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Los Alamos Scientific Laboratory
Geothermal Test Hole No. 2**

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GEOPHYSICAL LOGGING IN LOS ALAMOS SCIENTIFIC LABORATORY

GEOHERMAL TEST HOLE NO. 2

by

F. G. West, P. R. Kintzinger, and A. W. Laughlin

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ABSTRACT

The Los Alamos Scientific Laboratory drilled Geothermal Test Hole No. 2 to a depth of 2932 m (9619 ft) as a part of the "Dry Hot Rock" Geothermal Energy Project. The hole encountered 732 m (2402 ft) of volcanic and sedimentary rocks before penetrating 2200 m (7217 ft) of crystalline rock. Various geophysical logs were run, the most useful for the purposes of the project being the full-wave sonic logs, as an indication of relative competence of the rock, and the spectral gamma-ray log, to indicate general rock type.

INTRODUCTION

Geothermal Test Hole No. 2 (GT-2) was drilled as a part of the field program of the Los Alamos Scientific Laboratory's (LASL) Dry Hot Rock Geothermal Energy Source Demonstration Project. The project thesis is simply that by drilling deeply enough one can find rock at a temperature which would be useful as an energy source. The depth of drilling required is primarily a function of the temperature needed for a particular application, the local geothermal gradient, and the efficiency of the thermal extraction process. Except when relatively low-intensity heat is useful, the temperature requirement is usually met only at depths where rock permeabilities are generally thought to be quite low, such that in most frames of reference the holes would be termed "dry."

The low thermal conductivity of rock requires exposure of a substantial surface area if a meaningful amount of thermal energy is to be extracted. (The assumption of low hydraulic permeability of course precludes development by the circulation of fluid through the rock.) Hydraulic fracturing of the rock is suggested as one method of developing the contact area necessary for a thermal mining operation.

GT-2 was drilled to a depth of 2932 m (9619 ft)* using drilling procedures and equipment typical of

*Hole depths given throughout this report are measured downward from the Kelly bushing on the drilling rig, which was 3.7 m above the ground surface at the wellhead.

hard-rock drilling. Coring was performed using a core bit slightly modified from that developed for the Deep Sea Drilling Project (JOIDES) and by the use of standard diamond core bits. The details of the drilling project as summarized by Pettitt^{1,2} are shown in Appendix A.

LOCATION

The project area is located on Fenton Hill, 3 km (2 miles) northwest of La Cueva, Sandoval County, New Mexico. The site location is as follows: NE 1/4, Sec 13, T19N, R2E NMPM. The land-surface elevation is 2648.7 m (8690 ft).

GEOLOGY

The project site is approximately 3 km (2 miles) west of the ring fault zone associated with the collapse of the Valles Caldera. Faults associated with the Rio Grande rift valley are thought to be the locus of former volcanic activity in the area.³ One group of faults, the Jemez Springs fault zone, is some 5 km (3.1 miles) southeast of the site. The Jemez-Nacimiento Mountains area has been a structurally active area to varying degrees since Precambrian time. Evidence of structural activity after the last eruption from the Valles Caldera is seen along the Jemez Springs fault zone, the closest known fault being the Virgin Canyon fault.⁴ Some post-volcanism uplift may have taken place west of the Rio de Las Vacas in the Nacimiento Mountains. Drilling information and geophysical logs suggest that

Fig. 1. Diagnostic logging services performed in GT-2 from March through May 1974.

Fig. 2. Diagnostic logging services performed in GT-2 during June 1974.

Fig. 3. Diagnostic logging services performed in GT-2 during June and July 1974.

fracture zones with unknown displacement were encountered in GT-2.

The hole penetrated some 137 m (449 ft) of volcanics, 238 m (780 ft) of Permian red beds, and 355 m (1165 ft) of Pennsylvanian-Mississippian shales and limestones, before encountering granite at 732 m (2402 ft).⁵ The crystalline Precambrian rocks include granites, granodiorites, monzonites, biotite schist, and amphibolite. The textures ranged from fine to coarse grained and the colors from pink to black.

GEOPHYSICAL LOGGING

The logging program for GT-2 was drafted in anticipation of the information which would be necessary or useful to the project. Practical considerations occasionally caused the deletion or addition of particular logs. The logs run and the coverage of each log are shown in Figs. 1-5. Four commercial logging services were used at various times. The Water Resources Branch of the U. S. Geological Survey ran a short suite of logs with plans to log the completed hole at a later date. Thermal recovery with time was measured at the bottom of the

in determining the dip of fracture-zone washouts encountered. Principal use of the caliper logs has been for the selection of sites for seating the packers required to seal off a section of hole for tests to determine rock permeability⁷ and for the hydraulic fracturing experiments.

ELECTRIC LOGS

The various electric logs run were useful in accomplishing the primary project purpose of logging, that is, in locating zones of permeability, which were usually found to be coincident with zones of intense fracturing. The electric logs run were the self-potential, 16-in.-normal, 64-in.-normal, lateral, wall-resistivity, induction, and the dip log.

Few of the physical situations are present in crystalline rocks that generate the electric self-potentials found in sedimentary rocks. Occasionally at permeable fracture zones small potentials were measured which were probably due to electrokinetic effects. The largest potentials found were probably due to electrochemical effects associated with mafic rocks.

The resistivity logs, although somewhat subdued in an environment of highly resistive crystalline rocks, were effective as indicators of permeable zones. The resistivities measured by even the longest electrode spacings of the lateral log are probably somewhat less than the true formation resistivities due to the shunting effect of a conductive drill mud in relation to an extremely high formation resistivity. Generally the longer electrode spacings indicated higher resistivities than the shorter electrode spacings. This effect, which might normally indicate invasion of the formation by drilling fluids is not confirmed by the shallow depth of investigation of wall-resistivity logs. Fracture zones give some indication of drill-fluid invasion on the wall-resistivity logs as interpreted from mud cake buildup in these zones. Focused-current type devices may be somewhat more effective for measurement of true formation resistivity in this particular situation. Induction-log records, although giving indication of some fractures in the crystalline rock, were off-scale for most of the log due to high crystalline-rock resistivity.

The electric formation-dip-orientation log appeared to give good data; however, overlapping of

logging runs did not produce particularly good agreement, nor was the correlation with the assumed standard, the seisviewer log, good. The electric dip log tended to give low values of dip relative to the seisviewer log.

BULK-DENSITY LOG

Porosity determination is one of the main uses of the bulk-density or scattered gamma-ray log in sedimentary drill holes. Although crystalline basement rocks do not generally have the range of bulk densities that is exhibited by sedimentary rocks, the density log may be useful in crystalline rocks as an indicator of lithology. The relative mafic content of the rock may be inferred from the departure of the log from values typical for granite rock.⁸⁻¹⁰ Confirmation of the validity of the procedure is found in correlations with the self-potential, resistivity, neutron, and spectral gamma logs. The sonic log cannot always be used for confirmation as can be seen in the mafic zone from 1692 to 1725 m (5550 to 5660 ft), where the bulk density increases but the sonic velocity does not increase as one might expect.¹¹ Since mafic-type rocks have higher electron densities than does the medium generally used to calibrate density logging tools, some correction must be made to the logged values in a mafic rock zone. Otherwise the bulk-density log correlates reasonably well with densities determined from cores.¹²

NEUTRON LOG

The log which appears to have the least potential in crystalline basement rocks is the neutron log. The primary use of the log is usually for estimation of fluid filled porosity. Crystalline rocks generally have a rather limited range of porosities, except possibly in fracture zones.

The neutron logs were not without some character, as for instance the zone at 1178 m (3865 ft). This zone shows a high-in-bulk density with an attendant increase in sonic velocity as indicated by the blip on the full-wave sonic log, but the neutron log would seem to indicate an increase in porosity which usually indicates a decrease in sonic velocity. Since the density and sonic logs indicate reduced porosity, the neutron log is probably indicating the presence of a material with a high cross section to neutrons, quite likely a mafic type of intrusion. The zone of

mafic rocks, from 1692 to 1725 m (5550 to 5660 ft) shows a slight apparent increase in porosity, a similar increase in density, but in this case without a confirmation on the sonic log of increased velocity, probably indicating a material with a high neutron cross section and high electron density.

SPECTRAL-GAMMA LOG

Certain logs are relied on more than others to define the lithology in sedimentary rocks; for crystalline basement rocks the lithology log is possibly the spectral gamma log. This log consists of four records, one for total gamma activity and one each for thorium, uranium, and potassium. Thorium is determined by measuring the activity of the 2.62-MeV daughter isotope ^{208}Tl . Uranium is determined from the 1.76-MeV ^{214}Bi gamma activity and potassium from the 1.46-MeV ^{40}K peak. Sensitivities for the three elements were potassium, 0.42% per chart division; uranium, 2.8 ppm per chart division, and thorium, 6.8 ppm per chart division.

Thorium showed the least amount of character, having only minor excursions from the 6.8 ppm line, except below the depth of 2591 m (8500 ft) where a shift to about 11 ppm occurs. Positive anomalies in the thorium content are often accompanied by increases in the potassium content and occasionally in the uranium content. The thorium content varies from 2 ppm to 23 ppm.

The uranium content often exhibits a high either in, or close to, fracture zones. Because uranium is more mobile than thorium, a depth plot of the ratio of activities of thorium to uranium accentuates fracture zones. The uranium content varies from almost zero to 32 ppm.

Potassium content appears to give the most information on lithology. The hornblende-biotite schists and amphibolites are easily recognized by low, uniform, total-gamma activities of about 4000 $\pm$ 1000 counts. The low count rate in these rocks is due largely to a relatively low potassium content, which ranged from 1.1 to 1.8%. The uranium content varied from almost zero up to 2.8 ppm and the thorium content varied from 1.8 to 4.1 ppm. The mafic-rock radioactivity anomaly can also be correlated with a high electric self-potential, a slight low in apparent porosity (neutron), and a high-in-bulk density.

It does not appear likely that felsic granitoid and gneissic rocks can be distinguished by using the spectral log. The activities of the felsic granitoid rocks are usually higher than those of the mafic rocks, but the activities are extremely variable, often with sharp peaks. The variable activities reflect compositional variations in these rocks which may be either sharp or gradual.

FULL-WAVE SONIC LOG

One of the most useful logs for project purposes is the full-wave sonic log. In contrast to the sonic travel-time log which displays only the time of first arrival, the full-wave log displays the full-wave train beginning with the pressure wave. This log gives one an immediate feeling for the character of the rock. Fracture zones that are merely suspected on other logs jump out on the full-wave sonic log, for instance, the zones at 914 m (3000 ft) and 1829 m (6000 ft). The sonic velocity decreases in fracture zones as a result of an increase in porosity. The relative intensity of fracturing in a zone can be estimated from the decrease in velocities, or from the change in the V-pressure/V-shear ratio.^{13,14} Even small fractures can be seen in the "X" pattern in the wave train between the arrival of the primary wave and the shear wave.¹⁵ Some zones do not exhibit this effect as much as other zones. Based on information from cores, zones which do not exhibit the effect probably have complete healing or cementing of the fractures. Slight, or a general increase in velocity due to increased loading with increased depth is not observed in these logs as has been suggested from laboratory investigations.¹⁶ The full-wave sonic log in conjunction with the density log was used to compute the in situ elastic constants of the rock. The constants derived from geophysical logs were in reasonable agreement with those measured in the laboratory when the volume sampled and the altered environment of cores are considered.

SEISVIEWER LOG

The seisviewer (borehole televiewer, USGS), a sonar type of borehole-wall scanning tool, is quite valuable to the "dry hot rock" project because of its capability for delineating fractures directly and not merely by inference.¹⁷ The orientation of natural fractures may give some insight to previous stress

fields. Induced-fracture orientation may be controlled by the remnant of stress fields which caused the original natural fractures, or simply by the planes of weakness created by previous fracturing (if a hydrostatic stress field is assumed to be present).

The seisviewer log also detected several zones in the hole which exhibited the grooved helical feature known as "rifling." This feature may appear for intervals of 3 m (10 ft) to sometimes over 30 m (100 ft), starting and ending abruptly. Rifling is probably related primarily to drilling dynamics, and it is of interest to note the occurrence in "hard" rock. The caliper log and to some extent the density log respond to the rifling with a scalloped appearance, as seen at a depth of 1387 to 1454 m (4550 to 4770 ft).

TEMPERATURE LOG

Fluctuations in the apparent geothermal gradient indicated by the temperature logs decreased with increased depth. Perturbations on the log usually coincide with washouts caused by the less competent rock in fracture zones. The relative permeability of a fracture zone is probably indicated by the amount of temperature reversal or perturbation and the interval of the hole in which the effect is observed. The gradient in the hole varied from 50 to 60°C/km. The extrapolated equilibrium bottomhole temperature was 197°C (386.6°F).

CONCLUSIONS

Although the response of most of the geophysical logs in an environment of crystalline rocks was not altogether ordinary, still the logs were most useful. Interpretation of geophysical logs of crystalline rocks may often require a review of the physical principles on which the log is based.^{18,19} It appears that a quantitative interpretation of the logs will require an experience or empirical base not unlike that developed for logging in sedimentary rocks. The single most useful log for project purposes was the full-wave sonic log. The lithologic log in crystalline rock is the spectral gamma log. Of course a full suite of geophysical logs is the best assurance of obtaining the necessary data for any project.

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APPENDIX A

LOS ALAMOS DRY GEOTHERMAL RESERVE DEMONSTRATION PROJECT
 GEOTHERMAL TEST HOLE NO. 2 (CONTINUED)
 SUMMARY OF DRILLING, LOGGING, CORING, GEOPHYSICAL AND GEOSCOPIC DATA
 Depth measured from Kelly Locker - Station 5201.0

APPENDIX B
LOS ALAMOS SCIENTIFIC LABORATORY
GEOHERMAL TEST HOLE N° 2

LOS ALAMOS SCIENTIFIC LABORATORY
GEOTHERMAL TEST HOLE N°2

LOS ALAMOS SCIENTIFIC LABORATORY
GEOTHERMAL TEST HOLE NO. 2