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USE OF SEISMIC IMAGING TO IDENTIFY GEOTHERMAL RESERVOIRS AT THE HOT POT AREA, NEVADA

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ABSTRACT

A five-line (23 mile) reflection- seismic survey was conducted at the Hot Pot geothermal prospect area in north-central Nevada under the USDOE (United States Department of Energy) Geothermal Technologies Program. The project objective was to utilize innovative seismic data processing, integrated with existing geological, geophysical and geochemical information, to identify high-potential drilling targets and to reduce drilling risk. Data acquisition and interpretation took place between October 2010 and April 2011. The first round of data processing resulted in large areas of relatively poor data, and obvious reflectors known from existing subsurface information either did not appear on the seismic profiles or appeared at the wrong depth. To resolve these issues, the velocity model was adjusted to include geologic input, and the lines were reprocessed. The resulting products were significantly improved, and additional detail was recovered within the high-velocity and in part acoustically isotropic basement. Features visible on the improved seismic images include interpreted low angle thrust faults within the Paleozoic Valmy Formation, which potentially are reactivated in the current stress field. Intermediate-depth wells are currently targeted to test these features. The seismic images also suggest the existence of Paleogene sedimentary and volcanic rocks which potentially may function as a near- surface reservoir, charged by deeper structures in Paleozoic rocks.

INTRODUCTION

The Hot Pot geothermal prospect lies in the Humboldt River valley in the eastern part of Humboldt County, between Battle Mountain and Winemucca (Figure 1). Hot Pot is approximately equidistant from Edna Mountain, approximately 12 mi (20 km) to the west, the Osgood Mountains to the northwest, Antler Peak to the south, the Snowstorm Mountains to the northeast, and the Sheep Creek Range to the east (Figure 2). Treaty Hill, a small, low lying hill to the southwest, is the nearest rock outcrop and lies approximately 3 mi (5 km) to the south west, near Valmy.

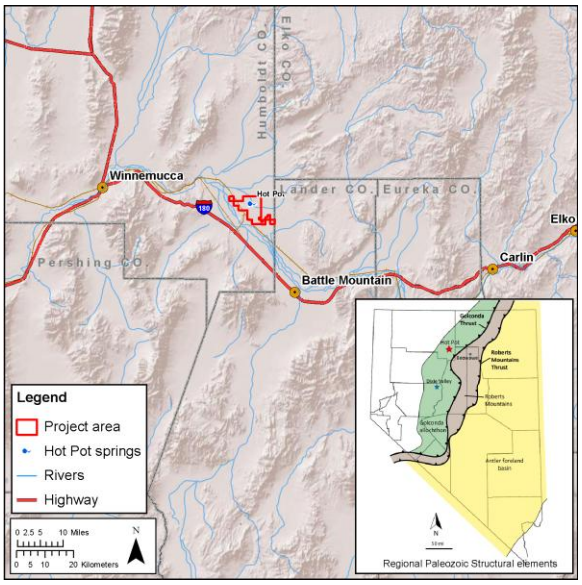

Figure 1: Project Location Map.

Subsurface geology at Hot Pot is inferred, from the geology of the surrounding ranges, to consist of a thick section of i) lower Paleozoic deep marine sedimentary and volcanic rocks of the Roberts Mountains allochthon (probably the Valmy Formation), and ii) possible local occurrences of stratified units of the Mississippian to Permian Antler overlap sequence (Figure 2). The section of Paleozoic rocks is unconformably overlain by a succession of Cenozoic rocks that may include: a) Paleogene tuffs and lavas, b) Miocene basin deposits, c) Pliocene basaltic rocks, and d) Pleistocene to Holocene alluvial deposits of the Humboldt River.

The USGS fault database shows several Quaternary faults in and near the project area (Figure 2). A north-northwest striking fault (referred to as the eastern fault in later sections of this report), with east-facing Quaternary scarps, lies along the eastern edge of the area, and several short, north-northeast-trending scarps are plotted within, and north of, the project area. One of the north-northeast-trending scarps is plotted at the location of Hot Pot hot springs, reflecting the alignment of the springs.

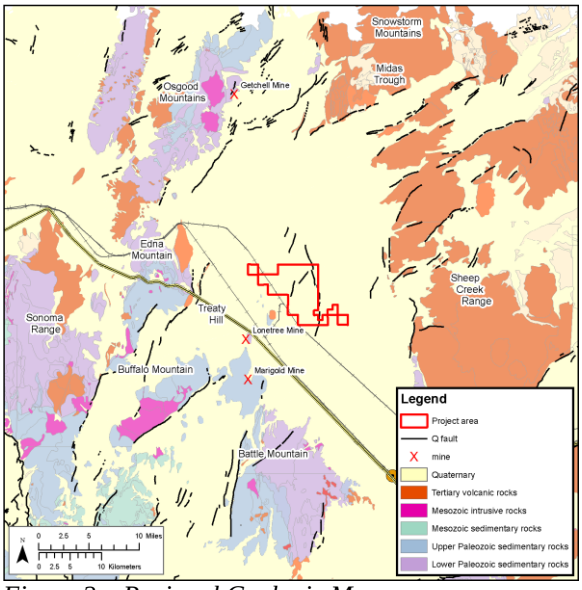

Figure 2: Regional Geologic Map..

The earliest Hot Pot geothermal exploration probably occurred in the early 1970's when Chevron Resources Company, and most likely other organizations as well, conducted geological reconnaissance and geochemical sampling in the region. Interest in the geothermal potential of the Hot Pot area continued into the early 1980's when Trexler et al. (1982) conducted regional temperature gradient studies. There have been numerous geological, geophysical and geochemical studies in the area related to mineral exploration. Results are in many cases proprietary.

Geothermal exploration activity at Hot Pot resumed in 2009, when Oski acquired geothermal leases, began data compilation, and initiated several field surveys including gravity, soil geochemistry, and shallow temperature gradient holes. Much of this work yielded information useful for planning and interpretation of the DOE-funded seismic program.

DATA ACQUISITION & PROCESSING

Five seismic lines were laid out in a grid pattern (Figure 3). Lines 101 and 201 are oriented N45°W approximately 6000 ft (1850 m) apart. Lines 301, 401 and 501 were oriented N45°E and approximately 6000 ft (1850 m) apart. The grid location utilized input from other surveys, particularly gravity and temperature gradient programs and the grid was oriented to image as many known structures as possible. At Hot Pot, the two most probable Quaternary fault orientations (U.S. Geological Survey, 2006) are approximately northeast and northwest. The grid was oriented accordingly. Line length was also a factor in obtaining interpretable seismic reflection results. Lines extending (with appropriate permits) beyond the project boundary and into the adjacent basin were particularly useful because the outlying data points allowed seismic information to be obtained completely to the edge of the area of interest. Additionally, these line segments extended beyond the basement high and therefore provided information on Neogene basin fill thickness and potential Paleogene reservoirs.

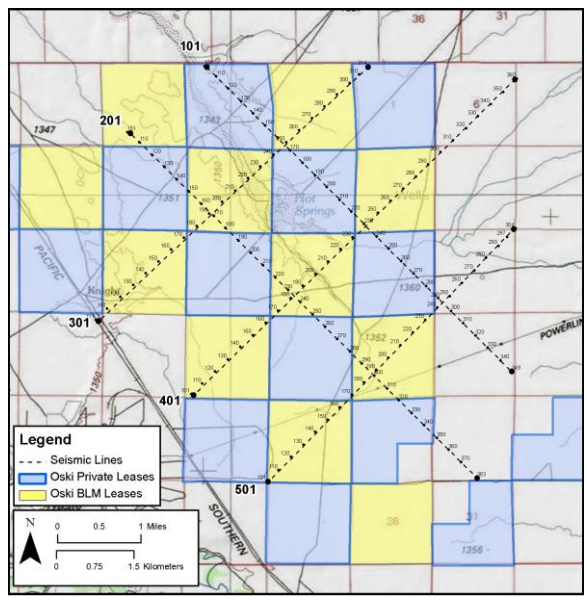

Figure 3: Seismic Program Line Location.

Three 65,000 pound Vibroseis units were used to provide the seismic source. Data acquisition parameters included 110 foot geophone group interval, 6 geophones /station, 220 foot shot interval, and a record length of 6 seconds at a 2 millisecond sample interval.

The seismic processing generally follows the procedure described in Honjas (1997). Project-specific detail is contained in the contractor's report (Optim, 2011) which appears as Appendix A in the US Department of Energy Phase One report (Oski, 2011). In summary, the processing steps were:

- Derive velocities from first arrivals
- Extend velocity control using coherency optimization
- Refine velocity model using full waveform inversion

- Perform Kirchhoff prestack depth migration to derive steeply dipping reflectors interpreted as faults
- Interpolate velocity model to obtain a 3D velocity volume.

During preliminary interpretation, it was apparent that the major reflectors, such as top Paleozoic basement, appeared to be as much as 1000 ft (300 m) below their known elevation. This information was used to adjust the velocity model, and Figure 4 illustrates the resulting improvement. Not only were the reflectors moved to match the known stratigraphy, but better constraints allowed more detailed interpretation of basement structure.

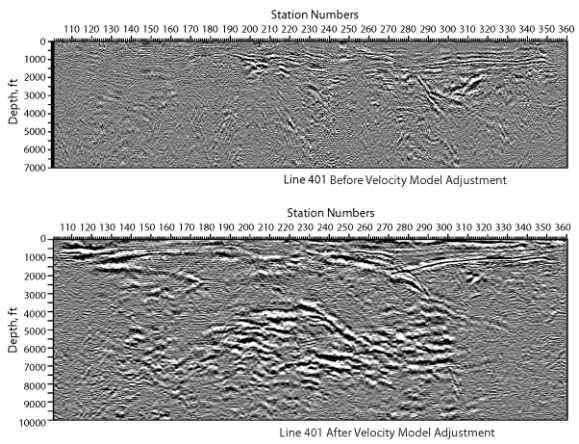

Figure 4: Results of Velocity Model Adjustment

INTERPRETATION

All lines show Cenozoic basin deposits that locally include Pliocene basalt flows. These deposits unconformably overlie Paleozoic basement. In the Hot Pot area, this basement mainly consists of the Ordovician Valmy Formation, an important unit of the Roberts Mountains allochthon. Upper Paleozoic units may also occur within the basement. In all lines, the Valmy Formation includes both reflective and non-reflective zones, which here are interpreted to represent well-layered and non-layered subunits. The non-layered subunits may include melange, while the units with discontinuous layering may be large slices of chert, quartzite, and/or greenstone.

Line 101

Line 101 (Figure 5) images two large normal faults with a southeast dip component. Fault A projects to the surface at the Hot Pot hot springs and has an apparent dip of approximately 45 degrees to the south east. If Fault A strikes north northeast, fracture distributions would match the hot spring vent alignments at Hot Pot. In the Valmy Formation, Fault A includes a prominent reflective zone approximately 400-500 ft (120-150 m) thick that

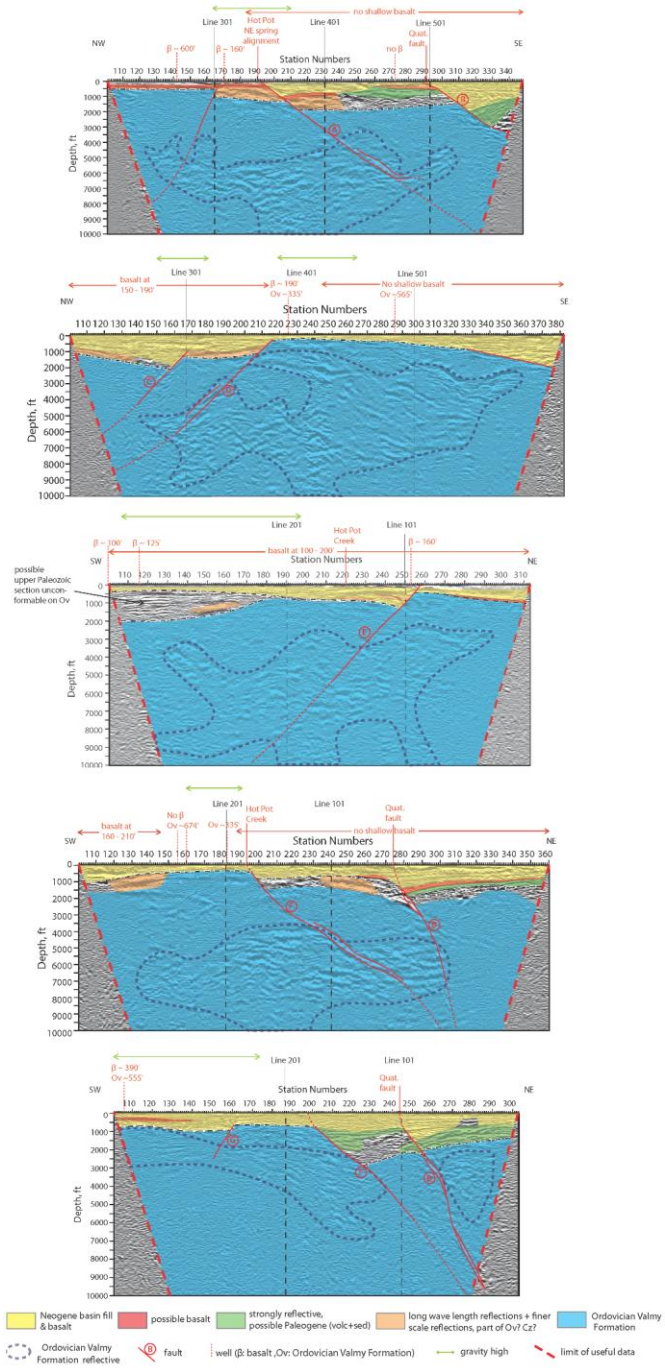

Figure 5: Interpreted Seismic Lines. From top to bottom, Lines 101, 201, 301, 401 and 501.

intersects the subhorizontal reflection fabric of the Valmy. This could be interpreted as a tectonic slice along the fault. Within the top 2000 ft (600 m), Fault A shows a normal displacement of a set of two long wavelength reflections to the south east, separated by fine-scale reflections. This reflective unit is approximately 1200 ft (365 m) thick and may be part of the Valmy or part of a Paleogene volcanic unit. In line 401, a unit with similar reflection characteristics is within the upper part of the Valmy, so this unit is

regarded as part of the Valmy. As interpreted, Fault A bounds a half-graben filled with approximately 900 - 1200 ft (275-365 m) of Neogene sediment.

A second fault (Fault B) has a surface projection near Station 290, where it coincides with a north-striking Quaternary fault scarp. Fault B shows large apparent normal displacement (~2800 ft; ~850 m) of a reflective unit tentatively interpreted as Paleogene volcanic and sedimentary rocks with apparent dips up to 45 degrees toward the interpreted fault plane. The hanging wall of Fault B also includes a large half-graben with up to 2000 ft (600 m) of sedimentary fill showing dip-fanning which suggests the fault is a growth fault that was active during sedimentation in hanging wall block.

A shallow, highly reflective unit lies at approximately 250 ft (75 m) in the northwest portion of Line 101 and appears discontinuously near the base of the Neogene section. Near Station 170, this reflection matches Pliocene basalt in a nearby borehole. Boreholes show no evidence of basalt in the vicinity of line sections southeast of Station 170, making the identity of this unit uncertain in other places. This highly reflective horizon may represent an older volcanic unit near the base of the Neogene section.

Line 201

Line 201 (Figure 5) images two faults with northwest dip components, one near Station 165 and the other near Station 215. Fault C, near Station 165, produces <1000 ft (300 m) of apparent normal displacement of the top of the Valmy, and shows part of a small half-graben in its hangingwall. Fault C does not appear to cut the upper 1000 ft (300 m) of Neogene strata. Fault D, at Station 215 and may have a possible tectonic slice in the Valmy Formation aligned along the interpreted fault plane at depths of approximately 3500-4500 ft (1060-1670 m).

Fault D appears to truncate a long wavelength reflective unit in its hanging wall that, from relations in line 401, may represent a unit in the Valmy Formation. In the footwall of Fault D, Valmy is intercepted at Station 225 in a nearby borehole at a depth of 335 ft (100 m). In the hangingwall of Fault D, the top of Valmy is apparently at approximately 1000 ft (300 m), suggesting apparent vertical throw of approximately 700 ft (215 m). Line 201 may show Fault B, although at an oblique angle, near stations 350 – 360. Alternatively, this low angle (apparent dip) feature is the southerly extension of Fault F.
The top of the Valmy is at shallow depths from Station 220 to approximately 295, and then descends gradually to approximately 2000 ft (600 m) near Station 380. At Station 287, a nearby borehole intercepted greenstone at the top of the Valmy at a depth of 565 ft (170 m). The upper 200-300 ft (60-90 m) of the Valmy in this area shows some reflectivity.
The Cenozoic (Neogene?) section appears to reach maximum thicknesses at Station 155 (~2000 ft; 600 m) and at Station 380 (~2000 ft; 600 m). Pliocene basalt that is present at shallow depths (150-190 ft; 45-60 m) in boreholes between Stations 101 and approximately 250, is not imaged in line 201. Other data indicates Pliocene basalt is absent from Station 250 to 380.

Line 301

Line 301 (Figure 5) prominently images Fault E near Station 255, with a southwest component of dip. Fault E apparently defines a half-graben and hanging wall units show dip fanning and a hangingwall rollover anticline. The footwall of Fault E shows a gently dipping, highly reflective unit at depths of approximately 600 to 1000 ft (180-300 m) near the base of the Cenozoic section between Stations 270 and 310 that cannot be a Pliocene basalt because boreholes show Pliocene units between 100 and 200 ft (30-60 m) throughout this section. If the basalt is not imaged in this line, this prominent reflector may be an older volcanic unit near the base of the Neogene section.

The southwest end of this line, between Stations 101 and approximately 180, shows a wedge-shaped, strongly reflective and continuous unit between the Valmy and the Cenozoic section. This unit varies in apparent thickness from approximately 1500 ft (450 m) at Station 110 to a pinchout near Station 180 and may be an upper Paleozoic unit resting unconformably on the Valmy Formation. Interestingly, Permian Edna Mountain Formation that is younger than the Valmy occurs locally on Treaty Hill approximately 2.5 miles (4 km) south southwest of the end of line 301. In surface exposures, the Edna Mountain Formation rests unconformably upon Valmy Formation.

A northeast-facing scarp at Hot Pot Creek is near Station 222. Although line 401 images a northeast - dipping fault coincident with this scarp, there is no clear seismic reflection indication of a northeast - dipping fault near Station 222 on this line.

Line 401

Line 401 (Figure 5) images two normal faults with northeast dip components. Fault B, the same fault noted in line 101, projects near a Quaternary scarp at Station 274 and is well defined in the Valmy Formation as it truncates various reflective and non-reflective zones. The hangingwall of Fault B is an asymmetric half-graben with Neogene and, speculatively, Paleogene units showing dip fanning toward the fault. Both hanging wall and footwall of Fault B are prominent reflectors and may be a

volcanic unit near the base of the Neogene section (discussed previously) with approximately 1500 ft (450 m) of apparent normal displacement on the fault.

Fault F is a second prominent normal fault that projects near the surface at a NE-facing Quaternary fault scarp near Hot Pot Creek, at Station 195. Fault F, where it passes through the Valmy, has a large tectonic slice at depths of approximately 3000 to 6000 ft (1-2 km). In the footwall of Fault F, the top of the Valmy Formation is as shallow as 335 to 340 ft (102-104 m) from nearby boreholes while the top of the Valmy in the hanging wall is apparently approximately 1000-1500 ft (300-460 m) deep. The hanging wall of Fault F also includes a 1000-ft-thick (300-m-thick) Neogene section, while the footwall includes a much thinner Neogene section, approximately 300 ft (90 m) thick.

Line 401 locally displays a long wavelength reflective unit with fine-scale reflections between Stations 115 and 145 and between Stations 238 and 266. From two nearby boreholes at Stations 155 and 160 the top Valmy at 674 ft (205 m) coincides with a continuation of a long wavelength reflection suggesting that this particular distinctive reflection is part of the Valmy. Pliocene basalt occurs at depths of 160-210 ft (50-65 m) between Stations 101 and 150 but is absent elsewhere and is not imaged in this line.

Line 501

Line 501 (Figure 5) images at least three faults. Fault B penetrates to the surface near a Quaternary fault scarp at Station 245 and is imaged in lines 101 and 401. Two other faults surface near Stations 200 (possibly Fault F) and 166 (Fault G). Fault B shows no obvious displacement of Neogene units yet has a Quaternary scarp. Fault B dips steeply as it passes into the Valmy Formation and tectonic slices in the Valmy appear to be aligned with the fault. Both the hanging wall and the footwall of Fault B have a highly reflective unit that in other sections has been tentatively interpreted as Paleogene volcanic rocks. The hangingwall of Fault B also includes a half-graben of Neogene basin fill as in lines 101 and 401. In this line, the Neogene section has a thickness up to 1500 ft (460 m) and shows dip fanning. The footwall of Fault B has a thick, well-layered section within and below the possible Paleogene reflective unit that may be part of a half-graben lying in the hangingwall of Fault F.

The footwall of Fault F has the top of the Valmy at approximately 1000 ft (300 m) depth while definite Valmy occurs below 3000 ft (900 m) beneath its hanging wall half-graben. Fault F, imaged here and in line 401, apparently strikes northwest, dips northeast and coincides with a Quaternary fault scarp mapped at the surface along Hot Pot Creek. Line 401 does not show any detectable displacement of the Neogene units at Fault F. Fault G, a third fault in this line, has a SW-dip component and produces approximately 700 ft (215 m) of apparent displacement of the top of the Valmy.

At Station 105, a nearby borehole encountered greenstone in the Valmy Formation at 555 ft (170 m) depth. The contact between Neogene sediments and Valmy greenstone is not particularly distinct at this point in line 501, probably because this is 500 ft (150 m) from the end of the line, and geophone coverage was poor. A borehole near Station 105 penetrated Pliocene basalt at 390 ft (120 m) but this unit is not imaged in line 501 and no Pliocene basalt was logged in wells lying near the central parts of the line.

Summary of Structural Interpretation

Figure 6 contains a summary of faults interpreted from the integrated analysis. Faults A, B, and F appear to be major faults, and have clear surface expression, while Faults C, D, E, and G appear to be minor faults. Many of these faults were originally inferred from detailed gravity data.

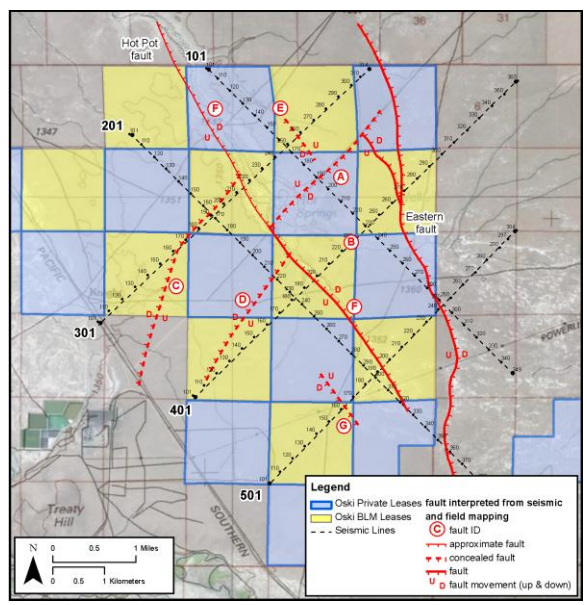

Figure 6: Summary of Structural Interpretation

Fault A is a largely concealed normal fault with a northeast strike and dip to the southeast . It coincides with the spring alignments at Hot Pot hot springs and the associated lineament to the northeast. Line 101 shows a ~1000-ft-thick (~300-m-thick) Neogene section in its hangingwall.

Fault B (Eastern fault) is a normal fault which strikes to the north-northwest with a dip to the east. It is imaged in lines 101, 401, and 501. This fault has a notable east-facing scarp approximately 15-25 ft (5-8

m) high, and also has a major half-graben with over 2000 ft (600 m) of Neogene (and possibly Paleogene) strata in its hanging wall.

Fault C, which is imaged only in line 201, apparently strikes northeast and dips northwest, and does not extend to the surface. Its south west extension is inferred on the basis of gravity data. It has up to 2000 ft (600 m) of Neogene strata in its hanging wall.

Fault D is imaged in line 201, may be subparallel in strike to Fault C, and also dips northwest. It also contains a thicker Neogene section in its hanging wall, possibly over 1000 ft (300 m) in thickness.

Fault E is imaged in line 301 and appears to strike northwest and dip south west. It may be relatively short, but a half-graben in its hanging wall contains over 1300 ft (400 m) of Neogene strata.

Fault F (Hot Pot fault), which is imaged clearly in lines 401 and 501, strikes northwest, dips northeast, and coincides with a 20-ft-high (6-m-high) scarp along Hot Pot Creek. From continuity of the scarp, this fault is projected northwest toward the edge of the project area, although the fact that the fault is not imaged in line 301 is problematic. Both lines 401 501 show a significant half-graben with Neogene strata in the hangingwall of Fault F. Line 401 shows a large slice of Valmy aligned with the fault from approximately 3000-6000 ft (1-2 km) depth.

Fault G, which is imaged in line 501 appears to be a fairly minor normal fault with a strike to the northwest and southwest dip. It does not have any surface expression.

RESERVOIR CONCEPTUAL MODELS

Conceptual models provide the framework within which exploration data can be used to generate drilling targets. In areas with relatively high regional heat flow, such as the Great Basin, the conceptual models generally focus on how and where geothermal fluids may move in the subsurface. Although the Hot Pot model is still being developed, it will likely include some combination of secondary permeability in Paleozoic formations, permeability within the Paleogene section, and reactivated major faults in the Paleozoic basement. Consequently, when identifying drilling targets, the detailed seismic images were utilized to select locations where these potential conceptual model ingredients could be confirmed.

PROPOSED DRILLING LOCATIONS

Five drilling locations were selected for two intermediate depth (~2500 ft; 760 m) slim holes (Figure 7). The additional locations were included to provide backup sites in case permitting or access were to become an issue. All locations are within the identified thermal anomaly and utilize results from the seismic program to target specific structures or potential reservoir formations.

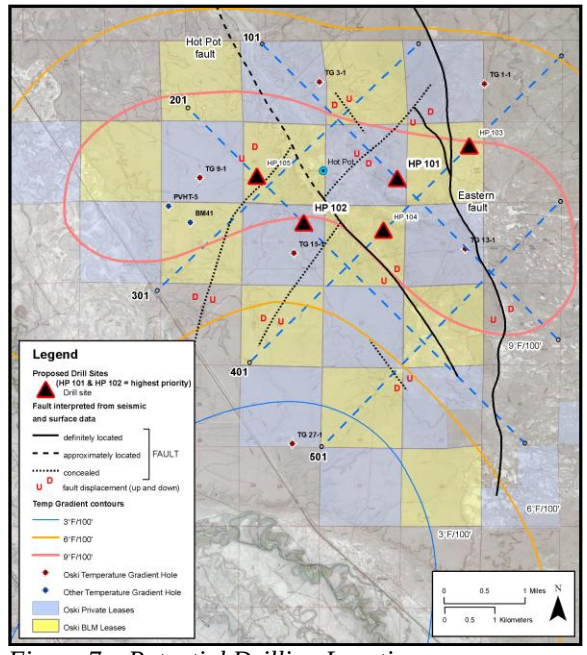

Figure 7: Potential Drilling Locations

Central Hot Pot Area

Potential drill sites **HP 101** and **HP 104** target Faults A and E that apparently bound a shallow (~1000 ft; 300 m depth) half graben and that are also associated with a deep highly reflective zone that is interpreted to be a fault within the Valmy Formation. A well at either location is expected to penetrate approximately 1000 ft (300 m) of Neogene basin fill, followed by ~ 1000 ft (300 m)of Paleogene or upper Valmy before passing into Paleozoic basement. Location HP 104 is closer to the interpreted axis of the Hot Pot temperature gradient anomaly than location HP 101, but would require approximately a mile of road construction.

West Hot Pot Area

Potential drill sites **HP 102** and **HP 105** target west-dipping Faults C and D that are associated with a graben filled with approximately 2000 ft (600 m) of Neogene sediments. A well at location HP 102 is expected to penetrate ~ 1000 ft (300 m) of Neogene basin fill before reaching strong reflectors that could represent Paleogene sediments and basalts, or alternatively, the upper Valmy Formation. HP 102 could be penetrate a fault at approximately 2000 ft (600 m). A well drilled at location HP 105 should penetrate nearly 2000 ft (600 m) of Neogene basin fill before reaching a fault and potentially passing into Valmy in the footwall.

Location HP 105 is less than a mile east of TG 9-1 where the temperature gradient is the highest calculated from the Oski temperature hole program; however, the boring extended to only 187 ft (57 m) TD due to drilling problems. The HP 102 location appears to lie at the intersection of east and west dipping basement faults. The east dipping fault is also manifested by a small Neogene half graben. A well at location HP 102 would penetrate a strongly reflective Paleogene(?) interval, and therefore provide information regarding the viability of permeability within shallower Paleogene section rocks.

East Hot Pot area

Potential drill site **HP 103** targets Fault B that forms the eastern boundary of the basement high beneath the Hot Pot area identified from seismic and gravity interpretations. Fault B is visible on the surface as an approximately 15 ft (5 m) high scarp, down to the east. The fault also appears on the USGS Quaternary fault database and corresponds to a strong horizontal gravity gradient. The HP 103 slim hole is expected to penetrate the Neogene basin fill section to approximately 1500 ft (450 m) before penetrating possible Paleogene sediments. Fault B could be penetrated at 2000 ft (600 m) followed by Paleozoic basement to TD of 2500 ft (760 m). The location is near existing roads and within, but at the north margin, of the interpreted 9˚F/100 ft (163°C/km) anomaly.

CONCLUSIONS

The Hot Pot project experience shows that seismic data applications extend beyond simply identifying faults in the subsurface. If high-quality seismic images can be obtained relatively early in the exploration process there are several benefits.

- Good seismic data and informed interpretation constrained by other subsurface data allows better targeting of intermediate depth wells. While intermediate wells have traditionally been used primarily as deep temperature gradient holes, the detailed seismic images allow these wells to function as limited shallow exploration wells. Potential reservoir formations and faults can be confirmed, and if the intermediate well is properly configured, tested, before a full-scale well is drilled.

- Reduced drilling risk due to improved target selection and well drilling programs designed for anticipated subsurface conditions can result in reduced exploration cost.

- The detailed seismic images greatly assist with development of a reasonable geologic conceptual model prior to the expense of deep drilling. Utilizing a plausible and continually refined geologic conceptual model is arguably the single most effective exploration risk reduction technique.

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