FENTON HILL SITE SELECTION AND EVALUATION: A CASE HISTORY

A. W. Laughlin
Earth and Space Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

Introduction

Continuing technical success in the development of techniques for hot dry rock (HDR) energy extraction justifies review of the Fenton Hill "case history." This history begins with the original site selection criteria, proceeds through the compilation of existing data and collection of new data to the evaluation of methods and results and finally to the application of these results to the search for new sites. Reviewed in perspective the case history shows that the original site selection criteria were correct. It also shows that the site selection techniques were effective in determining if the criteria were met at a particular site. Based on the Fenton Hill results, a generalized site selection and assessment plan can be proposed.

Site Selection

After the general concept for extracting geothermal energy from HDR was conceived (Robinson et al., 1971), a suitable site for developing and testing the extraction techniques was needed. The most obvious criteria for the site were that it should be underlain by very low permeability rock at high temperatures. To reduce drilling costs, high geothermal gradients were sought. Low seismicity was also specified as a criterion because of the effects of seismicity on permeability and because of earthquake hazards. Logistic and environmental concerns, although important, will not be discussed here.

The original geothermal group at Los Alamos was fortunate that the Laboratory is located within the Jemez Mountains, a region of known late-Cenozoic volcanism. The close proximity of a young silicic caldera alleviated many logistic problems and prior geologic interest in the area provided considerable evidence of a high-temperature volcanic heat source. Of primary importance was the excellent geologic map of Smith, Bailey and Ross (1970), which detailed the volcanic stratigraphy, structure, and some thermal manifestations. Adequate geochronology was available indicating volcanism continuing from about 10 m.y. to 0.04 m.y. (Doell et al., 1968). Direct evidence for geothermal resources within the Valles Caldera was also provided by newspaper accounts of successful well drilling by a private company. The seismicity was known to be low in the area minimizing risks of inducing earthquakes during later hydraulic fracturing and suggesting the probability of low secondary permeability. Some knowledge of basement structures was obtained from unpublished gravity and aeromagnetic data provided by Lin Cordell of the U.S. Geological Survey. Both Cordell and Roy Bailey of the U.S.G.S. met with Laboratory staff to assist in site selection.

Several small investigations were initiated to narrow down the choices for a site within the Jemez Mountains. Bailey and Cordell had suggested the western flank of the Valles Caldera to minimize the effects of faults related to the Rio Grande rift and the resurgent dome within the Valles Caldera. To confirm that elevated subsurface temperatures were present outside the caldera, Marshall Reiter of New Mexico Institute of Mining and Technology and Los Alamos staff drilled and logged seven shallow and four intermediate depth gradient holes on the southern and western flanks of the caldera. Heat flow values of about 230 mW/m^2 were measured in the deeper holes on the western flank.

An aerial photographic fault investigation was initiated to assist in evaluating the secondary permeability. A preliminary version of the fault study by Slemmons (1975) indicted that the Barley Canyon-Fenton Hill region of the Jemez Plateau was seismically quiet and within a large intact fault block. Concurrently, a slim hole (GT-1) was drilled in Barley Canyon to evaluate heat flow and the permeability of potential basement reservoir rocks. This well reached a total depth of 785 m, 143 m into the Precambrain basement. Because of hydrologic disturbances the geothermal gradient was 129°C/km in permeable Paleozoic rocks and 45°C/km in low permeability Precambrian rocks. Permeability measurements ranged from 5×10^{-8} to 6×10^{-3} darcies. Hydraulic fracturing was also accomplished in GT-1 indicating low permeability.

After evaluation of the results obtained in these studies a new drill site was selected at Fenton Hill. This site was within the same intact fault block as the Barley Canyon site, had about the same heat flow and was better located for logistic and environmemtal reasons.

Phase I System Development and Investigations

The Phase I HDR system was constructed at Fenton Hill using two drill holes - GT-2 and EE-1. Drill hole GT-2 had a total depth of 2.93 km and a bottom-hole temperature of 197°C and EE-1 a total depth of 3.06 km and a bottom-hole temperature of 205.5°C. Cores, cuttings samples, and geophysical logging were used to characterize the basement rocks in which the Phase I system was developed. A metamorphic complex intruded by biotite granodiorite and monzogranite bodies was recognized. Samples of the various lithologies were used for whole-rock chemistry, petrology, geochronology, rock mechanics, rock-water interaction and permeability studies. Results of these studies are given in Laughlin (1981), Brookins et al. (1977), Zartman (1979), Laughlin et al. (in press), Brookins and Laughlin (in press), and Charles and Bayhurst (in press).

The Phase I system was developed entirely within the 385-m-thick biotite granodiorite body. This rock is a very homogeneous igneous rock characterized by high modal biotite and sphene contents and high concentrations of K_2O, TiO_2, and P_2O_5. Although the biotite granodiorite contains fractures, they are almost invariably sealed with a variety of minerals. Calcite, epidote, hematite, chlorite, quartz, clays, feldspars, and sulfides have all been observed as fracture filling minerals. These sealed fractures show spacings of 1 to 8 cm and are variously horizontal, vertical, or steeply dipping. Strontium isotopic studies by Brookins and Laughlin (1976) indicate that the calcite in the fractures was probably derived from adjacent Precambrian rocks and not from overlying limestone.

The results of the geochronological investigations show a history of metamorphism at 1.62 b.y., intrusion of the biotite granodiorite at 1.50 b.y., and intrusion of the monzogranite at 1.44 b.y. (Brookins and Laughlin, in press). These Rb-Sr results as well as the U-Th-Pb results of Zartman (1979) suggest that these systems have remained closed despite present high temperatures. The results of K-Ar dating (Turner and Forbes, 1976), also indicate little movement of the daughter isotope despite temperatures as high as 313°C in EE-2.

While the Phase I was being developed, a number of surface geologic and geophysical investigations were performed to better characterize the Fenton Hill site. In hopes of predicting the orientation of hydraulic fractures, fracture-orientation data were obtained from Precambrian exposures in the Jemez Mountains. In these outcrops the two fracture sets with the greatest frequency trend north-northwest and northeast to east-northeast. These directions are consistent with fractures trending N42°E, N49°E, N52°E, and N25°W in cores from GT-2.

Two shallow seismic reflection surveys were run in the area to refine the knowledge of the structural setting near the drill site. Results were reported by Kintzinger and West (1976) and Kintzinger et al. (1978). Several faults were recognized by these surveys. A prominent NNE striking fault with a SE dip lies immediately west of the drill site, an E-W striking fault with a S dip was detected N of the drill site and a NE striking horst was observed in the Precambrian subsurface N of Barley Canyon. This horst is in part coincident with a gravity high mapped by Cordell (1976).

Electrical resistivity methods were employed by Jiracek (1975) to characterize the Fenton Hill site. Schlumberger soundings and the roving dipole and dipole-dipole methods were used. Several relatively shallow conductive zones were recognized. The outermost ring fault was particularly well defined, probably because of hot water moving up along it.

Hermance (1979) was funded by Los Alamos and the U.S.G.S. to conduct a telluric-magnetotelluric survey of the Jemez Mountains and northern New Mexico. A total of 30 stations was run in the Jemez Mountains; 17 stations were occupied on the Baca Grant with permission from Union Oil Company. Hermance found that his results within the Jemez Mountains were very similar to those from the Rio Grande ift. He presented evidence for a partial melt accumulation at a depth of 15 km.

Because of the limited number of cores available, additional evidence was sought for the nature of the basement rocks. Eichelberger and Koch (1979) investigated xenoliths present in the Bandelier Tuff. Although Precambrian xenoliths are rare in the tuff, 22 were found. In contrast to the cores from Fenton Hill, which are dominantly granitic, the xenoliths were roughly evenly divided between granitic and gabbroic rocks. The xenoliths were also typically more altered, sheared, and of a higher metamorphic grade than were the core samples. High-fluorine biotite and actinolite were common in the xenoliths as alteration products of original hornblende.

Phase II System Development and Investigations

After the technical feasibility of extracting geothermal energy from HDR was demonstrated in the Phase I system, drilling began on a pair of deeper holes for a larger Phase II engineering system. Drill holes EE-2 and EE-3 are inclined at a 35° angle and have true vertical depths of 4.39 km and 3.97 km respectively. The bottom-hole temperature of EE-2 is 323°C. Cores and cuttings from these wells indicate a continuation of the metamorphic complex observed in wells GT-2 and EE-1. Dikes of biotite granodiorite and monzogranite are intrusive into this complex. No single large homogeneous unit was observed in the deeper Precambrian section and, as a result, the Phase II system is much more heterogeneous than is the Phase I system. Cuttings analysis and structural analysis on cores suggested the possibility that several altered zones were intersected by the well bores.

Implications for Other Sites

The results of the deep drilling at Fenton Hill and subsequent fracturing and engineering tests can be used to evaluate the various exploration and assessment techniques. These evaluations have implications for the search for other HDR sites.

Although hydrologic disturbances resulted in erroneously high predictions of the geothermal gradient, the combination of field geology, geochronology, and gradient drilling was generally effective in identifying areas underlain by rock at elevated temperature. Additional hydrologic work would help in interpreting the results of gradient drilling.

Passive seismic techniques appear to be the most useful in evaluating reservoir permeability prior to drilling. Low seismic activity apparently fails to reopen fractures sealed as a result of high temperature and mineralizing fluids. Active seismic techniques were demonstrated to be useful in defining structures such as faults. Higher energy sources should be employed, however, to provide deeper penetration.

Permeable zones can also be identified using electrical or MT techniques. Although a thorough test was not performed because of financial constraints, preliminary results are encouraging.

Structural investigations, both surface and subsurface, can be valuable in predicting and interpreting the results of hydraulic fracturing. Low sun angle aerial photograph interpretation and joint analysis appear to be particularly useful. As much coring as possible should be done in future holes and techniques for orientation at high temperature should be developed. Much information was lost or confused because of the lack of orientation.

Petrologic investigations are fundamental in predicting the results of rock-water interactions along the hydraulic fractures. Complete mineralogical and chemical characterization is also important in predicting and interpreting fluid compositions.

From the results of the Fenton Hill drilling and the accompanying site investigation, the following HDR exploration and evaluation plan is proposed.

A Proposed HDR Exploration and Evaluation Plan

I. Identify areas of elevated subsurface temperature
- Field geology
- Volcanology
- Geochronology
- Geophysics
- Gradient drilling

II. Evaluation of permeability
- Passive seismic
- LANDSAT and aerial photograph interpretation
- Field geology
- Active seismic
- Electromagnetic

III. Prediction of hydraulic fracture behavior
- Field and structural geology
- Petrofabrics
- Stress orientation

IV. Prediction of fluid chemistry
- Petrology
- Whole-rock geochemistry

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