Progress and Future Plans at the Desert Peak East EGS Project

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ABSTRACT

An industry-DOE cost-shared project is underway to evaluate the technical feasibility of developing an EGS power generation project on the eastern side of the Desert Peak geothermal field. Analysis of existing geological and geophysical data is complemented by new geologic mapping and gravity work in the Hot Springs Mountains undertaken by researchers with funding from the Great Basin Center for Geothermal Energy at the University of Nevada Reno (UNR). An existing well (DP 23-1) is the focus of much of the Phase I investigation, including re-interpretation of lithology, acquisition and analysis of a wellbore imaging log, and conducting and analyzing a step-rate injection test. As of June 2003, the project is about half complete; results are summarized below. Phase I work remaining to be completed includes conceptual modeling, numerical modeling and the development of a detailed plan to guide upcoming field activities.

Geological analysis of well DP 23-1 indicates possible target formations for hydraulic stimulation. The uppermost is a Jurassic/Triassic ~300-foot thick quartz monzodiorite with its upper contact at a depth of 5,060 feet; this is correlated across to core hole 35-13 TCH about 1.5 miles to the east. A second intrusive interval of similar age extends from 6,800 to 7,020 feet in DP 23-1 but is not encountered in 35-13 TCH owing to the relatively shallow depth of the core hole. Both of these units contain ubiquitous and healed fractures and veins. A deeper, massive, two-mica granodiorite extends from 7,020 feet to TD (9,641 feet) in DP 23-1; the presence of dikes related to this unit in the deeper part of 35-13 TCH suggests that it is also present in that area, although below the bottom of the core hole. Below about 8,000 feet, this unit becomes less brecciated and less altered than in its upper part.

Two samples from corehole 35-13 TCH were subjected to mechanical testing: a quartz monzodiorite from 3,484 feet and a granodiorite from 3,833 feet. Results indicate very low porosity ($\leq$ 2.1%) and moderate to high rock strength. Several samples showed evidence of post-failure strength increase, which may represent slippage along pre-existing veins or fractures. Ultrasonic velocity measurements indicate no anisotropy or open fractures.

Numerous geophysical surveys run by previous owners of the Desert Peak field are of limited use in the context of the EGS project; a seismic noise survey suggests that it may be possible to detect some microseismic events from surface recording locations. A recent gravity survey undertaken by researchers at UNR provides very useful information on the structure of the pre-Tertiary basement, which includes the EGS target formations discussed above. In support of this work, rock samples from all geologic units were provided to UNR for density measurements. Gravity modeling is now underway to further evaluate basement structure across the EGS area and into the hydrothermal portion of the field, and elsewhere in the Hot Springs Mountains.

A wellbore imaging log was acquired in April 2003 in DP 23-1 and is presently being analyzed to evaluate the local stress tensor and to determine if optimally oriented, critically stressed fracture are present. This will assist in identifying a target formation for hydraulic stimulation. While cooling the well for logging, an injection test was run. Analysis of these data confirms that the reservoir around the well has very low porosity, injectivity, flow capacity and storage capacity, and does not intersect any major fracture. Injection for several days resulted in a modest improvement in injectivity. Analysis of the injection test data resulted in the development of a practical, low cost and approximate methodology to measure the success of future hydraulic stimulation.

Work remaining to be completed in Phase I includes conceptual modeling with an emphasis on the pre-Tertiary stratigraphy and structure, numerical modeling to evaluate various fracture parameters and well placement strategies, and planning for Phase II. Future plans for the project in Phase II focus on planning, conducting, monitoring and evaluating a massive hydraulic stimulation of well DP 23-1. Should the stimulation create a large enough reservoir, a second and perhaps a third well would be drilled and stimulated, and the system would be tested for several months to determine its capacity. Ultimately a 2-5 MW stand-alone binary power plant would be built and operated at Desert Peak East, with

the power either sold to a utility customer or used to supply the parasitic power for the two existing Desert Peak hydrothermal power plants.

Introduction

ORMAT Nevada Inc. (ORMAT) has received funding from the US Department of Energy (DOE) on a cost-shared basis to investigate the technical and economic feasibility of creating an artificial geothermal reservoir in the eastern part of the Desert Peak geothermal field. This project has as its ultimate goal the development of 2 - 5 MW of EGS-derived power from a stand-alone binary power plant supplied by 2 - 4 wells. Focusing initially on well DP 23-1, a hot but tight hole about 1.5 miles east of the producing hydrothermal wells at Desert Peak (Figure 1), a systematic evaluation of the EGS potential of this area is underway. This Phase I evaluation includes:

- evaluation of existing geological data, including new petrologic evaluation of DP 23-1 and a nearby corehole (35-13 TCH);
- review of previously collected geophysical data;
- mechanical testing of cores from 35-13 TCH;
- determining stress field and fracture orientations from evaluation of a new wellbore imaging log run in DP 23-1;
- conducting an injection test of well DP 23-1 to determine baseline (pre-stimulation) well and reservoir characteristics;
- conceptual modeling, with a focus on the EGS portion of the field;
- numerical modeling to enable estimation of required fracture densities and approximate well locations/configurations to support commercial production; and
- preparation of a detailed plan to guide the next activities at the field (Phase II).

A Go/No-Go decision point was reached in December 2002, when a sinker bar run and subsequent temperature survey revealed that well DP 23-1 was accessible for additional work. As of June 2003, Phase I of the project is about half complete. Analyses of geologic data from DP 23-1 and 35-13 TCH are complete (Lutz *et al.*, 2003) and all existing geophysical data have been evaluated. Two core samples from well 35-13 TCH have been subjected to mechanical testing (NER, 2003). A wellbore imaging log acquired in DP 23-1 in early April is currently being analyzed to identify stress field orientation and evaluate the intrinsic fracture population in anticipation of hydraulic stimulation. Injection testing was conducted while cooling the well prior to logging; test results are analyzed and presented in Sanyal *et al.* (2003). Conceptual modeling is underway, and numerical modeling is getting started. Once these are complete, a determination of feasibility will be made and plans for implementing the project will be developed and submitted to DOE.

Work Completed To Date

Evaluation of Existing Geological Data

The cuttings and cores from the two wells in the EGS area are the focus of this task. The first well is DP 23-1, a full-diameter well that may be used in the EGS development; the second is 35-13 TCH, a now-abandoned core hole located about 1.5 miles NE of DP 23-1 (Figure 1).

The first work undertaken in this task was to log, box and photograph core samples from 35-13 TCH. Although the core samples had been left uncovered outside for more than 10 years, more than 70% of the original core was recovered. A core log was made, including lithology, alteration, fracture density and fracture orientation. Several cores in the pre-Tertiary granitic section were chosen for further analyses, including thin section preparation, petrologic examination, XRD analysis and mechanical testing.

The second major part of this task was the preparation of an updated lithologic log for well DP 23-1 with an emphasis on the pre-Tertiary section, and correlation with the lithologies noted in 35-13 TCH. A simplified lithologic column for DP 23-1 is presented in Figure 2. As noted in Lutz *et al.* (2003) and Lutz (2003), the pre-Tertiary section in DP 23-1 is formed of two distinct subgroups with a sharp contact between them. The upper subgroup (pT1), which covers a depth range of 3,260 to 5,060 feet in well DP 23-1, is dominated by marine metasediments that have undergone regional greenschist facies metamorphism. The lower subgroup (pT2) extends to 7,020 feet and is composed of a series of

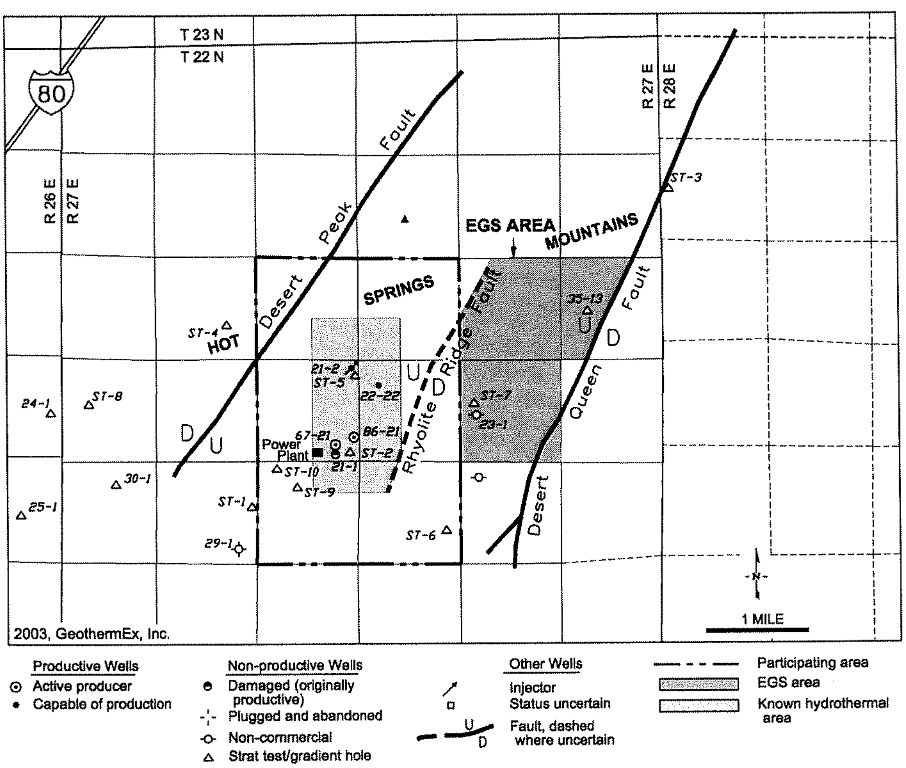

Figure 1. Project and well location map, Desert Peak East EGS site.

Jurassic/Triassic phyllite, schist and mafic-to-intermediate granitic rocks, all more strongly metamorphosed than the pT1 section. This is underlain and intruded by a two-mica granodiorite that is similar to Cretaceous intrusive rocks typical of the Sierra Nevada batholith found to the west in Nevada and California.

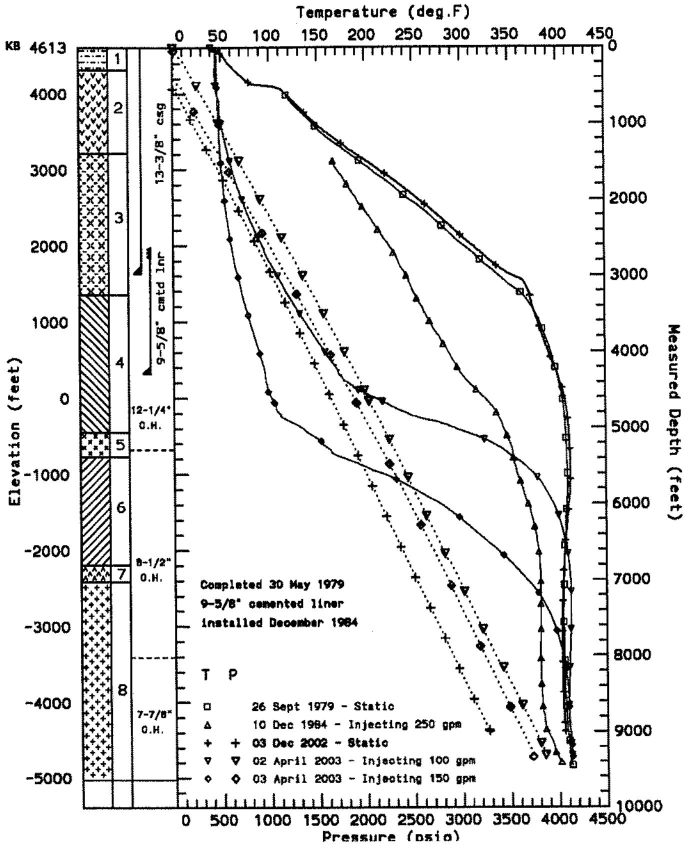

Figure 2. Lithology, completion and selected temperature/pressure surveys, well DP 23-1.
Explanation: 1 - Truckee and Desert Peak Formations; 2 - Chloropagus Formation; 3 - Rhyolite Unit; 4 - pT1 Metasediments; 5 - Quartz Monzodiorite (pT2); 6 - pT2 Metasediments; 7 - Hornblende Diorite (pT2); 8 - Two-Mica Granodiorite (see Lutz *et al.*, 2003 for full descriptions of these units).

Two formations of interest from an EGS perspective were identified in the pT2 subgroup. The first is a quartz monzodiorite extending from 5,060 feet to 5,380 feet in well DP 23-1, which was also found in 35-13 TCH from 3,123 to 3,484 feet. The second is a hornblende diorite unit extending from 6,800 feet to 7,020 feet in well DP 23-1; this is not observed in 35-13 TCH owing to the relatively shallow depth of the core hole. Beneath these units is a third formation of interest: a two-mica granodiorite that is less altered, less veined and more massive than the two intrusive units above. Small dikes near the bottom of 35-13 TCH imply the presence of this two-mica granodiorite beneath the bottom the core hole (Lutz *et al.*, 2003).

New Geological Data

Although not part of the Grant Award under which this project is being conducted, researchers at UNR are developing a new geological map and structural transect through the Hot Springs Mountains. As detailed in Faulds *et al.* (2003), the rock units in the Desert Peak area are fragmented into multiple NNE-trending fault blocks, which are bounded by *en echelon*, overlapping NNE-striking faults. Most faults dip WNW and have dip-slip normal displacement, indicating a WNW-trending least principal horizontal stress; this is compatible with the regional extension direction inferred from geodetic data (Thatcher *et al.*, 1999). The pattern of folding suggests that most folds resulted from a combination of east-tilting of fault blocks and drag along the west-dipping normal faults. The work of Faulds *et al.* (2003) confirms that the EGS area is located on a horst block between the Desert Queen and Rhyolite Ridge faults (Figure 1). This work is useful to the project in that it improves upon previous mapping and assists in the determination of the present-day stress field, which is important for evaluating the feasibility of developing an EGS system by stimulating pre-existing fracture surfaces.

Mechanical Testing of Core Samples

No core samples were available from well DP 23-1; therefore, cores from the granitic section in TCH 35-13 were used for analysis of petrophysical properties. Two cores that were the least fractured and veined of the available material were selected: a quartz monzodiorite from 3,484 feet and a granodiorite from 3,833 feet. Both belong to the pT2 subgroup (Lutz *et al.*, 2003). As described in NER (2003), four 1-inch diameter, 2-inch long cores were cut (vertically) from each of the two samples. Grain density and dry bulk density were determined and used to estimate porosity (Table 1). Single stage (static) triaxial tests were conducted on dry samples at four confining pressures to the point of failure and beyond. Young's Modulus and Poisson's Ratio were computed for each test (Table 1) using the linear portion of the (axial) stress versus strain curve for each sample.

The maximum differential stress was recorded at the yield or failure point, and the maximum axial stress was calculated by adding the confining pressure to the maximum differential stress. These data were used to determine the unconfined compressive strength via a Mohr-Coulomb analysis for the two core samples. Ultrasonic velocity measurements were also made while loading and unloading one of the sub-plugs cut from each core (before doing the static triaxial test on that sample). Compressional (p) and shear (s_1 and s_2) velocities were measured and used to determine dynamic elastic constants.

Table 1. Summary of Triaxial Testing Results (NER, 2003).

Sample depth (feet) and lithology	Sample ID	Porosity (%)	Confining pressure (psi)	Young's Modulus (million psi)	Poisson's Ratio
3,484 quartz monzodiorite	A	1.6	300	9.600	0.220
	B	1.5	725	8.262	0.172
	C	2.0	1,450	9.134	0.242
	D	1.9	2,900	9.518	0.214
3,833 granodiorite	A	1.5	300	7.545	0.180
	B	2.1	725	7.265	0.183
	C	1.3	1,450	7.708	0.152
	D	1.5	2,900	6.237	0.285

Table 2. Mohr-Coulomb Analysis Results (NER, 2003).

Sample depth (feet) and lithology	Sample ID	Max. Diff. Stress (psi)	Max. Axial Stress (psi)	Cohesion (S_0) (psi)	Friction Angle (Φ) (deg.)	Failure Angle (β) (deg.)	Unconfined Compressive Strength (psi)
3,484 quartz monzo-diorite	A	35,560	35,860	9,129.5	34.8	62.4	34,852
	B	36,940	37,670				
	C	38,960	40,410				
	D	42,540	45,440				
3,833 grano-diorite	A	39,130	39,430	9,327.7	37.6	63.8	37,913
	B	35,270	35,990				
	C	23,650	25,100				
	D	49,920	52,820				

Table 3. Observed Sonic Velocities and Elastic Moduli, Sample 3484D.

Event	Confining Pressure (psi)	V_p (ft/sec)	V_{s1} (ft/sec)	V_{s2} (ft/sec)	Young's Modulus (million psi)	Poisson's Ratio
0	148	16,650	10,312	10,436	8.96	0.183
1	292	16,736	10,328	10,486	9.03	0.185
2	732	16,847	10,390	10,502	9.12	0.188
3	1,464	17,077	10,456	10,518	9.27	0.197
4	2,899	17,464	10,623	10,689	9.62	0.203
5	4,365	17,838	10,761	10,843	9.94	0.210
6	1,453	17,224	10,591	10,604	9.45	0.195
7	726	16,962	10,472	10,518	9.23	0.190
8	141	16,762	10,456	10,502	9.11	0.179

Table 4. Observed Sonic Velocities and Elastic Moduli, Sample 3833D.

Event	Confining Pressure (psi)	V_p (ft/sec)	V_{s1} (ft/sec)	V_{s2} (ft/sec)	Young's Modulus (million psi)	Poisson's Ratio
0	151	16,191	9,987	9,777	8.21	0.203
1	285	16,230	10,046	9,806	8.27	0.201
2	729	16,512	10,171	9,925	8.51	0.206
3	1,449	16,847	10,410	10,151	8.89	0.203
4	2,899	17,746	10,712	10,505	9.61	0.222
5	4,359	18,333	10,978	10,830	10.19	0.226
6	1,447	17,329	10,541	10,358	9.27	0.214
7	728	16,762	10,328	10,138	8.81	0.203
8	141	16,352	10,138	9,895	8.41	0.200

As summarized in NER (2003), the results show that the two core samples are moderately strong, fractured intrusive rocks with low porosity (Table 1). The deeper sample was slightly stronger than the shallower sample. Post-failure strength increase was observed in several samples and indicates heterogeneity, the initial failure point probably representing slippage along pre-existing veins or fractures. The Mohr-Coulomb analysis (Table 2) provides useful information to be used in conjunction with the analysis of the wellbore imaging log (see below) for constraining the stress tensor at Desert Peak and will provide input for the design of the hydraulic stimulation program planned for Phase II of the project. The elastic constants determined from dynamic testing are very similar to those determined from static testing (Tables 1, 3 and 4). Orthogonal shear velocities V_{s1} and V_{s2} are nearly identical (*i.e.*, no anisotropy); furthermore, sonic velocity changed only slightly with confining pressure (Tables 3 and 4), indicating an absence of open fractures.

Review of Existing Geophysical Data

Various geophysical surveys have been conducted in the Desert Peak area, mostly in connection with the geothermal exploration and development carried out by Phillips Petroleum and subsequent field operators. The principal surveys and their results relative to the EGS project are summarized below.

- ***A roving dipole survey*** covering the entire Desert Peak/Bradys Hot Spring area, including several vertical soundings. The distribution of the inferred anomalous resistivity zones is irregular, and does not show any correlation with geothermal activity, inferred geologic structure or near-surface lithology, limiting the utility of this work for the present study.

- ***Seismic refraction and reflection experiments*** in part of the Desert Peak area. The seismic surveys, limited as they are to a part of Section 29 (see Figure 1), do not provide information of direct interest to the present study. However, they do provide some indication that the Desert Peak area may be characterized by a seismic velocity structure coherent enough to facilitate the collection and interpretation of data related to induced microseismicity, which will be important to the success of the EGS project.

- ***A reconnaissance gravity survey*** covering the western part of the Carson Sink region, including the Desert Peak area. As described briefly by Benoit *et al.* (1982), the results showed a general NNE structural trend, and a less distinct northwest trend. No significant gravity anomalies were revealed within the Desert Peak area.

- ***Magnetotelluric (MT) surveys*** consisting of a total of 39 stations in the Desert Peak area. At deeper levels (4,000 feet depth and greater), resistivities are moderate and show very little variation over most of the survey area, both horizontally and vertically, even at basement rock levels.

- ***An aerial infrared survey.*** Benoit *et al.* (1982) mention in passing that an aerial infrared survey was carried out in the Desert Peak area in 1978, but state that no superficial heat anomaly was revealed. No other information from this survey is available.

- ***A detailed gravity survey*** consisting of 113 stations in an area of 15 square miles. Habiger (1979) concluded, based on his modeling of the gravity data, that the observed anomalies originate from density variations present within about 2,000 feet of the ground surface; that is, within the volcanic sequence overlying the basement rocks. Attempts to correlate the pattern of gravity with the depth to basement rock were unsuccessful, but the survey was thought useful for inferring shallow structure (Benoit *et al.*, 1982).

- ***A ground magnetic survey.*** The most significant feature observed is a distinct NE trend in the pattern of magnetic anomalies, consistent with the grain of the topography in the area and the structural trend inferred from geologic mapping.

Because of the possible influence of shallow lithologies, the usefulness of the magnetic survey data for interpreting conditions at deeper levels (within the basement rocks) may be limited. Because the surveyed area does not include the zone of interest for the present investigation, the magnetic data are probably of marginal interest unless complemented by additional surveys.

- ***A self-potential (SP) survey.*** Much of the survey area, including most of its eastern part, shows limited SP variation and is free of significant anomalies. Those that do exist are likely to be related to the geothermal activity at Desert Peak, but their implications for the location, shape and extent of the geothermal reservoir (or other aspects of subsurface conditions in the area) are highly uncertain. The degree of uncertainty in the interpretation of the SP results makes them of very limited use for prediction of subsurface conditions, particularly on an area-wide basis. The present area of study lies at the extreme eastern margin of the SP survey area, further limiting the applicability of these data.

- ***A seismic noise survey.*** Two results of this survey may be applicable to the present study: 1) zones of naturally occurring microseismicity have been identified that may affect the ability to distinguish or characterize induced microseismicity; and 2) it may be possible to detect some microseismic events from seismometers installed at the ground surface.

- ***DC resistivity surveys,*** employing the dipole-dipole and Schlumberger methods. The results of the DC resistivity surveys are principally of local interest, within the limited area (sections 21 and 22, see Figure 1) and shallow depth range investigated. They do not have any significant bearing on the interpretation of conditions over the broader Desert Peak area, including the present study area.

- ***A principle-direction audiomagnetotelluric (AMT) survey.*** As is the case for the DC resistivity surveys, the results of this survey are of interest mainly within the limited area of the survey in sections 21 and 22, and could potentially be used to supplement the MT results. They do not have significant implications for the interpretation of conditions within the present study area.

In addition to these data, downhole geophysical logs (deep induction resistivity, gamma ray, density and sonic logs) were plotted and analyzed from well DP 23-1. Their analysis has assisted in the identification of lithologies, the interpretation of the wellbore imaging log and the evaluation of the local stress tensor.

New Geophysical Data

A detailed gravity survey was recently undertaken by researchers at UNR (Faulds *et al.*, 2002). In contrast to the earlier survey, this work is able to distinguish the pre-Tertiary basement rock quite well from the overlying rock, which is useful for identifying areas where potential reservoir rocks may be shallowest. Furthermore, the more recent survey corrects a largely contrary conclusion based on the earlier gravity survey, which covered much less of the Desert Peak horst system and was corrupted by a few large measurement errors. As summarized in Faulds *et al.* (2003), the gravity anomaly pattern reflects the main features of the known relief in the buried pre-Tertiary bedrock in the northern Hot Springs Mountains, and as such is quite useful for the current project. However, because of insufficient density contrast, the gravity modeling does not permit a distinction to be made between the meta-sedimentary (pT1 and pT2) and intrusive (deeper granodiorite) units in the basement.

As part of this work, ORMAT supplied UNR with the earlier gravity data discussed above for integration into this new survey, and supplied UNR with 18 core samples from the entire stratigraphic sequence in 35-13 TCH for density measurements. ORMAT also contracted UNR to collect additional gravity data points to increase station coverage in and around the EGS area (the survey area covers much of the Hot Springs Mountains). Modeling of the surface of the pre-Tertiary basement and the development of several 2-D model sections through the EGS area are currently underway by UNR.

Wellbore Imaging Log of DP 23-1

The successful collection of this log was a strong focus point for the project. The first step was to ensure that the well was open and available for logging. On 3 December 2002, a sinker bar and temperature/pressure log were run to 9,600 feet, allowing the project to pass its single Go/No-Go Decision Point, and to confirm earlier temperature data. The next step was to evaluate available wellbore imaging tools. Although the latest generation tools (either Schlumberger's FMI tool or Halliburton's EMI tool) were preferred, particularly for better coverage of the 12-1/4-inch section of open hole (being 8-pad as opposed to 4-pad tools), both have a temperature limitation of 350°F, whereas the well has a maximum measured downhole temperature of 421°F.

A review of the limited history of injecting into DP 23-1 suggested that injecting from the surface would be unlikely to cool the entire open interval to less than 350°F, and the preliminary geologic results indicated targets in the deeper portions of the well. Cooling by downhole circulation using coiled tubing was considered, but even with maximum pumping rates (requiring the use of friction reducers), calculations made using Sandia National Laboratory's wellbore cool-down/heat-up code GEOTEMP2 (Mondy and Duda, 1984) indicated that the well would heat up too quickly after circulation stopped to make this option economically feasible.

The focus on the deeper, granitic section in DP 23-1 proved beneficial with respect to the logging at this point: the hole diameter is smaller (8-1/2 and 7-7/8 inches) at depth, and therefore adequate wellbore coverage could be afforded by the older generation, 4-pad tools, including Schlumberger's "hot hole" Formation Microscanner (FMS) tool, which is rated to 450°F. Despite the tool rating, Schlumberger guaranteed better image quality at temperatures closer to 400°F, so a cooling program was developed involving the construction of a temporary pipeline from the ponds near the power plant along the roads to the DP 23-1 site. An injection test was designed, to be conducted as part of the cooling operations for evaluation of pre-stimulation hydraulic characteristics of DP 23-1 (for details, see Sanyal *et al.*, 2003).

Field activities were initiated with the construction of a 6-inch temporary aluminum pipeline from the ponds (sumps) at wells DP 67-21 and DP 87-21 (Figure 1) to the target well (DP 23-1). The sumps were partially filled with cooling tower blow-down diverted from the Desert Peak power plant during a plant trip in March. Two pumps were installed, one at each sump, to push the water through a temporary 6-inch pipeline to DP 23-1. The well-head equipment was appropriately modified to enable connection to the injection line, installation of flow metering equipment, and installation of pressure control equipment for logging.

On 1 April 2003, injection into DP 23-1 began at a rate of ~100 gallons per minute (gpm). After about 24 hours of injection, a detailed (logging speed 30 feet per minute) temperature survey was run (Figure 2). The injection rate was increased to ~ 150 gpm, a second detailed temperature survey was run, and a step-rate injection test began on 3 April with pressure monitoring at 6,000 feet. Three rate steps (100, 70 and 40 gpm) were run for 2 hours each, after which time the injection rate was increased back to ~200 gpm. While attempting to run a third TPS survey, an obstruction was encountered at 5,850 feet, in a section of pre-Tertiary phyllites and schists (Figure 2). After breaking through the obstruction, a maximum reading thermometer run to bottom indicated 410°F. Based on the progress of the cooling program, it was decided to run the FMS log at this point, while injecting at ~120 gpm. Logging up from 9,260 feet, the tool got hung up and had to be worked free three times; logging stopped at 5,930 feet (below the obstruction encountered earlier). Therefore, the upper quartz monzodiorite unit (discussed above as a potential EGS target formation) was not logged. After rigging down the logging tool, the injection rate was increased to ~200 gpm, and the pressure monitoring equipment was run in to 4,201 feet. Pressures were monitored during the last phase of injection and during a fall-off period for 4.5 hours after shut-in. Operations were completed late on 4 April 2003.

The digital data for the FMS log were obtained from Schlumberger and passed on to GeoMechanics International for analysis, along with supporting data from the well, including previously collected geophysical logs, drilling data and well test data. The purpose of this work is to look at wellbore failure for analysis of stress field orientation, to estimate the local stress tensor, and to evaluate the fracture population. This will assist in the selection of targets for hydraulic stimulation, which will likely include the two-mica granodiorite below 7,020 feet, and/or the shallower instrusives of the pT2 package.

Injection Testing Results From Well DP 23-1

As described by Sanyal *et al.* (2003), the injection rate and pressure data were analyzed using transient pressure analysis techniques. This analysis confirmed that the reservoir around the well has very low flow capacity (4,000 md-ft) and storage capacity (0.001 ft/psi), and the well does not intersect any major fracture. The well has very low injectivity (0.69 gpm/psi). The analysis indicates that injection for several days reduced the wellbore "skin factor" (from 1 to –0.2), and thereby improved the injectivity somewhat. The positive skin factor of this well may be due to well damage and the fact that only a fraction of the open interval in the well accepts fluid. The average porosity of the reservoir is very low (on the order of 2%). The radius of investigation of the test was estimated at 1,440 feet. The flow and storage capacities at this well are far lower than encountered within the hydrothermal reservoir at Desert Peak.

The results of this test provide a baseline against which any future permeability enhancements at this well can be assessed; a practical, low cost and approximate methodology for such assessment is proposed (Sanyal *et al.* 2003). The methodology consists of a short-term injection test followed by a long-term test (several weeks) that will yield the following measures of stimulation success: increase in injectivity, flow capacity and/or fracture length; reduction in skin factor; and volume of the reservoir stimulated.

Future Work

Phase I Work to be Completed

Conceptual modeling is currently underway to integrate the results of the geologic mapping, petrologic work and gravity modeling described above to refine stratigraphic and structural concepts of the EGS area. Emphasis is being placed on the structure of the basement rock, the nature of faulting within and at the edges of the EGS area, lateral and vertical temperature variations, and the nature of the separation between the EGS area and the main production field. Subsurface temperature data will also be used to make an estimate of the heat reserves.

The focus of numerical modeling will be the prediction of heat extraction rates from the EGS system based on reasonably conservative estimates of the permeability enhancements that will result from hydraulic stimulation operations, and various well placement options. Three-dimensional numerical reservoir simulation models will be constructed, consisting of one or two production-injection couplets, using the subsurface temperatures and hydraulic properties previously reported and/or determined during the course of this project. The numerical model will be used to study the sensitivity of temperature decline trend (the most critical parameter in EGS development) to variations in the characteristics of matrix and fractures, and in well spacings. The results will indicate what range of well spacing and fracture characteristics will lead to an acceptable long-term cooling rate.

Building upon all the analyses described herein, a detailed plan to guide the next activities at the field (Phase II) is being formulated.

Subsequent Phases

Future work will be directed toward re-completing and stimulating well DP 23-1, drilling and stimulating a second well to complete the EGS couplet, testing the system, and constructing and operating a dedicated 2-5 MW binary power plant.

Using the results of the petrologic analysis and the evaluation of well log analysis, one or more target intervals will be selected in well DP 23-1, and the well will be re-completed to case off formations that are mechanically unstable or otherwise unsuitable for stimulation. If rendered possible or valid on the basis of re-completion, a "mini-frac" (small-volume hydraulic stimulation with downhole pressure monitoring) will be performed to determine the magnitudes of the minimum and maximum horizontal stresses. Detailed TPS data will be collected during the mini-frac injection to identify permeable zones.

Drilling and stimulation activities will require significant quantities of water, and a source of make-up water is likely to be needed for routine circulation of the system. Therefore, the development a semi-permanent water source is being considered, with a steel above-ground pipeline providing separated brine from the production wells supplying the Desert Peak power plant to one or more newly constructed ponds at well DP 23-1.

One or two ~6,000-foot core holes will be drilled in the vicinity of well DP 23-1 for several purposes: further collection and mechanical testing of cores in the target formation(s), performing mini-fracs, and possibly running wellbore imaging logs or other analyses aimed at characterizing the fracture distribution in the vicinity of the planned EGS couplet. After completing the data collection and analysis from the core holes, the hydraulic stimulation of DP 23-1 will be undertaken, with seismic monitoring in the newly drilled core holes and possibly at surface locations. Analysis of the seismic data will be used to determine the location of the second well of the EGS couplet, which will then be drilled, logged and stimulated. Using the water source from the existing Desert Peak power plant, a circulation test of the system will be conducted for several months to confirm the viability of the system. Tracer tests will be run to estimate reservoir volume and flow-through times. Upon successful completion and evaluation of the first couplet, a third well or perhaps a second couplet may be drilled to obtain the production rate required for the power plant. A program of seismic monitoring and testing will be followed as for the first couplet.

Analysis of the circulation test data will be used to design the stand-alone binary power plant to be constructed and supplied by the EGS wells. The EGS-derived power will be either used to supply the parasitic load for the existing Desert Peak power plant or will be sold to a utility customer.

Collaboration

This project has benefited significantly from concurrent studies being undertaken by researchers with funding from the Great Basin Center for Geothermal Energy at the University of Nevada Reno (UNR). New geologic mapping and gravity surveying for a structural transect across the Hot Springs Mountains from Bradys Hot Springs through Desert Peak is being completed; these efforts are contributing significantly to the conceptual model of the field, and are a welcome addition to the existing body of information. Future UNR collaborative efforts being pursued or considered include detailed gravity modeling, baseline seismic monitoring, GIS data compilation, and additional geologic/structural analysis incorporating deep well data from all of the Desert Peak wells. ORMAT has entered into a Memorandum of Understanding with UNR to formalize and guide these efforts. Researchers in rock mechanics and fluid flow at Lawrence Livermore National Laboratory will use core data from Desert Peak to help identify the important physical and chemical attributes and phenomena that control fracturing in intrusive rocks, and to identify optimal fracturing techniques. Ongoing collaboration with the Energy and Geoscience Institute (EGI) at the University of Utah will focus on petrologic characterization of EGS reservoir rocks for better interpretation of both regional and local geology, subsurface stratigraphy, and fault or fracture zone mineralogy.

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References

Benoit, W. R., Gaddis, B. L., and Maas, J. P., 1985. Desert Peak participating area. Internal report by Phillips Petroleum Company, March 18, 1985, 63 p. plus appendices and plates.

Benoit, W. R., Hiner, J. E., and Forest, R. T., 1982. Discovery and geology of the Desert Peak geothermal field: a case history. Nevada Bureau of Mines and Geology Bulletin 97, 82 p. plus plates.

Faulds, J.E., L.G. Garside and G. Oppliger, 2003. Structural analysis of the Desert Peak-Brady geothermal field, western Nevada: implications for understanding linkages between NE-trending structures and geothermal anomalies in the Humboldt Structural Zone. Transactions, Geothermal Resources Council, Vol. 27 (in press).

Faulds, J.E., L.G. Garside, G.L. Johnson, J. Muehlberg and G.L. Oppliger, 2002. Geologic setting and preliminary analysis of the Desert Peak-Brady geothermal field, western Nevada. Transactions, Geothermal Resources Council, Vol. 26, pp. 494 - 494.

Habiger, R. M., 1979. Gravity data for Desert Peak. Phillips Petroleum Company inter-office correspondence, June 21, 1979, 2 p. plus plates.

Lutz, S.J., A. Schriener Jr., D. Schochet and A. Robertson-Tait, 2003. Geologic characterization of the pre-Tertiary rocks at the Desert Peak East EGS project site, Churchill County, Nevada. Transactions, Geothermal Resources Council, Vol. 27 (in press).

Lutz, S.J., 2003. Petrographic and X-ray diffraction analyses of samples from corehole 35-13 TCH and drillhole DP B23-1, Desert Peak Geothermal Field, Nevada. Report prepared for Ormat Nevada, Inc., 84 pp. plus appendices.

Mondy, L.A. and L.E. Duda, 1984. Advanced Wellbore Thermal Simulator GEOTEMP2 - User Manual. Sandia National Laboratory Report SAND84-0857, 147 pp.

NER, 2003. Mechanical properties of Desert Peak granite. Report prepared for ORMAT Nevada, Inc. by New England Research, Inc., 28 pp. plus figures and tables.

Sanyal, S.K., J.W. Lovekin, R.C. Henneberger, A. Robertson-Tait, P.J. Brown, C. Morris and D. Schochet, 2003. Injection testing for an Enhanced Geothermal Systems project at Desert Peak, Nevada. Transactions, Geothermal Resources Council, Vol. 27 (in press).

Schochet, D., A. Robertson-Tait and A. Schriener, 2002. Desert Peak East, Nevada: a step toward EGS commercialization in the Basin and Range. Transactions, Geothermal Resources Council, Vol. 26, pp. 251 - 254.

Thatcher, W., G.R. Foulger, B.R. Julian, J. Svarc, E. Quilty and G.W. Bawden, 1999. Present-day deformation across the Basin and Range province, western United States. Science, v. 283, pp. 1,714 - 1,718.