DOE/ER-0071

Summaries of Physical Research in the Geosciences

August 1980

U.S. Department of Energy
Division of Engineering, Mathematics & Geosciences
Office of Energy Research

Printed in the United States of America

Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed Copy:	$ 6.50
Microfiche Copy:	$ 3.50

DOE/ER-0071
UC-11

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Washington, D.C. 20545

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FOREWORD

The Department of Energy supports research in the geosciences in order to provide a sound underlay of fundamental knowledge in those areas of the earth, atmospheric, and solar/terrestrial sciences that relate to the Department of Energy's many missions. The Division of Engineering, Mathematical and Geosciences, which is a part of the Office of Basic Energy Sciences and comes under the Director of Energy Research, supports under its Geosciences program major Department of Energy laboratories, industry, universities and other governmental agencies. Such support provides for payment of salaries, purchase of equipment and other materials, and an allowance for overhead costs. It is formalized by a contract between the Department and the organization performing the work.

The summaries in this document, prepared by the investigators, describe the overall scope of the individual programs and details of the research performed during 1979-1980. The Geoscience program includes research in geology, petrology, geophysics, geochemistry, hydrology, solar-terrestrial relationships, aeronomy, seismology and natural resource analysis, including the various subdivisions and interdisciplinary areas. All such research is related to the Department's technological needs, either directly or indirectly.

INTRODUCTION TO BASIC ENERGY SCIENCES GEOSCIENCES RESEARCH PROGRAM

Research in Geosciences program of the Department of Energy's Office of Energy Research, Office of Basic Energy Sciences, Division of Engineering, Mathematical and Geosciences is divided into five broad categories:

(1) geology, geophysics and earth dynamics;
(2) geochemistry;
(3) energy resource recognition, evaluation and utilization;
(4) hydrologic and marine sciences and
(5) solar-terrestrial-atmospheric interactions.

The following outline of the content of these categories is intended to be illustrative rather than exhaustive, and will evolve with time. Individual research efforts at the Department of Energy, university, college, corporate, not-for-profit and other Federal agency laboratories supported by this program frequently will have components in more than one of the categories or subcategories listed.

Research supported by this program may be directed toward a specific energy technology, national security, conservation of the environment, or the safety objectives of the Department of Energy. Developing geoscience and geoscience-related information of relevance to one or more of these Department of Energy objectives or the development of a broad, basic understanding of geoscience materials and processes necessary for the attainment of long-term Department of Energy goals is the purpose of this program. In general, individual research efforts supported by this program may involve elements of all four objectives.

A. Geology, Geophysics, and Earth Dynamics

1. Large-Scale Earth Movements: Research related to the physical aspects of large-scale plate motion, mountain building and regional scale uplift and subsidence.

2. Evolution of Geologic Structures: Research bearing on history and development of geologic structures (e.g., folds, faults, landslides and volcanoes) on a local or subregional scale (subsets of A.1.).

3. Properties of Earth Materials: Research on physical properties of rocks and minerals determined in the laboratory or in the field (*in situ*) by direct or indirect techniques.

4. Rock Flow, Fracture and Failure: Research related to response of minerals, rocks and rock units to natural or artificially induced stress. Includes the range of strain rates from those appropriate to drilling to viscoelastic response.

5. Continental Scientific Drilling Program (CSDP): Research on advanced technology and services as well as science-motivated projects concerned with utilization of shallow (>0.3 km), intermediate (0.3 to 1 km) and deep (1 km to 9 km) drill holes in the United States continental crust to: (a) obtain samples for detailed physical, chemical, mineralogical, petrologic, and hydrologic characterization and interpretation; (b) correlate geophysical data with laboratory-determined properties and (c) use of the drill hole as an experimental facility for study of crustal materials and processes. The Department of Energy focuses on drilling through an active hydrothermal system (or systems) into a magma chamber or into high-temperature igneous rocks. Includes research aspects of drilling technology development for such hostile environments. Part of a multiagency (United States Geological Survey, National Science Foundation, Department of Energy and Department of Defense) coordinated program.

B. Geochemistry

1. Thermochemical Properties of Geologic Materials: Research related to thermodynamic, physical and transport properties of natural geologic materials and their synthetic analogues. Emphasis is on generic rather than site-specific studies.

2. Static Rock-Water Interactions: Laboratory-based research on chemical, mineralogical and textural consequences of interaction of natural aqueous fluids, or their synthetic analogues, with rocks and minerals.

3. Organic Geochemistry: Research on naturally occurring carbonaceous and biologically derived substances of geologic importance. Includes research on origin and development of coal, petroleum and gas.

4. Geochemical Migration: Research on chemical migration in materials of the earth's crust where emphasis is on generic rather than specific understanding, which may (ultimately) lead to predictive capability. Focus is on experimental and theoretical studies of chemical transport induced by pressure, temperature and composition gradients within, between and by a phase or phases. Part of a multiagency (Department of Energy, National Science Foundation, United States Geological Survey) joint program.

C. Energy Resource Recognition, Evaluation and Utilization

1. Resource Definition and Utilization: Research with a principal goal of developing new and advanced physically, chemically and mathematically based techniques for energy and energy-related resource exploration, definition and use.

2. Reservoir Dynamics and Modeling: Research related to dynamic modeling of geothermal and hydrocarbon reservoirs in their natural and perturbed (by production, injection or reinjection) states.

3. Magma Energy Resources: Field, laboratory, experimental and theoretical research bearing on origin, migration, emplacement and crystallization of natural silicate liquids or their synthetic analogues. Emphasis is on studies related to energy extraction from such liquids.

4. Information Compilation, Evaluation and Dissemination: Research activities which are principally oriented toward the evaluation of existing geoscience data to identify significant gaps. Includes the necessary compilation and dissemination activities.

D. Hydrologic and Marine Sciences

1. Groundwater Hydrology: Research related to chemical and physical principles underlying the flow of water through porous and permeable rocks near the earth's surface.

2. Fresh Water Systems: Research on the chemistry, physics and dynamics of fresh water systems, including streams, rivers and lakes.

3. Oceanography: Research involving materials and processes of the marine environment. Principal emphasis on geological, geophysical and geochemical research related to rocks and sediments beneath the water column.

E. Solar-Terrestrial/Atmospheric Interactions

1. Magnetospheric Physics and Chemistry: Research directed toward development of a fundamental understanding of interactions of the solar wind with the terrestrial magnetic field. Research related to the earth's magnetosphere as a model magnetohydrodynamic generator and associated plasma physics research.

2. Upper Atmosphere Chemistry and Physics: Research on thermal, compositional and electrical phenomena in the upper atmosphere and the effects induced by solar radiation.

3. Solar Radiation: Research on the solar constant, spectral distribution and characteristics of solar radiation on the earth. Includes long-term effects of solar radiation on climate.

4. Meteorology and Climatology: Interrelationships of weather and climate with energy systems and vice versa.

PART I

GEOSCIENCES

ON-SITE

Contractor: ARGONNE NATIONAL LABORATORY
Argonne, Illinois 60439

Contract: 109 ENG 38

Title: I. Geosciences Program

Persons in Charge: F. A. Cafasso, P. R. Fields and M. J. Steindler

Scope of Work

Geoscience research at Argonne National laboratory is concerned with the thermochemistry and structure of minerals, with trace element and radionuclide solution chemistry, and with transport in geologic media. Results should contribute to the advancement of technological efforts in geothermal energy exploitation and in radioactive waste disposal.

A. Thermochemistry of Geothermal Materials (P. A. G. O'Hare)

By means of solution, fluorine bomb and drop calorimetric techniques, thermochemical data for well-characterized minerals are being measured. Properties measured include standard enthalpies of formation, high-temperature heat capacities and enthalpy increments relative to 298.15 K. Structural measurements are also made as appropriate. Current research includes sulfur-containing minerals such as chalcopyrite ($CuFeS_2$) and hauerite (MnS_2), and the zeolites analcime, natrolite, scolecite, mesolite and thomsonite. Study of the zeolite series is expected to give an indication of how the enthalpies of formation and structures vary as a function of metallic substituents. This information could serve as an important input for estimating the properties of analogous systems. Subsequent research will attempt to delineate the variation of thermodynamic and structural properties for a variety of analcimes with different silicon to aluminum ratios.

The information obtained in this program should be valuable in connection with the exploitation of geothermal systems.

B. Trace-Element Transport in Geologic Media (M. G. Seitz and R. A. Couture)

The goal of this program is to understand fundamental mechanisms that underlie transport by fluid flow of trace elements in rocks. Transport of trace elements can produce ores or, in other situations, they can upset schemes to extract geothermal energy or to dispose of wastes. In this work, solutions at elevated temperatures are pumped through rock or through columns of minerals. Trace elements introduced into the fluid stream are then followed analytically as they move through the geologic media. These

experiments reveal the effects of (a) reaction kinetics, (b) streaming potential, and (c) chemical speciation--effects that are not evident in simpler non-flow experiments.

Inasmuch as adsorption often exerts a major control on trace element migration, the initial part of the program focused on the exchange properties of clay minerals at elevated temperatures and on the mechanisms of anion exchange with oxides. The program is currently being extended to study trace element migration controlled by precipitation-dissolution reactions. Generally these reactions produce abrupt changes in rock and solution compositions over small distances and occur, for example, in a solution moving through a thermal gradient or in a solution flowing across a geologic contact.

C. Migration of Heavy Element Chemical Species in Geologic Strata

(S. M. Fried, A. M. Friedman and J. C. Sullivan)

This program is concerned with elucidating the fundamental parameters affecting the rate of transport of radionuclides from a potential nuclear waste site located in deep geologic media. The program is specifically concerned with the conditions that affect oxidation states and hence the migration rates of various actinide ions that may be leached by groundwater from a source emplaced in a deep geologic repository. Among the parameters under investigation are (a) radiolysis (due to the radiation field of the repository), (b) redox potentials in the geologic media and (c) complex formation with various anions (Cl^-, CO_3^{2-}/HCO_3, and SO_4) occurring in groundwater. In all these studies attempts will be made to simulate, as closely as possible, the environment of geological media.

1. Radiolysis Effects on Oxidation States of Actinides

Radiolysis effects are being determined in various solutions such as saturated brines and seawater. These solutions are of importance in developing various nuclear waste disposal sites in bedded salt and subseabed media. With pulse radiolysis, the relative importance of the actinides in solutions of interest will be determined.

2. Thermodynamic Stabilities

Attempts will be made to measure the redox potentials of actinide cations in various geologic media.

3. Complex Constants

Complex constants of formation of actinides with the anions Cl^-, CO_3^{2-}/HCO_3^- and SO_4^{2-} will be measured.

Contractor: BATTELLE MEMORIAL INSTITUTE
Pacific Northwest Laboratories
Richland, Washington 99352

Contract: EY-76-C-06-1830

Title: I. Remote Sensing/Geoscience Data Analysis Methodology

Persons in Charge: G. E. Wukelic and H. P. Foote

Scope of Work

The objective of this project is to conduct basic research in selected areas of remote sensing which are most relevant to the Department of Energy's objectives in geoscience. The effort emphasizes the development of advanced computer procedures for processing, integrating, displaying and using combinations of remote sensing, geophysical, and geologic data. This continuing project encompasses a combination of research activities including (a) updating and expanding the relevant digital data bases at Pacific Northwest Laboratories (PNL), (b) developing capabilities (software and hardware) for integrating and displaying remote sensing and geoscience data sets in common map formats and geographic projections, and (c) demonstrating the potential utility of the developed computer analysis programs to the Department of Energy's geoscience research and applications community.

A. Remote Sensing/Geoscience Data Base Expansion (H. P. Foote, S. C. Blair and G. E. Wukelic)

Each year, new data [National, regional and local (Hanford)] are acquired directly, in digital form or digitized as appropriate, to support the development and demonstration of interactive procedures for merging remote sensing and geoscience data sets. Current emphasis is on satellite data (e.g. Landsat multispectral scanner data); topographic data; and regional geologic, gravity, seismic, and magnetic data.

B. Software Development and Testing (H. P. Foote and S. C. Blair)

1. Remote Sensing/Geoscience Data Integration

This continuing activity involves the development of software for reformatting and geographically registering remote sensing and geoscience data sets, producing stereo pairs, and manipulating data for color display and product generation. Current emphasis is on developing and testing software to generate the following demonstration products:

- o Color-coded stereo topographic maps (where color corresponds to elevation and stereo parallax shows relief).
- o Color-coded stereo geologic map and topographic data (color for rock type and stereo parallax from topography).
- o Combined Landsat and topographic data (stereo image will show terrain contour and color will be Landsat composite).
- o Selected combinations of Landsat, topography, and geoscience (gravity, magnetic, or seismic) data.

2. Further Development of Software for Processing of Earthquake and Other Geophysical Data

PNL's graphic display and analytical capabilities for processing geophysical data are being extended and improved in the following ways:

- o A computer program is under development that will display crustal cross-sections. This type of display, when used with topographic, earthquake, and structural data, will aid in interpretating earthquake parameters and sources.
- o Preliminary software is being developed to display and analyze geophysical well-logging data. This will be the first step in development of a sophisticated interactive tool for quantitative analysis of geophysical well-logging data.
- o Maps of crustal seismic velocity structure for North America and for the Pacific Ocean are being integrated into PNL's system.

C. Utility Demonstration/Assessment (G. E. Wukelic, H. P. Foote, and S. C. Blair)

The basic requirement for this task is to develop and test advanced computer techniques for integrating and mapping remote sensing, geophysical, and geologic data. This task, however, also has the goal of producing sample products for evaluation by appropriate basic and applied research workers in the geosciences community. This potential interaction with geoscience users is being accomplished by a combination of personal communications, laboratory visits, and workshops.

Contractor: BATTELLE MEMORIAL INSTITUTE
Pacific Northwest Laboratories
Richland, Washington 99352

Contract: EY-76-C-06-1830

Title: II. Development and Operation of DOE Insolation-Aeronomy Observatory

Person in Charge: R. A. Stokes

Scope of Work

The insolation and aeronomy programs at Battelle-Pacific Northwest Laboratories (PNL), are concerned with measurement and characterization of ground-based solar flux (insolation) and nighttime upper-atmospheric optical emissions (auroras). The insolation program is directed toward high spectral resolution studies of direct and diffuse solar radiation and high spatial resolution measurements of the diffuse component of solar radiation. The information acquired has direct applicability to solar power site evaluations and to photovoltaic and photobiological programs. In addition, the program provides a basis for quantifying changes in insolation by clouds and aerosols.

As studies of insolation and auroral emissions share a common instrument and, to a certain extent, data handling techniques, much of the development of the two programs has proceeded in parallel. The aeronomy program focuses on use of nighttime optical emissions as a diagnostic tool for investigating the state of the upper atmosphere and the plasmasphere-magnetosphere interaction region. It is important to obtain an understanding of the Earth's magnetosphere because it not only influences radiation belts but helps protect the ozone layer and significantly affects radio communications. Furthermore, it has recently been suggested that a close but subtle relationship exists between the state of the magnetosphere and terrestrial weather.

A. Insolation Studies (J. J. Michalsky and E. W. Kleckner)

1. Analysis

Analysis of insolation data has proceeded at several levels. The fundamental objective is to provide carefully calibrated spectral data in the 300-1100 nm range to potential users. Data are to be archived at the National Climatic Center in Asheville, North Carolina. Direct solar measurements through seven filters are taken at five-minute intervals throughout each day, and total-sky scans are made every half hour. Routine data collection also includes high spatial resolution solar-zenith and solar-almucantar scans at half-hour intervals. On clear days, data provided by these latter

measurements, as well as direct measurements, are used to derive aerosol properties. These include average size, size distribution, index of refraction, and quantity.

2. Experiment

The principal goal is to measure and calibrate solar radiation, both direct and diffuse, at seven specific wavelengths. A mobile automatic scanning photometer (MASP) was developed for this purpose. It is capable of making nighttime observations as well.

The MASP system measures insolation in spectral bands centered at 395.0 nm, 470.0 nm, 570.0 nm, 680.0 nm, 785.0 nm, 900.0 nm and 1010.0 nm. The field of view of the solar photometer is 1.5°. Basic data yield both direct and diffuse measurements of radiation. The detection mode provides a basic stability in the measurement of ±2%. The instrument module is portable and suitable for remote siting.

B. Aeronomy (L. L. Smith and E. W. Kleckner)

1. Analysis

A recently completed analysis included correlating nights when satellite observations of plasma densities, temperatures, and spectral energies, obtained by the ISIS-II, AEC, AED and ESRO-4 satellites, were made simultaneously with ground measurements of auroral optical emissions obtained by the MASP units at PNL, Richland, Washington and at Hinsdale, Montana. A high spatial coincidence was found between the equatorward boundary of the diffuse 630.0 nm auroral emission as observed from the ground and the equatorward boundary of soft particle precipitation and the poleward cliff of the F region electron density trough as observed from satellites. If a diffuse aurora is indeed the ionospheric counterpart of the plasma sheet's earthward boundary, then the 630.0 nm diffuse boundary affords a means of monitoring convection characteristics of the spectrally soft, near-earth plasma sheet boundary over large spans of time and activity.

2. Observations

a. Battelle Observatory

Beginning in September 1967, all sky photometric observations of the emissions [OI] at 557.7 nm, N_2^+ at 427.8 nm and Hβ at 486.1 nm and continuums at 535.0, 608.0 and 715.0 nm have been taken routinely on all cloudless, moonless nights from PNL, Richland, Washing-

ton. The observing technique consists of scanning the night sky in a series of almucantars at elevations of 10°, 15°, 20°, 30°, and 50°. Since the photometric field of view is approximately 5°, these scans adequately cover the entire circle of view.

b. Global Program

Because most detailed investigations are done at single stations, understanding of emission patterns tends to be regional. Syntheses that might be provided by simultaneous global observations has been lacking. What is needed is a set of simple, reliable, identical optical instruments dispersed over the globe.

PNL scientists have developed an instrument called the mobile automatic scanning photometer (MASP) to obtain the necessary data. The same all-sky scanning technique used at Battelle Observatory is implemented on the MASP. The main thrust of the aeronomy observational program is siting, calibrating, and operating MASP units as part of the "Global Patterns" program. For this, four MASP units are now in operation, one each at Richland, Washington; Hinsdale, Montana; Boulder, Colorado; and Ft. Providence, Northwest Territories, Canada.

PNL is a member of the International Magnetospheric Study (IMS). Three MASP units have been constructed and installed for this program. They provide data from Iron Mountain, Michigan; Leduc, Alberta, Canada; and Albany, New York. Two additional units are to be constructed.

PNL reports its observations to the IMS data center in Boulder, Colorado and retrieves pertinent observations by other IMS members from this center.

C. Carbon Dioxide (G. M. Stokes and R. A. Stokes)

1. Background

The earth's atmosphere now contains 85 x 10^9 more metric tons of carbon, as CO_2, than in 1860. This is mostly as a result of burning fossil fuels. Because of the CO_2 content, the earth's average surface temperature is 35 K higher than the bolometric temperature observed from space.

For models that attempt to predict either the results of CO_2 increase or the exchange of CO_2 between various reservoirs, or both, an estimate of the "pre-industrial"

atmospheric carbon dioxide abundance is critical. The current program is designed to obtain a "pre-industrial" CO_2 abundance from a hitherto unexploited source of data, namely, measurements of the near infrared solar spectrum that have been accumulated for astronomical purposes since the mid-1890s.

2. Analysis

In the past year, research focused on evaluating the accuracy required of any technique designed to contribute to the historical study of the carbon cycle, organizing new and existing data for analysis, and determining carbon abundances. Accuracy requirements for carbon dioxide abundance studies were estimated in several ways. In particular, the annual variation in CO_2 concentration over and above any long-term change in CO_2 has been determined. At Mauna Loa, Hawaii, this variation amounts to approximately 1% of the total CO_2 abundance.

The first two areas of concern in analysis of data have been line identification and continuum placement. Using a line identification scheme contained in the REDUCER data reduction package developed by Kitt Peak National Observatory as a starting point, a method was developed that automatically gives the wavelengths of lines found in a digitized spectrum. This scheme is extremely important since the spectral region chosen for analysis, the 1,000 to 2,500 nm (1 to 2.5 micron) region, contains well in excess of 10,000 lines, more than 7,000 of which originate in the earth's atmosphere. The second step in analysis is placement of the solar spectral continuum which is the reference level against which the strength of telluric absorption lines is measured. The continuum placement scheme is being tested.

Contractor: BATTELLE MEMORIAL INSTITUTE
Pacific Northwest Laboratories
Richland, Washington 99352

Contract: EY-76-C-06-1830

Title: III. Mechanistic Studies of Trace Constituent Sorption and Migration in Geologic Media

Person in Charge: D. Rai

Scope of Work

The principal goal of this project is to develop a capability for predicting trace constituent sorption and migration in geologic media based on a physical understanding of rate, extent, and mechanisms of migration of selected elements in the earth's crust. Elements, trace metals, and nuclear waste products were chosen for this study because their migration behavior must be considered in resource exploration and development as well as in the environmental effects of waste disposal.

A. Structure and Mechanisms of Interaction of Transition Metal-Organic Complexes with Soil (L. Y. Martin)

The basic experimental approach involves preparation of metal-organic complexes and the subsequent use of these in batch and column experiments to determine their mechanisms of sorption.

Initially technetium (Tc) was selected for these experiments. Technetium is capable of exhibiting multiple oxidation states [Tc(-I) through (VII)] depending upon the chemical environment. All the states from Tc(I) through Tc(VII) are capable of undergoing complex formation with organics. Methods of preparing organic complexes (EDTA, DTPA, citrate) of Tc(III), Tc(IV), and Tc(V) were developed. Crystalline products of Tc organic complexes have been isolated and are being characterized. This includes determining formation constants for these complexes.

B. Investigation of Mechanisms that Control Concentration of Radionuclides in Geologic Solution (D. Rai and R. G. Strickert)

The goals are to determine the mechanisms and the effects of various factors (such as pH, Eh, complexing and competing ligands, tracer concentration, oxidation state of the element, solid phases etc.) in controlling the concentration of elements in solutions in equilibrium with different geomedia.

Initially plutonium (Pu) and americium (Am) were selected for these studies. Contaminated Hanford soils were used to determine the factors or mechanisms controlling the concentration of Pu and

Am in solutions contacting these soils. The concentrations of Pu in solutions equilibrated with these soils were found to be controlled by crystalline PuO_2. The concentration of Am in solutions appeared to be controlled by an Am solid phase. Although the nature of the Am solid phase is not known, it does have very low solubility ($\sim 10^{-11}$ M at pH 7). The results indicate that very high Am sorption (reported in literature) by different minerals is due to the precipitation of Am solid. In an effort to identify this Am solid, studies on the solubility of AmO_2 and $Am(OH)_3$ were initiated. Studies are also underway to further check the applicability of these mechanisms to other geomedia and environments.

Contractor: BATTELLE MEMORIAL INSTITUTE
Pacific Northwest Laboratories
Richland, Washington 99352

Contract: EY-76-C-06-1930

Title: IV. Chemical Migration by Contact Metamorphism in Granite-Carbonate Rocks

Person in Charge: J. C. Laul

Scope of Work

The main objective of this project is to study the migration of major, minor, and, in particular, trace elements during contact metamorphism between granite and carbonate rocks. Specific emphasis will be on the rare earth elements and barium (Ba), strontium (Sr), rubidium (Rb), cesium (Cs), zirconium (Zr), hafnium (Hf), nickel (Ni), thorium (Th) and uranium (U). A study of these trace elements can provide an understanding of and a basis for predicting the long-term (10^3 - 10^7 years) behavior and movement of their analogs, fission products, activation products, and transuranic elements in nuclear waste in a geological confinement.

The geological site under study is the Notch Peak intrusion near Delta in western Utah. The porphyritic quarz monzonite was emplaced in a Cambrian limestone and shaly limestones interbedded with argillaceous layers. The Notch Peak granite intrusion discordantly intersects nearly all depositional environments of a carbonate platform edge and outer shelf of Cambrian age. Outcrops for sampling from the metamorphosed and unmetamorphosed areas are excellent. Appropriate samples of carbonates ranging from highly metamorphosed to unmetamorphosed have been collected from different locations along horizontal and vertical traverses away from the granite intrusion.

A comparison of trace element signatures in metamorphosed and unmetamorphosed samples from granite and carbonate zones should reveal the degree and importance of transport of various elements. It should also disclose any chemical fractionation and partitioning trends among minerals. This research is directly aimed at predicting the movement, under different physical and chemical conditions, of high level radioactive waste in geological confinements when the burial container fails. This study is in collaboration with J. J. Papike of the State University of New York, Stony Brook, N. Y. (see p. 78), who will obtain petrographic, petrologic and some chemical information by X-ray fluorescence spectroscopy (XRF) on the same samples. Chemical information on some 30 major, minor and trace elements will be obtained by instrumental and radiochemical neutron activation analysis (INAA and RNAA). Preliminary results do show evidence of migration of trace elements from the granite into the carbonate zones.

Contractor: LAWRENCE BERKELEY LABORATORY
University of California
Berkeley, California 94720

Contract: W-7405-ENG-48

Title: I. Geosciences Program

Person in Charge: P. A. Witherspoon

Scope of Work

The Geosciences Program at Lawrence Berkeley Laboratory (LBL) consists of ten projects. These projects are broadly based fundamental studies that support development of geothermal energy, hot water energy storage, stimulated recovery of oil, isolation of radioactive wastes, and uranium resource evaluation and recovery. Studies include formulation of theoretical concepts, development of new instrumentation, the execution of experimental measurements in the laboratory and field, and simulation of processes using computer models.

A. Non-Isothermal Reservoir Dynamics (P. A. Witherspoon and C. F. Tsang)

This project encompasses a wide range of fundamental studies related to the development of geothermal energy, thermal energy storage in aquifers, and geologic isolation of nuclear wastes. The objective is to obtain a better understanding of various underlying physical and/or chemical processes and their effects through analytic studies and numerical modeling.

1. Reservoir Dynamics Related to Thermal Energy Storage

The possibility of storing hot or cold water in aquifers has attracted considerable attention during the last few years. The goal is to store large amounts of heated or chilled water in a confined aquifer and at a later time to recover the water for space heating or cooling. Through previous work at LBL and elsewhere, the feasibility of this concept was established and there is currently worldwide interest in carrying out demonstration experiments to test it.

A number of key problems yet remain to be studied which would define the best operating conditions and parameters, and optimize the storage-recovery ratio. One of these is thermal buoyancy flow where, because of the difference in density and viscosity of waters with different temperatures, hot water tends to flow to the top of cold water. This induces mixing, resulting in heat dissipation that decreases the energy recovery ratio. This process is being analyzed in detail both analytically and numerically.

2. Reservoir Dynamics Related to Geothermal Energy Development

Most reservoir engineering and well testing experience has been in the hydrology and petroleum engineering fields where isothermal conditions are usually assumed. The presence of non-isothermal fluid flow in a geothermal reservoir introduces a number of interesting problems.

A study is being made to understand the behavior of reservoir pressure and temperature when a doublet of one production and one injection well is present, with the injection well being used for injecting colder water. Another study on single-well cold water injection pressure transient effects is being extended. Earlier calculations assumed that the transition in temperature between the injected cold water and native hot water zones could be represented by a Fermi-Dirac distribution function. Updated work will take into account cases in which a step function or a trapezodial function will simulate this transition region.

3. Reservoir Dynamics Related to Nuclear Waste Storage

Heat released by the radioactive decay of nuclear wastes in an underground repository causes a long-term thermal disturbance in the fluid flow in the fractured rock mass in which the repository is situated. Studies in regional thermally induced convection around and above the repository in the rock mass are being made.

B. Properties and Behavior of Rock-Fluid Systems (W. H. Somerton)

The physical properties and behavior of fluid saturated reservoir rocks are highly dependent on environmental conditions. Thus the depth, temperature, stresses, pore fluid pressure, and the nature and amounts of fluid saturants are all variables that must be considered in relating surface-measured properties to subsurface conditions. The properties of importance in subsurface applications include fluid flow and storage capacity, geophysical data such as electrical properties and wave velocities, thermal properties, and deformational characteristics such as pore and bulk compressibilities and thermal expansions.

In the present work, methods and equipment have been developed to measure the above properties under simulated environmental conditions. A new apparatus nearing completion will permit simultaneous (or sequential) measurement of these properties on the same test specimen under the same environmental conditions. Data so generated will be used to test and further develop existing models. This will make possible the prediction of physical properties from the basic characteristics of the rock-fluid system and will further

provide a method of prognosticating changes in physical behavior as environmental conditions are changed.

Results of this work will have broad applications. Studies of the mechanics of oil and gas production in primary and enhanced recovery phases, geothermal reservoir engineering, and analyses of underground nuclear waste disposal are but some of the important applications of these data.

C. Thermodynamics of High Temperature Brines (K. S. Pitzer)

Theoretical and experimental studies of solution thermodynamics of strong aqueous electrolytes over a wide temperature range provide essential information for technical utilization of many geothermal resources. Theoretical work has successfully dealt with complex mixtures at room temperature, simple systems over wide temperatures, moderately weak electrolytes involving dissociation equilibria and moderately soluble electrolytes. Work will continue using existing volumetric and thermodynamic data for modeling. A recently constructed flow calorimeter and densimeter are yielding heat capacities and densities up to about 300°C and 100 MPa on systems previously unreported. In addition, existing data are being extended to higher temperatures and pressures. Results will be integrated with theoretical work to develop equations allowing prediction of properties at temperatures and compositions other than those measured.

After present tests with aqueous solutions of sodium chloride (NaCl) have been completed, measurements will proceed to other pure components important in geothermal fluids, including sodium sulfate (Na_2SO_4), magnesium sulfate ($MgSO_4$), and then mixtures. The important parameters in modeling equations will be determined over the range to 300°C and 100 MPa and the accuracy of these equations for mixed electrolytes will be verified. The resulting equations will provide thermodynamic properties of geothermal brines as well as predictions of phase equilibria. These are needed inputs for engineering geothermal resources.

D. Rock-Water Interactions (J. A. Apps)

This project is designed to elucidate the chemical reactions that occur between common rock-forming minerals and the aqueous phase under subsurface conditions. The results will help determine the mechanisms responsible for chemical changes in rocks saturated with groundwater, particularly with regard to processes operating in geothermal reservoirs and during the mass transport of radionuclides in water-saturated rocks.

In order to accomplish these objectives, the rates of dissolution and precipitation of common rock-forming minerals are measured

at temperatures between 25° and 400°C and at pressures between 0.1 and 50 MPa. This information is used to test and refine codes modeling rock-water interactions and will eventually be used to assess the effect of such interactions on rock and groundwater composition.

The first phase of the project involves measurement of the solubility of low albite as a function of temperature and solution composition. Once it is established that true equilibrium values are being measured, albite solubility as a function of pressure as well as temperature and solution composition will be determined.

Other common rock-forming minerals for analogous solubility studies are chlorite, tremolite and epidote. The data from these solubility studies will be evaluated in a similar manner to those of albite.

E. Thermodynamic Properties of Silicate Liquids (I.S.E. Carmichael)

This project is designed to investigate the properties of silicate liquids over a range of compositions found to occur naturally. Measurements of density as a function of temperature (1000-1600°C) have allowed partial molar volumes of eight oxide components to be calculated, and these values give excellent agreement with values measured on natural liquids. Within the temperature and compositional span of the experimental data, silicate liquids mix ideally with respect to volume.

The volume measurements, in conjunction with previous measurements of the heat capacities of silicate liquids, have been used to derive a simple solution model for liquids covering the range found on Earth and on the moon, using experimental solid-liquid equilibria. Equilibration temperatures, immiscibility and partial molar free energies predicted by the model are in accord with observations of these properties.

The heats of fusion at 1 bar have been measured for the compounds $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$ (the end members of the plagioclase group), two of the most prominent components in the rock-forming minerals. This work is being extended to include all accessible heats of fusion of the common rock-forming minerals, as so few data of this type exist.

The first measurements of the adiabatic compressibility of silicate liquids have been made, and these will be extended in temperature and composition. The eventual goal is to obtain partial molar isothermal compressibilities of the common oxide components.

F. Chemical Transport in Natural Systems (C. L. Carnahan)

This program is directed toward development of conceptual models of solute transport in natural flow systems using chemical reactions which are based on thermodynamic concepts applicable to irreversible (or non-equilibrium) processes. Such concepts include the use of the gradient of a thermodynamic potential as the driving force for diffusive transport of a solute, and the use of the thermodynamic affinity (a linear function of chemical potentials) as the driving force for a chemical reaction. Theoretical studies of steady-state systems have been made first because the thermodynamic concepts can be used while preserving linearity in the governing equations. More important is that steady-state non-equilibrium systems (which are necessarily open) possess a minimum property that is potentially useful in their analysis, i.e., in such systems, the rate of production of entropy by irreversible processes achieves a minimum (non-zero) value. Application of this property to analysis of open, steady-state systems is, therefore, being investigated.

Following the studies of steady-state systems, the thermodynamic concepts are to be extended to time-dependent systems. In this case, the non-linear relationship between the mass concentration and the chemical potential of a solute will render the equations of transport non-linear. Algorithms for numerical simulation of transport with time dependence are to be developed. Initially, this phase of the work would be restricted to consideration of a small number of components and reactions. Later studies would attempt to extend computational abilities to a larger number of constituents and to include consideration of thermodynamic coupling among vectorial processes.

Concurrently with the theoretical studies, experimental studies of the sorption of cesium ions and uranyl ions on the surfaces of a smectite clay and on silica are being conducted. The objectives of these studies are the determination of thermodynamic properties of sorption processes and the evaluation of the significance of kinetic effects during sorption.

G. Aqueous Solutions Data Base (S. L. Phillips)

This project provides a single comprehensive, computerized data base consisting of the basic properties of aqueous solutions involved in geothermal energy. The compilation, which includes critical evaluation and correlation, constitutes a source of recommended values to be used in research and development for both power production and direct utilization. The results of this work are mainly of two kinds:

(1) Tables of smoothed values generated from correlation equations using computer-assisted methods. The skeleton tables cover the temperature, pressure, and concentration ranges of interest.

(2) Reviews of the current status of data, including comprehensive and in-depth references to available data. The references are mainly in the form of an indexed and annotated bibliography.

Another result of this project is identification of areas where data are either lacking or inadequate, leading to recommendations for research designed to provide the needed data. Enthalpy, heat capacity, viscosity, thermal conductivity, solubility, density, and electrical conductivity are tabulated to 350°C, 50 MPa, and saturation concentration. The primary emphasis has been on the study of sodium chloride properties, but other important solids and gases, such as calcium and potassium chloride, and hydrogen sulfide are also being considered.

H. Feasibility of Shear Wave Vibrators for Deep Crustal Studies in Geothermal Environments (S. Coen and H. F. Morrison)

The use of horizontally polarized shear wave sources to detect the low shear rigidity zones characteristic of a geothermal resource has been studied with a time domain, finite element program, a frequency domain, integral equation program, and an analytical solution for the radiation pattern and radiation impedance of a torsional shear wave vibrator.

Because of the energy limitations imposed upon vibratory shear wave sources, the effectiveness of beam forming with phased source arrays has been studied as a means of enhancing the detectability of low shear rigidity zones.

The radiation pattern and radiation impedance of a torsional vibrator are being formulated as an integral equation to permit description of a more general stress distribution between the source plate and the earth's surface. The integral equation method is being extended to include the scattering of coupled compressional and vertically polarized shear waves in two dimensions as a step toward implementing the integral equation method for the scattering of elastic waves in three dimensions.

I. Deep Electromagnetic Sounding of the Crust (H. F. Morrison)

Controlled-source electromagnetic sounding of the earth's crust to depths of 20 km in Nevada are to be made using a system developed by the Lawrence Berkeley Laboratory. The system operates over a range of loop current frequencies between 0.02 and 100 Hz.

The results will be compared with results from magnetotelluric soundings in the same area in an attempt to verify the existence of the low resistivity zone in the deep crust beneath the Basin and Range province. There is considerable debate about this zone. One interpretation is that it is only an artifact of some other effect that influences magnetotelluric interpretations.

Initial tests will be made to concentrate on the feasibility of using widely spaced transmitter-receiver stations with a distant reference magnetometer for cancellation of low frequency natural (geomagnetic) noise. All stations will be linked to a microprocessor receiver in the field by rented telephone lines or FM radio telemating or both.

Contractor: LAWRENCE BERKELEY LABORATORY
University of California
Berkeley, California 94720

Contract: W-7405-ENG-48

Title: II. Continental Scientific Drilling Program: Geothermal Fluids

Person in Charge: P. A. Witherspoon

Scope of Work

A. Geothermal Fluids (A. F. White)

The specific objective of the Department of Energy in the Continental Scientific Drilling Program is to obtain a better understanding of thermal regimes and hydrothermal magma systems. The first phase of the program deals principally with constituting and organizing the Interlaboratory Working Group (IWG), composed of personnel from Lawrence Berkeley, Lawrence Livermore, Los Alamos Scientific, and Sandia Laboratories. The group is conducting a comparative site assessment of the most promising thermal regimes, including the Geysers, Long Valley, and Salton Trough in California; Roosevelt Hot Springs, Utah; and the Rio Grande rift zone in New Mexico. The assessment will identify a site suitable for drilling deep into a hydrothermal regime. Broader objectives of the IWG are: (a) identification and evaluation of the scientific questions that can be optimally addressed at each site; (b) collection, evaluation, and interpretation of available geologic, geochemical, and geophysical data at each site; and (c) identification and evaluation of the intensity and type of drilling in progress or planned at each site for other purposes and to recommend possible add-on experiments and studies.

B. Geochemistry Subgroup (A. F. White)

LBL is chairing the geochemistry subgroup in the IWG and is providing members to the geology, geophysics, and modeling subgroups. An initial report has been completed by the IWG listing the specific wells at each site that could be employed for add-on experiments and the types of questions that could be answered. LBL provided input for the Geysers geothermal area in this report and will coordinate the writing of the geochemical section of the "Comparative Site Assessment Review Document" to be completed by the IWG by the end of FY 1980.

Contractor: LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California
Livermore, California 94550

Title: I. Geosciences

Contract: W-7405-ENG-48

Person in Charge: R. N. Schock

Scope of Work

Geosciences at Lawrence Livermore National Laboratory (LLNL) is organized to study physical and chemical properties and responses of earth materials that are important to Department of Energy programs and initiatives. All of these efforts make use of experimental work, novel diagnostic techniques and computer modeling. The common objective of this integrated program, from a scientific viewpoint, is to develop models that can be used to predict and understand the behavior of the earth, both near- and far-field.

The current effort is divided among studies of (a) basic rock mechanics, (b) determination of seismic Q (attenuation factor) with depth in the earth, (c) kinetics and transport in aqueous solutions, (d) information dissemination and data management of Department of Energy drilling activities, (e) participation in the planning of the Department of Energy contribution to a national Continental Scientific Drilling Program, (f) studies of the diffusivities of atoms in minerals and (g) development of laboratory, field, and computational tools to utilize remote sensing techniques for inferring geophysical parameters so as to achieve the capability of imaging geologic structures underground.

A. Basic Rock Mechanics (F. Heuze)

Basic rock mechanics studies incorporate both experimental and computational work aimed at understanding how rocks and rock masses respond to an imposed mechanical or thermal load.

1. Discrete-Interacting Blocks Computer Model (O. Walton)

A computer program to model discrete interacting blocks has been developed, and an oil-shale retort block-motion during slumping has been simulated. This has been compared to model simulations with several simple mechanical experiments involving toppling and sliding blocks. The code is presently being modified to allow calculation of thermally generated deformation of an underground nuclear waste repository in jointed rock.

2. Ultrasonic Analysis of Crack Structures (F. Sears)

A state-of-the-art digital ultrasonic acquisition system has been developed to measure attenuation using amplitude degradation, pulse broadening, and spectral amplitude ratios. P- and S-wave attenuation is being evaluated in dry, polycrystalline sodium chloride from Avery Island, Louisiana. Controlled heat treatment is used to induce thermal cracking for variation of crack density. The attenuation dependence on frequency is being studied in the range from 0.1 to 10.0 MHz. Test samples are 14.3 cm in diameter by 4.3 cm long with an average grain size of 0.5 cm. The large grain size allows study of the attenuation characteristics where the wavelength is much greater than, equal to, and much smaller than the average grain size.

B. Determination of Seismic Q with Depth (J. M. Mills)

A unique suite of seismic and geologic data gathered through the LLNL seismic net is being used to calculate interval velocity and seismic Q between reflectors in the earth's mantle within the Basin and Range province. This will allow detailed knowledge of a particularly interesting part of the upper mantle, from the viewpoint of plate tectonics as applied to North America. The information gained is also particularly relevant to treaty verification associated with foreign nuclear testing.

C. Thermodynamics, Kinetics and Transport in Aqueous Electrolyte Solutions (D. G. Miller and T. J. Wolery)

The major goal of this project is to help understand the mechanism and kinetics of selected geochemical processes, especially those involving the isolation of radioactive wastes. To accomplish this, diffusion and osmotic coefficients of certain electrolyte solutions are being measured, and computer equilibrium codes to predict speciation, solubility, and reactions in various mineral-solution systems are being developed.

D. Diffusion in Earth Materials (R. H. Condit and A. J. Piwinskii)

A novel technique of radiotracer diffusion, developed by staff at the LLNL, is being used to study ionic diffusivity in silicate minerals relevant to processes in the earth's crust and mantle. Rare, but stable, isotopes are used in diffusion experiments and are then made selectively radioactive afterward. Oxygen-18 is made radioactive by ion bombardment to produce fluorine-18 (half life = 1.8 h). Autoradiography is used to locate the tracer and measure concentrations. Silicon-30 will be used in a similar manner. Measurements on olivine, a major mantle constituent that has been relatively well characterized, have

begun. Studies will then be extended to pyroxenes, feldspars, and other minerals. These measurements are concerned first with single crystal diffusion, then with grain boundary and interface diffusion, and finally with liquid-solid interface problems of material transport.

E. Underground Imaging (A. G. Duba and R. J. Lytle)

The thrust of the underground imaging effort is development of geophysical data collection methods, data processing procedures, integrated data interpretation techniques and enhancement of data presentation. These efforts are directed toward providing an enhanced diagnostic capability for characterizing the subsurface environment.

Development work now underway includes building and testing automated instrumentation for a non-invasive impedance camera and a laboratory system for the experimental determination of material properties (e.g., electrical, seismic, fluid flow, electrokinetic potential) of core samples over a pressure range of 0.1 to 400 MPa and a temperature range of 25 to 300°C.

Contractor: LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California
Livermore, California 94550

Contract: W-7405-ENG-48

Title: II. Continental Scientific Drilling Program: Data Management and Site Assessment

Person in Charge: R. N. Schock

Scope of Work

Lawrence Livermore Laboratory's involvement in the Continental Scientific Drilling Program (CSDP) consists of two components: (a) a service role in information and data management for the entire program and (b) comparative site selection.

A. Information and Data Management (N. W. Howard)

The information and data management project provides data bank and information services for the CSDP program. It includes: (a) subsurface data from programmatic drilling by federal agencies and new wells drilled by industry that offer opportunity for cooperative efforts and (b) a computerized data bank for drill hole data acquired in CSDP projects. Information can be disseminated to the scientific community on plans and drilling activities.

B. Comparative Site Assessment (D. O. Emerson)

LLNL is participating in a comparative site assessment of areas in which drill hole studies would expand the fundamental understanding of magma-hydrothermal systems by obtaining samples and data and by conducting down-hole experiments. The rationale and scientific basis for this endeavor has been presented in the National Academy of Sciences/National Research Council (NAS/NRC) Workshop Report on CSDP (1979).

Given the large fixed costs associated with drilling and the need to extract the maximum amount of scientific information and data from samples and down-hole experiments in each drill hole, sites must be assessed and compared for maximum scientific values.

Five promising sites have been identified. These sites are: (a) The Salton Trough, California; (b) The Rio Grande rift zone, New Mexico; (c) The Geysers, California; (d) Long Valley, California and (e) Roosevelt Hot Springs, Utah.

Contractor: LOS ALAMOS SCIENTIFIC LABORATORY
University of California
Los Alamos, New Mexico 87545

Contract: W-7405-ENG-36

Title: I. Geology/Geophysics

Person in Charge: R. E. Riecker

Scope of Work

Multidisciplinary geology and geophysics basic research at Los Alamos Scientific Laboratory (LASL) advances the fundamental understanding required for nuclear waste isolation, geothermal energy exploration and development, and coal use. Waste isolation studies provide rock models to evaluate long-term stability and integrity of repositories. Geothermal research focuses on understanding structure, tectonics, and evolution of potential geothermal resources and properties of reservoirs. Coal work concerns characterization of accessory minerals and determination of occurrence and distribution of minor and trace elements, especially sulfur. Rock physics research supports engineering of waste isolation facilities by exploring the brittle-ductile transition in granite, basalt, and tuff and by determining effects of water on ductile and brittle deformation of silicates. Geothermal support includes seismic profiling, radioactive heat transfer measurements, numerical modeling, field geology, trace elements, and isotopic analyses of geothermal waters as well as electron microprobe, x-ray diffraction, and petrographic examinations of deep hole rock samples. Minor and trace accessory phases in coal are studied by electron microanalysis, x-ray diffraction, and petrographic techniques.

A. Thermal Regimes of the Jemez Lineament and the Northern Rio Grande Rift (F. Goff)

Research on magmatic and hydrothermal systems, tectonic settings, and heat transport models is being pursued. Basic data still need to be acquired on volume, composition and ages of magmatism and hydrothermal fluids, and on tectonic evolution of various areas of the Jemez lineament and the Rio Grande rift.

Petrologic and geochemical research is being performed on the Lucero, Zuni, and Mt. Taylor volcanic fields, which occur along the Jemez lineament or parallel structures transecting the Rio Grande rift. Basalts in these fields reside in an area of exceptional geothermal resource potential. Petrologic research on selected samples from key basaltic units focuses on: (a) origin and source conditions (depth, temperature, total pressure, water pressure, etc.) of these magmas, (b) petrologic and chemical evolution, and (c) crustal residence history, including crustal interactions and eruption history.

This information is integrated with on-going geothermal, gravity, magnetotelluric, tectonic, and thermomechanical investigations at LASL.

Thick accumulations of Neogene sediments in the Espanola basin are also being studied to unravel tectonic history of the Rio Grande rift. Sedimentary petrology and facies mapping is used to model basin development. In addition, geomorphic surfaces are being investigated to estimate relative rates of uplift. These data are used in numerical thermal models of rift valley evolution.

Geochemistry and geology of three active hydrothermal systems within the Rio Grande rift at Valles Caldera, Ojo Caliente, and Lucero uplift are being investigated. The goal is to catalog various water types for each system, discover how geology and structure affect chemical composition and "plumbing," evaluate geothermal potential, and speculate on their evolution.

Thermomechanical models of the dynamic structure of continental rifts presently incorporate creep theory for subsolidus flow and are constrained by petrologic, seismic, and heat flow data. Additional theory for latent heat of fusion and phase changes has been incorporated to study magma convection and thermal stress regimes of the earth's crust. Models are compared with previous studies on origin, source conditions, evolution and magmatic history using petrology, volcanology, and rock physics. Resulting studies provide a better assessment of energy budgets associated with geothermal resources.

1. Petrologic and Geochemical Investigation of Lucero, Zuni and Mt. Taylor Volcanic Fields (W. S. Baldridge, B. Crowe A. W. Laughlin and D. Vaniman)

   The geology, petrology, and geochemistry of the Mt. Taylor, Zuni, and Lucero volcanic fields are being studied. Research focuses on the origin of magmas, their residence in the crust, and their effect on the hydrologic regime. It enhances the ability to explain observed geophysical anomalies. Ultimately this work will lead to an understanding of the underlying control exerted by these transverse fracture zones, their persistence through time and their effect on the rift.

2. Tectonic Evolution of the Central Espanola Basin (C. Potzick)

   The detailed Neogene geologic history of the Espanola Basin is being investigated. Sedimentary facies mapping and sedimentary petrology are used to model tectonic development. Petrologic analyses yield diagenetic information on the thermal history of sediments. These histories constrain numerical models of mechanical and thermal evolution of rift valleys.

3. Active Hydrothermal Systems (F. Goff, J. Gardner, R. Vidale)

Detailed geochemical and geologic characteristics of three geothermal systems of the northern Rio Grande rift at Valles Caldera, Ojo Caliente and the Lucero volcanic field are being investigated. Each system possesses many thermal/mineral waters, but they display widely divergent discharge temperatures, concentrations of dissolved solids, and geologic settings. No integrated investigation has been performed on any of these systems.

Valles Caldera contains many hot springs of varying types and is currently being explored for high temperature conventional and hot dry rock geothermal resources. The system at Ojo Caliente is of moderate temperature and concentration (about 2,000 mg/l of total dissolved solids) and may offer potential for space heating and agricultural uses. Waters of the Lucero volcanic field are concentrated but discharge at low temperature. Their existence is not understood.

New research was initiated at Ojo Caliente and the Lucero uplift. Its goals are to (a) collect thermal and non-thermal waters for chemical and isotopic analysis; (b) map local geologic and tectonic features crucial to hydrology; (c) integrate and model resulting geologic, geochemical and (where appropriate) existing geophysical data, and (d) evaluate the geothermal potential of each system.

4. Thermomechanical Models of Magmatism Under Continental Rifts (J. Bridwell)

An advanced finite element code (SANGRE) is being developed and is partially supported by the Office of Basic Energy Sciences. The model is designed to better understand the Rio Grande rift in three dimensions and to help interpret its evolution through geologic time. Thermodynamic relations are being added to SANGRE to study phase changes, melting, and evolution of the thermal energy budget associated with formation of a continental rift such as the Rio Grande rift.

B. Rock Physics (J. D. Blacic, P. M. Halleck, T. N. Dey and T. J. Shankland)

Thermal regimes, including rifts whose geological and geophysical studies are treated in Part A, are also regions of substantial tectonic interest. Understanding how to couple tectonic forces with thermal regimes requires a knowledge of the rocks, minerals and magmas that transmit stress and heat. LASL rock physics research focuses on providing part of the quantitative physical basis for this coupling.

Two research tasks are concerned with mechanical strength. One deals with the brittle-ductile transition in mafic rocks that comprise much of the lower crust. In this regime tectonic stresses can cause either plastic deformation or brittle fracture, depending on stress magnitude, local temperature, and water content. Much geology, from slow flow to earthquakes, takes place in this regime. The other task concerns theoretical and experimental studies of tensile fracture mechanisms. Research focuses on crack surface energies and processes occurring at a crack tip.

Inasmuch as heat transport is at the heart of thermal studies, a third task deals with radiative thermal conductivity, a process that is surprisingly important in crustal magma chambers. In some regions of magmatic intrusion fluid pressure exceeds at least one component of the local stress. The fourth task treats this condition of negative effective pressure (pore pressure greater than confining pressure) using water as the pore fluid.

Research in rock properties ranges from physical properties of separate rocks to properties of component minerals and glasses. Due to the fact that more than apparent rock strength is involved, the term rock "physics" rather than just "mechanics" is used. While each task finds its source and principal application in a particular Department of Energy program, each is basic research in that it expands the understanding of rock behavior.

1. Radiative Heat Transfer in Minerals, Glasses and Melts (T. J. Shankland)

   The contribution to total thermal conductivity from the radiative component in a variety of rocks and minerals, pertinent to geothermal and waste isolation technology needs, is being determined. Radiative thermal conductivity is calculated as a function of temperature from measured optical adsorption spectra taken at temperatures up to 1500°C in a controlled atmosphere.

2. Mechanical Properties of Rock Under Negative Effective Confining Pressures (T. J. Shankland and P. M. Halleck)

   Elastic properties of rocks, when the pore fluid pressure exceeds the confining pressure, are measured in the laboratory. This condition is a new departure in rock physics. Although unusual in nature, the condition of negative effective confining pressure occurs frequently when drill holes are overpressured during hydrofracture or during energy extraction from a man-made geothermal reservoir.

3. Brittle-Ductile Transition in Mafic Rocks (J. D. Blacic)

The brittle-to-ductile transitions of selected mafic rocks, especially basalt, are being studied in the laboratory. This research is accomplished through deformation experiments over a wide range of temperatures, confining pressures, stresses, and strain rates in order to understand how rocks behave in this transitional deformation realm. Observations of mechanisms of deformation, with particular emphasis on effects of water, contribute to the analytical evaluation of the results.

4. Micromechanics of Tensile Fracture of Rocks (T. N. Dey)

The micromechanics of tensile fracturing is being studied. The interaction of microcracks near the tip of a much larger tensile fracture is analyzed theoretically to determine the effects of stress heterogeneity on crack growth. Experimental research is also being performed on the variation of fracture surface energies as a function of confining pressure to gain additional insight into the processes occurring near a crack tip.

Tensile fracturing of rock is important to numerous energy technologies. Hydraulic fracturing is necessary before heat recovery is possible in geothermal projects. Thermally induced fracturing has implications in determining the lifetime and economics of a geothermal reservoir. Tensile fracturing of surrounding rock must be considered in nuclear waste disposal and in mining.

Prediction of the behavior of fractures is based on laboratory measurements made on relatively small samples subjected to conditions of temperature, loading rate and confining pressure which may be much different from those in the field. A better understanding of the nature of a tensile fracture in rock, especially with regard to processes occurring near the crack tip, aids in extrapolating laboratory data to field conditions.

Theoretical work focuses on assessing the importance of stress inhomogeneities and the interaction among microcracks near the tip of a much larger crack. Experimental results test the predictions of the theoretical work. Furthermore, experimental data provides a means of testing the range of applicability of existing data on critical stress intensity factors and surface energies of rocks.

C. Seismic Research in Northern New Mexico (K. H. Olsen)

It is the objective of this research to analyze seismic data, collected by LASL's northern New Mexico seismic net and by the cooperating central New Mexico net operated by the Albuquerque Seismological Laboratory (ASL), to investigate geodynamics of the rift where several major tectonic regions (Colorado Plateau, Basin and Range; Rio Grande rift; and Southern Rockies and Great Plains stable area) intersect.

Lateral variations in crustal structure, seismic wave propagation and attenuation and their relationships to the major geothermal regimes of northern New Mexico are being investigated. This is accomplished by analyzing data on local and near-regional earthquakes and mine blasts recorded since 1972 by a network of seismic stations operated by Los Alamos Scientific Laboratory and the U.S. Geological Survey in the region. Analysis at LASL is facilitated by improved computer codes for hypocenter determination, synthetic seismogram modeling and focal mechanism determination.

D. Organic Sulfur in Coal (R. Raymond, R. Gooley and T. Davies)

Sulfur in peats is being studied by means of an integrated three-phase program: (a) electron probe microanalysis, scanning electron microscopy and bulk chemical analysis to characterize sulfur occurrence and distribution; (b) establishment of the significance of particular coal precursor plant tissues with regard to sulfur abundances and (c) determination of the relationships between modes of sulfur occurrence and various peat types.

The research provides a wide range of important information. First, the amount of sulfur in peats from a variety of environments is determined. Second, sulfur concentrations of various plant organs, tissues and cell inclusions (such as resins) important to peat formation is established. Third, concentration and forms of sulfur occurrence with specific environments of deposition are correlated.

Contractor: LOS ALAMOS SCIENTIFIC LABORATORY
University of California
Los Alamos, New Mexico 87545

Contract: W-7405-ENG-36

Title: II. Geochemistry

Person in Charge: R. Vidale

Scope of Work

The geochemistry program includes: (a) rock-water interaction in geothermal systems; (b) thermochemical measurements that are needed to permit modeling of rock-water interaction; (c) geochemical calculations; (d) production of well-characterized synthetic minerals and mineral assemblages and (e) studies of element migration and fixation in crustal rocks.

These studies have application to: (a) the efficiency of energy extraction in geothermal systems, (b) the isolation of hazardous chemical and radioactive waste from the biosphere in geologic repositories, (c) the migration and concentration of elements within the earth's crust and (d) the modeling of chemical and energy transport systems.

A. Rock-Water Interaction in Geothermal Systems (R. Vidale and R. Charles)

Experimental, analytical and theoretical studies are being conducted on reactions between rock and aqueous solutions at high temperature and pressure in closed reaction vessels and in circulation loops. The circulation loops include both hot rock reservoirs and cool heat exchangers. One loop provides a controlled temperature gradient within the hot rock reservoir. Rock alteration, scaling and solution composition (major, minor and trace elements) are monitored during eight-month runs.

The sodium-potassium-calcium (Na-K-Ca) geothermometer has been equilibrated in the circulating systems at 200°C and 300°C. Longer-term experiments in static and rocking vessels are underway to determine the buffering of mineral assemblages and their temperature range of stability.

B. Thermochemical Measurements (C. Holley)

A molten oxide calorimeter has been constructed and is being calibrated. The laboratory is equipped to determine heats of solution for materials (such as the alkali oxides) that are corrosive, hygroscopic or otherwise difficult to handle in existing laboratory thermochemical facilities.

C. Geochemical Calculations (C. Herrick)

Two computer codes are used at LASL to simulate geochemical reactions. The first models an irreversible dissolution, followed by a series of partial equilibrium calculations, along the reaction coordinate. As the rock-fluid interaction attains equilibrium, it settles into a steady state or the rock (mineral assemblage) dissolves completely. The second approach computes the final equilibrium mineral assemblage based on the initial component states and assigned thermodynamic parameters without regard for the reactions taking place along the reaction coordinate.

Finite element codes are employed to analyze the high-pressure apparatus required in synthetic mineral preparations and will be used to interpret observations in thermal and chemical gradients.

D. Synthetic Minerals (C. Herrick)

Synthetic minerals and mineral assemblages are prepared using chemical, ceramic and metallurgical techniques. These techniques include calcining, sintering, hot pressing, organometallic reactions, gels and fusion. Fusing oxide components by direct high-frequency energy absorption (skull melting) is proving to be the most versatile approach. This "cruciblelessness" technique yields single crystals, pure minerals, mineral assemblages, and reaction interfaces. The method seems to have no temperature and few chemical reaction constraints.

E. Element Migration and Fixation in Crustal Rocks (R. Vidale and C. Duffy)

The general approach being taken in these studies is determination of: (a) the exact location of trace elements of interest within specific crustal rocks, (b) the processes that remove the elements from the source material, (c) the mechanisms of transport in aqueous solutions and (d) the fixation processes that precipitate them in a new environment. The experiments are being run in hydrothermal rocking vessels and in controlled temperature and pressure circulating systems.

Contractor: LOS ALAMOS SCIENTIFIC LABORATORY
University of California
Los Alamos, New Mexico 87545

Contract: W-7405-ENG-36

Title: III. Solar-Terrestrial Physics

Person in Charge: G. A. Keyworth

Scope of Work

The solar wind and magnetospheric plasmas are the media through which solar-generated disturbances propagate and in which steady-state solar wind convection energy is stored and subsequently released to the auroral ionospheres, thereby coupling the near-earth environment to solar variations. The scope of this project is to analyze and interpret existing satellite data to yield information and an understanding of: (a) physical mechanisms and long-term effects of sun-earth coupling through the solar wind, (b) processes that determine heavy ion abundances and charge states in the solar wind, (c) sources of free energy in particle velocity distribution in the earth's magnetically confined upper atmosphere and (d) evolution and saturation of microinstabilities driven by nonequilibrium plasma configurations found near the earth. The relationship of this research to the Department of Energy's missions include applications to: (a) plasma physics and magnetohydrodynamics (MHD) problems relevant to fusion energy technology, (b) understanding long-term solar wind and earth climate variability and (c) future space-based energy technologies.

A. Energy Conversion and Transport in Space Plasma (S. P. Gary, J. R. Asbridge, S. J. Bame, W. C. Feldman and J. T. Gosling)

Mass, momentum, and energy flow into the earth's magnetosphere from the solar wind through the bow shock and magnetopause. The rate and efficiency of this flow depend critically on a variety of kinetic phenomena which also determine the microscopic structures of these boundaries. For example, recent observations of high-speed plasma flows at the magnetopause indicate that at least part of the solar wind-magnetosphere coupling occurs through magnetic field reconnection. The first consistent survey of electrostatic plasma instabilities driven by gradients perpendicular to a magnetic field has been carried out to understand why reconnection proceeds at the observed rate. Correlations with space plasma data from the magnetosphere indicate that the lower hybrid density drift instability may be important in this regard.

B. A Study of the Electrodynamical Aspects of the Solar Wind-Magnetosphere Interaction (E. W. Hones, Jr., J. Birn and T. G. Forbes)

The magnetospheric substorm is the primary process whereby solar wind energy, coupled to the earth's magnetosphere, is dissipated into the ionosphere and atmosphere. The dissipation process is thought to occur through magnetic field reconnection in a region of the magnetotail about 100,000 kilometers from the earth. Evidence supporting this belief is found in high-speed jets of plasma that are observed specifically at times of substorms. Two-dimensional distribution functions of such jetting plasmas have been subjected to theoretical analyses. These show that the distributions are consistent with acceleration of plasma in a region of very low magnetic field, quite possibly at a site of magnetic reconnection. A three-dimensional time-dependent MHD computer code has been written to provide the first three-dimensional description of the substorm processes in the magnetotail. Preliminary short tests of this program on LASL computers have been made.

Contractor: LOS ALAMOS SCIENTIFIC LABORATORY
University of California
Los Alamos, New Mexico 87545

Contract: W-7405-ENG-360445

Title: IV. Continental Scientific Drilling Program: Drilling Technology

Person in Charge: R. E. Riecker

Scope of Work

The objective of the thermal regimes part of the Continental Scientific Drilling Program (CSDP) is the development of a fundamental understanding of hydrothermal-magma systems through utilization of drilling to obtain samples and data, and to conduct down-hole experiments. The rationale and scientific basis for this endeavor has been presented in the National Academy of Sciences/National Research Council (NAS/NRC) Workshop Report on CSDP (1979). The goals are directed toward understanding the heat and mass transfer within and between magma and hydrothermal systems, and the evolution of hydrothermal-magma systems in space and time. Attainment of the program objectives rests on an ability to characterize and interpret hydrothermal-magma systems at depth, in terms of physical, thermal, mechanical, chemical and mineralogical properties. Both dedicated scientific drill holes and add-on experiments in existing or planned holes drilled primarily for other purposes can be used in achieving the program goals.

Several potential sites have been identified that should provide the capability for resolving fundamental questions related to the hydrothermal-magma system. In the CDSP, the effective use of financial and personnel resources will require focusing on a particular subset of the large number of potential sites. Five of the many possible sites have been identified for detailed and comparative analysis. Given the large fixed costs associated with the drilling activity and the requirement to extract the maximum amount of scientific information and data from samples and down-hole experiments in each drill hole, it is necessary to assess the sites in a comparative fashion to provide the basis for specific recommendations regarding future scientific drilling and experimentation.

A. Curatorial Needs (G. Heiken)

The core and cuttings curatorial needs of a national continental drilling program for scientific purposes are being determined. This study includes:

1. Philosophy of curation. Why should there be curation and how should it be managed.

2. An overview of how curation of cores and cuttings have been handled in similar programs elsewhere.

3. A compilation of state laws regarding handling of and responsibility for cores and cuttings.

Contractor: OAK RIDGE NATIONAL LABORATORY
Union Carbide Corporation
Oak Ridge, Tennessee 37830

Contract: W-7405-ENG-26

Title: I. Geosciences Research

Person in Charge: R. E. Mesmer

Scope of Work

In the Geosciences program at the Oak Ridge National Laboratory, basic research is conducted in two general areas of experimental geochemistry: (a) physical chemistry of geothermal solutions and materials and (b) interactions of aqueous media with constituents of natural formations. Experimental investigations of igneous processes and aqueous interactions with minerals and rocks provide generic information with broad application (e.g. energy extraction from magmatic and hydrothermal systems, location and extraction of mineral resources and chemical waste disposal). High temperature-high pressure studies of silicate melts are aimed at better understanding igneous processes, such as the generation of magma at depths, migration to the upper portions of the crust, crystallization and release of energy. Rock-water interactions and mineral solubility measurements being done up to 500°C and 100 MPa provide data on the responses of rocks to static or circulating water systems. Homogeneous equilibria and thermodynamic properties of species in solution are studied by physical chemical methods to provide essential data for the detailed interpretation of both equilibria and kinetic studies on natural materials.

A. Physical Chemistry of Geothermal Solutions and Materials

1. High-Temperature High-Pressure Silicate Geochemistry
(M. T. Naney)

The scientific goal of these studies is to understand the chemical and physical processes occurring during melting and solidification of rocks in crustal geologic environments. Studies are in progress to investigate phase equilibria, crystallization kinetics, diffusion, and element partitioning in chemical systems that model natural rhyolitic and basaltic magmas. Results of phase equilibria and crystallization kinetics investigations have application to energy extraction from magmas and to development of crystalline ceramic matrix materials for nuclear waste isolation. In both cases, the experimental results provide information needed for predicting the physical and chemical character of complex natural silicate systems as a function of temperature, pressure and composition.

Element partitioning and diffusion experiments in rhyolitic and basaltic systems have begun utilizing knowledge obtained in equilibrium experiments. Systematic additions of economically and strategically important elements are being made to the previously investigated model magma systems. A study of uranium diffusion and partitioning in model rhyolitic and basaltic systems is in progress. This investigation will provide information about the mobility and distribution of uranium in magmatic systems as a function of temperature, pressure, composition and oxygen fugacity.

Facilities for high temperature experimentation to 1400°C at atmospheric pressure have been assembled for use during these and future investigations. An internally heated pressure vessel system suitable for 1035 MPa (10 kilobar) pressure hydrogen service and simultaneous temperatures to 1400°C will be installed in 1980. Both high-temperature facilities permit control of oxygen fugacity during experimentation.

It is planned to adapt electromotive force (emf) methods to high-temperature, high-pressure studies of silicate systems. This is a potentially powerful technique for obtaining activity-composition relations and melt structure information from systems of geologic interest.

2. Brine Chemistry (R. E. Mesmer, R. H. Busey and C. S. Patterson of Furman University)

The speciation and equilibrium thermodynamics of components in solution in geothermal brines are the subject of this program. Physical chemical methods, principally in the temperature range 50°C to 300°C at modest pressures, are applied to study such reactions as ionization, complexation, hydrolysis and association reactions. The initial emphasis has been on the ionization reactions of water, silicic acid and carbonic acid. The stability of fluorosilicates below 60°C has also been examined. The goal of a comprehensive description of the acid buffering properties of brines is being attained. The thermodynamic properties of major components of natural brines and mixtures are also being studied by the isopiestic method, and complex mixtures of chlorides can now be described to 200°C. In addition, the kinetics of the deposition of dissolved silica onto amorphous silica is being defined under conditions occurring in reservoirs and in plant equipment.

B. Interactions of Aqueous Media with Constituents of Natural Formations

1. Solid-Aqueous Solution Interactions (F. W. Dickson)

The interaction of solids with aqueous solutions are being studied up to 500°C and 100 MPa with the use of a gold-cell apparatus from which it is possible to withdraw an internally filtered liquid sample with negligible disturbance. The time dependency of the reaction is determined, and the approach to equilibrium from undersaturated and supersaturated conditions is followed conveniently. The kinetics of reaction of powdered shales with sodium chloride (NaCl) and seawater solutions are being determined to provide data of relevance to scientific questions such as the origin of ore deposits, rock alternation, low to moderate temperature metamorphism and geochemical cycling. The data should bear on engineering and exploration matters, such as searching for and exploiting geothermal power resources, underground storage of solids and fluids, solution mining and enhanced recovery of petroleum. The equilibrium of quartz with NaCl solutions is being studied to provide background information useful in the interpretation of the kinetic work on rock-water reactions as well as to better understand the fundamental thermochemical behavior of this important geochemical system. Future studies will extend the rock-water interaction work to other rocks with high surface area constituents, notably volcanic tuffs. The mineral solubility work will consider a series of minerals and mineral associations of prime geochemical interest, including oxides, hydroxides, sulfides, sulfates and carbonates and their associated silicates.

2. Homogeneous Equilibria (W. L. Marshall and J. D. Frantz of the the Geophysical Laboratory of the Carnegie Institution, Washington, D.C.)

Many of the metamorphic and transport processes occurring in natural formations are promoted by the presence of an aqueous phase. For a basic understanding of these phenomena it is essential that the chemical processes in the aqueous phase as well as in the solid phase be defined under broad conditions of temperature, pressure and composition corresponding to the actual hydrothermal conditions that produce geological anomalies such as ore and salt deposits. In the initial stage the conductance method is being applied to the study of the association behavior of calcium and magnesium chlorides in dilute solutions to 600°C and at pressures to 400 MPa. From the observed conductances, models are being tested that describe association behavior in quantitative terms. The models will enhance understanding of the geochemical cycling of these

elements. In addition, this basic information on the behavior of 2:1 type electrolytes will be applicable to other technological problems that involve high temperatures and pressures. The program will also provide thermodynamic information in which interactions between aqueous phases and selected pure and natural brines are studied.

Contractor: SANDIA LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: I. Magma Energy Research

Person in Charge: R. K. Traeger

Scope of Work

The Magma Energy Research Project for assessing the scientific feasibility of extracting energy directly from buried magma sources is divided into five major research tasks: (a) magma source location and definition, (b) magma source tapping, (c) magma characterization, (d) magma/material compatibility, and (e) energy extraction.

The definition and characterization of magma chambers also provides information on heat sources for geothermal systems and may provide insight into the location of mineral resources. Consequently, background studies from magma energy research provides preliminary studies on other magma-hydrothermal geoscience research.

A. Magma Source Location and Definition (J. L. Colp and W. C. Luth)

Previous geophysical measurements in Kilauea Iki lava lake in Hawaii suggested but could not confirm the presence of a low viscosity, molten rock lens. Recent drilling and thermal studies in the lava lake show that the lake is in a late stage of solidification, with no low-viscosity lens, but rather a plastic, multiphase region of crystals (mainly olivine) in melt with intermittent, thin (1-4 cm?) veins of very fluid molten rock. Models to predict the thermal behavior of the lava lake geothermal system and to estimate the solidification state of the multiphase lens are being developed.

Petrographic studies of the Kilauea Iki cores are under way to study: (a) the presence of disequilibrium mineral assemblages presumably reflecting high chill rates, (b) the role of *in situ* crystallization as well as crystal settling in the observed differentiation, (c) the overall chemical changes that have occurred (multiphase crystallization is required) and (d) the consistency of preliminary mass balance calculations with the inference of 35% to 40% liquid phase remaining in the the melt-crystal suspension lens.

Analysis and interpretation of the chemical data on the crystalline phase is presently in progress. Research will include continued petrographic analysis of cores from freshly drilled holes in the lava lake to more clearly define the state of the magma reservoir.

B. Magma Source Tapping (J. L. Colp)

The program to investigate strengths of dry andesite, basalt, granodiorite and obsidian to 1050°C and confining pressures of 0 and 50 MPa at Texas A&M University under contract with Professor M. Friedman, was transferred to direct funding by OBES. Future investigations will include continuation of the investigation of potential water-weakening of the three crystalline rocks being studied to temperatures of partial melting.

C. Magma Characterization (T. M. Gerlach, W. C. Luth and R. P. Wemple)

Restoration computations of all known high-temperature volcanic gas analyses from tholeiitic and alkaline lavas are now completed. Results are being reported.

The petrologic characterization of samples obtained from Kilauea Iki lava lake drilling in 1978-79 is continuing. Extensive calculations were carried out on chemical data obtained for glass and mineral phases present in the recovered core. A package of computer codes has been developed and implemented to calculate norms, standard rock classification parameters, density, viscosity and mass balance models from the chemical analyses. Plotting codes have been developed to display the results of the above calculations as a function of depth to allow a comparison and evaluation of the results in a convenient and systematic fashion. Work on the characterization of magmatic gases at higher pressures continues.

The Magma Simulation Facility (800 cc, 1500°C and 400 MPa) was completed, brought on-line and proven reliable and repeatable. Ten experimental runs for phase and gas-melt equilibria were completed.

Several falling sphere viscosity experiments at 40 MPa in argon with NBS 717 borosilicate glass and Hawaiian tholeiitic basalt (HTB) have been performed. The apparent viscosities correlate fairly well with data obtained at ambient pressure on the bench.

Viscosity and other magma physical property experiments in the facility will continue.

D. Magma/Material Compatibility (J. L. Colp and N. J. Magnani)

Stability diagrams were developed for 15 pure metals. The pure metals, plus 16 alloys, were evaluated in low-pressure, simulated-magma environments. Preliminary results suggest that iron, cobalt and molybdenum, each containing chromium, will show little degradation. The chromium content of both ferritic and austenitic stainless steels is the most important factor in provid-

ing corrosion resistance. Type 310 is by far the most corrosion-resistant alloy of any of the commercial stainless steels.

Compatibility studies will continue in conjunction with Professor D. L. Douglass at the University of California at Los Angeles. The magma simulation facility will be used for further studies at magmatic conditions.

E. Energy Extraction (H. C. Hardee and D. W. Larson)

A limited experiment performed in a cased hole in the lava lake gave energy extraction rates on the order of 11 kW/m^2, approximately twice that expected from conduction alone. A thermal model is being developed to explain these high rates, believed due to convection set up by residual drilling water, which suggests that use of convection-enhancing fluids may be a means of extracting energy from magma chamber margins.

Improved calculational models for convective heat extraction have been developed for several types of magmas and are being used. These improved models include corrections for high Prandtl-number fluids, and cylindrical geometry. The effect is a moderate increase (20%) in the expected convective heat flux. The formation of a large cylindrical crust of solidified magma on the heat exchanger results in a favorable geometrical situation which seems to increase the effective heat flux at the heat exchanger surface by a factor of 2 to 20. Typical heat extraction rates for a 25 cm radius vertical heat exchanger in various types of magma range from 2.3 to 42.6 kW/m^2. Laboratory tests are under way to measure convective heat fluxes in molten basalt in the vicinity of the liquidus (1100-1300°C). The test data are being compared with convection calculations based on a power law (non-Newtonian) viscosity model.

Further research will include: (a) continuation of calculational studies, (b) observation of future volcanic eruptions, (c) laboratory tests to experimentally verify calculations and (d) *in situ* experiments in the "magma" and solid margins of the lava lake during the planned 1981 drilling experiments.

Contractor: SANDIA LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: II. Continental Scientific Drilling Program: Thermal Regimes

Person in Charge: O. E. Jones

Scope of Work

The objective of the thermal regimes part of the Continental Scientific Drilling Program (CSDP) is the development of a fundamental understanding of hydrothermal-magma systems through utilization of drilling to (a) obtain samples and data and (b) conduct downhole experiments. The rationale and scientific basis for this endeavor has been presented in the National Academy of Sciences/National Research Council (NAS/NRC) Workshop Report on CSDP (1979). The goals are related to understanding the heat and mass transfer within and between magma and hydrothermal systems and the evolution of hydrothermal-magma systems in space and time. Their attainment rests on the ability to characterize and interpret hydrothermal-magma systems at depth in terms of physical, thermal, mechanical, chemical and mineralogical properties.

Sandia Laboratories is contributing to the CSDP Program in three areas: (a) program coordination, (b) joint participation in comparative site assessments and (c) geoscience research on hydrothermal/magma systems.

A. CSDP Program Coordination (H. C. Hardee and W. C. Luth)

Sandia Laboratories provides a coordination for the activities of CSDP's thermal regimes research. This function involves coordinating the following program elements:

(1) Program development, utilizing input from the Department of Energy, the U. S. Geological Survey and the academic community.

(2) Service functions provided by Lawrence Livermore National Laboratory (data base on active drilling), Los Alamos Scientific Laboratory (assessment of core and sample repository needs), Lawrence Berkeley Laboratory (geothermal fluids data base) and Sandia Laboratories (drilling, logging and instrumentation technology needs).

(3) Site specific research based on research proposals submitted to and reviewed by DOE's Office of Basic Energy Sciences/ Geosciences (OBES/Geosciences) dealing with field-based geological, geophysical and geochemical studies at potential sites of interest to the thermal regimes work of CSDP.

(4) Generic research broadly supportive of the scientific objectives of CSDP but which is not site-specific and is oriented toward generic processes important in understanding thermal regimes in the earth's continental crust. Research is based on research proposals submitted to, and reviewed by OBES/ Geosciences.

(5) Drilling activities, which require considerable logistical and contractual support to achieve the scientific objectives of the program.

Program coordination of these five functions involves OBES/ Geosciences-supported research activities conducted at academic institutions, industrial organizations and government laboratories around the country.

B. Comparative Site Assessment (H. C. Hardee)

To aid in selecting appropriate sites for both dedicated scientific drilling and to employ more effectively other drill holes, a comparative site assessment report is being prepared. This activity is a joint effort involving research workers at Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory and Sandia Laboratories. The overall program is coordinated by Sandia Laboratories and is focused on five sites (The Geysers, Long Valley and the Salton Trough, California; the Rio Grande Rift, New Mexico; and Roosevelt Hot Springs, Utah) that offer potential opportunities for understanding behavior and evolution of hydrothermal-magma systems in the upper 10 km of the earth's crust.

To this end, the available geologic, geophysical and geochemical data for each site are being reviewed and compared. In addition, the status of analytical/numerical models for heat and mass transport within and between hydrothermal and magma systems is being reviewed in the context of the five sites. This comparative review is intended to identify the specific scientific questions on the evolution of hydrothermal-magma systems that can be optimally resolved at each site. The review will also identify additional site-specific research needs that must be satisfied prior to planning for dedicated scientific drilling.

The resulting report is intended to provide information necessary for decisions on site selection based on the nature of the scientific opportunities presented at the five sites. A preliminary report, prepared jointly by the four participating laboratories and submitted to OBES/Geosciences, identifies specific opportunities for obtaining fundamental scientific information through exploitation of drilling planned for technological purposes.

C. Hydrothermal/Magma Geoscience Research (W. C. Luth)

This research program, initiated in 1980, is concerned with geochemistry and energy transport associated with geothermal systems ranging from the hydrothermal to the magmatic regime. Results obtained in these and other related studies will be used to identify what drilling and *in situ* field measurements are required to develop, test and confirm physical and chemical models of coupled hydrothermal and magmatic systems.

1. Geochemistry of Magma Systems (W. C. Luth and T. M. Gerlach)

The current study is directed toward understanding the crystallization history of a specific basaltic composition at pressures of less than 150 MPa (1.5 kbar), in the presence of appropriate volatile components dissolved in the silicate liquid or partitioned between the silicate liquid and the coexisting gas phase. The specific basaltic composition, typical of that filling Kilauea Iki lava lake since 1959, has been selected because of the vast amount of data collected on this system by the U. S. Geological Survey and Sandia Laboratories, and by other investigators. This investigation will correlate the on-going, long-term ($\sim$ 21-year), large-scale natural experiment with short-term, small-scale laboratory experiments. Although the filling episode(s) of Kilauea Iki lava lake resulted in degassing of the basaltic magma, appropriate gas phase compositions have been estimated at low pressure, from related submarine basalt flows.

The kinetics of crystal nucleation, growth and approach to the equilibrium state in the Kilauea Iki lava lake magma are being investigated with a high-temperature heating stage (1350°C) on a petrographic microscope. The resulting crystal and liquid phases are being analyzed by the electron microprobe.

Experimental studies at pressures of 10, 50, and 100 MPa are being conducted jointly with Dr. P. M. Fenn at the University of California, Davis.

2. Energy Transport (H. C. Hardee and D. W. Larson)

A transient, compressible, single-phase, porous flow code has been developed, and preliminary runs have been made with this code. Plans are underway to extend this code to compressible, two-phase porous flow problems.

Measurements of porous convection near the critical point have been made. The data, which show enhanced heat transfer rates, is currently being analyzed. An attempt is underway to correlate these data with analytical predictions.

Contractor: SANDIA LABORATORIES
Albuquerque, NM 87185

Contract: DE-AC04-76DP00789

Title: III. Modeling of Geodetic Crustal Strain Data

Persons in Charge: O. E. Jones and J. B. Rundle

Scope of Work

Programs for monitoring and predicting crustal deformation are important for determining long-term tectonic stability. This research program is centered around a program to develop models of inelastic strain accumulation in the earth. The models, based on a Green's function approach, allow computation of theoretical data for quantitative comparison with geodetic observations from the field. The models emphasize the importance of vertical variation of mechanical properties in the earth using a layered half-space structure to introduce such variation. One or more layers are allowed to be linearly viscoelastic, or in some cases, more generally inelastic. The source functions, double-coupled Green's functions, are well known to accurately represent the discontinuity due to faulting and are available in the literature.

Up to the present, the models have not included the effects of gravitation or of possible pore fluid migration in the crust. Nevertheless, some success has been achieved in modeling post- and interseismic deformation due to faulting in both Japan and California. Present efforts at Sandia are being devoted principally to the inclusion of coupled self-gravitation and pore fluid effects in the models. The coupled equations describing such effects have been solved analytically, and the results are being coded for computational purposes. The computations are somewhat more intricate than in the uncoupled case owing to the presence of certain numerical singularities. Methods are available in the literature to deal with these problems and results should be forthcoming shortly. Predictions from the models will be useful in assessment of hazards in siting critical energy facilities in tectonically unstable areas.

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: EY-76-S-06-2229 005

Title: I. The Magnetic Field Annihilation Process in the Magnetosphere

Person in Charge: S.-I. Akasofu

Scope of Work

It has long been believed that solar flares result from a sudden conversion of stored magnetic energy. A similar mechanism has long been contemplated for magnetospheric substorms. It has been shown, however, both observationally and theoretically, that the solar wind (a magnetized plasma flow) couples its energy to the magnetosphere (a magnetized celestial body) as described by equation (1):

$$\varepsilon = VB^2 \sin^4\left(\frac{\theta}{2}\right)\ell_0^2 \qquad (1)$$

where V and B denote the solar wind speed and magnetic field respectively, θ the polar angle of the solar magnetic field (projected to the dawn-dusk meridian) and ℓ_0 is a constant ($\sim$ 7 earth radii).

With this new finding, the solar wind-magnetosphere interaction--which can be described as a gigantic natural magnetohydrodynamic generator--is much better understood than in the past.

It remains to be discovered how the solar wind-magnetosphere generator causes a large-scale discharge through the polar upper atmosphere and how such a discharge process causes an intense radiation belt (the so-called "ring current belt"). It is believed that the discharge processes associated with solar flares are very similar. A concentrated effort, therefore, will be made to prove this point.

University of Alaska researchers are also interested in energy-related geophysical problems in the Arctic region. Help is being given to the corrosion engineers of the Alyeska Pipeline Company in monitoring the amount of aurora-induced electric current in the trans-Alaska oil pipeline, in locating where induced current leaves the pipe and in estimating the expected amount of corrosion. The amount of induced current is typically of the order of a few hundred amperes during medium magnetic activity. During an intense storm, current exceeds one thousand amperes.

The aurora also induces electric currents in power transmission lines. As a result, serious fluctuations of power can occur during intense auroral activity. Work is being carried out in close collaboration with the local power-line company to monitor induced current and to examine performance of a transformer when quasi-dc currents are induced in a power transmission line.

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: EY-76-S-06-2229 006

Title: II. Alaska Peninsula Telemetered Seismic Network

Person in Charge: H. Pulpan

Scope of Work

The Aleutian-Alaska arc system is the result of two lithospheric plates converging, the Pacific plate subducting beneath the American plate. With its associated features--a deep sea trench; a shallow thrust zone with high potential for large, tsunamigenic earthquakes; a Benioff seismic zone; and an overlying chain of andesitic volcanoes--the system is unique in the United States. The analysis of seismic data generated by the frequently occurring earthquakes in the arc system provides one of the best means of understanding the fundamental tectonophysical processes associated with the natural phenomena observed. This understanding is required to assess the geothermal energy potential of the arc system's volcanism and to assess the seismic and volcanic hazards to energy-related development in an area of high potential for both fossil and geothermal energy sources.

The project involves operation of a network of eleven short-period, vertical component seismographs on the Alaska Peninsula and some of the off-shore islands comprising the arc. The net is part of a seismic monitoring system operated by different agencies under various grants to cover approximately 1000 km of the eastern end of the arc. The earthquake catalogue (threshold M_B = 2) derived from the network has been used to provide insight into the space-time behavior of seismicity and its bearing upon the occurrence of large earthquakes, the mechanics of the subduction process and the relationship of the subduction process to the active volcanism of the system.

Contractor: ASPEN INSTITUTE FOR HUMANISTIC STUDIES
1229 University Avenue, 2nd Floor
Boulder, Colorado 80302

Contract: ER-78-S-02-4634.A000

Title: I. Mechanisms for the Effect of Variable Solar Activity on the Weather

Persons in Charge: W. O. Roberts and R. H. Olson

Scope of Work

The purpose of this project is to discover the most feasible physical mechanisms by which variable solar activity affects the earth's weather and climate. The first area of research is to describe the most important relationships, in sufficient detail, so that an attempt can be made to construct a physical model to explain them.

Numerous solar parameters have been used by investigators of solar activity to investigate short-term sun-and-weather effects. Using the size of low-pressure troughs integrated over the northern hemisphere as one meteorological parameter, it has been found that various solar signals give different responses. If the solar signal is such as to increase electromagnetic radiation received by earth--e.g. a solar flare--then cyclonic activity increases. Flares, however, are characteristically followed by geomagnetic storms within a few days, and the geomagnetic storm is associated with a sharp decrease in cyclonic activity. Thus when a large flaring region on the sun approaches the sun's central meridian, the earth's cyclonic activity increases, but shortly after, when the region passes by the central meridian, magnetic storms occur and cyclonic activity declines to a minimum. There is increasing evidence that thunderstorm frequency also responds to the same forcing function.

Contractor: BROWN UNIVERSITY
Department of Geological Sciences
Providence, Rhode Island 02912

Contract: DE-AC02-79ER10401

Title: I. Application of Natural Electromagnetic Field Methods to Exploring for Energy Resources

Person in Charge: J. F. Hermance

Scope of Work

The focus of activity at this laboratory is on applying geophysical and electromagnetic techniques to detecting and characterizing geological features within the earth that are related to energy resources.

Present attention is being directed toward acquiring an understanding of dynamical processes and thermal regimes associated with centers of major volcanic activity. Clearly, this is of central importance, not only to basic science, but to national priorities on research programs in resource related areas such as geothermal energy, chemical transport and the emplacement of economic ore deposits, and deep drilling for scientific purposes. It is felt that to understand the dynamic evolution of intraplate silicic centers in the western United States, it is necessary to understand the evolution of precursive high-level basaltic activity. This is because the segregation of basaltic magma from parent mantle material at depth (30 to 100 km), and its migration to higher levels in the crust (5 to 15 km), offers an effective mechanism for transferring heat from deep mantle sources to the crust, leading in turn to episodes of crustal melting at shallow depth and silicic volcanism at the surface.

To investigate these phenomena, a long-term geophysical field program (using tellurics, magnetotellurics and geomagnetic variations; over the frequency range 10^3 Hz to 10^4 sec) has been mobilized under joint support of the Department of Energy Office of Basic Energy Sciences/ Geosciences (OBES/Geosciences) and several other Government agencies. A comparative study will be undertaken of selected major volcanic centers in terms of their association with regional tectonomagmatic phenomena in the deep crust and upper mantle.

The focus this year has been on developing a magnetotelluric/ magnetic variation field system capable of (a) high data quality, (b) increased frequency band coverage (10^3 Hz to 10^4 sec), (c) on-site data processing, (d) computer-generated graphical displays of data parameters (on maps of the survey area while the field system is on-site) and (e) minimal turn-around time from making the measurement to final data analysis.

A background study is also being performed on the past application of these techniques to various tectonic areas around the world in an effort to ascertain the effectiveness of electromagnetic methods in constraining models of the thermal regime of the crust associated with active volcanoes.

Contractor: UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

Contract: DE-AS03-76F00034

Title: I. Isotopic Studies on Rare Gases in Terrestrial Samples and in Natural Nucleosynthesis

Person in Charge: J. H. Reynolds

Scope of Work

This laboratory conducts research in rare gas mass spectrometry. The broad objective is to read the natural record that isotopes of the rare gases comprise as trace constituents of natural gases, rocks, and meteorites. A new program is to design, construct and operate an apparatus to analyze the elemental and isotopic composition of rare gases from fluid sources in the field, at or near the sampling site. Long-range scientific goals are to search for additional manifestations of primordial gases and to see how they relate to convection patterns within the earth. Rare gases from steam wells and other geothermal energy sources will also be examined. Particular interest will be paid to assaying proportions of recycled atmospheric gas versus radiogenic gas. While instrumentation for field studies on fluids is being fabricated, work is underway with volcanic xenoliths and megacrysts and suboceanic volcanic basalts. The objective is to determine what information the rare gases can provide about their genetic relationships and about the out-gassing sequence of magmas. Interesting isotopic and elemental patterns have also been observed in these volcanic samples and from these patterns an attempt is being made to determine the primordial and radiogenic rare gas components of the mantle.

Isotopic inhomogeneities are also being studied, such as those observed in the carbonaceous chondrites. It is likely that they originate from incomplete isotopic mixing of fractions with different histories of nucleosynthesis.

The current emphasis is on the carbonaceous, acid-resistant residues in chondritic meteorites which, although they represent less than one percent by weight of the stony meteorites, carry virtually all planetary gases. Markedly anomalous isotopic patterns for argon, krypton and xenon are observable in these residues after the bulk of the gases has been released by selective chemical treatments. In collaboration with cosmochemists at the National Aeronautics and Space Administration's Ames Laboratory, research is being performed to locate trapping sites for these gases in fine-grained residues by such means as chemical treatments, colloidal techniques and density separations.

Contractor: UNIVERSITY OF CALIFORNIA
Institute of Geophysics and Planetary Physics
Los Angeles, California 90024

Contracts: DE-AS03-76SF00034; PA #DE-AT03-76ER70224

Title: I. Relationship of Rock Physics to Geothermal Energy Technology

Persons in Charge: O. L. Anderson and N. Warren

Scope of Work

The basic logic for the integrated analysis of mechanical properties and microstructure is being developed. The core of a set of computer programs has been constructed to analyze statistically the cross-correlations and functional dependences among mineralogical and rock texture variables, crack pattern parameters and sample elastic deformation properties.

From this work it has been demonstrated that statistically significant relationships can be established between observable rock structure and bulk physical properties. These results represent a major step toward the goal of generating physically realistic theoretical models of laboratory data.

Future research will continue this line of investigation. Three classes of variables are input into the analysis: (a) petrographic and mineralogical variables, (b) crack map variables and (c) descriptor variables of the elastic deformation of a sample. The output of the analysis is a set of cross-correlation coefficients between the variables in the three classes. These form the basis for quantifying functional forms of the relations between variables and for generating probability calculations (or quantitative predictions) of bulk physical properties from petrographic variables.

Two other projects related to this effort are being supported: (a) volumetric strain measurements on thick-walled cylindrical rock samples under pore pressure and triaxial loading and (b) crack modeling and inversion of elastic moduli data into crack spectra.

Contractor: UNIVERSITY OF CALIFORNIA
Institute of Geophysics and Planetary Physics
Los Angeles, California 90024

Contract: EY-76-5-03-0034 171

Title: II. Compressibility Measurements

Persons in Charge: G. C. Kennedy* and R. Boehler

Scope of Work

The objective of this research is to investigate methodically many substances from various groups such as salts, metals, oxides and minerals to find a systematic behavior in the equation of state of solids.

The compressibility and thermal expansion of lithium fluoride (LiF) up to 3,200 MPa and 400°C are being measured simultaneously. A much stronger decline of thermal expansivity with pressure was found than by recent X-ray measurements. An electrical contact piezometer was used in a piston cylinder apparatus using a fluid cell arrangement.

For LiF it has been found that $\alpha_V K_T$ (where α_V is the volume coefficient of thermal expansion and K_T is the isothermal bulk modulus) remains nearly constant over the experimental pressure and temperature range. This is in agreement with previous observations on sodium chloride (NaCl).

The behavior of the Grüneisen parameter through the phase transitions of potassium bromide (KBr), rubidium chloride (RbCl), bismuth (Bi) and cerium (Ce) have been investigated. For all four substances we find a much larger increase in gamma (γ) at the transition than suggested by theory. Here γ is defined by $\gamma = K_S/T(\partial T/\partial P)_S$ where K is the adiabatic bulk modulus, T is temperature, P is pressure and the subscript s denotes constant entropy.

Adiabats have been measured for a number of fluids, salts, metals and minerals, and a systematic behavior of $(\partial T/\partial P)_S$ with volume has been found. The objective is to carry out these measurements at both high pressures and high temperatures in order to predict the adiabat in the interior of the earth. Preliminary measurements on lead have shown that accurate data can be obtained up to 3,000 MPa and 500°C.

*Died March 18, 1980

Contractor: COLUMBIA UNIVERSITY
Lamont-Doherty Geological Observatory
Palisades, New York 10964

Contract: DE-AS02-76ER03134

Title: I. Seismotectonics of the Eastern Aleutian Arc and Associated Volcanic Systems

Persons in Charge: J. Davies, K. Jacob and L. Sykes

Scope of Work

In recent work it has been demonstrated that the Shumagin Islands segment of the eastern Aleutian arc is a seismic gap with a much higher potential for a great earthquake in the near future (i.e., the next decade) than previously thought. Based on this assertion, research will continue as follows: (a) continue monitoring regional seismotectonics; (b) analyze space-time patterns of seismicity; (c) determine fault plane solutions, P-residuals, crustal deformation and volcanicity, and (d) study, in the greatest possible detail, seismic wave-forms, crustal velocities and empirical seismic Green's functions (for evaluation of strong ground-motion levels). Many of these tasks require installation of triaxial sensors at a few sites and of a digital central recording system. The volcano-geothermal study of the Pavlof volcano will strongly benefit from analysis of digital recordings of seismic wave-forms whose associated raypaths travel through magma bodies beneath the Pavlof volcano. Since it is expected that these bodies will be highly mobile and variable during an eruptive cycle, a search will be made for time-dependent propagation effects. The possible imminence of major seismic activity in this arc segment, which also is a candidate for off-shore oil exploration, makes the conversion to an automatic, digital seismic recording mode a matter of urgency.

The specific scientific objectives of this project are to:

1. Use seismic body-wave information to constrain geometry of major structural or acoustic boundaries beneath the Shumagin network.

2. Develop two- or three-dimensional velocity models from Shumagin network data based on the first results from objective 1.

3. Start a catalogue of empirical Green's functions for representative earthquakes using broad-band data for the Shumagin Islands seismic gap.

4. Continue ambient stress determinations from earthquakes in the Shumagin Islands region.

5. Apply seismic waveform matching techniques to teleseismic data to constrain focal depth and mechanisms of moderate-sized regional events.

6. Complete the Pavlof volcano eruptivity record, using records from nearby seismic stations, so that it is current.

7. Start seismic waveform analysis using Pavlof array data to study the magma plumbing system in and beneath the Pavlof volcanco.

8. Continue the search for seismic, volcanic or geodetic indicators of imminent great earthquakes.

Contractor: COLUMBIA UNIVERSITY
Lamont-Doherty Geological Observatory
Palisades, New York 10964

Contract: DE-AS02-76ER04054

Title: II. Fluid Transport Properties of Rock Fractures at High Pressure and Temperature

Persons in Charge: C. Scholz and T. Engelder

Scope of Work

In order to understand the effect of fracture closure on permeability, the precise effects of changing fluid pressure on the rate of flow along smooth joints in rock at effective pressures to 300 MPa are being studied. Detailed measurements of the change in joint aperture with effective pressure show that, at effective pressures of less than 20 MPa, changes in confining pressure have a larger influence on the aperture than changes in pore pressure. For example, for surfaces prepared with 80-grit polishing compound, the aperture changes at a rate of about 2 μm/MPa for confining pressure changes and 1 μm/MPa for pore pressure changes. Joint permeability changes with aperture. Thus changes in confining pressure are more influential on permeability than changes in pore pressure. Hysteresis loops in pressure versus aperture curves are evident for both pore and confining pressure cycles with work being lost during both types of cycles. To further test the validity of the cubic-law model for flow along joints, flow measured during constant head tests with flow measured by pulse decay tests were compared. Data derived from these two types of tests are comparable. Thus the transients developed during pulse decay tests do not affect the quality of the permeability data. Based on both pulse decay and constant head tests, it can still be concluded that the cubic-law model for flow along a joint gives a rough estimate of joint permeability, but measurements of the changes in flow rate with aperture suggest that the cubic law is inadequate for smooth joints at high pressure.

Contractor: UNITED STATES GEOLOGICAL SURVEY
National Center for the Thermodynamic
Data of Minerals
National Center, Stop 959
Reston, VA 22092

Contract: EG-77-A-01-6150, Amendment A001

Title: I. National Center for the Thermodynamic Data of Minerals

Person in Charge: J. L. Haas, Jr.

Scope of Work

The National Center for the Thermodynamic Data of Minerals provides, on a continuing basis, critically evaluated descriptions of the thermodynamic properties of minerals and other geologic materials over the ranges in temperature, pressure and composition that are observed in the geologic environment. In relation to the Department of Energy, Office of Basic Energy Sciences/Geosciences (OBES/Geosciences) mission, the Data Center provides those thermodynamic data for minerals that are needed to test and use computer simulations of physical properties of minerals and the chemical interactions among minerals or between minerals and the pore fluid.

During the latest contract year, the Data Center completed the evaluation of heat capacity (C_p), entropy (S°), molar heat of fusion $\Delta(H_f)$ and Gibbs's free energy $\Delta(G_f)$ for phases containing aluminum (Al), oxygen (O), hydroxide (OH), silicon (Si) and calcium (Ca) having the following chemical formulae: $AlO(OH)$, $Al(OH)_3$, $Al_2Si_2O_5(OH)_4$, $Al_2Si_4O_{10}(OH)_2$, Al_2SiO_5, $CaSiO_3$, $Ca_3Si_2O_7$, Ca_2SiO_4, Ca_3SiO_5, $CaAl_2Si_2O_8$, $CaAl_2SiO_6$, $Ca_2Al_2SiO_7$, $Ca_3Al_2Si_3O_{12}$, $CaAl_4Si_2O_{10}(OH)_2$, $Ca_2Al_2Si_3O_{10}(OH)_2$, and $Ca_2Al_3Si_3O_{12}(OH)$. The properties are available in tabular form at 1 atm between 273.15 K and the upper stability limit or the limit of the data, whichever is lower. The tabulations also include the 2-sigma confidence limits at 250 K intervals. With each table is a summary of the experimental data used to obtain the final evaluation.

The evaluation program was enlarged to include the simultaneous fitting of the volumetric data for minerals, including expansivity and compressibility. Future tables will also include these data. An improved equation of state for water was also adopted. Both of these tend to eliminate evaluator errors in extracting the experimental data and entering them into the evaluation routines.

Current work includes examination of chemical buffer systems that are used to determine the properties of oxides, sulfides, carbonates, silicates, and other compounds that have cations and anions with variable oxidation states.

Contractor: INDIANAPOLIS CENTER FOR ADVANCED RESEARCH, INC.
1219 West Michigan Street
Indianapolis, Indiana 46202

Contract: DE-AC02-80ER10586

Title: I. Computerized Underground Image Reconstruction

Person in Charge: K. A. Dines

Scope of Work

The primary goal of this study is to define the optimal processing algorithms and data collection strategies for geophysical tomography (geotomography). The techniques used in medical computerized axial tomography (CAT scanning) will be adapted for use in underground imaging. Processing algorithms for hole-to-hole, hole-to-surface, hole-to-surface-to-hole and multiple-intersecting-hole scanning geometries will be defined, analyzed and tested for their imaging capabilities.

Image reconstruction techniques to be explored are applicable to electromagnetic and seismic tranmission data measured as line-integrals of electrical and acoustic properties in a planar underground cross-section. The feasibility of adapting this technology for imaging by using data obtained from reflected signals will also be studied.

The trade-offs and fundamental limitations will be assessed to form a knowledge base for designing field instrumentation and selecting an appropriate imaging technique for a given site configuration. A detailed study of these imaging capabilities is necessary to achieve the required level of confidence for interpreting geologically specific parameters such as fracture density, water content and fluid flow.

The ability of image reconstruction techniques to display underground parameters (attenuation and wave velocity) in the form of pictures would aid in the discussion and interpretation of results for applications such as the characterization and monitoring of nuclear waste isolation sites, oil and mineral exploration and *in situ* coal gasification.

The long-range goal of this research is to develop an arsenal of quantitative imaging techniques that can be used in the field to provide real-time images of known resolution and accuracy for a variety of Department of Energy needs and programs.

Contractor: MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Earth and Planetary Sciences
Cambridge, Massachusetts 02139

Contract: EY 76-S-02-25430134

Title: I. Seismology of Crack Formation and Natural Geothermal Systems

Person in Charge: K. Aki

Scope of Work

This research program has grown through participation in two major geothermal projects, namely, the Hot Dry Rock project of the Los Alamos Scientific Laboratory and the Magma Tap project of Sandia Laboratories. In both studies, a theory for interpreting data on seismic wave generation, transmission, scattering and attenuation in a medium containing a fluid-filled crack has been developed.

The main conclusion from these studies is that a multiple approach is essential for exploring a complex geological body like a geothermal system. Conventional and unconventional techniques, based on both active experiments (using artificial signal sources such as seismic waves generated by buried explosions) and passive experiments (using signals generated by the geothermal system itself or by natural processes outside the system) are needed.

The "fluid-filled crack" model of geothermal systems has proved to be quite versatile and useful for various static and dynamic problems. It has been used not only to study the fracture in Fenton Hill and the magma lens in Kilauea Iki, but to relate the volcanic tremor data from Kilauea with the rate of magma transport during an eruption.

A new method for determining seismic attenuation at high frequencies, based on a combined use of direct body waves and coda waves of local micro-earthquakes, has also been developed.

These methods are being applied to various geothermal areas including Kilauea, Hawaii; Fenton Hill, New Mexico; Newberry Peak, Oregon; and Cerro Prieto, Baja California. The data needed for study are obtained from the U. S. Geological Survey, Los Alamos Scientific Laboratory, the Massachusetts Institute of Technology digital seismographs operated at Newberry Peak and the Centro de Investigacion Cientifica y de Educacion Superior de Ensenada in Mexico.

Contractor: MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Earth and Planetary Sciences
Cambridge, Massachusetts 02139

Contract: DE-AS02-78ER04972

Title: II. Microcrack Technology

Person in Charge: G. Simmons

Scope of Work

The scanning electron microscope (SEM), petrographic microscope, differential strain analysis (DSA) and the data on various physical properties measured as a function of pressure are used to characterize microcracks in rocks that are related to various energy programs.

Samples of core from geothermal areas (Coso and Raft River) have been examined. A set of microcrack features has been observed that appears to be unique to geothermal rocks.

Samples of core from the 0.9 km (3,000 foot) hole at Redstone Quarry, New Hampshire, Granite Mountains, Wyoming, and Sherman Granite, Wyoming, are being examined to determine the relationship, if any, between microcracks and the migration of radioisotopes in igneous rocks. Sufficient evidence has been obtained to propose the tentative working hypothesis that uranium (U) moves through source rocks by means of a three-dimensional network of microcracks.

Techniques that are adequate (but could still be improved) have been developed for preparing specimens of shale to be examined with the SEM Eastern black Devonian shales will be studied. The intent is to characterize microcracks, texture and physical properties of the shales as a function of pressure. Similar techniques for the rocks of coal gasification projects are currently being developed.

Contractor: NATIONAL ACADEMY OF SCIENCES
Washington, D. C. 20418

Contract: EX-76-C-01-3772

Title: I. Studies in Geophysics

Person in Charge: P. J. Hart

Scope of Work

The Geophysics Study Committee was established under the Geophysics Research Board of the National Academy of Sciences-National Research Council, to serve as a steering committee for the Geophysics Research Board to implement the plan for the Studies in Geophysics. Members of the committee are: C. L. Drake, chairman; L. J. Battan, vice-chairman; J. D. Bredehoeft; A. V. Cox; H. Odishaw; C. B. Officer; R. G. Roble and T. M. Usselman, staff.

The studies include: (a) problem-oriented studies such as demands on geophysical knowledge in connection with climatic variations, fresh water resources, mineral resources, geothermal and other energy sources, geophysical predictions, air quality and food and (b) science-oriented studies such as international programs in geophysics, status of developments and opportunities in geophysics, impact of technology on geophysics and criteria for assessment of priorities. The preliminary findings of each study are presented to the scientific community for comment at a suitable symposium. Two or three studies are expected to be completed each year.

Studies Completed:

1. Energy and Climate (Roger R. Revelle, panel chairman). Published in 1977 (158pp.).

2. Estuaries, Geophysics and the Environment (Charles B. Officer, panel chairman). Published in 1977 (127pp.).

3. Climate, Climatic Change, and Water Supply (James R. Wallis, panel chairman). Published in 1977 (132pp.).

4. The Upper Atmosphere and Magnetosphere (Francis S. Johnson, panel chairman). Published in 1977 (169pp.).

5. Geophysical Predictions (Helmut E. Landsberg, panel chairman). Published in 1978 (215pp.).

6. Impact of Technology on Geophysics (Homer E. Newell, panel chairman) Published August 1979 (136pp).

7. Continental Tectonics (B. Clark Burchfiel, Jack E. Oliver and Leon T.Silver, panel co-chairmen). Published in February 1980 (197pp).

Studies in Preparation

1. Mineral Resources (Paul B. Barton, Jr., panel chairman). Publication is expected in late 1980 or early 1981.

2. Sun, Weather, and Climate (John A. Eddy, panel chairman). Publication is expected in late 1980 or early 1981.

3. Scientific Basis of Water Resource Management (Myron B. Fiering, panel chairman). Publication is expected in late 1980 or early 1981.

4. Pre-Pleistocene Climate (Wolfgang H. Berger and John C. Crowell, panel co-chairmen). Publication is expected in 1981.

5. Geophysical Data and Public Policy (Michael A. Chinnery, panel chairman). Publication is expected in late 1981 or early 1982.

6. Estuarine Research Perspectives (L. Eugene Cronin and Charles B. Officer, panel co-chairmen). Publication is expected in 1981.

The Geophysics Research Board (GRB) of the National Academy of Sciences-National Research Council is conducting a series of studies in geophysics dealing with timely scientific and societal aspects of geophysics and the corresponding demands on geophysical knowledge.

The studies are guided by the Geophysics Study Committee (GSC), which consists primarily of members of the GRB or their designated alternates. Each study is conducted by a panel selected for the purpose.

The modular pattern for the studies in geophysics was designed to permit selection of the most timely topics and rapid completion of individual studies to meet the following objectives:

1. To set forth the current and prospective contributions that the geophysical sciences can make to such concerns of mankind as energy, nonrenewable resources and the environment.

2. To provide government officials with technological and scientific evaluations that can serve as a rational basis for decision making in matters involving geophysical research and knowledge, both in policies and programs.

3. To provide to the scientific community itself a basis for rational judgments with respect to the development of the basic science of geophysics in the broad sense and with respect to the relative importance to society of the developments within various branches of geophysics.

Contractor: NATIONAL ACADEMY OF SCIENCES
Washington, D. C. 20418

Contract: EY-76-C-02-2708-028

Title: II. U.S. Geodynamics Committee

Person in Charge: P. J. Hart

Scope of Work

The United States Geodynamics Committee (USGC) was established in 1969 to foster and encourage studies of the dynamic history of the earth, with appropriate attention to both basic science and applications. The USGC carries out its work largely through the recommendations developed by its reporters (initially 10 and now 19) and their associated working groups. In 1976, at the request of the Geophysics Research Board, the USGC began planning for United States research activities in solid-earth studies in the 1980's. In the following years, the committee devoted a considerable amount of effort to the program for the 1980's, leading to the report that was published in April 1980, "Geodynamics in the 1980's." The report urges emphasis on research in: (a) the origin and evolution of continental and oceanic crust, (b) the continent-ocean transition, (c) the relation of mantle dynamics to crustal dynamics and (d) a geodynamic framework for understanding resource systems and natural hazards.

The list of topics and corresponding reporters have been subject to a continual review and revision as appropriate. As of April 1980, the list was:

	Topic	Reporter
1.	Fine Structure of the Crust and Upper Mantle	J. E. Oliver
2.	Evolution of Oceanic Lithosphere	J. R. Heirtzler
3a.	Internal Processes and Properties	(vacant)
3b.	Crystal Growing	T. M. Usselman
3c.	Large Volume Experimentation	R. E. Riecker
4.	Application of Isotope Geochemistry to Geodynamics	B. R. Doe
5.	Geodynamic Modeling	D. L. Turcotte
6.	Drilling for Scientific Purposes	E. M. Shoemaker
7.	Magnetic Problems	C. E. Helsley
8.	Plate Boundaries	J. C. Maxwell
9.	Plate Interiors	L. L. Sloss
10a.	Geodynamic Data	M. N. Toksoz
10b.	Data Centers and Repositories	A. H. Shapley
11.	Geodynamic Activities in the Caribbean Area	(vacant)
12.	Lithospheric Properties	T. H. Jordan
13.	Aeromagnetic Survey	W. J. Hinze

14.	Comparative Planetology	J. W. Head
15.	Continent-Ocean Geodynamic Transects	R. C. Speed
16.	Ancient Suture Belts	E. M. Moores
17.	Electrical Properties of the Asthenosphere	C. S. Cox
-	Final Symposia and Reports for the Geodynamics Project	C. L. Drake

It is expected that further revisions will take place in 1980-81.

The activities of the reporters and concomitant actions of the USGC are reviewed by the Committee at its semi-annual meetings. They have been reported in Progress Reports published in 1975, 1976 and 1977, and in unpublished reports for 1970-79.

The USGC has been particularly active in encouraging drilling on land for scientific purposes. The USGC was instrumental in organizing the Workshop on Continental Drilling in 1974 that led to the report "Continental Drilling" (1975). The USGC organized a second Workshop on Continental Drilling for Scientific Purposes in 1978 that led to the report "Continental Scientific Drilling Program," issued in 1979. A key element in the report is the conclusion that, with advance planning, a great increase in scientific return could be yielded from the existing large investment in drilling by government and industry for a relatively small incremental expenditure. The report recommended that a National Continental Scientific Drilling Program be organized to bring about the necessary communication and coordination mechanism. As a result of the response of Federal agencies to the recommendations in the report, a Continental Scientific Drilling Committee was created under the Geophysics Research Board in January 1980. The United States Geodynamics Committee (USGC) will work closely with the Continental Scientific Drilling Committee to ensure coordination of the program with the relevant endeavors of the Geodynamics Committee, especially coordination with the program of deep reflection seismic profiling and the efforts of the USGC to bridge the gap between terrestrial and marine techniques for studying the continental crust and the continent-ocean transition.

The committee plans to work closely with scientists of other countries in dealing with problems pertinent to geodynamics. It has already taken steps in this direction in connection with the program of continent-ocean transects. Canadian and Mexican groups have joined the effort which will therefore result in a North American program of transects.

The International Union of Geodesy and Geophysics and the International Union of Geological Sciences are developing an international program of geodynamics for the 1980's. The Geodynamics Project of the 1970's formally ended in December 1979. As of March 1980 a title for the new program had not been adopted. The international program is developing in ways that are completely in harmony with the recommendations of the USGC. In particular, there will be a relative shift of

emphasis toward the continents and the continent-ocean transition for both scientific reasons and societal relevance, especially resources and natural hazards.

The USGC is increasingly recognizing the importance of understanding the thermal state of the earth's crust and mantle. To that end it took steps to organize the symposium on Thermal Structure and Evolution of the Earth at the meeting of the American Geophysical Union in December 1979. In addition the USGC agreed to cosponsor, with the Committee on Mathematical Geophysics of the International Union of Geodesy and Geophysics, a meeting on a similar theme to be held in California in July 1980. The topics of the reporters are likely to be revised somewhat to take account of this increased interest in the thermal state of the earth's interior.

Members of the Committee are: John C. Maxwell, chairman, Don L. Anderson, Albert W. Bally, Hubert L. Barnes, Arthur L. Boettcher, Bruce A. Bolt, William R. Muehlberger, Jack E. Oliver, David W. Scholl, Hartmut A. Spetzler.

Contractor: NATIONAL ACADEMY OF SCIENCES/
NATIONAL RESEARCH COUNCIL
Washington, D.C. 20418

Contract: DE-AT02-76CH93003

Title: III. Committee on Seismology

Person in Charge: J. W. Berg, Jr.

Scope of Work

The Committee on Seismology meets twice a year to discuss important topics in seismology; to review, with government agency personnel, the actions that have resulted from recommendations of the committee and its panels; and to take actions to assure a healthy science that can provide maximum benefits to the nation and to society.

These activities are directed at fulfilling the fundamental mission of the committee, which has been defined as follows: (a) to monitor major trends in seismology and pertinent developments in allied scientific and technical fields; (b) to provide special studies for government agencies on appropriate subjects or problems; (c) to observe and to advise on international seismological activities; (d) to advise government agencies on the operation of federally supported seismograph networks and data dissemination facilities and (e) to coordinate seismological activities in the National Research Council, particularly in the fields of earthquake engineering, rock mechanics, geodesy, geodynamics and geology.

The Panel on Earthquake Problems Related to the Siting of Critical Facilities has completed its report. It has been published (1980). The report identifies research needed to minimize earthquakes as a hazard in siting and constructing critical facilities.

The Panel on National, Regional, and Local Seismograph Networks met twice during the past year. A report is being prepared.

The joint Panel on Crustal Movement Measurements has met twice during the past year. A report is being written.

Two new panels have been formed to address: (a) deep refraction and reflection seismic studies and (b) problems in seismology related to data handling. As necessary, the committee establishes ad hoc groups to attack important problems such as these. Included in the studies are scientific and technical evaluations and consideration of implications for society.

Contractor: NATIONAL ACADEMY OF SCIENCES/
NATIONAL RESEARCH COUNCIL
Washington, D.C. 20418

Contract: DE-A101-79ER10442

Title: IV. Committee on Geological and Materials Sciences

Person in Charge: J. W. Berg, Jr.

Scope of Work

The Committee on Geological and Materials Sciences has been appointed by the Assembly of Mathematical and Physical Sciences of the National Research Council. A study in progress is reviewing the scientific and technological status of the border area between these two groups of sciences to: (a) identify and help ameliorate impediments to effective interdisciplinary interactions in universities, industry and government agencies; (b) examine the mechanisms through which basic interdisciplinary research needs are incorporated into the long-range planning for major projects in the geosciences; (c) examine the need for regional and/or national centers to provide special facilities; (d) support interdisciplinary conferences between geoscientists and materials scientists; (e) bring together more of the rank and file of the two fields who do not have a preexisting common interest and (f) stimulate the publication of state-of-the-art reviews with special emphasis on interdisciplinary research opportunities. The study is being conducted with members selected from academia, industry and government.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: AT03-76ER71045

Title: I. Porosity with Fluids: Origin and Effects on Physical Properties of Crustal Rocks

Person in Charge: A. M. Nur

Scope of Work

A. Physical Properties of Porous, Saturated Rocks (A. M. Nur)

A great variety of attempts have been made to model the pore space of rocks with the least number of parameters possible. Single-parameter models cannot adequately predict the properties of rocks. With two parameters it is possible to roughly predict closely related properties such as saturated compressional wave velocity (v_p) from dry v_p or v_p from shear wave velocity (v_s) at a given confining pressure. The two-parameter model, however, is inadequate in predicting properties not closely related, such as hydraulic permeability versus velocity. It is also insufficient for predicting the relative pressure dependence of physical properties in rocks. One way of gaining more fundamental insight into the nature of the pore space is by matching physical properties of rocks as a function of confining pressure. Here all measurements such as velocities, attenuation, permeability and electrical resistivity are made on the same rock and, preferably, the same sample as a function of confining and pore pressure. At present, an extensive experimental program is being carried out to obtain the seismic velocity, attenuation and permeability data needed. It is hoped that eventually enough rock types can be measured and a general theory developed relating all physical properties to pore space parameters.

B. Thermal Relaxation and Wave Attenuation in Rocks (E. Kjartansson)

Thermal relaxation is a well-known mechanism for adsorption of elastic wave energy in heterogeneous solids. The thermal expansivity of liquids is much greater than in rocks and even greater for gases, so the presence of pore fluid will increase the loss due to thermal effects. The theory of thermal relaxation in hot water/steam/melt systems has been developed. The frequency at which the elastic wave attenuation is greatest is inversely proportional to the square of crack thickness. One-millimeter cracks contribute to the attenuation in the seismic frequency band.

In water-saturated rocks the attenuation of compression waves (P-waves) is low at room temperatures, but increases rapidly with temperature above 40°C, with a quality factor (Q) of a few tens predicted for P-waves at temperatures approaching the critical temperature (374°C).

For partially saturated rocks two cases can be distinguished: (a) when the gas phase does not interact to a significant degree with the liquid phase, the attenuation is sensitive to the ratio between pore pressure and volume fraction gas, with a maximum in attenuation occurring at pore pressures of several tens of MPa's in gas-saturated rocks; and (b) interaction between the two phases--for example, when the gas dissolves in the liquid or when two phases of the same component are present--has the effect of increasing the attenuation, especially for small volume fractions of gas phases. Experimental results show greatly enhanced attenuation of P-waves in partially saturated rocks while S-wave attenuation is much less affected by the degree of saturation.

The final case considered is for partially melted rocks. When a melt is present, a change in pressure induces phase transitions which have the effect of significantly increasing the relaxed compressibility. Calculations for olivine imply a Q for compressional deformations on the order of 20.

Results of these studies should lead not only to refinement of existing reservoir exploration methods but also to the development of new methods utilizing attenuation to infer *in situ* pore pressure and permeability.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: EY-76-S-03-0326-045

Title: II. Seismic Velocity Variations and Attenuation to Delineate Geothermal Reservoirs

Persons in Charge: R. L. Kovach and A. M. Nur

Scope of Work

To measure seismic waveform distortion, a sound velocity log was run in a 1-kilometer-deep borehole in fractured granite near Lancaster, California. Full waveforms of selected time arrivals were digitized and analyzed for attenuative amplitude effects. The distortion of the waveform is readily apparent in the time domain as a broadening of the pulse, and in the frequency domain as a shift in the dominant frequency to lower values as the wave propagates. Where the borehole wall is significantly fractured, distortion is high, but the velocity is only weakly dependent on borehole character. This suggests that both velocity and amplitude measurements give useful information about the properties of the rock in boreholes. Specifically, the interest is in obtaining numerical values for the quality factor, Q. One direct measure of waveform distortion is to examine the position of the zero crossing with time as the wave propagates. If $d\tau/dt$ is the change in average zero crossing time, τ, per unit of travel time, t, it can be shown that $d\tau/dt = c/Q$ where c is the phase velocity. It has been found the value to $d\tau/dt$ correlates with the character of the borehole. Where the borehole is unfractured, the ratio is large, indicating little distortion. Where the borehole is fractured, the ratio is controlled by the degree of fracturing and the effect of intrinsic attenuation is swamped. Thus changes in velocity in these regions are not correlated with changes in $d\tau/dt$ inverse.

The results will provide the basis for improved, high-resolution sonic well logging techniques, with particular application to geothermal reservoir evaluation.

Contractor: STATE UNIVERSITY OF NEW YORK
Stony Brook, New York 11794

Contract: DE-AC02-79ER10412

Title: I. Thermally Induced Chemical Migration in Carbonate Rocks

Person in Charge: J. J. Papike

Scope of Work

This investigation concerns the thermally induced transport of major, minor and trace elements, and the use of rare earth elements (REE) as analogs for actinide element migration.

The geologic site chosen for this study is a late Jurassic quartz monzonite pluton intrusive into Cambrian limestones and shaly limestones in western Utah. This intrusion discordantly intersects nearly all depositional environments of a carbonate platform edge and outer shelf of Cambrian age. This is an ideal area to study chemical migration in carbonate rocks. Topographic relief of over 1 km permits comparative studies of effects of heat transfer and movements of solutions both parallel to and perpendicular to bedding. The quartz monzonite pluton acts as a trace-element-rich heat engine (or as an analog for ruptured cannisters containing high-level radioactive waste) capable of driving the migration of the REE into the trace-element-poor carbonate country rock.

One field season has been spent at this locality and the first carefully documented sample collection has been made. Preliminary results of the neutron activation analysis (INAA) and X-ray fluorescence (XRF) analysis demonstrate conclusively that migration of the trace elements has taken place over distances of several kilometers. Future work will document the migration both laterally and vertically from the pluton. In addition, it is planned to model the transport mechanism and make predictions about the degree to which radioactive nuclides may be expected to migrate during geologically significant periods of time.

This work is being done in collaboration with J. C. Laul (Battelle-Pacific Northwest Laboratories) who is conducting the NAA (INAA plus RNAA) analyses (see p. 13).

Contractor: TEXAS A&M UNIVERSITY
Center for Tectonophysics
College Station, Texas 77843

Contract: DE-AS05-79-ER10361

Title: I. Mechanical and Transport Properties of Rocks at High Temperatures and Pressures

Person in Charge: M. Friedman

Scope of Work

The purpose of this study is to determine what effects high temperatures and pressures have on the mechanical and transport properties of rocks. Three specific tasks are being addressed: (a) the physical nature of fracturing at depth; (b) fracture permeability of crystalline rocks as a function of pressure, temperature and hydrothermal alterations; and (c) mechanical properties of rocks at high temperatures and pressures.

A. The Physical Nature of Fracturing at Depth (N. L. Carter)

The primary goal of this research is to determine the fracture state and fracture stress under simulated conditions at depth where thermally activated processes are expected to play a major role. The boundary in pressure, temperature, strain-rate and stress (P-T-$\dot{\varepsilon}$-σ) space between elastic-brittle and transient-semibrittle behavior for selected isotropic and anisotropic crystalline rocks deformed in both hydrous and anhydrous environments will be determined experimentally. Focus is on: (a) transient creep flow laws and macroscopic fracture criteria which include effects of thermally activated processes; and (b) physical nature of fractures, to the atomic level, in the semibrittle regime and comparisons of the results with naturally deformed rocks.

Preliminary new creep data for Westerly granite, deformed to low strains, were obtained in dry compression tests in a Griggs solid-pressure-medium apparatus at 1,000 MPa confining pressure, temperatures from 470° to 765°C, constant stress differences of from 6,000 to 1,200 MPa, all in the α-quartz stability field. High-temperature transient creep data fit an exponential-decay flow law very well and were also fit to a power law, for comparison with previous work, with the result:

$$\varepsilon_t = 7 \times 10^{-5} \sigma^{2.2} t^{0.5} \exp\left(-\frac{30.5}{RT \cdot 10^{-3}}\right)$$

for stress in MPa; time, t, in seconds. The upper term of the exponential is the activation energy, E, whose value is 30.5 kcal/mole based on the experimental results to date. The subscript t refers to a transient state. Steady-state creep results best fit the power law:

$$\dot{\varepsilon}_s = 1.4 \times 10^{-9}\sigma^{2.9} \exp\left(-\frac{25.3}{RT \cdot 10^{-3}}\right)$$

where the subscript s refers to a steady state.

Differences in the activation energies and stress exponents for ε_t and $\dot{\varepsilon}_s$ are well within experimental uncertainties and are regarded as negligible.

The experiments and analyses indicate that high-temperature transient creep gives way to steady-state creep at strains less than one percent and generally in short times. Steady-state flow should thus dominate natural creep of granitic rocks at moderate to high temperatures. Preliminary optical and TEM analyses of the specimens indicate that these low creep strains are accommodated primarily by quartz, secondarily by micas, and little, if at all, by feldspars. This seems also to be true of the naturally deformed granitic rocks examined. The close accord of the activation energies for creep of granitic rocks observed here and in previous studies with those found for steady-state creep of quartzite also suggests that deformation of quartz controls the creep rate of granitic rocks. Under most favorable conditions for low energies, activation energies for creep of feldspars are too high, by about a factor of two, to account for the results for granitic rocks.

B. Fracture Permeability of Crystalline Rocks as a Function of Pressure, Temperature and Hydrothermal Alterations (B. Johnson)

The primary objective is to measure the variation in fracture permeability in Sioux quartzite, Westerly granite, and a fine-grained gabbro as a function of hydrothermal reaction with through-flowing distilled water and aqueous sodium carbonate (Na_2CO_3), sodium chloride (NaCl) and sodium chloride-magnesium chloride ($NaCl/MgCl_2$) solutions at temperatures to 350°C, fluid pressures to 30 MPa, and effective pressures to 70 MPa. The experiments are designed to evaluate the relative importance of dissolution and secondary mineral formation upon changes of fracture permeability when rock type and fluid compositions of geologic and/or engineering significance are varied. Two complementary studies will provide guidelines and insight into the permeability experiments: (a) experimental and theoretical study of the relationship between fracture asperity characteristics and the variation of room-temperature, fracture permeability with effective pressure; and (b) closed-system hydrostatic water-rock reaction experiments to

characterize the hydrothermal alterations likely to occur during the elevated-temperature, fracture permeability experiments.

C. Mechanical Properties of Rocks at High Temperatures and Pressures (M. Friedman and J. Handin)

For the range of temperatures and pressures (depths) likely to be encountered in geothermal recovery and in excavation and maintenance of underground-waste projects, previous work at Texas A&M University (Contract 13-2242, Sandia Laboratories) has demonstrated that: (a) crystalline rocks will probably be drillable even by conventional techniques, because of brittle behavior, right up to the temperatures of partial melting; and (b) under some reasonable assumptions, open boreholes in dry or water-saturated crystalline rock could fail in shear at only a few km depth or they could be stable to depths > 10 km at 700°C. Thus, although drillability does not appear to be a problem, the question of borehole stability is still open, especially since certain factors, in addition to time-dependent flow, remain to be evaluated. These include: (a) water-weakening at slow strain rates, (b) frictional sliding along pre-existing discontinuities, (c) effects of inherent planar anisotropies, and (d) the influence of the intermediate principal stress. Accordingly, the experimental investigation of borehole stability will continue with the experimental deformation of several different rock types (both room-dry and water-saturated), specimen configurations at temperatures to 1000°C, and effective pressures to 200 MPa. In order of priority, these are deformation of: (a) intact room-dry and water-saturated specimens of Mt. Hood andesite, charcoal granodiorite and Cuerbio basalt with independently controlled pore pressure at a strain rate of $10^{-7}s^{-1}$ to evaluate effects of water-weakening of strength and ductility; (b) pre-cut or prefractured wet specimens of these same three crystalline rocks to determine their ultimate and residual strengths, (c) thick-walled, hollow cylinders of two fine-grained crystalline rocks and selected anisotropic rocks, deformed to simulate borehole failure at depth, and (d) intact cylinders of metasedimentary rocks with strong planar anisotropy with their S-planes inclined at various angles to the load axis.

Contractor: THE UNIVERSITY OF TULSA
Tulsa, Oklahoma 74104

Contract: DE-AS05-79ER10400

Title: I. Stability of Natural Gas in the Deep Subsurface

Persons in Charge: C. Barker and M. K. Kemp

Scope of Work

The components of natural gas are reactive in the deep subsurface and may not survive under all conditions. The stability of natural gas in reservoirs of various lithologies is being studied using a combined theoretical and experimental approach.

A computer program has been developed using real gas data to calculate equilibrium in multicomponent (up to 50), multiphase (up to 30) systems simulating subsurface conditions to 12 km (40,000 ft.). This program has been used to investigate the stability of hydrocarbons in sandstone reservoirs by first considering clean sands and then sequentially adding feldspars and clays, carbonate cements and iron oxides. In all cases equilibrium compositions have been computed for low, average and high geothermal gradients; hydrostatic and lithostatic pressures; and with and without graphite. Graphite is present when deep gases are generated by the cracking of oil but is absent in reservoirs originally filled with dry gas. Similar calculations have also been made for limestone and dolomite reservoirs with various combinations of clays, iron minerals, anhydrite and sulfur, again with and without graphite. Natural gas shows considerable stability in sandstone reservoirs under most conditions, but its concentration in deep carbonates is much more variable and tends to a hydrogen sulfide-carbon dioxide (H_2S-CO_2) mixture except when an appreciable concentration of iron is present. Hydrogen is present at the 1-2 percent level for most lithologies.

A multicolumn gas chromatograph has been installed and calibrated with pure gases and synthetic mixtures. A Teflon ball mill for crushing samples has been built and tested and is now being used to release gases from samples obtained from deep wells in the Anadarko basin. The compositions of these gases are being compared with the compositions predicted from the computer program using the rock mineralogies and subsurface temperatures and pressures.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

Contract: EG-77-S-02-4392 006

Title: I. Organic Geochemistry of Outer Continental Margin and Deep Ocean Sediments

Person in Charge: J. M. Hunt

Scope of Work

The objectives of this study are to understand the nature and time scale of organic matter diagenesis and maturation leading to the origin and accumulation of petroleum in continental margin and deep sea sediments. Work has been completed on hydrocarbon type distributions in two Gulf Coast wells offshore south Texas. Mechanisms have been proposed involving three successive types of reaction in the formation of specific hydrocarbon structures such as normal and branched alkanes. Evidence for upward migration of the lighter hydrocarbons (C_5H_{12} through $C_{11}H_{24}$) has been observed at sediment depths in the range of 3 to 5.0 km (10,000 to 16,000 feet).

Cuttings from an offshore well drilled to 5 km (16,000 feet) in the Mississippi Canyon area are currently being obtained to compare with the Texas well results. The Mississippi area has a lower geothermal gradient and more sapropelic organic matter. It is expected that samples from a fourth well in the Gulf Coast will also be obtained where oil was encountered at 6.7 km (22,000 feet) and the hole bottom temperature was 250°C. Thermodynamic considerations would predict a gas at those temperatures. It is felt that an investigation of this well is important in understanding the oil phase-out depth under natural conditions.

Contractor: YALE UNIVERSITY
Department of Geology and Geophysics
Box 6666 Yale Station
New Haven, Connecticut 06511

Contract: DE-AS02-79ER10445

Title: I. Experimental Study of Opening Mode Crack Growth in Rock

Person in Charge: R. B. Gordon

Scope of Work

Experiments show that a zone of dilatation forms around an opening mode crack advancing through rock. The extent of the zone of dilatation determines the amount of rock debris produced by the advancing crack and the amount of new surface area present in the rock after passage of the crack. The relationship between rock microstructure, crack-induced dilatation and fracture toughness is being examined with stable crack growth experiments in the laboratory. A double cantilever beam configuration for specimens and a testing procedure that permits reproducible measurements of fracture toughness have been developed. Motion pictures made during crack growth tests are used to reveal the development of the crack path and the changes of microstructure surrounding the crack. The development of a zone of plastic deformation surrounding the crack is also shown by cyclic-loading internal-friction tests. Experiments are done with a fluid phase present so as to detect stress-corrosion effects. Quartzite and marble have been studied and additional rock types will be examined. Fracture characteristics such as the size and distribution of mineral phases and the distribution of microcracks in the rock will be related to rock microstructure and compared with the observed structure of joints in the field. The results should prove useful in evaluating the fracture characteristics of a rock formation from its structure as determined from core or other samples, as well as contributing to understanding of the basic mechanics of opening mode crack growth in rock.

GEOSCIENCES RESEARCH (AEC/ERDA/DOE)
(Historical Summary)
Operating Funds - Thousands

ON-SITE	FY 1969	FY 1970	FY 1971	FY 1972	FY 1973	FY 1974	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980
ANL	$ 0	$ 0	$ 50	$ 50	$ 201	$ 60	$ 98	$ 60	$ 50	$ 100	$ 140	$ 240
BNL	—	—	—	—	65	41	0	—	—	—	—	—
LASL	0	0	0	0	95	291	630	906	750	810	1,084	1,420
LBL	—	—	—	—	—	295	315	816	620	660	735	995
LLL	—	—	—	—	—	—	75	135	130	250	630	910
ORNL	195	195	180	145	0	0	50	140	150	180	240	280
PNL	75	105	76	85	100	123	175	265	250	280	450	565
Sandia-A	—	—	—	—	—	—	245	500	450	500	800	1,165
On-Site Total	$ 270	$ 300	$ 306	$ 280	$ 461	$ 810	$1,588	$2,822	$2,400	$2,780	$4,079	$5,575
OFF-SITE												
U/Alaska (Akasofu)	$ 21	$ 20	$ 21	$ 25	22	45	41	92.4	78.8	—	85.4	84.3
U/Alaska (Pulpan)	39	40	40	44	0	102	79	31.5	41.8	58.6	112.7	86.6
U/Alaska (Kienle)	—	—	—	—	—	—	90T	—	—	—	—	—
U/Arizona (Hill)	—	—	—	—	—	—	—	—	—	—	—	90.598
Arizona State (Navrotsky)	—	—	—	—	—	—	—	—	—	—	—	34.96
Aspen Institute (Roberts)	—	—	—	—	—	—	—	—	—	47.6	57.2	70.5T
Brown U. (Hermance)	—	—	—	—	—	—	—	—	—	—	94.7	140
U/California (B) (Reynolds)	70	75	61	61	61	60	63	130	127	148	127	167.9
U/California (B) (Price)	0	30	37	65	—	—	—	—	—	—	—	—
U/California (D) (MacGregor)	—	—	—		—	—	—	—	—	71.2	61.4	23.04
U/California (LA) (Knopoff)	—	—	—	—	—	—	—	—	—	—	—	—
U/California (LA) (Anderson/Warren)	—	—	—	—	—	—	45	55	41	50	103.3	107
U/California (LA) (Kennedy)	62	60	60	60	60	60	60	60	60	60	72	72T
Carnegie-Mellon (Kohman)	—	—	—	—	40	38T	—	—	—	—	—	—
U. Chicago (Anderson)	—	—	—	—	—	—	—	—	—	—	—	54.036
Columbia U. (Fairbridge)	—	—	—	—	—	30	75T	—	—	—	—	—
Columbia U. (Sykes/Jacobs)	0	70	70	66	80	137	180	200	240	256	274	311.8
Columbia U. (Scholz/Engelder)	—	—	—	—		—	—	65	62.1	75	100	140
Ft. Lewis College (Ellingson)	—	—	—	—	—	—	—	2	—	—	—	—
Indianapolis Center for Advanced Research (Dines)	—	—	—	—	—	—	—	—	—	—	—	80
MIT (Grodzins)	170	164	94	50	0	—	—	—	—	—	—	—
MIT (Aki)	44	29T	—	—	—	—	35	100	130	112.6	142	152
MIT (Simmons)	—	—	—	—	—	—	—	—	—	100	100	90
NAS/NRC (Petrie: Alaskan Earthquake)	—	—	—	—	—	—	—	—	—	—	—	—
NAS/NRC (Hart: Studies in Geophysics)	17	16	11	4	2	3	4	4	4	—	6	27
NAS/NRC (Berg: Committee on Seismology)	—	—	—	—	—	—	—	8.8	9	8.8	8.8	8.8
NAS/NRC (Berg: Geological/Materials Sciences Study	—	—	—	—	—	—	—	—	—	—	14.17	—
NAS/NRC (Hart: Geodynamics Committee)	—	—	—	—	—	—	—	—	—	—	15	20
NAS/NRC (Hart: CSDC)	—	—	—	—	—	—	—	—	—	—	—	60
Naval Weapons Support Center (Tanner)	—	—	—	—	—	—	—	5.6	—	—	—	—
NOAA (Donnelly)	—	—	—	—	—	—	—	—	—	5	—	—
U/Pennsylvania (Faul)	19	25T	—	—	—	—	—	—	—	—	—	—
Pennsylvania State University (Martin)	—	—	—	—	—	—	—	—	—	—	—	61.646
Princeton U. (Hollister)	—	—	—	—	—	—	—	22.9	—	—	—	—
Rice U. (Baker)	—	—	—	—	—	—	—	—	—	—	—	15.6
Stanford U. (Nur/Kovach)	—	—	—	—	—	—	—	59.6	65	103.6	146.6	140
SUNY, Stony Brook (Schaeffer)	—	—	—	—	54	51T	—	—	—	—	—	—
SUNY, Stony Brook (Papike)	—	—	—	—	—	—	—	—	—	—	50.7	59.1
Texas A&M (Friedman)	—	—	—	—	—	—	—	—	—	—	62.5	208.485
U/Tulsa (Barker)	—	—	—	—	—	—	—	—	—	—	59.7	N.F.X.
USGS (Haas)	—	—	—	—	—	—	—	—	9.1	54	54	—
U/Wisconsin (Wang)	—	—	—	—	—	—	—	—	—	—	—	57.39
Woods Hole (Hunt)	—	—	—	—	—	—	—	—	30.5	—	102	140.68
Yale U. (Gordon)	—	—	—	—	—	—	—	—	—	-	45.14	3.6
Yeshiva U. (Cameron)	41	36	16T	—	—	—	—	—	—	—	—	—
Total Off-Site	$ 483	$ 565	$ 410	$ 375	$ 319	$ 526	$ 672	$ 842.75	$ 898.3	$1,150.4	$1,894.31	$2,507.035
TOTAL GEOSCIENCES	$ 753	$ 865	$ 716	$ 655	$ 780	$1,336	$2,260	$3,664.75	$3,298.3	$3,930.4	$5,973.310	$8,082.035

TOPICAL INDEX

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*U.S. GOVERNMENT PRINTING OFFICE : 1980 0-310-912/1059