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MAGMA ENERGY FOR POWER GENERATION

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ABSTRACT

Thermal energy contained in crustal magma bodies represents a large potential resource for the U. S. and magma generated power could become a viable alternative in the future. Engineering feasibility of the magma energy concept is being investigated as part of the Department of Energy's Geothermal Program. This current project follows a seven-year Magma Energy Research Project where scientific feasibility of the concept was concluded.

INTRODUCTION

Energy contained in molten or partially-molten magma represents a huge potential resource for the U. S. Smith and Shaw (1,2) estimated this resource within the upper 10 km of the crust to be 50,000 to 500,000 quads - larger than the current estimate for fossil resources.

In 1975 the Magma Energy Research Project was initiated by ERDA (now DOE) to investigate the scientific feasibility of extracting energy directly from deeply buried magma sources. The project addressed five task areas: source location and definition, source tapping, magma characterization, material compatibility, and energy extraction. Work on these topics proceeded for seven years and culminated in a demonstration of many of the magma energy concepts in the molten zone of Kilauea Iki lava lake. The conclusion reached after this seven year study was that energy extraction from active magma bodies is indeed scientifically feasible. Two different scientific review panels agreed with this conclusion. Several highlights and major conclusions from the research project will be briefly described below by task area and the current status of the engineering program will be presented.

Source Location and Definition

Three series of geophysical sensing studies were conducted over the molten lens of Kilauea Iki lava lake. The studies were designed to demonstrate the capability of a variety of geophysical sensing techniques to correctly identify and define the areal extent, depth, and thickness of the molten zone. The first series of experiments immediately discovered the importance of determining in situ properties (especially electrical conductivity and seismic velocity) of the molten zone and surrounding layers before field data can be properly interpreted (3). We found that the magma source environment is very complex and this was mirrored in measurements of p-wave velocity through the fractured hydrothermal and melt zones. Nevertheless, commonly used geophysical techniques were found to provide definition of the melt zone that agreed reasonably well with data obtained from drilling.

Source Tapping

Early questions in this area were: Can magma roof-rocks be drilled? Will drillholes through the roof-rocks be stable and remain open long enough to allow emplacement of energy extraction tubing? These questions were addressed at the Center for Tectonophysics, Texas A&M University, by analyses and experimental measurements of representative magma roof-rock properties at expected temperature and pressure conditions. Results of these studies [Friedman et al. (4)] showed that rock strength decreased with increasing temperature and, most importantly, all crystalline rocks exhibited brittle failure up to partial melting temperature (indicating that these high temperature rocks can be drilled using conventional bits). The conclusion was also reached that unfilled boreholes maintained at 700°C will remain stable at depths up to 10 km.

Several attempts were made during the research program to drill through the molten zone of Kilauea Iki lava lake. This objective was realized during the successful 1981 drilling program where 100% core recovery was obtained in a 29 m sequence of molten rock where temperatures ranged from 1070 to 1170°C (5). In all, seven holes totaling 701 m were cored with 105 m of core taken from zones where temperature exceeded 1020°C. The upper crust of the lava lake was cored using conventional drilling techniques. When the melt zone was approached, specially designed core barrels and water-cooled diamond coring bits were used. The bits used forward facing high velocity, high stagnation pressure jets to penetrate and cool magma ahead of the bit. Rates of penetration in the melt zone (commonly 20 m/hr) were actually somewhat higher than rates in the overlying crust. After drilling was completed, holes into the melt zone were stabilized and maintained open by supplying cooling water downhole. Some holes were entered several times during a two week experiment period.

Magma Characterization

Our efforts in characterizing magma were primarily concentrated on basaltic systems. A unique Magma Simulation Facility for in situ pressure and temperature experiments was designed, built, and put into operation. Both property measurement and heat transfer studies were carried out in this facility. Viscosity measurements in large samples were made at temperature and pressure conditions using an electromagnetic falling-sphere technique (6). The heat transfer experiments showed that magma water content has a significant effect on convective heat transfer rates (7). Other studies showed that gas compositions of in situ magmas can be determined from surface emissions of volcanic gases (8). These in situ compositions are needed to properly assess magma/material compatibility. Petrologic/geochemical studies of Kilauea Iki core provided insights on the cooling history of a totally enclosed molten-rock body that are useful in predicting magma body lifetimes.

Material Compatibility

Our studies here concentrated on metal/basaltic magma compatibility at temperatures up to 1150°C. Screening tests of pure metals showed that iron, nickel, and cobalt cannot be used without alloying because of liquid sulfide formation and high reaction rates (9). Molybdenum was found to have a good resistance to the environment as long as the oxygen fugacity remains low.

Platinum is the only precious metal tested that can survive the environment. Alloy testing resulted in the conclusion that the highest degree of corrosion resistance was obtained with ternary alloys containing molybdenum and chromium. The final conclusion was that engineering materials could survive normal operating conditions (300 to 600°C) in a basaltic magma for long time periods and also survive much higher temperatures up to 1150°C for short time periods under emergency conditions (10).

Energy Extraction

Much of the early work in this area was directed at evaluating natural convection heat transfer rates in magma, both analytically and experimentally. Hardee (11) used these results to calculate energy extraction rates for a "closed" heat exchanger system where concentric pipes are inserted into the magma zone. Fluid is circulated within the pipes without coming into direct contact with the magma. These calculations predict extraction rates of 20 to 80 MWth/well for basaltic magma and 4 to 19 MWth/well for rhyolitic magma. An "open" heat exchanger concept was identified whereby the heat transfer fluid would be circulated in direct contact with solidified and thermally fractured magma. The concept was tested in the melt zone of Kilauea Iki lava lake where an open hole, sealed test zone was created (12). During a five-day test period, energy extraction rates were found to increase with time (indicating growth of the fractured region). Extraction rates reached more than 10 times the expected value for a closed heat exchanger in the same borehole.

CURRENT ENGINEERING PROGRAM

In 1984, the Magma Energy Extraction Program became part of the Department of Energy's Geothermal Program. The objective of this follow-on program is to assess the engineering feasibility of the magma energy concept and to provide the data base needed for industry to evaluate economic feasibility. We are working to answer the question: Is magma generated power practical from an engineering point of view? The project was organized to address five areas: (1) overall system concept, (2) geophysics/site selection, (3) drilling, (4) energy extraction, and (5) magma characterization and materials compatibility. We have the ultimate objective of drilling into an active crustal magma body, emplacing energy extraction hardware, and conducting a medium-term energy extraction experiment. The location for this experiment has been selected in Long Valley caldera, California, where magma drilling targets have been identified and drilling is scheduled to begin in 1988.

System Studies

Two system analyses have been completed. The first was carried out by Well Production Testing (13) and included well and casing design, surface plant design, and energy extraction analysis. Major results from this investigation are: (1) a 6 km well drilled and completed into magma at Long Valley caldera was estimated to cost $16 M, (2) plant capital costs were estimated to be $1.45M per MW of installed electrical capacity, and (3) energy extraction rates of 20 MWe were predicted for the base case open heat exchanger system.

The second study was a combined Sandia/WPT evaluation of the economics of magma power generation (14). Economic calculations determined the price that would need to be charged for electricity in order to balance the costs of power generation and provide a real rate of return of 10% (before taxes but above inflation). A typical result is shown in Figure 1 where energy extraction rate and well depth were used as variable parameters. Well maintenance costs, surface plant capital costs, and plant operating and maintenance costs were included as were realistic plant lifetime and operating factor. Magma based electricity prices required are in the neighborhood of 80 to 100 mils per kilowatt hour. These prices are higher than current prices for fossil fuels and hydrothermal resources, but below current prices for new nuclear plants. Based on the uncertainties associated with well costs and energy extraction rates, the conclusion at this point is that magma appears to be in the same "economic ballpark" with other energy resources. The analysis identified well cost, well productivity, and well lifetime as the parameters most critical to the economics of magma power generation.

Geophysics/Site Selection

Early in the current program, twenty-one potential magma sites were evaluated in terms of suitability for conducting a long-term energy extraction experiment (14, 15, 16). This resulted in the selection of two primary sites: Long Valley caldera and the Coso Hot Springs area, both located in California. Existing geophysical data at these two sites were then evaluated in detail and additional surveys were conducted. Both of these sites provide reasonable magma targets, but Long Valley was selected as the primary site based primarily on the extensive geophysical, geological, and geochemical studies that had been completed in the area.

Rundle et al. (18) combined the seismic data at Long Valley to form a preliminary composite view of the magma chamber underlying the caldera. The inferred chamber was large, with dimensions on the order of the caldera diameter (20 km). Two cupolas were identified, extending toward the surface, at drilling depths of 5 and 7 km. A later overlay of published geophysical data (19) is reproduced in Figure 2. Two distinct anomalous regions associated with the inferred magma cupolas are clearly identified. Estimates of depth to the shallowest cupola in the southern resurgent dome area range from 4 to 7 km. Elbring and Rundle (20) obtained more detailed definition of the southern cupola by recording local earthquake events with a three-component seismometer emplaced in the bottom of a 900 m deep well. Their estimate of depth to the top of the anomaly is 3.7 km.

Recently Lawrence Berkeley Laboratory held a symposium on the Long Valley caldera that brought together current data and models for the caldera. Results from geology, geohydrology, geochemistry, seismology, potential field and electromagnetics studies were presented. New data continue to show anomalies in the basement beneath the resurgent dome. In addition, the first evidence of an anomalous region beneath Mammoth Mountain has emerged. New data also support location of the highest temperature hydrothermal system in the western portion of the caldera to the west of the resurgent dome.

Future magma energy support for geophysics in Long Valley will be for downhole measurements in the Long Valley exploratory well which will be spudded during 1988. Downhole measurements will avoid the attenuation and structural complications introduced by caldera fill and provide higher resolution data. Plans are to drill the well in three phases with downhole geophysical measurements conducted between each phase. These measurements may, in fact, lead to early termination of the drilling if a suitable magma target is not confirmed.

Drilling

Conceptually, deep crustal magma bodies can be drilled with the same technology used to core Kilauea Iki lava lake. The differences that must be considered are that a deep magma body will have an overlying high temperature hydrothermal system of considerable extent and the deep body will be at much higher pressure and contain dissolved gases. The temperature problem has been addressed first by designing an insulated drill string to control drilling fluid temperatures (21). Drilling fluid temperature affects the properties and degradation of additives, the strength and corrosion rate of tubulars, bit cooling, and borehole stability. The advantage of using an insulated drill string can be seen in Figure 3 where fluid temperatures were calculated for drilling 3000 ft into a magma body whose roof is located at a depth of 17,000 ft. An idealized temperature profile for Long Valley caldera was used that matches the heat flow data and shallow temperature logs. The calculations assume a 12.25 inch wellbore, 5 inch drillpipe, and a water flow rate of 350 gpm. Fluid temperatures reached in the conventional drillpipe without insulation are clearly unacceptable. The addition of a 3/8 inch insulation shell to the drillpipe has a large effect and reduces temperatures to acceptable levels throughout the 20,000 ft well. Pipe insulation also affects temperature distribution in the solidified magma region surrounding the hole. An example of this effect can be seen in Figure 4 which gives the radial temperature distribution when drilling reaches the 20,000 ft depth. Since rock strength is a strong function of temperature, the benefits of cooler drilling fluid may be crucial to hole stability.

While general wellbore stability problems were considered in the research project by Friedman (4), problems associated with creep were not treated. Two problems are of concern. The first is creep of the surrounding hot rock that could cause the wellbore to squeeze in behind the bit during drilling. The second involves reheating of the surrounding rock and creep closure of the well after circulation is lost. Both situations were analyzed using a finite element rock mechanics code (21). The results were generally encouraging. Displacement of the wellbore wall during drilling was only a few millimeters and, therefore, is not expected to be a problem. One result that addresses the second problem is shown in Figure 5. Displacements are shown as a function of time after a break in circulation which is assumed to occur exactly when the depth of 20,000 ft is reached. The figure shows that at least one day is available to regain circulation before significant displacement takes place.

Energy Extraction

The current engineering project is investigating energy extraction from silic magma systems which are most representative of magma bodies expected at western U. S. sites. Unlike basaltic bodies, the more viscous rhyolites will probably require direct contact fluid circulation to achieve economic energy extraction rates. Figure 6 shows a conceptual representation of a single well open heat exchanger system. The well is cased into the plastic transition zone and a concentric inner injection tube extends into the magma. The region surrounding the injection tube is cooled, solidified, and thermally fractured by circulation of the heat transfer fluid. Extent of the fractured zone is controlled by the rate of energy extraction. Beyond the fractured region, is a transition zone which behaves as a plastic solid and does not support fracturing. Cooling in the magma zone induces large scale natural convection that enhances heat transfer to the solidified region.

Initially, a simplified mathematical model of the open and closed energy extraction systems was developed (22) to address basic engineering questions. We found that energy can be brought efficiently from the magma to the surface using concentric pipes with counterflowing heat transfer fluid. Calculations show that the proper flow path is cold fluid down the annulus with hot fluid returning to the surface through the central core. Insulation of the core results in both higher wellhead temperatures and cooler fluid in the annulus. Insulation thickness of only 1/4 inch produces adequate wellhead temperatures and is sufficient to ensure a net heat gain from the overlying formation rather than a heat loss. The calculations also confirm that for a fixed magma heat transfer coefficient there is a flow rate that maximizes electric power production. Single well extraction rates of about 25 MWe were predicted with the simple model.

Recently, a numerical code named MAGMAXT was developed to more accurately model the energy extraction process (23). Two-phase compressible fluids are treated to fully evaluate flashing problems in the return pipe. By specification of the injection pressure and mass flow rate, the flow state throughout the circulation path is computed in an iterative marching procedure. The open heat exchanger is assumed to be a permeable annulus whose outer diameter can vary with depth according to the rate of heat transfer. Figure 7 gives temperature results for a high flow rate of 800 gpm. In this calculation, water was used as the heat transfer fluid and well geometry was based on the WPT well design for Long Valley (13). At this flow rate heat transfer occurs within the counterflowing fluids and in the magma zone between states C and D. The pressure-enthalpy diagram for this set of conditions is shown in Figure 8. As in the simplified model, optimum flow rates exist that maximize the rate of electric power generation. This can be seen in Figure 9 where an ideal Carnot cycle is assumed for the conversion of thermal to electric energy. Three curves are shown: (1) a closed heat exchanger without fluid/rock direct contact, (2) an open heat exchanger (case 1) with conservative estimates of fluid/rock heat transfer in the solidified zone, and (3) an open heat exchanger (case 2) with higher heat transfer characteristics to account for developing flow in the annulus and buoyancy effects not included in case 1. The conservative estimate of about 30 MWe per well must be reduced to account for more realistic power conversion cycles. We are currently working with the University of Utah to confirm our numerical energy extraction calculations, evaluate the effects of buoyancy assisted porous media flows, and develop realistic power conversion cycles.

Several additional conclusions were reached based on simulation of the energy extraction process with MAGMAXT. Heat transfer to the fluid in the solidified magma zone occurs essentially isobarically but with substantial volumetric expansion. The resulting density imbalance between the injection and return flow paths is sufficient to allow the well to flow as an open thermosyphon without pumping. In all cases analyzed, flashing to two-phase flow in the return line does not occur. Thus two-phase choking problems commonly encountered in geothermal wells is avoided. As expected, the extent of the solidified magma region was found to vary with depth. However, large variations in diameter only occur for low flow rates. For optimum conditions, the average diameter is approximately 10 to 20 m.

The open heat exchanger concept depends on fracturing of the solidified magma region. Theoretical models that describe fracturing of this region due to thermal stresses have been developed (12, 24). The analyses predict vertical and horizontal fractures even for large over-burden pressure. A series of experiments was carried out to verify the analytical models and to examine the qualitative features of initiation and propagation of thermal stress fractures in a solidifying melt (24). Simulant glass cylinders were axially cored, heated, and then suddenly cooled along their inner boundary. Extensive fracturing occurred and fracture distribution was in general agreement with theoretical predictions. Melt solidification experiments were conducted using simulant glass in an induction furnace with a central cooling tube passing through the melt. The outer melt zone was maintained at 1000°C while water was circulated through the cooling tube giving an inner temperature of about 150°C. This experiment produced a solidified zone with a large number of horizontal and vertical fractures. In the actual open heat exchanger, secondary fracturing processes, not yet evaluated, are expected to play a significant role in the formation of the fractured region. Fluid flow in the primary fractures will have two effects: (1) creation of secondary thermal fracturing normal to the primary fractures, and (2) hydraulic extension of the fracture due to pressure build up. Future experiments are designed to evaluate these processes.

Geochemistry/Materials

=> Completion

While the previous geochemistry/materials effort of the research project dealt completely with basaltic systems, the current effort is focused on rhyolitic systems typical of Long Valley. Sulfidation, a major problem in basaltic magmas, is not induced by rhyolitic magma. Here, the main corrosion problem for most alloys is oxidation. Four specific problem areas are being investigated: (1) characterization of rhyolitic magma typical of Long Valley, (2) materials compatibility in this magma, (3) vesiculation hazards of drilling into a volatile-rich rhyolitic magma, and (4) solution transport in the fractured open heat exchanger.

Mineral compositions and volatile concentrations have been determined for crustal magma bodies in the Long Valley and Coso locations. Extensive testing of metals in the expected volatile rich magmatic environment at 850°C and 200 MPa lead to the conclusion that nickel based superalloys have very good chemical resistance and strength in this environment (25). Reaction rates between alloys and silicates are significantly reduced at normal heat exchanger operating conditions of 500°C and 50 MPa.

An experimental facility was recently completed to measure silicate dissolution rates and solution composition in open direct contact heat exchangers. The potential for loss of permeability due to precipitation of secondary minerals will also be evaluated. The importance of several different mechanisms on reaction rates will be assessed. This includes temperature which has a large and measureable effect, solution composition, defect concentration, and hydrodynamic effects.

LONG VALLEY EXPLORATORY WELL

A deep exploratory well is planned for Long Valley caldera. The well will be drilled in the southern portion of the resurgent dome near the peak of recent uplift within the caldera (roughly 0.5 m uplift since 1979). The primary objective of the well is to determine the nature of identified geophysical anomalies at 4 to 7 km depth that have been interpreted as magma. Surface geophysical measurements have reached a point of diminishing return and new information from depth is needed to more accurately characterize anomalous regions beneath the dome. A deep hole at this location will also provide data to test the accepted hypothesis that a long lived magma body has existed beneath the caldera for a time period of about one million years. If high temperature near magmatic conditions are reached, the well can be used to test newly developed drilling technology, evaluate engineering materials, and confirm heat transfer calculations. The well is planned in three stages. The first stage would penetrate caldera fill, enter basement, and set casing to a depth of 7,000 to 8,000 ft. The second stage would extend the hole to a depth of about 14,000 ft where casing would again be set. The final stage would reach a total depth of 18,000 ft. Between each drilling phase, the well will be open for downhole geophysical measurements. Critical programmatic experiments include: temperature and heat flow measurements, fluid and gas sampling, in situ stress measurements, physical and chemical analysis of limited core samples, permeability measurements, and passive and active seismic observations. The data from these measurements will be evaluated to determine if the drilling should proceed into the next phase.

If the well is drilled to total depth it will be the world's deepest observation port into an active caldera. Thus, there would exist the opportunity for numerous scientific add-on experiments that could lead to a better understanding of the evolution and dynamics of magmatic systems. If an active magma target is confirmed, the project will proceed to a final phase where the magma body will be drilled and the long term heat extraction experiment carried out.

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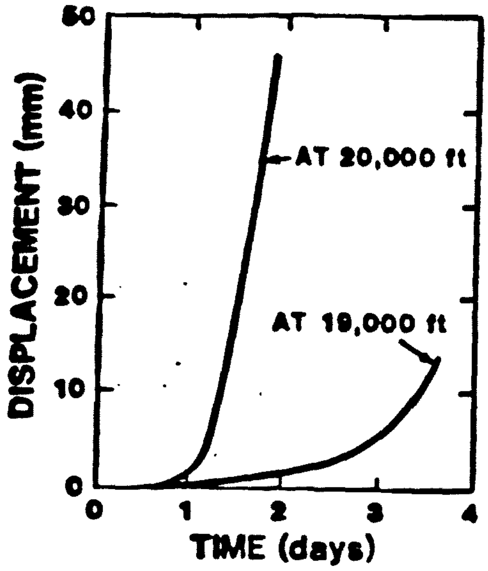

Figure 5. Wellbore displacement after circulation is stopped

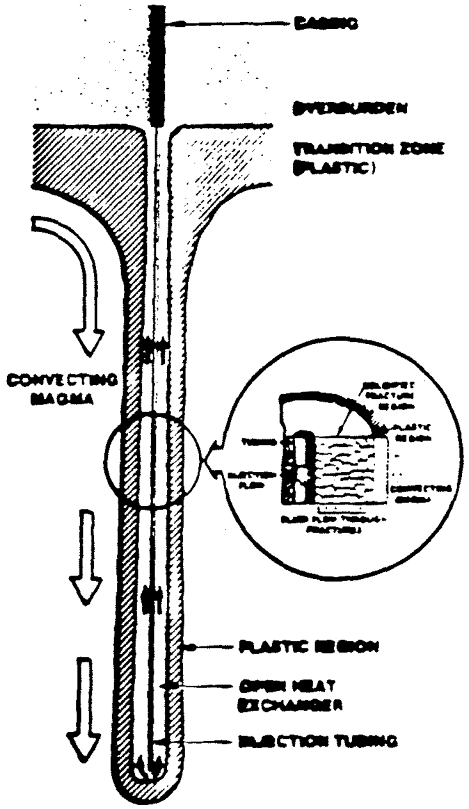

Figure 6. Conceptual representation of a single well open heat exchanger system.

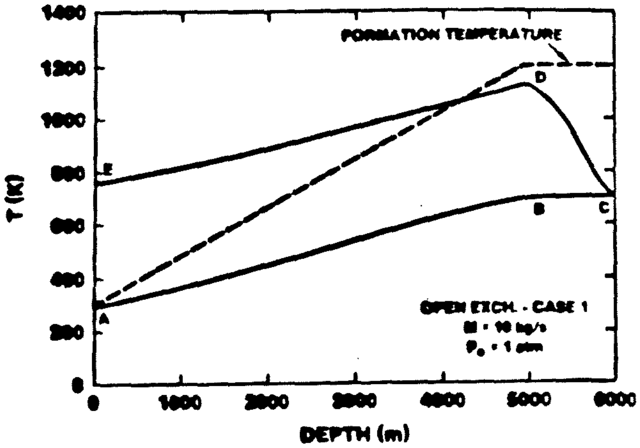

Figure 7. Fluid temperatures for circulation in an open heat exchanger

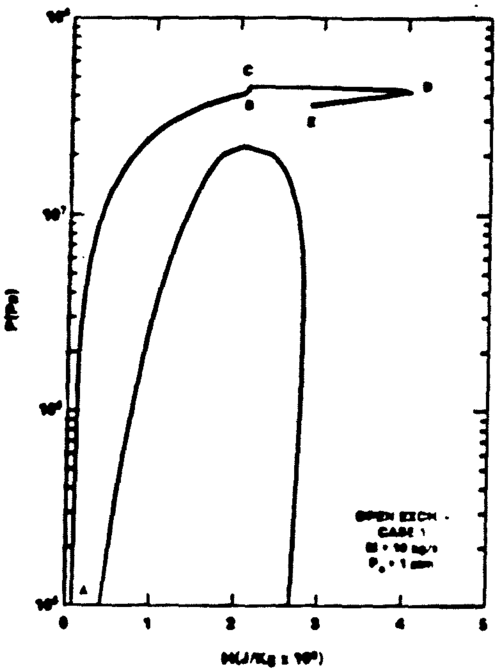

Figure 8. Pressure-enthalpy diagram for magma heat extraction

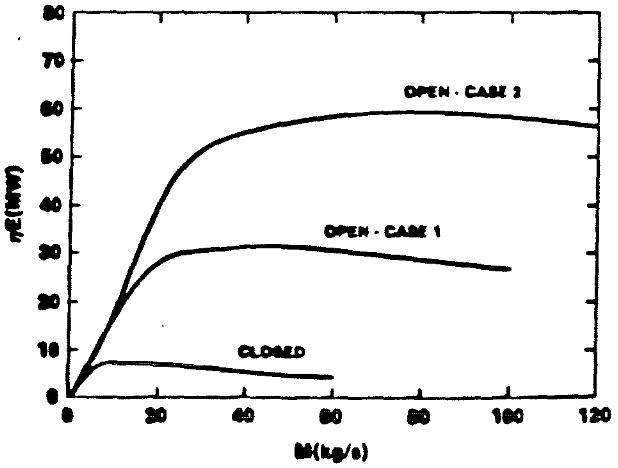

Figure 9. Energy extraction rate as a function of mass flow rate

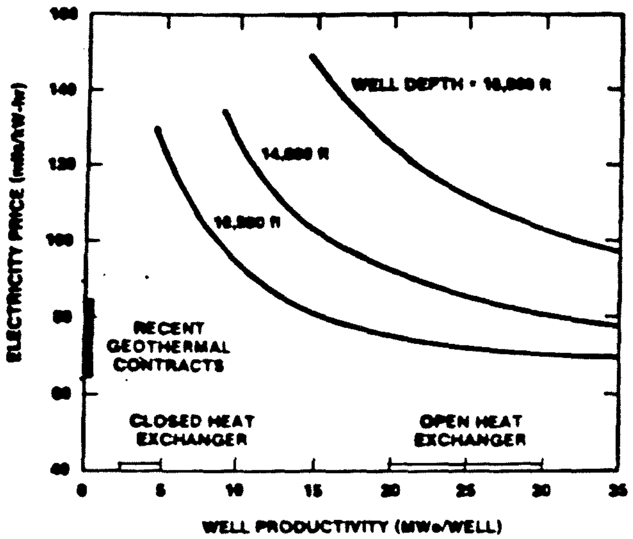

Figure 1. Effect of well depth and productivity on magma energy costs

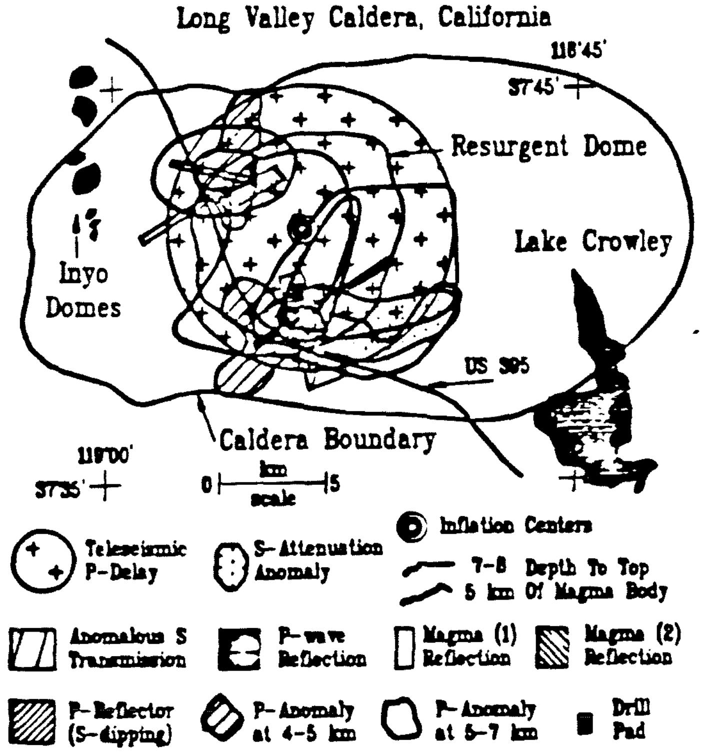

Figure 2. Geophysical anomalies in Long Valley caldera

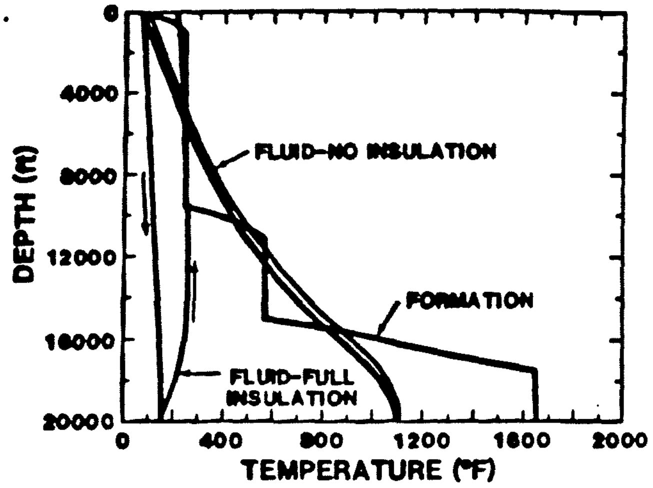

Figure 3. Fluid and formation temperatures in a magma well Long Valley

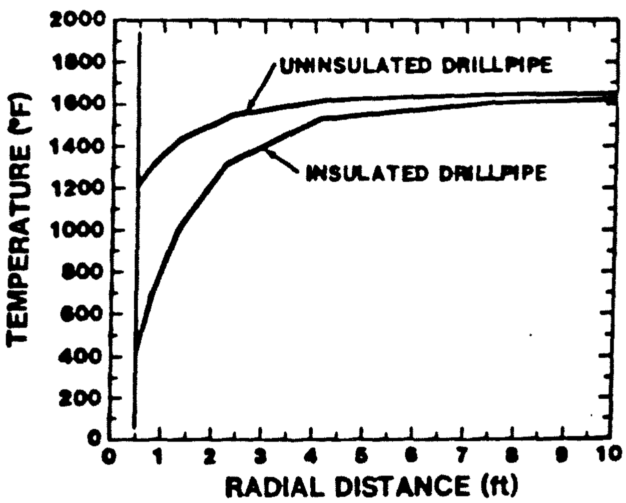

Figure 4. Bottom hole formation temperatures after drilling to 20,000 ft in Long Valley