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DRY HOT ROCK PROJECT*

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INTRODUCTION

Recent political events have greatly accelerated shortages of various critical natural resources, in particular our prime energy source petroleum has been predicted by many authorities, perhaps most succinctly by the analysis of M. King Hubbert (1969). New energy sources, such as geothermal are now receiving frenzied attention in contrast to the previous lackadaisical development. The immense theoretical potential of the geothermal energy source has long been recognized but was regarded as undevelopable, except under rather exotic geologic circumstances where dry steam is available. This restricted view is partially changing as a result of advances in technology and improvement of the economics which will allow the utilization of thermal waters. The Los Alamos Scientific Laboratory is presently investigating methods for tapping the heat stored in the crustal rocks by the thermal mining concept called the "Dry-Hot Rock Project." Terrestrial heat flow studies indicate that this would provide a relatively viable energy source once the techniques for exploitation are developed.

The area proposed for initial experiments in the development of a man-made geothermal-energy system, the Jemez Mountains, lies in the southern part of the Rocky Mountain belt between the Colorado Plateau and Texas foreland physiographic provinces (Fig. 1). The project area is just to the west of the Valles Caldera on a relatively undeformed structural island. Various geologic and geophysical environments of interest relative to geothermal energy investigations which may be characteristic of high heat flow areas, particularly in the western third of the United States, are therefore available within a small area.

GEOPHYSICAL SETTING

The project area is situated astride a volcanic trend, along a transition in the regional geologic structure and attendant geophysical anomalies. Comparison of the various geophysical maps show that, in general, the regional anomalies are coincident. The synthesis of available geologic, geophysical, and chemical data suggests a thermally young region of predominantly low-density silicic rocks that are hydrated at depth (Hyndman and Hyndman, 1968) to give a petrographic zone with an unusual sensitivity of the elastic and electrical properties to temperature and pressure. A complete understanding of the processes that causes all of these anomalies to be coincident would be of great scientific importance especially in the area of plate tectonics. Certainly, any meaningful exploration and exploitation of geothermal energy will require such a basic understanding. It is hoped that this project may in part provide some insight into the problem.

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Heat Flow

Tectonic provinces have long been known as areas of higher-than-average terrestrial heat flow, and the Rocky Mountain belt is no exception (Sclater, 1972). The mean heat flow of a tectonic province appears to be largely a function of the age of the activity. The relatively old Texas foreland, east of the Rio Grande rift zone, has a nominal heat-flow value of 1.1 cal/cm^2-sec (Roy and others, 1972). The Rocky Mountain and the Basin and Range provinces, which are moderately young, have heat-flow values that commonly range from 1.5 to 3.4 cal/cm^2-sec. These above-average heat flows may reflect elevated isotherms in the crust, increased thermal conductivity of the crustal rocks, or both. Certainly, the heat flow in the region is enhanced by the abundance of silicic rocks that contain above-average amounts of heat-producing radioactive elements.

Gravity

The Bouguer gravity map of the region exhibits a general northeast-southwest trend of anomaly closures along this part of the Rocky Mountain belt (U.S. Air Force, 1968). The axis of the gravity lows is along the western edge of the Rio Grande rift, with a parallel trend of gravity highs farther to the west. To the east, the anomalies become more random in that they do not exhibit the marked trends found along the rift. The Jemez Caldera, which is formed from low-density silicic rocks, coincides with one of the gravity lows. The Nacimiento Mountain ridge of gravity contour drops uniformly eastward across the project area to the Jemez Caldera gravity low. A map of relatively low-density silicic rocks in the western United States shows a striking resemblance to the Bouguer gravity map (Moore, 1962).

Seismic

A fringe benefit of nuclear-device testing at the Nevada Test Site has been the opportunity to study the regional variation of crustal-seismic-transmission characteristics (Pakiser, 1963). The compressional wave velocity seems to vary in a systematic fashion with the geologic environment (Stuart and others, 1964). The velocity also apparently varies with crustal thickness; where the crust is thick the velocity tends to be high, and where the crust is thin the velocity is low (Jordan and others, 1965). Crustal thickness interpreted from the seismic records indicates that a crustal thinning occurs west of the Texas foreland, with the Basin-and-Range province having the thinnest crust (Archambeau, 1969), and in general, the area of crustal thinning is also an area of unusually high attenuation of seismic wave energy (Hales and Doyle, 1967). Maps of seismic-wave travel-time anomalies correlate reasonably well with areas of known high heat flow. This has led to an explanation of the relationship of crustal parameters based on a partial crustal melting (Soloman, 1972). Recent laboratory results indicate

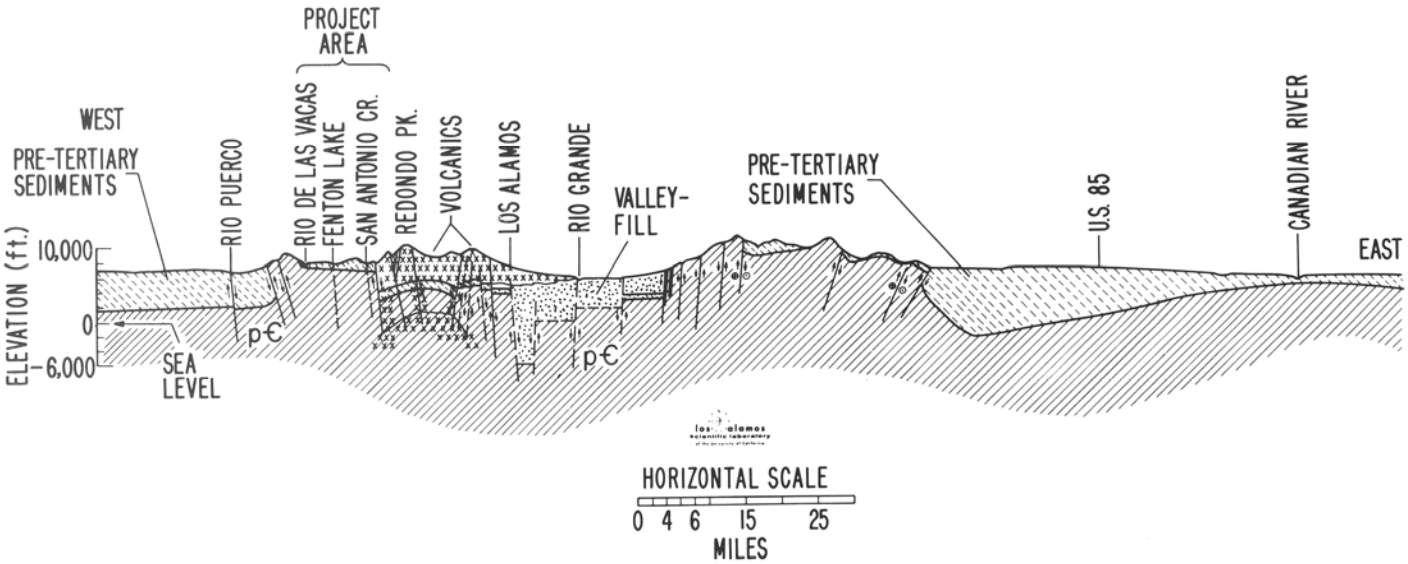

Figure 1. Regional geological cross-section.

that the relationship can be explained on the basis of the variation of elastic constants with temperature and pressure (Anderson, 1972).

Magnetics

Various types of magnetic surveys have been performed in the region. It has been found that low-bandpass-filtered aeromagnetic profiles of the static field generally become much flatter as one proceeds westward from the plains across the Rocky Mountain belt (Zeitz and others, 1969). The aeromagnetic maps of the West reflect the relative youth of the area and the relative lack of mafic rocks. Aeromagnetic maps of the western United States have been interpreted as indicating a continuance eastward of the Pacific transcurrent-fracture zones associated with seafloor spreading (Fuller, 1964). This type of global structural feature would assist in the explanation of the apparent westward offset of the Rio Grande rift on the south side of the Jemez uplift. The aeromagnetic map of the project area reflects the varied geologic history of the area (Zietz and Kirby, 1968). The Nacimiento Mountains and the Jemez Plateau have north-south trending anomalies with subsidiary east-west trending anomalies. The trend of these anomalies is possibly controlled by metamorphic-basement-rock features such as the fracture pattern (Gay, 1972). The Jemez Caldera is outlined by anomalies with an arcuate pattern, especially in the area of the ring dikes. The project area is in a saddle between the probable metamorphic rock generated anomalies and those associated with the caldera.

Magnetoelectric and geomagnetic profiles of the western United States have suggested that the region has a unique reaction to magnetic events with periods of about 1 to 100 minutes (Caner, Cannon, and Livingstone, 1967; Schmucker and Jankowski, 1972; and Porath and Gough, 1971). The interpretation of the crustal profiles is that to varying degrees the region is one of relatively low electrical impedance. The relationship of the resistivity of rocks with temperature suggests that the anomalies are due in part to thermal enhancement (Warren and others, 1969). The preliminary maps of heat flow trends correlate with magnetic reaction trend maps. Crustal thicknesses inferred from transient magnetic studies also correlate with those from seismic studies (Mitchell and Landisman, 1971; and Reitzel and others, 1970). It appears that heat-flow anomalies of regional nature can be delineated by magnetoelectrics, while detailed mapping of these anomalies can be accomplished by geomagnetic soundings (Caner and Cannon, 1965). The skin effect, which is frequently dependent, controls the depth of these investigations. Geomagnetics, as an exploratory tool, are in the developmental stage, both from the standpoint of field methods and interpretation (Keller, 1970). It appears quite likely that this method will see greatly increased use in the solution of not only terrestrial heat-flow problems but basic problems of the structural features and processes of the earth's interior.

HOT-DRY-ROCK PROJECT

Based on the geology and geophysics of the western third of the United States, it has been estimated that a widely distributed collective area of 2.46 x 10^5 km^2 (95,000 mi^i) exists in which rock at a temperature of 248°C (478°F) will be encountered at a depth on the order of 5 km (16,400 ft) (Brown, 1973). Development of methods to utilize this resource could provide more electrical capacity than the projected requirements for the western United States until the year 2000.

The aim of the Los Alamos project is, therefore, to develop methods of establishing the large surface area necessary for effective heat transfer in a media of low thermal conductivity and low hydraulic conductivity. Hydraulic fracturing methods typically used in oil-field stimulation offer one possible means of developing a subsurface heat exchanger system. Although the technique of hydraulic fracturing has not been generally applied to crystalline basement rocks, the principles of rock mechanics on which hydraulic fracturing is based are still applicable (Hubbert and Willis, 1957). The pressure necessary in excess of hydrostatic to fracture a rock is a function of the *in situ* tensile strength of the rock and the stress field around the hole, natural and induced. The pressure required to hold an induced vertical fracture open should be, at the least, equal to the horizontal compressive stress. At the depths necessary to find a useful temperature, the induced hydraulic fracture is expected to be vertical with an orientation normal to the least compressive stress. Fracture extension pressure is intermediate to fracture initiation pressure and the pressure for propping the crack open. To date, the exact geometry of a hydraulic fracture has not been mapped, but most authors suggest the form of an eliptical disc. The radius of a fracture created for project purposes would reflect in part the desired thermal production capacity of the hole and the geologic environment.

Of the various circulation methods possible, the two hole system will be investigated first. In this scheme a second hole is used to intercept the top part of the fracture induced by the first hole, thus creating a circulation loop. The water in the loop would be kept at a pressure sufficient to hydraulically prop the crack open, which as it turns out is also usually sufficient to keep a fluid phase at all times for a maximum efficiency of heat transfer. Density differences between the water in the hot and cold legs of the circulation loop could provide all or most of the differential pressure necessary for circulation. A complex dynamic interrelationship between the hydraulic radius and the temperature dependent fluid parameters of viscosity and density will control the circulation regimen. The net effect will be that the wider parts of the crack will be cooled first while some circulation is maintained in the narrower and hotter parts of the crack by virtue of the reduced viscosity and density. This picture may be further complicated by temperature-pressure dependent chemical action and additional cracking induced ultimately by thermal stresses resulting from volume contraction. It has been estimated that the decay of the thermal production capacity of a typical system will cease in approximately 5 years and return gradually to near the original capacity as a result of new transfer areas exposed by thermal stress cracking (Harlow and Pracht, 1972).

Project Progress

Several shallow geologic and heat-flow exploratory holes have been drilled between the Rio San Antonio and Rio Cebolla. Based on this information Granite Test Number 1 (SE 1/4, Sec. 1, R. 2E., T 19N) was drilled to a depth of 785 m (2575 ft). A temperature of 100.4°C was measured at the bottom of the hole. The geologic log as given by Purtymun (1973) is as follows:

Elevation of land surface	— 8475 ft
Depth drilled	— 2575 ft
Hole diameter	— 13-3/4 in. to 280 ft 9-7/8 in. to 1600 ft 6-3/4 in. to 2410 ft 4-1/4 in. to 2575 ft
Casing Schedule	— 10-3/4 in. o.d. to 258 ft 7-5/8 in. o.d. to 1357 ft 5 in. o.d. to 2400 ft Open hole 2400 to 2575 ft
Drilled-Air-Mist Rotary	— To 2410 ft
Core-Water Rotary	— 2410 to 2575 ft
Date Completed	— June 30, 1972

	Thickness (ft)	Depth (ft)
Bandelier Tuff		
Tuff, gray, moderately welded, rhyolitic; crystals and crystal fragments of quartz and sanidine, rock fragments of pumice, rhyolite, and latite, in ash matrix.	60	60
Abiquiu Tuff		
Sandstone, light gray, with pebbly conglomerate containing rock fragments of pumice, latite and rhyolite, and unidentified rock fragments ranging from light gray and green to dark gray and black.	100	160
Abo Formation		
Shale and fine-grained sandstone, some clay lenses; predominantly red to dark red in color, with some lenses of white to gray; arkosic with a few thin beds of limestone. Shale, dark red, 160 to 290 ft; sandstone, fine-grained, dark red, 290 to 350 ft; sandstone, fine-grained, alternating with shale, dark red, 350 to 680 ft; shale and sandstone, fine-grained, predominantly red, with lenses of white to gray shale and sandstone, a few thin beds of limestone, 680 to 1030 ft; clay, dark red with minor lenses of shale and sandstone, 1030 to 1070 ft.	910	1070
Magdalena Group		
Madera Limestones		
Upper limestone member consists of limestone alternating with gray and red shales and sandstone, arkosic; limestone, gray, alternating with sandstone, fine-grained red, 1070 to 1250 ft; shale, red with some thin lenses of limestone, gray, 1250 to 1330 ft; limestone, gray, with some lenses of sandstone, fine-grained red, and shale, light red, 1330 to 1440 ft; shale, dark red, with lenses of limestone, dark gray, 1440 to 1530 ft; limestone, gray, with thin lenses of light red and gray sandstone, fine-grained, 1530 to 1670 ft.	590	1660
Lower limestone member consisting of dark gray limestone and thin lenses of white to gray shale and fine-grained sandstone. Limestone, dark gray, with thin lenses of sandstone, fine-grained, white to light gray and shale, dark gray.	155	1815
Sandia Formation		
Upper elastic member, limestone, gray, with lenses of gray shale and fine-grained sandstone ranging from light gray to light green.	235	2050
Lower limestone member, limestone, dark gray, siliceous, dense.	55	2105
Precambrian Rocks		
Augen gneiss, brownish gray, with inclusions of pink plagioclase, 2105 to 2430 ft; granite, reddish brown, medium-grained, 2430 to 2480 ft; gneiss, reddish brown, medium-grained, foliated, 2480 to 2520 ft; amphibolite, dark gray, fine-grained, 2520 to 2575 ft.	470	2575

The permeability of the crystalline basement rock in the bottom 53 meters (175 ft) was determined at several different levels of over-pressure. The decay of water level during a period of several months indicated a permeability of 5.4×10^{-8} darcys. The pressure decay from a straddle packer injection test yielded a permeability of 1.5×10^{-5} darcys. The pressure decay from repressurization of a hydraulic fracture gave a permeability of 1.5×10^{-4} darcys. The increase in permeability in a fractured porous media resulting from increased injection pressure, has been described by Barenblatt and others (1960). The permeabilities observed indicate that for project purposes the basement rock at this site can be considered "Dry."

Several hydraulic fracturing experiments were conducted in the Precambrian basement rock. The tests indicate that tensile failure by hydraulic fracture is related to strain rate, a relationship that is difficult to define in rocks of appreciable permeability. The near-field pore pressure and hence effective stress is permeability dependent for a particular injection rate and therefore controls the pressure necessary for fracture. The less permeable the rock the closer one approximates the condition of a non-penetrating fluid, making the interpretation of a pressure build-up versus volume plot somewhat more straight forward. In our particular experiments, hydraulic fractures in crystalline rock were obtained at pumping rates ranging from 3.1×10^{-5} to 1.1×10^{-2} m^3/sec (0.5 to 180 gpm) and at downhole pressures of 153 to 191 bars (2220 to 2770 psi). The least compressive stress was determined to be in the range of 135 to 140 bars (1960 to 2030 psi) downhole pressure.

The fractures in the hole "pre" and "post" experiment were mapped using oriented inflatable impression packers and by the use of Birdwell's Seisviewer logging tool. The induced fractures mapped were vertical with an orientation of approximately N. 45° W. This orientation appears to correlate with the fracture system found in the Colorado Plateau by Kelley (1955) and the alignment of buffalo wallows observed in the high plains of New Mexico.

Plans call for the drilling of Granite Test Number 2, a 1372 meter (4,500 ft) hole (work in progress) to further test conditions in the basement rock and perfect the hardware necessary for project research of various sorts.

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