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GEOLOGICAL AND STRUCTURAL RELATIONSHIPS IN THE DESERT PEAK GEOTHERMAL SYSTEM, NEVADA: IMPLICATIONS FOR EGS DEVELOPMENT

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ABSTRACT

This paper integrates existing and new geologic information to develop a structural model of the Desert Peak geothermal system.

The major structural features of the field include: 1) a horst block composed of pre-Tertiary basement rocks that host the geothermal fluids; 2) vertical offsets of up to 1500 ft on the northern and southern faults bounding the horst; 3) Jurassic metamorphic rocks in the horst rock directly overlain by silicified Tertiary tuffaceous rocks; 4) a thick package of pre-Tertiary weakly metamorphosed mudstones that overlies Jurassic rocks in non-productive, downdropped blocks north and east of the reservoir; 5) a Cretaceous granitic pluton northeast of the field, but not beneath the main production area; 6) a thick sequence of Tertiary basalt flows; and 7) the development of calcite veins and chlorite-bearing fault gouge along reactivated Mesozoic-age thrust faults separating major stratigraphic units in the basement rocks.

Well 27-15, the well proposed for hydraulic stimulation and creation of an enhanced geothermal system, is located north of the horst block in downthrown basement rocks. The proposed stimulation interval in this well is composed of complexly interstratified fault splices containing Jurassic-age diorites, Triassic phyllites, and hornfels that have undergone hydrothermal alteration and contact metamorphism. These rocks contain tourmaline, amphibole, and biotite that were deposited by high temperature magmatic fluids (>325^{o}C). Overlying pre-Tertiary mudstones in the upper part of the basement sequence, in contrast, contain only low to moderate temperature clay minerals (<220^{o}C). The two basement units are interpreted to be in fault contact. Formation imaging logs and temperature logs run in Well 27-15 document the presence of natural open fractures and minor fluid flow along these older fault contacts.

INTRODUCTION

The objectives of this study were to log selected wells to determine the distribution of rock types, faults, alteration minerals, and mineralized fractures, and then develop a geologic and structural model of the geothermal system based on this information. This information is then used to assess the continuity of target formations, the nature of formation contacts, the competency and potential geomechanical character of these formations, and to evaluate faults as potential barriers or conduits to fluid flow and the development of an enhanced geothermal (EGS) system.

The structural model presented in this paper is a conceptual interpretation based on analysis of mud logs, and X-ray diffraction and thin section analyses of well cuttings and core. The model incorporates new data from three wells located in the production portion of the well field (43-21, 74-21, and 77-21; Fig. 1), and previous well descriptions of Benoit et al., 1982; Lutz et al., 2004; Robertson-Tait et al., 2004). The emphasis of this work is on the pre-Tertiary reservoir rocks, where temperatures reach 220 ^{o}C.

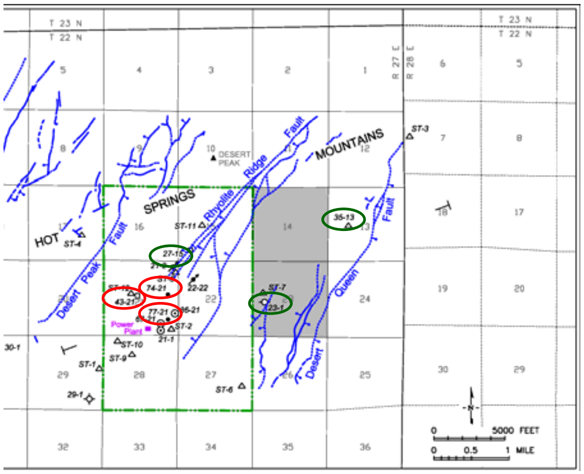

Figure 1: Location of wells in the Desert Peak geothermal field, most of the productive wells are located in Section 21. Wells circled in green represent previously studied wells, those circled in red are wells in the current study. Well 27-15 is the proposed EGS candidate well. Surface fault traces in blue are based on mapping by Faulds and Garside (2003).

METHODS

For the three 'in-field' wells (43-21, 74-21, 77-21), a total of about 100 well cuttings samples were analyzed by X-ray diffraction (XRD) methods. Whole rock and clay separates (<4 micron) were analyzed to determine the mineralogy of major lithologies, and identify the clay, zeolite, and other hydrothermal alteration minerals at various depths through the geothermal system. In addition, the expandability of mixed-layer clays was determined to assess the competence of argillaceous lithologies and to evaluate clay zoning related to the geothermal system. Corresponding thin sections were made from the well cuttings at the same depths as the XRD samples. Using the mud logs for guidance, the sampling interval was nominally every 100 feet. Additional samples were collected where obvious lithologic breaks, structural features, or veined zones were noted on the mud logs.

The well cuttings were stored at the Nevada Bureau of Mines and Geology, and a small subset of the selected cuttings samples were collected for the XRD and petrology work. The preservation of these samples underscores the importance of maintaining repositories of drill samples and data.

STRATIGRAPHIC RELATIONSHIPS IN THE STUDY BOREHOLES

In general, the rocks exposed at the surface are Quaternary eolian deposits and lacustrine deposits from Pleistocene Lake Lahontan (the Truckee and Desert Peak Formations), Miocene basalts and andesites (Choropagus Formation), and Oligocene to Miocene rhyolitic to dacitic tuffs and lava flows, all variably faulted. The distribution of these outcropping Tertiary formations and exposed traces of recent faults in the northern Hot Springs Mountains have been mapped in detail by Faulds and Garside (2003). Subsurface rocks in the Desert Peak geothermal area are composed of late Oligocene to late Miocene volcanic and sedimentary rocks that rest directly on Mesozoic metamorphic and granitic basement. A thick sequence of variably altered Tertiary rhyolitic ash flow tuffs and lava flows overlies the eroded top of the buried metamorphic basement.

Based on the analysis of well cuttings, pre-Tertiary rocks in the Mesozoic basement are composed of three major rock packages. The uppermost package is composed of weakly metamorphosed, fine-grained dolomudstones and metasedimentary rocks of probable Jurassic age (the Pre-Tertiary 1 unit). The next package is a combination of complexly interstratified and faulted metamorphic rocks of Triassic to Jurassic age (the Pre-Tertiary 2 unit). Strongly metamorphosed, propylitically-altered diorites and hematitic metavolcanic rocks of the Jurassic Humboldt Mafic Complex (Johnson and Barton, 2000) are the dominant reservoir rocks in the Desert Peak geothermal field. Deformed metasedimentary rocks associated with the Humboldt Mafic Complex are recognized within the Pre-Tertiary 2 unit and are correlative with the Boyer Ranch Formation where they are pure quartzites (Speed and Jones, 1969), or the Lovelock or Muttlebury Formations where they are carbonate or evaporite-rich (Johnson and Barton, 2000). Correlative quartz arenites and gypsum are exposed at the northern end of the Hot Springs Mountains and in the nearby Mopung Hills (Willden and Speed, 1974). In the six study drillholes, this sequence is generally recognized as silty dolomite, calcareous mudstone, or marble. South of the production area, the correlative unit in well 29-1 (Fig. 9) appears to be quartzite of the Boyer Ranch Formation (Benoit et al., 1982).

The third major rock type in the basement is an extensive granitic intrusive that underlies the metamorphic rocks north and east of the geothermal field. Well 23-1 to the east of the production area intersects the top of the Cretaceous granodiorite at about 7000 ft (Fig. 8). Extensive thermal metamorphism of surrounding metasedimentary rocks has resulted in recrystallization to tourmaline, amphibole, and biotite.

In the following section, we compare the general stratigraphy in the proposed stimulation well (27-15) with the lithologies and alteration mineralogy in the three study wells within Section 21 (Fig. 1).

Well 27-15

Based on petrographic and X-ray diffraction analyses of selected well cuttings samples, the distribution of lithologies and secondary and alteration minerals in 27-15 is shown in Figure 2.

The contact between the Tertiary section and the Mesozoic basement rocks occurs at about 3300 ft depth in this well. The top of the well is within basalt flows of the Miocene Chlorapagus Formation. The Tertiary sequence is dominated by ash flow tuffs and flows of rhyolite composition and is variably devitrified to quartz and potassium feldspar, and altered to smectite clay. The base of the Tertiary section is highly silicified and altered to mixed-layer illite-smectite (il/sm) along the contact with the basement rocks.

The upper part of the Mesozoic basement is comprised of shales and clay-rich dolomitic and calcareous mudstones of the Pre-Tertiary 1 Unit (Figure 2). These weakly metamorphosed mudstones are underlain by strongly propylitically-altered and metamorphosed diorites and phyllites of the Pre-Tertiary 2 unit. The development of recrystallized, tourmaline-biotite-amphibole hornfels at the base of the well is interpreted to reflect hydrothermal alteration and contact metamorphism during intrusion of the Cretaceous granodiorite. The hornfels are characterized by well-defined metamorphic foliation with alternating quartz-rich and biotite-rich banding.

Even though 27-15 did not intersect the granitic body, it is present to the east in 23-1. Here, tourmaline and hydrothermal biotite are typically first encountered within about 1500 ft of the granitic contact (Lutz et al., 2004). This suggests that the main granite body underlies or is close to the base of the 27-15 well.

Because of the absence of metamorphic minerals in the Pre-Tertiary 1 mudstones and the distinct change in foliation and degree of metamorphism within the Pre-Tertiary 2 rocks, we interpret the sharp contact between Pre-Tertiary 1 and Pre-Tertiary 2 as a post-intrusion fault that juxtaposes the two different rock suites.

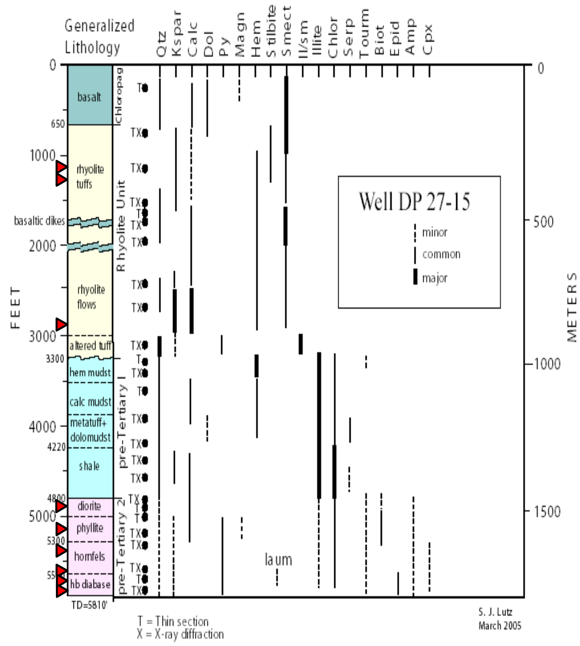

Figure 2: Lithologic column and distribution of secondary and hydrothermal alteration minerals in Well 27-15 (from Lutz, 2005). Red arrows show the locations of lost circulation zones.

Well 43-21

The upper part of 43-21 is generally similar to 27-15. However, in contrast to 27-15, the entire Pre-Tertiary 1 sequence of mudstones and shales is missing. Here the upper part of the basement is composed of Jurassic diorites of the Humboldt Mafic Complex, dolomitic rocks correlative to the Boyer Ranch/Lovelock Formations, and underlying hematitic and chloritic metasediments. Overall alteration is relatively weak, and the most significant geothermal minerals include the clay minerals: smectite (to depths of at least 1000 ft), mixed-layer illite-smectite (2000-3250 ft), and illite to the base of the well. The top of the illite- smectite zone implies temperatures of around 180^{o}C, while the top of the illite zone would indicate temperatures of near 220^{o}C (Browne, 1993).

No cuttings samples were returned between about 1200 ft and 2100 ft. This interval of lost circulation is interpreted as a major fault zone.

Table 1. Secondary and Hydrothermal Alteration Minerals:	
Qtz	Quartz
K-spar	Potassium Feldspar
Calc	Calcite
Dol	Dolomite
Py	Pyrite
Magn	Magnetite
Hem	Hematite
Leu	Leucoxene/Titanite
Cpx	Clinopyroxene
Epid	Epidote
Amp	Amphibole, Hornblende/Actinolite
Biot	Hydrothermal Biotite
Tourm	Tourmaline
Kaol	Kaolinite
Sm	Smectite
Chl/Sm	Mixed-layer Chlorite-smectite
Il/Sm	Mixed-layer Illite-smectite
Chlor	Chlorite
Serp	Serpentine
Clinop	Clinoptilolite
Anal	Analcime
Stil	Stilbite
Laum	Laumontite
Anhy	Anhydrite

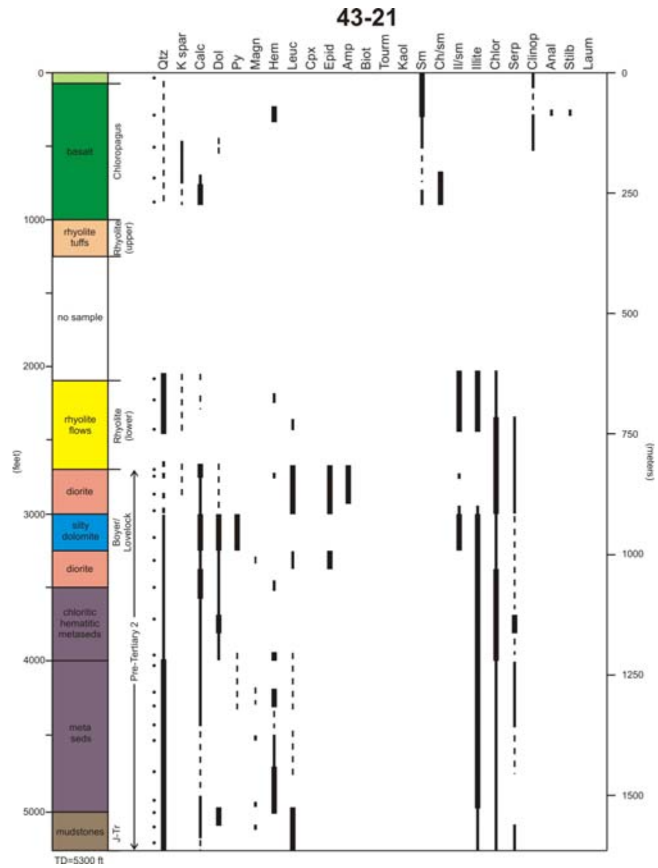

Figure 3: Lithologic column and distribution of secondary and hydrothermal alteration minerals in Well 43-21. No cuttings samples were collected from a thick lost circulation zone in the upper part of the well.

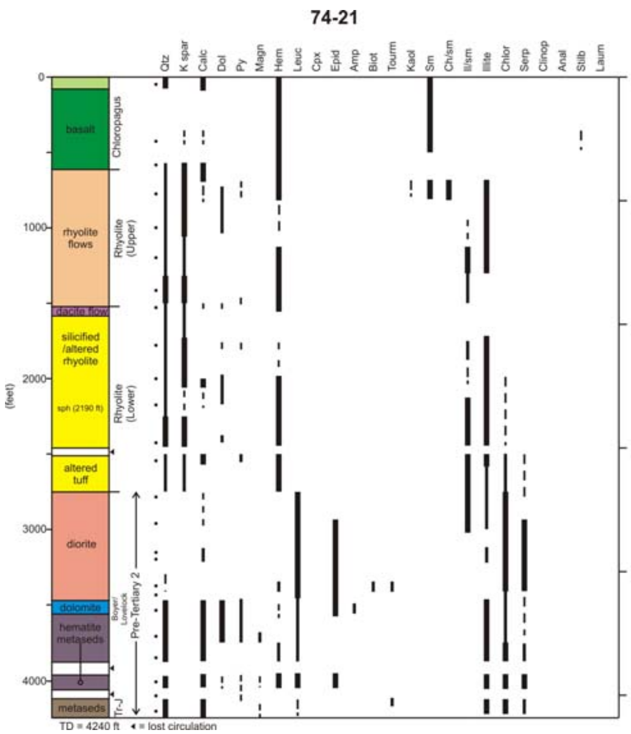

Figure 4: Lithologic column and distribution of secondary and hydrothermal alteration minerals in Well 74-21. Black arrows show the positions of lost circulation zones.

Well 74-21

The lithologies and stratigraphic relationships in 74-21 are similar to 43-21. The basement rocks consist of Jurassic diorite and underlying metasedimentary rocks within the Pre-Tertiary 2 sequence. Mineral zoning is also similar; with shallow smectite and zeolite, followed by illite-smectite and illite. The top of the illite-smectite zone is shallower (at about 1000 ft depth) than in wells 43-21 and 27-15 (2100 ft and 3000 ft, respectively).

At least two lost circulation zones are present near the base of the well. Traces of amphibole, biotite and tourmaline in the Pre-Tertiary 2 sequence suggest that Cretaceous granite may be present within 1500 ft of the well.

Well 77-21

The cuttings in 77-21 display alteration and rock type distributions (Fig. 5) similar to those in 43-21 and 74-21. Zeolites and smectite occur in shallow portions of the well, followed by a thick mixed-layer illite-smectite zone extending close to the base of the well at 3640 ft.

As in 43-21 and 74-21, the upper part of the basement sequence is composed of Jurassic diorites in the Pre-Tertiary 2 sequence. Low-temperature geothermal veins in the basement are composed of anhydrite, and may be associated with open fractures and a lost circulation zone at about 3200 ft.

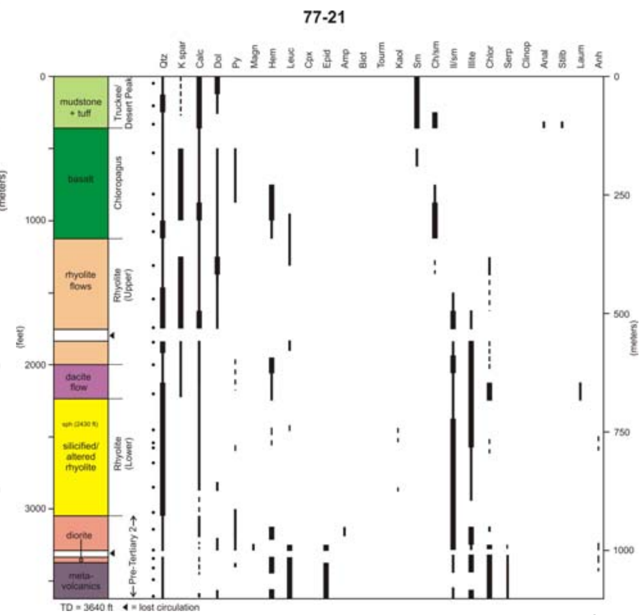

Figure 5: Lithologic column and distribution of secondary and hydrothermal alteration minerals in Well 77-21. Black arrows show the positions of lost circulation zones.

STRATIGRAPHIC RELATIONSHIPS ACROSS THE DESERT PEAK GEOTHERMAL FIELD

Based on the geological relationships observed in these wells, two cross-sections were constructed (Fig. 6).

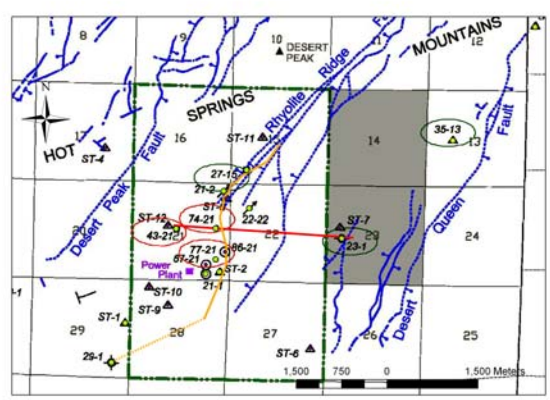

Figure 6: Locations of Desert Peak boreholes used to construct stratigraphic cross-sections. The north-south cross-section is constructed along wells parallel to Seismic Line 2.

Here we have liberally borrowed lithologic descriptions from Benoit et al. (1982) to interpret the stratigraphy of outlying wells. For several of the post-1980s boreholes, we also used mudlogs supplied by Ormat to interpret the stratigraphic sequences. The positions of lost circulation zones in the wells are interpreted as fault zones and incorporated into the structural model.

Figure 7 is a conceptual cross-section that shows the stratigraphy and interpreted structure along a constructed cross-section from well 29-1 to the south to well 27-15 to the north. The key features of this section are the gently dipping top of the basement rocks in the north, the presence of pre-Tertiary 1 in well 27-15, and the thick Tertiary section in the southern wells.

Especially notable is the large vertical offset of phyllite and diorite in upper pre-Tertiary 2 sequence between wells 21-1 and 27-15 (located less than 500 ft apart). At least 1500 ft of displacement occurs between the downdropped basement in well 27-15 and the horst block represented by the Section 21 wells (21-2, 74-21, 43-21, 77-21, and 21-1). Overlying Tertiary strata between wells 27-15 and 21-2 do not appear to be significantly offset, suggesting that development of the horst and subsequent erosion of the uplifted basement occurred long before deposition of the basal Oligocene tuffs (Faulds et al., 2003).

To the south, well logs and lithologic descriptions show a much thickened sequence of Miocene Chlorapagus basalt flows in wells ST-1 and 29-1. This thickening suggests the presence of a pre-Miocene fault that has downdropped basement rocks to the south. Basalt flows may have filled a paleovalley adjacent to a fault scarp. Thickening of the basalt could also be due to forced folding over a buried basement fault, as suggested by Benoit (1995).

The youngest interpreted faults displace upper Tertiary tuffs (for example, between wells 77-21 and 74-21 (see Fig. 7). A distinctive sphene-bearing rhyolite flow can be used to correlate between wells. This marker bed is present at 2190 ft in 74-21 and at 2430 ft in 77-21. This 240 ft difference is similar to the offset between the Chlorapagus Formation and the upper tuff contact between these two wells.

Figure 8 is the interpreted cross-section from well 43-21 to the west and 23-1 to the east. The major features of this cross-section are the presence of the upper pre-Tertiary 1 sequence and the thick Cretaceous granodiorite in the basement in well 23-1. Compared to the next nearest well on the cross-section (well 74-21), the upper contact with the pre-Tertiary 2 in 23-1 is downdropped by over 2000 ft. The eroded top of the basement rocks gently slopes to the east and overlying Tertiary strata are not significantly offset, at least in a vertical direction. In general, there does not appear to be much expression of the Rhyolite Ridge fault system based on stratigraphic relationships along this east-west section.

The presence of the thick pre-Tertiary 1 sequence of dolomudstones in wells 23-1, 22-22, and proposed EGS-stimulation well 27-15 suggests that the fault controlling the northern boundary of the horst block trends west to northwest. This fault separates the productive Section 21 wells to the south from non-productive (but still hot!) wells north of the basement fault.

HYDROTHERMAL ALTERATION

The hydrothermal alteration assemblages shown in Figures 3-5 reflect multiple periods of alteration at different temperatures. As noted above, the presence of tourmaline, biotite and amphibole implies alteration by high-temperature magmatic fluids (>325 ^{o}C). Propylitic (epidote-chlorite) alteration and iron oxide (hematite) mineralization is characteristic of the extensive Jurassic hydrothermal system that affected metamorphic rocks of the Humboldt Mafic Complex. These minerals show no relationship to present-day conditions and their distributions are restricted to the Pre-Tertiary 2 unit. In contrast, both the clay minerals and the zeolites display progressive changes with depth and temperature in the modern geothermal system. Stilbite, analcime, and clinoptilolite occur in shallow tuffaceous rocks whereas laumontite veins are found in the deeper reservoir rocks. The presence of low-temperature minerals: zeolites, smectite, interlayered chlorite-smectite, and dolomite characterizes the alteration assemblage at shallow depths. Interlayered illite-smectite occurs at intermediate depths, followed by illite. No higher temperature geothermal minerals such as epidote or wairakite are found in any of the study wells. The clay and zeolite minerals are consistent with present reservoir temperatures of ~220^{o}C. We therefore interpret these minerals as being geothermal in origin. Geothermal veins consist primarily of calcite, dolomite, chalcedony, and zeolites, with minor anhydrite in well 77-21.

DISCUSSION

Rock-based investigations of the Desert Peak geothermal system are providing new insight into the structural setting of the resource.

The horst model described here is consistent with the earlier Benoit et al. (1982) structural model based on the distribution of subsurface lithologies in the geothermal boreholes. Extensive field mapping of

Tertiary rocks and gravity surveys conducted by Faulds and Opplinger (2002, 2003) provide further evidence the Desert Peak geothermal reservoir is developed in a basement horst.

Recent seismic surveys by Blackhawk Geophysics have imaged several major faults in the Desert Peak geothermal field. The seismic lines show at least one steeply-dipping fault between wells 21-2 to the north and 77-21 to the south that shows large displacement within basement lithologies, presumably where pre-Tertiary 1 mudstones are against pre-Tertiary 2 metamorphic rocks along the fault. Along the SE-NW Seismic line (Line 2), two subparallel faults are imaged in the Tertiary section between wells 23-1 and 86-21 that extend to the surface. These dip steeply to the northwest and are thought to represent the southeastern-most strands of the Rhyolite Ridge fault system (based on mapping by Faulds et al., 2003).

Recent tracer studies (Peter Rose, Status Report for Tracer Testing in the Desert Peak Geothermal Field, DOE January 2009) show that tracer injected into well 22-22 returned to well 74-21 almost immediately, followed by later returns to well 67-21. Tracer injected into well 21-1 also reached well 74-21, but much later and in low concentrations. The tracer tests seem to indicate strong fluid flow along a NE-trending strand of the Rhyolite Ridge fault system from 22-22 to 67-21, which is isolated from an eastern fault block containing wells 21-1, 77-21, and 86-21.

So far, it seems that the NW-SE basement fault that separates non-productive rock to the north from productive wells in the horst to the south controls the depth and distribution of Jurassic reservoir rocks, but not the fluid flow. The fluid flow appears to be controlled by NE-trending open structures related to the Rhyolite Ridge Fault system. The productive portion of the Desert Peak geothermal system is where Jurassic reservoir rocks in the basement occur in an uplifted horst block that is fractured along NE-trending structures.

Geophysical logs acquired for structural and stress analysis of well 27-15 include Advanced Logic Technologies Borehole Televiewer logs (Davatzes and Hickman, 2009) and Schlumberger Formation Microscanner (FMS) image logs (Kovac et al., 2009). In 27-15, temperature/pressure/spinner (TPS) logs reveal fluid flow at about 4800 ft at the contact between shale in pre-Tertiary 1 and Jurassic diorite in pre-Tertiary 2, where we have previously inferred the presence of a Mesozoic thrust fault based on the sharp contact between thermally-metamorphosed, tourmaline-bearing rocks in the lower plate (pre-Tertiary 2), and weakly metamorphosed mudstones in the upper plate (pre-Tertiary 1). FMS images identify a large open fracture at the lithologic contact with conductive material along the fracture. Based on our petrographic analyses, we interpret the conductive layer as chloritic clay fault gouge within the older fault zone. The presence of open natural fractures and minor fluid flow along this surface indicates reactivation of the older fault plane in the current stress regime (see Davatzes and Hickman for a more comprehensive analysis of the stress regime in well 27-15). The fracture has a NNE-SSW orientation and dips about 50^{o} to the west which is essentially parallel to the Rhyolite Ridge fault system expressed at the surface.

CONCLUSIONS

The productive portion of the field lies within a structural horst, bounded by northwesterly-trending faults. These faults affect the basement and the depths of Jurassic reservoir rocks but do not extend to the surface within the field. The northern boundary fault of the horst block does not appear to offset overlying Tertiary rocks. It is not yet known whether this fault is a barrier or conduit to geothermal fluids. Tracer data however indicate that injected fluids can cross this fault zone along structures parallel to the Rhyloite Ridge fault system. Fluid flow in the reservoir is controlled by NNE-trending open fractures associated with the Rhyolite Ridge fault system.

The basement rocks in the proposed stimulation interval in 27-15 are composed of two pre-Tertiary rock units, an upper unit of incompetent mudstones and a lower sequence of diorites and hornfels. Numerous open natural fractures and minor fluid entries are encountered only in the lower sequence. Many of the fractures occur along lithologic contacts and may represent reactivated older fault zones that have opened in the current stress regime.

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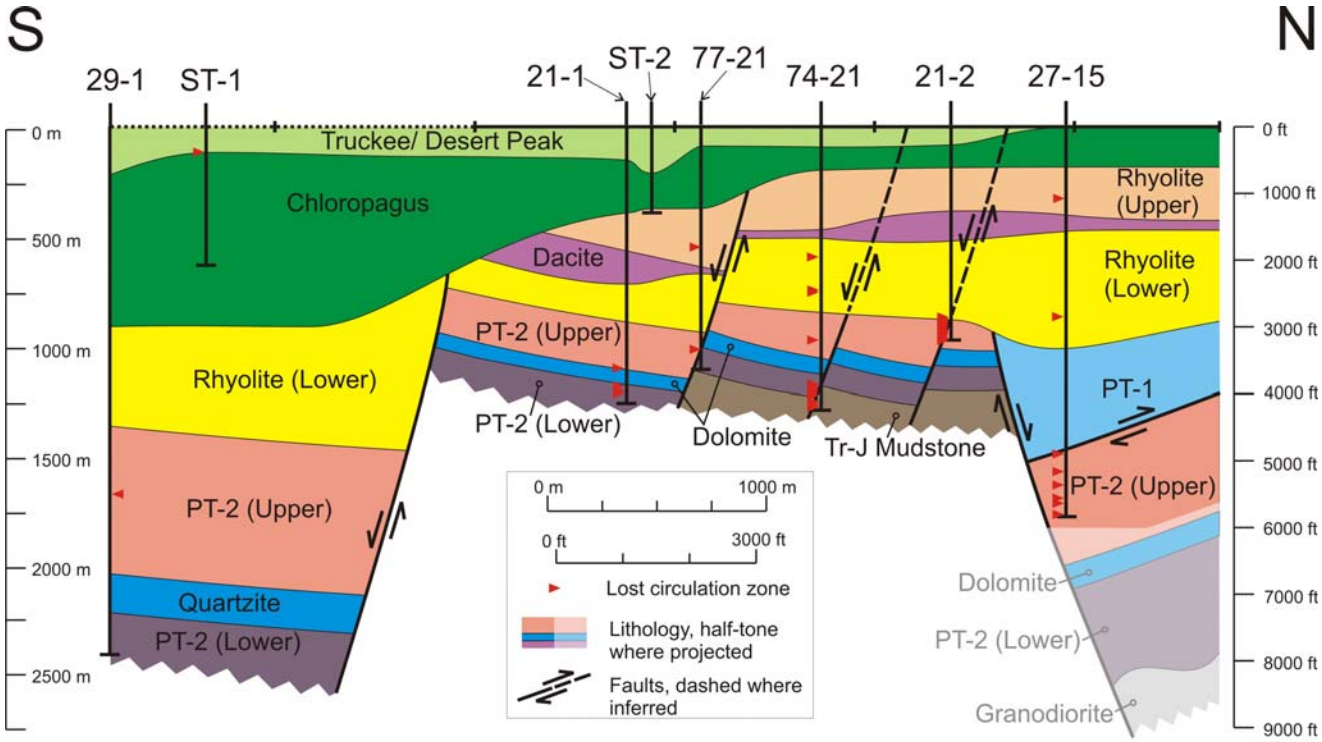

Figure 7: Interpreted south (left) to north (right) cross-section across the Desert Peak geothermal field. Faults and structural interpretations are based on lithologies, stratigraphic sequences, and locations of lost circulation zones identified in well cuttings and well logs. As in well 23-1(see Figure 8), granodiorite may underlie the base of well 27-15.

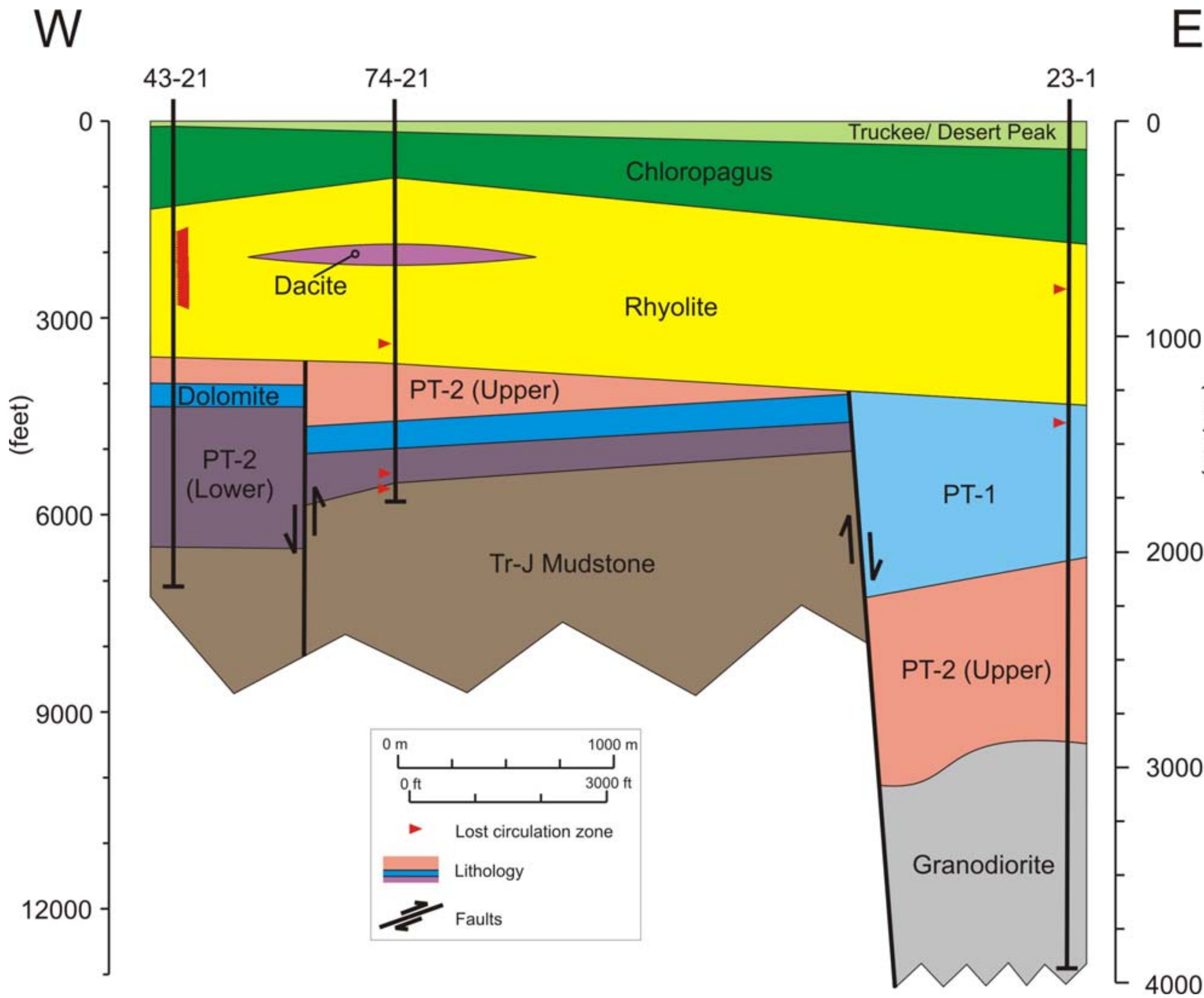

Figure 8: Interpreted west (left) to east (right) cross-section across the Desert Peak geothermal field. Faults and structural interpretations are based on lithologies, stratigraphic sequences, and locations of lost circulation zones identified in well cuttings and well logs.