogical variations, and metamorphic grades. Pre-Tertiary subunit 1 (pT1) is a sequence of fine-grained pelites, shales, graywackes, tephra deposits, dolomitic mudstones, and minor siltstones and rhyolitic conglomerates and volcaniclastics. This sequence has undergone low-grade regional greenschist metamorphism, consistent with the definition of Miyashiro (1973). The metamorphic mineral facies consists of quartz, muscovite, paragonite, chlorite, talc and anatase, a typical assemblage

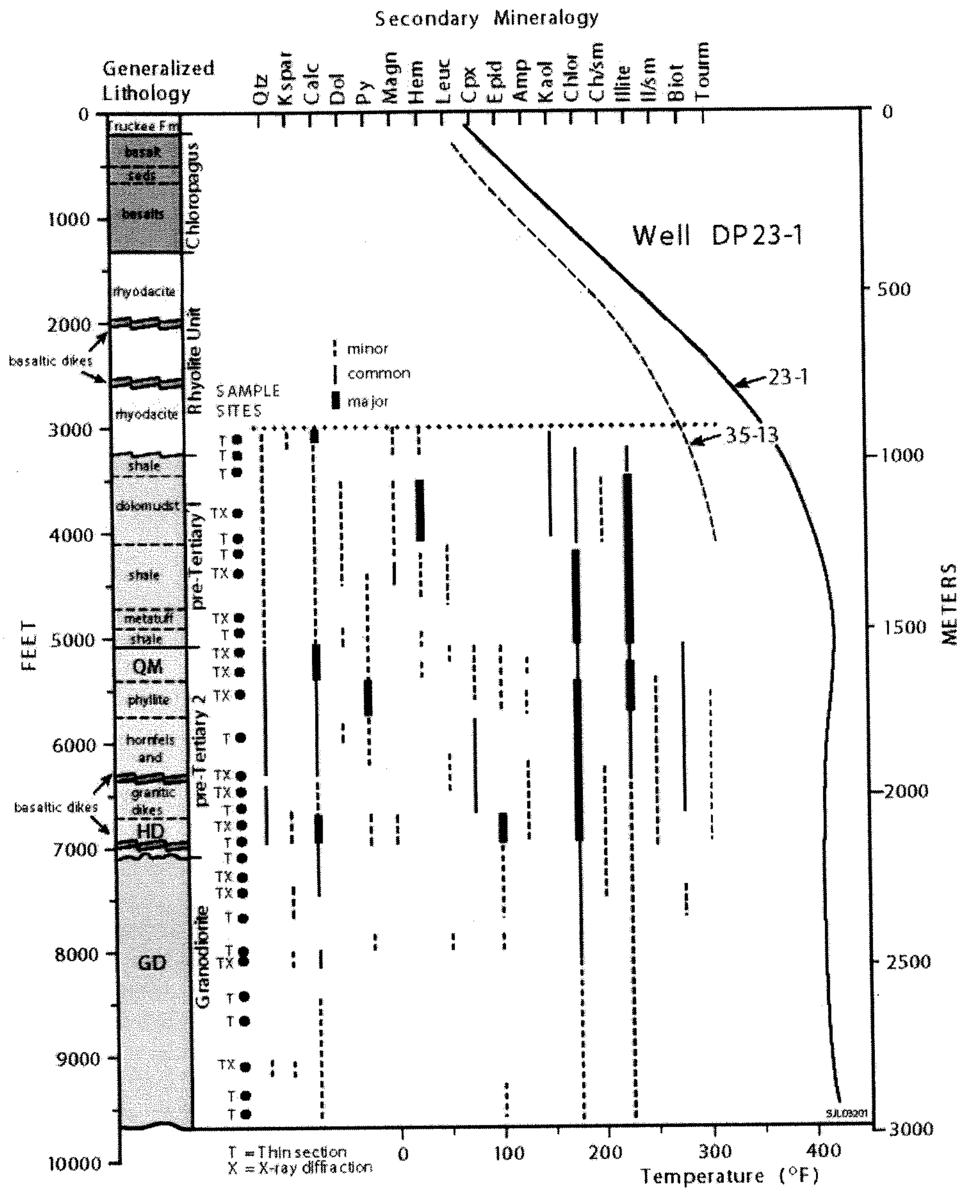

Figure 3. Lithologic column, distribution of secondary and hydrothermal alteration minerals in the pre-Tertiary section, and measure wellbore temperatures for well DP 23-1. Measured temperatures for core hole 35-13 TCH are also shown.

Explanation - Mineral abundances: Major = 15-5-%; Common = 5-15%; Minor = 1-5%. Pre-Tertiary intrusives: QM = quartz monzodiorite; HB = hornblende diorite; GD = granodiorite.

for weakly metamorphosed pelitic rocks. The upper 940 feet (287 m) of the pT1 sequence in DP 23-1 was misidentified by the original workers who assigned these visually nondescript fine-grained rocks to the Oligocene-aged Rhyolite Unit. X-ray diffraction analyses confirm that these are lower greenschist-grade metasediments with 30 wt % quartz, 15 wt % feldspar, 20 wt % chlorite, and 20 wt % illite and other fine-grained white mica.

Subunit 2 (pT2) underlies pT1 in the DPEEP area, and consists of both metasedimentary rocks and dioritic intrusive rocks. The metasedimentary rocks consist of chloritic and illitic shales, dolomitic mudstones, phyllites, biotite and chlorite schists, and a few thin marbles. Although all the metasedimentary rocks in the pre-Tertiary section are at least slightly foliated, the degree of foliation and deformation increases with depth toward the younger granodiorite intrusion. Black phyllite in DP 23-1 is strongly schistose and exhibits some boudinage-type fabrics at 5,500 feet (1,676 m). A similar black phyllite occurs at 3,047 feet (929 m) in 35-13 TCH. Here the carbonaceous shale is foliated and contains sericite-replaced andalusite porphyroblasts.

The dioritic rocks, which make up nearly 50% of pT2, include rocks with compositions between quartz monzonite, quartz monzodiorite, and hornblende diorite. The dominant composition in both DP 23-1 and in 35-13 TCH is a quartz monzodiorite with 7-10 wt % quartz, 40-45 wt % plagioclase, 10-15 wt % potassium feldspar and 1 4 wt % sphene (the latter replaced with titanium oxides and calcite). Primary hornblende in the monzodiorite is completely replaced with hydrothermal biotite, chlorite, apatite, quartz and calcite.

The quartz monzodiorite may be an important and laterally extensive plutonic unit within the pT2 package. In 35-13 TCH, it is present from 3,123 to 3,484 feet (952 to 1,062 m) and is 351 feet (107 m) thick. In well DP 23-1, quartz monzodiorite in a similar stratigraphic position is present from about 5,060 to 5,380 feet (1,542 to 1,640 m) and is about 320 feet (98 m) thick. The quartz monzonite may represent a tabular to sill-like body that is semi-concordant with adjacent sedimentary units. In both wells, it is overlain by (or has intruded beneath) black argillite to phyllite and dolomudstone in the pT2 metasedimentary package. In 35-13 TCH, the monzodiorite is cut by younger quartz and tourmaline-bearing granitic dikes related to the younger granodiorite intrusion. The contacts between the granitic dikes and the quartz monzodiorite are microbrecciated, sheared, and possibly faulted. In 35-13 TCH, the breccia zones are filled with kaolin and fine-grained quartz. In DP 23-1, the monzodiorite is separated from the main granodiorite intrusive body by about 1,640 feet (500 m) of black phyllite, granitic dikes, hornfels, and diorite (Figure 3).

In both wells 35-13 TCH and DP 23-1, the quartz monzodiorite is moderately sericitized, fractured and veined. In 35-13 TCH, two generations of carbonate veins are present. Thick (at least 7 mm wide) composite dolomite-calcite-chalcedony veins appear to predate thinner calcite veins. The calcite in both vein assemblages is dissolved out and the veins have been filled with late-stage kaolin. No kaolin is present in the quartz monzodiorite of DP 23-1, and calcite veins are more abundant.

In DP 23-1, a clinopyroxene and hornblende-bearing diorite is present between the depths of 6,800 and 7,020 feet (2,073 and 2,140 m) where it directly overlies the main granodiorite intrusive body. The diorite is medium crystalline and contains primary hornblende phenocrysts with cores of clinopyroxene. The diorite is strongly propylitically altered to epidote, chlorite, pyrite and calcite, is moderately sericitized, and has also been thermally metamorphosed by the granodiorite intrusive. A 60-foot (18 m) thick granitic dike cuts the diorite from 6,860 to 6,920 feet (2,091 to 2,109 m). The diorite is also cut by thin basaltic andesite dikes that are interpreted to be feeder dikes for the overlying Miocene-age Chloropagus Formation (Figure 2).

The shallow core hole 35-13 TCH was not apparently deep enough to intersect the pT2 hornblende diorite observed in well DP 23-1. However, similar hornblende-bearing rocks and hornblende diorite have been described from both subsurface samples in the Desert Peak field, and at the Desert Queen Mine (Willden and Speed, 1974), located about 4 miles (6.5 km) NE of the DPEEP site (Figure 1). Willden and Speed mapped the Desert Queen intrusive as a middle Jurassic diorite. The hornblende diorite in DP 23-1 may also correlate to the "hornblendite" reported in Desert Peak well B29-1 by Benoit and others (1982). Well B29-1 is located about 3.5 miles (5.6 km) southwest of the DPEEP area (Figure 1).

A two-mica (biotite and muscovite) granodiorite is present below 7,020 feet (2,140 m) in well DP 23-1. The granodiorite is equigranular, medium to coarsely crystalline, and contains primary biotite and muscovite, microcline and orthoclase, and large quartz crystals. The X-ray diffraction mineralogy indicates that the composition of the granite is fairly consistent with 22-28 wt % quartz, 37-42 wt % plagioclase, and 14-19 wt % potassium feldspar. Mica contents range from 3 to 5 wt %, but much of the primary biotite has altered to chlorite. There are also some late-stage tourmaline-bearing aplite dikes and pegmatitic veins containing muscovite and biotite within and above the two-mica granodiorite in DP 23-1. Similar tourmaline-bearing pegmatitic dikes occur in the quartz monzodiorite in 35-13 TCH, and imply that the two-mica granodiorite may be present beneath the bottom of this relatively shallow core hole.

The granodiorite appears to have intruded into and partially altered the pT2 sequence in both DP 23-1 and 35-13 TCH. Hornfelsic-type alteration (quartz-amphibole-pyroxene-biotite-tourmaline-epidote-pyrite) and recrystallization of the metamorphic rocks is evident at the contacts between this intrusive unit and the surrounding rocks. The granodiorite was not found to intrude or alter subunit pT1 or any of the overlying Tertiary formations.

Hydrothermal Alteration History

The basement rocks in the DPEEP area are composed of multiple intrusions of different ages and have undergone several episodes of metamorphism and hydrothermal alteration. Some of the metasedimentary rocks were probably weakly metamorphosed before being intruded by either the Jurassic (?) pT2 diorites or the Cretaceous (?) granodiorite (see below for discussion of intrusion ages). The highest temperature and oldest hydrothermal assemblages are magmatic-hydrothermal alteration minerals related to intrusion of the granodiorite. The oldest fractures contain secondary biotite, tourmaline and potassium feldspar, and likely formed at temperatures above 600°F (315°C). These mineral phases are replaced by or crosscut by younger veins with low-temperature (<350°F or 175°C) mineral phases, such as chalcedonic quartz, dolomite, hematite, calcite and kaolin, that are in thermal equilibrium with the current temperature regime in the wells (Figure 3; mineral stabilities from Elders and others, 1978; and Browne, 1993).

In DP 23-1, early high-temperature tourmaline and secondary biotite alteration occur both within the upper part of the granodiorite and within a contact metamorphic aureole along the granodiorite-pT2 contact at 7,020 feet (2,140 m). Zoning within the aureole is poorly defined but there are some clinopyroxene-quartz-actinolite veins and hydrothermal biotite alteration developed as far as 1,970 feet (600 m) away from the granodiorite contact (Figure 3). Tourmaline occurs within 1,640 feet (500 m) of the contact, and sugary quartz-clinopyroxene-biotite-tourmaline-pyrite hornfels has developed in the metasedimentary rocks within 1,240 feet (378 m) of the contact.

A moderate temperature (430-460°F; 220-240°C) propylitic-phyllic assemblage consisting of chlorite, pyrite, calcite, epidote and sericite is present in the granodiorite and overlying rocks in DP 23-1. The propylitic alteration appears to be younger than the magmatic-hydrothermal alteration and may represent cooling of the granite after its initial emplacement. The upper 1,000 feet (300 m) of the granodiorite body is moderately sericitized. Most of the primary biotite and some of the hydrothermal biotite has undergone retrograde alteration to chlorite and calcite. There is a general decrease in chlorite with depth in the granodiorite and also a slight increase in epidote in the granodiorite below about 8,000 feet (2,438 m). The granodiorite is microbrecciated in sheared or fractured zones at 7,240 feet and 7,700 feet (2,207 m and 2,347 m), and the comminuted rock is cemented with chloritic gouge. The youngest veins in the granodiorite are rare calcite, calcite-hematite and calcite-quartz veins that cut across fractures containing higher-temperature minerals such as biotite and epidote. These carbonate veins may represent alteration related to the current geothermal system.

The most altered rocks in the pre-Tertiary section are the quartz monzodiorites of the pT2 subunit. At least four major stages of hydrothermal alteration can be documented in the monzodiorites. The first two stages represent high to moderate temperature hydrothermal alteration related to the Cretaceous (?) granodiorite intrusion; these are the early hydrothermal-magmatic and the propylitic-phyllic assemblages. Propylitic-phyllic alteration is recorded by: traces of epidote in feldspar; chlorite replacement of primary hornblende; pyrite and calcite; and moderate sericitization of the feldspars. The last two stages of hydrothermal alteration may be related to the Desert Peak geothermal system, and consist of carbonate veining, and in 35-13 TCH, subsequent dissolution of the calcite and infilling with late-stage kaolin.

Local and Regional Stratigraphic Relationships

The Mesozoic basement lithologies and stratigraphic sequences found in wells DP 23-1 and 35-13 TCH can generally be traced throughout the DPEEP area and across the northern

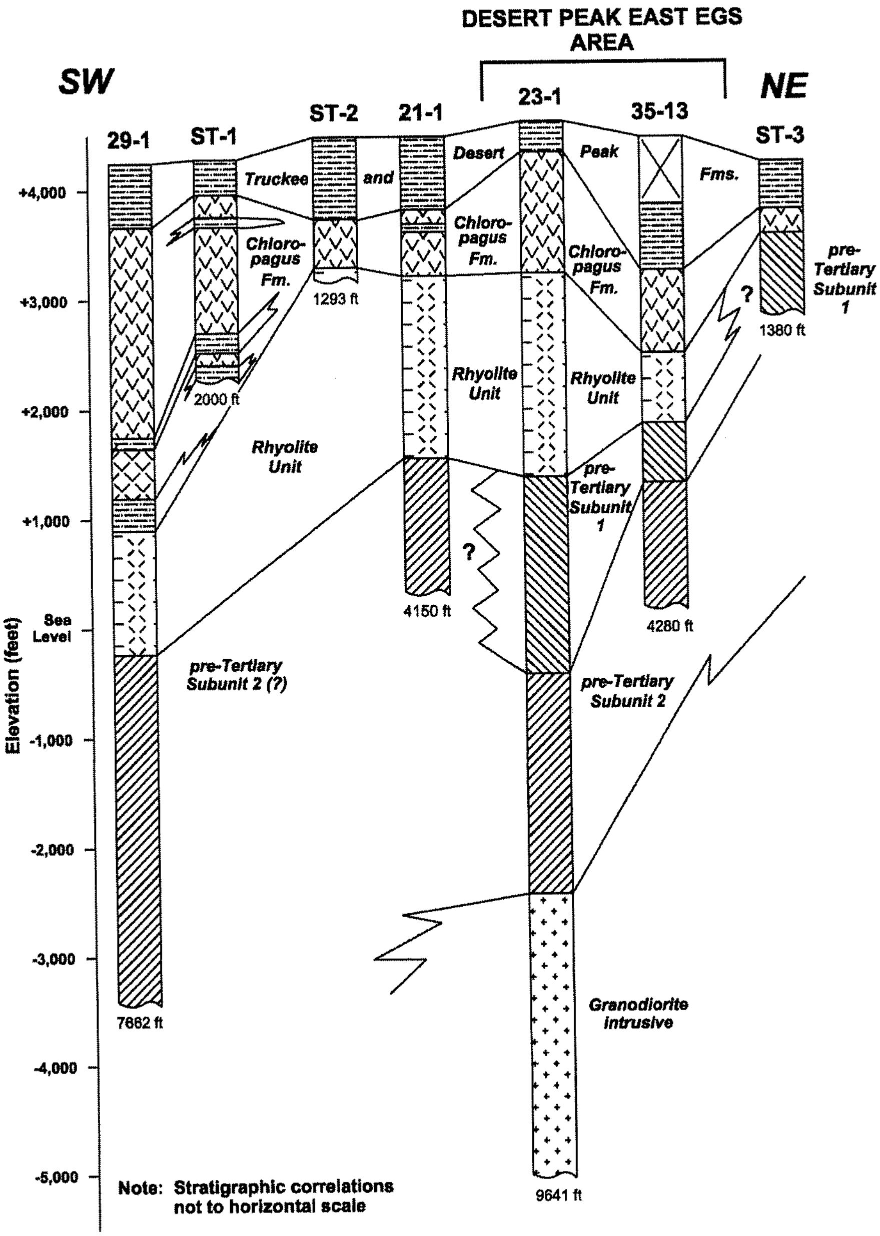

Figure 4. Stratigraphic correlations across the Hot Springs Mountains and the Desert Peak East EGS project area (stratigraphy of wells within the hydrothermal portion of the Desert Peak field from Benoit and others, 1982). Structural interpretations have not been attempted nor are implied.

Hot Springs Mountains. The pre-Tertiary section, although over 1,000 feet (300 m) shallower in 35-13 TCH than in DP 23-1, can be correlated across the DPEEP area. Using the work of Benoit and others (1982), Figure 4 illustrates general stratigraphic correlations across the northern Hot Springs Mountains and the EGS project site.

The pT1 and pT2 sequences appear to be similar to weakly metamorphosed Jurassic rocks that overlie metavolcanic and metasedimentary Triassic-Jurassic rocks found to the northeast in the Stillwater Range and within the Dixie Valley geothermal reservoir (Willden and Speed, 1974, Lutz and others, 1997; Plank, 1997), and to other Mesozoic formations in northwestern Nevada described by other workers (Garside, 1998; Oldow and others, 1990). The hornblende diorites and quartz monzodiorites of the pT2 metamorphic package are generally similar to intrusives in the Jurassic-age Humboldt mafic complex (Dilek and Moores, 1995; Johnson and Barton, 2000; Lutz and Hulen, 2001). We tentatively correlate the hornblende-bearing quartz monzodiorite in 35-13 TCH and DP 23-1, the hornblende diorite in DP 23-1, the "hornblendite" noted in well B29-1, and the propylitically-altered hornblende diorite outcrops at the Desert Queen Mine, and suggest that these hornblende-bearing plutonic rocks represent portions of the Jurassic Humboldt complex. This interpretation places the Desert Peak geothermal area at the southwestern edge of this Jurassic back-arc basin, while the Dixie Valley geothermal field lies at its northeastern edge. In both geothermal areas, fractured Jurassic-age dioritic rocks may serve as important reservoir rocks or permeability pathways for present-day geothermal fluids.

The widespread occurrence of the diorites in the pT2 metamorphic package suggests that Jurassic basement rocks underlie much of the northern Hot Springs Mountains. Individual units within the metasedimentary packages (pT1 and pT2) are more difficult to correlate over the area, or to assign to a specific formation or age. The pT1 sequence appears to be discontinuous; it was not recognized in most of the wells in the Desert Peak field, but is clearly present in both DP 23-1 and 35-13 TCH (see Figure 4). The difference in metamorphic grade between pT1 and pT2 suggests a fault contact between these two units, but the nature and age of this fault is unknown. If the diorites are middle Jurassic in age, the intercalated black phyllites of the pT2 subunit are likely late Triassic to early Jurassic rocks. The overlying pT1 metasediments and metavolcanics may represent middle to late Jurassic strata, age equivalents of the Jurassic Gardnerville or Peavine Peak Formations described from the Talapoosa and Olinghouse mining districts in the Virginia and the Pah Rah Ranges, respectively (Garside, 1998; John and others, 1999). A detailed stratigraphic/structural analysis of the subsurface Triassic-Jurassic rocks in the Hot Spring Mountains has not yet been conducted. Further research on well cuttings and core material from the other geothermal wells could help resolve some of these issues, and could be combined with surface mapping, geophysical surveys and age dating of the plutonic units (Faulds and others, 2003) to more fully interpret the stratigraphy of the Mesozoic basement.

Summary

There are three major intrusive bodies in the pre-Tertiary section that are good candidates for future hydraulic stimulation, and all three appear to be present across the Desert Peak East EGS project area. Two of these are strongly altered, strongly veined, sill-like Jurassic plutons. The quartz monzodiorite is about 100 meters thick and found at a depth of about 1,500 m in well DP 23-1 and at 950 m in 35-13 TCH. In DP 23-1, there is a hornblende diorite that is about 65 m thick at a depth of about 2,050 m. Both of these plutons are cut by granitic dikes that are up to 20 meters thick. By far the thickest intrusive in the project area is the younger two-mica granodiorite, which is 775 m thick in well DP 23-1 at a depth of about 2,140 m. The similarity of the two-mica granodiorite to Cretaceous-aged Sierran granites in western Nevada and northern California implies that the granodiorite may represent portions of an even larger plutonic body that underlies the project area.

On the basis of petrographic and mineralogical studies and stratigraphic correlations, the most attractive EGS target in the project area is the two-mica granodiorite (Robertson-Tait and Morris, 2003). Near DP 23-1, the granodiorite is consistently over 200°C and becomes less altered and fractured below fracture zones at about 2,350 m. The shallower quartz monzodiorite and hornblende diorites may also be attractive, although they are thinner units and cut by numerous dikes. They are more intensively altered and veined than the granodiorite and may have less predictable mechanical properties. Analysis of a well bore imaging log of well DP 23-1 currently in progress will evaluate *in-situ* stresses, and the orientations and apertures of natural fractures. These characteristics will be used to discriminate between possible EGS target zones in the well.

Acknowledgments

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