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**Solid Earth Geosciences
Research Activities at LASL
July 1 - December 31, 1974**

Compiled by
T. R. McGetchin

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scientific laboratory
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SOLID EARTH GEOSCIENCES
RESEARCH ACTIVITIES
AT THE LOS ALAMOS SCIENTIFIC LABORATORY (LASL)
1 JULY TO 31 DECEMBER 1974

Compiled by

T. R. McGetchin

ABSTRACT

Los Alamos Scientific Laboratory 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 efforts in energy related research are the dry hot rock geothermal energy project and the rock melting subterrene, an electrically powered, high-temperature experimental drilling technique.

A geoscience group was formed at LASL in 1974 to support existing and future geo-related engineering programs, to maximize the scientific yield of the applied programs and to conduct a basic research program related to energy and earth resources. The primary interests of the group are igneous geology and solid earth geophysics - the origin, emplacement, and chemical evolution of plutons and volcanoes, and the nature of heat and mass transfer in the earth's interior. The research program includes seismology, rock mechanics, experimental high-pressure geophysics, experimental geochemistry, observational petrology and geochemistry, field geology, and modeling by theoretical numerical and physical simulation.

Research activities in support of 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, and 5) field and laboratory investigations of heat flow and the thermal properties of the cores. 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.

Basic geoscience research activities in other divisions of LASL include preparation of high-purity crystals for experimental studies, thermochemistry, and the application of shock wave and other high-pressure techniques to investigations of the equation of state of rocks and minerals of the earth's interior.

Basic research of the geoscience group is focused on three field activities: 1) The Jemez Mountains-Rio Grande program provides information on the geothermal energy potential of the Rio Grande rift zone and problems of seismic risk to LASL facilities as well as probing interesting questions in volcanology such as caldera formation. Many investigators believe that the Rio Grande rift zone may be an incipient spreading center which may eventually split the American continent. 2) The Cascade program will deepen our understanding of andesite volcanoes, which are typical of the entire circum-Pacific volcano-seismic belt. Some andesitic volcanoes are known to contain important ore bodies and are a potential geothermal energy source. The andesitic 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.

I. GEOSCIENCES RESEARCH AT THE LOS ALAMOS SCIENTIFIC LABORATORY - AN OVERVIEW

A. Background

The Los Alamos Scientific Laboratory was created for weapons research, design, and development. The earth sciences are an important part of the weapons testing program, especially since test ban treaties require knowledge of both yield and containment problems. These considerations led to a commitment of the Laboratory to seismology and some aspects of rock mechanics. Materials chemistry and radiochemistry research are an important part of the weapons design and fabrication mission of the Laboratory and the weapons test programs require collection and analysis of both field test data and samples. Environmental concern regarding containment of radioactive materials underground also generated geoscience activity at the Laboratory.

With time, however, the Laboratory has expanded its interests widely; one particularly active area of research currently is in a wide range of energy problems relating to production, transmission and storage. Among these are two vigorous applied programs with the Energy Division (Q) at LASL, one focused on geothermal energy and the other on advanced rock penetration (drilling) techniques.

The Laboratory's principal experience and capabilities of significance to the earth sciences fall in three areas: materials science, high-pressure and high-temperature physics, and field studies of weapons effects. These capabilities and their relationship to the earth sciences are summarized in Table I-I. Some LASL geoscience activities are illustrated in Figure I-1.

B. Establishment of the Geosciences Group

The geosciences group was formed in May of 1974 and conceived to:

- support the existing applied programs and future geo-engineering projects;
- maximize the scientific yield from the applied projects;
- explore fundamental geoscience, especially those questions related to energy and resource matters.

The specific goals and objectives of the geosciences group at LASL are:

- to provide technical continuity and a local focal point for sustained research efforts in the geosciences throughout the Laboratory and to seek new and effective ways to apply

geoscience knowledge to the functions and missions of LASL as they evolve;

- to provide both direct and advisory support for the applied engineering and demonstration programs in energy, resource, and environmental areas;
- to conduct research and contribute understanding of the origin and emplacement of igneous rocks, volcanic phenomena, and the nature of the dynamics of heat and mass transfer in planetary interiors.

It is anticipated that the geosciences effort will be organized with equal emphasis in supporting research roles and in basic research activities. These programs are illustrated in Fig. I-1 and listed in Table I-II.

The organizational structure of LASL and the geosciences group is shown in Fig. I-2. At present the geosciences group contains three staff members and one secretary. Current staff, consultants, visiting staff members, and summer graduate students are listed in the Appendix. Additional staff positions are sought in the following areas: igneous field geology, geophysical mathematical modeling, experimental and field geophysics, experimental rock mechanics, remote sensing and planetology, and experimental petrology.

The existing laboratory facilities of the geosciences group include a library, a rock mechanics laboratory, and a petrography laboratory. The rock mechanics laboratory consists of permeability testing apparatus (designed and fabricated in this laboratory), a compression and tensile testing unit (manufactured by Instron), two large presses -- one manufactured by Tinius Olsen with 1400 mPa capacity, the other manufactured by Research Incorporated (RI) with 350 mPa capacity, -- an RI hydraulic power supply ($590 \times 10^{-6} \text{ m}^3/\text{s}$, 21 Mpa) which serves both presses, and other minor equipment, and has been in operation since 1973. The petrography laboratory contains a Zeiss Universal petrographic microscope, an Olympus stereomicroscope, and a Polaroid MP-4 photographic unit; the laboratory was formed in November 1974.

A reference library, called the Geosciences Library, has been established in cooperation with the LASL Information Services Division. It is housed in TA-33 (Building 114) for the general use of Laboratory personnel working in geoscience related projects. The core of the collection is a set of about 34 journals, given to LASL by Dartmouth College. The collection includes many long runs

TABLE I-I
THE UTILIZATION OF LASL CAPABILITIES FOR NATIONAL NEEDS IN ENERGY AND RESOURCES
THROUGH THEIR APPLICATION TO THE EARTH SCIENCES

<u>Area of Research</u>	<u>LASL Capability or Experience</u>	<u>Activity in the Geosciences</u>	<u>Application to Present or Future Program Needs and/or National Needs</u>
Materials science	Analytical chemistry; isotope and radio-chemistry; material fabrication; thermo-dynamics.	Observational, analytical, and experimental petrology and geochemistry and isotope studies.	Advanced rock penetration methods; resource problems; ore extraction and exploration; geothermal solution geochemistry; isotopes in natural systems.
High-pressure and high-temperature physics	Equation-of-state studies on metals, oxides, and minerals; transport properties.	High-pressure experimental and theoretical geophysics.	Provides fundamental knowledge of the earth's interior and processes active there.
Field studies of weapons effects	Instrument design and development; high-speed photography and other documentation techniques; rock mechanics; seismology; numerical modeling in continuum mechanics.	Field and theoretical studies in igneous processes; ore deposits and volcanology; eruption phenomenology.	Geothermal energy site evaluation; ore deposits; volcanic hazard evaluation.

TABLE I-II
RESEARCH PROGRAMS IN THE GEOSCIENCES*

<u>Research Program</u>	<u>Description and Goal</u>
Supporting Research for the Geothermal Energy Project	Laboratory and theoretical studies of reactions and kinetics of hot aqueous solutions and crystalline rock; rock mechanics and physical properties of porous and fractured rock; hydraulic fracturing; petrologic and geochemical studies of cores from GTE drill holes; evaluation and selection of future sites.
Supporting Research for the Rock Penetration (Subterrene) Project	Petrographic studies of rocks and glasses produced by melting penetrators; site documentation; properties of silicate melts.
Jemez - Rio Grande Program	Geological, petrological, geophysical investigations directed towards understanding the origin, mode of emplacement, eruption mechanisms, present thermal, dynamic and stress state, and chemical evolution of the Valles Caldera and its lavas; the relationship of the Jemez complex to the Rio Grande rift; the tectonics and seismicity of the Rio Grande.
Cascade Investigations Program	Geological, petrological, and geophysical investigations designed to understand the nature of circum-Pacific volcanism, the genesis of andesites, the tectonics of subduction zones and the resulting GTE and ore deposit potential. We have focused on the Southern Cascades in northern California, particularly Lassen, Shasta, and Medicine Lake Highland areas.
Eruption Phenomenology	Field and theoretical investigations designed to provide understanding of how active volcanoes work by gathering coordinated quantitative data at eruptions. Geophysical, petrologic observations together with high-speed movies and spectroscopy are the principal techniques. Volcanic gases are a topic of special interest. The goal is to understand dynamic igneous processes and to gain insight into volcanic materials behavior.

*Each program contains field, laboratory, and theoretical components; detailed descriptions of these programs are covered in subsequent sections of this report.

A. Supporting research for geothermal energy project. Photo shows the dry hot rock drill site (GT-2) in the Jemez Mountains west of Los Alamos.

C. Jemez - Rio Grande Program. Apollo 9 photograph showing the Valles Caldera and the northern Rio Grande rift, New Mexico.

B. Supporting research for rock penetration project. Photo shows molybdenum penetrator used in the Subterrene project.

D. Cascade Investigations Program. Aerial photograph of the Medicine Lake Highlands area of northern California, a site of recent volcanism and known geothermal anomalies.

Fig. I-1. Research programs of the geosciences group.

Fig. I-2. Organization Chart of LASL and Q-Division, showing the location of various geoscience activities.

and a nearly full set of U. S. Geological Survey Professional Papers, Bulletins, and Water Supply Papers. This collection, together with existing materials in the main LASL library, will serve as the core of an effective geosciences reference library.

C. Geoscience Activities at the Laboratory

The Laboratory's interest in the earth sciences is based upon need for technical inputs from various geoscience disciplines in some environmental, many energy, most resource, and all underground field test and engineering projects. Some of these are summarized in Table I-III.

Current earth science related projects at LASL include field projects, laboratory studies, theoretical and mathematical modeling studies, and geo-engineering projects directed at drilling methods and instrumentation and geothermal energy. Table II-IV contains a brief outline of the geoscience activities at LASL.

D. Future Development

Perhaps the most important feature of the Los Alamos Scientific Laboratory in the context of geoscience problems is its history of focusing intensely on well-defined problems. Many LASL projects have been multidiscipline in nature, commonly involving field testing and data acquisition. This ability to focus many of the Laboratory's skills on

earth science problems may be unique and certainly holds great promise.

We anticipate that geoscience activities at LASL will be stimulated by national interests and needs in both resources and energy in the 1975-1980 period in at least some of the following areas: (1) dry hot rock geothermal energy, designed to extract electric power from hot rocks in dry volcanic terranes or near young and still-hot bodies of intrusive plutonic rocks; (2) geothermal projects designed to extract heat for such purposes as space heating from sites where the temperature gradient is near or only slightly above normal; (3) attempts to extract geothermal energy directly from magma or molten rock bodies within or near active volcanoes; (4) problems generated by weapons test limitations in rock mechanics, cratering phenomenology and seismology; (5) requirements for deep drilling and rock penetration in hot terranes for geothermal purposes and perhaps for ore extraction by solution mining techniques; (6) exploration for ore deposits; (7) development of oil shale deposits of the western U.S.; (8) geological and hydrological problems associated with management of radioactive wastes; (9) environmental problems of reactor and facility sites, including the seismicity of northern New Mexico and the Los Alamos vicinity; and (10) exploration of planetary surfaces, particularly the volcanic terranes of Mars.

TABLE I-III

GEOSCIENCE PROBLEMS GENERATED BY LASL PROGRAMS

Past and Continuing Geoscience Problems

Evaluation of Underground Test Sites
 Containment of Nuclear Explosions
 Equation of State under Nuclear Explosion Conditions
 Seismic Response of the Earth to Nuclear Explosions
 Seismic Risk to Sensitive Structures
 Hydrology and Transport of Nuclear Materials Underground
 Waste Disposal and Management

Some New Geoscience Problems and Interests

Geothermal Energy
 Rock Penetration and Drilling Technology (Subterrene)
 Hydrofracturing
 Secondary and Tertiary Oil and Gas Recovery
 Fracture Technology Applied to Chemical Mining
 Subsurface Transport and Waste Management
 Underground Reactor Siting
 Underground Saline Water and Potable Water Problems
 Uranium Exploration and Evaluation
 Energy-related Minerals (U, Th, Pb, Ni, Ge, Cu, Nb)
 Artificial Rock and Mineral Standards
 Shockwave Applications to Geophysics
 Underground Coal Mining Technology
 Mineralogy and In-Situ Coal Mining Methods
 Trace Element Recovery from Coal
 Geophysical and Chemical Properties of Oil Shale
 Pacer-Nuclear Heat in Salt Domes for Power

The following outline (Table I-V) summarizes specific areas within existing programs, described in detail in the remainder of the report, which could be effectively expanded in order to contribute to these national needs. This outline describes supporting activities and research programs of the Los Alamos Scientific Laboratory and it includes many areas of potential cooperative programs with other laboratories, institutions, universities, and government agencies. Collaborative efforts in many areas have been established and we are very interested in seeking others.

E. Relationship of LASL Geosciences to the International Geodynamics Project

The International Geodynamics Project (IGP) was formulated to serve as a focus for major problems in the geosciences, so it serves as a convenient means of relating LASL geoscience activities to the broad interests of the geological sciences community. The IGP is currently serving in much the same capacity that the International Geophysical Year and Upper Mantle Projects did before it. The IGP is organized into logical interest categories which bear on understanding the dynamics of the earth's surface and interior in the context of plate tectonics. Viewed in this setting, the relationship of LASL's various geoscience activities to the important problems in the geosciences at large become somewhat better defined. Table I-VI is a matrix showing how LASL's various geoscience programs mesh with the various categories of activities within the U. S. Geodynamics Project.¹ It is clear from this summary that the breadth of interests and capability at LASL is significant for geophysical problems.

REFERENCE

1. U. S. Geodynamics Committee, "U. S. Program for the Geodynamics Project," National Academy of Sciences, Washington, D. C., 1973. pp. 52-53.

TABLE I-IV

OUTLINE OF THE GEOSCIENCES ACTIVITIES AT LASL

Hydrothermal Alteration in Crystalline Rocks	Study of morphological, porosity, permeability, and 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 experiments will be performed in circulating systems with continuous monitoring 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 ₂ SO 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 processes in metamorphic 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.
Properties of Geological Materials at High Temperatures and Pressures	Programs include measurement of density of geologic materials in a hydrostatic environment up to 120 kbar; measurement of ultrasonic wave velocities in liquids up to 2000°C to determine equation of state; measurement of Hugoniot parameters in natural rocks with shock waves, including properties of crystalline rocks, and the melting phase line of iron; study of fracture processes relating to mining by explosive techniques; and preparation of high-quality, pure isotropic samples for experimentation and supply to the geophysical community.
Rock Analysis from Aerial Imagery	Development of techniques for recovering surface rock data from aerial imagery. This has been done for extraterrestrial bodies by using infrared wavelength shifts due to lattice binding to identify lattice type, and may be made applicable to some areas of the earth by evaluating effects of atmospheric absorption and surface contaminants.
Igneous Processes	Existing commitments to engineering projects in geothermal energy and in rock penetration by melting 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 rocks 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.

TABLE I-V

POTENTIAL DEVELOPMENT AREAS WITHIN EXISTING
GEOSCIENCE PROGRAMS AT LASL

Experimental Geophysics and Rock Mechanics

- Extend high-temperature and pressure ultrasonic and equation-of-state studies in geophysical problems.
- Conversion and calibration of existing 4.5 Mkg press for experimental geophysics.
- Completion of rock mechanics lab for hydraulic fracturing and permeability.
- Extend studies of transport properties (conductivities) and acoustic velocities of rocks and minerals.
- Preparation of high-purity, low-porosity standard minerals or assemblages for experimental determination of their properties.

Experimental Geochemistry

- Extend solution geochemistry studies.
- Establish hydrothermal lab for ore deposit work.
- Establish lab capability for high-pressure phase equilibria investigations emphasizing volatile bearing systems.
- Investigate physical and chemical properties of silicate melts, especially viscosity, solubility of gases, latent heats, density.
- Extend mineral thermodynamics, especially to high-pressure and temperature precision calorimetry.

Observational and Analytical Geochemistry and Petrology

- Expand the petrography, thin section photomicrography laboratory.
- Establish electron microprobe laboratory.
- Expand geological analysis capability to other techniques (XRF, ESCA, SEM, TEM, X-ray, Crystallography).
- Establish stable isotope geochemistry and geochronology laboratory.

Modeling Studies

- Numerical (computer) modeling of geological processes.
- Physical (scale) modeling experiments of intrusion mechanism and geological processes.

Topical Geological Studies

- Extend field-petrology and geochemical studies of kimberlites and andesites.
- Planetology - Martian volcanism and thermal evolution of the planets; effects of large scale cratering on planetary surfaces and interiors.

Jemez-Rio Grande Program

- Expand field and petrologic studies.
- Mathematical and physical modeling studies.
- 300-m bore hole program with down-hole geophysics.
- Regional and local geodesy (tilt, long base line leveling, Geodimeter surveying).
- Deep seismic reflection profiling.
- Seismic array studies.
- Solution mining.
- Very deep drill near a magma chamber (5 to 10 km) in geothermal area.

Cascades, Northern California Program

- *Regional seismic array.
- Surface geophysical survey (gravity, HF, E-M).
- Deep seismic reflection profiling.
- 300-m bore hole program and instrumentation (5 to 10 per year).
- Remote sensing and synoptic aerial photography.
- Detailed geophysical monitoring of 3 large volcanoes (Lassen, Shasta, Medicine Lake Highlands) local array: bore holes and geophysics.
- *Detailed and reconnaissance mapping, petrology, and geochronology.
- Geodesy from Hat Creek Radioastronomy Observatory (Geodimeter, laser, quasars).

Eruption Phenomenology

- *Photographic documentation of vent activity (TV, time-lapse and high-speed photography).
- Acoustics (jet noise) and seismology.
- *Synoptic aerial photography and remote sensing throughout eruption.
- *Aircraft or RPV (robot aircraft) sampling of air, gas, and ash.
- *Gas analysis by FFT interferometry or laser backscatter spectroscopy.
- *Penetrometer geophysics package.
- *High-altitude sample collection, particulates.
- Shallow bore-hole geophysics, core and in-situ chemistry.
- Space photography and remote sensing.
- Extended surface mapping and sampling techniques.
- Extend petrological and geochemical evolution of lavas.
- Physical properties of silicate melts in situ.

*Collaborative project

TABLE I-VI

MATRIX SHOWING LASL GEOSCIENCE ACTIVITIES AND THEIR RELATIONSHIP TO VARIOUS CATEGORIES
OF THE INTERNATIONAL GEODYNAMICS PROJECT

Categories of Activities and Elements of the Geodynamics Program	FIELD STUDIES				LABORATORY STUDIES				MODELING	ADVANCED GEOTECH- NOLOGY	
	Jemez-Rio Grande, New Mexico	Cascades, Northern California	Eruption Studies	Topical Studies	Experimental Geo- physics and Rock Mechanics	Experimental Geo- chemistry and Petrology	Observational and Analytical Geochem- istry, Petrology	Computer and Numerical Studies	Physical (Scale) Modeling	Rock Penetration	Instrumentation
<u>Americas Plate</u>											
Pacific Margin		■					△				
Basin-Range-Colorado Plateau-Rockies	■										
San Andreas											
Pacific Margin of Alaska				△			△				
Eastern U. S. and Continental Interior				△			△				
<u>Small Plates and Plate Margins</u>											
Plate Evolution and Inter-plate Tectonics: Caribbean											
Processes at Plate Margins: Mid Atlantic Ridge	△										
Evolution of Plates							△				
Arctic Geodynamics											
Antarctic Plate											
<u>Internal Properties and Processes</u>											
Dynamic Models			△	△				■	■		
Geophysical Observations of Internal Processes				△		△					
Physical and Chemical Properties of Minerals and Rocks				△	■	■	△				
Geological Constraints			■	■			■				
<u>Boundaries, Movements, and Structure of Lithospheric Plates</u>											
Present Plate Boundaries		△									
Present Motion of Plates	△										
Plate Boundaries and Rates of Movement in Past	△	△									
<u>Deep Drilling, Advanced Technology</u>											
<u>Data Exchange</u>											

■ Box indicates a major commitment at LASL and its main impact on IGP.

△ indicates a secondary impact on IGP.

II. SUPPORTING RESEARCH

A. Introduction

Current geo-engineering activities at the Laboratory include dry hot geothermal energy and the subterrene project, whose goal is to develop techniques for rock penetration by melting. In this section the current status of each of these projects is reviewed briefly and the supporting geosciences research activities described.

B. Dry Hot Rock Geothermal Energy Project

1. Status. A vigorous effort to develop the so-called dry hot rock (DHR) 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. II-1). The basic concept is to drill a hole into hot but dry (and 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. II-2). This concept has

Fig. II-1. Location of the two major drill holes of the Los Alamos Dry Hot Rock Geothermal Energy Project. Granite test hole No. 1 (GT-1) was completed in 1973 at a depth of 785 m with bottom temperatures of 100.4°C. GT-2 is currently at 2.928 km, with a bottom temperature of 197°C.

been described in detail by West.¹⁻⁵

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. The demonstration program will undoubtedly define others. One of the most severe problems encountered by all attempts to

Fig. II-2. Basic concept of dry hot rock geothermal energy project; configuration of energy extraction experiment.

drill in hot, geologically young volcanic areas for geothermal purposes has been the uncertainty of these terranes, in spite of extensive surface explorations by geophysical and geological methods. Deep drilling at Kilauea, Hawaii,⁶ Marysville, Montana,⁷ and Jemez Mtns., NM⁵ 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 DHR 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. Rock permeability measured in the laboratory and estimated in situ is low and small hydraulic fractures have been made on an experimental basis, and the bottom hole temperature (197°C) is sufficiently high. A large number of bottom hole and associated experiments are planned (Table II-I). These 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.

Supporting research activities are directed at finding solutions to several of the problems defined above. These problems range from some more practical engineering types of questions to basic scientific ones. The former include determination of the crack location by seismological or other geophysical means, management and control of the fracture geometry, questions of solution geochemistry, and corrosion of heat exchange parts. Also understanding the history and evolution of caldera complexes such as the Valles Caldera - their dynamic thermal and eruption history, the significance of their tectonic historical setting, and the questions of genesis of the various rock types erupted from them, through time are important in an engineering sense as well as being scientifically interesting matters. When we have much stronger models for caldera formation, buttressed by specific geological, geophysical and geochemical data, predictive modeling for such practical items as the thermal state at a given place will be on much sounder ground.

TABLE II-I

RESPONSIBILITIES FOR EXPERIMENTS PLANNED OR IN PROGRESS IN GT-2 (M.C. SMITH, GROUP LEADER). PERSONS CARRYING PRIMARY RESPONSIBILITY ARE SHOWN IN PARENTHESES.

- Core Studies (A. William Laughlin)
Petrologic, structural, and geochemical characterization of the reservoir region by studies of cores and cuttings. Thermal and stress history of the reservoir region.
- Hydrology (Francis West)
Permeability of rocks in the reservoir region and also hydrological problems in the upper parts of the stratigraphic section.
- Heat Flow (James Albright)
Field measurements of the thermal gradient in the drill hole, laboratory measurements of thermal conductivity. Determination of heat flux.
- Geophysics (Paul Kintzinger)
Active and passive seismic experiments; deep and shallow E and M sounding and tilt studies designed to locate the fracture and monitor its effects.
- Hydraulic Fracturing (Robert Potter)
Prediction and control of the orientation, size and geometry of the hydraulic fractures.
- Down Hole Logging (Francis West)
In situ properties of rock determined by standard logging methods; comparison with experimentally determined properties on cores.
- Systems Modeling (Robert MacFarland)
Mathematical modeling of fluid flow and heat transfer in the reservoir region.
- Geochemical Studies (John Balagna, Jefferson Tester)
Solution chemistry of hot aqueous-solutions in contact with crystalline rocks, and the problem of dissolved material deposited in cool parts of the system such as the heat exchanger. Also enhancement of heat transfer by solution. Possible solution mining.
- Fracture Characterization Communication and Flow Impedance Studies (R. Lee Aamodt)
Problems of management of the hydraulic fracture, completion of the circulation system with a second drill hole.
- Geology of the Site (William Purtymun)
Description of the stratigraphy and structural geology of the drill site.
- Drilling (Don Brown, Darrell Sims)
Contracting and creation of the hole and cores.

2. Core Studies in GT-2. During the drilling of GT-2, 26 coring attempts were made; 24 of these were successful for a total of about 35 m of core. The core recovered was of two sizes. A modified deep sea (JOIDES) bit produced an unoriented 62-mm core (Fig. II-3) and a Christensen bit of 133-mm oriented core. Location of cored intervals, percent recovery and lithology are summarized in Table II-II. Lithologies were determined from thin sections using standard petrographic techniques.

A large number of studies are now underway utilizing GT-2 core. The extent of these studies is summarized in Table II-III and a typical core is shown in Fig. II-4. At the present time cooperative working agreements have been established with the U.S. Geological Survey, and the U.S. Bureau of Mines, Brown University, and the Universities of Arizona, Alaska, New Mexico, Oklahoma, and Tulsa for some geophysical, chemical, and isotopic studies. Other studies are being conducted by LASL staff members.

The preliminary petrographic description of the core is complete. Detailed study has begun on oriented samples and on several particularly interesting samples. Twenty whole rock chemical analyses have also been completed and twelve additional ones are in progress. Preliminary Rb-Sr

Fig. II-3. Modified JOIDES bit used in core drilling in GT-2.

Fig. II-4. Cores of Precambrian granitic gneiss from GT-2.

geochronological results indicate events at 1.7 and 1.45 Gyr. with the possibility of a third event 1.1 - 1.2 Gyr. Strontium isotope ratios on calcite from fracture fillings indicate that the Sr and presumably the Ca were derived from the Precambrian wallrock and not from overlaying Madera limestone. Fluid inclusion geothermometry suggests that the calcite was deposited at about 200°C.

Future geochronological studies will be combined with annealing, fluid inclusion, and stable isotope geothermometry to derive the time-temperature history of the core material. With these data we hope to address the question of the thermal history of the Precambrian terrane into which GT-2 penetrated and in particular the perturbation resulting from the emplacement of the magma body responsible for the Valles Caldera complex. We will continue to expand our research effort on these cores, including collaborative studies with interested scientists from universities and other government agencies.

3. Seismology of the GTE Site. Seismicity of the Los Alamos region is of interest for a variety of reasons ranging from the GTE project and evaluation of the earthquake hazard to facilities of the Laboratory, to the tectonics of the Rio Grande

TABLE II-II
SUMMARY OF CORING RUNS FOR GT-2

Core Run	Cored Interval, Depth	Recovery (%)	Core Bit ^{a,b}	Rock Type ^d
1	633.4-639.5 m (2078-2098 ft)	25 ^c	J	Clay w/limestone chips
2	685.2-688.2 m (2248-2258 ft)	50 ^c	J	Shale w/limestone chips
3	776.3-786.4 m (2547-2580 ft)	35	J	Leucocratic quartz monzonite
4	789.4-792.5 m (2590-2600 ft)	33	J	Leucocratic quartz monzonite
5	862.9-866.9 m (2831-2844 ft)	30	J	Granite
6	866.9-870.8 m (2844-2857 ft)	20	J	Quartz monzonite
7	960.4-969.9 m (3151-3182 ft)	20	J	Biotite granodiorite
8	1055.8-1059.5 m (3464-3476 ft)	17	J	Leucocratic quartz monzonite
9	1125.9-1129.3 m (3694-3705 ft)	100	C	Leucocratic quartz monzonite
10	1303.9-1306.1 m (4278-4285 ft)	85	C	Leucocratic granodiorite and quartz monzonite
11	1491.1-1492.6 m (4892-4897 ft)	100	C	Biotite trondhjemite, leucocratic granodiorite, and quartz monzonite
12	1498.1-1499.9 m (4915-4921 ft)	100	J	Leucocratic quartz monzonite
13	1595.3-1597.1 m (5234-5240 ft)	38	J	Quartz monzonite, granodiorite
14	1672.4-1674 m (5487-5492 ft)	90	C	Quartz monzonite
15	1723.3-1725.2 m (5654-5660 ft)	92	J	Hornblende biotite schist
16	1822.7-1824.5 m (5980-5986 ft)	100	J	Hornblende biotite schist
17	1874.5-1876.3 m (6150-6156 ft)	66	J	Quartz monzonite
18	1876.3-1878.2 m (6156-6162 ft)	100	J	Quartz monzonite
19	1933.7-1935.5 m (6344-6350 ft)	16	J	Granodiorite
20	1935.5-1937.3 m (6350-6356 ft)	5	J	Granitic chips

^aJ - JOIDES bit.

^bC - Christensen Diamond Products Company bit.

^cWireline core barrel retrieval.

^dRock type for Cores No. 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, and 19 determined from petrographic examination of thin sections. Identification of the remainder of the cores by hand specimen examination.

rift. In 1968, northern New Mexico was designated an area of moderate earthquake risk.⁸ Consequently, the AEC and the Laboratory became concerned with earthquake hazards. In order to evaluate this hazard the LASL seismic array was installed. Data from this array, however, also provided interesting information on the seismic activity along the Rio Grande Valley, which is a large continental rift feature similar in many ways to the East African rift and the Rhine Graben, for example. There is a significant body of data which suggests that the Rio Grande rift may be the site of currently active rifting. Geological data suggest that the rate of separation is on the order of 0.2 mm/yr. Some investigators have speculated that the valley could be opening into an area of new sea floor such as the Red Sea. The location of

caldera complexes along the graben is another interesting aspect of the tectonic setting of the rift.

LASL's regional seismic array was begun in 1972 to determine the local and regional seismicity of the area for the purpose of estimating earthquake hazards to structures and operations. Another application of the network appeared with the LASL geothermal experiment because of the necessity to monitor possible microseismicity caused by earth movements resulting from the injection of fluid into deep reservoir rocks.

4. Status and Operation of the Regional Seismic Net. Table II-IV gives the parameters of existing and planned stations of the LASL regional seismic net (Figs. II-5 and II-6). The operation of stations TSP and CLP have been disrupted by problems of

TABLE II-III
DIAGRAM SHOWING THE PROGRAM OF INVESTIGATION
OF GT-2 CORES CURRENTLY IN PROGRESS

radio interference at CLP, but no corrective actions to date have been successful at TSP. Installation of additional stations during the spring of 1975 will be accomplished through services of the Radio Communications Department of the state of New Mexico

The state Radio Microwave System will be used to transmit the seismic signals from each station (using this net) to Santa Fe. An interim means of relaying the data from Santa Fe to the Los Alamos Scientific Laboratory uses a radio operating at 226 MHz and was built by LASL's electronics division. Because this interim relay limits the quantity of data which can be received in Los Alamos to approximately the same carried by a single microwave voice channel, we are planning a simplex microwave link from Santa Fe to Los Alamos. With the installation of the state microwave link from Eureka Mesa (EUM), shown in Fig. II-7, we will be able to increase our station density in the geothermal area (stations 1 through 4 on the accompanying map) by means of VHF and UHF feeder links.

Fig. II-5. Location of existing and planned seismometers of LASL array.

TABLE II-IV
REGIONAL LASL SEISMIC STATIONS OPERATING AND PLANNED

Int'l Station Code Abbrev.	Station Name	Latitude	Longitude	Elevation (m)	Telemetry	Date Installed	Instruments
Stations Operating							
LOA	TA-49-62	N35°49'28.6"	W106°17'40.6"	2144	Telephone	15 Jan. 72	SPZ SPN SPK
FCN	TA-33	N35°46'19"	W106°15'02"	1945	Telephone	7 May. 73	SPZ SPN SPE
LCV	La Cueva	N35°52'36"	W106°40'18"	2620	Telephone	19 Jul. 73	SPZ
SPD	St. Peter's Dome Lookout	N35°45'30"	W106°22'12"	2578	VHF	14 Sep. 73	SPZ
CLP	Clara Peak Lookout	N36°02'06"	W106°14'24"	2606	VHF	27 Sep. 73	SPZ
TSP	Tesuque Peak	N35°47'06"	W105°46'54"	3426	VHF	17 Oct. 73	SPZ
Stations Planned							
APS	Apache Spr.				Microwave		SPZ
MSA	Mt. San Antonio				Microwave		SPZ
MTL	Mt. Taylor.				Microwave		SPZ
EUM	Eureka Mesa				Microwave		SPZ

Fig. II-6. Location of existing and planned regional seismic stations throughout northern New Mexico.

Fig. II-7. Plans for expansion of LASL seismic network using state of New Mexico microwave stations.

Further modifications of the regional network will be made on the basis of the instrumentally determined seismicity.

Local and regional earthquakes detected by the array are routinely located using a very simple velocity model. As more events are recorded the velocity model and station corrections are being upgraded to reduce the station residuals. P-delays from teleseisms are being tabulated for earthquakes within 90° and magnitudes of 6 or greater. These data can be used to infer lateral variations in crustal velocities within the array. With the array expanded, using the state microwave network, more horizontal seismometers will be installed. Seismograms from these instruments will give much better S-wave data permitting variations in Poisson's ratio of the crustal rocks within the array to be determined. Such variations within the Valles Caldera will be one of the principal means of locating a possible magma chamber.

The epicenters for the local regional earthquakes as determined from time readings at the LASL net stations for this period are listed in Table II-V and plotted in Figs. II-8 and II-9. Because of the drilling activity of GT-2 during 1974 period, the background noise levels at the LCV telemetered station have been very high, making this station of no utility for locating low-level regional and local microearthquakes. This gap in the LASL net coverage has been somewhat filled by the installation of another station at Seven Springs about 5.5 km to the northwest.

During the period September 1973 to May 1974, there have been no detectable earthquakes in the eastern section of the Rio Grande rift zone between Albuquerque and Taos, while there have been at least 5 events along the western part, probably associated with the western flank fault systems (Pajarito-Ojo Caliente complex - Fig. II-8). This region of the Pajarito fault system is known to be active. Reports exist of several moderate earthquakes felt by residents of the Los Alamos, Espanola, and Abiquiu communities over the past several years. The strongly felt earthquake of 17 March 1973 (intensity V at Los Alamos) is the most recent "larger" magnitude ($M_L < 4$) event on this fault system.

The event on 4 January was located very near the central section of the Nacimiento fault and indicates that this topographically prominent feature is also seismically active. This is the first event on this fault during the past year that has been detected and located by the LASL net. The level of activity is probably somewhat less than that on the Pajarito fault system. This difference may be only apparent because the Nacimiento fault is outside the area of maximum sensitivity of the LASL net, hence is in a region of higher detection threshold. A recently installed seismometer site at Eureka Mesa very close to the Nacimiento fault zone should improve our detection and location capabilities for this region.

The data in Table II-II indicate that two other general areas were moderately active over

Fig. II-8. Location of micro-earthquake epicenters, September 1973 to May 1974.

TABLE II-V

PRELIMINARY EPICENTRAL SOLUTIONS FOR
LOCAL AND REGIONAL EARTHQUAKES
September 1973 to May 1974

DATE	ORIGIN TIME (GMT)	LATITUDE	LONGITUDE	APPROX. MAGNITUDE	NOTES
				(M_L SCALE)	
10 Sept. 73	20:29:23.26	34° 27.2'N	106° 51.7'W	2.6	1
19 Sept. 73	13:28:20.5	37° 12'N	104° 36'W	3.3	2
19 Sept. 73	21:19:46.8	37° 12'N	104° 35'W	~ 2.0	
22 Sept. 73	23:38:35.8	34° 30'N	107° 00'W	3.1	
23 Sept. 73	03:58:54.9	37° 06'N	104° 36'W	3.2	1,2,3,4
13 Oct. 73	03:56:02.68	35° 54.2'N	106° 20'W	1.0 - 1.5	5
14 Nov. 73	07:56:08	36° 57'N	107° 00'W	2.6	1,6
25 Nov. 73	16:45:20.9	35° 36'N	105° 53.7'W	1.3 - 2.0	
25 Nov. 73	16:52:01.3	35° 36'N	105° 53.7'W	1.3 - 2.0	
24 Dec. 73	02:20:13.3	35° 18.2'N	107° 49.4'W	>2.5	1
24 Dec. 73	15:06:12.5	35° 30.9'N	106° 05.7'W	~2.0	
4 Jan. 74	23:29:31.6	35° 48'N	106° 54'W	1.3	7
12 Jan. 74	14:14:01.2	35° 08'N	107° 21.8'W	1.7	8
17 Jan. 74	23:04:20.8	36° 09'N	106° 12.4'W	1.9	9
17 Jan. 74	23:06:26.3	36° 11'N	106° 12.0'W	1.3	9
8 Mar. 74	06:46:19.0	35° 16.5'N	107° 43.7'W	1.6	8
14 Mar. 74	13:50:28.7	35° 33.9'N	107° 56.8'W	2.0	8
2 Apr. 74	11:06:53.4	36° 15.4'N	106° 11'W	1.6	9
29 Apr. 74	23:24:41.5	37° 14'N	107° 17'W	1.9	10
30 Apr. 74	02:47:26.0	36° 29.4'N	105° 57.7'W	1.7	9
30 Apr. 74	10:44:47.4	37° 16.3'N	107° 10.6'W	1.5	10
30 Apr. 74	14:19:25.5	37° 16.0'N	107° 10.6'W	1.9	10
8 May 74	21:58:57.4	35° 02.4'N	107° 03'W	2.0	8
25 May 74	20:09:16.1	34° 44.9'N	106 25.1'W	0.2	9

- NOTES: 1. Larger events ($M_L > 2$) usually include ALQ (Albuquerque) and SNM (Socorro) time readings in solutions.
2. Felt in Segundo, Colorado.
3. At least two strong aftershocks ($M_L \sim 2.5$) same day.
4. 3.2 is LASL M_L reading. PDE m_b value is 4.2. This is the typical difference in the two magnitude scales in this range.
5. Very near Los Alamos townsite; depth ~ 5 km.
6. Felt at Dulce, N.M. LASL array solution very approximate (± 20 km).
7. Near Nacimiento Fault.
8. Puerco - Mt. Taylor Area
9. Pajarito - Ojo Caliente Fault System
10. Dulce Area.

Fig. II-9. Location of earthquake epicenters in northern New Mexico, September 1973 to May 1974.

the past few months. The first is the area between the Rio Puerco and Mt. Taylor (north of Interstate 40), and the second is the vicinity of Dulce, New Mexico near the New Mexico-Colorado border (Fig. II-9). Both areas are known to have experienced moderate sized individual earthquakes and lower magnitude swarm-like activity in the past. In fact, residents near Grants, New Mexico, most recently felt a strong shock on 24 December 1973 and residents of Dulce were jolted on 14 November 1973. Our computer program for epicenter solutions places the recent Dulce area activity about 30 km NW of the townsite of Dulce in the Piedra River valley. At this range, however, our knowledge of regional seismic crustal velocities and their local variations is as yet inadequate so precise epicenter determinations are not possible.

5. Magma Chambers of the Valles Caldera. We are very interested in determining whether there is seismic evidence for chambers beneath the Valles Caldera which may still contain molten or partially molten magma.

Almost every weekday, the LASL seismic net records seismic signals from explosions originating at the open pit coal mines near Fruitland, New Mexico about 175 km west-northwest of Los Alamos. These

signals are from an azimuth (296° True) such that the seismic ray paths from Fruitland to two stations, LOA and TSP (Figs. II-10 and II-11) pass almost directly under the center of the Valles Caldera while ray paths to CLP and SPD pass appreciably to the north and south of the central regions of the volcanic complex. The situation is very similar but slightly less favorable for ray paths originating from explosions at the Nevada Test Site (NTS) and received at these stations (the azimuth to NTS is 282° True). Large regions of molten or partially molten material in the travel paths of seismic waves will delay the compressional (P) wave arrival time, may not transmit shear (S) waves at all - and will strongly attenuate amplitudes. Thus, a comparison of arrival times and the presence or absence of an S phase at the CLP, LOA, and SPD stations could be used to "probe" for existing molten regions.

The relevant seismograms show that there is a

Fig. II-10. Regional seismic net - ray configurations for magma location studies.

Fig. II-11. Sites of frequent explosions in quarrying and mining operations.

large P-wave delay at LOA compared to SPD and CLP and that the S waves at LOA do not have as sharp onsets and clarity as do those observed at SPD and CLP. However, the arrivals at TSP on a similar azimuth as LOA do show a sharp S and in fact a computed time "lead" rather than a delay. This suggests that most of the differences in station time anomalies and S-wave amplitudes can be explained in terms of differences in geology immediately (a few km) beneath the individual stations rather than more distant differences in crustal paths. Stations CLP, SPD, and TSP are all emplaced on hard, high velocity rock units (basalt for CLP and SPD, granite for TSP) whereas LOA is known to be underlain by at least 300 m of very low velocity ($V \sim 2$ km/sec) highly attenuating ash flow tuff layers.

It thus appears that the existing data can be largely explained by localized near-surface geological differences; and at least for those depths beneath the caldera that are traversed by rays from these particular explosions, there are no significant liquid regions. The search for melted, partially melted, or solid but heated chambers will be dependent on second-order effects such as: anomalously high values of Poissons ratio (derived from the ratio of P- and S-wave travel times), careful measurements of differential seismic travel times across and tangent to the caldera, measurements of selective attenuation, scattering and diffraction of several seismic phases (for example,

vertically and horizontally polarized S-waves) passing through different regions. Some data for such a study are now being accumulated from local and regional earthquakes and explosions but the local geology is so complex that a careful calibration of existing and planned stations in the seismometer network in the Jemez Mountains will be required in order to properly interpret these data.

6. Seismic Network for Observation of Small Events Near GT-2. Figure II-12 shows the distribution of high-gain, high-frequency seismometer sites installed around GT-2 in an effort to see if very small (magnitude > 0) natural events are present in the region and to attempt to measure surface seismic manifestations of underground hydraulic fracturing experiments. The stations were installed to obtain as broad a coverage in azimuth and range from GT-2 as was consistent with operational constraints imposed by topography and cable availability. The range of distances and azimuths are required in order:

- to obtain reasonably precise locations of hypocenters within 2 km of GT-2,

Fig. II-12. Local seismic array at GT-2.

- to obtain a sufficient coverage of first motion and S-wave polarization data for fracture orientation and mechanism determinations,
- to obtain sufficient data to estimate source energy and near-source attenuation parameters.

In Fig. II-12, LCV is the existing 3-component station of the regional network which is telemetered to LASL by telephone line and is recorded at the data center. Signals from all other stations are transmitted by either surface cables or VHF radio (stations 4-R and 5-R) to tape recorders in trailers near the GT-2 well head. Three-component seismometers (geophones) (1-Hz natural period; 0.5-100 Hz data band pass) are located at stations Q-1, Q-2, Q-3, Q-4, Q-5, Q-6, 2 and 6 (as well as LCV). All other stations use single-component (vertical) geophones except station 13, which is to employ a marine hydrophone in a 180-m hole half filled with water. The high-frequency (50-300 Hz) response of the hydrophone is significantly better than that of the geophones so that a more reliable measurement of high-frequency signals is expected. The sensitivity of each station is such that ground motion detection threshold is limited only by the level of continuous earth background noise arising from microseisms (ground velocity of 6 nm/s in the 1- to 100-Hz frequency range).

During the period 5 August to 3 October 1974 several preliminary hydraulic fracturing experiments were initiated in GT-2. On a few occasions (with flow rates up to 36,000 gal/min) the hydrology data (volume, flow rate, and fluid pressure) indicated that small hydraulic fractures may have been produced. No seismic signals were detected by the surface arrays as a result of these experiments nor were there natural earthquakes produced as a result of fluid injection into the borehole.

Active seismic experiments (using explosives) are now being considered to detect velocity changes in formations at depth resulting from introduction of fluids during hydraulic fracturing experiments. There is both theoretical and experimental evidence for detectable changes in Poisson's ratio, when pores in rocks become filled with fluids.

Seismic data recorded to date indicate there is no reason to believe that the area of the geothermal demonstration (hole GT-2) is not suitable for future large-scale hydraulic fracturing experiments. No earthquake activity in that area was observed during the fracturing experiments of August and September.

C. Rock Mechanics

An experiment program in rock mechanics was undertaken by J. C. Roegiers (now at the University of Toronto). The principal goal of the research is to investigate the mechanisms of formation of hydraulic fractures in crystalline rocks and to develop experimental data required to determine in-situ stress in bore holes by the behavior of hydraulic fractures. Conversely, it is anticipated that reliable estimates of fracture behavior can be made, given knowledge of depth and the properties of the formation. The program also includes attempts to determine the permeability of crystalline rocks under varying pressure and stress conditions, and the acoustical emission associated with fracturing.

The experimental results show that the permeability of granite cores from the first geothermal test hole (GT-1) varies significantly with pressure, decreasing from 10^{-9} (mm^2) at atmospheric pressure to between 10^{-10} and 10^{-11} at 0.5 kbar, and increases by over an order of magnitude in fractured specimens.¹⁰ The permeability of the granite increases greatly under tensile stress.

Detailed rock mechanics studies have been made on the GT-2 cores from a depth range of 780 to 1600 m (2580 to 5200 ft), the upper ~1 km of the Precambrian basement rock. Right circular cylinders approximately 2 cm in diameter and from 5 to 15 cm in height were diamond cored from the core sections with the sample axis parallel to the bore hole axis. The initial objective of the studies is to perform measurements on the core samples that can be compared to the bore hole logging data, especially the dynamic modulus measurements. Mechanical properties of the in-situ rock are particularly significant in the interpretation of hydraulic fracturing. These initial results were obtained principally from measurements performed on the above core samples by the U.S. Bureau of Mines,

Twin Cities Research Center. All measurements were performed on dry specimens at ambient temperatures and pressure.

The dynamic elastic moduli are obtained from the three-dimensional velocity log and the gamma-gamma density log (with the caliper log used for appropriate corrections). The core sample bulk density compared generally to within $\sim 1\%$, with one location showing a deviation of 5%. Axial compressional and circumferential shear wave velocities were determined from the core samples and compared to the bore hole log data obtained over comparable zones of the bore hole. The results indicated that the compressional velocities compared to within a few percent. Velocities measured in situ systematically exceed the laboratory data. These differences are smaller than those noted for similar comparisons which have been conducted previously.¹¹ Such differences apparently are real and due to true differences in the material, not the measurements. The possible causes include stress relief features in rocks around the bore hole which are not developed in the core samples, the differential "microcontractions" experienced by the cores in cooling from the formation temperature to the ambient, and the fact that the laboratory data were obtained at ambient temperature and pressure.

The dynamic elastic moduli are calculated for both the in situ and laboratory values from the density (ρ), shear (v_s), and compressional (v_p) velocities from the relations,

$$\mu = \rho v_s^2, \text{ shear modulus}$$

$$E = 2(1 + \nu_d)\mu, \text{ Youngs modulus}$$

$$\nu_d = \frac{\left(v_p^2 - 2v_s^2\right)}{2\left(v_p^2 - v_s^2\right)}, \text{ Poisson's ratio}$$

$$B = \rho v_p^2 - \frac{4}{3}\mu, \text{ bulk modulus}$$

which assume the granite cores to be isotropic. Table II-VI records a summary of the dynamic moduli derived from the in situ measurements.

These results agree with earlier work by Simmons and Nur¹¹ and Smithson and Ebens¹² which indicated that laboratory velocity data on cores from depths less than 3 km will be lower than in situ values even when water content and pressure and temperatures are simulated. It is concluded that the in-situ moduli derived from the three-dimensional velocity log data rather than laboratory results should be utilized in interpretation of hydraulic fracturing data.

Data were also obtained on static stress-strain characteristics and moduli, compressive and tensile strengths and porosity. Analyses of these data are in progress.

Preliminary results from hydraulic fracturing experiments at 2-km (6700-ft) depth in GT-2 suggest that vertical cracks were formed. Impressions taken at the bore hole surface indicate that the fracture orientation is northeast to southwest. This implies a minimum horizontal stress component in the northwest-southwest direction. These directions are in approximate agreement with other determinations, of the in situ stress in crystalline rocks in North America,¹³⁻¹⁵ however, it is not known whether this reflects a general feature of the North American continent or is the result of the local tectonic stresses associated perhaps with the Rio Grande rift, or the Valles Caldera

D. Geochemistry

Geochemical research has been focused on four areas:

1. Chemical effects and morphological changes in minerals resulting from chemical alterations as a consequence of interaction with aqueous solutions;
2. Pure mineral standards;
3. In-situ mining studies;
4. Trace element studies.

All of these activities are part of a program designed to learn more about the interaction between rocks and water (hydrothermal alteration) at temperatures and pressures of interest to the LASL geothermal energy project. These conditions (200° to 300°C, 1 to 2 kbar) also are of fundamental importance in

TABLE II-VI

SUMMARY OF DENSITY, VELOCITY & DYNAMIC MODULUS IN-SITU DATA

Depth* (m)	Density, (g/cm ³)	Compressional Velocity, V _p (km/s)	Shear Velocity, V _s (km/s)	Young's Modulus, E (10 ¹⁰ kPa)	Shear Modulus, μ (10 ¹⁰ kPa)	Bulk Modulus, B (10 ¹⁰ kPa)	Poisson's Ratio, ν_d
785	2.697	6.055	3.440	8.05	3.19	5.64	0.261
790	2.714	5.999	3.422	8.00	3.18	5.53	0.258
865	2.645	6.313	3.480	8.21	3.21	6.27	0.282
868	2.645	6.341	3.546	8.46	3.33	6.20	0.272
960	2.685	5.780	2.972	6.26	2.37	5.81	0.320
1056	2.625	6.022	3.433	7.79	3.09	5.39	0.259
1126	2.632	5.856	3.512	7.92	3.25	4.70	0.219
1304	2.597	5.986	3.495	7.88	3.17	5.07	0.241
1492	2.588	5.932	3.516	7.86	3.20	4.85	0.230
1498	2.637	5.983	3.540	8.18	3.30	5.00	0.231
1596	2.554	6.030	3.560	7.98	3.24	4.97	0.233

*Values averaged over 2-3 m intervals to correspond to locations of cores.

understanding natural processes in the upper few kilometers of the earth's crust. Both chemical and morphological changes occur as a result of these processes, and our work has been directed at investigating these changes and their implications for the GTE project.

Four experimental hydrothermal systems have been constructed or are being completed to study rock-fluid interaction. Presently operational are three circulating systems and two rocking vessels capable of 220 kg/cm² ($=P_{\text{Total}}$) at 300°C. Nearing completion are circulating systems to 710 kg/cm² ($=P_{\text{Total}}$) at 800°C.

These systems will be valuable in studying solid material from both polymineralic and monomineralic systems. Natural substances will be used until sufficient pure minerals are grown. Experiments using natural systems will allow us to gain valuable engineering knowledge for our present geothermal experiment. Extrapolation to other environments is only possible using data from experiments on pure end-member systems. These latter results can be used to proceed into more complicated systems which

approximate natural rock composition. We will proceed with both approaches.

1. Interactions of Rock and Hot Aqueous

Solutions. The heat extraction simulation apparatus has been used to study chemical and physical effects of the interaction of granite and hot water. The rate of material removal from granite is independent of surface area exposed. It is also constant with time up to 500 h. This rather surprising result is not expected to change since it is observed that there is a continuing production of new rock surfaces due to intergranular channeling and the formation of solution channels throughout individual mineral phases.

Porosity measurements indicate a large change in the physical character of the rock. In a typical case, a granite core from GT-1, with an initial porosity of 1.05% had an observed porosity of 2.65% after 300 h at 260°C in water. Pore size is increased in the exposed rock. Petrographic examination of these samples shows also that many new voids were produced by dissolution of minerals, particularly feldspars. Micas swelled, which also contributed to an increase in porosity. In a granite

sample 2 mm thick, solution channels are observed to entirely traverse the piece.

2. Chemical Effects and Morphological Changes due to Chemical Alteration. We are interested in the interaction between rock and minerals (both pure and natural) and the following fluids: distilled water, carbonates, chlorides, natural waters, and solutions with suitable chemical potentials for mineral extractions.

Essential to characterizing and understanding the alteration processes operating under both hydrostatic and nonhydrostatic stresses we need well-characterized rock and mineral compositions, both initial and final. Time-dependent observations of changes in porosity and permeability and sequence of appearance of rock alteration products are necessary. The solutions tapped from the reacting system are monitored continually and characterized as to: x_1 , i = chemical species in solution, f_1 , CO_2 , H_2O , O_2 , etc., pH, Eh, flow rate, suspended material, precipitates from the leach fluid, P_{Tot} and T .

Studies of natural rock systems using a flowing system and selected chemical environments have begun to show how a rock composed of several minerals is altered by naturally occurring solutions. For example, with high-pH solutions containing the CO_3 ion, quartz is selectively removed from a granitic matrix. Pure water, however, preferentially dissolves sodium feldspar from the same rock and causes severe channeling along grain boundaries by solution of the yet unknown material which occupies the intergranular voids.

An experimental run on a calcite-veined quartz monzonite from GT-2 with distilled water ($P_{\text{Total}} = 150 \text{ kg/cm}^2$, $T = 240^\circ\text{C}$, $t = 300 \text{ h}$) resulted in the following chemical alteration. The albite component of the originally oligoclase feldspar was selectively leached leaving a spongy network of feldspar of bytownite or anorthite composition on the surface. This effect had been reported at higher temperature by Adams.¹⁶ Quartz crystals are channeled. The microcline in such experiments is relatively resistant but may have fine overgrowths of clays.¹⁷ However, these surface effects were inferred, not observed directly. In general, techniques for surface analysis, such as ESCA (electron scattering for chemical analysis) will have to be employed for

these very fine overgrowths. Some potassium is removed from the biotite. We think this may occur according to the reaction:

creating a ferribiotite.¹⁸ A minor amount of calcite and quartz was dissolved from the vein, but it remained relatively resistant. Some pyrophyllite was detected in the vein. Whether this is primary or secondary is unknown.

Experimental alterations of the same rock under similar run conditions but with a 0.1N NaCO_3 solution produced quite different results. Most dramatic is the complete removal of quartz in solution producing a texture like "Queen's Lace". The oligoclase in this case is albitized. The anorthite component is removed, producing a "pot-holed" topography. Even the original microcline is at least coated on the surface by albite. We infer that instead of a simple overgrowth this reaction may be a base exchange according to the reaction:

Such base exchange is observed with the biotites. The calcite veins are the most resistant feature of the rock. In contrast to the results of the previous run, using pure water, secondary overgrowths are quite prominent. Most prominent are acicular growths of metastable zeolites. Compositions suggest a mordenite $(\text{Ca}, \text{Na}_2)\text{Si}_{10}\text{Al}_2\text{O}_{24} \cdot 7\text{H}_2\text{O}$ core grading into a heulandite $(\text{Ca}, \text{Na}_2)\text{Si}_7\text{Al}_2\text{O}_{18} \cdot 6\text{H}_2\text{O}$ near the tip. Since zeolites are metastable at high concentrations of CO_2 , we expect the trend to continue until a less siliceous phase, possibly albite or nepheline, precipitates from the solution as the stable phase.

These experimental results will be valuable in comparing observed activity-activity diagrams with theoretical results. With pure end-members we will be able to predict the time-dependent reactions and extrapolate these results to other areas. Reconnaissance experiments were performed with various additives to access the effects on the solution rate of rocks from GT-1. A mineral oil saturated solution of distilled water in a 300-h run showed a mass loss of $1.62 \times 10^{-5} \text{ g/cm}^2$. This is a material removal rate only one third as large as that using distilled water alone. Such an additive would pose a decreased disposal problem in an operating geothermal system and might also ease heat exchanger management problems.

Another low-cost additive having selective chemical properties is NaCl. An experiment in a static system with a saturated solution of NaCl gave material loss rates comparable to those using distilled water but very selective mineral attack. The plagioclase was not eroded. The quartz displayed a fine etch pitting on the surface but the biotite was almost completely dissolved from the 2-mm-thick specimen. This was an expected result since any iron-bearing mineral (biotite) should show strong complexing with the chloride ion.

These results were repeated in a flow system. The silica in solution in this experiment was down a factor of ten from that in a distilled water system.

We also find a difference in weight loss of a factor of thirty in a temperature drop from 250°C to 200°C. This may prove to be very useful in operating a GTE demonstration system at lower temperature to avoid heat exchanger problems.

3. Numerical Geochemical Modeling.

In order to predict and understand the chemical behavior of the reservoir region of the dry hot rock geothermal experiment, we are involved in a project of geochemical computer modeling. We are attempting to model the behavior of an assemblage of minerals and solutions as an array of chemical reactions in which we seek the transfer of mass from reaction to product phases. The basic equation is:

where: Aqueous Solution and P(aq) are the initial and final aqueous solutions. Our computer program accepts at most 128 different aqueous chemical species and $\Sigma \text{P(solid)}$ is a mixture of up to 131 different possible product minerals. Presently the model computes the mass transfer anticipated in a thermodynamically closed system. From Eq. (1) the initial step is irreversible, whereas any chemical processes associated with the right-hand side of the equation are assumed to be homogeneous equilibrium reactions of the form shown in Eq. (2).

Written in this form the multiple paths to equilibrium plus the initial irreversible reaction are readily distinguishable. Hereafter such a process, Eq. (2), will be referred to as one of partial equilibrium.

Such a model requires a sizeable code and a large data base. Our numerical simulation experiments are restricted to CDC 7600 machines because of code size. Nearly all 150 K words of small core plus 200 K additional words in large core are necessary.

Although the model is conceptually capable of predicting results in open systems, the following discussion is limited to "thermodynamically closed" ones. Perhaps most important, the model is totally dependent on the reliability of the thermodynamic data employed. Small errors in the initial data base may be propagated and magnified many-fold in the results.

Our primary objective is to predict the reaction products resulting from reactions between amphibolite and/or granite samples simulating LASL's GT-1 and GT-2 cores and an assumed aqueous solution. These calculations are compared with experimental runs on the cores. The reactant mineral concentrations are taken from petrographic descriptions of cores by Perkins.¹⁹ Minerals such as biotite are commonly solid solutions with undetermined thermodynamic parameters. In such cases, their thermodynamic properties are estimated on the basis of data on end-members of the solid solution series. Water analyses from Fenton Lake near the GT-2 drill site is the assumed solution.

4. Results. A summary of calculated results for reactions between GT-1 granite and Fenton Lake water at 260°C are shown in Table II-VII. But some more specific results are also of interest. Figure II-13 shows changes in hydroxyl ion concentration as the reaction variable, ξ , approaches equilibrium. Each change of slope represents a reaction involving the condensed phase. Practically speaking this tells us we can monitor the hydrogen ion activity and obtain information concerning the extent of reaction.

As an illustration of the results in a simple system, let us trace a hypothetical path through the system $\text{CaO-MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ at 300°C. Figure II-14 is a portion of an n-dimensional phase

TABLE II-VII-a

PRODUCT MINERALS FROM GRANITE-WATER REACTIONS

<u>Initial Mineral Assemblage</u>		
<u>pH = 4.0</u>	<u>pH = 7.2</u>	<u>pH = 10.0</u>
Corundum	Hematite	Magnetite
Hematite	Phlogopite	Brucite
Minnesotaite	Zoisite	Diopside
Phlogopite	Corundum	Phlogopite
Zoisite	Andalusite	Wollastonite
Andalusite	Adularia	Minnesotaite
Adularia	Quartz	Zoisite
Quartz	Low Albite	Adularia
Marialite	Minnesotaite	Low Albite
Low Albite		Paragonite
		Andalusite

TABLE II-VII-b

PRODUCT MINERALS FROM AMPHIBOLITE-WATER REACTIONS

<u>Initial Mineral Assemblage</u>		
<u>pH = 4.0</u>	<u>pH = 7.2</u>	<u>pH = 10.0</u>
Corundum*	Hematite*	Magnetite*
Chalcocite	Chalcocite*	Copper*
Minnesotaite	Chrysotile*	Brucite*
Phlogopite	Phlogopite	Diopside*
Pyrope*	Tremolite	Chrysotile*
Talc*	Pyrope*	Phlogopite
Tremolite	Bornite*	Tremolite
Zoisite	Zoisite	Chalcocite*
Quartz	Minnesotaite	Minnesotaite
Marialite	Talc	Zoisite
	Quartz	Low Albite
	Marialite	Quartz
	Low Albite	Talc
	Calcite	Bornite
		Marialite
		Chalcopyrite
		Calcite

*Destroyed

diagram in this system on which an arbitrary path has been imposed. Various straight line portions of Fig. II-14 are the result of precipitation followed by destruction of mineral phases. For the reaction course illustrated, the model predicts

Fig. II-13. Computer hydroxyl ion concentration vs reaction variable ξ , run using Fenton Lake water.

precipitation with progressive disappearance of larnite, wollastonite, mervinite, diopside and chrysotile terminating with the phases monticellite and forsterite.

Let us examine the calculated results for the granite cores from GT-1. First, the solubility of

Fig. II-14. Representation of a portion of the n-dimensional phase diagram for reactions in the system $\text{CaO-MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ at 300°C .

various components in an aqueous phase is critically dependent on its composition and especially its initial pH. Results for various assumed initial pH values, shown in Figs. II-15 and II-16, reveal how sensitive the calculated results are to the initial pH assumed. In these experiments only the concentrations remained constant. The granite was assumed to be the mineral assemblage quartz, microcline, low albite, anorthite, muscovite, annite and phlogopite. Proportions or modal abundance of each mineral phase was taken from¹⁹ Table II-VII-a. The order of precipitation and destruction of mineral products as the pH is varied are listed in Table II-VII-a. At pH = 4.0 only corundum was precipitated and destroyed; at pH = 7.2 hematite and corundum, and at pH = 10.0 brucite, diopside, magnetite and wollastonite. As anticipated the path with a basic solution reflects greater complexity than in acid solution. The simpler path computed with a neutral solution is somewhat surprising.

The various paths for an assumed amphibolite starting material are shown in Figs. II-17 and II-18 for acidic, neutral, and basic solutions. Mineral assemblages composed of chalcopryrite, calcite, low albite, anorthite, illite, annite, tremolite and phlogopite were assumed to simulate the rock. The results at various values of pH, shown in

Fig. II-15. Computer composition diagram for Fenton Lake water - initial pH = 4.0 - reacting with granite.

Fig. II-16. Computed composition diagram for Fenton Lake water - initial pH = 10.0.

Table II-VII-b, indicate increasing complexity with hydroxyl ion addition. These minerals designated with an asterisk are not present in the final solution, that is, they are present only during an intermediate stage of the reaction.

In none of the computer simulations described above were reactions taken to equilibrium²⁰; they

Fig. II-17. Product composition diagram for amphibolite - Fenton Lake water, pH = 4.0.

Fig. II-18. Product composition diagram for amphibolite - Fenton Lake water, pH = 10.0.

were terminated shortly after the reaction variable, ξ , became equal to unity.

The reactions between amphibolite and water are more complicated than those involving granite. In both rocks simpler reaction paths occur with increasing hydrogen ion concentration. The model also predicts significant solubility of copper, as the complex CuCl_3 , when amphibolite reacts with a 2 N NaCl acid solution. The reliability of the model's predictions must await results of investigations concerning (1) the partial equilibrium concept, (2) the numerical analysis scheme, and (3) reliability of the thermodynamic data. We believe a rather useful tool for theoretical modeling of geochemical processes will evolve.

E. Heat Flow Studies

A technique has been developed for the direct determination of successive bottomhole equilibrium rock temperatures during economically acceptable interruptions in drilling operations: 12 to 24 h, depending on depth and rock type. This technique was developed during the drilling of GT-2, the second deep exploratory test hole in the Los Alamos Scientific Laboratory's Dry Hot Rock Geothermal Energy Project (Fig. II-19).

The major innovative aspect of this technique is a new method of analyzing bottomhole thermal recovery data, enabling equilibrium rock temperatures

Fig. II-19. Temperature gradients measured in GT-2.

to be determined from measurements of substantially shorter term than previously possible. Assuming for an arbitrary time interval, short in comparison with the time required for temperature recovery to be complete, that the rate of temperature relaxation

Fig. II-20. 84-mm Mo penetrators used in rock penetration experiments in the field during 1974.

depends only on the difference between the bore-hole temperature and the undisturbed rock temperature, we can write for the time interval, t ,

$$\frac{\theta_{\infty} - \theta(t)}{\theta_{\infty} - \theta_0} = e^{-ct}$$

A linear dependence of C and θ_{∞} enables determination of equilibrium rock temperature. Relaxation temperatures observed at any specific depth can be treated in this manner giving the same rock temperatures predicted by theory. However, sufficient data can be collected in hours rather than months or years, if direct bottomhole temperature measurements are used.

Using this technique, the equilibrium rock temperature at the GT-2 terminal depth of 2928 m is 197°C, with a measured temperature gradient of 60°C/km over the bottom 0.8 km.

F. Advanced Drilling Technology (Subterrene Project)

1. Status. In March 1973 the NSF (RANN) released funds for the Rapid Excavation Rock Melt-ing Subterrene Project. Design and development of a 66-mm-diameter extruding penetrator was completed and holes were melted experimentally in basalt, granite, tuff, and soils.^{21,22} The excess volume of melt products are extruded in a gas stream. Two larger (84 mm) molybdenum penetrators have been designed and recently underwent their initial field tests (Fig. II-23). The first hole reached 30 m in a flow of the Cerros del Rio basalt (Quaternary or late Tertiary age). Both molybdenum (Mo) and tungsten-Mo penetrators were used; the former yield better results. Power applied was 9kW. The penetrator produces a glass-lined bore hole (see Fig. II-3) and its principal advantages over existing conventional (rotary) drilling methods is its possible utility in hot rocks where conventional bits fail, and in deep drilling, since a rotating shaft is not used. Future development of this technique is planned. Its potential applications include deep drilling, particularly in hot environments, tunnelling, and many others.^{23,24}

2. Petrographic Studies of Products. A catalog has been completed containing petrographic descriptions of all materials previously used in laboratory and field tests of the hot-tip rock penetration experiments.²⁵ A summary of the petrographic descriptions of rocks and melts has been

prepared.²⁶ These melting experiments provide an interesting body of data on the disequilibrium melting of silicate rocks, hence many necessary engineering questions may generate some significant science. Photographs of typical melt boundary layers produced during penetration are shown in Figs. II-24, and II-25.

With possible future deep continental drilling projects in mind, a collection of large rock specimens was made from Moses Rock dike, a kimberlite pipe in SE Utah. In this volcanic dike, fragments from the lower crust occur as fairly large unaltered blocks.²⁷ These fragments (xenoliths) are pieces of the vent walls sampled and transported to the surface during violent eruptions. This suite of rocks, believed to be representative of lower crust (garnet-bearing gneisses), will be useful in future laboratory tests of the subterrene as the technique evolves to a stage where its possible use in deep crustal drilling requires evaluation in relevant rock systems.

Fig. II-21. Close-up of glass-lined hole produced by extruding penetrator in granite, 65-mm-diameter holes shown.

Fig. II-22. Photomicrograph of the boundary layer of glass produced during rock penetration by melting. The rock in the penetrator was a 66-mm Mo device operating at about 1200°C. Penetration rate in this experiment was 0.15 mm/sec.

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III. EXPERIMENTAL GEOCHEMISTRY AND GEOPHYSICS

A. Introduction

The analytical chemistry and radiochemistry experience and capability of the Laboratory is large because of previous work on separation of fissionable materials from rocks. Weapons test products are commonly mixed with glass and/or rock. The Laboratory's work has been focused in the past on the fission products, not the rocks. Programs have been in operation for three decades in material science, fabrication and synthesis of materials, high pressure equation-of-state studies and chemical and radiochemical analysis. As energy and resource related programs at LASL continue to expand there will be increasing need for petrologic and geochemical application of this already strong base.

The shock wave group at Los Alamos has contributed significantly to our knowledge of the equation of state of metals, silicates and oxides at high pressures, hence to models for the earth's deep interior - the core and mantle. The physical properties of minerals, rocks and silicate melts (sound speeds, viscosity, transport properties such as electrical and thermal conductivities) are data required for LASL's geo-engineering projects and many experimental programs in these areas already are in progress. Two potentially useful applications of LASL's experience in fabrication of materials by hot pressing are in preparation of high-purity, low-porosity standard mineral and rock specimens for geophysical measurements and geochemistry, especially phase equilibria studies. A very large press (5000 tons), previously used in fabrication, could be modified and calibrated for very high-pressure static-pressure experiments to 10^{10} Pa or more with very large samples. Its unusually large working space would permit simultaneous measurement of many parameters.

Existing experimental programs directed at determination of fundamental properties of geologically interesting materials are described below.

B. Pure Mineral Standards

Although a great deal of thermochemical data has been calculated or directly measured for many minerals of geologic interest, much of these data

are only of limited use for one of the following reasons:

1. Impure compounds were measured.
2. Samples of uncharacterized composition were measured.
3. Improper measurement techniques were employed.

In addition, many phases are as yet untreated. Powerful techniques for handling these minerals in time-dependent rock-fluid interactions such as PATHCALC¹ by Helgeson require precise thermodynamic quantities. Important applications of these data include geothermal power, chemical mining, and shale oil production. We have compiled much of the known phase equilibria for the pyroxenes which will be the first mineral group synthesized and have aided in assembling and planning modifications to existing apparatus throughout the Laboratory.

It is important to emphasize that only a few pure minerals appropriate for our granite-granodiorite rocks must be synthesized and characterized at the present time. These are primarily: two feldspars, a few zeolites, muscovite, a biotite, pyrophyllite, kaolinite and a few other clays, clinocllore, an amphibole, and clinozoisite.

We stress the need to examine pure well-characterized systems, whether natural or synthetic, in order to extend our experimental results to other areas. Because future field studies are likely to encounter a wide variety of rock types, we are establishing an experimental approach based on well-known starting materials. This will permit us to avoid the pitfall of having to characterize every new rock system experimentally.

C. Permeability Studies. Requirements to understand the chemical and physical conditions in the GTE reservoir regime has led us into new experiments involving the measurement of permeability of crystalline (granitic) rock at elevated temperatures. Temperatures of 200°C and significant pressure gradients are anticipated with the hydraulic fracturing experiments in hard rocks.

The only data presently available on permeability of granite are those at ambient temperature by Brace, Walsh, and Frangos². Experiments at 200°C show permeability in the range from 4.8×10^{-7} darcies,² whereas at room temperature values are

4.7×10^{-6} darcies. These measurements are of general interest to the geophysical community because of their application to a number of problems including earthquake prediction, and they are necessary to understand hydrology experiments planned for GT-2. Our experiments also have shown that permeability varies by a factor of two with time (from an initial value of 7.0 to 3.5 microdarcies). This decrease is believed to be due to chemical alteration as water flows through the intergranular spaces. These results suggest in situ mining experiments. Seventy percent of the uranium in granites, for example, is present in the intergranular spaces. We believe that the proper application of chemical treatment of the reservoir might significantly increase permeability, thereby facilitating the removal of uranium and other trace metals by solution methods.

We have begun studies on the recovery of the kerogen from oil shales by hot water, as an initial project in exploring possible solution mining techniques. Oil is almost completely removed by water, leaving a highly fractured residue, at 300°C, 150×10^5 Pa and 100 hours.

D. Trace Element Studies

The opportunity to study the distribution of trace elements over a large depth span such as the 3 km exposed in GT-2 is unusual. We are conducting a reconnaissance study by activation on core samples and cuttings from GT-2. Three different neutron energy flux distributions are being used: thermal, epithermal, and moderated fission spectrum. By use of these fluxes and different irradiation times and measurements we can determine thirty-three elements of geochemical interest. GT-2 core samples are being analyzed at present, and a search for cores from deep holes in the Precambrian throughout North America is in progress. We are particularly interested in perturbations in trace element distribution in granites imposed by leaching in surface and near surface samples.

E. Thermochemistry

1. The Enthalpy of Formation of Barium Oxide. Fitzgibbon, Huber, and Holley³ published a value for the enthalpy of formation of barium oxide, BaO, based on their measured values of the heats of solution in 1 M HCl of Ba metal and BaO. The value for Ba metal -127.95 ± 0.41 kcal/g.at., differed significantly

from the value -125.44 ± 0.10 kcal/g.at. obtained by Vorob'ev, Monaenkova, and Skuratov⁴ at Moscow State University. Because this is a key datum for thermochemical tables, Wagman at the National Bureau of Standards, and Vadim Medvedev, Wagman's counterpart in the USSR, asked LASL's help in resolving the discrepancy and suggested that samples be exchanged.

Vorob'ev was sent the remainder of LASL's barium metal; he reciprocated with some newly prepared barium metal and also strontium metal, with preliminary analytical results indicating that these samples were of high purity. Subsequent analysis, however, indicates ~ 3% BaO in the Ba and ~ 5% SrO in the strontium; other impurities were also present. Preliminary measurements of the heat of solution of the barium in 1 M HCl were made. The resulting values were low by about the amount expected from the impurity content. No further work is planned on these impure samples.

2. The Gibbs Energies of Formation of Well-Characterized Minerals. A program is planned to determine the Gibbs free energies of formation of well-characterized minerals as a function of temperature. Minerals synthesized in LASL's facilities for preparing pure minerals will be used as well as from other available sources. We are particularly interested in solid solutions which occur in nature; in general, much less is known about the solid solutions than about end members. The purpose would be to provide data for geochemical equilibrium calculations, and for bonding models.

The experimental method involves measuring the enthalpy of formation at one temperature and the heat capacity as a function of temperature. The entropy of formation, enthalpy of formation, and the Gibbs free energies of formation can then be calculated as functions of temperature.

The enthalpy of formation requires measurements of the heat of solution of the mineral and of its components in some solvent. For some minerals aqueous HF will do, for most minerals the best solvent is the proper molten oxide or oxide mixture.

3. The Partial Molal Heat Capacities of Aqueous Solution up to 350°C. We also plan to determine the partial molal heat capacities of aqueous solutions up to about 350°C or higher. The proposed solutes are NaCl, KCl, CaCl₂, Na₂SO₄, FeCl₂, and

FeCl_3 . The purpose is to provide data which are necessary for the calculation of solubilities under geothermal conditions, provide key data for modeling calculations so that the partial molal heat capacities of other solutes can be estimated, and provide data for theories of the effect of ions on the structure of water.

The method would be the determination of the heat capacities of solutions of various compositions at various temperatures and finding the partial molal heat capacities by differentiation.

F. Geophysical Applications of High-Pressure Material Science

The shock wave group at LASL has been an active contributor to problems of the earth's interior through their work on the equation of state of geologically interesting materials such as olivine, quartz, and iron.⁵ Present programs include measurement of the density of geological materials under hydrostatic pressures up to 1.2×10^{10} Pa; measurement of ultrasonic velocities in liquids up to 2000°C for equation-of-state determinations; measurement of Hugoniot parameters in natural rocks with shock waves including the melting curve of iron; study of explosive fracturing processes relating to mining; and preparation of high-purity isotopic samples for experimentation. Recently completed work includes determination of isothermal and volume compression of α -quartz to 10^{10} Pa;⁶ experimental determination of the relative compression of cell edges in olivine using new high-pressure x-ray diffraction methods;⁷

and a study of the structure of ice VII using high-pressure x-ray diffraction method which has general implications for the high-pressure equation of state of solids.⁸

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IV. FIELD PROGRAMS FOCUSED ON IGNEOUS PROCESSES

A. Introduction

Motivated by applications in geothermal energy and resources, we are pursuing field programs designed to provide basic understanding of igneous processes in the earth's crust and upper mantle (see Fig. IV-1). We recognize that successful application of laboratory methods and mathematical models to geological problems requires careful systematic field observations. Field investigations are in progress in New Mexico (Valles Caldera-Rio Grande Rift), northern California (Southern Cascades), on active volcanoes (eruption studies) and on a number of topical studies, at various localities, which are focused on kimberlite pipes and andesite volcanism. The goals of these field programs are:

Jemez Mountains-Rio Grande Rift Complex (Jemez-Rio Grande Program). The goal is to define the thermal and stress state of the magma chamber which may underlie the Valles and Toledo Calderas, its thermal, chemical, and mechanical evolution through time, its mode of emplacement and eruption mechanism. This volcanic complex is an excellent example of large silicic calderas, which as a class provide some of the world's best geothermal sites; during the late stages of development of these complexes important ore bodies are known to develop.

MAJOR QUESTIONS

HOW ROCKS MELT AT DEPTH AND PROPOGATE TO THE SURFACE

EVOLUTION OF MAGMAS, THEIR VOLATILE PHASE AND THE MECHANISMS OF ORE DEPOSITION

THERMAL AND STRESS ENVIRONMENT NEAR PLUTONS

ERUPTION PHENOMENOLOGY, ESPECIALLY: EXPLOSIVE VOLCANISM - VOLCANIC GASES

APPROACHES

GEOLOGIC MAPPING AND - ANALYTICAL/OBSERVATIONAL
FIELD PETROLOGY GEOCHEMISTRY

FIELD GEOPHYSICS - SEISMOLOGY
GEODESY
BOREHOLES

PROCESS MODELING - MATH MODELS
SCALE SIMULATIONS

ERUPTION STUDIES - MOVIES
SPECTROSCOPY

Fig. IV-1. Focus of geosciences field research program.

Cascade Volcanic Province of Northern California (Cascade Investigations Program)

We seek to understand processes operating in andesite volcanic provinces typical of the circum-Pacific region. These areas of active subduction of oceanic plates beneath continental margins are volcanically and seismically active, the site of current ore deposition and important geothermal potential.

Eruption Phenomenology and Topical Studies.

Serious consideration is being given to engineering projects involving drilling into or manipulation of active volcanoes for geothermal as well as resource purposes. It is essential to acquire sound knowledge of the processes acting within active volcanoes, and detailed descriptions of the thermal, physical, and chemical environments within them. We are particularly interested in eruption dynamics, in gathering observation data at eruptions of sufficient quality to reconstruct phenomenology in detail, and generating mathematical models for eruption processes. Volcanic gas is also a topic of particular interest.

B. Valles Caldera Complex, and the Rio Grande Rift (Jemez-Rio Grande Program)

The Jemez Mountains, just west of Los Alamos, consist of a complex of young basaltic to rhyolitic volcanic rocks which overlie a thin layer of Paleozoic sedimentary rocks resting on a basement of Precambrian granitic gneisses. The most spectacular feature of the volcanic complex is an extensive ash deposit, the Bandelier Tuff, which was erupted in two violent blasts 1.1 and 1.4 million years (M yr) ago (Fig. IV-2), and a very large caldera located in the Jemez Mountains to the west of Los Alamos. Geologically young activity included collapse of the caldera (the Valle Grande) and emplacement of a series of rhyolite domes and flows, the youngest of which is only about 40,000 years old. The volcano, therefore, must be considered dormant, not extinct. The caldera complex is located on the western margin of the Rio Grande graben, an extensional rift feature of continental extent which runs from central Colorado into Mexico. The rift began opening about 25 M yr ago; its present width implies an average rifting rate of about 0.2 mm/yr.

We seek to understand the origin, emplacement, and eruption mechanisms of large calderas; the thermal and stress state of the environs of a possible magma chamber and the physical, chemical, and dynamic

Fig. IV-2. Aerial photograph of Los Alamos showing the Bandelier tuff which forms the flat-lying mesas.

state of its content. The Valles Caldera complex is one of the most promising geothermal sites in the United States, and two active geothermal projects underway include LASL's dry hot rock program on the southwest margin of the caldera and a commercial wet steam program inside the caldera, conducted by the Union Oil Co. (Fig. IV-3). LASL's project plans include a demonstration heat extraction plant. The relationship of this research to broader geological problems lies in understanding the volcanism associated with large continental rift systems such as the Rio Grande. The relationship of the Rio Grande rift to other large-scale world rift features such as the East African rift valleys, the Rhine graben and the great mid-ocean rift system is a matter of heated debate at present. Also important are mechanisms of magma genesis, the breakup of plates, volcanic mechanisms, and the identity and role of volatiles in internal processes and explosive volcanism.

The Los Alamos investigations in the Valles Caldera have an unusually strong base to build upon because of some thirty years of detailed mapping and petrology of the complex by members of the U. S. Geological Survey.¹

The problem on which our research will focus is to determine the existence and nature of the magma chamber which exists, or existed in the recent geologic past, under the Valles Caldera complex. Active research projects in the Jemez Mountains include regional and local geophysics, emphasizing

Fig. IV-3. Sketch map and geological cross sections of the southwest part of the Valles Caldera showing drill-hole locations, known and possible geological relations.

seismology, but includes extensive surface and down-hole investigations and detailed studies of the cores. Supporting studies include numerical hydrodynamic, thermal history and thermochemical calculations, experimental solution chemistry, rock mechanics, and hydraulic fracturing. In addition, a ground-water monitoring program is in operation, directed principally at assessing possible environmental effects. Petrologic and geochemical investigations have been started on the older basaltic rocks of the Valles Caldera, basalts of the Rio Grande rift, and in the volcanic rocks in GT-1 drill cores.

Possible future developments and projects in the Jemez-Rio Grande Program include the following:

- extensive growth of regional and local seismic networks
- geodesy involving laser, tiltmeters, and precision long leveling lines
- 300-m drilling program, including bore-hole instrumentation

- deep seismic reflection profiling
- solution mining experiment
- mathematical and physical modeling
- topical field studies on geochemistry and petrology
- possible deep drilling to explore the region near a magma chamber

C. Cascade Volcanoes of Northern California (Cascade Investigations Program)

We have begun a research program in southern Cascades of northern California (Fig. IV-4). The research is directed at understanding a large number of important and interesting problems associated with circum-Pacific andesite volcanism, namely: the relationship of the volcanism and seismicity to plate structure and motion; the genesis and evolution of the Cascade magmas and the mode of their emplacement; the eruption mechanism of the volcanoes and in particular the natural eruption hazard, precursor activity associated with eruption episodes,

and understanding which will lead to the evaluation of risks associated with volcano engineering projects (such as attempts to drill into magma chambers); genesis of ore (principally base metals) found in massive sulfide deposits associated with andesite volcanoes, and the assessment and understanding of the deep and near surface thermal regime.

The approach in answering these questions will be a coordinated geophysics, field geology, and petrochemistry program extending over a period of approximately five years. Crustal movements can be detected by geodetic, seismic, and tiltmeter nets. Subsurface structure can be inferred from field mapping, gravity, and seismology. Magmatic processes are studied most effectively by detailed field and petrochemical investigations of individual volcanoes and lava flows. Geophysical evidence exists for application to the problem of the position of magma bodies. Heat flow measurements, monitoring of fumaroles, and remote sensing data are useful in attempts to model the internal thermal state of individual volcanoes and the volcanic province.

The Cascade province, in northern California, Oregon, and Washington, has been the site of historic volcanic activity (Cinder Cone eruption in 1851 and Mt. Lassen in 1915) and seismicity (see Table IV-I,² Fig. IV-5 and 6).

The Cascades of northern California are a desirable locality for a multidiscipline study because they are compact, easily accessible, and relatively active. Because they are near population centers they constitute both a potential threat to property and life, and they also may be economically productive should their energy and ore potential prove to be significant.

The relationship of the Cascades studies to the larger geodynamics or geological problems lies in several categories, but principally in understanding the relationships of the Pacific margin of the Americas plate to the volcanism and processes in subduction zones, the nature of andesite volcanism, and processes at plate boundaries. The northern end of the Sierra Nevada batholith coincides with the beginning of the Cascade volcanic province; and this boundary occurs at the eastward extension of the Mendocino fracture zone, a major feature of the Pacific Ocean floor. The Gorda and Americas plate must intersect somewhere under the province so that a

Fig. IV-4. Map of the Cascade Range in northwestern U. S. showing the major volcanic centers and the area of study.

TABLE IV-I
SUMMARY OF ACTIVITY OF CASCADE VOLCANOES²

Volcano	Location	Elevation (m)	Type	No. Historic Eruptions	Recent Activity
<u>California</u>					
Lassen	40° 29.5 N 121° 30.5 W	3186	Dome	4	Ash blast 5/22/1915 preceded by dacite flow, 150 small eruptions; steam 1857; blast and dacite flow 1732; mudflows 1400.
Cinder Cone	40° 32 N 121° 20 W	2105	Cinder cone	1	Eruption of cone witnessed in 1851.
Shasta	41° 24 N 122° 11 W	4317	Stratovolcano	2	Central vent eruption 1855(?); possible eruption seen from sea 1786; youngest flow within last 1000 years.
Medicine Lake, Little Glass Mountain	41° 35 N 121° 37 W	2089	Obsidian flows & basaltic cinder cones & flows	-	Pumice flows and cinder cone within last 500 years.
Glass Mountain	41° 37 N 121° 30 W	2331	Pumice cone with obsidian flows	-	Lava eruptions and three pumice eruptions in recent times.
<u>Oregon</u>					
Crater Lake	42° 57 N 122° 07 W	1882	Caldera formed by collapse following violent ash blast	-	Cinder cones within caldera (caldera about 7000 years old).
Three Sisters	44° 08 N 121° 47 W	3157	3 stratovolcanoes	-	Obsidian and basalt flows.
Mt. Jefferson	44° 39 N 121° 49 W	3200	Stratovolcano	-	-
Hood	45° 22 N 121° 42W	3428	Stratovolcano	1	Possible central vent eruption about 1801.
<u>Washington</u>					
Adams	46° 13 N 121° 30 W	3751	Stratovolcano	-	-
St. Helens	46° 12 N	2975	Stratovolcano with domes	6	Flow 1802; smoke & ash from central vent in 1842, 1844(?), 1845, 1847 & 1854.
Rainier	46° 52 N 121° 45.5 W	4395	Stratovolcano	6	Lahar, 1.5 km ³ , 4900 b.p.; Indians describe prehistoric blast; summit activity 1843, 1882.
Baker	48° 47 N 121° 50 W	3285	Stratovolcano	5	Ash & smoke 1843, 1854; summit light 1858, 1859; jets, blasts, smoke 1859; smoke 1870.

Fig. IV-5. Aerial photograph of Lassen Peak, showing the 1915 dacite flow.

Fig. IV-6. Aerial photograph of Cinder Cone, an andesitic pyroclastic cone which resulted from an eruption in 1851.

complex subduction zone must be present here, forming the Pacific boundary of the Americas plate.

A reconnaissance seismic and geothermal study has been made. A seismic network has been planned and three station platforms established. We are pursuing a new seismometer design for use in such array investigations. This seismology program is a cooperative effort with Massachusetts Institute of Technology geophysicists. A base for geodesy was established at the Hat Creek Radioastronomy Observatory (University of California, Berkeley). An aerial and ground reconnaissance has been completed. Possible developments in this program including cooperative projects are:

- extensive regional seismic array (cooperative with M.I.T.), including a new type seismometer
- an extensive surface geophysics survey (gravity, HF,* E, and M; seismic profiles)
- 300-m drill-hole program - cores and geophysics
- remote sensing and aerial photography (repeated annually)
- regional and local detailed mapping, petrology, and geochemistry
- detailed geophysical monitoring of three volcanoes (local array, HF, shallow holes - Lassen, Shasta, Medicine Lake Highlands)
- geodesy, using Hat Creek Radioastronomy Observatory as a base and possible line-of-sight experiments
- cooperative program for regional petrology with the U. S. Geological Survey.

D. Volcanic Eruption Phenomenology

The goal of this research program is to understand the mechanics of eruptions as means of exploring the internal processes of volcanoes. One major goal is defining the composition and flux of volcanic gases; another is to define precursor activity to destructive activity as well as understanding the physics of eruptions themselves. Applied concerns related to this research include geothermal energy, ore deposits, eruption hazards, and possible space missions designed to explore known volcanic features, such as the large shield volcanoes of Mars.

Our operating philosophy can be summarized as follows. Volcanoes result from the transport of fluid and solid material from the earth's interior to its surface. The chemical and physical processes involved, while complicated, can be defined individually and so treated. Yet volcanoes are best and

*HF = heat flow, E = electrical resistivity, and M = magnetism.

most truly understood as systems, hence coordinated observations of volcanic geology, petrology, chemistry, and physics provide the strongest approach to understanding their behavior. Such observations are much more powerful when taken together than separately. Our research begins, therefore, with detailed field observations; laboratory activities include both petrologic studies and theoretical investigation of eruption mechanisms, such as numerical hydrodynamics. Some of these problems and approaches are illustrated in Fig. IV-7.

One basic goal of such research, of course, concerns eruption prediction and evaluation of volcanic hazards. For particular volcanoes we are interested in some simple questions concerning eruptions: when, where, and how big? Other applied motives include how the many types of ore bodies found in volcanic rocks originate. Many involve the migration of a volcanic gas phase and the ores are believed to be emplaced by alteration and enrichment occurring within volcanoes during the terminal stages of their life cycle. As heavy metals become increasingly short in supply, the economic aspects of volcanic geology will become increasingly important. An understanding of volcanic mechanisms will play a key role in developing new approaches to mineral and ore extraction techniques as well.

Work by LASL volcanologists has included eruption photography (high-speed movies); jet noise; detailed mapping, petrology, and geochemistry; ash studies (terrestrial and lunar volcanic ash); exterior ballistics; space photography as a means of studying the evolution of volcanic plumes, fallout, and atmospheric effects; and numerical studies of eruption hydrodynamics. Some of the volcanoes studied by LASL geologists are listed in Table IV-II and Fig. IV-8. Eruption phenomenology, while fundamentally different from the physics of blasts, requires much the same type of documentation, suggesting that some of LASL's experience in weapons test monitoring may be quite applicable to studies of volcanic eruption phenomenology. During field testing of weapons aerial photography, high-speed motion pictures, spectroscopy, geophysics, atmospheric and particle sampling, and extensive post-event drilling are required to characterize the phenomenology of the blast. These data are used to construct and to test the accuracy of theoretical models for the blast.

TABLE IV-II

SUMMARY OF VOLCANOES AND PROBLEMS STUDIED BY LASL GEOLOGISTS

Volcano or Eruption Site	Type of Feature	Petrogenesis	Xenoliths/Mantle	Volatiles/gases	Eruption hydro- dynamics	Exterior hydro-	Flow emplacement	Acoustic emission	Seismology	Geomorphology	Additional
Moses Rock Dike, Utah	Kimberlite	X	X	X	X						
Nanwaksjiak, Alaska	Alkali basalt maar	X	X		X	X					
Cane Valley, Arizona	Carbonatite	X	X	X							
Maars (Bend), Central Oregon	Phreatic maars	X							X		Ash
Hekla, Iceland	Andesite stratovolcano	X									
Etna, Italy	Cinder cone/shield volcano				X	X			X		Ash
Stromboli, Italy	Pyroclastics on shield				X	X					
Cascades, California	Andesite stratovolcanoes	X						X			Ash
Pacaya, Guatemala	Pyroclastic & lava flows	X					X	X			
Acatenango, Guatemala	Stratovolcano							X			Ash
Mauna Kea, Hawaii	Cinder cones on large shields								X		
Puyehue, Chile	Ash blast eruption of strato- volcano								X		
Apollo 16 & 17 Sites	Lunar mare basalts & pyro- clastic rocks	X			X				X		Ash
Mons Olympus, Mars	Shield volcanoes								X		
Jemez Mountains, New Mexico	Shield & ash blast volcano	X			X			X			Bore hole core studies
Shiprock, New Mexico	Lamprophyre dike with xeno- liths	X	X								
Cotopaxi, Ecuador	Andesite & dacite strato- volcano	X									
Hualalai, Hawaii	Basaltic lava flow	X	X				X				
Mauna Loa, Hawaii	Shield volcano			X	X	X					Geodesy
Mono Craters, California	Pumice and lava flows								X		
Santorini, Greece	Ash blast eruption				X						Tsunami

SOME PROBLEMS IN VOLCANO PHYSICS

1. Composition and thermal state of the mantle as revealed by xenolith investigations
2. Origin and localization of magma in the mantle; evolution of magmas
3. Mineralogical sites, diffusion and localization of volatiles in the mantle
4. Migration of magma; physical properties of multi-phase systems; reservoir performance
5. Fracture propagation; deformation (strains and measurable tilt)
6. Hydrodynamics of flow; heat and mass transfer (viscous effects important)
7. Hydrodynamics of expanding complex multiphase media (vesiculation, fluidization, etc)
8. Mechanical stability and heat transfer to wall rocks; contact metamorphism
9. Ballistics, thermal and comminution history of entrained fragments
10. Hydrodynamics of the exhaust jet; interaction with atmosphere or vacuum
11. Exterior ballistics of fragmental ejecta; atmospheric drag
12. Ash distribution by wind; fall out
13. Mechanics of emplacement of lava and ash flows (heat and mass transfer)
14. Volcano acoustics; airwaves and atmospheric shocks
15. Seismicity

Sources of Data (Constraints on all models)

Direct field observation of active volcanoes

Reconstruction of events using:

Geological relations to reconstruct a detailed sequence of events (or direct data).

Petrology (P, T, H₂O physical and chemical history revealed by mineral chemistry, textures, etc.).

Fig. IV-7. Some problems and approaches to volcanological problems.

Our volcanological research is directed at almost identical goals.

The following are being seriously explored (including cooperative programs):

- aerial photography and remote sensing from aircraft
- surface observation stations, including movies, spectroscopy, TV, acoustics, and geophysics
- sampling of air and airborne particulate material by manned and drone aircraft
- remotely sensed gas analysis by fast Fourier transform interferometry or laser backscatter (Raman) spectroscopy
- possible penetrometer emplaced geophysics experiments

- geologic mapping, petrology, and geochemistry
- high-altitude sample collection program, space photography, and remote sensing
- shallow holes for samples, chemical and geophysical monitoring.

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A. Hawaiian lava lake during 1972 eruption. Such lava lakes have been proposed as sites for testing engineering concepts for placing heat exchangers directly into the magma bodies for extraction of geothermal heat.

B. Time-lapse photograph of eruption plume at Stromboli, Italy, September 1971.

Fig. IV-8. Two markedly different types of volcanic eruptions.

V. PROBLEMS AND PROJECTS IN IGNEOUS PROCESSES

A. Introduction

In this section individual research projects are described. Most are focused on igneous processes: (1) in the Jemez Mountains, (2) in the Cascades, and (3) at selected sites related to eruption mechanisms. Since most aspects of these programs were initiated during the summer of 1974, many consist of progress and status reports.

B. Valles Caldera

1. Tectonic Setting of the Rio Grande Rift and Colorado Plateau (T. McGetchin). The Rio Grande rift and the adjacent Colorado Plateau province present one of the most interesting and as yet unresolved problems in tectonics, namely the explanation for vertical motion within stable continental blocks. The Rio Grande Valley, (Fig. V-1) forms the eastern boundary of the Colorado Plateau province and the western boundary of the Great Plains. It is recognized as a feature similar in many respects to the world's large rifts, such as the East African Rift

in Kenya and Ethiopia (Table V-I). Such features are related to active splitting of large continental blocks which leads, in some cases, to the creation of new ocean basins. Commonly associated with these rifts is a suite of unusual composition for volcanic rocks^{1,2} (Fig. V-2).

The Cenozoic evolution of the western United States, of which the Rio Grande rift and the Colorado Plateau are important elements, has been an especially lively topic particularly in the context of plate tectonics.³⁻⁷ While there is general agreement that the mid-Tertiary uplift of the Colorado Plateau, formation of the block faulting and volcanism in the Great Basin, and uparching rifting and volcanism along the Rio Grande rift are related to the major tectonic events along the western Pacific margin, there is no general agreement about the details. Atwater³ first pointed out that the western U.S. was the site of an active (oblique) subduction zone prior to 30 M yr ago as the lithospheric (Farallon) plate migrating eastward from the east Pacific rise was underthrust beneath the western edge of the Americas plate. At about 30 M yr, however, the Americas plate overrode the ridge and oblique subduction motion began

Fig. V-1. Generalized map of the Rio Grande Rift showing the location of the Jemez Mountain Complex.

Fig. V-2. Aerial photograph, southwest of Taos, New Mexico, showing fault bounded terraces in Tertiary basalts along the western margin of the Rio Grande Valley. These features are very similar to those of the East African and Ethiopian rift valleys although somewhat smaller in scale.

TABLE V-I
COMPARISON OF SOME PROPERTIES
OF THE WORLD'S RIFT SYSTEMS^a

Rift Zone	Age (M yr)	Total Extension (km)	Minimum Extension Rate (mm/yr)	Total Volume of Volcanics (10 ³ km ³)	Flux per Kilometer of Length (10 ³ m ³ /yr)
Rio Grande	25	3 (5)	0.1 (0.2)	12 (60)	2 (10)
Kenya	25	2 (20)	0.1 (0.2)	150	6
Ethiopia	25	up to 50	2	300	10
Iceland	20 (80) ^b	400	20	1000	200
East Pacific Rise	--	--	100	--	100

^a R. W. Decker, Dartmouth College, personal communication, August, 1974.

^b Limiting values shown in parenthesis.

being progressively transformed to transcurrent faulting on the San Andreas Fault in California. Scholz et al.⁴ pointed out that this event might nicely account for normal faulting and copious volcanism at about that time in the Basin-Range province as compressive stresses were relaxed in the upper mantle under the province and heating took place at the same time. Atwater³ had previously pointed out that the underthrust lithospheric plate would be progressively thinner as the Americas plate approached the ridge because at the ridge the oceanic plate has almost zero thickness. This implies that the underthrust plate grew significantly and progressively hotter with time.

These tectonic events have a very interesting correlation with the major structural and igneous events of the Colorado Plateau and Rio Grande rift areas. There is rather clear evidence in the kimberlite and carbonatite diatremes that the Colorado Plateau upper mantle became wet or warmer or both during the mid-Tertiary.⁸⁻¹⁰ The major tertiary events in the province are summarized in Table V-II.

Within the Rio Grande rift, a similar upper mantle episode must have occurred but with considerably more effect. Uparching of the rift amounting to about 2 km occurred about 25 to 30 Myr ago and the extensional rifting followed. Several possible mechanisms operating in the upper mantle could

effectively account for this uparching (summarized in Table V-III). Sanford¹¹ has shown that there apparently is no upfaulted mantle horst under the southern part of the Rio Grande rift zone, however, data suggest a zone of very low rigidity and low seismic velocity at about 18 km depth near Socorro which is probably a large sill-like body of magma. These observations, together with the abundance of young basaltic volcanic rocks particularly along the western margin of the graben (near Taos, west of Albuquerque, and near Socorro) and the large and young silicic volcanic complexes (San Juan, Jemez, and Mogollon Mountains), attest to the activity of the rift.

A schematic east-west profile from the Colorado Plateau province to the Great Plains, shown in Fig. V-3 summarizes the main features of the upper mantle structure across this transitional region. The heat flow in both sides of the Rio Grande

TABLE V-II
SEQUENCE OF SOME MAJOR TERTIARY EVENTS
OF THE COLORADO PLATEAU

Event	Age (M yr)
Ore Deposits	35-40
Kimberlites	30
Minettes	28
Laccoliths	45, 23-26
Uplifts	20
Calc-alk basalts	0-5

TABLE V-III

SOME POSSIBLE MECHANISMS FOR PRODUCING THE INFERRED UPLIFT
ABOUT 30 M YR AGO ALONG THE RIO GRANDE RIFT BY MELTING,
PHASE CHANGES, OR HYDRATION OF THE MANTLE.

<u>Mechanism</u>	<u>Requirement for Vertical Uplift</u>
● General heating and thermal expansion: $\frac{\Delta h}{h} \sim \alpha \Delta T$ $= 36.0 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1} \Delta T$ (olivine, 500°C)	Increase in surface heat flux from 1.2 to 1.3 would produce an average $\Delta T \sim 400^\circ\text{C}$ above 150 km, or $\Delta h \sim 2.0$ km
● Partial melting of the upper mantle: $(\Delta v/v)_{\text{fusion}} \sim 10\%$	Approximately 20% partial melting over 100 km of upper mantle would produce 2 km of uplift
● Introduction of new water from below: $(\frac{\Delta v}{v})$ for 1% H_2O ~ 3%	Approximately 0.7 wt.% water introduced into a previously anhydrous upper mantle (either in hydrous minerals or as free phase) would produce about 2% expansion, or 2 km for 100 km
● Hydration reactions in an already wet mantle: $\begin{array}{l} \text{anhyd} + \text{H}_2\text{O} \rightarrow \\ \text{hydrous} \quad \frac{\Delta v}{v} \sim 1 \text{ to } 2\% \end{array}$	If water & dry peridotite reacted to form hydrous assemblages the volume increase is 1 to 2%, hence 1 to 2 km of uplift would be produced by hydration of rocks constituted of anhydrous minerals & interstitial water
● Phase transition involving gabbro and eclogite	The volume change is about 10% so 20 km of eclogite transformed to gabbro would result in 2 km of uplift

graben is near or slightly above normal, about 1.5 heat-flow units (HFU), whereas along the axis rift itself values are typically 2.5 HFU or higher.¹²

The kimberlite pipes^{8,9} provide an indirect look at the composition of the upper mantle and perhaps its fossil thermal state. Predominant upper mantle rock types are spinel-lherzolite, partly serpentinized at shallow depths, with some high-pressure hydrous minerals (humite, phlogopite, and amphibole present). Minor eclogite and pyroxenite may be present but peridotite is probably representative. Seismology provides the most direct data in present upper mantle structure. The upper mantle in the west has a well-developed low-velocity zone¹³ and a

typical upper mantle P-wave velocity near 7.8 km/sec whereas the east has no low-velocity zone and an upper mantle P-wave velocity of 8.2 km/sec. These data have been interpreted by a number of authors to indicate that the west is hot and/or wet. If indeed the east is dry, and the west wet, then the depth of the base of the lithosphere may be very different in the two provinces. The base of the lithosphere is commonly assumed to be near or at the intersection of the geotherm with the peridotite solidus. The temperature of the solidus at any pressure depends critically on whether the system is wet or dry (Fig. V-4). Clearly, the lithosphere will be much thicker in a dry mantle as

Fig. V-3. Heat flow and seismic velocity of the upper mantle along an east-west profile from the Colorado Plateau (CP) to the Great Plains (GP), crossing the Rio Grande rift (RGR). The diagram is generalized and schematic but is representative of conditions in central and northern New Mexico. LVS refers to the seismic low-velocity zone in the upper mantle.

in the eastern United States, whereas the lithosphere will be thin in a wet and/or hot mantle. This model suggests significant relief on the base of the lithosphere, (Fig. V-5) as one proceeds along an east-west profile. If the lithosphere has such a corrugated bottom surface this must place limits on the amount or rate of the relative horizontal displacements possible along this boundary, and it also could provide an effective "keel" for

Fig. V-4. Melting relations in a dry and wet peridotite upper mantle.

Fig. V-5. Base of the lithosphere along an east-west profile from the Colorado Plateau (CP) to the Great Plains (GP), as defined by the peridotite solidus for an upper mantle in the west which is assumed to be wet, and a dry eastern upper mantle. Numbers (7.8, 8.2 km/sec) indicate upper mantle P-wave velocity. If the eastern upper mantle velocity (8.2) indeed indicates a cool dry upper mantle, then the depth to the melting curve (Fig. V-4) may be quite deep (300 to 400 km); where as if the low-velocity zone (LVZ) within the upper mantle (7.8) implies hot-wet conditions, then the (wet) solid curve is intersected at shallow depths (100 km). Heat flow under the Rio Grande rift (2.5 HFU) is sufficiently high to imply melting at 30 to 40 km depth.

driving continental drift by fluid dynamic drag if convection is active in the asthenosphere below.

Some investigators feel that the Rio Grande may be an incipient spreading center, a newly born mid-ocean ridge, and that the continent may evolve to a stage such as the Red Sea and eventually a major ocean ridge as the American continent separates and drifts (or is carried) away in two directions. Others believe the Rio Grande to be only a regional uparch or swell with keystone blocks fallen into the rift forming a graben. The high heat flow along the western margin of the rift and the tholeiitic nature of the basalts found within it are consistent with an incipient major rift structure.

A crucial piece of evidence is whether the crust is thinned (and is thinning) over the axis of the rift. As previously mentioned, Sanford¹¹ reports that no horst of mantle rock exists under the graben; gravity data are indeterminate because of uncertainties over rock density at depth.¹⁴

It is tempting to speculate about the processes within the upper mantle which might integrate some of these observations. It appears that some of the major Cenozoic historical events of the Colorado

Plateau can be reconciled perhaps quantitatively with a model in which heat (and possibly volatiles) was released into the upper mantle from below in mid-Tertiary time. In a cool upper mantle a number of minerals are stable at high pressure, such as phlogopite, humite, amphibole (Fig. V-6). If at about 50 M yr a thermal perturbation was introduced, approximated by a step increase in temperature, at a moderate depth, 150 km, then we may calculate the consequences (Fig. V-7). Initially, the depth limit of hydrous minerals in a mantle where the temperature gradient was moderate or low (i.e. cool) would be about 120 km. The stable assemblage below would contain anhydrous mineral phases and a free volatile phase - which might easily diffuse upward leaving the mantle dry below the stability field of anhydrous minerals. In such a state the solidus curve would be between about 850° and 1000°C to 120 km depth, but it would abruptly rise to 1500°C at 120 km. If we examine the results of upward diffusion of heat from such a model we find: (1) release of some bound volatiles at depth as hydrous phases become unstable with temperatures below the solidus - these are the conditions inferred for emplacement of the Colorado Plateau kimberlites;⁹ (2) upward diffusion of heat gradually raises the temperature

Fig. V-6. Stability fields of hydrous minerals which can exist in a "wet" upper mantle as shown by shaded area.

Time, t (M yr)	Temperature Ratio (T/T _∞) At Indicated Depth		Surface Heat Flux (Q/Q _∞)
	75 km	100 km	
84	14%	30%	0%
363	24%	47%	4%
730	54%	69%	30%
1430	82%	88%	73%
2170	94%	96%	-
3600	100%	100%	-

Fig. V-7. Response to mantle thermal pulse. Summary of the effects of a thermal pulse (of arbitrary size) introduced into the upper mantle at 150 km depth. Thermal effects due to diffusion are not felt at the surface for the order of 100 M yr; melting effects at depth probably control subsequent history (as shown in Fig. V-8). In the Table shown above T_∞ and Q_∞ refer to temperature and best flux at infinite time.

of the mantle to solidus temperatures - partial fusion in the mantle results leading to emplacement of minette,¹⁵ and carbonatite dikes;¹⁰ (3) heat and volatiles diffuse upward eventually reaching the base of the crust - partial fusion of the base of the crust follows, resulting in laccolith emplacement as small diapirs; (4) eventual pervasive mantle melting leads to younger basaltic volcanism around the boundary of the province. Uplift of the province goes on throughout the entire episode due to thermal expansion, and positive volume changes accompanying fusion, hydration and possibly solid-state phase transitions. This scenario is summarized schematically in Fig. V-8. The peak of the activity seems to have been in the time period about 30 to 20 M yr ago. As relations at the continental margin

Fig. V-8. Schematic summary diagram showing the sequence of events resulting from the introduction of heat into the Colorado Plateau upper mantle.

changed from active subduction to strike-slip faulting, the heat source apparently was turned off.

A possible alternative is that the east Pacific rise has migrated eastward under western North America in the manner shown in Fig. V-9. In this view the Rio Grande rift, indeed, could be an incipient major oceanic spreading center. It will be some time before we have sufficient data on the deeper parts of the upper mantle and the structure of the Rio Grande to evaluate such hypotheses.

2. Structure and Reconnaissance Petrology of the Precambrian Rocks of Northern New Mexico (John Callender, Univ. New Mexico). The structure and petrology of the Precambrian is of interest for several reasons. Consequently, understanding the details of the petrology and structure (fracture and joint systems, their spacing and orientation) are important in evaluating data from *in-situ* and core measurements. These data bear critically on the behavior of the reservoir regime during geothermal energy extraction. It has been postulated that the major faults along the Rio Grande rift and the form of the rift itself is controlled by older structures in the Precambrian, produced long before the current rifting began. In this view, the deep crust was fractured into large blocks; deformation (uplift and rifting) associated with the Rio Grande

Fig. V-9. Diagram showing the possible evolution of the Rio Grande rift (RGR) area during Tertiary time. The upper diagram is early Tertiary time, the middle at about 30 m. yr ago; the bottom, a highly speculative view of the present in which the ancestral east-Pacific rise now underlies the Rio Grande rift. In this view the faulting and copious volcanism in the basin-range province during the mid-Tertiary, coincides with heating from below and tension in the crust,

resulted in differential motion between large (10-20 km) blocks.¹⁶ With these problems in mind, the exposed Precambrian rocks in northern New Mexico are of considerable interest.

This report summarizes, briefly, the Precambrian geology of north-central New Mexico (Fig. V-10). The emphasis is on the structural features, such as foliation, faults, joints, and trend lines, displayed by these rocks. The major portion of the data in this report is from the literature and is generally not sufficiently detailed to allow either regional correlation or the prediction of structural environments in covered areas.

The data assembled in Table V-IV summarizes the major structural and petrographic features of rocks in the Sangre de Cristo, Picuris, Sandia-Manzanita, Nacimiento and Brazos (Tusas) Mountains. Figure V-11 is a columnar section of the Precambrian rocks exposed in the Sangre de Cristo Mountains; the

Fig. V-10. Outcrop map of Precambrian rocks exposed in northern New Mexico.

Precambrian is complex, consisting of medium to high rank metamorphic rocks of both felsic and mafic compositions, metavolcanics which are generally intermediate but with both felsic and mafic material present, and younger intrusive granitic rocks.

The history of the Precambrian rocks of this region can be summarized schematically as follows:

- Clastic and volcanic deposition in one or two major stages beginning about 1.8 billion years (G yr) ago.
- Folding and synkinematic regional metamorphism in 1 to 3 stages, with "early" granitic intrusion locally developed during this period.
- "Granitic" intrusion, metasomatism, contact metamorphism, and mineralization, occurring in from 1 to 5 stages in a complex manner.
- Dilation, jointing, faulting, shearing, and mafic dike intrusion.
- Uplift, beginning about 1.2 G yr ago.

No attempt is made to trace the evolution of specific rock units in this report. The complexity of various regions, the diversity of deformational and thermal events and their relative intensities, and the lack of detailed information in many areas makes regional correlations premature.

An understanding of the mechanical behavior of Precambrian rocks is critical to the development of tectonic and engineering models for this region. It is commonly assumed that these crystalline rocks act as brittle and rigid units during later deformation. For example, Woodward and others¹⁸ relate the deformation of Precambrian rocks during the development of the Nacimiento uplift in Laramide and later time to the formation of vertical fractures and shear folds. Muehlberger¹⁹ describes the development of drape-folds in cover over narrow fault zones in underlying Precambrian rocks. If the assumption of rigidity is valid, then the anisotropic

TABLE V-IV

SUMMARY OF THE GEOLOGIC FEATURES OF PRECAMBRIAN ROCKS IN NORTH-CENTRAL NEW MEXICO

Area	Geology	Age (M yr)	Trends of Major Structural Features	Foliation Trends	Joint Trends	Comments	References
Sangre de Cristo Mountains a. North of Taos	<u>Rock Units:</u> amphibolite, schist, metadiabase, biotite granite, granitic and mafic gneiss, granodiorite, and metaquartzite. <u>Metamorphism:</u> greenschist to lower amphibolite-grade; local sillimanite; multiple phases (?) and local contact metamorphism.	N.A. probably coeval with Tusas Mtns. 1500-1800	<u>Folds:</u> NE, NW <u>Faults:</u> NE, NW (steep) <u>Dikes:</u> WNW, ENE, (steep)	NE with NW dips; local NW trends. Steep dips.	Strong: E-W N60E (steep). Moderate: N-S (Steep).	Metadiabase dikes fill N-S joint locally. Pegmatite dikes in E-W and N-S joints locally. Mylonites in some areas with variable trend. Mineralization locally controlled by structure.	21, 22, 23, 24, 25, 26, 27, 28, 29
b. South of Taos (Refs. 14, 22)	<u>Rock units:</u> granite, biotite granite, quartz monzonite, quartz, diorite, granodiorite, amphibolite, schist, metadiabase meta-quartzite, granulite, granitic and mafic gneiss, phyllite, and metaconglomerate. <u>Metamorphism:</u> amphibolite-grade, with Stt-Ky-Si locally; multiple phases, including metasomatism and contact metamorphism.	1300-1700 (Refs. 14, 22)	<u>Folds:</u> E-W, overturned to N. <u>Faults:</u> N-NE trending, with some right-lateral strike-slip. <u>Dikes:</u> NE and NW, steep.	Highly variable. NE, NW, E-W prevalent (steep dips).	Strong: N30E N70W N10W (all steep). Weak: variable, mainly steep.	Metadiabase dikes intruded along NE and NW joint trends. Granite is syntectonic, catazonal, according to Ref. 8. Mineralization locally strongly controlled by structure.	30, 31, 32, 33, 17, 34
Picuris Range (Refs. 14, 22)	<u>Rock units:</u> granite, biotite granite, quartz monzonite, diorite, quartz diorite, granodiorite, amphibolite, mafic and granitic gneiss, schist, phyllite, metaconglomerate, metaquartzite, granulite, metadacite (see Fig. V-11 for typical section). <u>Metamorphism:</u> amphibolite-grade (Si-Stt-Ky locally); multiple phases, with metasomatism and contact metamorphism.	1300-1700 (Refs. 14, 22)	<u>Folds:</u> E-W, ENE overturned to N. <u>Faults:</u> N and NW with left and right-lateral movement.	E-W, ENE, with south dips (generally steep).	Strong: N-S N40E N70W (all steep). Weak: N20E Steep.	N-S joint filled with quartz veins. Granite ranges from epizonal to catazonal; intruded in 5 episodes. Mineralization commonly structurally controlled.	35, 33, 17, 36

TABLE V-IV (cont.)

Area	Geology	Age (M yr)	Trends of Major Structural Features	Foliation Trends	Joint Trends	Comments	References
Sandia-Manzanita Mountains	<p><u>Rock units:</u> granite, granitic gneiss, schist, phyllite, amphibolite, metaquartzite, metarhyolite, and greenstone.</p> <p>(Ref. 7)</p> <p><u>Methamorphism:</u> greenschist to lower amphibolite-grade; superimposed contact metamorphism and K-metasomatism; some migmatization.</p>	1350-1600	<p><u>Folds:</u> NE, ENE, some overturned to NW.</p> <p><u>Faults:</u> N-S, NNE, NE; N-trending breccia zones.</p> <p><u>Dikes:</u> some N-trending (mainly aplites).</p>	Variable, mainly NE, NW dips variable mainly steep.	<p>Strong: N50E N40W N-S (all steep).</p> <p>Moderate: E-W.</p> <p>Weak: 3 others, variable dips steep to low angle.</p>	<p>Most diabase dikes are Phanerozoic and trend parallel to N-S joint.</p> <p>Strong, low-angle unloading joint locally present.</p> <p>Epidote zonation and pegmatite, barite, and fluorite structurally controlled.</p>	37, 38, 39, 40, 41
Nacimientto Mountains	<p><u>Rock units:</u> granite; quartz monzonite and granodiorite gneiss; schist, amphibolite, ultramafics, and metaclastics.</p> <p><u>Metamorphism:</u> amphibolite-grade, with some metasomatism and contact metamorphism.</p>	1800	<p><u>Folds:</u> N.A.</p> <p><u>Faults:</u> N-S, NE; flaser gneiss along fault traces locally.</p> <p><u>Lineations:</u> NE, plunge NE.</p>	<p>ENE (south part).</p> <p>NW (north part), dips generally 30-70°.</p>	<p>Strong: N-S N30W N60E (all steep).</p> <p>Weak: numerous & variable.</p>	<p>Precambrian diabase dikes intruded along faults.</p> <p>Local mafic dikes trend NE, NW; emplaced during dilation episode.</p>	42, 43, 44, 38
Brazos (Tusas) Mountains	<p><u>Rock units:</u> metaquartzite, schist, leptite (metarhyolite?), quartz diorite and granitic gneiss, granite, metaconglomerate, and common pegmatites.</p> <p>(Ref. 3, 7, 21)</p> <p><u>Metamorphism:</u> generally amphibolite-grade (Si-Stt-Ky) although variable; multiple phases, including metasomatism.</p>	1425-1700	<p><u>Folds:</u></p> <ol style="list-style-type: none"> NE recumbent isoclinal, NW, overturned to NE, E-W. <p><u>Faults:</u> Small, variable; mylonite zones locally.</p>	<p>NW (south part).</p> <p>E-W (north part).</p> <p>minor NE.</p>	<p>Strong: N20E N70W N-S (all predominantly steep to vertical).</p>	<p>NE joint is extension joint.</p> <p>Area of complex structural and metamorphic history</p> <p>Strong structural control of Mineralization.</p>	45, 46, 47, 48, 49, 50, 51, 52, 19

Fig. V-11. Columnar section of Precambrian rocks, southern Sangre de Cristo Mountains, New Mexico. 35

behavior of the blocks of Precambrian crystalline rock is likely related to their internal structure. However, a direct relationship between zones of structural weakness in the Precambrian and later tectonic patterns has not been demonstrated in this region. Furthermore, the more simple relationship between surface outcrop patterns and regional structures has not yet been satisfactorily developed.

A few obvious relations can be reported. First, there are well-developed NE and NW foliation-trends in these rocks; these trends correspond closely to

those found elsewhere in the southwest.²⁰ Secondly, 3 sets of joints trending NE, NW, and N-S, are well displayed in the Precambrian of this region. Although no definite relationship has yet been discovered for the timing of these sets, the N-S joint set is locally seen to be superimposed on the other two.

The structural inhomogeneity introduced by these two features alone probably has a significant effect on the mechanical behavior of the crystalline basement. Zones of weakness related to the

intersections of these trends surely provide important foci for local deformation and perhaps act as conduits for igneous activity.

In summary, while structural trends in the Precambrian suggest some interesting possible relationships of recent tectonic patterns, such as the shape of blocks along the Rio Grande graben, tectonic synthesis clearly awaits more detailed studies of the Precambrian in this region.

3. Trace Element and Petrologic Investigations on Volcanic Rocks of New Mexico (J. Reid).

a. Introduction. This report concerns the relationship of the basalts of the Jemez Caldera to the basaltic rocks of the Rio Grande rift as indicated by their uranium and rare earth element geochemistry. These data may bear on the question of whether the Rio Grande is an insipient sea floor spreading center.

During the last 10 M yr or so, basaltic activity has occurred in north-central New Mexico in two distinct tectonic settings; eruptions associated with the complex central volcanic edifice of the Jemez Mountains immediately west of the Rio Grande Valley^{53,54} and in eruptions associated with rifting in the valley itself.^{55,56}

The purpose of the investigation is to examine the petrographic and trace element characteristics, principally uranium and the rare earth elements (REE) of the two groups of basalts with several related goals in mind. One is an effort to delineate the evolution through time of the basaltic rocks associated with the Jemez complex itself. Another is to determine what interaction, if any, has occurred beneath the surface between the magmas of the central complex and those erupted at varying distances from the Jemez Mountains along the Rio Grande rift. A third is to investigate the tectonic nature of the rift.

In order to examine these questions, determinations of uranium and rare earth element (REE) concentrations in the basalts are being made using instrumental neutron activation analysis techniques. The rare earth element group is particularly well suited to an investigation of this sort: the electronic structures of the REE differ from one another only in the numbers of 4f electrons they contain; ⁵⁷La for example has no 4f electrons; ⁷¹Lu has the full complement of 14 4f electrons. Since the 4f

orbital is an interior one in the REE electronic configuration, and hence not involved in the bonding interactions with other ions, all the REE have very nearly identical geochemical behavior. The small differences which exist result mainly from differences in their ionic radii; the REE decrease uniformly with increase in atomic number, Z, due to a shrinking of their electronic structure resulting from the increased proton-electron attraction as the 4f orbital is filled and additional protons are added to the nucleus. This uniform decrease in ionic radius with increase in Z, the so-called lanthanide contraction, provides an extremely powerful geochemical tool, in that the ease with which a given trace ion can substitute for a major ion of a crystal structure is, for ions with charge differences no greater than one essentially a function of the degree to which their ionic radii match. The ionic radii of the REE range from 10^{-10} m for ⁷¹Lu at the "heavy" end to about 1.4×10^{-10} m for ⁵⁷La at the light end, and so, for example, in the diopside structure ($\text{CaMgSi}_2\text{O}_6$) trace ions with ionic radii near 10^{-10} m ($r_{\text{Ca}} = 0.98 \times 10^{-10}$ m) can substitute for Ca, while larger ions are excluded ($r_{\text{Mg}} = 0.66 \times 10^{-10}$ m, and so the Mg sites are incapable of accommodating REE substitution). The result is that if diopside crystallizes from a silicate melt it will more readily incorporate the heavy REE than the light, leaving the liquid enriched in light REE relative to its initial REE distribution pattern.

A good deal of effort has been made in recent years to determine crystal-liquid distribution coefficients for the REE in a number of igneous minerals.⁵⁷⁻⁶⁰ These investigators have consistently found marked differences in the distribution-coefficient patterns for olivine, clinopyroxene, garnet, plagioclase and hornblende in equilibrium with silicate liquids. With these data, and the experimentally determined REE patterns in the basaltic rocks themselves, one can model the pre-eruption histories of spatially related volcanic rocks, both from the point of view of the mineralogy of the source materials from which the magmas may have initially been generated, and the fractional crystallization events the magmas may have undergone enroute to the surface. Investigation of REE patterns in these basalts serves not only to address the questions outlined above, but will be the basic

geochemical framework upon which a better understanding of the evolution of the associated andesitic, dacitic and rhyolitic rocks in the Jemez Mountain complex, itself, can be based.

b. Status of the Investigation. Seven weeks were spent during the summer field season, 1974, collecting basalt samples from the Jemez Mountains area and along the Rio Grande rift as far north as Arroyo Hondo, New Mexico. Locations of the collection sites are shown in Fig. V-12. Sample numbers and descriptions of the collection sites are given in Table V-V. Polished petrographic thin sections have been made of each rock sampled; description is in progress. One hundred gram interior pieces of each rock have been coarse-crushed; fine-crushing

in a tungsten carbide ball mill is in progress. REE standards have been prepared at M.I.T. in cooperation with F. A. Frey; preliminary irradiations will be accomplished at M.I.T. in spring, 1975. The analysis will be completed at LASL during the summer and fall of 1975.

4. Ultramafic Inclusions in Colorado Plateau Minette (S. Ehrenberg, UCLA). The most direct evidence regarding the nature of the deep crust and upper mantle underlying the region has been provided by xenoliths, or foreign rock fragments which are found in kimberlite pipes and dikes of the Colorado Plateau. In this report a summary is presented of the first occurrence of such xenoliths in minette, a potassium-rich lamprophyre.

Fig. V-12. Sampling sites in north-central New Mexico basaltic rocks, July-August 1974.

TABLE V-V
KEY TO SAMPLING LOCATIONS SHOWN IN FIGURE V-12

Sampling Site No.	Sample I.D. Nos.	Description
1	BRC 001,002	Road cut samples from two lower most flows at Dunn Bridge, Black Rock Canyon
2	CDT 001-005	Variety of basalts from summit and south slope of Cerros de los Taoses
3	RGB 001-023	Collections every 25 vertical feet from river level to canyon rim, 200 yds N or Rio Grande Gorge Bridge
4	TCC 001-003	Samples of each of the three summits of Tres Orejas cinder cones.
5	TJC 001-007	Stratigraphic section of Rio Grande Gorge basalts W of Taos Junction Bridge
6	CMR 001	Road cut on U.S. Hwy 285 1 mile S of Stong, N.M., on Comanche Rim
7	EMB 001	Fresh talus block at base of basalt-capped hill W of post office, Embudo, N.M.
8	VEL 001	Fresh talus block at base of basalt-capped mesa, Hwy 68, 0.5 miles N Velarde, N.M.
9	SJP 001-005	Samples of mesa capping flow, collected in place, 1 mile E of U.S. 285, La Chuachia, N.M.
10	AGC 001	Fresh piece, in place, of recently blasted road cut, 0.5 miles S of Agua Caliente spring, Abiquiu, N.M.
11	PVD 001-003	Samples of basalt ridge east of Polvadera Creek near El Alto, N.M.
12	ALT 001	Fresh talus block from hill 7789 on floor of El Alto, due E 3/4 mile from Cerro Chato, N.M.
13	RCM 001-002	Samples from summit of Rincon de Mora, El Alto, N.M.
14	CTS 001-003	Augite porphyry on hill 8290, and smaller hill to NE, Los Cerritos, El Alto, N.M.
15	CLP 001-010	Stratigraphic sequences from two new roadcuts 10.7 and 12 miles W of Hernandez, N.M. on Chicoma Mt. Forest Service Road
16	HW4 001	Very fresh olivine porphyry from State cut, 4 miles W of Jct. of Rtes. 4 and 30
17	TA-33 001	Quartz-bearing cinders from pit 100 yards W of TA-33 site, Frijoles Point, N.M.
18	FPC 001-012	Stratigraphic sequence from river level to canyon rim, at Frijoles Point 2 miles E of TA-33
19	TWH 001-013	Variety of samples from cinder cones at Twin Hills, Montoso Peak, 7.5 min. quad, N.M.

Abundant eruptive centers comprised of the potassium-rich basaltic rock, "minette", occur within a restricted area of the central and eastern Colorado Plateau on the Navajo Indian Reservation (Fig. V-13). The minettes were first described in detail by Williams.⁶¹ These rocks are of interest both because of problems of their mode of emplacement⁶²⁻⁶⁴ and because their petrogenesis relates directly to the broader problems of the composition of the upper mantle and the nature of partial melting and volatile accumulation processes in the subcontinental upper mantle^{8,10,15} as well as the geophysical history of the Colorado Plateau region.^{9,65} In addition, detailed petrographic studies may provide data leading to a better understanding of the kinetic (as opposed to equilibrium) parameters effecting rock fusion, particularly in high-pressure volatile-rich environments.

Fig. V-13. Distribution of minette intrusions in the central Colorado Plateau.

Xenoliths from within minette were collected at Shiprock, Agthla Peak, and a small intrusion near the Moses Rock kimberlite dike (Fig. V-14). The xenoliths fall into the following four general categories: (a) peridotite, (b) mica pyroxenite and pyroxenite, (c) garnet and clinopyroxene-bearing rocks, and (d) granitic rocks. Each has a different kind of potential significance with regard to the minette host.

An unaltered peridotite (lherzolite) xenolith found in one of the radial dikes at Shiprock is of special interest because it contains phlogopite, a magnesian mica, and fine-grained intergrowths which are thought to be altered garnets. Garnet lherzolite is likely to be the dominant rock type at the depth in the mantle where the minette magma is suspected to have originated.^{15,18} Only one such xenolith, about 3 cm in diameter, has been found in the Colorado Plateau pipes.⁶⁶ The presence of phlogopite-bearing lherzolite suggests that the mantle contained "incompatible" components such as water and potassium. Such rocks could be the source material from which the volatile-rich minette magma was derived. On the other hand, since the inclusions consist of various combinations of diopside, phlogopite, olivine, and leucite, which were also found in the minette, the inclusions may be the result of crystallization of the minette at depth. Analysis of the inclusions and their constituent minerals may reveal the crystallization history of

Fig. V-14. Xenolith locality at Agthla Peak, Arizona. A large intrusion of minette, potassium-rich lamprophyre, near Kayenta, Arizona.

the minette or its genetic relationship to the garnet lherzolite xenoliths.

Garnet granulite and garnet clinopyroxenite xenoliths, found in abundance in the Shiprock tuff-breccia neck, are probably pieces of the Colorado Plateau's lower crust. A few of these xenoliths contain appreciable phlogopite and carbonate, suggesting possible chemical affinities with the minette. Large fragments of various granitic rocks are abundant in the minette and commonly show evidence of partial melting. Study of these xenoliths may allow evaluation of the degree of contamination of the minette by crustal material and may provide information on processes of rapid, volatile-fluxed rock melting.

5. Basaltic Volcanism of the Jemez Mountains, New Mexico (W. S. Baldrige, C.I.T.)

a. Introduction. The Jemez Mountains are the remnants of a formerly very large volcanic edifice. Collapse of this volcanic pile to form the Toledo and Valles Calderas occurred between 1 and 1.5 M yr ago with simultaneous eruption of broad rhyolite tuff sheets. Subsequent resurgence of rhyolite domes as recently as 50,000 years ago completed the development of the Jemez Mountains.^{53,54} The Jemez Mountains are located on the western margin of the Rio Grande rift depression (Rio Grande trough), a major graben extending from southern Colorado to southern New Mexico.⁶⁷ The margin of the rift is delineated by a zone of northeast-trending faults extending from near Jemez Pueblo in the south to beyond Canones in the north.

The Jemez Mountains are known primarily for an extensive and broad ash flow tuff sheet, the Bandelier rhyolite tuff, which was deposited between 1 and 1.5 M yr ago during the formation of the Toledo and Valles Calderas. More mafic, and particularly basaltic, rocks have received comparatively less attention. However, because of their abundance and their persistent association with the felsic lavas the basalts are important rock types and warrant further study. Basaltic volcanism of the Jemez Mountains encompasses two and possibly three extrusive episodes. The present work has focused on the last of these, those labeled Qtb and Qbtn by Smith, et al.,⁵⁴ of probable Quaternary age, because: (1) these basalts are most abundant and relatively unaltered, and (2)

their chemistry and petrology can be related most directly to other areas of the Rio Grande rift where Quaternary basalts have been studied. We have sampled these basalts extensively and petrological and chemical work on them is in progress.

b. General Geology. The younger basalt flows occur in three areas, all peripheral to the main Valles Caldera. These three areas are: (a) El Alto, located 6 to 10 km SW of Abiquiu; (b) Cerros del Rio, immediately SE of White Rock Canyon; and (c) Santa Ana Mesa, between the pueblos of San Felipe on the east and Santa Ana on the west. Basalts of all three areas are probably contemporaneous. In the El Alto area volcanism consisted mainly of isolated small cinder cones; probably extensive flow sheets never existed. By contrast, volcanism in the Cerros del Rio and Santa Ana Mesa areas formed broad, relatively high standing basaltic piles.

The vents from which these basalts were extruded are clearly associated with a roughly north-south fracture system, generally paralleling the Rio Grande rift as a whole. For example, in the Cerros del Rio area a line of small cinder cones runs N-S slightly east of Arroyo Tetilla. This tectonic trend is even more pronounced in the Santa Ana Mesa area. Here not only is there a strong lineation to the cinder cones and small craters but also the underlying fracture system is manifested as numerous approximately N-S trending normal faults.

To date, an age determination on the basalts has not been published. They probably postdate the Servilleta basalts of the Taos Plateau, which are 3.6 to 4.5 M yr old.⁶⁸ Most of the volcanism was completed before the eruption of the Bandelier tuff sheet. The relationship between the basalts and the Bandelier can be seen particularly clearly in the vicinity of White Rock Canyon, where both the lower (Otowi) and upper (Tshirege) members of the Bandelier tuff overlie the basalts. Volcanism continued slightly longer in the southern part of the Cerros del Rio area, where the Tank Nineteen basaltic andesite (Qbtn⁵⁴) postdates the Otowi but predates the Tshirege members.

c. Chemistry and Petrology. These basalts are characterized by phenocrysts of olivine and plagioclase generally less than 2 mm in size (occasionally larger) surrounded by reaction

rims of clinopyroxene. Rare, small (less than 3 cm) granitic xenoliths also occur. The basalts are uniformly more fine grained than basalts from other areas in the rift.^{55,56,69} At present the basalts cannot be characterized chemically, since no chemical analyses exist.

d. Discussion - Future Work. The origin of the quartz grains which are clearly a disequilibrium phase in these olivine-bearing basalts, is an intriguing problem with an important bearing on the origin of the basaltic magmas. Some contamination of these basalts by Precambrian basement has occurred, as evidenced by the rare granitic xenoliths. If all the quartz is xenocrystic, then significant contamination by sialic crustal material has occurred and their chemistries are no longer primary. Alternatively the quartz may be a relict phenocryst phase from a higher pressure regime.^{70,71} Further work will be directed toward answering this question.

Lipman⁵⁵ and Lipman et al.⁵⁶ suggested that tholeiitic basalts are confined primarily to the Rio Grande rift depression whereas basaltic rocks become increasingly alkalic with distance from the depression. This difference could result from either of the following causes: partial melting of mantle material might occur at shallower depth under the rift to yield tholeiitic basaltic melts—alternatively, a greater degree of partial melting might occur beneath the rift. So far no work has been done on basalts from the Jemez Mountains to determine their relationship to other basalts of the rift. Their location on the margin of the rift makes an understanding of their chemistry and phase petrology particularly important to an understanding of rift volcanism (Fig. V-15).

A long-term goal of this work will be to construct a model of magma generation under large-scale rift structures. Such a model must include the formation not only of basaltic melts but also of the silicic melts which occur in great abundance at isolated volcanic centers such as the Jemez Mountains.

6. Thermal Evolution Models for the Valles Caldera (C. Kolstad, T. McGetchin). In order to gain a better understanding of the thermal behavior of plutons, a finite element computer model for heat conduction from igneous bodies of arbitrary

Fig. V-15. Map 54 showing location of latest basalts (Qtb) of the Jemez Mountains area. The "o's" are cinder cones; prominent faults are shown as solid curvilinear lines.

size, shape, depth of burial, and initial thermal environment has been constructed. The model has been used to examine heat conduction around a magma body such as may underlie the Jemez Mountains. The computer code is in its initial stages of development but some preliminary results have been obtained which we report here. Prominent among previous authors who have concerned themselves with the thermal effects of intrusions are Jaeger,⁷² Lovering,^{73,74} Rikitake,⁷⁵ Ingersoll et al.,⁷⁶ Reilly,⁷⁷ and Maaløe.⁷⁸ One of the advantages of using a finite element scheme over analytical methods is that substantially more flexibility in geometry and initial conditions is possible

and individual processes can be included as subroutines.

In our first model we assume a crustal thickness of 40 km, an initial temperature gradient of 25°C/km, surface temperature maintained at 23°C and crust-mantle interface maintained at 1000°C. Next we assume a magma chamber (initially at 1000°C) is emplaced instantaneously, clearly a simplification of nature. The geometry assumed is a cylinder 20 km in height, 10 km in radius, buried at a depth of 3 km below the surface.

The crust and magma chamber were assumed to be homogeneous granite with a latent heat of fusion of 420 J/g, heat capacity of 0.21 cal/g°C, density of 2.6 g/cm³, and thermal conductivity of .025 W/cm°C. The melting point of the granite was assumed depth dependent with $[T_m (^{\circ}\text{C}) \approx 790^{\circ} + 4.4 d]$, where d is the depth in km.⁷⁹ The effect of latent heat of crystallization is included by an appropriate alteration of the heat capacity term at the fusion temperature.

The thermal evolution of a hypothetical pluton over a million years was calculated; results are shown in the accompanying figures. A typical result for the temperature distribution as a function of depth and radial distance for the center of the magma chamber is shown in Fig. V-16. In this particular case, the time since emplacement of the pluton

Fig. V-16. Location of isotherms and residual melt after 500×10^3 years. Outline of original cylindrical magma chamber is shown by the dotted lines.

is 500,000 years. The thermal effects of the pluton are negligible at one radius from the margin, that is at a distance of 10 km outside the ring fracture. The magma body shrinks continuously as a function of time (Fig. V-17); the body is completely solid at just over 700,000 years. The evolution of the 200 and 500°C isotherms are shown in Fig. V-18. The LASL dry hot rock drill hole (GT-2) is located about 2.4 km outside the ring fracture of the Valles Caldera; its present depth is approximately 3 km (2.928 km) and hole-bottom temperature is 197°C. The behavior of the 200°C isotherm is particularly interesting because it is remarkably stable for the period from 500 to 1000×10^3 years. The thermal evolution of a hypothetical drill hole located 2.4 km outside a cylindrical pluton is shown in Fig. V-19. Isotherms are severely perturbed from their initial values in the first 100,000 years but the subsequent decay of this perturbation is very slow.

A large number of approximations and assumptions are included in the analysis and the preliminary nature of the results should be emphasized. Nonetheless there are a number of tentative conclusions which can be made.

First since the most recent rhyolite volcanism in the Jemez Mountains is only 50,000 years old, and the characteristic cooling time of large plutons is the order of 500,000 to 700,000 years, there is a real possibility that a magma chamber still exists beneath the Valles Caldera. Another conclusion

Fig. V-17. Calculated configuration of residual melt (magma chamber) as a function of time.

Fig. V-18. Calculated shape of 200 and 500°C isotherms as a function of time. Note the location of GT-2, approximately 2.4 km outside the caldera. At this site, temperatures at 3 km depth change only very slowly with time.

is that the conductive heating near a magma chamber is a fairly local phenomenon; at twice the radius from the magma chamber the geothermal gradient is nearly normal after a million years. It is very likely that the temperatures at the bottom of GT-1 and GT-2 were severely perturbed from their values prior to the formation of the Valles Caldera, which must have occurred at a time somewhat beyond the 1.1 M yr age of (uppermost member of the) Bandelier tuff. The observed hole-bottom temperature in GT-2 (197°C) is in good qualitative agreement with this model. More quantitative agreement should result from further refinement, perhaps using data

Fig. V-19. Temperature as a function of time and depth in a vertical hole located 2.4 km outside a cylindrical caldera 10 km in radius.

from GT-2 cores and considering the effects of circulating fluids. Experience in the upper part of GT-2 revealed severe perturbations of the geothermal gradient from a simply interpreted conduction case. These perturbations, in general, were associated with water-rich zones. Even in hard dry rocks water flow permeabilities of the order of several hundred microdarcy can perturb conductive heat transfer.

Further development of the model will include, (a) comparison with analytical results for confirmation of the code's performance, (b) incorporation of more complex and geologically realistic cases for magma chamber geometry and depth, (c) cooling models which include convection, (d) cooling by mass transfer, either of volatiles or by dike or sill emplacement, and (e) models for details of crystallization. We anticipate application of the code to attempt to match calculated and observed results by variation of appropriate model parameters. Data will include bore hole measurements and data from geobarometers, geothermometers, and ages to be obtained on GT-2 cores.

7. The Mechanics of Caldera and Ash-Forming Eruptions (T. McGetchin). The large resurgent caldera complexes (Fig. V-20) associated with silicic lavas, ash flows, and ash flow tuffs contain economically significant ore deposits, have geothermal potential and represent an important style of volcanism. Within the constraints of observed geology, especially the detailed descriptions of the Valles Caldera,^{54,80,81} we are attempting to understand the eruption mechanism of these volcanoes.

The structural evolution of large resurgent calderas as described by Smith and Bailey⁸¹ proceeds through several stages including (a) regional swelling, construction of large volcanic shield consisting of both mafic and silicic lavas and development of ring fractures, (b) caldera forming eruptions, (c) caldera collapse, (d) pre-resurgence volcanism and sedimentation, (e) resurgent doming, (f) major ring fault volcanism, and (g) terminal solfatara and hot spring activity.

In the caldera complex of the Jemez Mountains the shield building stage began about 10 M yr ago (Toledo Caldera), the second 1.1 M yr ago (Valles Caldera), which deposited the two units of the Bandelier rhyolite tuff. Major ring fault volcanism began about 1.04 M yr ago; the youngest

Fig. V-20. Physiographic sketch maps of five large resurgent calderas, from Smith and Bailey (81). Valles Caldera is in northern New Mexico; Creede, in Colorado; Timber Mountain, Nevada; Long Valley, California; and Lake Toba in Sumatra. The Valles, Timber Mountain and Long Valley structures currently are being investigated for geothermal energy commercially and by government agencies.

rhyolite domes on the ring fracture are 0.43 M yr old.⁸² The youngest volcanism is manifested as rhyolite flow only about 50,000 years old. Figure V-21 is a generalized geologic map of the Valles Caldera complex showing some of the major features described above.

We are interested in the conditions of the caldera forming eruptions, in particular the details of the hydrodynamics of the event. The time scale of the eruption is not known with any certainty. Smith and Bailey⁸¹ note, however, that erosional features observed in the second cycle Bandelier tuff suggest that the eruptions spanned some period exceeding a few days but probably less than 10 years. Large historic eruptions which might be analogous (such as Hekla, 1948; Krakatoa, 1883; Katmai, 1912;

Tambora, 1815) occurred over periods of a few days at most. Typical volumes of the ash flow cycles are in the range 150 to 1500 km³.

The large ash forming eruptions apparently begin with a violent blast which taps the volatile rich top of the magma chamber. Also, it appears that the resulting flow is quite similar to that which occurs in a shock tube (Figs. V-22, V-23). Such a mechanism for some volcanic eruption has been previously suggested by Bennett.⁸⁴

A shock tube is a device used to generate high speed flows for aerodynamics purposes. It consists of a tube, with a diaphragm separating two chambers containing gases at different pressures; when the diaphragm is broken flow results due to the pressure difference. The flow conditions are uniquely determined by the pressure difference and the properties of the gases. Figure V-24 shows solutions for the shock strength resulting from rupture of a hypothetical diaphragm separating 800°C steam from ambient air as a function of the pressure difference. Given shock strength, analytical solutions exist for all the flow parameters (velocity, density, pressure, temperature, and sound speed).⁸⁵

Numerical results for the flow conditions accompanying the eruption of steam-charged magma based on the equations describing the flow in shock tubes are summarized in Table V-VI. Reasonable geological constraints suggest that the temperature and pressure at the top of the magma would be about 800°C and 1×10^5 kPa. Results for flow from these initial conditions show that a moderately strong shock wave (about 30×10^5 Pa) is propagated into the atmosphere at a velocity of about 1.75 km/sec (Fig. V-23). The air behind the shock is compressed and heated to ~1550°C. Behind the shock wave, air and volcanic material travel at a velocity of about 1.5 km/sec at a pressure of 3×10^6 Pa. A rarefaction wave propagating downward into the magma chamber at the local sound velocity is responsible for accelerating the material upward out of the vent. The initial burst phase of the eruption will last until the rarefaction is reflected off the bottom of the gas-charged part of the magma chamber and propagates back to the surface, which might take from 3 to 10 seconds. During this time the flow conditions at the vent should be nearly uniform.

Fig. V-21. Generalized geologic map of the Valles Caldera Complex from Smith (83) showing its major structural features, the location of major test holes (squares), heat flow stations (circles, 23-30 m; triangles, 150-230 m).

The second phase of the eruption is continuous in time with the first, as conditions decay to steady flow. Details of the flow will depend on how the pressure within the reservoir decays with time, which may be largely a function of the process of roof collapse.

An isentropic (frictionless adiabatic) model suggests that the flow (if choked as in a convergent nozzle) would erupt as an underexpanded jet at a pressure of about 55 M Pa and 58 m/sec.

Mach 1. Models for flow in rough ducts including friction suggest more modest velocities on the order of 180 to 300 m/sec. Since the duct size is poorly constrained, the mass flux is uncertain, but eruption time compared with observed volumes suggests durations of 1 to 12 days.

Finally, the terminal stage of igneous activity involves emplacement of highly siliceous and viscous magma along the ring dikes to form domes. For these viscous magmas we calculated a velocity of about

Fig. V-22. Configuration of a typical shock tube and its relationship to the conditions in a large ash blast eruption.

10 m/hr, requiring the time scale of several hundred years to build a volcanic pile the size of the rhyolite domes of the Valles Caldera.

The model is a simplified one. Many theoretical improvements can be made, particularly in modeling the equation of state and dynamic expansion properties of gas-charged magmas. Experimental data describing such systems are largely absent. One is forced to use equilibrium data and make many assumptions. No direct observational data of eruptions of this type exist because of problems with time and logistics. One major purpose of this work is to define the eruption parameters of interest with such observations in mind. Experimental simulation on a moderate (field rather than laboratory) scale would yield interesting data.

Fig. V-23. Simplified conditions in flow following release of the diaphragm, or rupture of the volcanic edifice.

Fig. V-24. Solutions for shock strength as a function of initial pressure ratio for two shock tube cases and one assumed volcano case.

TABLE V-VI

CALCULATED INITIAL FLOW PROPERTIES FOR CALDERA ERUPTIONS AS A FUNCTION OF MAGMA CHAMBER, PRESSURE P_2 , TEMPERATURE ASSUMED IS 800°C, AND AMBIENT ATMOSPHERIC CONDITIONS (P_1).

P_2 (kPa)	P_2/P_1	Y, Shock Strength P_3/P_1	Speed of Erupting Medium and Compressed Air, (m/sec)	Shock Velocity		Temperature of Compressed Air, T (°C)
				U (m/sec)	M	
500	$5 \cdot 10^3$	47	1860	2160	6.35	2380
100	10^3	30.5	1480	1743	5.13	1550
10	10^2	13	920	1142	3.36	680

C. Cascade Investigations

1. Regional Tectonics and Geophysics of the Cascade Range of Northern California (J. Eichelberger, T. McGetchin). The Cascade Range occupies a particularly interesting position with respect to large-scale tectonic features.³ Seaward, west of the Cascade range, the only remaining fragment of the Farallon plate exists, presumably still spreading eastward from the Gorda Ridge, a piece of the East Pacific rise. The southern boundary of the Cascade Range is abrupt and occurs at the landward extension of the Mendicino fracture zone. South of the interaction between this fracture zone and the continent (Americas plate), motion is taken up as strike-slip motion along the San Andreas Fault; most of it presumably by (oblique) subduction of the Farallon plate (Fig. V-25). The Cascade range is underlain predominantly by older basaltic rocks;

Fig. V-25. Tectonic setting of the Cascade volcanic province. Arrows indicate direction of crustal spreading. Numbers along coastline are age in million years of the easternmost magnetic anomaly of the Pacific plate. This age represents the maximum age of the ridge trench-collision and transition to strike-slip motion of the San Andreas Fault. Lines shown in the Pacific Ocean are fracture zones, abbreviated F.Z.

Cascades and Modoc Plateau, however, have no mutual boundary, but merge in the California Cascades. Northward in the Cascades the normal faulting characteristic of the Modoc Plateau becomes less important, and eastward the volcanism characteristic of the Cascades fades. The eastward change in volcanism is characterized by both reduced volume of lava and predominance of basalt (Fig. V-26).

QTV Quaternary - Tertiary volcanics of the Modoc Plateau, including recent volcanic centers of the Cascade range, marked (*).
TQa Tertiary clastic sediments and Quaternary alluvium of the San Joaquin Valley.
MTQ Complex of plutonic, volcanic rocks and alluvium of the basin and range province.
MZI Mesozoic plutonic and batholithic rocks of the Klamath Mountains and Sierra Nevada.
KJ Upper Mesozoic marine metasedimentary rocks of the Coast ranges.

Fig. V-26. Generalized geologic and tectonic map of the Southern Cascades of Northern California.

the young volcanoes, however, are andesitic. Andesitic volcanoes are typical of the circum-Pacific region and are generally associated with active subduction zones. However, no clear dipping earthquake belt (Benioff zone) indicating active subduction underlies the Cascade Range and the crustal structure is complex and not understood.

The Cascades of Northern California border the Klamath Mountains, Sierra Nevada, Great Valley, and Modoc Plateau provinces (Fig. V-26). Similar crystalline plutonic and batholithic rocks of the Klamath Mountains and Sierra Nevada emerge on the west and south of the Cascades with the thinning of the volcanic pile. To the southwest, vents end abruptly and the volcanoclastic deposits give way to the Great Valley sedimentary sequence.

The region is under east-west tension which is expressed by north-south trending normal faults. The influence of this tectonic activity upon volcanism is evidenced by north-south chains of vents, by eruption of lava directly from faults, and by the association of major volcanic centers with major fault systems. Two of the most spectacular fault systems are the east-facing scarps west of Tule Lake which strike toward the Medicine Lake Highland to the south and the west-facing scarps east of Hat Creek which strike toward the Lassen highlands to the south. In both cases the faults strike toward the center of the volcanic complex but decrease in displacement toward the pile (Fig. V-27).

This relationship is not unique to the southern Cascades. For example the Teton Fault strikes toward the center of the Yellowstone complex, but decreases in displacement in that direction.

Faulting is less severe at the other major center, Mt. Shasta, perhaps because it is farthest from the Modoc Plateau. Nevertheless, the entire mountain is cut by a north-south fissure, from which many of the recent flows and domes have erupted.

Fault scarps range up to 700 m in height, often displacing old volcanic cones such as those

Fig. V-27. Fault scarps west of Tule Lake which strike into the Medicine Lake volcanic pile.

located in the Bray Quadrangle. They occur both as en echelon normal faults and stepped normal faults, but nearly all are N-S or NNW-SSE and none show evidence of horizontal displacement, although a major right lateral strike-slip fault occurs just to the east of the California Cascades near Canby.⁸⁶ Despite the similarity in alignment of most of the faults, blocks are tilted both east and west in an apparently random fashion.

The well-preserved nature of even the largest fault scarps demonstrates that the activity is very recent. Among the major faults, there is somewhat ambiguous evidence⁸⁷ of several meters displacement on the Hat Creek fault over the past few thousand years (post-Hat Creek Basalt). On a smaller scale, a well-preserved 10-m-high scarp in cinders is associated with nearly historic rhyolite domes on the Medicine Lake Highland.

Gravity studies by Pakiser⁸⁸ have shown a negative gravity gradient from west to east across the southern Cascades. Superimposed on this are negative anomalies associated with Lassen and Shasta and a positive anomaly associated with the Medicine Lake Highland. The total amplitude of the negative anomaly at Lassen is - 70 milligals. Pakiser interpreted the low in the Lassen area as due to a low density mass in the upper crust of 15,000 km³ volume and 0.2 g/cm³ density contrast, and found that the overlying pile is in isostatic equilibrium with this mass. Hypotheses offered to explain this body are: (1) a silicic batholith, (2) thick accumulation of low-density volcanic or sedimentary deposits, (3) hot rocks

2. Chemical Evolution of the Cascade Magmas (J. Eichelberger). A marked characteristic of the California Cascades is the great diversity of lavas (Fig. V-28). At Lassen Peak and Medicine Lake the entire composition spectrum from basalt through rhyolite is well represented. At Mt. Shasta, the suite ranges from basalt to dacite. At each of the three centers all compositions are closely related in time and space. Lavas of contrasting composition have erupted within a few kilometers of each other within a time span of a few hundred years. In the case of the 1915 Lassen pumice eruption, diverse lava types erupted from the same vent at the same time. Early regional studies^{89,90,91} were strongly influenced by Bowen's⁹² ideas and attempted to

Fig. V-28. AFM (alkalies-iron-magnesium oxide) diagram for California Cascade lavas.^{87,89,91} R = rhyolite, D = dacite, A = andesite, B = basalt.

interpret the suite of lavas as products of fractional crystallization of high alumina basalt. More recent field and detailed petrologic studies utilizing an electron microprobe to investigate phenocrysts-groundmass relations, however, provide evidence which clearly contradicts this model. The origin of contemporaneous magmas of very different composition is an old but still active topic of debate.⁹³

A detailed study of an individual flow at Glass Mountain in the Medicine Lake Highlands, California, revealed lava ranging in composition from dacite at the distal end to rhyolite at the vent. If magmas evolve chemically between the time they are generated and the time they erupt, thereby producing the diversity of lavas observed on the surface, it is reasonable to expect to find such non-homogeneous flows. By treating such flows as quenched samples of magma bodies and reconstructing their emplacement, it is possible to infer the composition gradients within the parent magma and to evaluate various models of petrogenesis. Mapping of the Glass Mountain flow revealed that the eruption began with dacite and gradually changed in composition to rhyolite. It is therefore inferred that the original magma body was zoned from dacite at the top, downward into rhyolite. This is the opposite geometry of that required for crystal settling or diffusion.

The dacite, transitional banded rhyodacite, and rhyolite immediately upstream from the banded lava contain abundant basalt inclusions, but the final rhyolite erupted is free of inclusions. In thin section, the dacite is a streaked brown rock laden with microlites, phenocrysts, and clots of phenocrysts, whereas the rhyolite is clear glass with fewer microlites and almost no phenocrysts. The banded lava consists of brown, porphyritic, dacite-like bands and lighter, rhyolite-like bands. The dark bands swell and pinch around inclusions, which are porphyritic basalt similar to basalt exposed nearby. Phenocrysts of both porphyritic lava and inclusions are $An_{74} \pm 4$ plagioclase, $Fe_{79} \pm 3$ olivine, and $Wo_{41} \pm 2$ $En_{44} \pm 3$ $Fs_{15} \pm 2$ clinopyroxene as determined by electron probe analysis. The phenocrysts of the porphyritic lava and inclusions are also similar in size and shape, except that the olivine and clinopyroxene in the lava are more rounded. Larger euhedral An_{46-54} plagioclase and En_{57-81} orthopyroxene occur in dark bands around inclusions. Both are zoned in reverse. The few phenocrysts that do occur in the rhyolite are $An_{35} \pm 2$ plagioclase. Groundmass composition grades from rhyolite at the vent to rhyodacite at the distal ends.

It is unlikely that magmas with bulk compositions as different as dacite and basalt would crystallize into phases appropriate for basalt. Indeed, the appearance of the inclusions in the banded lava suggests that they were disintegrating and strewing bands of debris through the enclosing liquid. Fragments of basalt became the phenocryst clots of the dacite, and individual phenocrysts of the basalt became the phenocrysts of the dacite. Resorption of olivine and clinopyroxene from the basalt and partial assimilation of the basalt glass resulted in growth of the median plagioclase and orthopyroxene. Progressive contamination caused reverse zoning in these phases, as the liquid became enriched in calcium and magnesium. Remaining components of the basalt glass formed the microlites of the dacite groundmass. This destruction of the basalt glass was caused by disintegration of inclusions.

Thus the dacite of the Glass Mountain flow at Medicine Lake was produced by the contamination of rhyolite by basalt. The eruptive sequence and similarity of inclusions to nearby basalt imply that contamination occurred at the top of the

rhyolite magma body and within the structure of the Medicine Lake shield volcano.

Evidence of contamination of rhyolite and basalt also occurs in the other dacites of the Medicine Lake Highland. Similarly, the dacites of Lassen contain as much as 50% basalt inclusions and the lava derived phenocrysts from the inclusions. Mt. Shasta has numerous dacite domes on its flanks, and most of these also contain basaltic inclusions, although data on phenocryst composition are scarce. This suggests that the process of dacite generation at Glass Mountain may be the general case for the California Cascades. The evidence that dacite is derived from rhyolite rather than the reverse suggests that rhyolite is a primary magma and dacite is not.

The evidence that dacite is a hybrid rock opens the question of the origin of other intermediate magmas: those of andesitic composition. The Glass Mountain study showed that significant contamination of viscous rhyolite magma by the glassy debris of the basaltic volcanic pile can occur. In this case chemical interaction is limited because of the relatively low temperature of the rhyolite melt. In the reverse case, namely where basalt magma intrudes rhyolitic rocks, much stronger chemical, as well as mechanical, interaction would be expected. The assimilation process should proceed even more easily - probably with more complete destruction of inclusions. Indeed, there is evidence for such a process in the common presence of apparently rhyolite-derived phenocrysts and rhyolite inclusions in the basaltic andesites and andesites of the region.

If the intermediate lavas are hybrids then the parent liquids formed by partial melting in the zone or zones of magma generation are rhyolite and basalt. Intermediate lava forms by intercontamination of these parental magmas on their way to the surface. The distribution of lavas in the California Cascades, namely localized centers of basalt-andesite-dacite-rhyolite within regional basaltic volcanism, can be explained as the expression of localized rhyolite magma generation - probably in the lower crust, above widespread basalt generation in the upper mantle.

The test of this model is the variation of bulk composition of lavas at each volcanic center.

If the intermediate lavas are hybrids, their composition can be expressed as a linear combination of the associated basalts and rhyolites. If they are the product of a partial melting or fractional crystallization process, the compositional variation would be expected to be nonlinear. Table V-VII makes this test for the Lassen and Medicine Lake Centers using available data. A more complete test would include trace element data. J. Reid has begun work to obtain this. Table V-VIII summarizes the present status of application of the model to the California Cascades.

3. Eruption History of the Southern Cascades (J. Eichelberger). Historic eruptions have occurred at 7 volcanoes in the Cascade range and modern day hazards associated with these volcanoes include mud flows, violent ash eruptions, and avalanches.⁹⁴ In the context of geological time the Cascade range is both very young and very active. Following are descriptions of the activity in three areas of the Cascade range within northern California.

a. Medicine Lake Highland. The Medicine Lake Highland is one of the most active centers of volcanism in the Cascades^{91,95}. A study of natural remnant magnetism⁹⁶ on representative lavas has revealed no reverse-magnetized flows, suggesting that the entire complex developed in the last 700,000 years. The dominant and earliest structure of Quaternary volcanism is a broad shield volcano of basalt and basaltic andesite lavas and tuffs, 45 km in diameter and rising 1.2 km above its base. But even early in its evolution rhyolite and dacite flows were present. Prior to the end of glaciation, the summit of the shield volcano collapsed by about 150 m to form an ellipsoidal caldera 8 km by 6 km. Then viscous andesite, olivine-free unlike most shield lavas, erupted along the caldera rim to form a rampart of small, steep cones. Since glaciation many rhyolite flows, dacite flows, and the Glass Mountain (Fig. V-29) rhyolite and dacite flow have erupted at high elevations both inside and outside the caldera. Fresh cinder cones and associated floods of basalt and basaltic andesite, one of which is as young as Glass Mountain, mantle the flanks of the Highland. Nowhere is the shield deeply eroded.

The most stark and imposing feature of the Medicine Lake Highland is Glass Mountain, located on

TABLE V-VII

COMPARISON OF OBSERVED BULK COMPOSITIONS WITH COMPOSITIONS CALCULATED FOR MIXING OF RHYOLITE AND BASALT

Constituent	MEDICINE LAKE HIGHLAND						LASSEN					
	Rhyolite	4:1		Dacite			Basaltic		Basalt	Rhyolite	4:1	
					Andesite:		1:3	Andesite				Dacite
	(8)		(4)	1:1 Olivine	Platy		(3)	(5)		(4)		(6)
				(1)	(2)							
SiO ₂	73.2	68.3	67.2	61.0	58.4	60.0	54.9	54.9	48.8	71.0	66.3	66.1
TiO ₂	0.3	0.4	0.4	0.6	0.9	1.3	0.8	0.9	1.0	0.2	0.4	0.4
Al ₂ O ₃	13.9	15.0	16.2	16.7	17.0	17.0	18.1	17.9	19.5	15.2	15.8	16.4
FeO	2.2	3.5	3.6	5.5	7.6	7.2	7.1	7.2	8.7	2.2	3.6	3.5
MnO	..	..	..	..	..	..	..	..	..	0.06	0.08	0.07
MgO	0.4	1.8	1.4	3.8	3.4	2.2	5.5	5.3	7.2	1.2	2.8	2.1
CaO	1.5	3.4	3.5	6.3	6.6	4.8	8.7	8.3	11.1	2.1	3.7	4.4
Na ₂ O	3.9	3.7	3.9	3.3	3.4	5.0	3.1	3.3	2.8	3.8	3.5	3.9
K ₂ O	4.2	3.4	3.3	2.3	1.5	1.7	1.3	1.2	0.4	3.2	2.7	2.2

NOTE: Columns headed with rock names show average composition (wt %) of that lava type for the volcanic region in which it occurs. Numbers in parentheses are the number of analyses in each average. Columns headed with ratios show the composition of a mixture of the average rhyolite and basalt, ratios are parts rhyolite to parts basalt, by weight. References for analyses are as follows: Medicine Lake Highland - Anderson,⁹¹ Lassen - Williams,⁸⁹ Anderson,⁸⁷

TABLE V-VIII

STATUS OF MIXING MODEL FOR CALIFORNIA CASCADE LAVAS

Volcano	Evidence Supporting Mixing Model	Problems with Model	Unaltered, Well-Exposed Lavas to be Used in Testing Model
Medicine Lake Highland	<ol style="list-style-type: none"> 1. Glass Mountain rhyolite to dacite flow. 2. Basalt-derived phenocrysts and basalt inclusions widespread in dacite. 3. Rhyolite-derived phenocrysts and inclusions common in basaltic andesites. 4. Linear variations in composition and "Daly Gap" 60% - 65% SiO₂. 	<ol style="list-style-type: none"> 1. Some caldera-rim silicic andesites are phenocryst poor and depart from the overall linear composition trend. 	<ol style="list-style-type: none"> 1. Burnt Lava Flow (basaltic andesite), south flank of Highland. 2. Callahan Flow (basaltic andesite) north flank of Highland. 3. Caldera-rim andesites.
Lassen Park	<ol style="list-style-type: none"> 1. Universal occurrence of abundant basaltic inclusions in dacite + phenocrysts derived from those inclusions. 2. 1851 Quartz-olivine andesite flow. 3. Central plateau of quartz andesite. 4. Eruption of poorly mixed banded pumice¹⁰² in 1915. 5. Linear variation in composition. 	<ol style="list-style-type: none"> 1. Absence (?) of nonequilibrium phenocrysts in hornblende andesite of strato volcanoes. 	<ol style="list-style-type: none"> 1. 1851 Andesite Flow. 2. 1915 Dacite Flow. 3. Chaos Crags, dacite domes. 4. Hat Creek basalt flow. 5. Flow from saddle of Prospect + W. Prospect peaks.
Mt. Shasta	<ol style="list-style-type: none"> 1. Common occurrence of basaltic inclusions in dacite domes and highly calcic plagioclase phenocrysts in dacites. 2. Rhyolitic-basaltic banded bombs. 	<ol style="list-style-type: none"> 1. Abundance of andesite. 2. Lack of data - only reconnaissance.⁹⁰ 	<ol style="list-style-type: none"> 1. Olivine-andesite flow on NW flank. 2. Banded bombs. 3. Dacite domes.

the east rim of the caldera. The mountain is a single flow of 1 km^3 of rhyolite and dacite, nearly free from vegetation or alteration, and completely free from the effects of weathering and erosion. Further evidence of its youth comes from a charred but standing cedar engulfed by blocks at the flow's edge. Friedman⁹⁷ reported C^{14} dates of 100 to 400 years from this wood. Such an age is consistent with Modoc Indian legends⁹⁸ and the impression of an elderly citizen of Tulelake, who claimed that fumarole activity was present around the flow when the area was settled a century ago. The Forest Service reported rumblings and a possible explosion near the mountain in 1910.⁹⁹

b. Lassen Volcanic National Park. The volcanic highland around Lassen Peak, designated as Lassen Volcanic National Park and located 120 km south of Medicine Lake, is a region of great diversity both in lava composition and volcanic structures. Dominant features are the central plateau of thick andesite flows and associated cinder cones, four shield volcanoes of basalt and andesite, remnants of a large collapsed composite andesite cone, and a series of spectacular dacite domes. The entire spectrum of compositions is well represented,

Fig. V-29. Aerial photograph of the Medicine Lake Highland area. The Glass Mountain flow is in the foreground. Low wooded mountains are rim volcanoes of the caldera. Mt. Shasta is in the distance on the right skyline.

although no rhyolite has erupted for several thousand years. Andesites and dacites are far more abundant than at Medicine Lake. Williams⁸⁹ provided a thorough general description of the region. Detailed discussions of the dacites and their inclusions are given by Williams,⁹⁹ of Cinder Cone and its flow by Finch and Anderson,¹⁰⁰ of the Hat Creek basalt flow by Anderson,¹⁰¹ and of the 1915 lava of Lassen Peak by MacDonald and Katsura.¹⁰²

The earliest lavas were basalts which were followed by outpourings of andesite forming the central plateau. Since these andesitic lavas contain fragments and phenocrysts of rhyolitic material, Williams concluded that rhyolitic lavas, now concealed under the central plateau, were also present at this early stage. Meanwhile, eruptions of basalt continued elsewhere. Around the central plateau five andesite cones began to grow, of which four became shield volcanoes. Two of these ceased activity with the extrusion of massive rhyolite and dacite domes. The other two remain potentially active. The fifth cone became a major peak, Brokeoff Cone, with a summit elevation of perhaps 3500 m. But a vent on the north flank began extruding vast quantities of dacite, first as flows and then as the giant dome of Lassen itself. Subsequently Brokeoff collapsed. Sometime during the last few thousand years, the Hat Creek Valley graben at the north margin of the highland was flooded with basalt. About 200 years ago more dacite erupted near the Lassen dome to form Chaos Crags. In 1815, andesite erupted on the northeast margin of the central plateau. Finally, in 1915 dacite erupted again at Lassen Peak, producing bombs, ash, mudflows, and a lava flow. In general then, volcanism in the Lassen area produces marginal flows of fluid basalts, while the interior of the highland is characterized by intimately associated andesite cones and dacite domes on a platform of andesite and concealed rhyolite.

c. Mt. Shasta. Mt. Shasta and Shastina are twin stratovolcanoes (Fig. V-30), the larger of which is among the largest cones in the world, rising 3300 m above its base. The southern side of the mountain mass is moderately eroded, while the north half contains many fresh volcanic features: craters, spines, domes, cinder cones, and lava flows. The high region of the main cone is made of andesitic flows 5 m

to 200 m thick, interlaminated with debris and capped by a recent deposit of welded pumice. A loose surface layer of pumice may be the product of the reported 1786 eruption.⁹⁸ Most of these units were fed from or near the central vent, in which fumarole activity still persists. Both Shastina and the Shastina-Shasta saddle contain well preserved craters. The saddle crater is strewn with fresh bombs and the Shastina Crater is plugged with massive hornblende andesite domes and breached by Diller Canyon, apparently the result of a massive explosion and nuee ardente. The lower slopes of the mountain show much greater diversity both morphologically and petrologically. Dacite domes, ranging in size up to about 1.5 km³ (Black Butte), are common, as are cinder cones and associated flows of basaltic andesite. The town of Weed lies on a debris fan originating from the northwest side of Shasta crater. Recent vents are concentrated on a north-south fissure which cuts the entire mountain and includes the summit vent.

Fig. V-30. Mt. Shasta, twin andesite stratovolcanoes which rise 3300 m above its base. The last eruption is believed to have occurred in 1786.

d. Extrusion Rates. An absence of reverse-polarized lavas, implying ages of less than 700,000 years, is the general case for High Cascade volcanoes.¹⁰³ By using 700,000 yr as a maximum age, the lava output rate can be calculated for each volcanic center. A comparison of this rate and the average rate of extrusion for the past 1000 years is given in Table V-IX. Although the estimates are somewhat crude, they demonstrate that the California Cascades are not dead or dying, but are probably as active as they ever have been.

4. Thermal Areas and Geothermal Potential of the Southern Cascade Range (J. Eichelberger). Two types of thermal areas occur in the California Cascades region: high temperature steam and gas vents associated with the recently active volcanic vents of the three major volcanic centers, and cooler but widespread low elevation hot springs resulting from downward flow of meteoritic water through the volcanic piles.

The most intense activity is in Lassen Park at Bumpass Hell and the Sulphur Works, perhaps because this location is both adjacent to the most recent eruption sites and receives the greatest precipitation of the California Cascades (Fig. V-31). Both areas lie within the caldera with which Lassen is associated. Jets of steam issue from numerous vents, and temperatures range up to 118°C. The level of activity may be related to the 1915 eruption, as it has been declining since that time.¹⁰⁴

Similar activity, but on a much smaller scale, occurs on the east side of Shasta's summit crater at an elevation of 4300 m. Temperatures measured in the summer of 1974 (Fig. V-32) agree closely with earlier measurements starting in 1854.¹⁰⁴ Although at present there are only two small vents, Pearce reported finding a dozen vents emitting great quantities of steam in 1854. This may have been a prelude to the minor eruption of 1855.¹⁰⁵ Other early reports suggest major fumarole activity until about 1930 at the Shastina - Shasta saddle, where there is extensive alteration, fumarolic deposits, and a fresh crater, and at the terminus of the Whitney Glacier, where there is a fresh andesite flow.

The Medicine Lake Highland has an extensive

Table V-IX

COMPARISON OF RECENT OUTPUT OF CALIFORNIA CASCADE VOLCANOES WITH
OUTPUT REQUIRED TO BUILD PILES TO PRESENT SIZE IN 700,000 YEARS

Volcano	Estimated Volume of Pile (km ³)	How Estimated	Recent Feature	Age (yr)	Volume (km ³)	Average Output Rate Assuming 700,000 Yr. Age of Pile (km ³ /10 ³ yr)	Output Rate Last 1000 Years (km ³ /10 ³ yr)
Medicine Lake Highland	1000	segment of sphere:	Glass Mtn.	200-400	1.0	1.4	1.8
		h= 1.2 km a= 23 km	Burnt Lava Flow	200-400	0.3		
		where h is height and a is radius of the base	Little Glass Mtn. and domes	200-400	0.5		
Mt. Shasta	650	2 nested cones:	Olivine Andesite Flow, NW Flank	500-1000	1.0	0.9	1.0
		I h= 2.2 km r= 6.4 km					
		II h= 1.7 km r=18.0 km					
		Slope:					
		I. 5°					
		II. 19°					
Lassen Peak	1000	40 km x 25 km x 1 km	Chaos Crag	200+	1.2	1.4	1.5
			Cinder Cone Flow (a portion is older)	125	0.3		
			1915 Flow & Pumice	60	<0.1

Fig. V-31. Aerial Photograph of Bumpass Hell near
Lassen Peak, California.

thermal area, known as the Hot Spot (Fig. V-32), where temperatures exceed 80°C at $\approx 1/2$ m below the surface over an area of approximately 3000 m². The hot area is elongate, parallel to, and midway between two fissures which have given vent to over 2 km³ of silicic lava and pumice in the last 2000 years, half of that in the last 300 years. The Hot Spot is at least the same size or possibly has grown over the past 50 years, but prior to this century it was apparently accompanied by thermal activity around nearby Glass Mountain as that flow cooled. A 10-m steam plume lazily issues from one vent. Other-

Fig. V-32. Depth versus temperature curves for the "Hot Spot" on Medicine Lake Highland, and fumarole temperatures at the Hot Spot and Mt. Shasta. This represents the first data set for monitoring these thermal areas and was collected late July 1974. The three curves represent measurements in test holes at the Hot Spot in the areas of normal vegetation (pine and grass), barren ground, and moss-covered ground. For each type of area, 2, 3, and 3 holes were made, respectively.

Fig. V-33. Steam issuing from natural vent at the Hot Spot near Glass Mountain, Medicine Lake Highland, California. Hammer shows scale.

wise there is little steam and almost no sulfurous odor. This is clearly due to a lack of water and not a lack of heat. The heat may come from a shallow magma body, as suggested by the repetition of large volume eruptions on a time scale of about 500 years.

Thus the only major, continuous steam vents are in Lassen Volcanic National Park. Little steam is evident at the 28 hot springs of the California Cascades and neighboring Modoc Plateau cataloged by Waring.¹⁰⁶ However, a major explosion occurred at one of these sites (Lake City), in which at least 200,000 m³ of mud were erupted in about a day in 1951.¹⁰⁷ Hence, it is possible that major pockets of steam exist. Hard, hot, dry rocks may exist beneath the Cascades if the plutonic rocks of the Sierra Nevada continue under the volcanic pile. The repeated eruption of viscous material from a single location suggests the presence of magma bodies in the upper crust, which might be tapped directly for energy.

One interesting question to be pursued is the apparent relationship of thermal anomalies to silicic volcanism. This is illustrated by the fumarole activity in the historic to nearly historic silicic eruptions of Lassen, Glass Mountain, and Shasta in contrast to the lack of fumarole activity around the more mafic 1851 Cinder Cone and recent High Hole Crater lavas. The relationship is illustrated elsewhere by the thermal areas of the Jemez Mountains, New Zealand, Northern Chile, and Yellowstone. Possible explanations are higher volatile content of silicic magmas or longer residence time of silicic magmas in the upper crust.

5. Microseismicity at Glass Mountain (B. Chouet, M.I.T., and J. Eichelberger). A portable self-contained seismic station was established on the south side of the Glass Mountain Flow, Medicine Lake Highland, California, about 1/2 km from the flow's edge, and operated from 11 August 1974 to 17 August 1974. The flow is only a few hundred years old and therefore lacks vegetation which would induce wind noise into records. The station contains a temporary memory which, upon reception of a signal exceeding a preselected strength, places its contents on magnetic tape. The purpose of the station was to determine the level of microseismicity at recently active vents in the California Cascades. We were particularly interested in monitoring possible aftershocks following a reported small earthquake in the vicinity on July 1974. Strong seismic events have been associated with this volcano in historic time.⁹⁸ The geophone was placed at a depth of 1/2 meter in compacted pumice, which provided excellent coupling (Fig. V-34).

Eleven local events were recorded during the 6-day period. Most were of magnitudes 0-1 and of 15-20 s duration. The results show that this type of seismometer is an efficient, practical means of studying microseismicity in volcanic areas and that seismic activity in this region is sufficiently high to give a useful data set in a few months of observation.

D. Eruption Phenomenology

1. Energy Transport Mechanisms and Apparent Permeability of the Volcano Stromboli, Italy (T. McGetchin and B. Chouet, M.I.T.). Serious consideration is being given to utilization of volcanic heat

Fig. V-34. Emplacement of microseismometer in a rhyolite flow at Glass Mountain near Medicine Lake Highlands, Cascades of Northern California, August 1974.

for geothermal energy¹⁰⁸ in some instances by drilling for direct access to magma chambers.^{109,110} The question of the energy budget of specific volcanoes has become a practical as well as interesting matter. The bulk of the eruption energy of most volcanoes is associated with the enthalpy of ejected material or lava. However, quantitative data on the actual partitioning of energy among various energy transport mechanisms for specific eruptions of volcanoes are sparse and generally incomplete. Authors who have attempted to estimate eruption energies include Gorshkov,¹¹¹ Hedervari,^{112,113} Nakamura,¹¹⁴ Sakuma and Nagata,¹¹⁵ Vick and Schilling,¹¹⁶ and Yokoyama.¹¹⁷ In this paper we report the results of a preliminary investigation of the energy budget of the volcano Stromboli, Italy.

Stromboli is an island about 75 km north of Sicily and it rises some 918 meters out of the

Fig. V-35. Above, location map. Below, map of Stromboli, showing the active vents.

Mediterranean (Fig. V-35). Since the earliest historical records, vents near the summit have been in a more or less continuous state of episodic activity characterized by well-collimated jets of incandescent gas which last for several seconds to about two minutes and are loaded with molten fragments of basaltic vitric lapilli. This mode of geyser-like eruption has been termed Strombolian activity, and is found at several volcanoes in the world, including Pacaya (Guatemala), Erta'ale (Ethiopia) and Etna (Northeast Crater, Italy).

In a recent paper¹¹⁸ we reported results of detailed analyses of high-speed movies of two eruptions typical of the normal mode of activity at Stromboli. Some of the results are shown in Table V-X. Significantly larger paroxysmal eruptions have occurred numerous times (21 since 1900, 20

TABLE V-X
SUMMARY OF RESULTS OF ANALYSIS OF ERUPTION
MOVIES AT STROMBOLI, SEPTEMBER 1971

Data		References
Eruption Frequency	11 minutes	Settle ¹¹⁹
Duration	8 seconds	} Chouet ¹¹⁸
Particle Velocity	26 (2.5-72) m/sec	
Mass, Particles	100 $\pm$ ₂₈ ⁺⁶³ kg	
Kinetic Energy, Particles	16.2 kg	
Vent Area	2.3 m ²	
Mean Gas Density	0.5 to 0.30 mg/cm ³	
Peak Gas Velocity	112 m/sec	
Mass, Gas	240 kg	

between 1800 and 1900, and 4 prior to 1800).

Energy is transported to the surface from active volcanoes in at least 8 modes. These are: (1) conduction of heat through the surface, (2) radiative heat transfer from the vent, (3) acoustical radiation in blast or jet noise, (4) seismic radiation, (5) thermal energy of ejected particles, (6) kinetic energy of ejected particles, (7) thermal energy of ejected gas, and (8) kinetic energy of ejected gas. In addition, the rare large eruptions contribute energy episodically. It is possible, by using the data summarized in Table V-X on the eruption of Stromboli, to calculate or make reasonably precise estimates of most of the above modes of energy transport for Stromboli. The results of these estimates are shown in Table V-XI together with the assumptions used in calculating each value, where appropriate.

In its normal eruption state Stromboli delivers approximately 1.1 MW (for the part of the volcano above sea level). Approximately 60% of the eruption energy is carried in the thermal energy of ejected gas, approximately 20% by the thermal energy of ejected lava, and 20% by radiative heat transfer from the open vent. Energy transported in kinetic energy of lava particles, kinetic energy of the gas, seismic energy and jet noise or acoustical energy are trivial.

The large eruptions are important from the point of view of any attempt to construct an energy balance for the volcano. For example, the mass of material ejected in the 1930 eruption far exceeds the normal rate. The volume of the ash alone was more than $75 \times 10^3 \text{ m}^3$. If we assume a density of 2 g/cm^3 ,

the mass ejected was at least $150 \times 10^9 \text{ g}$, which at the rate of production of lava in the "normal" strombolian mode of activity (18 g/s, Table V-X) would require nearly 300 yr to produce. Similarly, more than $30 \times 10^{12} \text{ J}$ was associated with the 1930 ash eruption alone. This represents nearly one year's total energy production by all modes of energy transport and about 0.1 year's energy transport by conduction heat flow through the volcanic edifice. Clearly the energy and mass balance of the volcano are strongly influenced or even dominated by the rare large eruptions.

More promising than using the energy transported to the surface in a steady-state mode is the idea of tapping the reserve of thermal energy stored in the interior of the volcano. Geothermal energy used in this mode would be depleted over a period of time depending on the rate of extraction of energy, the size of the reservoir and the rate of recharge. For this reason the internal structure of any volcano and its plumbing system become important to understand. Some clue of the internal structure of Stromboli was provided by the eruption photoanalysis. Oscillations in the gas velocity were observed with approximately 0.6-second periods. Chouet et al.¹¹⁸ suggested that one possible mechanism to produce this is organ pipe resonance in the vent, requiring an open volume both at the top and bottom. After estimating the sound speed in the erupting medium to be in the range 350 to 500 m/sec, they infer the pipe to be about 500 m long. One might postulate, for the sake of calculation, that a magma chamber exists at the bottom of the vent. Let us assume a spherical magma chamber of the order of

Table V-XI
ESTIMATED VALUES FOR ENERGY FLUX FROM
STROMBOLI BY VARIOUS MECHANISMS

Energy Transport Mechanism	Estimated Power (MW)	Remarks and Assumptions
Conducted flux from surface of island above sea level	6	Assumes surface flux of ~ 10 HFU and an area of 12 km^2 . (No data exist on actual heat flow).
Radiative heat flux from large vent	0.2	Assumes black body (unit emissivity = 1) radiation from 1200°C and a vent area of 2.3 m^2 .
Heat flux in ejected lava fragments	0.2	Assumes 100 kg per eruption (a maximum), $T = 1000^\circ\text{C}$, $C_p \sim 1.3 \text{ J/g}^\circ\text{C}$, includes latent heat, and an eruption every 11 minutes.
Kinetic energy of solid particles	0.000024	Assumes 16 kJ per eruption and an eruption each 11 minutes.
Heat flux in erupted gas	0.7	Assumes mass per eruption is 240 kg, $C_p \sim 1.9 \text{ J/g}^\circ\text{C}$, and an eruption each 11 minutes.
Kinetic energy of gas	0.00065	Assumes 240 kg erupted each 11 minutes at an average eruption velocity of 60 m/sec.
Acoustical power	0.0001 $\pm$	Estimated maximum sound level at main vent was $\sim 120 \pm 10 \text{ dB}$ at 50 m range; peak level short duration however, about 2 sec. Assuming isotropic radiation (probably dipole in nature) peak power is about 30 kW, or time averaged, $\sim 100 \text{ W}$.
Seismic energy	?	No measurements of the seismicity at Stromboli are available to us.
Heat associated with rare large flows	0.01	Assumes 10^{12} J is delivered in each rare large eruption; assumed frequency is 1 in 4 years.

500 m radius under Stromboli; the heat content of such a magma-filled reservoir would be about $2 \times 10^{18} \text{ J}$. A 1000-MW plant would deplete the source in about 60 years, assuming such an engineering feat to be possible. Similarly, a 100-MW plant would last at least 600 years.

Analysis of the eruption movies of September 1971 showed that the mass of ejected gas exceeds the mass of ejected solids by a factor of 2.5 to 15.¹¹⁸ No direct data are available on the composition of the vapor phase during these eruptions, but Le Guern¹²⁰ reports Stromboli's vapor to range in composition with time from nearly pure H_2O to nearly pure CO_2 . The amount of volatiles far exceeds the amount reasonably held in solution in the erupting lava.

If we assume that the volatiles consist of sea water diffusing through the volcanic pile, we can calculate the average apparent permeability of the volcano required to permit the average flux of water (about 37 g/sec) into the magma. Stromboli is a nearly conical island which protrudes about a kilometer above the surface of the Mediterranean Sea, but which also extends some 2500 meters below sea level making it, in fact, comparable to Mt. Etna in size, if measured from its base. The hydrostatic head of water at the base is therefore approximately $130 \times 10^2 \text{ kPa}$. If we assume the pile has some uniform permeability, we can calculate the permeability required to account for the sea water forced into the pile under a pressure gradient equal to the local hydrostatic head of sea water.

By taking a series of stacked flat cylinders to simulate the submarine volcano, which to first order approximation is a 20° right circular cone, the apparent permeability, k , was calculated assuming the following values for the other parameters; viscosity of water, 3×10^{-4} poises (a reasonable value for $T \sim 500^\circ$ and $P \sim 10^2$ kPa);¹²¹ inside radius of the vent, $r_e \sim 100$ cm. The resulting "apparent average permeability" is $0.5 \cdot 10^{-15}$ cm² or 0.05 microdarcys. This is a very low value equivalent to highly impervious hard rocks. For example, clean gravels have permeabilities in the 10^3 darcy range; clean sand about 1 darcy; sandstone and silt, millidarcy; and limestones and granite all in the microdarcy range. It appears that the observed amount of water entering the Strombolian magma can be easily accounted for by permeation of sea water through the volcanic pile, even with very low apparent permeabilities implied.

This apparent permeability may be real or it may be an artifice of the model. We know that above sea level Stromboli is a strato-volcano, built of interbedded flows and ash, capped by pyroclastics. We can only guess or try to infer its submarine structure. If it is interbedded flows and pyroclastics we might expect true permeabilities in the millidarcy range, probably intermediate between hard rocks and poorly consolidated materials. Hence, it is not unreasonable to infer that true permeabilities may be higher than the calculated values throughout most of the cone but perhaps even lower near the volcanic vent. Kennedy¹²² has postulated that volcanic vents and active magma chambers may be essentially self-annealing glass-lined tanks. It is of considerable interest to know if such a configuration is real from the viewpoint of the stability of magma chambers and the eruption hazard which might be associated with perturbation by drilling.

2. Emplacement of the 1801 Hualalai Lava Flow, Hawaii (T. McGetchin, J. Eichelberger). Lava flows are interesting to us for a number of reasons: (a) locally they constitute a serious threat to property, as in Hawaii^{123,124} (see Fig. V-36) and Japan,¹²⁵ and more rarely to life;¹²⁶ (b) the thermal energy of lava is large and its properties are of interest in several schemes for extraction of geothermal energy directly from magma;¹⁰⁹ (c) they provide

clues about the compositional zonation of the magma chambers from which they were erupted; and (d) they constitute the mechanism by which the large shield complexes are constructed, such as in Hawaii, Iceland, and on the surface of Mars.

The 1801 Hualalai flow (Fig. V-36) is especially interesting because it had an unusually low viscosity, probably in the range 10^2 to 10^3 poises, whereas observations of most Hawaiian lavas suggests viscosities in the range 10^3 to 10^4 poises.¹²⁷ This flow is well known to geologists because of a spectacular occurrence of ultramafic nodules, some up to 50 cm in diameter, in a well-channeled part of one of the two (Kaupulahu) branches of the flow (Fig. V-37). Witnesses to the eruption included two victims; survivors described an unusually high velocity advance which reached the sea in the order of an hour, some 16 km from the source vents.

We are attempting to quantitatively model several aspects of the flow: (a) the settling of xenoliths, (b) viscosity of the lava, (c) eruption velocity and conditions of flow in the conduit to the surface, and (d) the parameters of the lava flow itself - velocity, depth.

The flow consists of alkalic basalt (Table V-XII) (normative nepheline 1.5 to 2.3% and normative olivine about 18 to 20%) in which olivine and augite occur as phenocrysts.¹²⁸ Yoder and Tilley¹²⁹ investigated rock with composition similar to Hualalai lava experimentally and found that at low pressures ($P \sim 1 \times 10^5$ kPa) olivine appears at 1200 to 1250°C; under water-saturated conditions the assemblage liquid plus olivine plus pyroxene is stable only at pressures greater than 2×10^4 kPa and temperatures less than 1120°C. An eruption temperature near 1100°C is consistent with the mineralogy, assuming water saturation, or perhaps 1200°C if unsaturated. The viscosity and density of the lava computed as functions of temperature, volatile content and composition^{130,131} fall largely between 10^2 to 10^3 poises, and 2.6 to 2.7 g/cm³ (Figs. V-38, 39).

The calculated settling velocity of the large (50-cm) ultramafic nodules in this lava is in the range 0.5 to 1.5 m/sec. Upward flow velocity in the volcanic vent, calculated for various reasonable vent and lava parameters appears to be marginally in the turbulent flow regime. If we assume the head

Fig. V-36. Map of the island of Hawaii showing:
 A. Location of the 1801 Hualalai lava flow
 B. Proposed barriers to divert flows from Mauna Loa's east flank from Hilo are shown. After Macdonald.

driving the flow upward results from the density contrast between rock and fluid lava, then solving for the flow velocity is a simple matter of solving the Fanning equation. Because the duct is long with respect to its width, the flow velocity is a function of the duct size, the density contrast, and a friction term. The peak volume flux for many Hawaiian eruptions has been observed (Table V-XV). If we assume a flux for the 1801 Hualalai flow similar to these values, then the flow velocity and pipe size can be constrained because the volume flux is critically dependent on the pipe size. For viscosities like the 1801 Hualalai lavas the resulting upward flow velocities are in the range 15 to 20 m/sec and the pipe diameter 4 to 6 m. Since this flow velocity is so much higher than the settling velocity of the largest

xenoliths, we conclude that the presence or absence of xenoliths in the 1801 lava and Hawaiian lava in general is probably not related to fluid mechanical sorting effects. Even passive tholeiitic eruptions may transport xenoliths with no trouble, so the presence or absence of xenoliths in general must reflect the conditions in the reservoir.

A model for lava emplacement on the surface using open channel theory was found to be in agreement with the qualitative descriptions of the actual event. Calculations suggest that the flow is dominated by drag induced by surface roughness and that viscosity is only of secondary importance. Using a von Mises formulation for the drag coefficient, we find flow solutions (summarized in Table V-XIV) which suggest velocities of 10 to 15 m/sec near the vents

Fig. V-37. A remarkable occurrence of dense ultramafic nodules in the 1801 Hualalai flow. The largest (not shown) are about 50 cm in diameter; rock types are dunite, peridotite, troctolite, and pyroxenite.

where the slopes are steep, 6 to 8 m/sec at the distal end of the flows. Toe advance velocities were probably of the order of half these values. Calculated flow thicknesses are 8 to 20 cm. The results of the emplacement model for the 1801 flow are summarized in Fig. V-40. They suggest that the toe advanced from the vent to the sea in just over an hour; live lava following the mid-stream path later in the eruption might follow the same course in only 12 to 15 minutes at velocities of up to 50 km/h.

Perhaps the most important result of this preliminary investigation is that it helps define the nature of the field observations required to adequately describe the evolution of a lava flow through time. Fig. V-40, a time-distance diagram, illustrates the requirement for quantitative synoptic data at (a) the vent, (b) the toe, and (c) at various localities in time-distance space. It is impossible for even a well-prepared team of observers to be everywhere at once, but it is clear that careful pre-planning will maximize the scientific return.

Fig. V-38. Computed density of the 1801 Hualalai lava as a function of temperature and water content at constant pressure.¹³⁰

Some intriguing possibilities and challenges exist in engineering lava flows, both in diverting potentially dangerous ones and in creating artificial lava lakes for geothermal purposes.

3. Tectonic Setting of Ore Deposits, Volcanoes, and Geothermal Fields (T. McGetchin). Many important resources are systematically associated with major tectonic elements of the earth's crust, and their distribution appears to be easily understood in terms of plate tectonics.^{133,134} Although many details remain to be resolved, an overall picture of remarkable clarity is beginning to emerge. The major categories of resource deposits and their tectonic setting are summarized in Table V-XV, after Elston.¹³⁵

Fig. V-39. Computed viscosity of the 1801 Hualalai lava as a function of temperature and water content.¹³¹

Table V- XII
COMPOSITION (wt. %) OF THE 1801
HUALALAI FLOW¹²⁸

Sample No.	1	2
SiO ₂	46.43	46.59
Al ₂ O ₂	10.91	15.19
Fe ₂ O ₃	3.15	2.96
FeO	10.26	9.89
MgO	11.98	8.74
CuO	10.09	10.02
Na ₂ O	3.16	3.01
K ₂ O	.54	0.96
TiO ₂	2.59	2.26
H ₂ O ⁺	.66	0.05
H ₂ O ⁻	.15	n.l
P ₂ O ₅	.67	0.29
SO ₃	.07	
MnO	.09	0.18
Cr ₂ O ₃		.06
Totals	99.85	100.20

The bulk of the world's metal-bearing ore bodies are hydrothermal deposits which are produced by melting of downgoing slabs of lithosphere at the intersection of convergent plates. The lithosphere, the outer 100 to 200 km of the earth, consists of the crust and the rigid (cool) part of the upper mantle; it is underlain by a relatively deformable zone called the asthenosphere. Many ore-bearing fluids are formed by melting of the downgoing slab and are concentrated in the folded structures and volcanoes marginal to the major subduction zones (island arcs, trenches, and associated volcanoes). Sulfide deposits (such as Kuroko district of Japan, the massive sulfides of the Philippines, and western North and South America: the coast ranges, Rockies, and Andes, and those in a belt extending from the Mediterranean to the Himalayas) and gold deposits (such as in Alaska, Canada, California, Venezuela, Brazil, West Africa, Rhodesia, India, and Australia) are found in rocks formed at these convergent plate boundaries. Rich metallic sulfide deposits have been found in the Red Sea, a divergent plate boundary - potential sources of copper, vanadium, and zinc. Sediments found on the divergent volcanically active mid-ocean ridges are generally enriched in iron, manganese, copper, nickel, cobalt, lead, chromium, uranium, and mercury. Veins of copper were found in the volcanic rocks of the Ninety East Ridge in the Indian Ocean under 2-1/2 km of sediment and sea water. A vein of metallic copper and dispersed copper crystals were found in bottom sediments above the volcanic basement on the continental rise under 5 km of sea water. The huge copper deposits of the Troodos massif, Cyprus, are found in a mass of upthrust sea floor, the result of the continental collision between Africa and Europe. The deposits are ellipsoidal lenses in the interbedded sediments and volcanics, and the ore bodies are clearly related to the volcanics in which they occur. Favorable conditions for the accumulation and preservation of petroleum deposits occur in trenches, in basins formed between volcanic island arcs, and also in the newly formed restricted seas between divergent plates; and it is expected that petroleum accumulations will be found seaward along the continental shelf and slope of both the North and South Americas.

Table V-XIII
OBSERVED VOLUME FLUX, VOLUMES AND SURFACE AREAS
OF SELECTED HAWAIIAN LAVA FLOWS¹²⁴

Flow	Source	Maximum Volume Flux (m ³ / sec)	Volume (km ³)	Duration of Flows (Days)
1940, Mauna Loa	summit	560	0.077	133
1952, Kilauea	summit	390	0.049	136
1955, Kilauea	East Rift	167	0.092	88
1959, Kilauea	Kilauea Iki	560	0.039	36
1960, Kilauea	East Rift	140	0.119	36

1801 Hualalai	Length (km)	Average Width (km)	Area (km ²)	Volume (km ³)
Kaupulehu	16.7	1.8	31.0	0.185
Huehue	8.5	1.7	14.5	0.130

Table V-XIV

SOLUTIONS FOR FLOW THICKNESS (T) AND VELOCITY (v)
AND ARRIVAL TIME (Δt) FOR THE OBSERVED CONDITIONS
OF SLOPE OF THE 1801 HUALALAI FLOW. CHANNEL
ROUGHNESS OF 0.05 (F = 0.25) AND WIDTH OF 1.8 km
WERE ASSUMED. v* AND Δt* REFER TO CONDITIONS AT
THE TOE.

v = 10 ⁹ cm ³ /sec						v = 0.5 x 10 ⁹ cm ³ /sec				
Dist. (km)	T (cm)	v (m/sec)	Δt (min)	v* (m/sec)	Δt* (min)	T (cm)	v (m/sec)	Δt (min)	v* (m/sec)	Δt* (min)
0.2	12	14	2.4	7.0	4.8	7.6	11	3.0	5.5	6.0
2-8	14.5	12	8.2	6.1	16	9.1	9.7	10.3	4.8	21
8-15	21	8.3	14.1	4.1	28	13	6.6	18	3.3	36
			24.7		49			31.3		63

Note that 7 m/sec = 25.2 km/h

Fig. V-40. Above, the longitudinal profile of the 1801 Hualalai lava flow (Kaupalehu branch); below, a calculated reconstruction of the 1801 flow shown in time-distance coordinates. Particle paths are shown by dotted and dashed lines. In this model the flow front reached the sea in just over an hour after the eruption began; the lava forming the toe at that point however, left the vent at about 48 minutes after eruption began.

The formation of most ore bodies from which important metals are obtained (either in hydrothermal or sulfide bodies) are formed by rock melting processes. Deposits may be found both at convergent and divergent plate boundaries.

The distribution of volcanoes also is clearly controlled by their structural setting (see Fig. V-41). Of the 600 to 700 active volcanoes of the world most are found over subduction zones along the convergent plate margins. The mid-ocean ridges, of course, produce vast amounts of volcanic material and in fact the lithosphere itself has been and is presently being produced on these ridges by volcanic processes, namely dike swarm emplacement as is visible on land in Iceland where the mid-Atlantic ridge is subareally exposed. Volcanism also occurs within the continental plates, some at sites of active rift zones such as in east Africa, the Rhine graben or the Rio Grande graben of New Mexico. A rare but exceedingly interesting type of volcanism originates from deep sources under the stable continents, producing some very exotic rock types - such as carbonate volcanoes (carbonatites) and the diamond-bearing kimberlite pipes. The associations of the rock types in each of these major tectonic settings, the style of eruption, the processes of rock genesis and landforms, are all characteristic of each setting (see Table V-XV).

The world's currently exploited geothermal areas (Fig. V-42) are without exception areas of active or recent volcanism.¹³⁶ The geothermal fields of the earth are located on spreading centers, over subduction zones or on rift valleys (Fig. V-43). The potential of the dry hot rock technique is not in principle restricted to active volcanic centers, but the areas being currently explored are sites of very young volcanism or plutonism and the technique will be best applied in hot areas. Areas having near or slightly above normal geothermal gradient may be exploited for space heating (as hot water is in Iceland currently) in non-volcanic areas but large-scale geothermal energy exploitation will probably be restricted to active or relatively young igneous terrains¹⁰⁹.

Tectonic Setting of the World's Volcanoes

3. Island Arc
Subduction Zone

1. Mid-Ocean Ridge

2. Seamount Chain

4. Subduction of
Ocean Crust Under
Continental Margin

6. Continental Rift
Zones

7. Mid-Continent
Volcanism on
Stable Platforms

5. Subduction of
Continental Crust
Under Continent

MID OCEAN VOLCANISM

SUBDUCTION ZONES

CONTINENTAL
VOLCANISM

Setting	Dominant Processes	Igneous Processes and Melting Mechanisms	Rock Types Produced	Structure and Style of Volcanism	Location and Example Volcano
1. Mid-Ocean Ridge	Creation of oceanic crust-lithosphere; separation of oceanic lithosphere	Partial melting of the upper mantle upon adiabatic decompression in rising convection cell	Principally primitive oceanic basalts; locally andesitic types. Tholeiitic types	Effusive submarine flood basalts; rare supracrustal volcanic shields with andesitic edifices	Iceland - Hekla Galapagos - Fernandino
2. Seamount Chain	Local melting in mantle; redeposition of melt on surface	Partial melting of upper mantle due to transport over hot spot (plum) or due to decompression accompanying tensional rifts	Predominantly primitive oceanic basalts; minor alkalic basalts	Large shield volcanoes produced from effusive tholeiitic basalt flows capped with alkali basalt, largely pyroclastic	Hawaii - Kilauea Mauna Loa
3. Island Arc	Destruction of oceanic crust by partial melting	Partial melting of downgoing slab; locally differentiation and contamination occur	Dominantly andesite; subordinate high Al-basalt	Andesite stratovolcanoes; long repose times and episodic violent explosive activity	Japan - Asama W. Aleutians
4. Continental Margin- Oceanic crust under continental crust	Destruction of oceanic crust by partial melting	Partial melting of downgoing slab; locally differentiation and contamination occur	Dominantly andesite; subordinate high Al-basalt (less basalt than #3, above)	Andesite stratovolcanoes; long repose times and episodic violent explosive activity	California - Shasta Guatemala - Pacaya Chile - Puyehue Ecuador - Cotopaxi E. Aleutians - St. Augustine
5. Continental collision; continental crust under continental crust	Deformation and partial melting of continental crust	Partial melting downgoing slab; locally differentiation and contamination occur	Dominantly andesite; subordinate high Al-basalt (less basalt than #3, above)	Andesite stratovolcanoes; long repose times and episodic violent explosive activity	Italy - Etna Stromboli
6. Continental rift zones	Separation of crust-lithosphere; and volcanism	Same as #1 but with partial melting of lower crust to produce acidic volcanics in addition	Bimodal suite of volcanic rocks. Basaltic suite like #1; rhyolitic suite produced by partial melting of crust	Effusive flood basalts; explosive rhyolitic ash and caldera complexes	New Mex. - Jemez E. Africa - Erta ale
7. Stable platform volcanism	Penetration of stable platforms by exotic volcanic types	Volatile-rich volcanism from within or below lithosphere; varying degree of partial melting	Generally exotic types - kimberlite, carbonatite, alkalic basalts, lamprophyres. Deep seated source within the mantle; xenoliths common	Diatremas common explosive gas-charged eruptions. Breccia dikes and pipes common	Utah - Moses Rock So. Africa - Kimberley Mine

M = Mohorovicic discontinuity
(Crust-mantle boundary)

L = Lithosphere (rigid plate)

A = Asthenosphere (plastic interior)

Fig. V-41. Tectonic setting of the world's volcanoes.

TABLE V-XV

TECTONIC SETTING OF MAJOR TYPES OF MINERAL DEPOSITS¹³⁵

<u>Tectonic Environment</u>	<u>Geological Setting</u>	<u>Resource</u>	<u>Example</u>
Mid-ocean spreading center	Pillow lavas	Cu, pyrite	Cyprus
Deep sea floor sediments	Manganese nodules	Cu, Co, Ni	Pacific and Atlantic sea floor
Subduction zones	Trench deposits (melange with serpentinites)	Ni, Cr	New Caledonia, Cuba, California to Washington
Behind major island arcs	Sedimentary basins	Oil and gas	Persian Gulf, Indonesia, California
Island arcs behind subduction zones	Andesite volcanism and shallow intrusions	Cu, Pb, Zn, Ag, Hg (GTE)	Western U.S., Andes, SW Pacific
Island arc behind subduction zones	Granite batholiths, pegmatite veins	Be, Sn, W, feldspar, mica	Malaya, Appalachians
Continental rift	Granite and alkalic intrusive and volcanic complexes	Sn, W, Mo, Nb	Bolivia, Colorado-New Mexico, SW Africa
Craton or margins of continents	Continental sediments	Coal, U, V	Colorado Plateau, Appalachians
Within continents or on margins	Evaporite basins, marine	Oil, gas, salt,	SE New Mexico - West Texas, Saskatchewan
	Evaporite basins, non-marine	Oil shale, NaCO ₃ zeolites, borax, lithium salts	Great Basin Rocky Mtns.
Continents	Intracontinental basin, shallow water marine	Pb, Zn, Cd, fluor spar barite, oil and gas	Mid-continental U.S.A.
Ancient shields	Deeply eroded (some by processes no longer active on the earth)	Banded Fe, Mn	Lake Superior, Brazil, Krivoi Rog, USSR
	Anorthosite bodies	Ti, Al	Adirondacks, Quebec
	Places in reducing conditions	Au, U	Witwaterstrand, Blind River, Ont.
	Volcanogenic, ancient Kuroko deposits	Cu, Zn, Pb	Timmons, Ontario; Broken Hill, N.S.W.
Continental margin Coastal Plain	Heavy sands	Ti, An, Zr, Th, Y	
	Sedimentary rocks	Fe, Mn	Birmingham, Ala., Lorraine France
		phosphates	Florida, N. Africa, Idaho
Fractured Continental Margin	Evaporite basins	oil, gas, sulfur	Angola, North Sea, US Atlantic Coast
Rifts	Large continental rifts valleys	GTE, Zn, Cu, Fe	Red Sea, Salton Sea
Random	Meteorite impact basins	Ni, Cu, Pt, Cu	Sudbury Ontario, Bushveld, So. Africa
		oil and gas	Redwing structure in Williston Basin, Montana

Fig. V-42. Geothermal electric power stations, after Koenig.¹³⁶

Fig. V-43. Relationship of known geothermal systems to boundaries of lithospheric plates. Spreading ridges are shown as double lines, rift valleys as dotted lines, and subduction zones as heavy barbed lines, after White.¹³⁷

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APPENDIX

VISITORS, VISITING AND SUMMER STAFF MEMBERS, AND PUBLICATIONS

I. PERSONNEL

A. Visitors, Visiting Scientists

<u>Name</u>	<u>Organization</u>	<u>Specialty</u>	<u>Date of Visit</u>
Prof. M. Gene Simmons	Massachusetts Institute of Technology	High Pressure Geophysics	6/14/74
Prof. Herbert Wang	University of Wisconsin	High Pressure Geophysics	6/14/74
Prof. Orson Anderson	University of California at Los Angeles	High Pressure Geophysics	6/14/74
Mrs. Carli Pieters	Massachusetts Institute of Technology	Planetary Astronomy and Remote Sensing Research	7/16/74; 8/20/74
Dr. H. H. Schmitt	National Aeronautics and Space Administration	NASA Energy Program, Lunar Science	7/15-16/74
Mr. Bernard Chouet	Massachusetts Institute of Technology	Monitoring of Microseismicity	8/19-26/74 12/2-9/74
Mr. Joel Iverson	California Institute of Technology	Thesis Research on U/Pb Systematics in Volcanic Rocks of the Southwest	9/25/74
Prof. Keiiti Aki	Massachusetts Institute of Technology	Seismology	11/9-13/74
Mr. Peter Lyttle	Harvard University	Structure and Petrology of Igneous Bodies	11/14-15/74
Prof. Arthur Boettcher	Pennsylvania State University	Experimental Igneous Petrology	11/25-26/74
Dr. John B. Adams	Massachusetts Institute of Technology	Remote Sensing	12/9-11/74
Dr. John Creasy	Middlebury College	Igneous Petrology and the Structure of Igneous Bodies	12/10/74
Lt. Mark Settle	Air Force Cambridge Research Laboratory	Cratering; Mathematical Modeling of Igneous Bodies	12/17-19/74

B. Visiting Staff Members

Prof. Wolfgang Elston	University of New Mexico	Ore Deposits; Regional and Volcanic Geology of New Mexico	4/28/74
Prof. Richard Birnie	Dartmouth College	Ore Deposits and Remote Sensing	5/14-15/74
Prof. Robert Decker	Dartmouth College	Volcanology, Lava Lake Energy Project	5/14-15/74
Dr. Michael Duke	NASA-Houston	Geochemistry	5/17-18/74
Prof. Jon Callender	University of New Mexico	Structural Geology of Pre-Cambrian Rocks of New Mexico	8/19-21/74; 11/27/74; 12/10/74
Dr. Grant Heiken	NASA-Houston	Volcanic Geology; Remote Sensing	11/7-13/74

C. Summer Staff (Graduate Students)

Mr. W. S. Baldrige	California Institute of Technology	Field Petrology	Summer, '74
Mr. B. Chouet	Massachusetts Institute of Technology	Seismology	Summer, '74
Mr. S. Ehrenberg	University of California, Los Angeles	Petrology	Summer, '74

D. Current Staff

Dr. Thomas R. McGetchin	Petrology-Volcanology
Dr. John C. Eichelberger	Petrology-Volcanology
Dr. Ronald Gooley	Mineralogy
Ms. Susan Hall	Secretary

II. LASL GEOSCIENCES ADVISORY PANEL, 1974

<u>Name</u>	<u>Organization</u>
Prof. Orson Anderson, Chairman	University of California at Los Angeles
Prof. Robert W. Decker	Dartmouth College
Prof. John W. Handin	Texas A. & M. University
Dr. John Healy	U. S. Geological Survey, Menlo Park
Dr. Allen V. Kneese	University of New Mexico
Dr. Arthur H. Lachenbruch	U. S. Geological Survey, Menlo Park
Prof. Priscilla Perkins	University of California at Los Angeles
Dr. Robert E. Riecher	Air Force Cambridge Research Laboratory
Dr. Hatten S. Yoder, Jr.	Carnegie Institute of Washington
Dr. David B. Slemmons	University of Nevada
Dr. Richard F. Taschek	Los Alamos Scientific Laboratory

III. ADMINISTRATIVE MATTERS

A. Papers Published and Submitted

1. B. Chouet, N. Hamisevicz, and T. R. McGetchin, "Photoballistics of Volcanic Jet Activity at Stromboli, Italy," *J. Geophys. Res.*, **79**, 4961-4976 (1974).
2. John C. Eichelberger, "Magma Contamination Within the Volcanic Piles: Origin of Andesite and Dacite," *Geology*, **2**, No. 1, 29 (1974).
3. John C. Eichelberger, "Origin of Andesite and Dacite: The Petrographic and Chemical Evidence for Volcanic Contamination," *Geological Society of America Bulletin*, (accepted for publication, 1974).
4. J. Eichelberger and T. McGetchin, "Petrogenesis of the 1973 Pacaya Lavas, Guatemala," *Bull. Volcanol.*, (accepted for publication, 1974).
5. R. C. Gooley, R. Brett, and J. L. Warner, "A Lunar Rock of Deep Crustal Origin: Sample 76535," *Geochim. et Cosmochim. Acta*, **38**, 1329-1339 (1974).
6. R. C. Gooley and C. B. Moore, "Native Metal in the Diogenites," (submitted to *Amer. Mineral.*, 1974).
7. D. Johnston, T. R. McGetchin and N. Toksoz, "The Thermal State and Internal Structure of Mars," *J. Geophys. Res.*, **79**, No. 26, 3959-3971 (1974).

8. T. R. McGetchin, M. Settle, and B. A. Chouet, "Cinder Cone Growth Modeled After Northeast Crater, Mount Etna, Sicily," *J. Geophys. Res.*, **79**, No. 23, 3247-3272 (1974).
9. J. C. Roegiers and D. W. Brown, "Geothermal Energy: A New Application of Rock Mechanics?," *Proc. 3rd Cong. of the Intern. Soc. for Rock Mechanics*, Vol. IIA, Denver (1974).
10. J. C. Roegiers, "De La Possibilite D'Extraire De L'Energie A Partir Des Roches Seches," *Proc. 2nd Intern. Cong. of Eng. Geo.*, (accepted for publication, 1974).
11. M. Settle, J. W. Head, and T. R. McGetchin, "Ejecta from Large Craters on the Moon: Discussion," *Earth & Planetary Sci. Lett.*, (accepted for publication, 1974).
12. G. Woulff and T. R. McGetchin, "Volcano Noise: Theory and Experiment," *Geophys. J., Roy. Phil. Soc.*, London, (submitted, 1974).

B. Presentations and Briefings

1. K. Olsen, "Recent Seismic Activity of the Rio Grande Graben in the Vicinity of Los Alamos, New Mexico," *Penrose Conf. on the Rio Grande Rift*, Santa Fe, August 12-16, 1974.
2. T. R. McGetchin, "The Role of Hydration-Dehydration Reactions in the Vertical Tectonics of Platform Areas such as the Colorado Plateau," *Penrose Conf. on the Rio Grande Rift*, Santa Fe, August 12-16, 1974.
3. T. R. McGetchin, "Geothermal Energy," Briefing for Richard Garwin, LASL, August 20, 1974.
4. J. C. Roegiers, "In-Situ and Seismic Measurements of the State of Stress in the Earth's Crust," and "Transmissivity of Fractures at Focal Depths," *Penrose Conf. on Fracture Mechanics and Earthquake Source Mechanics*, Aspen, August 27-31, 1974.
5. J. C. Roegiers and D. W. Brown, "Geothermal Energy: A New Application of Rock Mechanics?," *3rd Inter. Cong. on Rock Mechanics*, Denver, September 1-7, 1974.
6. J. Rowley, "Rock Melting Applied to Excavation and Tunneling," *3rd Inter. Cong. on Rock Mechanics*, Denver, September 1-7, 1974.
7. J. Eichelberger, "Petrogenesis of the 1973 Pacaya Lavas, Guatemala," *Inter. Symp. on Volcanology*, Santiago, Chile, September 9-14, 1974.
8. T. R. McGetchin, J. P. Balagna, and C. A. Newton, "Geosciences Research," *NATO-CCMS Information Meeting on Dry Hot Rock Geothermal Energy*, LASL, September 1-7, 1974.
9. T. R. McGetchin, "Geosciences Program at LASL," *Div. of Applied Technology, A.E.C., Briefings*, September 20, 1974.
10. T. R. McGetchin, "Geosciences Program at LASL," Briefing for Elliot Pierce, LASL, November 19, 1974.

11. J. Eichelberger, "Magma Contamination within the Volcanic Pile: Origin of Andesite and Dacite," Geology, Dept., Univ. New Mexico, Albuquerque, November 20, 1974.
12. T. R. McGetchin, "Geosciences and Related Energy Research at LASL," Roswell Rotary Club, Roswell, New Mexico, November 20, 1974.
13. T. R. McGetchin, "Geosciences Research at LASL," Briefing for Senator Fannin, LASL, December 7, 1974.
14. T. R. McGetchin, "Geosciences Program at LASL," Briefing for George Kolstad, LASL, December 17, 1974.