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Summaries of Physical Research in the Geosciences

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FOREWORD

The Department of Energy supports research in the geosciences in order to provide a sound foundation of fundamental knowledge in those areas of earth, atmospheric, and solar-terrestrial sciences that are germane to the Department of Energy's many missions. The Division of Engineering, Mathematical and Geo-Sciences--part of the Office of Basic Energy Sciences which is under the Director of Energy Research--supports the Geosciences Research Program. The participants in this program include the major Department of Energy laboratories, industry, universities, and other governmental agencies. Such support, formalized by a contract between the Department of Energy and the organization performing the work, provides the funds for salaries, equipment and other materials, and an overhead allowance.

The summaries in this document, prepared by the investigators, describe the scope of the individual programs and detail the research performed during 1981-1982. The Geosciences Research 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 either directly or indirectly to the Department of Energy's technological needs.

INTRODUCTION TO THE GEOSCIENCES RESEARCH PROGRAM OF THE OFFICE OF BASIC ENERGY SCIENCES

The Geosciences Research Program is directed by the Department of Energy's Office of Energy Research, within the Office of Basic Energy Sciences, Division of Engineering, Mathematical, and Geo-Sciences. 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. The purpose of this program is to develop geoscience or geoscience-related information relevant to one or more of these Department of Energy objectives or to develop a broad, basic understanding of geoscientific materials and processes necessary for attaining long-term Department of Energy goals. In general, individual research efforts supported by this program may involve elements of all four objectives.

The Geosciences Research Program is divided into five broad categories:

- Geology, geophysics, and earth dynamics
- Geochemistry
- Energy resource recognition, evaluation, and development
- Hydrologic and marine sciences
- Solar-terrestrial-atmospheric interactions.

The following content outline 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 have components in more than one of the categories or subcategories listed.

1. Geology, Geophysics, and Earth Dynamics

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

   B. Evolution of Geologic Structures. Research bearing on the history and development of geologic structures (e.g., folds, faults, landslides, and volcanoes) on a local or subregional scale.

   C. 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.

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

   E. Continental Scientific Drilling Program (CSDP). Research on advanced technology and services as well as scientifically motivated projects concerned with utilizing 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 the drill hole as an experimental facility for studying 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. Research includes aspects of drilling technology development for such hostile environments. Part of a multiagency (U.S. Geological Survey, National Science Foundation, Department of Energy, and Department of Defense) coordinated program.

2. Geochemistry

   A. 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.

   B. 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.

   C. Organic Geochemistry. Research on naturally occurring carbonaceous and biologically derived substances of geologic importance, including research on the origin and development of coal, petroleum, and gas.

   D. Geochemical Migration. Research on chemical migration in materials of the earth's crust, emphasizing a generic rather than specific understanding, which may (ultimately) lead to predictive capability. These experimental and theoretical studies focus on chemical transport induced by pressure, temperature, and composition gradients within, between, and by a phase or phases. This component is part of a multiagency (Department of Energy, National Science Foundation, U.S. Geological Survey) joint program.

3. Energy Resource Recognition, Evaluation, and Development

   A. Resource Definition and Utilization. The principal goal of this research is to develop new and advanced techniques that are physically, chemically, and mathematically based, for energy and energy-related resource exploration, definition, and use.

   B. 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.

   C. Magma Energy Resources. Field, laboratory, experimental, and theorectical research bearing on the origin, migration, emplacement, and crystallization of natural silicate liquids or their synthetic analogues. These studies emphasize the extraction of energy from such liquids.

D. Information Compilation, Evaluation, and Dissemination. These research activities are principally oriented toward evaluating existing geoscientific data to identify significant gaps, including the necessary compilation and dissemination activities.

4. Hydrologic and Marine Sciences

A. Ground Water Hydrology. Research related to chemical and physical principles underlying the flow of water through porous and permeable rocks near the earth's surface.

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

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

5. Solar-Terrestrial-Atmospheric Interactions

A. Magnetospheric Physics and Chemistry. Research directed toward developing a fundamental understanding of the 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.

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

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

D. Meteorology and Climatology. Interrelationships of weather and climate with energy systems.

PART I

ON-SITE

Contractor: ARGONNE NATIONAL LABORATORY
Argonne, Illinois 60439

Contract: 109 ENG 38

Title: Geosciences Program

Persons in Charge: F. A. Cafasso and M. J. Steindler

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

The primary objective of this program is to obtain reliable thermodynamic quantities for zeolites and minerals related to them. Systems chosen for study are those that are of importance in vapor-dominated, hot dry-rock geothermal systems, and in the treatment or storage of nuclear waste. Experimental goals are achieved by means of several techniques, namely, reaction (solution and combustion), high-temperature drop, low-temperature adiabatic, and differential scanning calorimetry.

Current studies are concerned with natrolite, scolecite, mesolite, pollucite and heulandite. Among those zeolites which we will study in the immediate future are mordenite and clinoptilolite.

Part of the present effort is concerned with the estimation of thermodynamic quantities for those zeolites. In this connection, the effects of cation substitution and of zeolitic water are currently of particular interest.

B. Trace-Element Transport by Fluid Flow (M. G. Seitz and R. A. Couture)

Infiltration of rock cores is used in this program to study the composition of pore fluids in subsurface rocks and to study solid/liquid interactions within the rock matrix. Pore fluids in rock cores are sampled by "elution," i.e., displacement under pressure, and by leaching methods. Reaction of aqueous solutions with rocks during fluid flow is also studied experimentally in rock columns. The program is designed to provide fundamental geochemical knowledge on transport of dissolved material by fluid flow, which is relevant to an understanding of natural processes such as ore formation, and to managing hazardous waste in a geologic repository.

The infiltration experiments allow study of trace-element transport, with all the complications of ion exchange, leaching, dissolution and precipitation, differences in major element concentrations, and diffusion in the rock, under flow conditions.

The major ion composition of ground water is an important consideration in transport of trace elements. In many cases, it is also useful as a tracer for ground-water movement. Ground water is sometimes difficult or impossible to sample in wells, but intergranular pore fluid can be sampled by techniques developed in this program, even in relatively impermeable rocks such as granites. Thus, sampling of pore fluid is complementary to other techniques for sampling ground water.

At present, work is in progress on salinity versus depth in deep drill holes in the Canadian Shield and in granite plutons.

C. Migration of Heavy Element Species in Geologic Strata
(N. J. Susak, A. M. Friedman, S. M. Fried, and J. C. Sullivan)

The scope of this program is to determine the geochemical factors upon which the mobility of radionuclides in geologic strata depend. The particular area of interest is the mobility of the actinides and the fission products. The important chemical properties under investigation include the oxidation states, the nature and stability of the complexes formed, solubility of compounds in ground waters, self-diffusion in rock strata and a study of hydrolysis reactions. The dynamics of reactions of the radionuclides with the rock matrix as well as with ground waters are being studied because they affect the patterns and rates of migration.

The objective of collecting information on speciation, oxidation states, and complex formation is the correlation of these data with mobilities of actinide elements and other relevant radionuclides. When the factors determining the mobilities of these ions are understood on a basic level, the information will provide the basis for the assessment of the safety of nuclear waste repositories in deep geologic environments. It will then be possible to make a credible assessment of the feasibility of deep geological radionuclide repositories, and make convincing long-term extrapolations concerning their safety.

In light of the proposal to emplace nuclear processing wastes in basalt, the reaction of neptunium with basalts has become a subject of study. Neptunium is of interest because it represents a potential long-term environmental hazard due to its long half-life and its relatively large abundance in nuclear processing wastes. Its redox chemistry is such that the pentavalent state is phenomenologically stable under a wide range of conditions, unlike the other actinides. In aqueous solution, neptunium also has a small tendency to interact with complexing species or be adsorbed on mineral surfaces. Thus, neptunium may be a most difficult cation to immobilize in waste disposal schemes.

Among the factors being studied to assess the effectiveness of basalts for immobilization of neptunium are the reducing power of basalts, the mineralogy of basalts, and the composition of ground waters.

Thus, basalts are quite capable of reducing Np(VI) to lower oxidation states. In the case of Columbia River basalts, Np(V) appears to be the predominant reduced state. Thus, there is a possibility that neptunium may not be immobilized following a breach in the disposal site. The reduction to Np(IV) is dependent on the reducing capacity (i.e., FeO content) and possibly the minerology. The presence of olivine even when foresterite-rich should enhance the ability of the rock to reduce Np(VI) to Np(IV). The composition of the ground water may also be important in determining the extent of reduction.

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

Contract: DE-AC03-76SF00098

Title: Geosciences Program

Person in Charge: P. A. Witherspoon

Scope of Work

The Geosciences Program at Lawrence Berkeley Laboratory consists of nine projects. These projects are broadly based fundamental studies that support development of hot water energy storage, stimulated recovery of oil, isolation of radioactive wastes, and uranium resource evaluation and recovery. Studies include formulating theoretical concepts, developing new instrumentation, executing experimental measurements in the laboratory and field, and simulating processes using computer models.

A. Nonisothermal Reservoir Dynamics (P. A. Witherspoon and C. F. Tsang)

This project encompasses a wide range of fundamental studies of fluid, heat, and solute transport in underground formations. These studies are relevant to underground thermal energy storage, geological isolation of nuclear waste, chemical wastes disposal, and other energy-related projects. The goal is to better understand various physical and chemical processes in porous or fractured media and their effects through analytical and numerical modeling. At the same time, graduate students and postdoctoral fellows will be trained in the expertise and experience that will allow them to participate in further advancements in this field.

Specifically, the following general topics will be addressed:

- A New Finite Element Method to Simulate Solute Transport in Fractured Media. Solute transport in porous media has been extensively investigated in the last three decades. However, the role of fractures in the transport of fluids is an active issue that figures importantly in the geologic disposal of hazardous waste. A fundamental study will be made to solve a two-dimensional transient transport problem in a fractured porous medium. A novel finite element method will be developed to model the fractures in a discrete fashion by one-dimensional, two-nodal-point elements. This is part of the laboratory's effort to develop advanced techniques to simulate heat and mass flow through fractured porous systems.

- An Advanced Testing Method with Coupled Pressure, Tracer, and Thermal Measurements. Conventional well testing methods use pressure measurements. They are able to determine two main parameter groups associated with a porous medium. In a fractured porous medium, key parameters, such as fracture apertures, separations, and orientations, will be averaged and hidden in these two parameter groups. The present work will develop new methods

that require not only pressure measurements, but also thermal and tracer measurements. Each of these three sets of measurements involves a different physical and chemical process which is affected by different characteristics of the fractured porous medium. By coupling these results researchers hope to arrive at a new well testing method that will help to characterize a fractured porous medium.

- The Modeling of Coupled Thermomechanical Hydrogeological Processes in a Fractured Porous Medium. Key processes in underground formations in many applications involve thermal, hydrogeologic, and mechanical effects. These correspond to heat flow, fluid flow, and mechanical stress-strain behavior in the formations. Currently, techniques are available to study thermomechanical and thermohydrological processes. However, a three-way coupled process involving all three components cannot yet be adequately handled. Lawrence Berkeley Laboratory has in recent years developed a numerical model to study this coupling effect. Once the model is completed the code can be validated. The model can then be applied to various generic problems. Understanding such coupled processes is important to many applications.

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

Properties and behavior of fluid-bearing rocks in subsurface environments are substantially different from rock samples brought to the surface and tested at surface conditions. Analyses of a number of subsurface reservoir operations and processes require reliable information on the properties and behavior of the fluid container (porous rocks) at reservoir conditions. The purpose of this project is to measure these properties under simulated reservoir conditions of pressure, temperature, and fluid saturation, and to determine how these properties will change in response to changing reservoir conditions. Models are also being developed that allow property changes to be predicted for changes in environmental conditions. These models will have important applications to numerical simulation of reservoir behavior.

Rock-fluid properties that are measured individually with existing equipment, and are to be measured simultaneously (sequentially) with newly constructed apparatus, include absolute permeability, electrical resistivity, elastic wave velocities, pore and bulk compressibilities and thermal expansions, and thermal conductivities. Rocks and fluids used in the studies include those which would be encountered in geothermal reservoirs, oil and gas reservoirs, subsurface energy storage projects, and underground nuclear disposal operations.

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

This project covers theoretical and experimental studies concerning the thermodynamic properties of aqueous electrolytes. The components important in natural waters and brines are emphasized. The resulting data are important in understanding certain geothermal and other natural resources. Moreover, this information has a wide range of applicability, since similar solutions arise in many industrial processes.

The experimental program involves measuring the heat capacity and the density of solutions in the range 0 to 300°C and 0 to 1 kbar. These measurements suffice to give a comprehensive equation of state, provided that other thermodynamic properties are known for a particular system at room temperature and pressure.

The theoretical work has yielded equations predicting the properties of mixtures based on the knowledge of the pure component solutions in water. In a number of cases, the calculated results for mixed brines are well verified by direct measurement. Phase equilibria can be predicted. Calculations for solutions of Na^+ with $CO_3^=$, HCO_3^-, OH^-, and Cl^- were recently completed as were those for Na_2SO_4 and for $KHCO_3$-KCl mixtures. Current experimental work relates to $MgSO_4$. When these data are combined with earlier results a comprehensive treatment can be given of phase equilibria over a range of temperature for solutions containing the geochemically important ions Na^+, K^+, Mg^{++}, Ca^{++}, and Cl^-, $SO_4^=$, CO_3^-, HCO_3^+, OH^-.

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

The objective of this project is to understand factors controlling ground-water chemistry by measuring the dissolution of common rock-forming minerals in aqueous solutions of 25 to 400°C and 0.1 to 50 MPa. The results are used to test rock-water interaction models and refine existing rock-water interaction computer codes and data bases. Such refinements are needed before chemical transport can be accurately modelled in water-saturated rocks.

Albite solubility measurements along the two-phase water saturation curve indicate that serious errors exist in the high temperature dissociation constants for the aqueous aluminum species, that current electrolyte models do not adequately account for ionic strength variations, and that the measurement of pH in quenched aqueous samples is subject to unpredictable error. Experiments to measure the solubility of diaspore α-Al(O)OH as a function of HCl or NaOH concentration between 150 and 350°C are being conducted to determine dissociation constants for the principal aluminum species. High temperature electrodes are being designed to meausre pH of the aqueous phase over the same temperature range.

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

The major concern of this project is to measure physical properties of silicate liquids (over a temperature range of 1300-1800 K) covering the range of those silicate liquids that exist in nature, in order that the generation of magmas deep in the earth, their ascent toward the surface, and their subsequent cooling can be quantified.

Preliminary measurements of the velocity of sound waves in multicomponent silicate liquids, which are needed to derive liquid compressibilities, show velocity has little temperature dependence, and that its variation as a function of composition is more restricted than the derived compressibilities. This conclusion depends upon knowing the density, and how it varies, over the natural range of liquids. Measurements have been made which, in conjunction with published data,

allow the density of any anhydrous natural silicate liquid to be calculated at 1 bar. Laboratory data, cast in terms of partial molar volumes of liquid oxide components (SiO_2, TiO_2, Fe_2O_3, MgO, CaO, Na_2O, and K_2O), are concordant to within 1-2% of the measured densities.

The heats of fusion of Fe_2SiO_4 and $KAlSiO_3$, both compounds which melt incongruently, have been determined. In the iron silicate, FeO disproportionates to Fe and Fe_2O_3 on melting, the latter component being dissolved in the liquid. A calorimeter to extend the working range above 1600°C is being designed, for the heats of fusion of the refractory phases Mg_2SiO_4, Al_2O_3, $NaAlSiO_4$, $KAlSiO_4$ have yet to be measured.

A solution model applicable to all natural silicate liquids has been formulated using a combination of experimental data on the composition of coexisting solids and liquids, and the appropriate thermodynamic data on the chosen multi-oxide components. The model allows the temperature of solid-liquid equilibria to be recovered to ±30 degrees within the range 1000-1700 K for any of seven different solid solution minerals. At present the model is being used to unravel some of the complexities of the equilibration of calcium-rich pyroxene with liquid.

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

Fundamental aspects of transport phenomena accompanied by chemical reactions in natural flow systems are being studied theoretically. The approach is based on the thermodynamics of irreversible processes, and allows consideration of nonequilibrium states of chemical reactions, study of systems which have evolved to nonequilibrium steady states, and inclusion of thermodynamic coupling of transport processes. Initial work has provided solutions to solute transport problems, formulated in the context of the classical transport theory, in which nonequilibrium chemical reactions are described by linear rate expressions. These solutions have served as references for comparison with results obtained from systems with nonlinear reaction kinetics. These investigations are being extended to steady-state and time-dependent systems with thermodynamic coupling between transport processes. The objective of the work is to derive descriptions of phenomena associated with chemical transport in natural systems which account directly for a system's irreversibility and produce quantitative results consistent with experience and with thermodynamic principles.

G. Aqueous Solutions Data Base for Nuclear Waste Disposal (S. L. Phillips)

The objective of this project is to publish critically evaluated basic data on relevant properties of aqueous solutions to high temperatures and pressures. Tables of recommended values are generated from both theoretical equations and empirical interpolating equations using computer-assisted methods. New methods for calculating or presenting data are emphasized.

The current emphasis is on providing mathematical equations and tabulated values to be used for calculations and in computer codes for the disposal of nuclear wastes from both commercial and defense facilities covering the following three major categories: leaching, migration, and corrosion in aqueous media. Of immediate interest are values of the solubility of those species which have been identified as key elements such as plutonium, uranium, and neptunium, and proposed canister materials such as glass, ceramics, and metals. One result of this work is the identification of areas whose data are lacking or are inadequate, and recommendations for research designed to provide the needed data.

Besides publishing critically evaluated data, the project includes research in calculating stability constants, solubilities, and adsorption equilibria to high temperatures; as well as computerized storage and retrieval of tables of data.

H. Deep Electromagnetic Sounding of the Crust (H. F. Morrison and N. E. Goldstein)

Variations of electrical conductivity within the crust are related to geologic structure and zones of past and present hydrothermal activity. Interpreted with thermal and seismic data, sounding data can provide important information on the thermal condition of the crust, including possible melt zones. The magnetotelluric method is the most common deep electromagnetic sounding method in use, but the data are often subject to severe interpretational problems because of distortions in the telluric currents by lateral boundaries, even those at some distance from the point of measurement. To overcome these problems the laboratory has been studying the feasibility of deep sounding by a controlled-source electromagnetic method in which a large alternating current is applied to a loop transmitter. Because the field amplitudes fall off as the inverse cube of the distance between transmitter and receiver, the secondary fields tend to be representative of the conductivity-depth distribution between transmitter and receiver.

A controlled-source electromagnetic sounding has been made over an area in central Nevada where higher-than-normal temperature gradients and a shallow crystal conductivity anomaly were previously observed. To obtain adequate depth of exploration in this area of generally high surface conductivities, the laboratory used a loop 2 km on a side and occupied receiver stations as far as 30 km from the loop. This approach required geomagnetic noise cancellation by a remote reference magnetometer whose signals were FM-radio telemetered to the receiver station. Data processing was done on-site by an in-field computer.

I. Effect of Fracture Characteristics Upon Acoustic Wave Propagation in Boreholes (M. S. King)

Fluid flow in rock is governed by the product of a single rock parameter, permeability and the hydrological potential gradient existing in the rock mass. The determination of permeability is critical to any endeavor where a knowledge of fluid is required. Such fields of interest include geothermal energy extraction, oil and gas recovery, deep crustal

studies, energy storage in aquifers, and the storage of hazardous wastes. In rocks of low porosity, including many igneous, metamorphic, and massive calcareous rock types, the in situ permeability is controlled by the presence of fractures rather than by rock matrix permeability, as determined on intact laboratory samples.

Geophysical borehole methods are available for detecting the presence of fractures adjacent to a borehole, and therefore potentially for assessing the rock mass permeability. In particular, the borehole sonic log has shown considerable promise for locating fractures in rock.

A study is being conducted of a field experiment which will provide digitized sonic waveform measurements across single horizontal, isolated fractures intersecting a borehole in a crystalline rock mass. The permeability of this single fracture will be measured using the conventional straddle packer technique, and the results compared. The field tests will be extended to zones where systems of fractures intersect the borehole, and again the results of sonic and conventional tests will be compared. In this way it is anticipated that correlations will be established between acoustic-wave parameter and the permeability of the rock mass adjacent to a borehole.

J. Continental Scientific Drilling Program: Site Studies and Downhole Sampler (A. F. White and J. M. Delany)

The focus of the LBL program is to geochemically characterize and evaluate the hydrothermal-magma system beneath the Valles Caldera, New Mexico for its potential as a CSDP site. The interrelationships between the shallow geothermal reservoir and the deep-seated hydrothermal-magma system are being investigated from observed fluid and isotopic compositions, metamorphic paragenesis and theoretical evaluation of water-rock interaction at deeper levels than have been reached by drilling to date. Currently in progress is a wellhead sampling program of a number of relatively deep (7000 ft) wells in the Baca geothermal field. This sampling program is a cooperative effort involving the LBL-CSDP program and the Union Oil Company of California, USGS, LANL, and U.C. Berkeley. Detailed petrographic and x-ray analyses of drill cuttings from the same wells are also in progress. Work is continuing on the conceptual design and engineering feasibility of a downhole sampler to be used at temperatures to 500°C.

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

Contract: W-7405-ENG-48

Title: I. General Geosciences

Person in Charge: A. G. Duba

Scope of Work

Work in progress at LLNL focuses on the physical and chemical properties and responses of earth materials, and in particular, on developing computer models that will aid in predicting and understanding these properties and responses. Our current effort is divided among studies of aqueous geochemistry, basic rock mechanics, seismology underground imaging, electrical properties of olivine and pyroxene, and diffusion in minerals.

A. Aqueous Geochemistry: Thermodynamics and Transport in Aqueous Electrolyte Solutions (J. A. Rard and D. G. Miller)

The goal of this project is to obtain experimental thermodynamic and transport data of interest to certain geochemical systems, especially those related to radioactive waste isolation problems. These data can also be applied to sediment water interactions related to diagenesis.

B. Basic Rock Mechanics: Migration of Molten Rock (H. C. Heard, F. E. Heuze, W. B. Durham)

The research is directed toward laboratory studies of thermal and thermomechanical properties of potential respository rock types and a modeling study of the movement of a rock melt that is produced in the crust toward the surface. The emphasis of our rock mechanics research continues to be directed toward problems associated with storage of radioactive waste, but the results of our research are of basic interest and could be used in a variety of problems associated with igneous rocks.

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

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. This involves developing improved laboratory and field instrumentation, acquiring fundamental data on the properties of materials under varied conditions in the laboratory, and improving the overall data interpretation process.

D. Electrical Conductivity and Temperature in the Upper Mantle (A. G. Duba) (joint project with T. J. Shankland at LLNL)

The thermoelectric effect in the mantle minerals olivine and pyroxene will be measured as a function of temperature, orientation, oxygen fugacity, and iron content. The effect of Mg/Si nonstoichiometry on mineral conductivity will also be studied. The results apply to inference of upper mantle temperatures from electrical data. While there are seismic models to explain the low velocity zone (LVZ) as a solid-state phenomenon not requiring partial melting, the most well-constrained laboratory electrical measurements are most consistent with the partial melting hypothesis for the high conductivity layer (HCL) apparently associated with the LVZ. If the LVZ/HCL is not a partial melt layer, then mantle geotherms would be considerably lower than previously inferred on the basis of a partial melt zone under extensive regions of the earth. Hence, it is necessary to better understand electrical conduction in mantle minerals to find whether electrical data are a serious constraint on the low temperature geotherms suggested by solid state explanations of the LVZ.

E. Diffusion in Silicates (R. H. Condit, H. C. Weed, and A. J. Piwinskii)

We are currently investigating one aspect of atomic transport in silicate minerals: grain boundary diffusion of oxygen. We are examining oxygen diffusion in grain boundary regions of forsterite, Mg_2SiO_4, between 1100 and 1370°C under atmospheric pressure. The boundaries contain impurities, often 5 μm, and sometimes 100 μm, thick. They have been identified by electron microprobe analysis as being close to diopside in composition, although aluminum and iron are also present. Our forsterite specimens are in the form of sandwiches of platelets having their b-axes normal to their planes and the other two directions random. Oxygen-18 tracer is used and is made radioactive by ion bombardment in a Van de Graaff accelerator, and autoradiography then allows us to follow the diffusion paths of the tracer.

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

Contract: W-7405-ENG-48

Title: II. Continental Scientific Drilling Program

Person in Charge: A. G. Duba

Scope of Work

Lawrence Livermore National Laboratory's role in the Continental Scientific Drilling Program (CSDP) is to provide information and data management services.

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

The information and data management project provides data bank and information services for the CSDP as follows: subsurface data from programmatic drilling by federal agencies and new wells drilled by industry that offer opportunity for cooperative efforts, and a computerized data bank for drill hole data acquired in CSDP projects. Information on plans and drilling activities are disseminated to the scientific community. The data base currently lists 1860 drill holes for which up to 25 parameters of information are stored. Drill holes may be selected and ordered on any parameter.

B. Transport Properties of Rock Melts Relevant to Continental Drilling (A. J. Piwinskii, F. R. Ryerson and H. C. Weed)

Calorimetric and viscometric data, as well as data on oxygen and chemical diffusion, on melts ranging from granitic to basaltic in composition are of vital importance in the interpretation of the chemical and physical evolution of magmas such as those in Kilauea Iki lava lake and in targets selected for deep Continental Drilling. In addition, similar data on simplified analogue chemical systems, (e.g., albite-anorthite-diopside), can provide the basis for development of a predictive understanding of important transport properties in more chemically complex systems.

The proposed joint research effort will take advantage of unique experimental facilities at both LLNL and SNL. The high temperature calorimetric, oxygen diffusion and viscometric facilities at LLNL will be complemented with high pressure, high temperature viscometric studies at SNL employing the large volume internally heated pressure vessel. It is anticipated that LLNL personnel would have the advantage of using the SNL facilities on-site.

C. Thermal and Petrologic Studies of Large Silicic Systems (L. W. Younker, T. A. Vogel, and P. W. Kasameyer)

Poor definition of what a drill hole might encounter reduces the effectiveness of scientific planning for drilling toward a continental

magma system. Smith (1979)* has recently published petrologic models of magma systems formed by the interaction of primary magma with crustal material. These models, based primarily on observations of eruption products, predict the occurrence of major thermal and petrologic boundaries in large silicic systems after eruptions cease. Two specific systems will be studied: the Elkhorn Mountain Volcanics/Boulder Batholith and the Valles Caldera. At each location, Smith's model will be tested by comparing the calculated boundary depths with observations of the exhumed Boulder Batholith. For the Valles, the calculated boundary depths will be used to predict conditions to be encountered by a deep drill hole, and to specify how such a hole could be used to test Smith's model. In both cases, the calculations will account for the uncertainties in boundary location. This work will either lead to improved models for the evolution of magma bodies, or to greater confidence in the models presently used.

* Smith, R. L. (1979), Ash-flow Magmatism, in Chapin, C. E., Elston, W. E., Eds., Ash-flow Tuffs, Geological Society of America Special Paper 180:5-25.

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

Contract: W-7405-ENG-36

Title: I. Geophysics

Person in Charge: J. T. Whetten

Scope of Work

Geophysics research in Los Alamos National Laboratory presently consists of three subtasks: (A) Creep Deformation of Rock, (B) Radiative Heat Transfer in Minerals, Glasses and Melts, and (C) Electrical Conductivity and Temperature in the Upper Mantle.

(A) Creep deformation of basalt, granite, and tuff is studied at simulated in situ conditions of temperature, pressure, pore pressure, and differential stress. Emphasis is placed on evaluating effects of water on creep of intact versus fractured samples. Results of the experiments are formulated into creep constitutive relations in a form amenable to predictive computer models.

(B) The contribution to total thermal conductivity from the radiative component is determined in a variety of minerals important in geothermal and waste isolation research. Radiative thermal conductivity is calculated as a function of temperature from measured optical absorption spectra taken at exceptionally high temperatures to 1500°C in a controlled atmosphere.

(C) The thermoelectric effect in the mantle minerals olivine and pyroxene is measured as a function of temperature, orientation, oxygen fugacity, and iron content. The effect of Mg/Si nonstoichiometry on mineral conductivity is investigated. The results apply to inference of upper mantle temperatures from electrical data.

These research tasks apply importantly to technology needs in waste isolation and geothermal energy.

A. Creep Deformation of Rock Under Simulated Nuclear Waste Repository Conditions (J. D. Blacic)

Assurance of long-term isolation of nuclear wastes in mined cavities in hard rock requires knowledge of time-dependent strength and transport properties of these rocks. Normal, short-time engineering tests do not encompass the full effects of phenomena such as water-aided stress corrosion and hydrolytic weakening. Therefore, we propose to study creep deformation of basalt, granite, and tuff at simulated in situ conditions of temperature, pressure, pore pressure, and differential stress. Emphasis will be placed on evaluating the effects of water on creep of intact versus fractured samples. Results of the experiments will be formulated into creep constitutive relations in a form amenable to predictive computer models of repository designs.

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

We propose to determine the contribution to total thermal conductivity from the radiative component in a variety of materials that figure in geothermal studies and nuclear waste isolation. We can calculate radiative thermal conductivity as a function of temperature from measured optical absorption spectra taken at exceptionally high temperatures up to 1500°C in a controlled atmosphere.

Heat transport is at the center of many geophysical problems. Our measurements of radiative heat conductivity K_R in magmatic glasses indicate that this could be a surprisingly important heat transfer mechanism in crustal magma chambers, and we plan to extend the measurements to actual melts. Another application of the same apparatus is to heat-transfer in glasses used for nuclear waste isolation. Finally, we plan to continue work on K_R of crystalline materials.

C. Electrical Conductivity and Temperature in the Upper Mantle (T. J. Shankland)

We propose to measure thermoelectric effect in the mantle minerals olivine and pyroxene as a function of temperature, orientation, oxygen fugacity, and iron content and to investigate the effect of Mg/Si nonstoichiometry on mineral conductivity. The results apply to inference of upper mantle temperatures from electrical data. While there are seismic models to explain the low velocity zone (LVZ) as a solid state phenomenon not requiring partial melting, the most well-constrained laboratory electrical measurements are more consistent with the partial melting hypothesis for the high conductivity layer (HCL) apparently associated with the LVZ. If the LVZ/HCL is not a partial melt layer, then mantle geotherms would be considerably lower than previously inferred on the basis of a partial melt zone under extensive regions of the earth. Hence, it is necessary to better understand electrical conduction in mantle minerals to find whether electrical data are a serious constraint on the low temperature geotherms suggested by solid state explanations of the LVZ.

Because temperature differences drive tectonic motions of the earth's surface and interior, improved knowledge of thermal patterns is a requirement for evaluating seismic and volcanic hazards to waste isolation and power plant sites. Further, locating high temperatures is essential for regional geothermal prospecting, particularly for the Los Alamos Hot Dry Rock project. The results should clarify our understanding of the regional geophysics needed for continental drilling site selection, and for nuclear event detection and discrimination.

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

Contract: W-7405-ENG-36

Title: II. Geochemistry

Person in Charge: R. W. Charles

Scope of Work

Research in geochemistry consists of five subtasks: (A) Rock-Water Interaction, (B) Element Migration and Fixation in Rocks, (C) Physicochemical Basis of the Na-K-Ca Geothermometer, (D) Cation Site Size and Coulomb Energy Calculations for the Principal Rock-Forming Minerals, and (E) Occurrence, Form, and Distribution of Sulfur in Peat.

(A) Rock-water interaction involves experimental and theoretical studies to model reactions in geothermal reservoirs using cold seal pressure vessels, agitating (rocking) vessels and dynamic (circulation) systems. Theoretical approaches include development of chemographic relations after the method of Schreinemakers.

(B) Element migration and fixation in rocks is an investigation into the location, mobility, and deposition of trace elements in rock reservoirs.

(C) The physicochemical basis of the Na-K-Ca geothermometer seeks the underlying mineral assemblages which control Na, K, and Ca composition in solutions and will attempt to expand the chemical geothermometer's usefulness to more varied rock reservoirs.

(D) Our cation site size and coulomb energy calculations will result in a reference publication which will facilitate understanding of inter- and intracrystalline major and trace element fractionation trends and the recognition of the effects of some accessory phases on whole-rock trace element distributions.

(E) In order to aid interpretation of various forms of sulfur in coal, we will investigate factors that influence abundances and forms of sulfur in peats from a variety of depositional environments. Our studies will include electron probe microanalysis, scanning electron microscopy, fluorescent and visible optical microscopy, and bulk analysis of sulfur in order to establish relationships between modes of sulfur occurrence, types of peat, and depositional environments.

A. Rock-Water Interation in Geothermal Systems (R. W. Charles and T. M. Benjamin)

Rock and solutions are allowed to equilibrate under physical conditions appropriate for rock reservoirs of interest to the Department of Energy. Currently, experiments are focused upon geothermal reservoirs. The reactants are subject to temperature and pressure in a

number of experimental hydrothermal systems under static conditions (cold seal pressure vessels), and dynamic conditions (continuous circulation systems with reaction vessels at a fixed temperature and under a temperature gradient). Experiments are allowed to proceed up to nine months in order to obtain mosaic equilibrium between fluid and the experimentally grown phase assemblage located on the rock surface or along fractures or grain boundaries interior to the reactant rock. Rock and solution are continuously monitored. Typical experimental conditions are up to one kilobar and 320°C.

The observed alteration assemblages are related in a chemographic network of suitable intensive variables (pressure, temperature, and chemical potentials) characteristic of the experiment. The chemographic results yield assemblages not directly observed in the experiment. The results allow one to postulate the results of longer duration experiments done under slightly different physical constraints and how these affect the rock reservoir with time.

B. Element Migration and Fixation in Rocks (T. M. Benjamin, R. W. Charles, P. Z. Rogers)

The circulation of fluid in a geothermal system may be a source of trace elements of economic value located in the reservoir rocks. The approach consists of (1) location of the element in question, (2) mobilization of the element, (3) speciation and transport of the element in an aqueous solution, and (4) precipitation of the element. Experiments are conducted in agitated (rocking) vessels and dynamic (circulating) systems. Source minerals, solution and deposited minerals are analyzed by neutron activation, plasma emission spectrometry, and scanning electron microscopy.

Studies of this nature have applications to the cost of energy derived from hot dry rock geothermal systems, to the mechanisms for the genesis of ore bodies, and to the isolation of hazardous waste from the biosphere in geologic repositories. They can also be used in conjunction with continental drilling to trace the migration of elements within the earth's crust, and to aid in future resource assessment.

C. The Physicochemical Basis of the Na-K-Ca Geothermometer (R. W. Charles and T. M. Benjamin)

The Na-K-Ca geothermometer was developed empirically by R. Fournier and A. Truesdell (USGS) to determine the temperatures of a rock reservoir at depth simply from the amount of Na, K, and Ca found in the fluid as it emerges at the surface. It has undergone some modification in succeeding years to take into account other elements in the solution. Direct application of the geothermometer occurs in, particularly, geothermal reservoirs. The usefulness of this technique is limited because its chemical basis is not understood. A series of experiments is under way to determine what phases control the Na, K, and Ca concentrations in solution. The activities of these elements are fixed by secondary phases produced by reaction of the feldspars ($\pm$ quartz) with water as the rock and water move toward mosaic equilibrium. The discovery, composition,

and structure of these overgrowths is the thrust of the experimentation. Because many of the geothermal systems emanate from granite-like rock, granite plus aqueous solution is being examined closely in static (cold seal vessels), agitated (rocking gold bag vessels), and dynamic (circulation) systems.

D. Cation Site Size and Coulomb Energy Calculations for the Principal Rock-Forming Minerals (J. R. Smyth, C. Depoorter)

We will compile published crystallographic data on ordered end-members of the principal mineral groups and common accessory phases in igneous and metamorphic rocks and calculate from these, mean bond distances, volumes and distortion indices or coordination polyhedra, and coulomb potentials for all cation sites. This research will result in a reference publication that will facilitate understanding of inter- and intracrystalline major and trace element fractionation trends, recognize effects of some accessory phases on whole-rock trace-element distributions, and facilitate understanding of intracrystalline diffusion kinetics and chemical effects on mineral compressibilities. Data allowing us to interpret these important phenomena are not presently available for most mineral groups.

This project was begun in FY82 and is currently on schedule. Computer program development and modification are largely completed, and data compilation is completed. Loading of crystallographic data onto computer disk files will be completed during the third and fourth quarters of FY82. We propose to continue our calculations and correlations of cation site sizes and coulomb potentials to observed inter- and intracrystalline fractionation trends, and we intend to collect our data in a reference publication.

E. Coal Maturation: Occurrence, Form, and Distribution of Sulfur in Peat (R. Raymond, R. C. Gooley, A. D. Cohen, Univ. of S. Carolina)

With repect to adverse environmental effects, sulfur is one of the most troublesome elements in coal. Conversely, some iron sulfides appear to have beneficial catalytic effects in processes such as coal liquefaction. We will investigate factors that influence abundances and forms of sulfur in peats from a variety of depositional environments, with the purpose of aiding interpretation of sulfur forms in coal. Since the coalification series begins with peat, and continues through lignite to bituminous and finally to anthracite coal, the logical place to initiate a systematic study of sulfur in coal is with peats. The amount of sulfur in most peats is sufficient to account for the total sulfur abundances in many coals, but details of its occurrence and distribution are poorly understood. We will study sulfur in peats via an integrated three-phase program: (1) electron probe microanalysis, scanning electron microscopy, fluorescent and visible optical microscopy, and bulk chemical analysis to characterize sulfur occurrence and distribution; (2) establish the significance of particular coal precursor plant tissues with regard to sulfur abundances; and (3) establish relationships between modes of sulfur occurrence and various peat types.

The research will provide a wide range of important information. First, the amount of sulfur in peats from a variety of environments will be determined. Second, the sulfur concentrations of various plant organs, tissues, and cell inclusions (such as resins) important to peat formation will be provided. Third, correlation between concentration and forms of sulfur occurrence and specific environments of deposition will be made.

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

Contract: W-7405-ENG-36

Title: III. Thermal Regimes

Person in Charge: J. T. Whetten

Scope of Work

Research in Thermal Regimes of Northern New Mexico at Los Alamos National Laboratory consists of five items: (A) Sulphur Springs, A Detailed Investigation, (B) Active Hydrothermal Systems, (C) Seismic Studies of Northern New Mexico, (D) Tectonics and Petrogenesis of the Paliza Canyon Formation, and (E) Petrologic and Geochemical Investigations of the Lucero and Zuni Volcanic Fields.

(A) At Sulphur Springs the waters, gases, and altered rocks are characterized geochemically; detailed mapping of alteration and fracture zones within and near the system is performed; and the compositions of alteration phase assemblages and fluids present are studied.

(B) In hydrothermal systems research, thermal and nonthermal waters of the Valles Caldera are collected for chemical and isotopic analysis; local geologic and tectonic features are mapped; the resulting geologic, geochemical, and geophysical data are integrated; and geothermal potential is evaluated.

(C) Refracting seismic profiling research in Northern New Mexico attempts to improve understanding of the third dimension of the Valles Caldera and its relationship to the Rio Grande rift. For example, we will determine whether or not there is a magma body beneath the Valles Caldera, and establish the causes for earthquakes near Espanola, New Mexico, the second most seismic active location in the state. These research tasks directly support needs of the Continental Scientific Drilling Program which designated the Valles Caldera as prime drill site, geothermal exploration, and nuclear test verification programs.

(D) Research on the Paliza Canyon formation in the Valles Caldera provides explanation of the evolution of the caldera and is critical to assessment of potential drill sites for the Continental Scientific Drilling Program.

(E) The geology, petrology, and geochemistry of the Zuni and Lucero volcanic fields are being studied. Research focuses on origin of magmas, their residence in the crust, and their effect on the hydrologic regime. This research will lead to an understanding of causes of magmatism, evolution of magmas, and their relation to rift tectonics.

A. Sulphur Springs, Valles Caldera, A Detailed Investigation (F. Goff)

Sulphur Springs is a small vapor-dominated geothermal system (approximately 1 km^2) on the west side of Valles Caldera, New Mexico,

that possesses a variety of acid-sulfate hot springs, mud pots, and fumaroles issuing from altered volcanic rocks and colluvium. The vapor-dominmated (steam) zone apparently overlies the 260°C liquid-dominated system deep within Valles Caldera. The vapor-dominated system has never been investigated.

Vapor-dominated reservoirs are specifically mentioned as target areas for research in Continental Drilling for Scientific Purposes (U. S. Geodynamics Committee, 1979) because they possess high energy potential and because they transport volatile elements of economic value (e.g., Hg). We will investigate the only known vapor-dominated system of the Rio Grande rift thermal regime. Sulphur Springs is part of the greater Valles Caldera geothermal system, which has enormous geothermal potential. Although Sulphur Springs is a small system, we believe the small size will aid us in gathering information applicable to larger vapor-dominated reservoirs. We plan to characterize the water, gases, and altered rocks of the Sulphur Springs system, to perform detailed mapping of alteration and fracture zones within and near the system, and to study the compositions of the alteration phase assemblages and fluid present. The object is to characterize the present Sulphur Springs system and to discover as much as possible about its evolution.

B. Active Hydrothermal Systems (F. Goff)

We propose to investigate detailed geochemical and geologic characteristics of three geothermal systems of the northern Rio Grande rift: Valles Caldera, Ojo Caliente, and the Lucero volcanic field. 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 2000 mg/P TDS) and may offer good potential for space heating or agricultural uses. Waters of the Lucero volcanic field are concentrated but discharge at low temperature. Their existence is not understood.

We plan to continue our geochemical and geologic investigations of Valles Caldera and to initiate new parallel research at Ojo Caliente and the Lucero Uplift. We intend to:

1. Collect thermal and nonthermal waters for chemical and isotopic analysis

2. Map local geologic and tectonic features (as needed) crucial to the hydrology of the waters

3. Integrate the resulting geologic, geochemical, and (where appropriate) existing geophysical data

4. Evaluate the geothermal potential of each system.

C. Seismic Refraction Profiling of the Rio Grande Rift/Jemez Volcanic Zone (K. H. Olsen)

This project proposes to investigate lateral variations in crustal structure, seismic wave propagation and attenuation and their relationships to the major geothermal regimes of Northern New Mexico. This is to be 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 and USGS in the region. The analyses will be facilitated by improved computer codes for hypocenter determination, synthetic seismogram modeling and focal mechanism determination now in regular use at Los Alamos National Laboratory.

D. Tectonics and Petrogenesis of the Paliza Canyon Formation (J. N. Gardner)

The Paliza Canyon Formation of the Keres Group, in the Jemez Mountains of Northern New Mexico, offers unique possibilities for obtaining informatin regarding tectonic and magmatic evolution of the central Rio Grande rift. Occurring at the western margin of the rift, the Paliza Canyon rocks represent revival of rift volcanism after a long mid-Miocene lull and the first of several major magmatic events that lead to the presently active Valles Caldera geothermal system. Detailed geologic mapping complemented with K-Ar dates will refine the stratigraphy of the formation and shed light on relations of tectonics and volcanism, and distribution and volume of volcanism through space and time. With tight stratigraphic control, major element whole rock and mineral chemistry, trace and rare earth element chemistry, and isotopic studies will provide the basis for petrogenetic models.

This study will provide information and models that are directly applicable to major objectives of the Continental Scientific Drilling Program in that it will contribute to the understanding of the evolution of continental crust, continental rift systems, and large magmatic geothermal systems. Furthermore, the results of this study will be critical to assessment of potential drill sites and interpretation of drilling data, and will directly complement the ongoing research of Smith and Bailey of the U. S. Geological Survey regarding caldera development and the geology of the Jemez Mountains. A number of research projects of the Los Alamos National Laboratory, the University of New Mexico, and the University of California, Davis (concerning tectonic and magmatic evolution of the Rio Grande rift, volcanism associated with shallow silicic magma chambers, and development of geothermal systems), will also benefit from results and models provided by this study.

E. Petrologic and Geochemical Investigations of the Lucero and Zuni Volcanic Fields (W. S. Baldridge)

The Rio Grande rift is a major Cenozoic continential rift, which extends from central Colorado across New Mexico to Chihuahua and West Texas. The rift is intersected obliquely by a series of parallel, northeast-trending fracture zones. These transverse fracture zones, which are probably of Precambrian origin, extend for hundreds of kilometers and are variously characterized by faults and by alignments of volcanic centers and intrusive bodies. These zones have exerted a major effect on both the structure and the magmatism of the rift.

We propose to study aspects of the geology, petrology, and geochemistry of the Zuni and Lucero volcanic fields. The project will focus in part on the origin of magmas, their residence in the crust, and their effect on the hydrologic regime. It will also enhance our ability to explain and predict the observed geophysical anomalies. Ultimately this work will lead to an understanding of the underlying causes of magmatism, of the evolution of magmas, and of their relationships to rifting tectonics.

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

Contract: W-7405-ENG-36

Title: IV. Space Plasma Physics

Person in Charge: D. N. Baker

Scope of Work

The solar wind and magnetospheric plasmas are the media through which solar-generated disturbances propagate and in which solar wind convection energy is stored and subsequently released to the auroral ionospheres, thereby coupling solar variations to the near-earth environment. The scope of this project is to analyze and interpret existing satellite data from the solar wind and earth's magnetosphere to yield an understanding of physical mechanisms and long-term effects of sun-earth coupling through the solar wind, sources of free energy in particle velocity distributions, and evolution and saturation of micro-instabilities driven by nonequilibrium plasma configurations. This research relates to the Department of Energy's missions through applications to plasma physics and magnetohydrodynamics (MHD) problems relevant to fusion energy technology, understanding long-term solar wind and earth climate variability, and future space-based energy technologies.

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

The goals of this research are to describe the structure and flow of plasma energy in the solar wind, bow shock, magnetosphere and ionosphere. Specific aims include determining long-term variations in solar wind structure near the earth, determining the electron and ion distribution functions of the solar wind in order to understand thermal energy transport and heating processes and evolution of large scale disturbances in interplanetary space, and understanding solar wind-magnetosphere coupling through fundamental studies of plasma transport in and near the earth's bow shock, magnetosphere, and ionosphere.

Our most important research result in 1981 was the development of a theory of transport (due to electrostatic plasma instabilities) that provides a consistent explanation for the short wavelength irregularities observed in the ionospheric F layer. Our research goal in 1982 is to extend this theory to electromagnetic instabilities and to apply it to transport in the magnetosphere and solar wind.

B. A Study of the Electrodynamical Aspects of the Solar Wind-Magnetosphere Interaction (E. W. Hones, Jr.)

The interaction of the solar wind with the earth's magnetosphere is essentially electrical in character, very much resembling the working of a magnetohydrodynamic (MHD) electrical generator. An MHD generator has ionized gas (plasma) jetted through a magnetic field where the Lorentz

force on the plasma ions and electrons effects a conversion of particle kinetic energy to energy of electric currents. In a completely analogous manner solar wind plasma, impinging on the earth's magnetic field, flows through its outer regions (the "boundary layer") and gives up its energy flow into the ionosphere and deposits energy there. Making full use of data from satellites in the outer magnetosphere, we attempt to develop quantitative understanding of at least some elements of this global system of energy conversion. Some major results of our work in the past year are:

1. Development and publication of a three-dimensional dynamic model of the magnetotail

2. Interpretation, using this model, of certain magnetic field variations in the magnetotail as indicative of energy release from the tail in the form of "plasmoids"

3. Discovery that solar wind entry to the boundary layer and electric current generation by this plasma may occur around the two magnetic "cusps" that are located at high latitudes on the sunward surface of the magnetosphere.

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

Contract: W-7405-ENG-26

Title: Geochemistry of Crustal Processes to High Temperatures and Pressures

Person in Charge: R. E. Mesmer

Scope of Work

The geosciences group at Oak Ridge National Laboratory carry out kinetic and equilibrium experiments designed to increase understanding of fluid-rock processes that occur in the Earth's crust. Present experimental equipment permit the study of natural systems and simplified analogues up to 1200°C and 1000 MPa (10,000 bars). Research on the properties of aqueous solutions up to 600°C and 400 MPa (4000 bars) yields data on speciation of dissolved constituents, kinetic pathways, and equilibrium constants vitally needed to understand solution behavior in the Earth's crust; the solution data add to the development of physical chemical theory and the ability to model natural systems mathematically. Studies on the reactions of natural solids (rocks and minerals) with aqueous solutions up to 500°C and 100 MPa (1000 bars) give insights to crustal processes, such as rock alteration, mineral formation, and migration of elements. Coupled with data on solution properties, the solid-fluid reactions generate thermodynamic data of interest to problems of fluid circulating through the Earth's crust. High temperature-high pressure studies of silicate systems to 1400°C and 400 MPa (4000 bars) provide data on phase equilibria, kinetics, and chemical partitioning applicable to igneous and metamorphic processes which operate at depths in the crust to 15 km. The data aid interpretation of the genesis of igneous and metamorphic rocks, and they permit predictions on the physical and chemical responses of rock forming silicate systems to variations in temperature, pressure, and composition.

A. Species Present in High Temperature Aqueous Calcium Chloride and Magnesium Chloride Solutions (W. L. Marshall; J. D. Frantz, Geophysical Laboratory, Carnegie Institution of Washington, D.C.)

Equilibria among $MgCl_2$, MCl^+ and Mg^{2+} in aqueous magnesium chloride solutions and among $CaCl_2$, $CaCl^-$ and Ca^{2+} in aqueous calcium chloride solutions have been determined at 25-600°C and 0.1-400 MPa (1-4000 bars) by conductance measurements. The first and second ionization constants of aqueous $CaCl_2$ and $MgCl_2$ were calculated. The behavior of the dissolved species with variations in temperature and pressure were calculated to provide a data base applicable to geochemical hydrothermal problems. Generalizations have been observed that permit simpler calculations of species distribution outside the experimental range, thereby facilitating the application of the data to geochemical questions and steam power generation. Present studies focus on the hydrolysis of NaCl to NaOH and HCl, by examining the conductances of separate solutions. Difficulties that stem from the corrosive natures of NaOH and HCl solutions we feel can be solved. The accurate measurements of the ionization constants of NaOH and HCl, combined with existing knowledge of

the ionization of H_2O recently determined and evaluated at ORNL, will permit the calculation of the hydrolysis of NaCl.

B. High Temperature pH Measurements with Stabilized Zirconia membrane Electrodes (S. E. Drummond)

The measurement of the pH of hydrothermal solutions as functions of temperature, pressure, and concentration is of fundamental importance to the interpretation of experimental studies and to geochemical applications of data on oxidizing and sulfide-bearing solutions. The use of zirconia membrane electrodes is an attractive method that potentially avoids difficulties encountered in the use of other electrodes. Efforts are being made to develop a zirconia electrode, with some encouraging results that warrant further efforts.

C. Tungstic Acid Dissociation in High Temperature NaCl Solutions (S. E. Drummond; D. Wesolowsik, Pennsylvania State University)

The dissociation constant of tungstic acid (H_2WO_4) in NaCl brines is being determined at elevated temperatures (300°C) by use of a hydrogen electrode concentration cell. Little is known about the aqueous chemistry of tungsten compounds, but current speculations are that +6 tungsten is a dominant form in high temperature hydrothermal fluids. The solubilities of tungstate (WO_4^{2-}) minerals are low and they decrease with rising temperatures. Determining the stability ranges of the various tungsten species in NaCl solutions will permit quantitative evaluations of the transport and depositional mechnisms of tungsten compounds in nature.

D. The Solubilities of Silica Phases in Aqueous Solutions (F. W. Dickson)

The reactions of quartz and amorphous silica with aqueous solutions are of prime interest because of the ubiquitous occurrence of silica minerals in nature. In spite of the existence of many prior studies on silica-containing systems, understanding of kinetic and equilibrium behavior is not clear. Quartz solubilities in H_2O and $NaNO_3$ solutions at 300°C and solution vapor pressures have been obtained to examine reaction kinetics, to obtain equilibrium solubilities, and to determine the role of water activity. Quartz reactions with H_2O at 200, 250, and 300°C at 160 MPa (1600 bars), done in static flow-through titanium alloy pressure vessels, have permitted reversible solubility determinations and kinetic studies of quartz-solution reactions.

E. Crystal Nucleation and Growth Kinetics in Calc Alkaline Silicate Melts at 0.1 MPa (M. T. Naney; S. E. Swanson, University of Alaska)

Crystal nucleation and growth kinetics in silicate liquids generated by melting natural rocks and model rock compositions are being investigated under controlled f_{O_2} conditions to 1400°C at 0.1 MPa (1 bar), as a function of undercooling. The purpose of the studies is to improve knowledge of the influences of cooling history on textural development, mineralogy, and chemistry of magmatic systems in hypabyssal and volcanic environments.

An investigation of olivine nucleation and growth kinetics from model basalt melts is nearing completion. Results of this study show that moderate changes in melt viscosity can significantly affect the predictability of olivine nucleation. The nucleation delay data permit determination of olivine growth rates with improved precision.

Iron oxidation/reduction kinetics of andesite and rhyolite melts under controlled oxygen fugacities have been investigated in collaboration with S. E. Swanson. These experiments using the wire loop technique indicate that ferrous/ferric equilibration in silicic melts is 2 to 5 times longer than recently reported by other investigators studying similar materials. The departures from equilibrium that may result from insufficient reaction times can significantly affect the quantitative value of data. Additional studies of silicic calc-alkaline melts are in progress to investigate parameters that influence groundmass mineralogy and textural development. The results provide data and concepts applicable to DOE programs with the purposes of: development of crystalline ceramic matrix material for nuclear waste isolation, extraction of energy from magma systems, and improving understanding of volcanic hazards.

F. Epidote Stability and Uranium Partitioning in Hydrous Granitic Melts (M. T. Naney)

Study of silicate systems at high temperatures (to 1400°C) and pressures (400 MPa or 4000 bars) will be conducted using the internally heated, pressure vessel and associated gas intensifier system designed for hydrogen service that is now in final stages of testing and calibration. The pressure-temperature conditions generated in this apparatus will simulate crustal environments to depths of 15 km. The planned initial study has been designed to simultaneously provide data on the stability of epidote in equilibrium with granitic melts and the partitioning of uranium between epidote, granitic melt and an aqueous fluid phase as a function of temperature, pressure, and H_2O content. This high pressure coexistence of epidote and silicate liquid can be a useful indicator of the depth of magma consolidation. Experimental measurement of the uranium partitioning will provide data on fractionation behavior of uranium as a function of temperature, pressure, and H_2O content of model granitic magmas.

G. Kinetics of Thermal Dissociation of Acetic Acid (S. E. Drummond, D. A. Palmer, F. W. Dickson)

The kinetics of the thermal breakdown of acetic acid to CH_4 and CO_2 is being studied at 360°C and 200 MPa (2000 bars) to examine the effects of catalysts (or their absence). Long standing interest in the mechanisms of generation of CH_4 by earth scientists has recently increased because of suggestions that some CH_4 now in the crust came from the mantle. The research aims at determining the time dependencies of the reaction in the presence of oxy and hydroxy minerals that occur in nature over a range of pH. We plan to ascertain the order, mechanism, and activation energy of the reaction and to examine the geologic consequences of the data.

H. Brucite Solubility by High Temperature EMF Studies (S. E. Drummond)

The hydrogen electrode concentration cell offers a unique way to determine the solubilities of minerals in aqueous solutions up to 300°C as functions of pH and salinity. The first studies are on brucite ($Mg(OH)_2$) a well-characterized mineral with a simple composition, chosen because of the importance of magnesium compounds in natural solutions and the relatively uncomplicated solution compositions. The OH^- activity can be measured directly with the hydrogen cell, Mg^{2+} is stable to hydrogen reduction, and the equilibria of chloride complexes of Mg^{2+} are important species in natural solutions. This prototype study is the first of a series which will examine mineral-aqueous solutions of increasing complexity.

I. CO_2 and H_2S Solubilities in High Temperature Aqueous NaCl Solutions (S. E. Drummond)

Solubilities of CO_2 and H_2S in hydrothermal fluids (0-6 m NaCl) were determined to 400°C and gas partial pressures to 10 and 3 MPa (100 to 30 bars), respectively, by a P-V-T mass balance method, at Pennsylvania State University. The experimental data are critically important in understanding the transport of components and the deposition of minerals in response to boiling.

J. Equilibria in System $NaHSO_4$-NaHS-H_2O (F. W. Dickson and M. H. Lietzke)

The distribution of solution species in $NaHSO_4$-NaHS-H_2O solutions from 25-300°C at the vapor pressures of the solutions was calculated at several total sulfate and sulfide concentrations by a computer method that minimized assumptions. The data were also of use in evaluating the accuracy of earlier experimental work and in planning future experiments. The quantitative interpretations of sulfur isotope compositions of sulfate and sulfide minerals depend on understanding speciation in natural solutions containing sufide and sulfate.

K. Mineral Deposition From Boiling Hydrothermal Solutions (S. E. Drummond)

A numerical model was constructed to predict mineral solubilities in boiling hydrothermal solutions. The model incorporated data on H_2S and CO_2 solubilities, as well as mineral solubilities from the literature. The significant physical and chemical variables operative in natural systems were considered: heat budget (adiabatic versus isothermal); mass constraints in open and closed systems; redox equilibria (controlled by carbon, sulfur or other equilibria); and mineral-solution equilibria (fluids were constrained to be in equilibrium with various minerals during the boiling process). Results of combinations of these variables provided a qualitative understanding of the chemical evolution of dynamic liquid-vapor systems, as well as quantitative information on specific natural boiling hydrothermal systems. The modeling efforts confirm that boiling can be a viable mechanism for mineral deposition in many types of geothermal and ore-forming systems.

L. Rock-Solution Reactions: Basalt-Seawater (F. W. Dickson; D. C. Pohl, Geology Department, Stanford University)

Basalt at spreading centers reacts with great amounts of seawater. The reacted fluid returns to the sea via fractures in the basalt floor in response to convective forces, altering rocks along the path and exchanging chemical components. We reacted glassy basalt powder with seawater at 400 and 500°C, 100 MPa (1000 bars) using gold-cell equipment in the hydrothermal laboratory of Stanford University. The results are applicable to the geochemical balance of the oceans and the origin of heavy metal deposits on the sea bottom.

M. Rock Solution Reactions: Basalt-Sodium Carbonate Solutions (F. W. Dickson; Y. Zeng, University of Peking, China; J. G. Liou, Geology Department, Stanford University)

In nature, large volumes of basalt have reacted with Na-CO_2 rich solutions, producing characteristic alteration minerals. The reactions of basalt glass with sodium carbonate solutions and H_2O at 300°C and 50 MPa (500 bars) were done in the Hydrothermal Laboratory of Stanford University to outline the alteration effects and solution changes. Both gold-cell and closed gold tube equipment were used. The results gave a physical chemical basis for interpreting the processes responsible in the alteration of basalt by sodium carbonate solutions.

N. Chemical Fractionation in Model Granitic Magmas at High Temperature and High Pressure (M. T. Naney; W. C. Luth, Sandia National Laboratory)

A collaborative research effort has begun with W. C. Luth (Sandia National Laboratory) to study liquid-crystal chemical fractionation in model granitic magmas as a function of temperature, pressure, and H_2O content. The chemical compositions of glass and crystalline phases in selected high temperature, high pressure experimental products provided by ORNL will be determined by microanalytical techniques at SNL. This chemical data on model granitic system at high pressure is needed to predict the responses of consolidating magma chambers to extraction of thermal energy.

Contractor: PACIFIC NORTHWEST LABORATORIES
Battelle Memorial Institute
Richland, Washington 99352

Contract: EY-76-C-06-1830

Title: I. Remote Sensing and Geoscience Data Analysis Methodology

Person in Charge: G. E. Wukelic, H. P. Foote, and S. C. Blair

Scope of Work

This multiyear program was established to conduct basic research in areas of remote sensing and image analysis most relevant to supporting DOE's objectives in the geosciences area. The goal is to develop and test new computer techniques for processing and using combinations of remote sensing and geosciences data so that geoscientists can analyze these complex data more completely and more rapidly. These advancements will contribute to geoscience-related activities involving resource discovery, national security, energy development and utilization, conservation of the environment, and the safety objectives of the Department of Energy.

The scope of research activities includes:

- Acquiring appropriate remote sensing and geoscience data sets.
- Upgrading computer capabilities (hardware and software) to advance the state-of-the-art in digital processing and integration of remote sensing and geoscience data.
- Demonstrating and evaluating the use of advanced computer-aided analysis techniques within PNL and other DOE research programs.

A. Remote Sensing and 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, 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 (mainly Landsat data), topographic data, borehole geophysical data, rock photomicrographs, and regional geologic, gravity seismic, and magnetic data.

B. Software Development and Testing (H. P. Foote, S. C. Blair, and G. M. Petrie)

1. Remote Sensing and Geoscience Data Integration

Currently, experimental computer integration programs are being used to produce a variety of demonstration products for characterizing the Continental Scientific Drilling Program (CSDP) site in the Valles Caldera in New Mexico for evaluation by CSDP participants.

Recently, PNL submitted a proposal to NASA to assist in characterizing the performance of the thematic mapper (TM) and multispectral scanner (MSS) on Landsat-D scheduled for launch in July 1982. The proposal requires NASA to acquire and provide Landsat-D data over several DOE sites so that PNL can evaluate the utility of these new data for energy research and technology applications.

2. Further Development of Software for Processing of Earth Science Data

Basic research has begun to use image processing techniques for analyzing photomicrographs of rock petrofabrics. Preliminary image processing algorithms have been developed for the identification and characterization of cracks and voids. Further research will include developing algorithms to provide data on porosity, pore shape, grain shape, crack distribution, and anisotropy of crack and pore orientation.

In addition, a system of computer programs are under development to provide for quantitative analysis of geophysical well logs. Preliminary outputs from this system are now being analyzed.

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

The basic requirement of this subtask is to test the utility of experimental computer techniques for processing, analyzing, and displaying combinations of remote sensing (aerial and satellite) data and geoscience (geophysical and geologic) data in ongoing PNL and other DOE research programs. This activity is performed in concert with scientists from other DOE, academic, and private sector organizations.

Contractor: PACIFIC NORTHWEST LABORATORIES
Battelle Memorial Institute
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

This program is composed of two major research tasks: studies of mid- and high-latitude ionospheric and auroral phenomena, and studies of ground-level solar radiation flux. The insolation research utilizes spectral measurements of the direct and diffuse components of solar radiation. The aeronomy task utilizes a large data base of optical measurements of nighttime auroral emissions to focus on questions of energy transport and interactions in the upper atmosphere.

The information acquired in the insolation task bears directly and indirectly on a number of energy technologies. Quantifying (1) the total power available for solar thermal plants or space and water heating applications, (2) the spectral distribution of solar radiation for photovoltaic stations, and (3) the biologically active spectral region for biomass farms is among the direct applications of the data. Direct solar radiation is attenuated by scattering and absorption due to aerosols, clouds, and gases in the earth's atmosphere, a fraction of which is present because of power generating facilities. Using direct and scattered light measurements to understand the character and the magnitude of atmospheric effects resulting from energy production is among the indirect applications of the data.

The aeronomy program uses nighttime optical emissions as a prime diagnostic tool to investigate the state of the upper atmosphere and the sources of energy flowing into this region. Significant quantities of energy are transferred into this region by processes within the magnetosphere, notably from the plasmasheet and the plasmasphere/magnetosphere interface region. Such energy fluxes can have profound effects on the upper atmosphere. The optical manifestations of these effects are monitored by this program.

A. Insolation Studies (J. J. Michalsky, G. J. Schuster, E. W. Kleckner, and G. M. Stokes)

The insolation portion of the task has been divided into four areas: (1) turbidity analysis, (2) spectra analysis, (3) trace gas analysis, and (4) subvisual cirrus analysis.

These tasks depend on a data base acquired using Mobile Automatic Scanning Photometers (MASP's). The MASP measures insolation in spectral bands centered at 395, 428, 470, 486, 535, 558, 570, 630, 680, 785, 900, and 1010 nm. The field of view is 1.5°, with a basic instrument stability of ±2%. The MASPs were designed and built to be portable

and operate routinely at remote sites; presently these include Eureka, Montana; Richland, Washington; Leduc, Alberta, Canada; and Ft. Providence, Northwest Territories, Canada. Additional archival data are acquired from cooperative programs which have instruments sited at Iron Mountain, Michigan, and Boulder, Colorado. There is now a base data set useful for analysis of seasonal or longer trends in the turbidity of the atmosphere. This base is continental in scale as monitoring sites have covered much of North America.

While this data set continues to be supplemented, specific short-term investigations are being conducted. Presently, all of the 1980 data collected at the Observatory following the initial eruption of Mt. St. Helens in March are being analyzed. PNL is situated in the plume of Mt. St. Helens on many occasions since the prevailing winds are west-southwesterly. On all clear days a mean turbidity, or attenuation due to aerosols, may be determined along with a wavelength dependence. Days on which a wind trajectory analysis indicates that PNL is in the path of the plume are separated from days when this is clearly not the case. Data on the gaseous emission of Mt. St. Helens are obtained from the USGS office in Vancouver, Washington. A technique which depends on clear conditions is used by the USGS; therefore, we have good gas emission and turbidity data overlap. The point is to ascertain whether the aerosols formed primarily by the SO_2 and H_2S emissions of the volcano are detectable, and, if they are, how they are characterized. This is analogous to the analysis of a large isolated coal-fired plant burning high sulfur-content coal. Initial findings are that the aerosols resulting from SO_2 transformation are occuring quite rapidly and are detectable as a substantial increase in the small particle component of the detected aerosol distribution.

Another investigation being conducted is a turbidity and insolation study to characterize the boundary layer above the Hanford Reservation in southeastern Washington. Two sites are used: the Hanford Meteorology Station (HMS) and the Observatory, which are vertically separated by one kilometer.

Recent improvements of a technical nature in the aerosol work include the incorporation of a very good algorithm to calculate the solar position (±0.02 degrees) and air mass to high values of the air mass.

The spectral analysis task's main goal is to provide an accurate absolute calibration of our MASPs. This will provide a useful low resolution spectral distribution of solar radiation from filter data. Two mathematical techniques are used to make reasonable and smooth estimations of the solar spectrum between actual measurements. The methods, employing smoothing matrices in one case and cubic spline fits in the other, have produced reasonable appearing spectra from actual measurements. One attempt to verify the spectral distribution obtained used a modified version of the Air Force Geophysical Laboratory's LOWTRAN5 program. The main inputs to this program to calculate the transmission in the silicon photodiode sensitivity region between 0.36 and 1.12 μm are turbidity and water vapor which are obtainable from the filter measurements of the MASP. While the agreement is generally good, it appears there may be errors in the extraterrestrial solar spectrum used as input to the LOWTRAN5 model--this and other means of corroboration are being pursued.

The third task is the extraction of ozone and water vapor abundances from the data as they are the most prevalent and, perhaps, most interesting trace species in the visible near-infrared region. Assuming the wavelength dependence of aerosol attenuation is quadratic in the visible and near-infrared when plotted on a log-log plot, and using the minimum chi-squared for the quadratic fit of log optical depth versus log wavelength, a step-by-step search, with different values of optical depth due to ozone subtracted, leads to a fair estimate of ozone. We are in the process of applying this technique or a light variant of it to extract ozone. We are investigating ways of using LOWTRAN5 or the optical depths in the part of the spectrum containing water to calibrate the instruments as total precipitable water meters.

The final task is based on the high inherent accuracy of the MASP. Throughout the period since solar data were first taken with the MASP, the plots of intensity in a particular filter versus time of day have not been smoothly varying functions even on cloud-free days. The noise has exceeded that expected from the data acquisition system, and the magnitude of the noise has varied from one clear day to the next. It is suspected that we are witnessing attenuation due to subvisual cirrus clouds or, perhaps, turbulent cells with variable aerosol properties. A program to concurrently run two MASPs and two normal incidence solar devices on clear days has begun. This problem is of interest because an ever present cirrus layer, which may be a product of the industrial age, can increase the effective albedo of the earth leading to a cooling effect over the long run.

B. Aeronomy Studies (E. W. Kleckner and D. W. Slater)

Building on the large data base acquired during the initial phases of this project, the aeronomy program is primarily concerned with the physics of mid-latitude auroral phenomena. Observations of upper atmospheric radiations at 630.00, 557.7, 427.8, and 486.1 nm are reduced to provide absolute emission intensities as a function of spatial location and time. Using these data, the energetics of some of the particle interactions within the ionosphere may be deduced. Given that experimentation by observation is the rule for many upper atmospheric studies, the past year must measure as a very fruitful one. During both equinoctal periods, significant events occurred which allowed the isolation of mechanisms causing the phenomena. For example, during the spring a large stable auroral red (SAR) arc was observed in the absence of competing effects from the polar aurora. Analysis of this event has shown that the current theory of atmospheric response to the heat fluxes associated with the formation of SAR arcs can be considered to have been verified. Although this confirmation was not unexpected, these observations provided the first direct evidence on the accuracy of the theory. From October of 1981, a series of days, centered about the 22nd, have been selected for detailed analysis in conjunction with experimenters who have instrumentation aboard the Atmospheric Dynamics-B satellite. This is an ongoing study of the energetics of the physical region and involves synthesis of information from diverse sources.

Additional goals of the aeronomy program include the development of a capability to model the physics of the F-region in the ionosphere. This

model, together with the extensive observational base, will provide a tool for detailed study of energy transport within this region. A compact and portable, 4-color meridian scanning photometer is under design and soon to constructed. This instrument will allow the acquisition of simultaneous absolute emission intensities at a number of auroral wavelengths. These ratios, in turn, will allow very specific statements to be made about the energy spectrum of the precipitating particles within this region. The aeronomy program has also cooperated with studies of diffusion rates and high-altitude electric fields by assisting in monitoring emissions of rocket-launched chemical releases. A "core" network of three photometer sites located near PNL will continue to be operated so as to provide the high spatial resolution needed for studies of D- and E-region phenomena (≃ 100-km height).

Contractor: PACIFIC NORTHWEST LABORATORIES
Battelle Memorial Institute
Richland, Washington 99352

Contract: DE-AC06-76RLO 1830

Title: III. Chemical Migration by Contact Metamorphism in Granite and Silt/Carbonate Systems

Person in Charge: J. C. Laul

Scope of Work

The main objective is to investigate the relative migration and transport mechanism of major, minor, and particularly trace elements during contact metamorphism between granite and silt/carbonate rocks. Specific emphasis will be on the rare earth elements (REE)--Ba, Sr, K, As, Sb, Pb, Cl, Rb, Cs, Zr, Hf, Ni, Th, and U. The applications of this study may enable us to understand and predict the long-term (10^3 to 10^7 years) behavior and movement of radionuclides in geologically confined nuclear waste.

The geological site under study is the porphritic quartz monzonite intrusion at Notch Peak, near Delta, in western Utah. The intrusion was emplaced in a Cambrian limestone 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. The metamorphic temperatures near contact are 500°C for the highest grade rocks. Samples of silt and carbonate, ranging from highly metamorphosed (near contact) to unmetamorphosed, were collected along horizontal and vertical traverses away from the granite intrusion in the Big Horse, Weeks, and Marjum formations.

Several samples have been analyzed for some 35 major, minor, and trace elements by neutron activation analysis and x-ray fluorescence. A comparison of trace element signatures from metamorphosed to unmetamorphosed samples, ranging from granite to silt/carbonate, as a function of distance should reveal the degree and importance of transport of various elements. The results suggest that some elements do migrate during contact metamorphism and that the degree of migration varies depending on the elements. The evidence is convincing on a meter scale. The migration beyond several meters is under study. There were apparently three granite intrusions and the chemistry of each intrusion is different. The chemical systematics of the intrusion, skarn, silt, and carbonate rocks from the Big Horse, Weeks, and Marjum formations are under study.

This study is in collaboration with J. J. Papike of South Dakota School of Mines and Technology, Rapid City, South Dakota, who will obtain petrographic, petrologic, and isotopic systematics on the same samples.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: I. Magma Energy Research

Person in Charge: H. C. Hardee

Scope of Work

The Magma Energy Research Project has been assessing the scientific feasibility of directly extracting energy from buried magma sources and has been divided into five major research tasks: magma source location and definition, magma source tapping, magma characterization, magma-material compatibility, and energy extraction. This program is in its final year, scientific feasibility being adjudged to have been established.

A. Magma Source Location and Definition (J. L. Colp and R. G. Hills)

The ability to locate and identify a source of molten rock in the earth's crust is critical to this project, and is the only major scientific issue remaining. It is imperative that the existence of a magma source, including its depth, areal extent, and general form be known with the greatest certainty before proceeding with drilling. A survey of industry and university geophysics experts was conducted to determine the next step in exploration for a shallow magma body. Three points clearly came out of an assessment of all the personal interviews conducted. Geophysical systems recommended as most useful for locating and defining magma bodies were (a) P- and shear-wave reflection active seismic techniques, (b) P-wave delay passive seismic techniques, and (c) controlled time-domain electromagnetic techniques.

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

During the 1981 Kilauea Iki tests, boreholes were maintained open during logging, seismic, and thermal test experiments. Texas A&M rock mechanics studies indicate that boreholes to the melt can be kept open and are stable to 10-km depth at near-molten temperatures under achievable conditions.

C. Magma Characterization (W. Luth and T. Gerlach)

Magma is known to be a high temperature, highly corrosive medium. A seismic velocity of 3.4 km/s was measured through the Kilauea Iki melt zone during the 1981 tests. Petrologic studies of Kilauea Iki cores are defining the vertical structure, liquid and mineral evolution, and the mineral-liquid relationships through the melt zone.

D. Magma-Material Compatibility (J. L. Colp and D. Douglas, UCLA)

It is scientifically feasible to expect materials to survive and function in a magma environment. Material samples have survived exposure to fumarolic gases and molten basalt; experimental equipment has survived exposure to the Kilauea Iki environment.

E. Energy Extraction (H. C. Hardee and J. C. Dunn)

The energy extraction task aims to understand energy transfer processes in molten magma and margin zones of magma systems and to find ways of extracting energy from the magma or its margins. Convective heat transfer processes in molten magma have been studied by theoretical calculations, by laboratory experiments in furnace-melted samples of molten lava or magma, and by field experiments in lava lakes and lava flows resulting from volcanic eruptions. Currently, the effects of high pressure and dissolved gases on convective heat transfer in a magma are being investigated. Energy extraction has been determined to be scientifically feasible. Energy extraction experiments at Kilauea Iki Lava Lake Laboratory in 1981 have demonstrated the operation of two types of heat exchangers. In an experiment in which a closed heat exchanger was placed in the solid margin directly overlying the molten zone, a heat extraction rate of 17 kW/m^2 of heat exchanger area was measured. In an experiment in which an open heat exchanger was formed in the molten zone, heat extraction rates of 980 kW/m^2 (steady) were measured.

F. Conclusions

Scientific feasibility, defined as "the demonstration, by means of theoretical calculations and supporting laboratory and field measurements, that there are no insurmountable theoretical or physical barriers which invalidate a concept or process," for the magma energy concept was concluded late in FY81. Presentations describing the results of the scientific work performed since FY75 upon which the conclusion of scientific feasibility was based were made to the Magma Energy Research Advisory Panel and to the Federal Geothermal Coordinating (Ogle) Committee. Both of these groups concurred with the assessment that the concept of extracting thermal energy from magma was scientifically feasible.

Contractor: SANDIA NATIONAL 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

Sandia contributes to the CSDP by providing program coordination, through involvement in developing appropriate drilling, logging, and instrumentation technology, by conducting broad-based generic research supportive of objectives in the thermal regimes program, and through participation in a site-specific assessment research program.

A. Program Coordination (O. E. Jones and R. Traeger)

Sandia National Laboratories provides coordination when needed for DOE's CSDP thermal regimes research activities involving the following program elements:

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

2. Drilling and logging activities, which require considerable logistic and contractual support to achieve the scientific objectives of the program.

B. Drilling, Logging, and Instrumentation (H. C. Hardee and J. Dunn)

Drilling, logging, and instrumentation support is concerned with developing advanced logging tools and downhole instruments for CSDP and then applying these tools to answer scientific questions of interest to CSDP. Early work has concentrated on downhole seismic tools and downhole high temperature thermal probes. Plans are underway for the drilling of shallow test holes at Mono Craters for the purpose of shallow logging and for instrumentation test and evaluation. High temperature (1200°C) thermal probes and associated cables and handling equipment are being developed for logging high temperature holes. Initial instrumentation work has concentrated on the development and testing of downhole periodic seismic sources. Both compressional-wave and shear-wave (P and S) sources have been developed. A swept-frequency periodic source is currently under development.

C. Thermal Geophysical Techniques (J. Dunn and H. C. Hardee)

The objective of this research is to develop and refine thermal geophysical techniques in order to characterize and understand in situ thermal processes in permeable convecting geologic media. Such thermal geophysical techniques are based on the measurement and analysis of thermal and fluid transfer, but particularly in regions where natural

convection heat transfer and/or ground water flow in aquifers significantly alter subsurface temperature profiles. Current research is concentrating on the design of a convective heat flow sensor for use in permeable convecting surface zones. Initial tests are planned at Long Valley and Mono Craters.

D. Hydrothermal-Magma Geoscience Research

This research is directed toward developing an understanding of mass and energy transport within and between hydrothermal and magma systems through a combination of field, experimental, analytical, and modeling approaches. Research activities include geochemical and mineralogical studies on silicic and basaltic natural and synthetic magma systems.

1. Kilauea Iki (1959) Lava Lake Geochemistry (W. C. Luth and T. Gerlach)

Drilling programs conducted at Kilauea Iki Lava Lake during December 1978 and April 1981 by Sandia as part of the Magma Energy Research Program have been successful in providing core samples of quenched, in situ basaltic magma. Geochemical analysis of these samples using the electron microprobe provides data on compositions of coexisting mineral and liquid (glass) phases. Data have been obtained on more than 100 samples obtained in both the 1978 and 1981 drilling programs. These data have been used to define the vertical structure and temperature distribution of the lava lake at the time of drilling.

2. Geochemistry of Volcanic Gases (T. Gerlach)

Direct analysis of volcanic gases has provided data of potential utility regarding the composition of the magmatic gas phase during and prior to eruption. Computer-assisted techniques are being employed to thermodynamically reverse the alteration processes that occur during gas sampling and to restore the analysis to a composition representing the actual erupted gases. An expanded approach involving field, analytic, and computer-based studies is underway. Gas sublimate and condensate samples are collected at fumarolic vents. Through analysis of the gas (followed by restoration), liquid (condensate), and solid (sublimate) fractions, it is possible to obtain a complete restoration of the volcanic gas.

3. Magmatic Volatiles (J. E. Eichelberger and H. C. Westrich)

Although volatiles are ordinarily lost from magma during shallow intrusion and/or eruption, some silicic magmatic materials are quenched so rapidly during explosive events that little or no degassing occurs. Analysis of these materials provides a new, direct means for exploring the behavior of volatiles in silicic magmas. Highly accurate and rapid analyses for water, the dominant volatile species, are currently being conducted in order to determine relationships among preeruption water content, eruptive behavior, eruption sequence, phase assemblage, and anhydrous composition.

4. Energy Transport (H. C. Hardee and J. Dunn)

This study aims to better understand energy transport processes in magma and hydrothermal systems. Research is being done on convection in permeable rocks above shallow magma bodies in the crust. Theoretical calculations are being done for single-phase and two-phase permeable convection, both above and at the edges of these systems. These calculations are being correlated with field data from lava lakes and regions above suspected magma bodies in the continental crust. Research is also being conducted on enhanced convective heat transfer in permeable media near the critical point. An analytical study of periodic magma intrusion in conduits is being used to investigate mechanisms for the onset of shallow magma chamber formation. A study of convective circulation patterns in magma chambers is underway. Emphasis is on the study of transient circulation patterns which can lead to zonation and layering in magma chambers.

E. Mono Craters Geophysical Study: CSDP Site Assessment (J. Rundle and J. C. Eichelberger)

Structural and petrologic features suggest that this volcanic field is in an early stage of caldera evolution, reflecting growth of a large body of silicic magma at mid- to upper-crustal depths. The study will provide a basic understanding of this magmatic/hydrothermal system and its crustal and tectonic setting. This investigation involves surface and near-surface geophysical and geological observations, and will specifically include gravity change measurements, a set of seismic refraction profiles across an arcuate vent system related to caldera development, heat flow measurements, petrologic studies of volatiles in rapidly quenched glasses, and tectonic modeling.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: III. Geophysics Research

Person in Charge: O. E. Jones

Scope of Work

This program involves a suite of diverse, but related, research activities leading to a more soundly based understanding of geophysical processes in the earth's crust and mantle.

A. Modeling of Geodetic Crustal Strain Data (J. Rundle)

The crustal strain program seeks to develop methods and techniques for interpreting time-dependent deformation of the earth's surface. Motions of a few centimeters a year are due to subtle stress relaxation processes associated with sudden catastrophic events such as earthquakes or volcanic eruptions. These motions may provide clues to the time of occurrence of a future event.

Numerical computer codes have been developed which compute time-dependent surface deformation due to faulting in layered, inelastic earth models. Other codes compute surface deformation, free air, Bouguer and surface gravity due to volcanic loading of the crust. Gravity gradient data associated with the 1975 Kilauea inflation-deflation episode have been interpreted by use of these techniques. Work using these codes is under way with collaborators at the U. S. Geological Survey and at the Earthquake Research Institute, Tokyo, Japan. Seismicity data, waveform modeling, and laboratory studies of rock deformation and slip suggest that shear stress is distributed inhomogeneously on fault planes. A model consisting of a finite fault embedded in an elastic medium has been constructed to explain these data.

B. Time-Dependent Deformation and Fracture of Brittle Rock (W. Wawersik and L. Costin)

This research is directed toward a basic understanding of the mechanics of microcrack growth and how this is expressed in the continuum response of the material. Both experimental and analytical efforts are in progress. The fundamental mechanism of time-dependent crack growth appears to be stress corrosion; thus, our experimental work is concentrating on determining the relationship between crack velocity, applied driving forces, and environmental conditions such as temperature and humidity.

To apply the experimental results to the problem of creep deformation in brittle rock, which occurs by the time-dependent growth of large numbers of microcracks, the relationship between micro- and macrocrack behavior must be established. Thus, analytical methods for determining the continuum response of a brittle rock resulting from the growth of microcracks need to be developed.

C. Natural Convection in Double-Diffusive Counter-Buoyant Systems
(R. Nielsen and J. C. Eichelberger)

In double-diffusive counter-buoyant fluid systems, gradients in temperature and composition produce opposing buoyancy forces, resulting in complex patterns of circulation. For example, heat is lost from the margin of a magma body but water may diffuse inward, resulting in opposing buoyancy forces within chemical and thermal boundary layers of greatly differing thicknesses. Recent measurements of water content in quenched volcanic ejecta suggest gradients in magmatic water content which could produce buoyancy forces far greater than those resulting from expected temperature gradients. These phenomena are being investigated through development of a two-dimensional finite difference model which solves the equations of motion for a fluid in which heat and a chemical species diffuse. The computational model will be verified by comparison with bench-scale simulant experiments.

PART II

OFF-SITE

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: DE-AM06-76RL 02229

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

Person in Charge: S.-I. Akasofu

Scope of Work

Interactions between two magnetized, collisionless plasma clouds and interactions between a magnetized cloud and a magnetic field are of great significance in understanding various phenomena in astrophysics and thermonuclear fusion studies. The earth's magnetosphere provides a unique opportunity to study these interactions in nature, in particular, how a natural dynamo (consisting of a magnetized plasma flow and a magnetized celestial body) operates, and how the generated power is discharged through the polar ionosphere. The power of this natural dynamo is about 1 million MW. A number of problems associated with the natural dynamo are being pursued in collaboration with the plasma simulation groups at UCLA, the University of Texas, Austin and the Plasma Physics Laboratory, Princeton University. This study also takes advantage of the very large memory size of the University of Alaska computer.

University of Alaska researchers are also interested in energy-related geophysical problems in the Arctic region. In particular, they are studying the electric current induced by auroral activity in power transmission lines and in oil/gas pipelines. We have successfully demonstrated that auroral activity causes surges in the protective relay system in power transmission lines. An intense surge will open the protective relay, causing a system blackout. By studying the characteristics of the surges, we are designing a protective relay system which will not be affected by auroral activity. This project is important for the proposed Anchorage-Fairbanks tie line. Intense electric currents (as much as 1000 A at times) in an oil pipeline, induced by the aurora, may cause serious corrosion of the pipe. Geomagnetic disturbances at Prudhoe Bay also cause serious problems in the operation of various drilling sensors which are oriented by a magnetic compass. We plan to develop a feedback system to make necessary corrections automatically.

In the artic region, permafrost provides serious obstacles in energy search and oil transport efforts. Thus, the determination of thickness of permafrost is increasingly an important problem. We have an impulse radar (GSSI), loop-loop induction systems (EM-31, -34), audio magnetotelluric systems, and electrical resistivity devices. We plan to cross-calibrate these instruments at locations where permafrost thickness and distribution are known.

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: EY-76-S-06-229 006

Title: II. Alaska Peninsula Telemetered Seismic Network

Person in Charge: H. Pulpan

Scope of Work

Seismicity and volcanism of the Aleutian-Alaska arc system are the result of the convergence of two lithospheric plates, with the Pacific plate subducting beneath the North American plate. The analysis of seismic data generated by the earthquakes that frequently occur in the arc system provides one of the best means of learning to understand fundamental tectonophysical processes associated with the observed natural phenomena.

The project involves operating a network of eleven short-period vertical-component seismographs on both the Alaska Peninsula and some of the offshore islands comprising the arc. This network is part of a larger, thirty-station network operated by the University of Alaska over an approximately 800-km portion of the arc. A part of the technical aspects of the program is the development of a digital recording and event detection system in order to provide data more suitable for certain types of quantitative analyses.

Data analysis presently focuses on:

- Determining the stress distribution in the subducting slab from fault plane solutions of regionally recorded earthquakes and from the determination of the moment tensor of teleseismically recorded events.

- Inverting regional and teleseismic travel time data into a three-dimensional crustal and upper mantle seismic velocity structure.

Successful completion of the above studies will both increase our fundamental knowledge about the subduction process and provide a better basis for assessing the geothermal energy potential of the arc's volcanism.

Contractor: UNIVERSITY OF ARIZONA
Department of Geosciences
Tucson, Arizona 85721

Contract: DE-AC02-81ER10842

Title: I. Rock Deformation in Hydrothermal Systems: The Nature of Fractures in Plutons and Their Host Rocks

Person in Charge: D. Norton

Scope of Work

The object of this project is to reconstruct the state of stress in magma-hydrothermal systems using field data and transport theory. We are developing mapping techniques for the collection of data on fractures in fossil magma-hydrothermal systems. Fracture characteristics such as frequency, spacing, continuity, and effective aperture are being mapped in one fossil system in detail and in several systems at a reconnaissance scale. New computer techniques are then being used to summarize the data in a form that will benefit engineers concerned with waste repositories and geothermal systems and that will improve the theoretical basis for analyzing processes in magma-hydrothermal systems.

A method for mapping fractures has been designed and partially tested: the geometry and relative ages of fractures are recorded on photographs, then converted into digital form for analysis by computer. These field methods are being used in our study of the Cochise, Diamond Joe, Papoose Flat, Ponder, and Dells plutons. Our intent is to reconstruct the thermal history of these plutons by comparing their structural state with that of mathematical models.

Contractor: UNIVERSITY OF ARIZONA
Tucson, Arizona 85721

Contract: DE-AC02-81ER10753

Title: II. Solar Variability Observed Through Changes in Solar Figure and Mean Diameter

Person in Charge: H. A. Hill and R. J. Bos

Scope of Work

The objective of this work is to develop and utilize an indirect diagnostic of solar constant changes through changes in the solar shape and mean diameter. The search for indirect diagnostics of luminosity is motivated by difficulties in obtaining reproducible radiometer data over the years to decades associated with terrestrial climatic changes. During the 1970's, SCLERA developed techniques to measure fractional solar diameter changes to accuracies of $\Delta D/D \simeq 10^{-5}$ to 10^{-6} over a one-day observing run (~9 hr). These techniques will be extended over climatically significant timescales. The relationship between the indirect diagnostic and the solar constant is also being examined theoretically.

A. Technical Developments

Currently, the stability of the telescope and interferometric measuring engine in the focal plane is maintained through features built into the telescope, by a recalibration mechanism for the interferometer which detects white light fringes, and by operating the telescope in a "frozen" configuration. A technique is now being developed to calibrate the telescope field absolutely. This technique will make possible measurements of angles in a telescope field with absolute errors of 10^{-3} to 10^{-4} arcsec. Several design studies of the effects of optical aberrations in the system have concluded that these aberrations present no intrinsic limitations. Thus, the groundwork has been completed for a testing of the absolute calibration technique.

A charge injected device (CID) camera has been developed for incorporation into the solar detector to help maintain its stability in the spirit of the absolute calibration system. The interface between the CID camera and on-line microprocessor with its mass storage device was successfully tested. Three solar diameters are now simultaneously measured rather than one, an improvement whose advantages were clearly demonstrated in the 1981 results. Plans are being made to extend the capability from three to five simultaneous diameter measurements.

B. Observations

Fourteen days of high-quality observations spanning 41 days were obtained in 1981 before the summer rainy season. Unfortunately, no additional observations were possible in the fall because of extensive damage to the on-line computer system caused by transients from a nearby lightning strike. Analysis of these data is proceeding and the current level of accuracy/day appears to be ≈0.01 arcsec, equivalent to an error

of 5×10^{-6} of a solar diameter. With this accuracy, fluctuations in the solar diameter can be clearly discerned. This error primarily results from solar oscillations with periods $\lesssim 9$ hr. A technique was successfully implemented and tested during the fall of 1981 that considerably reduces this source of fluctuations in the diameter measurements. Further analysis of the 14 days of data from 1981 is planned to take advantage of this new development.

The 1981 data set represents a significant step in the extension of the SCLERA techniques to longer timescales, and holds the first evidence of changes in the mean diameter over timescales of months. These results are scheduled to be presented at the International Astronomical Union General Assembly in August 1982 in a joint session on solar variability. The observing program put on line in 1981 and interrupted by lightning damage is projected to be operational in Spring 1982. Observations will be made regularly with the exception of weather and equipment interruptions, which historically have been minimal. The reduction of the 1981 data and new data obtained will also be a major activity.

C. Theoretical Work

Theoretical work concerned clarification of the relationship between the energy transport rate in the solar atmosphere and changes in the solar constant and indirect diagnostics. A study has essentially been completed of nonlocal effects of radiative transport; initial testing of the theory indicates that it coalesces many properties of the photosphere not previously understood quantitatively, and that it may describe, in a relatively accurate manner, the relationship between diameter changes and changes in luminosity.

Contractor: ARIZONA STATE UNIVERSITY
Department of Chemistry
Tempe, Arizona 85721

Contract: DE-AC02-80ER10765.A000

Title: Silicate, Aluminosilicate and Borosilicate Glasses and Melts: Thermochemical Studies by High Temperature Calorimetry

Person in Charge: A. Navrotsky

Scope of Work

High temperature solution calorimetry is used to determine heats of mixing in aluminosilicate glasses and melts. We are focusing on the role of oxide basicity in determining mixing properties along the joins $MAlO_2$-SiO_2 and in determining heats of vitrification and of fusion. These systematics lead to an understanding of effective heats of fusion of diverse components to an aluminosilicate framework. In addition, we are completing study of the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Si_4O_8 and continuing the modeling of phase equilibria in silicate systems, using experimental heats of mixing and of fusion and models for entropies of mixing.

A pressure vessel for the study of heat contents of hydrous melts in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Si_4O_8 up to 1000°C and 1 kbar is under construction. It will permit direct study of the thermodynamic properties of glasses and melts containing up to 50 mol% H_2O.

The data and models are correlated to the structure and physical properties of silicate melts and have potential application in such diverse fields as geochemistry, magma energy generation, ceramic science, nuclear waste disposal, and reactor safety.

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

Contract: DE-AC02-79ER10401

Title: Thermal Regimes of Major Volcanic Centers: Magnetotelluric Constraints on the Coupling of Deep-Seated Magma Genesis to High-Level Geothermal Reservoirs

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 and physical processes within the earth that are related to energy sources. Presently attention is being directed toward acquiring an understanding of dynamical processes and thermal regimes associated with centers of major volcanic activity. This work is related to questions of basic scientific importance, as well as to national priorities in resource-related areas such as geothermal energy, chemical transport of minerals in the crust, the emplacement of economic ore deposits, and deep drilling for scientific purposes. It is believed that to understand the dynamic evolution of intraplate volcanic centers in the western United States, it is necessary to understand 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). The physical transport of molten material offers an effective mechanism for transferring heat from deep sources to shallow depths in the crust, leading in turn to episodes of crustal melting at shallow depth and silicic volcanism at the surface. In addition, combined electromagnetic and seismic studies of the crust at depths less than 5 km can play an important role in characterizing the porosity and permeability of the crystalling basement above possible magma chambers. This information is important to understanding the manner in which active hydrothermal systems are dynamically coupled to magma sources at high levels in the crust; we need to identify whether the mechanism for heat transport is through simple conduction or through fluid-transport (advection or convection). In addition, geophysical constraints on the permeability of crystalline basement are important for characterizing the transport of chemical species in the crust (via ore-bearing fluids, for example).

A. Thermal Processes Associated with Major Volcanic Centers

Geophysical investigations of the major rift zones of the world typically indicate that all of these regions exhibit anomalously low values of electrical resistivity, density, and seismic velocity, either within the crust itself or at high levels of the mantle. Beneath intraplate rifts such as the Basin and Range or the Rio Grande rift in the western U.S., the emplacement of basaltic magma at mid-levels in the crust may lead to extensive remelting, triggering eruptive episodes of silicic magmatism, such as associated with the Valles Caldera or the Long Valley/Mono Basin complex. However, a reinterpretation of

magnetotelluric measurements made by our group in the Jemez Mountains (and the Valles Caldera) does not indicate a profound geophysical anomaly such as would be expected to be encountered if a major magma body were present. We feel, therefore, that silicic magma centers, beneath resurgent calderas of this type, solidify very quickly after eruption. This requires a mechanism for renewing thermal activity at depth in the crust. We are pursuing this question through geophysical field work in the Long Valley/Mono Basin area, as well as in the Valles Caldera. Preliminary inspection of data obtained during the Fall of 1981 suggests the presence of an anomalous conductor associated with the Eastern Sierra Front.

B. Physiochemical Processes Associated with the Genesis of Primitive Crust

We are continuing our interpretation of geophysical experiments on Iceland and adjacent areas of the Mid Atlantic Ridge. Crustal thickening due to underplating provides a significant contribution to mechanisms of crustal genesis in this region. According to this model, mantle-derived melt accumulates in a thin layer at the base of the crust beneath the neovolcanic zone. With time, this melt cools, solidifies, and accretes to the base of the crust leading to crustal thickening. The crust increases in thickness from 8-10 km directly beneath the neovolcanic zone to an average value of 10 km for the generally older (~10 my) Iceland plateau. Hence, segregation of material from a significant volume of the mantle and continued crustal underplating may persist well beyond the boundaries of surface manifestations of volcanic activity. There is a strong possibility that such a process may be operational beneath the Basin and Range Province and the Salton Trough in the western U.S. This is supported by the preliminary investigation of data acquired by our group during the Fall of 1981.

C. Magnetotelluric-Magnetic Variation Field System

To investigate these phenomena, a geophysical field system (using tellurics, magnetotellurics, and geomagnetic variations; over the frequency range 10^3 Hz to 10^4 Hz) has been developed under joint support of the Department of Energy Office of Basic Energy Sciences and several other Government agencies. A comparative study is being undertaken of selected major volcanic centers in the western U.S. in terms of their association with regional tectonomagmatic phenomena in the deep crust and upper mantle. This year Brown University completed the testing and development of a magnetotelluric field system which consists of a microcomputer-based (DEC, PDP 11/23) multi-component data acquisition system capable of real-time acquisition, analysis, and display of magnetotelluric data in field environments. The system, mounted on a 4-wheel drive GMC van, has been used for preliminary field work in the Mono Basin/Long Valley volcanic complex.

D. Theoretical Models of Electromagnetic Induction Phenomena

1. General. The application of geophysical techniques to problems in the field are often constrained by the inadequacy of modeling

algorithms necessary to interpret the actual data. Because of this we have devoted a significant part of our research effort to developing models to simulate the electromagnetic response of representative geologic structures.

2. Modeling Three-Dimensional Induction Effects. A new finite difference form has been developed for simulating the distortion of telluric fields by three-dimensional azimuthally symmetric structures. The technique involves a sequence of local integrations of the electric current density crossing closed surfaces surrounding each mesh mode. The resulting expressions, which are accurate to second degree everywhere, not only correctly describe first-order discontinuites in the electric field normal to electrical discontinuities in the interior of the model but also lead to significantly improved accuracy near sharp, localized discontinuities where the anomalous field decays as $1/R^2$ or $1/R^3$ with distance. When numerical simulations are compared with analytical solutions for simple models, the analytical and numerical results for a thin disk indicates an rms-accuracy of 1%, whereas for an imbedded sphere the rms-accuracy is 2%.

3. Bias of Long-Period Magnetotelluric Response Parameters Due to Lateral Heterogeneities. A simple three-dimensional model has been used to evaluate the bias of long-period magnetotelluric principal resistivity values in the presence of modest current channeling at shallow depth. It was shown that conventional MT are always good indicators of the degree to which the observed resistivities depart from a quasi one-dimensional response function. Large skew is sometimes associated with minimal bias. But unfortunately, small skew is sometimes associated with maximal bias. Also it appears that the geometric mean of the maximum and minimum principal resistivity values at a site may be regionally biased in a statistical sense for a large number of sites. A smaller bias can be achieved if one can identify the class of conductivity structures associated with local perturbations of the long period response parameters.

4. Finite Source Fields Coupled to Lateral Conductivity Heterogeneities: Effects on Magnetotelluric and Magnetic Gradiometric Deep-Sounding Experiments. Studies of the dynamical evolution of source fields in the ionosphere and magnetosphere are in many cases incompatible with global scale sources. In some cases, source fields have coherent scale distances of only a few hundred km, even at low and mid-latitudes. The possible effect of these finite source dimensions on induction experiments therefore require renewed scrutiny, particularly as deep-sounding measurements are performed at periods greater than 10^4 sec. The magnetic variation gradiometric technique appears to suffer from source effects at least as much, and perhaps greater than, the magnetotelluric technique. When finite source fields are coupled to lateral heterogeneities, the interaction becomes quite complex. We are attempting to generalize concepts regarding the interaction between the spatial wavelength of the source field and the scale-size of lateral heterogeneities.

Contractor: UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

Contract: DE-AS03-76F00034

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

Person in Charge: J. H. Reynolds

Scope of Work

This project is concerned with 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. In past years, these interests have led to the study of such diverse problems as the dating of rocks, the early chronology of the solar system as revealed by extinct radioactivities, and the elemental and isotopic composition of trapped primordial rare gases in meteorites. In recent years the project has focused progressively more on terrestrial problems.

Most of the effort in our current DOE research concerns the RARGA system for making elemental and isotopic analyses of the rare gases in terrestrial fluids. The lab is unified in a large van which can ultimately be used to carry out analyses and data reduction in the field near the sampling site. The system has been tested with a laboratory study of the solubilities of all the stable rare gases in water and brines over the entire range of salt concentrations and over the temperature range 0 to 65°C. The results, now submitted for publication, in addition to providing useful thermodynamic information, indicate that, because of regularities in the effects of temperature and salinity on rare gas solubilities, it will require relatively little additional work to extend the range of temperatures and pressures to those needed for the interpretation of data from natural samples.

The first natural samples to be studied with the RARGA system were water and gas samples from Yellowstone National Park and from the Lardarello geothermal field in Tuscany. Although the mass spectrometry is technically demanding, the RARGA system has made it easy for us to measure precise $^{3}He/^{4}He$ ratios and, since the ratio is very insensitive to atmospheric contamination, it provides an immediate measure of contributions from mantle sources where the ratio is high and from crustal sources where the ratio is low. Other isotopic ratios of particular interest are $^{40}Ar/^{36}Ar$, which is high in crustal gases and reportedly low in ancient diamond samples from the mantle, and $^{129}Xe/^{132}Xe$ which is high in some samples from the mantle. In collaboration with the isotopic information, we are presently attempting to interpret the elemental patterns from the geothermal areas in terms of a small number of components. There are enough regularities in the data to make these attempts promising. The laboratory work described in the preceding paragraph has already been useful in the interpretations.

We have developed contacts which are bringing in a fairly steady stream of good samples collected by others. A number of collaborations have been set up. In coming fiscal year we plan to operate the RARGA system for the first time at a field location in California.

The use of rare gases as tracers in geochemistry is still in its infancy and, with a powerful system in hand for acquisition of good data, the project is entering what should be a fruitful phase.

Another study we have begun has as its objective the measurement of solubilities of the rare gases in silicate liquids at various temperatures and compositions. A collaborating group at the Lawrence Berkeley Laboratory has the facilities for sample preparation. We are also planning to extend work we have done in the past in investigating isotopic equilibria in mineral separates from mantle xenoliths.

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

Contract: DE-AS03-76F00034; PA #DE-AT03-76ER70224

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

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

Scope of Work

This is a basic research effort which, in part, is directly coordinated with the Hot Dry Rock Geothermal Energy Development Project under the Geosciences Division at Los Alamos National Scientific Laboratory. The focus has been on developing analytical tools and carrying out integrated analyses of rock mechanical properties controlled by microstructure. The thrust of the work has been to define the statistical interrelationships of rock microstructure to petrographic and mechanical rock properties. These interrelationships then form the basis for developing a usable geophysical understanding of the mechanisms involved.

The research is being carried out as series of interconnected studies:

Dynamic and static elastic moduli of rock show systematic differences. It is clear that different stress-strain measurement techniques used to resolve crack porosity yield different estimates of porosity. This implies that nonlinear strains may persist to very low strain levels (10^{-7}). By considering both dynamic and static strain data, and strain spectra derived from the data, we are trying to resolve hysteresis, changes in crack populations with stress, and ratios of dynamic to static moduli which may yield a measure of crack porosity.

In an experimental and theoretical study of nonlinear stress-strain relations, volumetric strain measurements were made on thick-walled cylindrical rock samples under varying pore pressure and triaxial loading. Various constitutive relations for fitting such data are being studied in a comparative manner.

Techniques for the statistical analysis of petrographic structures have been developed. The output of this analysis is a set of evaluated parameters which cross-correlate petrographic, mineralogical, and microstructural variables, to aid in the prediction of rock mechanical properties.

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

Contract: DE-AT03-81ER10965

Title: II. Adiabats and Grüneisen Parameter of Earth Forming Materials at High Pressures and High Temperatures

Person in Charge: R. Boehler

Scope of Work

The adiabatic temperature gradient $(\partial T/\partial P)_S$ within the Earth is of great importance for all convection studies and for the prediction of the temperature profile in the Earth.

The systematic measurement of $(\partial T/\partial P)_S$ at high pressures for fluids, salts, metals, and minerals showed that the behavior of $(\partial T/\partial P)_S$ at high pressures can be described by a simple power law relationship between the adiabat and the compression of the material with good consistency in the power $n = -\partial \ln(\partial T/\partial P)_S / \partial \ln \rho$. This allows the extrapolation to very high pressures. All previous measurements have been carried out at room temperature using a fluid pressure medium.

For the study of the adiabatic gradient in the interior of the Earth, the pressure range of the experiment was extended and the measurements were carried out at high temperatures on materials that are relevant to the mantle of the Earth. A piston-cylinder apparatus with solid high pressure medium and *in situ* pressure gages was used.

Results on sodium chloride, quartz, forsterite, olivine, and magnesium oxide up to 50 kbar and 1000°C show the same consistency in the power n with which the adiabat $(\partial T/\partial P)_S$ decreases with compression. Furthermore, n is only slightly dependent on temperature. From this observation the adiabats were extrapolated to pressure and temperature conditions of the upper and the lower mantle of the Earth. The results are in good agreement with the latest theoretical predictions of the adiabatic gradient.

Contractor: THE UNIVERSITY OF CHICAGO
Chicago, Illinois 60637

Contract: DE AC02-80ER10763

Title: Depth to and Concentrations of Water in Large Silicic Bodies of Magma

Person in Charge: A. T. Anderson, Jr.

Scope of Work

Large bodies of silicic magma are potential sources of geothermal energy and ore. They also pose threats of catastrophic eruptions. The depths of such bodies are related to their economic potential and probably to their eruption mechanisms. The concentrations of water in the magmas are important for their eruptive and dynamical behavior and for the development of ores. Estimates of viscosity and density of melt require knowledge of concentration of water. The concentration of water in melt before ascent and eruption can be measured in inclusions of glass which became trapped in crystals before extrusion. The depth of a magma body can be estimated or delimited if we can find out the concentrations of both carbon dioxide and water in the inclusions of glass. Initial results on the Bishop Tuff of Long Valley Caldera, California yield 4.9 ± 0.5% H_2O for glass included in quartz from the Plinian air fall pumice. This result is comparable to estimates of about 3.5-4.9% H_2O in the lowermost part of the Bishop ash flow. However, our results for CO_2 are not yet reliable: consequently, we can only estimate a minimum pressure of about 1.3 ± 0.2 kbar at the top of the body of magma before eruption. The inclusions are devitrified in quartz phenocrysts from the ignimbritic parts of the tuffs notwithstanding quick cooling and preservation of glass outside of the phenocrysts. Devitrified inclusions are difficult to study petrographically and analytically. We do not understand the cause of the devitrification and consider it important to investigate further because of possible significance for the eruption and emplacement mechanisms of ignimbrites, and because inclusions revitrified by laboratory heating may nethertheless yield significant information.

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
Person in Charge:	K. Jacob, E. Hauksson, and L. Sykes

Scope of Work

The plate tectonic processes and associated physical properties of a subducting plate margin and of its related volcanic arc system are quantitatively studied mostly by systematically collecting, analyzing, and interpreting seismologic data. For this purpose a telemetered seismic network with digital event recording is operated in the 300-km-long Shumagin Islands seismic gap of the Eastern Aleutian Arc, Alaska. The digital seismic data are analyzed for detailed three-dimensional velocity structures in the arc, fore-arc and underlying mantle, for their associated anelastic behavior (Q-structures), for space- and time-dependent patterns in the stress distribution (from focal mechanism and seismic stress drop measurements), and for seismic and aseismic patterns related to the earthquake cycle. The root zone of one of North America's most active volcanoes, Pavlof volcano, is seismically screened by a subarray of stations for evidence of shallow and deep magma bodies and for migration of these bodies as indicated by seismic emissions before, during, and after eruptive cycles.

The local network data are analyzed and interpreted together with teleseismic information and available tectonic, geologic, and geodetic data to yield a comprehensive understanding of seismic wave propagation in an island arc structure and of the basic processes of subduction, accretion, volcanic arc formation, explosive volcanism, and generation of arc summit basins. While most of the work focuses on understanding the basic tectonic processes, important applications concern geothermal resource potential, basin formation, and assessment of seismic and volcanic risks to offshore oil exploration lease areas. Technical developments emphasize cost-efficient transmission and collection of digital seismic network data.

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

Contract: DE-AC02-76ER04054

Title: II. The Time-Dependent Transmissivity of Joints

Person in Charge: C. Scholz and T. Engelder

Scope of Work

The problem is to completely characterize fluid flow within the crust of the earth both in space and time. Part of the solution is to simulate in situ conditions in the laboratory. Previous laboratory work on fluid flow within jointed rock has focused on the transport properties in space (the effect of pressure and temperature on mechanical properties of joints). Current laboratory work involves characterizing time-dependent changes of the transmissivity of joints (the effect of dissolution and precipitation on the joint openings).

In order to understand the effect of fracture closure on permeability, the precise effects of change normal stress across the fracture have been studied. When rock is subjected to a stress cycle during which cracks open and close, hysteresis which has usually been attributed to friction is observed in the stress-strain curves. Scanning electron microscope studies, however, have shown that shear cracks are scarce in rock that has been deformed in the dilatant region. It has been argued that crack friction models are incompatible with the rheology of dilatant rock and are virtually untenable. It has been asserted instead that cracks are reversible in the sense of the Griffith energy balance. Here we demonstrate that two nominally flat rock surfaces in contact subject to a cycle of applied normal stress exhibit all the properties of crack opening, closing, and hysteresis exhibited by a dilatant rock and that in this case the mechanism must be friction. We conclude that an axial crack in dilatant rock will exhibit frictional interactions on opening or closing if the crack walls are not in perfect registration, and that there is no justification for accepting the reversible "Griffith" crack concept.

Current work on the time-dependent changes of transmissivity of joints involves the construction and calibration of a stainless steel pore fluid system. Proving tests for temperature and pressure are currently in progress.

Contractor: UNIVERSITY OF HAWAII AT MANOA
Hawaii Institute of Geophysics
Honolulu, Hawaii 96822

Contract: DE-AT03-80ER12099

Title: Characterization of the Physical, Seismic, Electrical and Thermal Properties of Kilauea Iki Lava Lake Samples to Melting Temperatures Under Elevated Pressures and Controlled Volatile Content: Potential Uses of the Results in Seismic Exploration and Delineation of Magmatic Bodies, and in Thermal Modeling

Person in Charge: M. H. Manghnani

Scope of Work

This proposal is concerned with two areas of laboratory investigation: (1) characterization of physical (density, porosity, and pore size distribution), seismic (V_p, V_s, Q^{-1}), and thermal (conductivity) properties of core samples from Kilauea Iki Lava Lake under in situ conditions, and (2) viscosity, electrical conductivity, and V_p, V_s, and Q^{-1} of magmatic fluids at elevated pressures and temperatures and as a function of controlled volatile (e.g., H_2O, CO_2) content.

The goals of the proposed research are threefold: (1) to understand how the physical properties of basalts relevant to geothermal exploration and thermal modeling in a volcanically active area are affected by a total environmental system; (2) to investigate interrelationships between the various properties; and (3) to correlate the laboratory data with the models based on theory and field measurements.

Although most of the proposed research will be carried out at the University of Hawaii, two parts of the proposed work (chemical and mineralogical analyses of Kilauea Iki and other samples, and viscosity and electrical conductivity of magmatic fluids at elevated pressures) will be conducted in cooperation with the two groups headed by W. C. Luth and M. J. Davis at the Sandia National Laboratories. One of the motivations of the proposed cooperative research is the availability of the unique Magma Simulation Facility at the Sandia National Laboratories.

The proposed research, involving close cooperation between the University of Hawaii and the Sandia National Laboratories, is not only relevant to the ongoing research efforts of the Magma Energy Research program of the Department of Energy, but it also provides an impetus to basic energy research needed for acquiring a better knowledge of the fundamental in situ physical properties of rocks relevant to planned projects such as the U. S. Continental Scientific Drilling Program.

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

Contract: DE-AC02-76ER02534 A006

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 Geothermal Energy Development Project of the Los Alamos National Laboratory and the Magma Tap Project of Sandia National Laboratories. In order to interpret data from various seismic experiments conducted at Fenton Hill, New Mexico, and Kilauea Iki, Hawaii, the theory and methods have been developed for seismic wave generation, transmission, scattering, and attenuation in a medium containing a fluid-filled crack(s).

The results of interpretation are synthesized for each geothermal site, and the model parameters are updated as new experimental results are analyzed. The MIT model is intended not only to define the geometrical and physical properties of the geothermal system but also to estimate the mass and energy transport through measurements of seismic signals generated by the geothermal system, such as volcanic tremors.

Models are being developed for the hot dry rock fracture system at Fenton Hill, magma lens in Kilauea Iki, deep and shallow tremor sources under Kilauea, inside Mt. St. Helens and other volcanoes. The data needed for study are collected by a network of mobile digital seismographs from the Massachusetts Institute of Technology as well as from the U.S. Geological Survey, Los Alamos National Laboratory, Oregon State University, the University of Washington, the Centro de Investigation Cientifica y de Educacion Superior de Ensenada in Mexico, the University of Paris, through cooperative arrangements.

We are also developing a new borehole seismograph which can be operated at high temperature.

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

Contract: DE-AC02-78ER04972

Title: II. Microcracks and Energy

Person in Charge: G. Simmons

Scope of Work

The objective of this project is to demonstrate the usefulness to the DOE energy programs of various aspects of microcracks in rocks. We use the petrographic microscope, the scanning electron microscope (SEM) equipped with both high resolution backscattered electron detector and imaging system and an energy dispersive x-ray system, and various physical properties measured as a function of pressure to characterize microcracks. The SEM yields information on healed cracks (composition and extent of the minerals that fill formerly open microcracks, extent of healing, and the physical dimensions). Presently open microfractures are characterized with the SEM and also with a high precision technique for the measurement of strain as a function of pressure (differential strain analysis, DSA).

At the present time, we are emphasizing studies on the geographical extent and physical conditions of the mobilization and migration of rare earth elements and uranium through microcracks in granitic rocks. Additional samples of core from the Redstone Quarry (New Hampshire) and Sherman granite (Wyoming) and new core samples of a highly radioactive granite from southeast England are being studied. We plan to begin work on microcracks (both open and healed) in eastern black shales.

In the past, we have examined samples from geothermal areas and shown that certain characteristics of microcracks are associated with geothermal areas. From the examination of microcracks in the Sherman granite and the 3000-ft core from Redstone Quarry, we have demonstrated that microcracks are the pathways for the migration of rare earth elements and uranium.

Contractor: UNIVERSITY OF MINNESOTA
Department of Geology and Geophysics
Minneapolis, Minnesota 55455

Contract: DE-AC02-10837

Title: Experimental Formation of Chalk from Calcareous Ooze

Persons in Charge: W. E. Seyfried, Jr. and T. Johnson

Scope of Work

A major problem associated with the recovery of hydrocarbons from chalk deposits results from the unpredictable, localized occurrence of low porosity, impermeable limestone at some horizons in the chalk. At the University of Minnesota, we have been concerned with diagenetic processes leading to chalk formation. Our approach to this timely and economically significant problem involves the use of hydrothermal solution equipment to monitor porosity and permeability changes and changes in solution chemistry during transformation of calcareous ooze to chalk. Samples of calcareous ooze were collected in box cores from the tropical Atlantic Ocean. These samples contain varying amounts of low-magnesian calcite (forams, coccoliths), aragonite (pteropods), biogenic opal (radiolarians, sponge spicules) and detrital silicate minerals. Hydrothermal experiments are conducted at a wide range of temperatures, pressures (hydrostatic and differential), solution compositions, and sediment mineralogy.

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

Contract: DE-FG01-82ER12018

Title: I. Studies in Geophysics

Person in Charge: T. M. Usselman

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

The studies include: (1) 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, and environmetal maintenance; and (2) science-oriented studies such as geophysical data, international programs in geophysics, status of developments and opportunities in geophysics, and impact of technology on geophysics. Each study is conducted by a panel selected for the specific purpose. 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.

The studies are guided by the Geophysics Study Committee (GSC). Members of the committee are Charles L. Drake (Chairman), John C. Crowell, Louis J. Battan (Vice-Chairman), John D. Bredehoeft, Allan V. Cox, Hugh Odishaw, Charles B. Officer, and Raymond G. Roble; Thomas M. Usselman, Staff.

Studies Completed

- ENERGY AND CLIMATE (Roger R. Revelle, panel chairman). Published in 1977 (158 pp.).
- ESTUARIES, GEOPHYSICS AND THE ENVIRONMENT (Charles B. Officer, panel chairman). Published in 1977 (127 pp.).
- CLIMATE, CLIMATIC CHANGE, AND WATER SUPPLY (James R. Wallis, panel chairman). Published in 1977 (132 pp.).
- THE UPPER ATMOSPHERE AND MAGNETOSPHERE (Francis S. Johnson, panel chairman). Published in 1977 (169 pp.).
- GEOPHYSICAL PREDICATIONS (Helmut E. Landsberg, panel chairman). Published in 1978 (215 pp.).
- IMPACT OF TECHNOLOGY ON GEOPHYSICS (Homer E. Newell, panel chairman). Published in 1979 (136 pp.).
- CONTINENTAL TECTONICS (B. Clark Burchfiel, Jack E. Oliver, and Leon T. Silver, panel co-chairmen). Published in 1980 (197 pp.).
- MINERAL RESOURCES: GENETIC CONSIDERATIONS FOR PRACTICAL APPLICATIONS (Paul B. Barton, Jr., panel chairman). Published in December 1981 (119 pp.).
- SCIENTIFIC BASIS OF WATER RESOURCE MANAGEMENT (Myron B. Fiering, panel chairman). Published in May 1982 (127 pp.).
- SOLAR VARIABILITY, WEATHER, AND CLIMATE (John A. Eddy, panel chairman). In press; expected to be available in mid-1982.

Studies in Preparation

- Climate in Earth history (Wolfgang H. Berger and John C. Crowell, panel co-chairman). Publication is expected in 1982.
- Estuarine research perspectives (L. Eugene Cronin and Charles B. Officer, panel co-chairman). Publication is expected in 1982.
- Geophysical data and public policy (Michael A. Chinnery, panel chairman). Publication is expected in 1983.
- Groundwater contamination (John D. Bredehoeft, panel chairman). Publication is expected in 1983.
- Explosive volcanism: Inception, evolution, and hazards (Francis R. Boyd, panel chairman). Publication is expected in 1983.

Studies Under Active Consideration

- Transient Ocean Tracers
- Recent Crustal Movements
- Thunderstorms and Atmospheric Electricity

Scope of Work

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 basis for decision making in matters involving geophysical research and knowledge, both in policies and programs

3. To provide to the scientific community a basis for 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/
NATIONAL RESEARCH COUNCIL
Washington, D.C. 20418

Contract: DE-FG01-82ER12018

Title: II. Committee on Seismology

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

Scope of Work

The Committee on Seismology meets twice a year to discuss current topics of major importance relevant to seismology, to review with government agency personnel, in particular, the actions that have resulted from recommendations of the committee and its panels, and to take actions to assure a healthy science which is in a position to provide maximum benefits to the nation and to society. These activities are directed at fulfilling the fundamental mission of the committee, as follows: to maintain an active surveillance of major trends in seismology and of developments related to seismology in allied scientifc and technical fields, to provide special studies for government agencies on appropriate subjects or problems, to maintain cognizance of and to provide advice on international seismological activities, to provide advice to government agencies concerning the operation of U.S. Government-supported seismograph networks and data-dissemination facilities, and to coordinate seismological-related activities within the National Research Council, particularly in the fields of earthquake engineering, rock mechanics, goedesy, geodynamics, and geology. Panels are established to conduct ad hoc studies on topics specified by the committee.

A Workshop on Seismographic networks was held in March 1982, to address problems associated with the Global, National, and Regional Networks. A draft report has been written which identifies problems and offers recommendations to help solve them. The report is currently being revised for publication.

A draft report on data management problems in seismology has been written, and is being revised for submission to the Committee on Seismology. Whether or not this report will be submitted for formal publication will be decided by the committee in early Fall 1982.

The Panel on the Seismological Studies of the Continental Lithosphere has prepared a draft report. It is currently being revised. The report should be in final form during late 1982. The subject matter corresponds well with the International Program on the Lithosphere.

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

Contract: DE-FG01-82ER12018

Title: III. U.S. National Committee for Geochemistry

Person in Charge: W. L. Petrie

Scope of Work

The U.S. National Committee for Geochemistry has two major functions: (1) acting as the corporate U.S. member adhering to the International Association of Geochemistry and Cosmochemistry (IAGC), representing the United States in appropriate international organizations and activities concerned with geochemistry, and (2) promoting the advancement of geochemistry in the United States.

The committee includes a member of the IAGC Council living in the United States who acts in an ex officio capacity as a coordinator who works closely with IAGC; George W. Wetherill, of the Carnegie Institution of Washington and the immediate past president of the IAGC, now holds that position. Other U.S. members of the IAGC Council include Ernest E. Angino (University of Kansas), treasurer, and Ivan Barnes (U.S. Geological Survey, Menlo Park, California), councilor.

The committee meets twice a year usually in conjunction with the spring meeting of the American Geophysical Union and the annual fall meeting of the Geological Society of America. In attendance are ex officio and liaison members and liaison representatives from government agencies, including the U.S. Geological Survey, the Department of Energy, and the National Science Foundation. The U.S. National Committee for Geochemistry regularly reviews and acts on reports on IAGC activities as well as special reports on a variety of geochemical topics.

The committee supports the IAGC and its council by paying corporate annual dues, nominating both the IAGC offices and council and appointing the NAS delegation to IAGC general assemblies and council meetings, and organizing and administering the travel grant program which aids the ablest young geochemists to attend the IAGC General Assembly and to present their papers at the quadrennial International Geological Congress (IGC) that convenes concurrently. The most recent IAGC met in Paris in 1980; the next such meeting is scheduled for Moscow in 1984.

The committee informs members of advances in geochemistry, sponsors scientific meetings, and establishes ad hoc subcommittees or panels, as appropriate, to report on timely topics concerning geochemists both in the United States and abroad. For example, the committee interacts with the U.S. Geodynamics Project via geochemists assigned to report on specific topics of interest, reviews documents related to radioactive-waste disposal, and arranges workshops, such as that entitled "Basic Research in Organic Geochemistry Applied to National Energy Needs," held at the University of South Florida, St. Petersburg, in December 1980. A study entitled the "Future

of Geochemistry" is planned as a sequel to "Orientations in Geochemistry" (1973), by the Panel on Orientations for Geochemistry under the chairmanship of R. M. Garrels.

M. L. Crawford is currently heading a study of fluid migrations in the lithosphere, which is being coordinated with the U. S. Geodynamics Committee. V. R. Murthy is planning to attend the Fifth International Conference on Geochronology, Cosmochronology, and Isotope Geology, June 27-July 2, 1982, in Nikko National Park, Japan.

The Committee's Constitution provides for members' terms that are normally three years in length, with one third expiring at the end of June each year. The current membership for the U.S. National Committee for Geochemistry is as follows: V. Rama Murthy (Chairman), Keith A. Kvenvolden (Vice Chairman), Maria Luisa Crawford, Larry W. Finger, David A. Hewitt, Everett A. Jenne, Fred Mackenzie, Werner J. Raab, William M. Sackett, and Peter J. Wyllie. Liaison with three government agencies is conducted through Edward Schreiber, DOE; Benjamin Morgan, III, USGS, and Robin Brett and Alan Gaines, NSF.

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

Contract: DE-FG01-82ER12018

Title: IV. 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 work is based largely on the recommendations developed by its 19 reporters and their associated groups. In 1976, at the request of the Geophysics Research Board, the USGC began planning U.S. research activities in solid-earth studies in the 1980's. In the years following, the committee devoted a considerable effort to the program, leading to the report, Geodynamics in the 1980's, published in April 1980. This report urges that research emphasize the origin and evolution of continental and oceanic crust, the continent-ocean transition, the relation of mantle dynamics to crustal dynamics, and a geodynamic framework for understanding resource systems and natural hazards.

The list of topics and respective reporters has been subject to continual review and revision, as appropriate. As of may 1982, the list is as follows:

Fine structure of the crust and upper mantle	J. E. Oliver
Evolution of oceanic lithosphere	J. R. Heirtzler
Large volume experimentation	R. E. Riecker
Application of isotope geochemistry to geodynamics	R. E. Zartman
Geodynamic modeling	D. L. Turcotte
Drilling for scientific purposes	E. M. Shoemaker
Magnetic problems	C. E. Helsley
Plate boundaries	J. C. Maxwell
Plate interiors	L. L. Sloss
Geodynamics data	M. N. Toksoz
Data centers and repositories	A. H. Shapley
Lithospheric properties	T. H. Jordan
Aeromagnetic survey	W. J. Hinze
Comparative planetology	J. W. Head
Continent-ocean geodynamic transects	R. C. Speed
Ancient suture belts	E. M. Moores
Electrical properties of the aesthenosphere	C. S. Cox
Coordination of major geodynamics-related programs	A. R. Palmer
Celebration of Polar Years and IGY; and Geophysics Film Series	C. L. Drake

The results of the work of the USGC and reporters have been issued in annual reports (published or unpublished).

In 1973, the USGC strongly urged the application of seismic reflection profiling techniques to the structure of the earth's crust and upper mantle. Two years later a consortium of four universities, Consortium for Continental

Reflection Profiles (COCORP), began applying this technique. That group has now completed profiles totaling 4000 km. This technique has now become a standard tool in investigating the earth's crust and upper mantle.

The USGC strongly supported efforts to develop a continental scientific drilling program. The work of the USGC reporter led to two workshops (1974 and 1978). The report of the 1978 workshop, Continental Scientific Drilling Program (1979), contained the principal conclusion that, with advance planning, a greater scientific return could be obtained through add-on experiments involving a relatively small increased expenditure to the existing large investment in drilling by government and industry. The 1979 report also recommended that a national Continental Scientific Drilling Program be organized to facilitate the necessary communication and coordination. As a result of the response by federal agencies to the report recommendations, a Continental Scientific Drilling Committee was created in January 1980 under the Geophysics Research Board. The committee actively encourages the development of this drilling program, including add-on investigations in mission-oriented holes and holes dedicated to basic scientific objectives.

The reporter for plate boundaries organized cross sections across ancient plate boundaries. Eighteen such cross sections are in preparation of which fifteen have been published.

The USGC places strong emphasis on the importance of the transition zone between continental and oceanic lithosphere. The USGC recommended that a series of transects be prepared to set forth existing geological, geochemical, and geophysical data along a series of 25 profiles around the North American coast--from the continental craton across the transition zone to oceanic lithosphere. The project began two years ago; it involves eight working groups and more than one hundred people. The working groups met in April 1982 to exhibit and review the results of their work to date; a public exhibit will be made in November 1982. Publication of the results will begin in 1983.

In 1980, the USGC appointed a reporter and associated working group to ensure coordination among major geodynamics-related programs, especially the Circumpacific Map Project, COCORP, Continental Scientific Drilling Program, Continent-Ocean Transects, Early Crustal Evolution, Deep Sea and Continental Margins Drilling, Gravity Anomaly Map for North America, LASE, Magnetic Anomaly Map for North America, Tectonic Map of North America, and the USGS Geological Framework Program.

The International Union of Geodesy and Geophysics and the International Union of Geological Sciences have organized an international program of geodynamics for the 1980's as a successor to the Geodynamics Project, which formally ended in December 1979. The new program is entitled Dynamics and Evolution of the Lithosphere: The Framework for Earth Resources and the Reduction of Hazards. International guidance is provided by the Interunion Commission on the Lithosphere. The secretariat of that commission is located in the United States; basic support for the practical operations of the secretariat is provided through the USGC. The international program is developing in a manner partly analogous to the new plans of the USGC. In particular, the emphasis has shifted toward the continents and the continent-ocean transition for reasons of scientific and societal relevance, especially in the areas of resources and natural hazards. The USGC will serve as the U. S. counterpart to the Interunion Commission on the Lithosphere.

The USGC organized a workshop on problems of the lithosphere which was held in March 1982, in Austin, Texas. The workshop focused primarily on areas of scientific controversy in connection with the lithosphere with the expectation that this will provide guidance regarding the most productive areas for research in the coming years. Proceedings of this workshop are expected to be published in 1982.

Members of the committee are John C. Maxwell (chairman), Don L. Anderson, Bruce A. Bolt, Francis R. Boyd, B. Clark Burchfiel, William C. Kelly, David L. Mackenzie, Frank Richter, Jack E. Oliver, David W. Scholl, and Pembroke J. Hart (secretary).

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

Contract: DE-FG01-82ER12018

Title: V. Continental Scientific Drilling Committee

Person in Charge: R. Andrews

Scope of Work

The Continental Scientific Drilling Committee (CSDC) was established in January 1980 under the Geophysics Research Board of the National Academy of Sciences--National Research Council (NAS-NRC) to implement the recommendations of the report of the July 1978 Workshop on Continental Drilling for Scientifc Purposes held at Los Alamos, New Mexico. This report, Continental Scientific Drilling Program, published by the NAS-NRC in 1979, identified a major goal for this program of maximizing the scientific value of current and planned drilling activities of federal agencies and of industry, through add-on experiments, and supplementing these efforts with "dedicated" holes drilled for scientific purposes.

Members of the CSDC are: Eugene Shoemaker (Chairman), Lawrence Bonham, Charles Drake, James Eidel, Howard Gould, Bob Greider, Charles Mankin, J. J. Patrick Muffler, Jack Oliver, Elburt Osborn, Richard Traeger, and Matt Walton; and Robert Andrews, staff officer.

Scientific objectives for the national Continental Scientific Drilling Program are formulated by the panels of the Committee, five of which currently exist: Panel on Thermal Regimes; the Panel on Basement Structures and Deep Continental Basins; Panel on Mineral Resources; Panel on Drilling, Logging, and Instrument Technology; and Panel on Sample Curation and Data Management. The CSDC has established two ad hoc task groups to address specific projects; one on the Valles Caldera in New Mexico and one on the Creede Mining District in Colorado.

A DEW (Drilling Early Warning) NEWSLETTER has been established by the Committee as its mechanism for communicating with the scientific community. This newsletter is sent out on occasion to a mailing list of about 1700 researchers from universities and other academic institutions, industry, government laboratories and geoscience administrators, and geoscience societies. It provides information on the Committee's activities and scientific objectives, announces important meetings and publications, and serves as a forum for interested scientists to exchange information related to drilling. The most important role of the DEW NEWSLETTER is to announce early in the planning stage important opportunities for add-on investigations to drilling activities of government and industry and encourage collaborative efforts to the benefit of all concerned. Four newsletters have been distributed to date.

The CSDC reviewed the scientific plan for add-on investigations to a drilling activity by industry in northern Illinois and issued a report entitled Comments of the Continental Scientific Drilling Committee on the Document "Illinois Deep Hole Project--Preliminary Plan" in May 1980. Much of

the research proposed in this plan has been completed by the investigators and was reported at annual meetings of the AGU (May 1981 in Baltimore) and the GSA (November 1981 in Cincinnati). The reports will be published in a future special issue of the AGU's Journal of Geophysical Research.

The Committee reviewed the Continental Scientific Drilling Program of the Office of Basic Energy Sciences (OBES), Department of Energy. The Committee issued a report in June 1981 entitled Comments of the Continental Scientific Drilling Committee on the Department of Energy Office of Basic Energy Sciences Continental Scientific Drilling Program. In this report, the CSDC recommended that the OBES inventory (including DOE and USGS drilling data) be continued and that the OBES data management activity be expanded, as feasible, to include drilling conducted by other government agencies. The Committee also concluded that the principal objective of the OBES program, a development of fundamental understanding of hydrothermal-magma systems through the use of drilling to obtain samples, make in-hole measurements, and conduct downhole experiments, is consistent with the aims and goals outlined in the report Continental Scientific Drilling Program.

The Panel on Thermal Regimes presented a report to CSDC recommending initiation of a new, highly focused scientific drilling program aimed at understanding the roots of hydrothermal systems related to young magmatic intrusions. Primary targets are high level silicic caldera systems of the Valles Caldera, New Mexico, and the Long Valley-Inyo-Mono region of California. The report is being reviewed for issuance by the CSDC.

The CSDC identified the Valles Caldera as the prime deep drilling target into hydrothermal-magma systems at this time and established a special task group to develop a 10-year plan for this drilling project. This planning is the direct result of a request from OBES for advice regarding its Continental Scientific Drilling Program; the USGS is collaborating with the DOE program. A report from the task group is presently being reviewed by the CSDC.

The Panel on Mineral Resources presented a report to CSDC recommending major emphasis on drilling to study stacked hydrothermal mineral deposits in three mining districts: Creede, Butte, and Tonopah. The report is being reviewed for issuance by CSDC. The CSDC established a task group to prepare a scientific and operational plan for research drilling at Creede, the top priority target.

The CSDC established a Panel on Sample Curation and Data Management to develop a policy concerning curation of drilling samples and ancillary data and to recommend means for implementation. The impetus for this Panel was based in part on results of a OBES workshop on core curation at Los Alamos in 1981.

The Panel on Basement Structures and Deep Continental Basins will address dedicated drilling based on the U.S. Geodynamics Committee Workshop on Problems of the Lithosphere, the COCORP seismic profiling program, and ocean-continent and ocean margin transect projects.

The Panel on Drilling, Logging, and Instrument Technology will develop plans for a workshop in late 1982 on diagnostics and drilling to develop dialogue between scientists and the drilling/logging community. Focus for the

workshop will be on scientific measurements required for projects in Valles and Creede. The Panel is studying the state of the art in slim hole drilling and logging, and will recommend to the Committee advance technology required to meet scientific needs.

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

Contract: DE-FG01-82ER12018

Title: VI. Geological Sciences Board

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

Scope of Work

The fundamental mission of the Geological Sciences Board (GSB) of the Commission on Physical Sciences, Mathematics, and Resources, is to provide a review of research and public activities in the geological sciences, to assess the health of the disciplines, to identify the research opportunities, and to coordinate geological activities in the structure of the National Research Council. This group is to take a leading role in helping to establish scientific policy bearing on larger programs in the geological sciences in and on behalf of the United States. A major charge of the GSB is to assess and recommend basic geological research and its applications to meet national and societal needs.

The GSB established four task groups when it met for the first time in April 1981 to report to the Board on specifics for new ad hoc studies of International Geology, Geological Mapping, Instrumentation Requirements for the Geological Sciences, and the Ocean Margin Drilling Program. Also, another task group has been formed to determine if a procedure should be established to provide advice to the U.S. Geological Survey, as requested.

A workshop was held in June 1981 at which 24 participants from universities, industry, and government reviewed the status of geology with respect to providing the information required for helping to solve societal and scientific problems that currently exist and that may be encountered during the next several decades.

Contractor: UNIVERSITY OF NEVADA
SEISMOLOGICAL LABORATORY
Reno, Nevada 89557-0018

Contract: DE-AS08-82ER12082

Title: Investigation of Magma Chambers in the Western Great Basin

Person in Charge: A. Ryall

Scope of Work

This research is in support of the Continental Scientific Drilling Site Assessment Program, and is aimed at resolving questions related to the depth and configuration of the Long Valley, California, magma chamber, depth and configuration of a possible magma chamber in the Adobe Hills volcanic complex, and temporal and spatial behavior of earthquakes in areas where seismicity is known to be related to movement of magma. This program is composed of three complementary research tasks: operation of a seismic network in the Long Valley-Mono Craters area, Nevada and eastern California; analysis of data from the new network plus data on hand for the 1980-82 Mammoth Lakes earthquake sequence; and interpretation of fracture patterns and magma injection in the Long Valley area, and earthquake locations and traveltime residual patterns in the Adobe Hills volcanic center.

A. Seismic Network

Seven additional seismic stations are being installed by the University of Nevada to improve coverage in the Long Valley-Mono Craters area. With existing stations of the Nevada seismic network this will bring to 22 the number of stations in the region between Bishop and Walker Lake. Average station spacing in the area of interest will be about 20 km, sufficient for 3- or 4-station detection of events with magnitude ML < 1.

The current 3-component, short-period analog seismic station at Mina will be replaced with a set of wideband, wide dynamic range, digital seismographs in connection with an AFOSR-supported investigation of upper-mantle attenuation in the Great Basin. Data from the Mina digital station will be available for research under this contract, and will be used to determine spectral characteristics of seismic signals affected by attenuation in the Long Valley magma chamber.

B. Data Analysis

Routine analysis efforts are focused on developing an improved picture of hypocentral distribution and focal mechanisms of microearthquakes and small earthquakes in the area covered by the Long Valley-Mono Craters network. Analog data transmitted to the Reno facility will be recorded digitally, so that waveform information as well as results of hypocentral determination can be stored on event tapes and made available to other participants in the Site Assessment program.

C. Interpretation

1. Fracture Patterns.

Analysis of field-seismic and network data collected after the May 1980 Mammoth Lakes earthquakes indicates that the area south of Long Valley Caldera was subjected to complex brecciation. Our data base on the Mammoth Lakes sequence consists of recordings of thousands of small-to-moderate earthquakes, from temporary field instruments as well as stations of the permanent University of Nevada network. These data are being analyzed to determine in detail the character of fracturing associated with the sequence, and the development of this fracturing pattern with time.

2. Magma Injection in Long Valley.

Analysis of network data for the Mammoth Lakes sequence indicates that that shallow earthquakes around the southwest boundary of the caldera were characterized by lack of S-waves at network stations to the north; P-waves for the same station-event combinations were deficient in frequencies higher than about 2-3 Hz. Further analysis of this effect as functions of distance, azimuth, focal depth and station location indicates the presence of magma in the general area of the resurgent dome in Long Valley caldera, at a depth of 7-8 km. In addition, earthquakes in one small area on the southwest caldera boundary tended to occur as intensive swarms, having the appearance of spasmodic tremor, and there is some evidence that this swarm activity may have been associated with magma injection, to depths as shallow as 4-5 km, along the caldera boundary. Analysis of the field and network data will continue to search for effects, such as changes in attenuation characteristics, that would provide more concrete evidence of new magma at the location in question.

3. Adobe Hills Volcanic Center.

Previous work identified a crustal low-velocity zone below the Adobe Hills, east of Mono basin, and suggested that the zone may represent a region of partial melting in the crust, in an area mapped as a buried cauldron complex. Work under this contract is aimed at characterizing the attenuation of seismic waves by a possible magma chamber in the Adobe Hills area, and comparing such effects with those observed for earthquake waves propagating through the Long Valley magma chamber. An improved crust/upper mantle velocity model will be determined from a study of teleseismic P-residuals for the entire region covered by the Long Valley-Mono Craters network, including the Adobe Hills.

Contractor: STATE UNIVERSITY OF NEW YORK
Albany, New York 12222

Contract: DE-AC02-82ER13013

Title: I. Investigations of the Thermal Evolution of Sedimentary Basins Using $^{40}Ar/^{39}Ar$ Thermochronology: Applications to Petroleum Exploration

Person in Charge: T. M. Harrison

Scope of Work

This investigation utilizes the ability of the $^{40}Ar/^{39}Ar$ thermochronological technique to resolve the age, temperature, and in some cases the duration of thermal events experienced by crustal rocks. We have observed that microcline feldspars analyzed by this approach yield temperature information in the range of about 100 to 200°C depending on the length of heating and several mineralogical variables.

Our objective is to analyze detrital microcline samples recovered from deep drill cores in sedimentary basins to obtain both temporal and thermal information that may lead to an understanding of the temperature evolution of the basin.

The initial study focuses on the already well characterized Tejon and Basin Blocks, southern San Joaquin Valley, California. Microcline separates recovered from depths between 2.2 and 6.2 km will be analyzed by the $^{40}Ar/^{39}Ar$ age spectrum technique. Results of these measurements will be compared to a preexisting model of the thermal evolution of the region to assess the compatibility of our approach with other, conventional methods. Given a successful outcome, we shall proceed to analyze basins with complex uplift/subsidence histories--geological situations where the real potential of this method lies.

Of some interest is our observation that for many microclines of igneous origin, the ^{40}Ar degassing systematics quite closely mimics the maturation kinetics of petroleum, providing additional important information regarding the economic potential of the basin under study.

Contractor: STATE UNIVERSITY OF NEW YORK
Albany, New York 12201

Contract: DE-AC02-81ER0933

Title: II. Crustal Stretching and Subsidence in Sedimentary Basins: A Pilot Study in the Austro-Alpine Nappes of Eastern Switzerland and Permo-Carboniferous Basins in the Continental United States

Person in Charge: J. F. Dewey

Scope of Work

Stretching and thinning the continental crust is critically important in the maturation, migration, and accumulation of hydrocarbons in and around rifts and sedimentary basins. Isostatic adjustment of the stretched crust/lithosphere leads to rapid synchronous subsidence, providing a basin for sediment accumulation which causes further subsidence. During this stage, the isotherm spacing is reduced by the factor, β, and heat flow increases in both the crust and rapidly accumulating sediment pile, producing conditions under which hydrocarbons mature and begin to migrate into basin flanks. Subsequent to the stretching phase, thermal reequilibration and thickening of the lithosphere are accompanied by an exponentially declining subsidence rate and lessening fault control on thinner sedimentary sequences. During this phase, paleoslopes develop, by differential subsidence, up which hydrocarbons migrate considerable distances into the flanks and adjacent platforms of sedimentary basins.

In such basins as the North Sea, the Pennsylvanian-Permian basins of Texas and Oklahoma, and rifted continental margin basins generally, the stretched continental basement is buried beneath a thick sedimentary sequence and is therefore inaccessible to direct study. Hence, in such basins, the stretching factor, β, must be inferred from the geometry and timing of the sedimentary infill. In some basins, where there is extensive deep well penetration to basement and where the timing of the early parts of the sedimentary infill are known with reasonable precision, the stretching/thermal history may be reconstructed with considerable confidence. Problems arise, however, from unknown or poorly known thicknesses and sedimentation rates in the early rifting phase of many basins. Furthermore, the geometry of and mechanisms by which stretching occurs in such basins are not known. The extent to which mafic dikes play a role in the extension process needs to be known, as well as the geometry of faults in the deeper crust, the relation between shallow fissuring and normal faulting, and the extent and depth of fluid migration during the stretching process.

The Austro-Alpine nappe complex of eastern Switzerland, together with the southern Alps, represents the thinned continental crust of the southern margin of the Alpine trough whose demise led to the growth of the Alps. Both the continental basement and the cover are exceedingly well exposed in eastern Switzerland. By detailed and systematic structural mapping in parts of the Austro-Alpine Nappes, it will be possible to reconstruct, with great precision, the stretching factor, β, and its variability across the basin

margin from which the subsidence and thermal history of a large rift complex can be deduced. From the results of this analysis, it will be possible to derive a basic picture of the mechanical behavior of the stretched crust-lithosphere during the attenuation process and a knowledge of lithospheric behavior during the prolonged period of Jurassic-Cretaceous cooling. A systematic and very detailed study is also being made of the stratigraphic-structural-thermal maturation history of the intracontinental Pennsylvanian-Permian basins and troughs of Colorado, Texas, and Oklahoma and will be integrated with the Alpine results.

Contractor: OREGON STATE UNIVERSITY
Geophysics Group
School of Oceanography
Corvallis, Oregon 97331

Contract: DE-AM06-86RL02227

Title: Study of Digital Seismic Data Obtained in Geothermal and Volcanic Regions

Person in Charge: M. Fehler

Scope of Work

The goal of this work is to gain a better understanding of the physical processes that occur under a volcano by studying seismic data collected in the vicinity of an active volcano. Specifically, we plan to analyze seismic data collected by a portable digital seismic array that we operated in the vicinity of Mt. St. Helens volcano during 1981 in collaboration with the Massachusetts Institute of Technology and the United States Geological Survey. Four of the stations deployed at Mt. St. Helens recorded three components of ground motion while the remaining instruments recorded only the vertical component. The instruments, developed at M.I.T. by Keitti Aki and his collaborators, have dynamic range of 72 dB and have automatic gain control. Bandwidth of the recorded signals ranges from 1 to 60 Hz. Data at each station were recorded digitally on magnetic tape.

We plan to study seismic waveforms recorded by the digital seismic array to determine local scaling laws of earthquake sources, to refine our understanding of the anelastic properties of the material in the vicinity of the volcano, to define the mechanical properties of the magma, and to obtain constraints on the geometry of the magma feeding and storage system under the volcano. Additional data for the study will be tremor and earthquake waveforms recorded by a single digital station operated in the vicinity of Mt. St. Helens during the summer of 1980 during the period of time that the volcano was undergoing a series of explosive-dome-building eruptions. Our studies are aimed at improving our understanding of the flow of fluids and seismic response in both natural and man-made geothermal environments.

Contractor: PENNSYLVANIA STATE UNIVERSITY
Department of Geosciences
University Park, Pennsylvania 16802

Contract: DE-AC02-80ER10762, Mod. #A001

Title: The Effect of Strain Rate and Stress Corrosion on the Long-Term Strength of Crystalline Rock

Person in Charge: R. J. Martin

Scope of Work

The compressive strength of a brittle crystalline rock in constant strain rate tests is not a unique function of temperature and confining pressure, but depends strongly on the partial pressure of water within the sample. For example, the strength of diabase loaded in uniaxial compression nearly doubles when the partial pressure of water in the test environment was decreased from approximately 10^3 to 10^{-5} mbar (Mizutani et al., 1977).* This moisture sensitivity is due to the chemical effect of water on the cracks within the rocks. In the presence of water, rocks undergo stress corrosion cracking; that is, strong Si-O bonds are hydrated to form weaker Si-OH bonds. The high tensile stress at the crack tips accelerates this corrosion reaction which in turn facilitates the propagation of the cracks at a much lower stress than would be expected for the virgin material. The overall effect of stress corrosion at crack tips is to reduce the strength of brittle materials, tested at a constant strain rate, as the moisture content is increased.

Although small variations in partial pressure of water may significantly influence rock failure in the lower crust, it is not at all clear how important this is for shallow crustal regions where the rocks are fully saturated with water. What may be important are variations in pore water pressure at high temperature. Pore water pressure in shallow crustal rocks may have a chemical effect analogous to the partial pressure of water effect on rocks tested in uniaxial compression in a gaseous environment; that is, for a fixed effective confining pressure, the effective strength of the rock decreases as the pore water pressure increases. A program is underway to investigate the relationship between rock strength, strain rate, temperature, and pore pressure on granite at an effective confining pressure of 300 bars at temperatures between 100 and 400°C.

Initial experiments have been carried out on a suite of Westerly granite samples at 150°C and a strain rate of 5×10^{-6} sec^{-1}. Two test conditions have been employed. Samples dried in a vacuum oven and backfilled with dry nitrogen have been compared with water-saturated samples. The water-saturated samples exhibited consistently lower fracture strengths; the strength decreased an average of 23 ± 8%.

Experiments at higher pore pressures but the same effective confining pressure are currently being conducted.

* Mizutani, H. H. Spetzler, I. Getting, R. J. Martin, III, and N. Soga, "The Effect of Outgassing Upon the Closure of Cracks and the Strength of Lunar Analogues," Proc. Lunar Sci. Conf., 8th, p. 1235-1248, 1977.

Contractor: RENSSELAER POLYTECHNIC INSTITUTE
Department of Geology
Troy, New York 12181

Contract: DE-AC02-81ER10921

Title: Deep Burial Diagenesis in Carbonates

Person in Charge: G. M. Friedman

Scope of Work

The purpose of this research program is to investigate deep burial diagenesis in carbonate rocks with emphasis on the evolution of rock textures, and porosity with depth. This investigation is being conducted along two parallel lines: (1) experimental compaction tests at various temperatures and pressures of natural carbonate sediments to study the evolution of porosity and textures as observed in deeply buried carbonate strata, and (2) petrographic study of carbonate rocks from boreholes extending to depth in excess of 20,000 ft.

Initial investigation of compression tests on pure ooids at a constant pressure of 64,200 lb (2.5 kbar), but at variable temperatures of 150, 200, and 250°C has resulted in dramatic reduction in visible porosity from 31% (uncompacted samples) to slightly over 16% in compacted ones. Furthermore, these have produced different deformational features that are found in the rock record. The visible porosity, however, remains constant in all the samples subjected to constant pressure, but variable temperatures. These results tend to suggest that temperature has an insignificant role in the mechanical compaction and porosity reduction. More experiments are in progress to confirm these and other observations.

Petrographic studies of carbonate-rock cuttings from depths in excess of 20,000 ft (6 km) in the Anadarko Basin of Texas and Oklahoma illustrate various diagenetic changes caused by the increased depth. These products of deep burial include:

1. Total recrystallization in which no depositional textures remain preserved. Crystals resemble marble, including high concentrations of tuning-fork junctions, with few enfacial junctions, equicrystalline texture, and sutured crystal boundaries.

2. Elongate calcite grains which show a preferred orientation of long axes abound in grainstones.

3. The presence of grain diminution in samples of this study are a possible indication of increased depth.

So far this work has involved only cuttings. We have now obtained the world's deepest cores in carbonate rocks (23,000 ft and 20,000 ft, respectively). Our next step is the study of cores where better depositional and diagenetic control is possible.

Contractor:	SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY Rapid City, South Dakota 57701
Contract:	DE-AC02-79ER10412
Title:	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 Upper Cambrian Big Horse Member of the Orr Formation was contact metamorphosed at a pressure of approximately 2 kbar by the intrusion of the late Jurassic Notch Peak stock, a porphyritic quartz monzonite. Maximum temperature estimates range from 450-475°C for the low grade limestones to 575-600°C for the high grade rocks. Mineral compositions and assemblages in the limestones show that fluids were buffered by metamorphic reactions, that domains of equilibrium are small, and that the limestones behaved as a relatively closed system during metamorphism.

Three separate intrusions form the Notch Peak stock and the observed chemical variations can be used to determine a possible source region and possible fractionation processes that relate the plutons to one another. Based on the major element and REE chemistry, it is possible to relate all three intrusions to progressive melting of a single graywacke parent in the lower crust; detailed geochemical modeling is now in progress.

Our study of mass transport in this magma/country rock system includes analysis of the fluid phase. The following ratios, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and D/H, have been determined in samples of the Big Horse and Notch Peak stock. Preliminary results show that little or no interaction with meteoric water and little or no isotopic exchanges between the intrusion and country rocks have occurred. Further analysis of the data is necessary.

This work is being done in collaboration with J. C. Laul (Pacific Northwest Laboratories), who is conducting the INAA and RNAA analyses, and J. R. O'Neil (U.S.G.S., Menlo Park, California), who is supervising and providing the facilities for the stable isotope studies.

Contractor: SOUTHERN METHODIST UNIVERSITY
Department of Geological Sciences
Dallas, Texas 75275

Contract: DE-AC03-81ER10973

Title: Implications of Fission-Track Annealing for Geothermal Models in the Pacific Northwest

Persons in Charge: D. D. Blackwell and I. J. Duncan

Scope of Work

The objective of this project is to use fission-track annealing systematics to constrain the temperature-time history of transient thermal events. Geothermal systems, thermal evolution of sedimentary basins, and the uplift history of the Rio Grande Rift are being investigated. The project was initiated in September 1981 when the fission-track dating laboratory was set up (with assistance of C. Naeser, USGS, Denver). Research in progress consists of (1) experimental and TEM studies of annealing systematics; (2) dating of active geothermal areas (Lakeview, Oregon; Meagher Mountain, British Columbia); paleo-geothermal systems (Idaho Batholith, Nelson Batholith, etc.); Precambrian uplifts in the Rio Grande Rift; detrital apatites in deep sedimentary basins; and hydrothermal systems associated with ore deposits (Middle Mountain deposit in Colorado, etc.); (3) numerical modeling of transient thermal events associated with the geologic settings outlined in (2). These models incorporate rate laws for the annealing kinetics developed from the experimental studies.

Considerable progress has been made in each of these three areas:

1. Annealing systematics--annealing experiments using apatite are in progress using lower temperatures and longer times than most previous studies. Experiments are being run under hydrothermal conditions to test the effect of H_2O on annealing rates. Due to the exponential character of the annealing kinetics, accurate temperature control is necessary. Previous experiments with ±5°C temperature control cannot be used to reliably infer the long-term annealing behavior. High-resolution TEM studies (at NASA, Houston) are being used to monitor the annealing process.

2. Preliminary fission-track dates for apatites, sphenes, and zircons from the Sandia Mountains, Lakeview, Middle Mountain, the Idaho Batholith, and the Nelson Batholith are complete or in progress. Results indicate the Rio Grande Uplift began 25 Ma B.P. in the southern part of the rift, consistent with other geologic data. Detailed interpretation of the dating results awaits completion of Phase (3) of the research program.

3. Computer programs have been written to predict fission-track dates as a function of depth for various geologic settings, including, contact metamorphism by a pluton, caldera formation, hot-fluid flow through a horizontal fracture, cooling with uplift and erosion, and several different models for sedimentary basin evolution.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: DE-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

The goals of this research program are (1) to find the relations between the physical properties of porous rocks with fluids, which are measured routinely by geophysicists and the state of these rocks; (2) to discover new effects or processes in these rocks, which influence the permeability of fluids flowing through the pore space, the changes of porosity with time, and the effects of compaction, chemical reaction, and temperature on the pore space; and (3) to develop applications of the results to new in situ geophysical techniques in boreholes and on the surface.

Measurements of wave velocities and attenuation as a function of confining presure, pore pressure, temperature, and pore fluid type are made on a variety of rocks to determine the effects of porosity, clay minerals, fluid chemistry, pore shape, and grain size. The results will provide the data necessary to determine what information about the state of rock in situ can be inferred from measurements of seismic waves.

Measurements of flow in porous rocks are done at elevated confining and pore pressures, with reactive fluids and gas. The reactive fluids--in which Fe^{+3} and pH are controlled--are used to understand the mechanism by which permeability in porous rock changes with time--an often observed effect in the lab, and potentially a desirable effect in situ. The gas flow is studied in very tight gas sandstones, in order to understand the dependence of flow rate on pore pressure and particularly the immobile partial water saturation.

The velocity and attenuation results from rocks with steam/hot water in the pores suggest that seismic methods can be developed to detect the presence of steam in the subsurface or to detect changes with time, such as during steam flooding of reservoirs. The relation between Q^{-1} and partial water saturation may be utilized to determine water saturation in situ. The results of the chemical permeability control experiments are being applied among others to modeling the effects of silica transport in the crust, crustal permeability, and pore pressure distribution. The last two parameters are the key to our understanding of a number of crustal phenomena ranging from reservoir-induced seismicity to the formation of overpressurized zones.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: DE-AT03-76ER71045

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

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

Scope of Work

A study of the effects of macroscopic fractures on P- and S-wave velocity has been completed in four wells drilled in fractured rock to depths between 0.6 and 1.2 km. The macroscopic fractures decrease both V_p and V_s and increase V_p/V_s. In wells with a low density of macroscopic fractures, the *in situ* velocity was similar to that of saturated core samples under confining pressure in the laboratory, and a clear correlation could be made between macroscopic fracture zones and zones of anomalously low velocity. In wells with numerous marcoscopic fractures, the *in situ* velocity is distinctly lower than that of intact samples under pressure, and a correlation was seen between the rate at which *in situ* velocity increases with depth and the rate at which velocity of laboratory samples increases with pressure. Differences in *in situ* P-wave velocity between wells could not be explained solely by differences in the degree of macroscopic fracturing, thus emphasizing the importance of composition and microfractures on velocity. The change of *in situ* velocity with depth in the wells indicates that only at very shallow depths (less than a few hundred meters) is the stress sensitivity of P-wave velocity appreciably greater *in situ* than in laboratory specimens under pressure.

The results of this study will enable us to estimate macrocrack density for sonic well logs.

Contractor: STANFORD UNIVERSITY
Department of Applied Earth Sciences
Stanford, California 94305

Contract: DE-AT0-38ER12018

Title: III. Hydrothermal Solubility of Uraninite

Persons in Charge: G. A. Parks and D. C. Pohl

Scope of Work

Uraninite or uranium dioxide is a constituent phase in many radioactive waste forms as well as being the major ore mineral of many uranium ore deposits. Assessment of the rate and geographic extent of dispersal from waste disposal sites or breached repositories requires sophisticated chemical and hydrodynamic modeling. Ore deposition represents the inverse case in which concentration and fixation of uranium from a dilute-dispersed medium takes place. The equilibrium solubility of UO_2, taking into account hydrolysis, complexation, nonideality, and oxidation, imposes limits on possible solution concentrations. These limits are boundary conditions which must be recognized in release, transport, and fixation models. While acceptable thermodynamic data needed to compute solubilities under near-surface conditions may be available, our study of the literature has revealed unresolved ambiguity for data at higher pressure and temperature conditions and particularly under reducing conditions.

The principal aim of this research is to obtain equilibrium solubility data on stoichiometric UO_2 in aqueous media at temperatures from 100 to 350°C. Initially the system UO_2-H_2O is being investigated under f_{H_2} conditions sufficient to maintain the U^{IV} valence state in the solid as well as solution. We shall also attempt to investigate the effect of carbonate and chloride ligands on UO_2 solubility. We shall attempt to extract equilibrium solubility products, and hydrolysis and complexation constants from the data.

The experiments are being conducted in modified Dickson-type hydrothermal apparatus which allows sampling of the aqueous phase at ambient pressure and temperature conditions. The redox potential of the system is maintained by a fixed P_{H_2}. We are also developing an *in situ* pH electrode to take direct pH measurements at experimental conditions. *In situ* measurements of pH should allow a much simplified approach to the problems of identifying various aqueous species and provide a check of computation methods.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: 03-82ER12051.000

Title: IV. Mechanism of Zeolite Crystallization

Persons in Charge: J. G. Liou and R. J. Donahoe

Scope of Work

Zeolites comprise the most abundant and widespread group of authigenic silicate minerals and provide useful information to exploration programs for petroleum and geothermal resources. Through study of synthetic zeolites precipitated in the laboratory, conditions of their formation in natural environments can be better understood.

A. Precipitation Experiments

Synthetic phillipsite and faujasite were precipitated at 25-100°C in the system Na_2O-K_2O-Al_2O_3-SiO_2-H_2O. By variation of solution composition parameters, chemical controls on the structure, composition and crystallization kinetics of the precipitated zeolite were evaluated. Through these experiments we are able to produce phillipsite of various Si/Al ratios by controlling the composition of the initial solution. Optimum physicochemical conditions for the crystallization of Na-K zeolites are being determined. This information will be useful in industrial synthesis of zeolites and in modeling the chemistry and evaluation of hydrothermal solutions through study of authigenic zeolite assemblages.

B. Calorimetric Study of Synthetic Zeolites

Heat of solution and heat capacity measurements will be used to determine the thermochemical properties of the synthetic zeolites. Small changes in the chemical composition of zeolites can result in significant variation in the free energy of formation; therefore, knowledge of thermodynamic mixing properties is necessary in order to apply the thermochemical data to natural systems. The thermochemical data are needed in order to model and understand the geochemistry of the many diagenetic environments in which zeolites occur.

C. Nuclear Magnetic Resonance Study of Solutions and Zeolites

Nuclear magnetic resonance (NMR) has been shown to be a useful tool in studying the structure of aluminosilicate solutions and solids. The ^{29}Si NMR spectra of the initial solutions from which zeolites precipitate were used to study the distribution of silicate species in solution as a function of solution composition before and after zeolite crystallization. We intend to explore the lower concentration limit of solution NMR by using SiO_2 enriched in ^{29}Si to determine if the distribution of silica species in solution is concentration-dependent. Solid ^{27}Al and ^{29}Si NMR spectroscopy is helping to define the structure of the synthetic zeolites and will aid in the application of the thermochemical data to natural materials.

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

Contract: DE-AS05-79-ER10361

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

Person in Charge: M. Friedman

Scope of Work

Several energy-related problem areas require a better understanding of the mechanical and transport properties of rocks under confining pressure at high temperature: geothermal-energy exploration and exploitation, safe underground isolation of toxic waste, siting of stable nuclear power plants, continental deep drilling, and earthquake hazards. Our objective is to learn more about these properties in the brittle and semibrittle regimes through experimental and observational studies, the results of which should be applicable to the prediction of the behaviors of rock masses in which heat has been stored naturally or artificially.

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

Static fatigue of Barre and Westerly granites has been determined under wet and dry conditions at 100-MPa effective pressure to 200°C. Both the addition of temperature and H_2O lower the time to failure at constant stress. The results predict that granite can support stresses near 300 MPa over long periods of time although thermally-activated weakening effects of H_2O would be expected to become important over durations appreciably longer than the experiments. Simultaneously, we are conducting experiments at 1000-MPa effective pressure, in the temperature range 400 to 900°C on Westerly granite, Quadrant quartzite, and generic diorite under both wet and dry conditions. Particular attention is being given to transient creep and semibrittle behavior under these conditions. The data obtained to date are well fit by an exponential-decay function and activation energies for steady state creep appear to be reasonable and are consistent with other data. It appears from these studies that the deformation of quartz controls the creep rate of the granite.

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

The variation of fracture permeability of low-porosity crystalline rock is being investigated as functions of effective normal stress and of pore-fluid/rock interactions produced under hydrothermal conditions. The latter is of primary concern, with special attention focused on the role of dissolution-related interactions.

Activities this past year are twofold: (1) theoretical and experimental studies of the permeability of "simulated" fractures for which the fracture-surface asperities' geometric characteristics and

mechanical response can be concisely described, and (2) hydrothermal alteration experiments to study the effect of dissolution upon the surface topography of single-crystal quartz and quartzite.

The "simulated" fractures consist of a monolayer of glass microspheres (≈100 μm) sandwiched between two smooth-surfaced halves of either a stainless steel or quartz split-cylinder. Measurements indicate this is a good physical model of a rock fracture. It is found that if asperity deformation is primarily elastic, the theoretical model of Greenwood and Williamson compares favorably with experimental measurements. The dissolution experiments of nonload-bearing surfaces indicate that dissolution increases surface roughness and is surface-reaction controlled. Defects, such as grain boundaries and microcracks or pores, play an important role.

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

The scientific feasibility of drilling through hot rocks above magma chambers has been established through study of the short-term strengths and ductilities of both dry and water-saturated, intact igneous rocks. This work, essentially complete, strongly suggests that up to temperatures of melting, these rocks could be drilled by conventional methods and that boreholes would be stable to at least 10-km depth, so long as the tools and rocks could be cooled and the boreholes pressured by the drilling fluids. These temperatures and pressures have been delineated for andesite, granodiorite, and basalt. In addition, the degree of water-weakening at effective pressures to 100 MPa and temperatures to partial melting, and the factors controlling this weakening (hydration of silanol bonds and thermally activated microfractures) have been investigated. An ancillary study, also finished during the year, has provided new data on the linear thermal expansions for these rocks to 800°C and 100-MPa effective confining pressure.

Static fatigue tests on room-dry and water-saturated Westerly granite at 100-MPa effective confining pressure and 300 to 800°C have been made to assess time-dependent effects relative to the above-stated problem. Below 600°C the rock undergoes brittle failure under creep stresses that decrease nearly linearly with increasing temperature and with time to failure. Corresponding activation energy (Q) is about 15 kcal/mol at 400°C and extrapolated times to failure are long relative to expected differential stresses at borehole walls and the life of a geothermal or scientific borehole. The rock is transitional in behavior at 700°C and ductile at 800-850°C. Q values increase with increasing temperature from 31 and 41 kcal/mol dry and wet, respectively, at 400 to 600°C to 88 kcal/mol in wet tests at 700-800°C. At the higher temperatures strengths decrease acceleratingly with increasing temperature. Micro- and macroscopic observations confirm this brittle-ductile transition.

Contractor: UNIVERSITY OF TULSA
Tulsa, Oklahoma 74104

Contract: DE-AS05-79ER10400

Title: Stability of Natural Gas in the Deep Subsurface

Persons in Charge: C. Barker and K. A. Kuenhold

Scope of Work

Investigation of the stability of natural gas in the deep subsurface has continued using a combined theoretical and experimental approach. The stability of natural gas in reservoirs of various mineralogies is being calculated using a computer program that finds the minimum free energy in multicomponent (up to 50), multiphase (up to 30) systems for conditions corresponding to temperatures and pressures down to 12 km (40,000 ft). Recently the program has been modified and converted to run on the University's new computer system. The calculations show that methane stability varies widely, and that reservoir lithology is an important factor influencing natural gas stability.

Gases in rocks associated with deep reservoirs are being extracted in a newly constructed vacuum system and analyzed with a computer-interfaced mass spectrometer. This system gives much improved gas sensitivity, especially for hydrogen (which is predicted by the computer simulations). Problems associated with partial gas loss during sample retrieval can be eliminated by analyzing gases trapped in fluid inclusions in late stage cements. These can be ruptured by heating cement samples in the vacuum system and give bursts of gas lasting 1-2 sec. The mass spectrometer scans in 75 msec and can provide complete gas compositions for the inclusions. Methane, carbon dioxide, and other components have been identified in fluid inclusions in cement minerals.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

Contract: EG-77-S-0204392

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

Person in Charge: J. Hunt

Scope of Work

The objective of this research is to better understand the processes of hydrocarbon generation and migration in coastal and offshore sedimentary basins as an aid in predicting favorable exploration areas. Samples from wells representing different lithologies and depositional environments through time are being analyzed for the hydrocarbons that have been generated by natural processes and those that can be generated as the sediments are buried to greater depths and temperatures. The Austin Chalk has been identified as a source rock of light crude oil in the Texas Gulf Coast Basin through a combination of geochemical techniques such as head space analysis and pyrolysis. Sand-shale sequences from five wells on the North Slope of Alaska and a well in Texas are being obtained and will be investigated for evidences of hydrocarbon generation and migration. The Alaska sediments have been subjected to periodic uplifting which has influenced the rate and duration of oil generating capability.

A major objective of both the Alaska and Texas studies is to define the gas window; that is, the depth interval in which most of the thermally generated methane is produced. Drilling companies now have the capability to drill to 50,000 ft but the real question is whether or not any hydrocarbons will be found at that depth. In the coming months we will try to obtain additional uncontaminated samples from very deep wells (greater than 25,000 ft) to help answer this question.

Petroleum source rock evaluation by pyrolysis is now a widely used industrial technique. Unfortunately, there has been little basic research on the validity of its interpretations. A study now underway is showing that the hydrocarbon volatility, the mineral matrix, and the pyrolysis instrument design all affect interpretation of source rock potential by pyrolysis.

Contractor: WOODWARD-CLYDE CONSULTANTS
Pasadena, California 91105

Contract: DE-AC03-82ER13014

Title: Earthquake Analyses for Structural Definition and Material Characteristics of the Mono Craters and Long Valley Magma Systems

Person in Charge: L. J. Burdick and D. M. Cole

Scope of Work

The first step in tapping the geothermal potential of the magma body in the Long Valley-Mono Craters area is to learn as much as possible about its physical characteristics before actually drilling down to it. There are a number of practical difficulties involved in achieving this step. For instance, the precise location and extent of the body is unknown. A broad area must be surveyed to locate it. It is therefore necessary to interpret relatively sparse data from a broad area and infer from the data as much scientific information as possible. The purpose of the program of research discussed here is to apply some of the most sophisticated techniques available to interpret the seismic data from the Long Valley-Mono Craters region.

A. Analysis of Short Period Seismic Reflections (L. J. Burdick)

The most successful method for detecting magma bodies in other regions of the world (the Rio Grande Rift, Iceland, etc.), has been the identification of short period seismic phases either strongly attenuated or reflected by them. Appropriate data in which to locate and analyze such phases are being collected from the study area. Strongly attenuated shear waves have already been found. Once the appropriate seismic phases have been identified, they can be characterized in terms of wave mode, apparent velocity, and attenuation rate. These properties can then be matched with synthetic seismograms permitting us to locate the magma body and estimate its physical characteristics.

B. Interpretation of Seismicity Patterns (K. C. McNally)

In this investigation, seismicity data collected in the Long Valley-Mono Craters vicinity since 1927, and particularly following the Bishop 1978 (M_L = 5.7) and Mammoth Lakes 1980 (M_L = 6) earthquakes, will be analyzed for locations and fault mechanisms. The purpose is to associate them with known geological surface features (e.g., faults, craters, and hot springs), geophysical measurements (e.g., gravity and heat flow data), and seismic velocity structures to investigate the currently operative stress regime of this region.

C. Location of Anomalous Zones with Regional Phase Data (J. A. Rial)

The objective of this work will be to provide bounds on the lateral extent of the magma body in Long Valley or Mono Craters through an examination of the radiation patterns and distortions of regional and teleseismic phases which sample the hypothesized anomalous structures. This will be accomplished in two ways. The first will be a study of the

$P_{n\ell}$ waves propagating in the crust-mantle wave-guide. The second will be an analysis of short period P, pP and sP for seismic events near the suspected geothermal regions. Appropriate data from the Mammoth Lakes earthquakes has already been collected and modeled. $P_{n\ell}$ waves propagating through Long Valley do have some anomalous properties.

D. Location of Magma Bodies from Passively Gathered Seismic Data
(L. J. Burdick and D. M. Cole)

It has recently been found that an analysis of body wave particle motion at a seismic station will provide much better resolution of the structure beneath the station than a classical travel time inversion. An effort is being made to collect three-component, broadband, teleseismic data over suspected magma sites in the study region. Because this is a very high resolution technique, it is anticipated that, if a magma body is present, this approach should yield the most information about its depth and character.

Contractor: XDATA CORPORATION
6124 N. Chester Avenue
Indianapolis, Indiana 46220

Contract: DE-AC02-82ER12054

Title: Computerized Underground Image Reconstruction

Person in Charge: K. A. Dines

Scope of Work

This research is aimed at developing computer-aided imaging techniques for visualizing the subsurface geology. The major goal for this phase is to develop a field-deployable image reconstruction system for tomographic imaging of geological media using data obtained by cross borehole electromagnetic probing. Image reconstruction techniques to be implemented are applicable to electromagnetic or seismic transmission data measured as line integrals of electrical and acoustic properties in planar underground cross sections.

The field deployable system will be used in conjunction with Lawrence Livermore National Laboratory's data acquisition system to perform on-site reconstruction and display of tomographic images. This capability to immediately analyze field data will aid in obtaining the highest quality results and help to protect the investment in field deployments. By reconstructing images as the data are acquired, it will be possible to interactively adapt the data collection to concentrate on subsurface regions that appear to be of greatest interest as the image evolves on the display.

In addition to providing an interactive scanning strategy capability, the field system will provide diagnostic images for on-site interpretation and comparison to other borehole logging results. An on-site capability will also open up new possibilities for monitoring and controlling dynamic underground processes such as those involving combustion or the injection of fluids.

This effort is aimed at providing diagnostic imaging techniques for applications such as in situ coal gasification, secondary oil recovery, mineral prospecting, tar sand extraction, and the characterization and monitoring of nuclear waste isolation sites.

Contractor: YALE UNIVERSITY
Department of Geology and Geophysics
P.O. Box 6666
New Haven, Connecticut 06511

Contract: DE-AS02-76ER10455

Title: Experimental Study of Opening Mode Crack Growth in Rock

Person in Charge: R. B. Gordon

Scope of Work

The relation between the fracture toughness and the mineral composition and microstructure of rock is being studied by means of stable crack growth experiments in the laboratory. A standardized double-cantilever test specimen and test procedure are used so that results on different rock samples can be compared free of the influence of specimen shape and mode of loading on the measured fracture toughness. Fracture toughness measurements can be reproduced to within about 10% in homogeneous rock. This accuracy is sufficient to permit detection of water weakening and the differences in the fracture properties of most rock types. Rocks from the U.S. Bureau of Mines standard rock suite as well as other samples are being tested. Microcracking and plastic deformation in the process zone surrounding the crack are observed with the scanning electron microscope, and the size of the zone of microcracking is found with the aid of permeability tests.

Internal friction measurements made on the rock sample while a crack is growing in it are being used to follow the development of the "process zone," the zone of deformation surrounding the crack tip. Such measurements on Westerly granite show that both the fracture toughness and the size of the process zone are sensitive to the direction of crack propagation relative to the foliation of the rock; both are larger when the tensile stresses are perpendicular to the plane of the foliation.

The results of these experiments are expected to be useful in evaluating the fracture characteristics of rock formations from core and other samples. They have been applied to the interpretation of field observations of joint systems in the Cardium sandstone.

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

	FY 1969	FY 1970	FY 1971	FY 1972	FY 1973	FY 1974	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
ON SITE														
ANL	$ 0	$ 0	$ 50	$ 50	$201	$ 60	$ 98	$ 60	$ 50	$ 100	$ 140	$ 240	$ 310	$ 330
BNL	–	–	–	–	65	41	0	–	–	–	–	–	–	–
LANL	0	0	0	0	95	291	530	906	750	810	1,084	1,420	1,500	1,375
LBL	–	–	–	–	–	295	315	816	620	660	735	995	1,075	1,180
LLNL	–	–	–	–	–	–	75	135	130	250	630	910	1,060	1,110
ORNL	195	195	180	145	0	0	50	140	150	180	240	280	380	430
PNL	75	105	76	86	100	123	175	266	250	280	460	565	580	520
SNL-A	–	–	–	–	–	–	246	500	450	500	800	1,165	1,310	1,546
On-Site Total	$270	$300	$306	$280	$461	$ 810	$1,588	$2,822	$2,400	$2,780	$4,079	$5,575	$ 6,215	$ 6,491
OFF-SITE														
U/Alaska (Akasofu)	$ 21	$ 20	$ 21	$ 25	$ 22	$ 45	$ 41	$ 82.4	$ 78.8	–	$ 85.4	$ 84.3	$ 108.055	$ 113.141
U/Alaska (Pulpan)	39	40	40	44	0	102	79	31.5	41.8	58.6	112.7	86.6	70	–T
U/Alaska (Kienle)	–	–	–	–	–	–	90T	–	–	–	–	–	–	–
U/Arizona (Hill)	–	–	–	–	–	–	–	–	–	–	–	90.598	95.518	98.541
U/Arizona (Norton/Bird)	–	–	–	–	–	–	–	–	–	–	–	–	65.695	59.757
Arizona State (Navrotsky)	–	–	–	–	–	–	–	–	–	–	–	34.96	61.532	66.453
Aspen Institute (Roberts)	–	–	–	–	–	–	–	–	–	47.6	57.2	70.5T	–	–
Brown U. (Hermance)	–	–	–	–	–	–	–	–	–	–	94.7	140	163.916	165
U/California (B) (Reynolds)	70	75	61	61	61	60	63	130	127	148	127	167.9	144.06	150
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)	–	–	–	–	–	–	46	55	41	50	103.3	107	121	NFXT
U/California (LA) (Boehler)	–	–	–	–	–	–	–	–	–	–	–	–	46.564	NFX
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	NFX	37.618
Columbia U. (Fairbridge)	–	–	–	–	–	30	75T	–	–	–	–	–	–	–
Columbia U. (Sykes/Jacobs)	0	70	70	66	80	137	180	200	240	256	274	311.8	317.963	318.001
Columbia U. (Scholz/Engelder)	–	–	–	–	–	–	–	65	62.1	75	100	140	150	156.369
Ft. Lewis College (Ellington)	–	–	–	–	–	–	–	2	–	–	–	–	–	–
U/Hawaii (Manghnani)	–	–	–	–	–	–	–	–	–	–	–	–	–	88.109
Headquarters Services	–	–	–	–	–	–	–	–	–	–	–	–	–	6.1
Indianapolis Center for Advanced Research (Dines)	–	–	–	–	–	–	–	–	–	–	–	80	53.924	T
U/Minnesota (Johnson/Seyfried)	–	–	–	–	–	–	–	–	–	–	–	–	68.175	86.758
MIT (Grodzins)	170	164	94	50	0	–	–	–	–	–	–	–	–	–
MIT (Aki)	44	29T	–	–	–	–	36	100	130	112.6	142	152	160.375	151
MIT (Simmons)	–	–	–	–	–	–	–	–	–	100	100	90	100	106.561
NAS/NRC (Petrie: Alaskan Earthquake)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
NAS/NRC (Petrie: U.S. National Committee in Geochemistry)	–	–	–	–	–	–	–	–	–	–	–	–	18.6	21.8
NAS/NRC (Usselman: Studies in Geophysics)	1	16	11	4	2	3	4	4	4	–	6	27	29	58
NAS/NRC (Berg: Committee on Seismology)	–	–	–	–	–	–	–	8.8	9	8.8	8.8	8.8	10.256	16.130
NAS/NRC (Berg: Geological/Materials Sciences Study)	–	–	–	–	–	–	–	–	–	–	14.17	–	9.624T	–
NAS/NRC (Berg: Geological Sciences Board)	–	–	–	–	–	–	–	–	–	–	–	–	–	12.5
NAS/NRC (Hart: Geodynamics Committee)	–	–	–	–	–	–	–	–	–	–	15	20	29.6	79.96
NAS/NRC (Andrews: Continental Scientific Drilling Committee)	–	–	–	–	–	–	–	–	–	–	–	60	70	93.3
Naval Weapons Support Center (Tanner)	–	–	–	–	–	–	–	5.6	–	–	–	–	–	–
U/Nevada (Ryall)	–	–	–	–	–	–	–	–	–	–	–	–	–	75
NOAA (Donnelly)	–	–	–	–	–	–	–	–	–	5	–	–	–	–
Oregon State (Fehler)	–	–	–	–	–	–	–	–	–	–	–	–	–	38.46
U/Pennsylvania (Faul)	19	25T	–	–	–	–	–	–	–	–	–	–	–	–
Pennsylvania State University (Martin)	–	–	–	–	–	–	–	–	–	–	–	61.646	83.278	NFX
Princeton U. (Hollister)	–	–	–	–	–	–	–	22.9	–	–	–	–	–	–
Queens College (CUNY) (Schreiber)	–	–	–	–	–	–	–	–	–	–	–	–	83	81.3
Rice U. (Baker)	–	–	–	–	–	–	–	–	–	–	–	15.6	–	0.193
RPI (Friedman)	–	–	–	–	–	–	–	–	–	–	–	–	91.066	99.275
SMU (Blackwell)	–	–	–	–	–	–	–	–	–	–	–	–	54.39	69.57T
So. Dakota School of Mines (Papike)	–	–	–	–	–	–	–	–	–	–	–	–	–	67.296
U/So. Florida (Sackett)	–	–	–	–	–	–	–	–	–	–	–	–	34.034T	–
Stanford U. (Liou)	–	–	–	–	–	–	–	–	–	–	–	–	–	33.537
Stanford U. (Nur/Kovach)	–	–	–	–	–	–	–	59.6	65	103.6	146.6	140	140	125
Stanford U. (Parks)	–	–	–	–	–	–	–	–	–	–	–	–	–	57.092
SUNY, Albany (Dewey)	–	–	–	–	–	–	–	–	–	–	–	–	88.193	–
SUNY, Albany (Harrison)	–	–	–	–	–	–	–	–	–	–	–	–	–	39.21
SUNY, Stony Brook (Schaeffer)	–	–	–	–	54	51T	–	–	–	–	–	–	–	–
SUNY, Stony Brook (Papike)	–	–	–	–	–	–	–	–	–	–	50.7	59.1	64.503	T
Texas A&M (Friedman)	–	–	–	–	–	–	–	–	–	–	62.5	208.485	202.414	200
U/Tulsa (Barker)	–	–	–	–	–	–	–	–	–	–	59.7	NFX	74.958	71.478
USGS (Haas)	–	–	–	–	–	–	–	–	9.1	54	54	–	–	–
U/Wisconsin (Wang)	–	–	–	–	–	–	–	–	–	–	–	57.39	37.8	–
Woods Hole (Hunt)	–	–	–	–	–	–	–	–	30.5	–	102	140.68	138.561	150
Woodward-Clyde, Pasadena (Cole/Burdick)	–	–	–	–	–	–	–	–	–	–	–	–	–	99.72
XDATA (Dines)	–	–	–	–	–	–	–	–	–	–	–	–	–	54.236
Yale U. (Gordon)	–	–	–	–	–	–	–	–	–	–	46.14	3.6	34.525	25.837
Yeshiva U. (Cameron)	41	36	16T	–	–	–	–	–	–	–	–	–	–	–
Total Off-Site	$483	$505	$410	$375	$319	$ 526	$ 672	$ 842.75	$ 898.3	$1,150.4	$1,894.31	$2,507.035	$ 3,025.528	$ 3,140.71
TOTAL OPERATING	$753	$805	$716	$655	$780	$1,336	$2,260	$3,664.75	$3,298.3	$3,930.4	$5,973.310	$8,082.035	$ 9,240.528	$ 9,631.71
TOTAL EQUIPMENT	–	–	–	–	–	–	–	–	–	–	$ 355.000	$ 560.000	$ 923.000	$ 900.000
TOTAL GEOSCIENCES	$753	$805	$716	$655	$780	$1,336	$2,260	$3,664.75	$3,298.3	$3,930.4	$6,328.310	$8,642.035	$10,163.528	$10,531.71

NFX: No Fund Extension

T: Terminal

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