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GEOSCIENCES RESEARCH
AT LOS ALAMOS RELATED TO NON-NUCLEAR ENERGY

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1. Introduction

Los Alamos Scientific Laboratory (LASL) has had a continuing interest in the earth sciences because they relate directly to containment of radioactivity in underground weapons testing programs, facility siting, and environmental monitoring. The past emphasis has been in seismology, rock mechanics, and experimental high-pressure geophysics. In response to national needs for energy resources, the Laboratory has expanded its interests. The present major non-nuclear energy related research is the hot-dry-rock (HDR) geothermal energy project.

As a consequence of this project and anticipated future national needs (and ERDA programs) in energy and energy related resources, research activities have been expanded to include igneous and volcanic processes, geophysical hydrodynamics and geochemistry.

This paper briefly describes the HDR - geothermal energy project, the geoscience activities directly in support of it and the basic geoscience research program of the Laboratory focused on the solid earth. There also is a significant LASL effort in non-solid earth research, namely atmospheric and space studies, which will not be discussed here.

2. Hot-Dry-Rock (HDR) Geothermal Energy Project

A vigorous effort to develop the so-called HDR technique of obtaining geothermal energy has been in progress at the LASL since 1970. Two holes have been drilled into Precambrian basement rocks near the southwest rim of the Valles Caldera, in the Jemez Mountains of northern New Mexico (Fig. 1). The basic concept is to drill a hole into hot but dry and impermeable hydrologically tight rocks, create a large planar crack by hydraulic fracturing, drill a second hole and intersect the fracture, and set up an artificial circulation loop in which cold water is pumped down one hole and hot water is extracted from the other. The temperature difference can be used, in principal, to generate power (Fig. 2). This concept has been described in a number of papers (West, 1973; Smith, 1972, 1974; Brown and others, 1973; Tester, 1974).

The principal problems anticipated and experienced in this technique are: (1) drilling techniques in hot hard crystalline rocks are not well developed, (2) techniques for creation, control and management of deep hydraulic fractures in crystalline rocks are rudimentary, (3) neither theory nor experience permit prediction of fracture geometry or mode of growth and reliable detection methods are in the development stage, (4) problems of solution of crystalline rocks by circulating hot aqueous solutions may be severe, particularly in recondensation in the cooler parts of the system such as the heat exchanger, (5) corrosion of metallic parts of the energy conversion system may be significant, and (6) heat transfer from the rocks to the circulating fluid must be optimized, perhaps by the thermal stress cracking and the prevention of channeling of the flow over the crack surface.

One of the most severe problems encountered by all attempts to drill in hot, geologically young volcanic areas for geothermal purposes has been uncertainty of the structure of these terranes, in spite of extensive surface exploration by geophysical and geological methods. Deep drilling at Kilauea, Hawaii, Marysville, Montana, and Jemez Mtns., New Mexico, presented each project with important surprises, many involving unanticipated hydrological situations which were simply not predictable from surface data. Most serious has been the effect of these ground water problems on predicted temperature at depth. Fortunately for the Los Alamos HDR project, as the drill hole was deepened, these problems became less severe and at present depth (2928 m) the geothermal gradient is nearly linear at about 60°C/km, and the bottom hole temperature (197°C) is high. Rock permeability measured in the laboratory and estimated from *in situ* flow measurements is low (.2 microdarcies). Hydraulic fractures have been made and their location successfully mapped using down-hole instrumentation, principally seismology. A large number of bottom-hole and associated experiments will proceed until sufficient data exist to confidently locate the fracture and after characterization of the terrane at the hole bottom. In general, however, the conditions are favorable for proceeding with the dry hot rock demonstration.

We feel that a major result of this project is that a new technology, namely controlled deep drilling in hot hard rock and hydrofracturing at depths of several kilometers, has been created. The hydrofracture location can be mapped and perhaps controlled. This technology probably has applications in geological engineering which transcend geothermal energy alone.

3. Geoscience Activities in Support of HDR-GTE

Research activities in geothermal energy include: 1) geochemical and petrological investigations of drill cores; 2) physical and mechanical properties of the cores, in situ and in the laboratory, 3) seismology, 4) experimental and numerical investigation of the chemical interaction of granite and hot aqueous solutions, 5) field and laboratory investigations of heat flow and the thermal properties of the cores, 6) characterization and selection of future HDR sites, (in cooperation with ERDA, USGS, Universities and industry), and 7) investigation of igneous and vo .anic systems.

Field activities in the last two catagories include 1) the Valles Caldera and Rio Grande rift of northern New Mexico, 2) the Southern Cascades of northern California, and 3) San Francisco Peaks, Arizona - in cooperation with the USGS.

Investigations of solution geochemistry have proved to be especially interesting because they have possible applications in solution mining, suggesting coupled geothermal energy and mineral extraction operations.

Figure 3.: shows a number of the fundamental geoscience problems related to the evolution and state of igneous-related geothermal systems. Some of the most useful results obtained to date have been obtained on down-hole measurements and on cores from the LASL geothermal drill hole (GT-2). These results were summarized in a special session of the American Geophysical Union, Annual Spring Meeting. (See EOS, Trans. AGU, 1976, abstracts V 80-90; 106-113).

4. Characterization of HDR Resources of the United States

A major geoscience activity of the Laboratory involves the characterization and assessment of the HDR geothermal resources of the United States - a cooperative effort involving scientists from the USGS, ERDA, several ERDA laboratories and universities. White and Williams (1975) point out that the heat stored in the conduction-dominated parts of the crustal rocks of the United States is vast. Smith and Shaw (1975) identified approximately 19 volcanic centers likely to contain magma and HDR resources; these centers must be considered the high-rank deposits of geothermal energy. Some of these being investigated by ERDA at present; others are being considered for future exploration (see Fig. 4). Much of the western U.S. is underlain with crustal rock likely to be hot enough (approximately 150°C) at sufficiently shallow depths (approximately 10 km) to be useful for power generation (Figure 5). The magnitude of the geothermal resources is very large with respect to man's present energy consumption (see Figure 6 and Table 2), although required extraction technology is at the limit of our current capabilities.

5. Basic Geosciences Research at Los Alamos

Basic geosciences research activities at LASL include geophysical hydrodynamics, thermochemistry of minerals, aqueous phases and rock-fluid systems, the application of shock wave and other high-pressure techniques to investigations of the equation-of-state of rocks and minerals to questions regarding the physics and chemistry of the earth's interior, and preparation of high priority crystals for experimental studies.

Brief thumbnail sketches of these activities are presented in Table 2; a more detailed list of some of LASL's basic geoscience research activities can be found in the recently published "Summaries of Physical Research in the Geoscience," ERDA-76-44, (p. 13-26).

Field activities in basic geosciences are focused on areas related to HDR geothermal energy, namely: 1) The Jemez Mountains-Rio Grande program provides information on the geothermal energy potential of the Rio Grande rift zone and its environs. Problems of seismic risk to LASL facilities are important to ERDA and LASL as well as interesting questions in volcanology (such as caldera formation) and tectonics (evolution of the Rio Grande rift). Many investigators believe that the Rio Grande rift zone may be an incipient spreading center which may eventually split the American continent (see Figure 1). 2) The Cascades program will deepen our understanding of andesite volcanoes, which are typical of the entire circum-Pacific volcano-seismic belt (see Figure 7). Some andesite volcanoes are also among the world's most dangerous and interesting in terms of their behavior and tectonic setting. 3) Investigations of active volcanoes and their eruptions provide data of interest in geothermal energy research, such as the composition of the volcanic gas phase, and the basis for working models of magma chambers, their location, size, and shape. Computer modeling of the thermal evolution of these systems bears directly on both geothermal resources (e.g. Smith and Shaw, 1975) and ore deposition (Cathles and Norton, 1975); eruption phenomenology (see Figure 9) is a small but very interesting part of the behavior of igneous systems.

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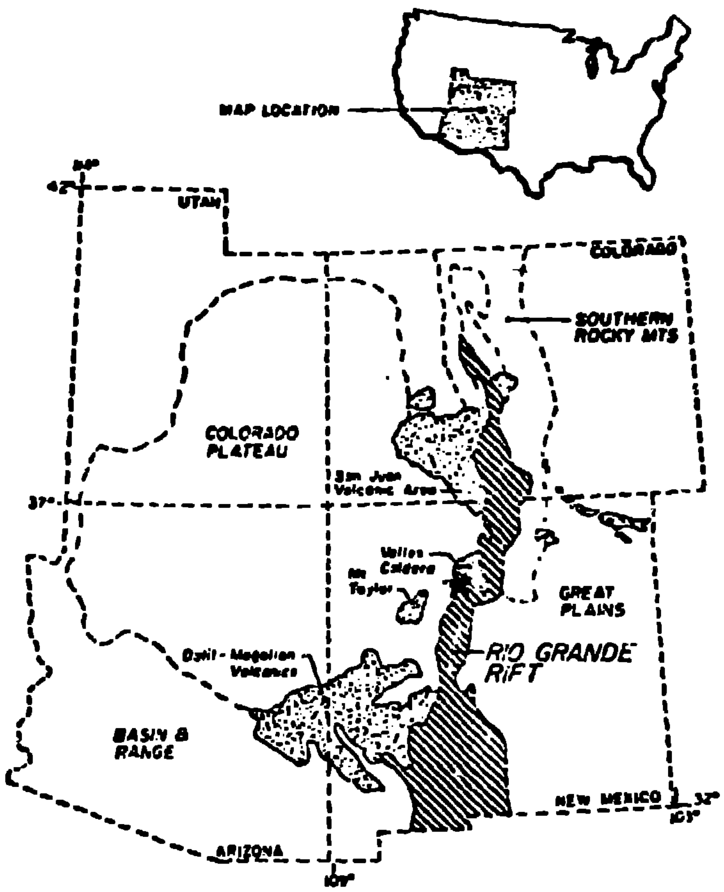
6. Conclusion

We believe that the need for energy and therefore energy-related resources will continue to grow. In response to this need, the Laboratory recognizes and stresses the importance of application of high technology to solution of technological problems of engineering the solid earth. The hot dry rock geothermal energy project is an excellent example of how this method can work. The geosciences were an important support activity to many activities of the AEC, but it is likely that the earth sciences will play a much more central role in the accomplishment of ERDA's missions. LASL's geosciences research program is designed to provide close support for specific engineering projects, to research important and relevant basic topics tied to these projects and to provide effective professional liaison to the earth sciences community at large, particularly the USGS and universities.



The Rio Grande Rift

Figure 1. Generalized map of the Rio Grande rift of New Mexico and southern Colorado showing the location of the Jemez Mountains. The Los Alamos HDR geothermal energy project is located on the southwest margin of the Valles Caldera, in north-central New Mexico, noted by the star.

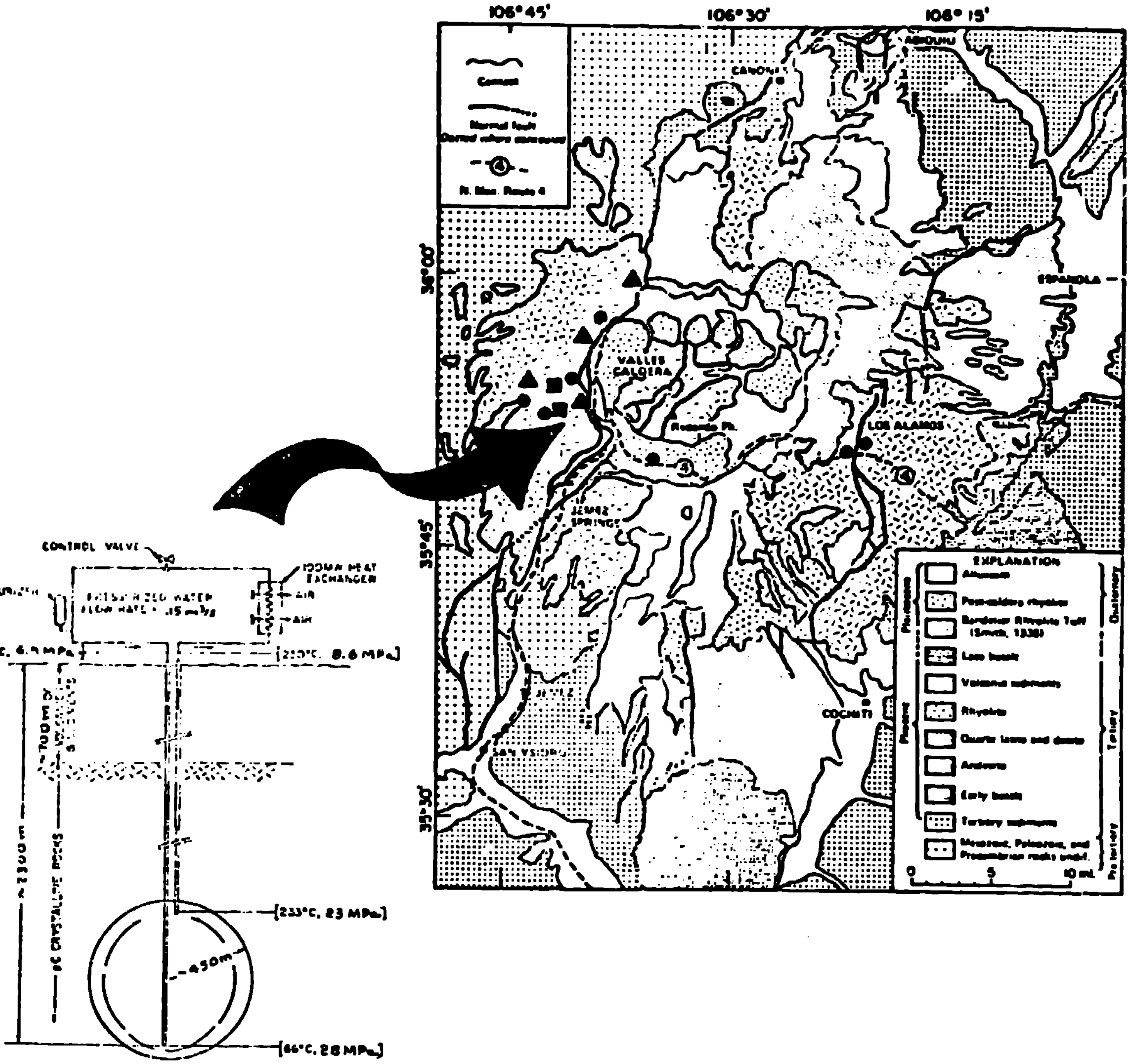


Figure 2. Lower left is sketch showing the initial basic engineering concept of the dry hot rock geothermal energy project and the configuration of the energy extraction experiment. The upper right figure shows the location of the Los Alamos drill holes (GT-2 and EE-1). The map shows geology of the Valles Caldera and its environs (after R.L. Smith and R. A. Bailey, U.S.G.S.). Shown are location of major test holes (squares), heat flow holes (circles and triangles). The actual down hole system currently bottoms at 2,928 m and 197°C.

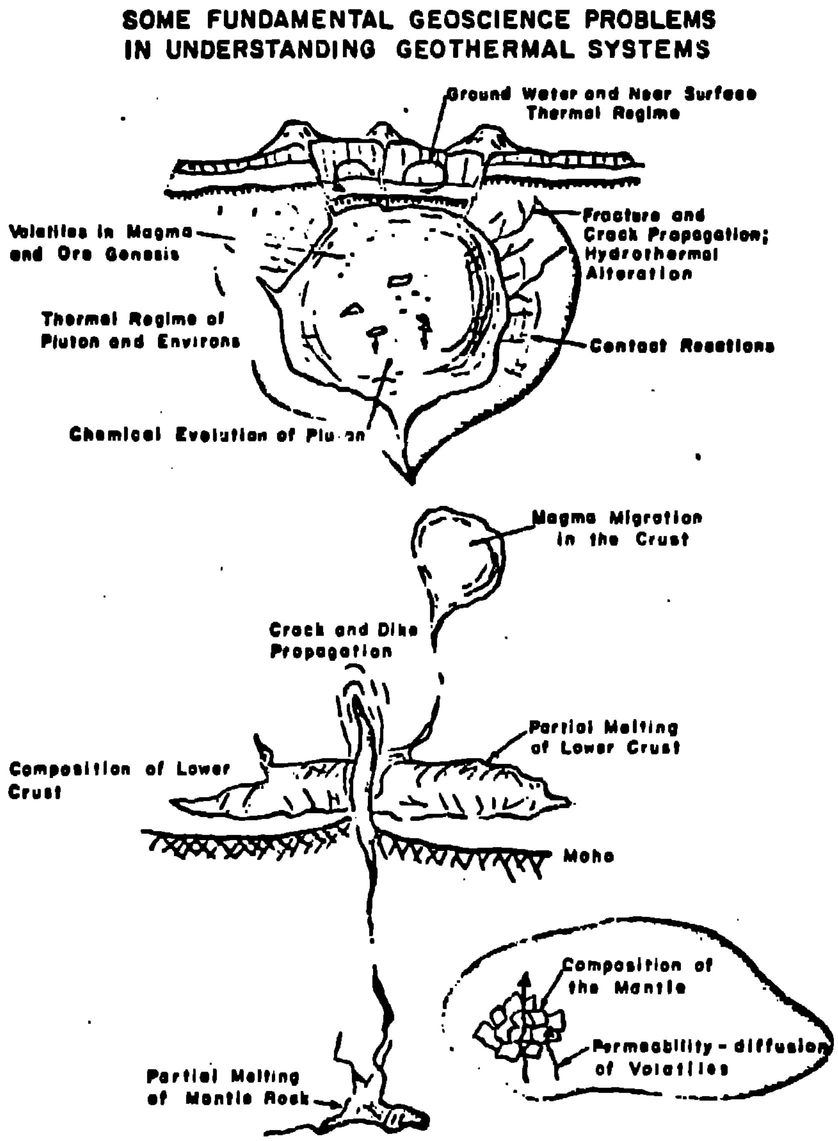


Figure 3. Some of the fundamental geoscience questions related to igneous-related geothermal systems.

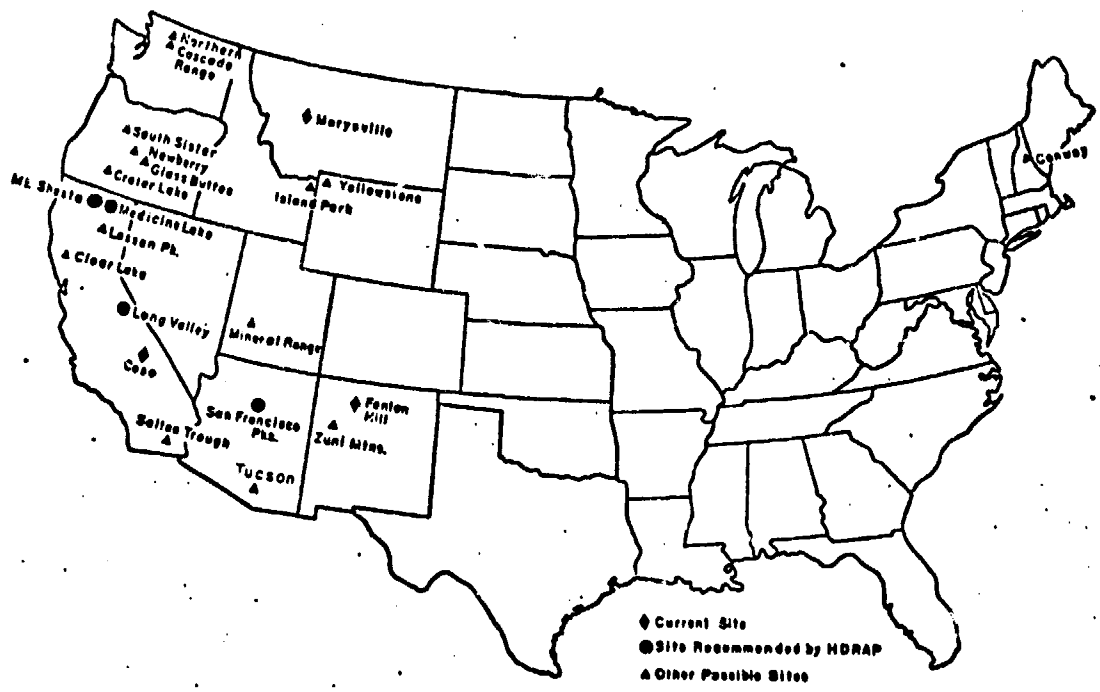


Figure 4. Locations where igneous-related HDR geothermal resources exist.

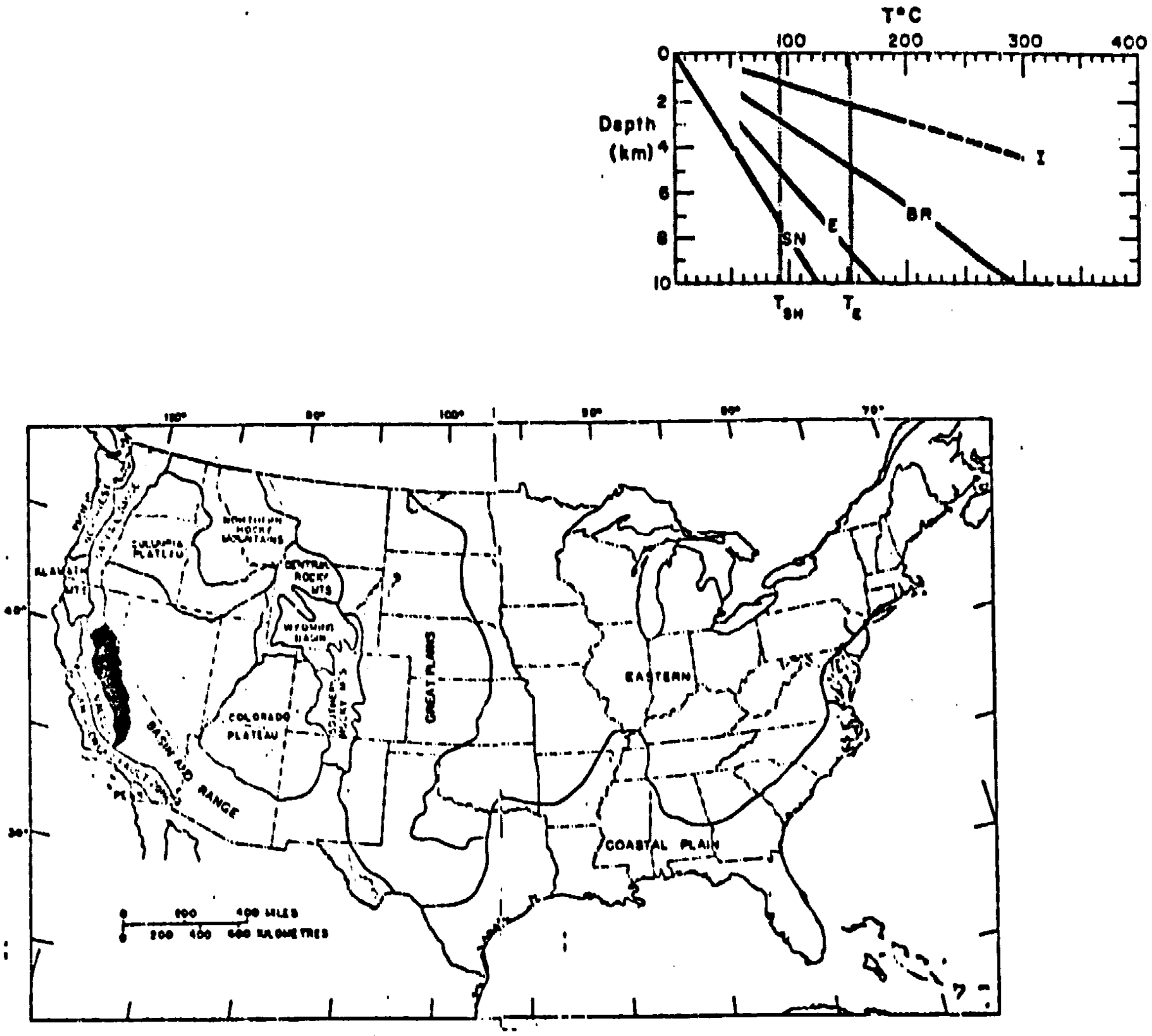


Figure 5. Map of the United States showing the three principal observed heat flow regimes; upper right is the approximate thermal gradient in each province. The Sierra Nevada province, shown in black on the map and (SN) on the profile has little geothermal potential. The Eastern province, shown in white, and (E), has geothermal potential only at depths approaching 10 km. The Basin-Range and similar areas, shown in grey, and (BR) has considerable geothermal potential, and igneous-related systems (see Figure 4) have geothermal gradients like (I) or greater, contain high rank geothermal resources at shallow depth.

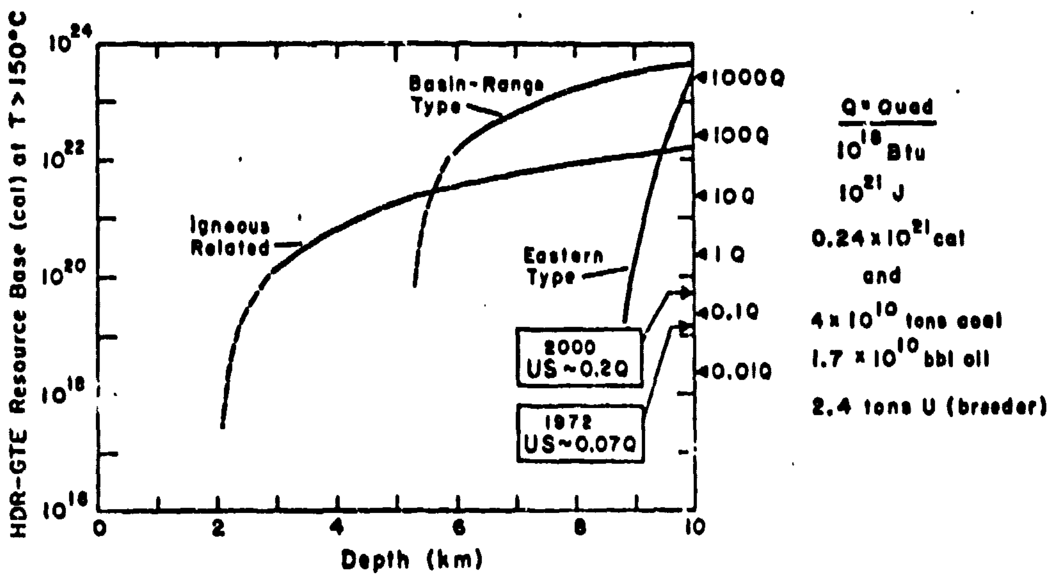


Figure 6. The estimated HDR-GTE resources of the United States given as a function of depth, in several different types of crustal setting. The highest rank deposits of geothermal energy expecially at moderate depth (<6 km), are stored in igneous-related sites; at greater depth in Basin-Range type crust large amounts of disoersed heat are stored. Only at greater depth is Eastern type crust important.

SOME PROBLEMS IN STRATOVOLOCANOES
OF THE CIRCUMPACIFIC OR CASCADE TYPE

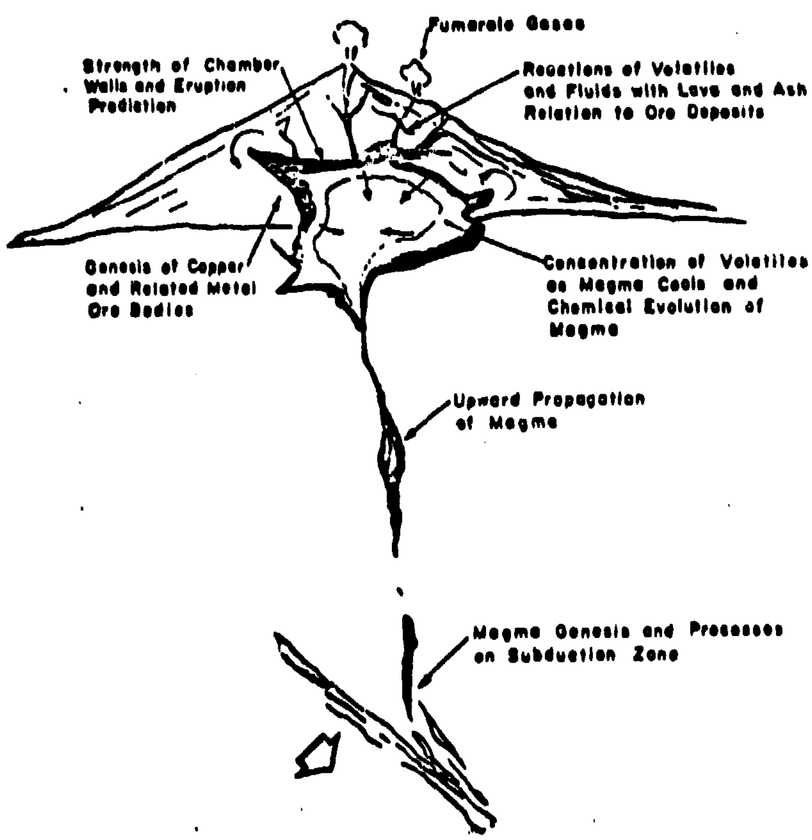


Figure 7. Schematic geologic crossection of Cascade type stratovolcano.

TABLE I

OUTLINE OF THE GEOSCIENCES RESEARCH ACTIVITIES AT LASL

Hydrothermal Alteration in Crystalline Rocks	Study of morphological, porosity, permea- mineralogical changes in crystalline rocks with time due to aqueous fluids at 3,000 to 30,000 psi and 300 to 800°C. Natural rock, "pure" natural minerals, and synthetic minerals in various solid solution ratios are subjected to distilled water carbonate, chloride, and natural solutions; also possible solutions for mineral extraction in solution mining. Some experiment will be performed in systems with continuous monitoring of of solutions.
Calorimetric Research in Geochemistry	Measurement of heat capacity as a function of temperature up to 350°C or more for aqueous solutions of NaCl, KCl, $CaCl_2$, Na_2SO_4, $FeCl_2$, and $FeCl_3$ for calculation of solubilities as a function of temperature for geothermal fluids. Measurement of enthalpy of formation at 298°K and heat capacity from low temperature to 1000°C of minerals, including pure synthetic minerals, relevant to the geothermal power program.
Self-Diffusion Coefficients of Atoms in Rocks	Investigation of mechanism of metasomatic rocks by measurement of jump times in crystal lattices with NMR.
Dynamic High-Pressure Studies on Materials of Interest in the Geosciences	Measurement at high, explosion-induced, pressure of shock and particle velocity and density in iron, sulfur, silicon, nickel alloys for modeling the earth's core in terms of composition, seismic wave propagation, density, and dynamo action.

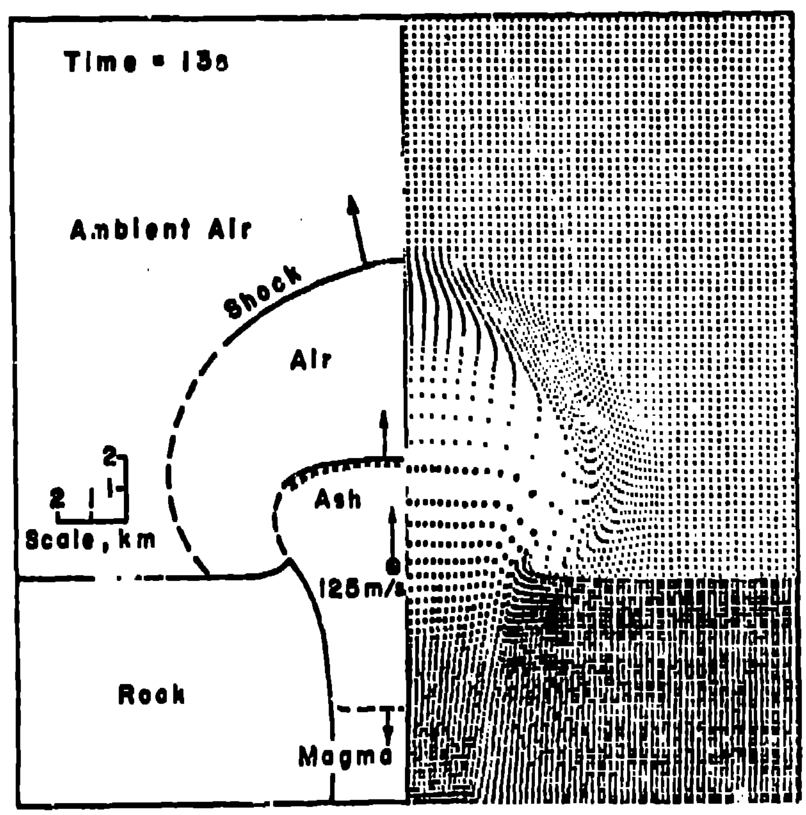


Figure 8. Computer Simulation of Eruption from Large Silicic Magma Chambers. (The Bandelier Tuff - 13 seconds old.) (After Sandford, Jones and McGetchin, 1975).

Remote Sensing Applied to Geological Problems	Development of techniques for recovering compositional and structural data from aerial imagery. Mineralogical mapping has been done on extra-terrestrial bodies by use of reflection spectroscopy, namely infrared wavelength shifts due to positions in crystal structure. These and other mapping techniques may be made applicable to some areas of the earth by evaluating effects of atmospheric absorption and surface contaminants. Several very advanced image enhancement projects also show promise.
Igneous Processes	Existing commitments to engineering projects in geothermal energy generate requirements for knowledge of volcanic terranes, the physics and chemistry of rock-melt-vapor systems and the mechanics of geological processes involving magmas. This program conducts research in the field and laboratory directed at the behavior of rock melts in the earth's interior and at eruption sites, using field and laboratory data to construct mathematical models for geological processes involving molten rock bodies and their environs.
Rock Mechanics and Geophysics	One of the most important aspects of the geothermal program at LASL is the production and management of large hydraulic fractures in hot rock bodies in the ground. This research program includes laboratory and theoretical work on fracture mechanics, detection methods and also the general geophysics of volcanic and geothermal areas.

Observational and Analytical Petrology and Geochemistry	The fundamental research capabilities required for support of field and laboratory studies in the earth sciences are in the analysis of rocks for mineralogical, chemical, and isotopic composition. Geochemical laboratory studies include analytical activities and experimental studies at elevated pressure and temperature. The goal of this research is to provide quantitative data regarding the conditions of origin and age of specific rock- or rock bodies of interest.
Environmental Geology and Hydrology	Investigations of the local geology and hydrology near Los Alamos directed at problems of ground water and waste management.
Seismology	Downhole seismology has proved to be a very effective means of determination of fracture orientation in the induced fracture system associated with the HDR project. Also, the regional seismic array provides both important data for possible earthquake hazards to LASL facilities and interesting data regarding the present seismicity and tectonics of the Rio Grande rift, a topic of much current geophysical interest.

TABLE 2

HDR RESOURCES OF THE UNITED STATES
(IN UNITS OF QUADS)

	IGNEOUS RELATED	BASIN-RANGE TYPE	EASTERN TYPE	SIERRA NEVADA	TOTAL
% OF TOTAL SURFACE AREA	.093	24.8	75.3	.87	
TOTAL RESOURCES $d < 10$ KM $T > T_{\text{SURFACE}}$	96 Q	8250 Q	15469 Q	130 Q	~24000 Q
RESOURCES AT $T > 150°C$ $d < 6$ KM	13 Q	54 Q	0	0	67 Q
RESOURCES AT $T > 150°C$ $d < 10$ KM	56 Q	1840 Q	1160 Q	0	3056 Q

1 QUAD = 10^{18} BTU = 10^{21} J = 0.24×10^{21} CAL

APPROXIMATE TOTAL U.S. CONSUMPTION FOR 1972 WAS .07 Q; ESTIMATED 2000 A.D. ~.2 Q