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Summaries of Physical Research in the Geosciences

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CONTENTS

FOREWORD

The Department of Energy supports research in the geosciences in order to provide a sound foundation of fundamental knowledge in those areas that are germane to the Department of Energy's many missions. The Division of Engineering, Mathematical and Geosciences -- 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 Department of Energy laboratories, industry, universities, and other governmental agencies. Their support, formalized by a contract between the Department of Energy and the organization performing the work, provides 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 1983-1984. The Geosciences Research Program includes research in geology, petrology, geophysics, geochemistry, hydrology, solar-terrestrial relationships, aeronomy, seismology, and natural resource analysis, including their 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 Geosciences. 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 the 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:

- o Geology, geophysics, and earth dynamics
- o Geochemistry
- o Energy resource recognition, evaluation and development
- o Hydrologic and marine sciences
- o 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.

2. Geochemistry

A. Thermochemical Properties of Geologic Materials. Research related to thermodynamic 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 Utilization

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, experi ental, and theoretical 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.

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) 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, and Department of Energy) coordinated program under the aegis of an Interagency Accord on Continental Scientific Drilling.

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. 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 of 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

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

Scope of Work

The Geosciences program at Argonne National Laboratory is focused on research in the areas of geochemical migration and mineral thermochemistry. In the migration area strong emphasis is placed on developing an understanding of the chemistry underlying actinide element transport in geomedia. Studies of the thermodynamics, kinetics and mechanisms of actinide complex formation reactions with organic compounds (e.g., humic and fulvic acids) and inorganic constituents in ground (e.g., $CO_3^{=}$, $SO_4^{=}$) are being pursued in this connection. Analytical studies of hydrothermally-altered materials are also in progress in an attempt to describe the more general phenomenon of trace element migration in rock-water systems. As research in this program area advances, investigations of rock surface reaction chemistry are expected to become prominent. The thermochemistry part of the program is largely focused on measuring, by a variety of calorimetric methods, the thermodynamic properties of zeolites and related materials. The intent is to develop thermodynamic-structure correlations for these materials and to use the data to explain mineral equilibria.

A. Trace Element Migration in the Earth's Crust (M. Seitz, N. Sturchio, S. Boggs, Jr., and D. Livermore)

An understanding of the distribution and mobilization of trace elements in natural rock-water systems is fundamentally important and is part of the basis for developing rational policies regarding the management of our environment and the evaluation and exploitation of our energy and minerals resources. In this program, we are currently concentrating on two main areas of research: (1) chemical mobility during hydrothermal alteration in active geothermal systems, and (2) the effects of organic compounds in groundwaters on the mobility of heavy elements.

Active geothermal systems provide excellent opportunities for the study of chemical mobility in rock-water systems at relatively high temperatures. This is especially true when rock cores and thermal water (or brine) samples are available from various depths and physical conditions are known. We are now performing a detailed study of hydrothermally altered rhyolitic vitrophyre samples from the Y7 and Y8 shallow research drill holes in

Yellowstone National Park, using electron microprobe, instrumental neutron activation analysis, inductively-coupled plasma atomic emission spectrometry, and mass spectrometry. This work is being done to quantify the chemical mobility concomitant with hydrothermal alteration in these rocks at temperatures of 110°-160° C. We have also analyzed several thermal water samples from the vitrophyre unit in these holes. In a separate study, granite from the 2 km deep drill hole at the Marysville Geothermal Anomaly, Montana, is being investigated to determine the effects of protracted interaction between this rock and the coexisting 95°C dilute sodium bicarbonate-sulfate water.

Organic compounds in groundwaters are known to form stable complexes with heavy elements. We are now investigating the effects of dissolved organics on the distribution ratios of 237-neptunium and 241-americium between basalt and groundwater, using both natural and synthetic groundwater compositions at 25° and 90°C. Special techniques for studying these effects in natural groundwaters are being developed. This work will have important implications regarding the influence of groundwater composition in the transport properties of hazardous waste elements in groundwater aquifers. In related work, we have examined the mobility of phenols in dolomite aquifers. Also under investigation is the use of catalysts in low temperature geochemical experimentation.

B. Migration of Heavy Element Chemical Species in Geologic Media
(F. Schreiner and A. M. Friedman)

The mechanisms of transport of heavy elements in natural geologic formations determine the rate and extent of their dispersal, and the potential localized concentration of these elements in the environment. The objective of the present program is the investigation of the chemical factors that are important in the transport of elements with atomic numbers of 92 and beyond. Chemical properties of importance include redox and hydrolysis equilibria and complex formation. To unravel the complex aggregate of physicochemical interaction modes a number of techniques are being utilized. Oxidation states and reaction rates are determined spectrophotometrically, and equilibrium parameters are established by calorimetry. Rate measurements are made on the microsecond time scale by using the temperature jump technique. The acquired data should provide information potentially useful in the assessment of the safety of nuclear waste repositories, and in the modeling of dispersion patterns for hazardous radionuclides after accidental release.

In recent months calorimetry of the system of complex uranium carbonates has received special attention, along with enthalpy

measurements on the reaction of uranyl (VI) ions with such common anions as chloride and sulfate. The calorimeter used for these measurements is a commercial titration microcalorimeter modified for special use with radioactive elements. The instrument is capable of measuring heat releases to $\pm$ 0.0005 K-degrees. The results show the calorimetric enthalpies for the carbonato complexes of uranium to be consistent with published equilibrium data based on potentiometric and spectrophotometric measurements. Literature values for the equilibrium constants of the stepwise formation of the dicarbonato- and the tricarbonato uranate ions are 10^{14} and 10^{18}, respectively, indicating very high stabilities for the complex ions. The bond energy for attachment of a carbonato group to the uranyl ion deduced from our calorimetric measurements is near 29 kilojoules, confirming the strong affinity of the carbonate group to the uranium central atom. Calorimeric measurements in the future will concentrate on the complexing reactions of neptunium and plutonium in systems analogous to the uranium systems. At the same time spectrophotometric techniques will be used to identify the reacting species and to establish kinetic parameters. By comparative evaluation of the chemistry of the closely related elements uranium, neptunium, and plutonium we expect to develop correlations which can be used to predict the unknown behavior of transuranium elements in geologic formations.

C. Thermochemistry of Geothermal Materials (P. A. G. O'Hare and G. K. Johnson)

The objective of this program is to measure precisely, by calorimetry, thermodynamic properties of zeolites, silicates, and structurally related compounds. Materials selected for study are often key components of geologic ensembles, they may have real or potential technological value, or they may be of basic scientific interest in terms of structure or chemical bonding. Calorimetric techniques are as follows: solution calorimetry in aqueous HF for the determination of enthalpies of formation, $\Delta_f H^o_m$; low-temperature Calorimetry (5-350 K) for the determination of heat capacities, $C^o_{p,m}$; and the derived standard entropy, S^o_m; drop calorimetry ($T \geq$ 350 K) for the determination of enthalpy increments, $H^o_m(T) - H^o_m$ (298.15), and the derived $C^o_{p,m}$; and differential scanning calorimetry for the determination of $C^o_{p,m}$ and temperatures and enthalpies of transition. Measurements cover the temperature range from 5 to 1500 K or the upper temperatures limit of stability.

Based on our published value for the Gibbs free energy of formation of analcime we have been able to estimate the effect that variations in the Si/Al ratios, and applied those estimated to naturally-occurring systems. Our estimated values for $\Delta_f G^o_m$ of analcimes of composition $Na_{0.8}Al_{0.8}Si_{2.2}O_6 \cdot H_2O$ along with our experimental values for $Na_{0.96}Al_{0.96}Si_{2.04}O_6 \cdot H_2O$ suggest that solid solution of quartz in analcime is nearly ideal. These new Gibbs energies have been used to construct a log $SiO_{2(aq)}$ against T phase diagram which depicts the stability of the analcimes with respect to quartz. This diagram is in complete harmony with geologic field observations and with the experimental determined stability limits of the analcimes.

In order to more completely understand the (heulandite-laumontite-SiO_2) and (heulandite-analcime-SiO_2) equilibria, our earlier studies on heulandite are being extended to include additional specimens with different Si-to-Al ratios.

Currently, the thermodynamic properties of mordenite and dehydrated mordenite are being determined in order, inter alia, to obtain a better understanding of the properties of zeolitic water.

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

Contract: DE-AC03-76SF00098

Title: Geosciences Program

Person in Charge: T. V. McEvilly

Scope of Work

The geosciences program at LBL encompasses investigations in geochemistry, geophysics, reservoir dynamics, and applied geomechanics. In their applications, these studies are divided into five categories, represented in the following summaries: projects related to drilling for scientific purposes in thermal regimes on the continents, basic geochemical investigations, geomechanics-fracture studies, investigation of chemical and fluid transport processes, and the effects of bolide impacts on mass extinctions.

A. Continental Scientific Drilling - Related Projects

1. Hydrogeochemical Investigations (A. F. White and H. Wollenberg)

The objective of the hydrogeochemical investigations is to evaluate active hydrothermal systems in the Long Valley and Valles calderas and the Salton Trough as potential targets for deep continental drilling into magma - hydrothermal regimes. The data derived are being used to determine to what extent chemical components are introduced into hydrothermal systems from deeper magmatic sources and to determine sources of meteoric water recharge and pathways of discharge. In cooperation with the U.S. Geological Survey, existing wells operated by geothermal companies have been sampled for major and trace fluid components and dissolved gases, including noble gas isotopes. Modeling of the chemical evolution of the systems is also under way using these data and reaction path geochemical codes. The project also provides geochemical and hydrogeologic support in the design of a downhole sampler for geothermal wells and the subsequent chemical analyses and their interpretation. The sampler system may be used in holes to be drilled by DOE in thermal regimes, beginning in 1984.

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

Variations in electrical resistivity within the crust are related mainly to the degree of connected porosity, saturation and salinity of pore fluids, as well as past and present

thermal effects; e.g., elevated temperatures and clays due to hydrothermal reactions. Interpreted with current thermal and seismic data, subsurface resistivities derived from electromagnetic soundings can yield important information on the source of thermal anomalies within the crust, including the possible location of shallow magma bodies.

Controlled-source EM (CSEM) soundings made in the Long Valley Caldera have delineated two apparently separate and distinct high conductivity areas at depths of 2.5 to 3 km and within pre-caldera rocks. One conductor occurs in the south moat and near the area of intense earthquake activity and presumed magma movement. It may be due to a combination of conductive rock within a Paleozoic roof pendant, high porosity due to fault-induced fractures, and elevated temperatures. The second conductor underlies the northeast corner of the resurgent dome and appears to plunge southeastward toward Lake Crowley. Because the conductor is concordant with a magnetic anomaly, there is the possibility that the conductor represents a post-caldera extensional zone intruded by mafic magnetic rocks. The presence of these conductors has raised new questions on caldera development and structure.

The 3-axis Superconducting Quantum Interference Detector (SQUID) magnetometers previously used with the CSEM system are being replaced by newly designed and built, lightweight induction coil magnetometers and matching amplifiers. Initial tests of the coils reveal that their intrinsic noise is as low or lower than the SQUIDs. The new magnetometers should result in lower operating and maintenance costs and be more reliable than the SQUIDs.

3. Center for Computational Seismology (T. V. McEvilly and E. L. Majer)

Seismology has traditionally been a data-intensive, multi-disciplinary science with consequent problems in the reduction and analysis of large volumes of data on the one hand, and in the efficient handling, analysis, and presentation of results on the other. To be fully effective in seismology, a modern research laboratory requires data manipulation and storage capabilities beyond those of most computational facilities, along with a sophisticated flexibility in graphics and interactive operations.

It was apparent that existing personnel, equipment, and mutual interests at (UCB) and and Lawrence Berkeley Laboratory (LBL) provided a unique opportunity to establish the Center for Computational Seismology (CCS). The combined expertise in computer science, hardware development, data file management

and manipulation, numerical analysis, computer graphics, and seismology offers a powerful center capability.

The basic LBL resources available to support CCS are the Computer Center and the Computer Science and Mathematics Department (CSAM). These resources can compensate for the hardware and software limitations discussed at the outset. The LBL Computer Center provides the basic computational equipment. This has the advantage of drawing upon the continuing hardware and software developments of a larger facility, thus minimizing the risk of obsolescence. We have added to these facilities the hardware and software necessary to run the seismic reflection imaging, and to provide the CCS user with terminal and graphics service. That is, we have established within a larger computational complex a specially equipped and staffed computational facility to support and advance the wide-ranging program of seismologic research and education within the UCB/LBL community.

The first year of operation has been devoted mainly to software development and utilization of the imaging package. The principal areas of research with our specific application are:

1. Deep reflection profiling techniques
   - San Andreas Fault
   - Charleston fault zone

2. Reflection profiling in thermal regions
   - Basin & Range (northern Nevada)
   - California Coast Range (The Geysers)
   - Salton Trough (Cerro Prieto)

3. Source mechanism studies
   - Long Valley microearthquake activity
   - The Geysers seismic activity
   - Coalinga earthquake sequence
   - Acoustic emission studies of thermally disturbed zones
   - Characterization of underground nuclear explosions

4. Wave propagation
   - Seismic tomography
   - Cross-hole seismic studies in basalt
   - Scattering and attenuation of seismic waves
   - Seismic polarization & signal enhancement
   - Surface wave studies across the Tibetan Plateau

5. Data base studies

Satellite data center for DARPA's Center for Seismic Studies
Regional data center for USGS Office of Global Seismology

In addition to the above research areas, CCS is interacting with Lawrence Livermore National Laboratory (LLNL) to provide facilities for reflection profiling processing for data acquired at the Nevada Test Site and to offer CCS as a host for the development of a VAX version of the LLNL seismic analysis code (SAC). CCS also became a member of the California Consortium for Crustal Studies (CALCRUST) initiative to the National Science Foundation for the processing, analysis, and archiving of reflection data in active western tectonic regions. In total, there is routine usage by seven graduate students, two postdoctoral research scientists, four faculty/LBL staff scientists and five undergraduates in geophysics or computer sciences. Visiting scientists came from LLNL(3), USGS, the State Seismological Bureau of the Peoples Republic of China, University of Washington, Penn State, and Cal State, Northridge.

4. Detailed Microearthquake Monitoring at the Long Valley Caldera (E. L. Majer and T. V. McEvilly)

The objective of the study is to determine the source mechanisms of the microearthquake activity inside the Long Valley Caldera compared with activity outside of the caldera. It has been postulated that much of the earthquake activity in this region may be due to magma intrusion. If so, the microearthquake activity may be an indication of the location of magma movement. A 15 and 12 station array of 3 component high frequency (4.5 hz) stations was deployed in successive 15 and 10 day studies in the south moat and Laurel Canyon areas, respectively, of the Long Valley Caldera. The data from the two separate arrays were telemetered to a central location and processed in real time with the Automated Seismic Processor (ASP). The results indicate that even at a detection threshold of Mo = 10^{16} dyne-cm, the micro-earthquake activity is diffuse, with no clearly defined planes or clusters. All events detected were strike slip, consistent with regional tectonics. Events inside the caldera were deeper than those outside of the caldera, but no evidence was seen for a magma conduit.

B. Basic Geochemical Investigations

1. Thermodynamics of High-Temperatures 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 and in high-pressure steam power plants.

A theoretically based equation was developed for the thermodynamic properties of aqueous NaCl valid form 373-823 K, to 1 kbar, and to saturation with the solid. This extends to higher temperature the earlier treatment valid from 273-573 K.

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.

Other recent 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. Recent calculations have included solubility calculations of Na_2SO_4 and several alkali halides in a variety of mixed electrolytes usually to about 250°. Densities were measured recently for Na_2SO_4 and $MgSO_4$, and the heat capacity of the latter is now being measured. When these data are combined with earlier results, a comprehensive treatment can be given of phase equilibria over a range of temperatures for solutions containing the geochemically important ions Na^+, Mg^{+2}, Ca^{+2}, and Cl^-, SO_4^{-2}, HCO_3^-, OH^-, K^+.

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

The objective of this program is to better understand the chemical and physical properties of silicate melts and their quench products, silicate glasses. These data see a wide range of applications, from the interpretation of the generation and evolution of natural magmas to the understanding of their molecular structure.

The ultrasonic velocity and attenuation of several dozen silicate liquids has been measured to obtain adiabatic compressibilities. Data have been collected on liquids with

substantial amounts of all geologically major elements, as well as the alkali and alkaline earth oxides. Liquid and glass heat capacities of similarly wide compositional range, as well as heats of fusion of many silicates, have been measured calorimetricly. These results have been modeled to allow prediction of the properties of complex, multicomponent liquids, and to assess the average behavior (i.e., structural role) of each component.

Study of volatile solubilities in silicate melts has continued with work on both very inert (He, Ne, Ar, Kr, Xe) and chemically active gases (SO_3, O_2). Again, the results serve both to suggest underlying chemical mechanisms and to contribute to solving petrologic problems.

A highly sophisticated new drop calorimeter has been designed and is under construction. The instrument will be capable of operating to 2400°C with an accuracy of 0.1%, and will be used to measure heats of fusion and solid and liquid heat capacities for a wide range of very refractory and often geologically very abundant materials (i.e., Mg_2SiO_4). The high precision should permit the quantification of subtle effects which may have major physical significance, such as variation with temperature in heat capacity.

3. Generation and Migration of Petroleum and its Precursor Compounds (O. Weres)

The objective of this project is to study the reactions that produce hydrocarbons under conditions that resemble those under which petroleum is formed in nature. However, reactions are run at high temperature (usually 315°C) to allow reactions that require millions of years in nature to take place in days.

Experiments have been performed with oil shale, humic acid, synthetic models of kerogen (polymerized tung oil and terpene resins), and a variety of organic compounds. Present emphasis is on carboxylic acid anions. An important result is that large yields of acetate ion are obtained from a variety of starting materials, and that acetate ion is converted to methane. This supports the theory that the abundant acetate ion in oil- and gas field waters plays a major role in the formation of natural gas. The chemical behavior of other carboxylic acids, cycloketones, and the phenols under gas field conditions has also been investigated.

Results of this project have already found application in two disparate areas. Techniques developed by this project have

been applied to analyzing a gas field brine from Texas, and helped explain why this brine was causing a serious environmental problem. The observation that humic acid yields a large amount of acetate at 315°C helped explain why acetate and similar species are the major anions in the condensate of nuclear powerplants. This is a major advance in the art and science of understanding and eliminating the chemical conditions that cause serious corrosion in many nuclear steam generators.

The use of propyl esters for the analysis of mixed carboxylic acids has been systematized, and a collection of propyl ester mass spectra will be published.

4. Rock-Water Interaction (J. A. Apps)

The objective of this project is to understand factors controlling albite solubility in aqueous solutions between 25°C and 400°C, and 0.1 to 50 MPa. The results permit refinement of rock-water interaction models. Presently, data from some 25 dissolution studies are being evaluated with the purpose of interpreting the thermodynamics and kinetics of albite dissolution in sodium chloride solutions over the temperature and pressure range specified.

5. Abiogenic Methane Production from Igneous and Metamorphic Rocks (J. A. Apps)

Hypotheses have recently been advanced in which it is asserted that large quantities of carbon remain trapped in the mantle after planetary accretion and differentiation, and that the progressive degassing of this carbon as methane may contribute to the world's oil and gas reserves. Petrological and geochemical arguments, however, infer that mantle degassing occurs primarily through release of carbon dioxide. Abiogenically produced methane may instead have a shallow, low temperature crustal origin due to hydrolysis by ultramafic and possibly mafic rocks.

Research is underway to determine, through theoretical and laboratory studies, the range of pressures, temperatures, and chemical conditions under which methane might form in igneous and metamorphic rocks during hydrolysis. Attention is being paid to the sources of carbon, and competing reactions involving sulfur and nitrogen.

6. Aqueous Solutions Database (S. L. Phillips)

The twofold objective of this project is the compilation of critically evaluated experimental data on selected equilibria in aqueous solutions to high temperatures, concentrations, and pressures; and, to publish tables of recommended values for these equilibrium quotients. The data are used, for example, in nuclear waste disposal, chemical oceanography, geothermal energy, hydrometallurgy and corrosion problems. However, emphasis is currently on nuclear waste disposal.

Besides chemical equilibria, data covered include electrode potentials, diffusion coefficients and adsorption. The basic data are used, for example, to predict solubility and speciation of radioelements in nuclear waste repositories that may be located in salt, basalt, and tuff. A result of this project is identification of gaps where data are lacking or are inadequate, and recommendations for research to provide the needed data.

Besides critical evaluation of data, research is included on calculation of stability constants to high temperatures and concentrations; as well as computerized storage and retrieval of tables of data using desktop computers.

C. Geomechanics/Fracture Studies

1. Effect of Fracture Characteristics Upon Sonic 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 for which a knowledge of fluid flow is required. Such fields of interest lie in 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 types, the in situ permeability is controlled by the presence of fractures rather than by the rock matrix permeability.

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 those cases that it is controlled by fractures. In particular, the borehole sonic log has shown considerable promise for locating fractures in rock. Field experiments have been conducted in which digitized sonic log waveforms were obtained across single, horizontal, isolated fractures intersecting a borehole

in a crystalline rock mass. The fluid flow characteristics of these isolated fractures were measured using conventional borehole packer techniques, and the results compared. The field test will be extended to zones in the same rock mass where systems of fractures intersect the borehole, and again the results of sonic and conventional packer tests will be compared. The theoretical aspects of elastic-wave propagation along a borehole intersecting a fracture or systems of fractures are also being studied, with a view to establishing the importance of fracture parameters such as aperture and roughness on acoustic velocity and attenuation. The field experiments and theoretical studies will be used to establish correlations between acoustic wave parameters and the permeability of the rock mass adjacent to the borehole.

2. Fundamental Studies of Fluid Flow in Fractured Rock Masses Under Stress (P. A. Witherspoon and Y. W. Tsang)

The objective of this research program is to gain a fundamental understanding of the factors governing fluid flow through a single rock fracture which is subject to stress. Understanding the fluid flow behavior in a single fracture is prerequisite to the determination of the permeability of fractured rock masses. This is of importance in many areas of practical interest such as the isolation of nuclear and toxic wastes, the recovery of fossil fuels, and the development of geothermal energy. Our theoretical studies show that the geometrical roughness of fracture surfaces holds the key to many hydromechanical properties which cannot be explained if fractures are assumed to be idealized, smooth, parallel plates. By incorporating fracture roughness, we find that: (1) the characteristic stress-strain curves for both well-mated and poorly-mated fractures can be derived, (2) the effect of sample size on the mechanical and hydraulic properties of the fracture are controlled by the large scale roughness of the fracture surfaces and (3) the tortuosity of flow paths may cause the fluid flow rate through the single fracture to be depressed by several orders of magnitude from values predicted from the parallel plate idealization.

D. Transport Processes

1. Nonisothermal Reservoir Dynamics (P. A. Witherspoon, C. F. Tsang, T. N. Narasimhan)

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 transport processes in porous or fractured media and their effects through mathematical modeling and laboratory investigations.

Specifically, the following topics are addressed:

Modeling of flows of heat, liquid, vapor and air through a fractured-porous medium. A computer code capable of calculating these processes is being developed. Applications are made to the study of non-isothermal unsaturated flow near an underground heating source.

A new well test method to determine aquifer vertical permeability and layering characteristics. This proposed technique involves the injection of hotter or colder water into an aquifer and monitoring of the temperature variations. Field data are analyzed to validate the new method.

Well test methods to characterize a fractured medium by means of coupled pressure, tracer, and thermal measurements.

Continuation of the validation and applications of the LBL coupled thermo-hydromechanical code to model flow through fractured porous media.

A new technique to improve grid orientation performance of a finite difference method with applications to pattern steam-flood problems.

A study of the possibility of determining the shape and location of a fluid plume by means of coupled hydrologic and geophysical methods.

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

The objective of this research program is to better understand and characterize certain chemical and physical phenomena that influence the movement of chemically reactive solutes in groundwater flow systems. The results of the research are applicable, for example, to the migration of contaminants away from nuclear waste repositories and uranium mill tailings ponds, as well as to studies of geothermal energy reservoirs, hydro-thermal ore deposits, and other energy-related topics.

The principal focal point is the nonequilibrium nature of certain processes influential in chemical transport. Computer codes have been developed to study solute transport by advection and hydrodynamic dispersion in three-dimensional,

axisymmetric flow systems in which chemical reactions occur between solutes and solid phases. Both linear, and nonlinear kinetic rate laws for these reactions have been used in the numerical models. The thermodynamics of irreversible processes is being used to describe coupled transport processes such as chemical osmosis, thermal osmosis, thermal diffusion, and ultrafiltration. Results obtained during 1983 show that certain coupled processes may be much more significant than previously realized in saturated geologic materials that behave as semi-permeable membranes. Such materials include clay-containing backfills for high-level nuclear waste repositories.

E. Bolide Impacts and Mass Extinctions (F. Asaro, W. Alvarez, and H. V. Michel)

The overall objective of this project is to determine the relationship between asteroidal or other large body impacts on the earth and repeated massive extinctions of life which have occurred in the last 570 million years (m.y.). The primary mechanism for the research consists of intensive chemical and selective mineralogical studies (on sediments near both major and minor extinction boundaries) which are run in parallel with floral and faunal fossil studies by collaborating geologists and paleontologists. A secondary but major objective is to ascertain if a series of time markers of very high precision and accuracy (in the form of iridium and other geochemical anomalies) can be developed for relative dating and correlation of sediments in many different parts of the world. A minor objective is to evaluate the major chemical and mineralogical alterations which have occurred in the sedimentation of the 65 m.y. old Cretaceous-Tertiary (K-T) boundary, the one most closely linked to a large body impact, in order to predict the behavior expected in older boundaries.

It has been shown by one of us (W.A.) in collaboration with Richard Muller of LBL that periodic extinctions, previously noted by others to occur in the fossil record every 26 m.y., are matched by a comparable periodicity in the ages of large well-dated craters on the earth. This match has given striking support and impetus to the new hypotheses which suggest the extinctions are related to comet showers originating in the outer fringes of the solar system. These showers could have been triggered periodically by a dark star orbiting the sun.

In studies with Miriam Kastner of U.C. San Diego of the mechanism of formation of the 65 m.y. old K-T boundary, it was found that the large bolide impact (which produced the anomalous iridium deposits) probably occurred on terrestrial basalt and that a homogenized mixture (10% bolide and 90% basalt) was distributed world-wide in the form of small glassy particles which altered to clay in the ensuing 65 m.y.

An exhaustive study was made of innovative new ways in which methods of x-ray fluorescence or neutron activation analysis could be economically and rapidly (i.e., within a few years) used to measure iridium concentrations continuously in 1 kilometer of sediment. X-ray fluorescence techniques appear fruitless but neutron activation analysis with new sophisticated electronic techniques of gamma-ray measurement is very practical. An Iridium Coincidence Spectrometer has been designed which will be capable of measuring iridium with high sensitivity in 100,000 samples per year at a reasonable cost and will permit a thorough search for iridium anomalies in sediments corresponding to the 26 m.y. periodicity found in the fossil and cratering records.

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

Contract: W-7405-ENG-48

Title: I. Geology, Geophysics, and Earth Dynamics

Person in Charge: L. W. Younker

Scope of Work

The Geology, Geophysics, and Earth Dynamics Program at Lawrence Livermore National Laboratory consists of six projects: (A) Rock Mechanics, (B) Diffusion in Silicate Materials, (C) Electrical Conductivity and Temperature in Upper Mantle, (D) Attenuation and Dispersion in Rocks Containing Fluids, (E) Surface Wave Method for Determining Earthquake Mechanisms with Applications to Regional Stress Field Studies, and (F) Thermal Stress Microfracturing of Granite.

These research tasks are broadly based fundamental studies which have applications in a variety of areas including geothermal energy development, nuclear waste isolation, and seismic verification of nuclear test treaties.

A. Rock Mechanics (H. C. Heard, B. Bonner, and W. B. Durham)

This Laboratory program involves four related sub tasks:

Determination of the Thermal Behavior of Igneous Rocks. We are currently determining the thermal diffusivity of igneous rocks to 400°C and 200 MPa lithostatic pressure. For use primarily on relatively fine-grained rock samples of the order of 2.5 cm in diameter, the measurement technique produces precise and accurate measurements in a relatively short time, allowing detailed studies to be made of subtle variations of diffusivity with pressure and temperature and of variations from rock to rock. Five different igneous rock types are being measured.

Surface Topography of Rock Joints. The occurrence of large scale fractures in situ controls important rock mass properties, such as stiffness and permeability. We have constructed a computer controlled digital measurement apparatus for surface profiling along a traverse of 25 cm with vertical sensitivity of 25 μm in order to produce quantitative descriptions of these rough surfaces. Several crystalline igneous rock types are being profiled to test mathematical models of the joint closure process which indicate that surface

topography is a critical parameter for prediction of both elasticity and fluid flow.

The Influence of Cation Impurities on Creep in Halite (salt). Since the design of high level waste repositories in salt can be expected to be strongly influenced by both depth and the maximum anticipated temperature, it is of vital importance to be able to predict accurately the closure rates of these underground workings. In nature, salt is usually very pure but occasionally exhibits important trace amounts of K^{+}, Mg^{+++}, and Ca^{++}. We have demonstrated that the steady-state flow rate in salt is dependent on stress, temperature, and impurity content. At impurity levels of 0.1 - 0.6% of K^{+} or Mg^{++}, closure rates of repository workings may be 10^{8} - 10^{4} times slower at temperatures of 30 - 150°C in impure salt as compared to the pure material. These results are being extended to include effects of Ca^{++} and deformation history.

Elastic Behavior of Dolomite Single Crystals at High Temperature. We have undertaken an experiment to determine compressional and shear velocities in dolomite to 450°C and 400 MPa carbon dioxide pressure. The plastic flow stress in at least one direction of dolomite increases with temperature, and data relevant to the elastic constants should help us understand this anomalous behavior. Preliminary data show anisotropic increases of travel time, and demonstrate that the techniques developed for this work are viable.

B. Diffusion in Silicate Materials (F. J. Ryerson, W. B. Durham)

Oxygen diffusion in natural olivine (Fo_{92}) is being investigated as a function of temperature, oxygen fugacity, and orientation employing oxygen-18 enriched gas reservoirs. Profiles are analyzed by both ion microprobe and nuclear reaction techniques. The dependence of oxygen diffusivity upon oxygen fugacity will produce a more complete understanding of the defect chemistry as olivine. These results can also be correlated with data on the anelastic deformation of olivine, hopefully providing the mechanistic data which will allow confident extrapolation of high-strain rate data acquired in the laboratory to the low strain rate regimes characteristic of the crust and upper mantle. Future work will include the evaluation of pressure effects and other important rock-forming minerals.

C. Electrical Conductivity and Temperature in Upper Mantle (A. G. Duba) (Joint Project with T. J. Shankland at LANL)

The thermoelectric effect in the mantle minerals olivine and pyroxene is being measured as a function of temperature, orientation, oxygen fugacity, and iron content to investigate the effect of Mg/Si non-stoichiometry 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. Data have been collected and are being analyzed for olivine from San Carlos Indian Reservation, Arizona and a synthetic forsterite.

D. Attenuation and Dispersion in Rocks Containing Fluids (J. G. Berryman, B. P. Bonner, R. C. Y. Chin, and G. W. Hedstrom)

The objective of this project is to combine theory and experiment to analyze attenuation and dispersion of elastic waves in partially or fully saturated rocks over a broad range of frequencies. The techniques developed in this work will be applicable to a broad range of basic problems in energy recovery, particularly hydrocarbon and geothermal exploration and resource assessment. The major accomplishments of this project so far include: (1) paper analyzing the dispersion of extensional waves in the experimentally important case of fluid-saturated porous cylinders, (2) two papers on new computational techniques, and very favorable comparison with experiments on pulse propagation and attenuation in fluid-saturated porous layers.

E. Surface Wave Method for Determining Earthquake Mechanisms with Applications to Regional Stress Field Studies (H. J. Patton and S. R. Taylor)

The primary purpose of this project is to use surface-wave excitation and seismic moment-tensor theories in order to obtain source mechanisms of remote western United States earthquakes. The source mechanisms will be used to study the state of stress in the northern Basic and Range and environs. Knowledge of the regional stress field and interpretations of sources of stress should aid in

identifying areas of potential geothermal energy production and supply constraints for geophysical models of convective hydrothermal systems.

Start-up work has involved studies of the Q-structure of the Basin and Range and regionalization of surface-wave phase velocities in the western United States. In addition to elucidating the earth structure, our aim is to develop a capability to compute accurately the path transfer function for any epicentral path in the study area.

Regionalized Rayleigh- and Love-wave attenuation coefficients were measured across the Basin and Range province of western United States in the frequency range 0.02 - 0.2 Hz and were inverted simultaneously for shear-wave attenuation as a function of depth. The resulting shear-wave Z model is characterized by low Q_β in the lower crust (Q_β ~ 100) and Q_β decreasing in the upper mantle with lowest values (Q_β ~ 30) beneath 60 km depth. Our interpretation of these results is that the lithosphere is poorly developed beneath the Basin and Range and that the partially molten asthenosphere may reach very shallow depths, possibly to the base of the crust. This interpretation of the Q model, in conjunction with a geological and geophysical information, suggests that attenuation mechanisms involving partial melt predominate in the lower crust and upper mantle of the Basin and Range.

A compilation of single- and two-station phase velocity measurements for Love and Rayleigh waves in the 6-60 sec period range was used to study regional variations of phase velocities in the western United States. A tentative regionalization consisting of four major, geophysically distinct provinces and three lesser provinces can explain up to 40% of the variation in Rayleigh-wave phase velocities and gives an RMS phase travel time error of 4-6 sec. The preliminary results are encouraging for the refinement of structural models of the lithosphere in major tectonic units of the western United States and for the capability to compute phase travel times accurately, a prerequisite for use of surface waves in source mechanism studies involving linear moment tensor inversion.

F. Thermal Stress Microfracturing of Granite (H. C. Heard, Joint project with H. F. Wang at the University of Wisconsin-Madison)

By applying a simple inclusion model, we are able to relate crack density to changes in either pressure or temperature. Comparison of these predictions for four igneous crystalline rocks with laboratory measurements of thermal expansion under pressure and bulk modulus at temperature indicate a good correlation. These initial results are being expanded to include characterization of

microcrack porosities, as well as the distribution of microcrack shapes and closure pressures. The effect of pressure-temperature path dependence on physical properties will be determined directly by measurements of elastic wave velocities, electrical conductivity, and permeability. It is hoped that the microcrack data and model will provide an understanding of the physical property data.

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

Contract: W-7405-ENG-48

Title: II. Geochemistry

Person in Charge: L. W. Younker

Scope of Work

The Geochemistry Program at Lawrence Livermore National Laboratory consists of two projects: (A) Thermodynamic, Kinetics, and Transport in Aqueous Electrolyte Solutions, and (B) Kinetic and Compositional Model of High-Pressure Kerogen Pyrolysis. Studies include laboratory measurements of diffusion coefficients and activity coefficients for mixed salts, and kerogen pyrolysis experiments up to 1 kbar. Data obtained in the first task is important for understanding and modeling salt mixtures. The chemical kinetic model for kerogen conversion to petroleum as developed in the second task will have applications in a variety of fossil fuel programs.

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

Transport of dissolved chemical species is important in a wide variety of geochemical situations, including radioactive and chemical waste isolation, diagenesis, and ore formation. Mutual diffusion coefficient data are required to understand and model these processes. Osmotic and activity coefficient data are needed to model chemical equilibrium, including speciation and solubility. Some data are available for one electrolyte in water (a substantial fraction measured at LLNL). Much less data are available for two salts in water. Because such data are difficult to predict a priori, experimental measurements are esential. More activity data are available, but many mixtures of interest have not been studied. Accurate approximation methods need to be developed for mixtures to supplement all these data.

We have completed diffusion coefficient measurements for aqueous $MnCl_2$ (Rayleigh interferometry), and activity measurements for $MnCl_2$ and $MnSO_4$ (isopiestic method), since Mn^{2+} salts are of diagenetic interest. Diffusion measurements are complete for five $NaCl$-$SrCl_2$ compositions (waste isolation), and activity measurements are about 40% done for $NaCl$- $MgCl_2$ (seawater

concentrates and brines), all at 25°C. These $NaCl-MgCl_2$ data extend to the crystallization limits.

B. Kinetic and Compositional Model of High-Pressure Kerogen Pyrolysis (A. K. Burnham)

The goal of this project is to link a chemical model for oil, gas, and water evolution that was derived from high pressure pyrolysis studies to the geological conditions present in the Uinta Basin. Various ways of interfacing the chemical model with the geology will be explored. The resulting calculations will be compared to observed deposits of oil and gas to understand more fully the mechanisms of oil formation and migration. The chemical model will be upgraded to more rigorously include the reactions of hydrogen so that H_2 and CH_4 production is more accurately calculated. Previous pyrolysis experiments will also be extended to variable porosity, hence variable residence time of the generated products in the pyrolysis region, in order to more fully decouple various mechanisms of oil degradation in the model. In addition, oil samples will be obtained and various biomarker ratios measured. Combined with analyses reported in the literature, these will provide further model verification when interpreted in terms of diagnostic trends establshied from analysis of oil samples produced in our laboratory at various conditions. This project will demonstrate how to effectively use laboratory pyrolysis experiments for other kerogens as an aid in both geochemical exploration and synthetic fuel production.

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

Contract: W-7405-ENG-48

Title: III. Energy Resource Recognition, Evaluation and Utilization: Continental Scientific Drilling Program: Thermal Regimes

Person in Charge: L. W. Younker

Scope of Work

The Continental Scientific Drilling Program at Lawrence Livermore National Laboratory consists of several projects, (A) Data Management, (B) Underground Imaging, (C) Viscosity Measurements, (D) Thermal and Petrologic Studies of Silicic Systems, (E) Information Base for the Imperial Valley, (F) Shallow Hole Drilling in the Long Valley, Valles, and Salton Sea Thermal Regimes, and (G) Seismic Studies of Possible Magma Injection and Magma Chambers in the Long Valley Region. These projects support the overall program in a variety of ways, including information and data management service, generic studies on site characterization techniques, generic studies on laboratory measurements of melt properties, studies of fossil analogue systems, thermal modeling of hydrothermal systems, and seismic characterization of target regions. In addition, a shallow research drilling program has been initiated at three thermal regime sites in cooperation with three other national laboratories (SNL, LANL, and LBL).

A. Continental Scientific Drilling Program Information and Data Management Unit (N. W. Howard)

Because of the extremely high cost of drilling, it is crucial that the geologic community be kept informed of the availability of drill holes and the data obtained from them. Numerous governmental agencies and research groups have drilled holes for a variety of purposes. In some cases, information has been disseminated on the availability of these holes for research purposes, and cooperative programs have been initiated between a number of academic, government, and industrial groups. More often, however, this information has not been disseminated and interested researchers have been unaware of the availability of these drill holes until it is too late to participate effectively. An information system has been established to avoid this problem. The efforts of a Continental Scientific Drilling Program (CSDP) can be expedited, unnecessary expenditures limited, and maximum data effectiveness attained by (1) utilization of pre-existing information; (2) reopening of abandoned holes; (3) participation in current industry

drilling tests; and (4) participation in the drilling and study of future wells.

LLNL has developed a computerized data base for drill hole data acquired in CSDP projects, and is providing information to the scientific community on plans and drilling activities in a timely manner. It will continue to do so through the initial period of intensive use. A study of potential long-term operating modes has proved that there is still an active interest in the data base which is best served by having LLNL provide data compilations as requested by researchers.

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

A significant portion of the Department of Energy budget is being spent on extracting energy from, or storing nuclear waste within, the subsurface environment. To asses whether the energy extraction or waste storage procedures are properly implemented, it is necessary to obtain detailed images of the subsurface environment. Such images will also be of value for continental drilling interests. LLNL has had success in developing and applying the concept of geophysical tomography to achieve such images. LLNL has also shown that improved interpretations of the subsurface environment can be obtained by combining laboratory data on the relations between remote probing observables (such as seismic attenuation or electromagnetic velocity) and the governing physical phenomena (such as in situ stress of temperature). Demonstrations of seismic shear, seismic compressional and electromagnetic geotomography has been successfully completed. This effort will continue the integrated program for advancing the state-of-art in data collection methods, data processing procedures, data interpretation techniques, and enhanced means of data interpretation.

C. Viscosity and Liquid Lines of Descent for Rock Melts: Continental Scientific Drilling Program (H. C. Weed, F. J. Ryerson, and A. J. Piwinskii)

Viscosities and liquid lines of descent are being determined for molten silicates under conditions of controlled oxygen fugacity (QFM). These data will relate rheological properties to the percentage of suspended crystals in a magma, and should be of value in understanding mass and thermal transport in petrologic phenomena. Materials currently under evaluation include primitive tholeiitic and high-Al basalts from Kilauea Iki and the Medicine Lake Highlands. The results should be applicable to targets selected for deep continental drilling.

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

An important aspect of continental crustal evolution is the injection into the upper crust of magma from the upper mantle or lower crust and subsequent modification of the crust as a result of thermal energy and volatiles released from the magma. The thermal regimes portion of the Continental Scientific Drilling Program (CSDP) seeks to understand these processes which involve development of geothermal systems, mineral deposits and volcanism through direct observation of the magmatic and near magmatic environment.

Our support for this CSDP initiative falls roughly into two categories (1) geological and geochemical field studies of selected exhumed fossil magma systems, and (2) thermal modeling of the shallow hydrothermal system at the Salton Sea Geothermal.

Exhumed Fossil Magma Systems. We have undertaken an integrated program of field and laboratory studies of the volcanic eruptions from two major volcanic systems in southern Nevada. The southern Nevada volcanic field of middle to late Miocene age is one of the most intensely studied and best understood fields in the world. Work, largely by geologists of the U.S. Geological Survey, has lead to the identification of more than twenty major ash-flow sheets and at least eight collapse calderas. These major volcanic eruptions provide a large instantaneous inverted sample of the subsurface magma body, and as a result, provide an excellent opportunity to study the evolution of high-level silicic magma systems. We have to date focused on the Black Mountain volcanic system for a detailed geological, geochemical and petrological study. We have complemented that study with an analysis of one of the major eruptions from the Timber Mountain Caldera complex. The results of the study have provided us with information on how these crustal magmas evolve and the dynamics of major volcanic eruptions.

Salton Sea Geothermal Field. The Salton Sea Geothermal System, a hot hypersaline convecting system driven by intrusions into a sediment-smothered rift system north of the Gulf of California, has been recognized as one place where magmatic/hydrothermal processes can be observed and analyzed. Modeling of the hydrothermal system based on thermal and geophysical data has enabled us to put constraints on the rate of magma intrusion, the timing of the initiation of the most recent hydrothermal system, and the associated flow pathways and rates. It is expected that future dedicated drilling at this site will help

to further resolve the relationship between the magma intrusions and the surrounding hydrothermal system.

E. CSDP: Imperial Valley Information Base (D. O. Emerson and P. W. Kasameyer)

To assist the CSDP-Thermal Regimes Program select sites for additional studies and determine the types of research that are needed, an information base is being developed for the Salton Trough. The data base will contain standard bibliographic data that can be searched using keywords, lists of researchers who are currently engaged in research in the area with a brief summary of their interests, and a generalized plan for future research, including possible drilling project. Using a conventional commercial data base management system on IBM-PC computers, this data will be distributed in printed form on a semi-annual basis with the first set being available September 1, 1984.

F. Shallow Hole Investigation of Long Valley, Valles, and Salton Sea Thermal Regimes (L. W. Younker, P. W. Kasameyer, and J. F. Scheimer) (Cooperative program with SNL, LANL, and LBL)

The intrusion of magma into the upper crust, the release of heat and volatiles from these intrusions, and the development of associated hydrothermal systems are problems central to understanding the evolution of continental crust and its resources. Recent research into magma/hydrothermal systems under the Continental Scientific Drilling Program have concentrated on Long Valley Valles Caldera, and the Salton Sea. All three areas contain major, recently active magmatic systems and currently active hydrothermal systems. A general reconnaissance phase of work is well advanced at these sites, and has defined specific questions which can be addressed by shallow drilling. These questions involve the mechanical, chemical (particularly with respect to volatiles), and thermal behavior of magma at shallow depth, and the the composition and circulation pattern of hydrothermal fluids. An interdisciplinary and interlaboratory program of investigations in shallow holes is proposed for the three candidate Continental Drilling sites, as a necessary step toward deep drilling at these sites. Drilling targets are the conduits beneath the youngest vents at Long Valley and Valles Calderas, and an unexplored region of the Salton Sea thermal anomaly.

LLNL involvement in the project will concentrate on thermal model development, geophysical characterization of the sites and petrological support. At Banco Bonito, we will use borehole geophysics to define the geometry of the vent structure. In addition, monitoring of the response of pore pressure to tidal strain will allow us to characterize the orientation of the major

fractures, encountered in the well. Combined interpretation of these two sets of data would provide constraints on the nature of the ring fracture system. At the Salton Sea, we will plan the heat flow survey, select the subcontractor and interpret the data using a recently developed model. We will use the new data and the refined model to provide new constraints on the volume, density, and location of the igneous dikes which provide the heat to the system.

G. Seismic Studies of Possible Magma Injection and Magma Chambers in the Long Valley Region (J. M. Mills, A. T. Smith, and J. F. Scheimer)

Our seismic research program in Long Valley/Mono Craters area emphasizes two approaches:

High resolution seismic studies to determine mechanisms of possible magma injection.

Crustal structure studies to locate and define a possible magma chamber.

Data collected in August 1982 and August 1983 in cooperation with a number of other agencies, including the USGS, provides the basis for the analysis.

Subtask 1: High resolution seismic studies of possible magmatic intrusion. The basic analysis will be extended from a single swarm to the remainder of the high-resolution data set. In addition, more advanced analysis of the entire data using source and attenuation models will enable us to further constrain the mechanics of the apparent injection process.

Subtask 2: P and S wave crustal structure studies. We will analyze the existing 3-component seismic data from the timed explosions and earthquakes using 2-D and 3-D inversion techniques, and applying 2-D forward modeling techniques. Modeling converted phases already identified in the seismic records may determine if they are produced at a solid-rock/magma interface. The Q_{coda} method of Aki will also be used to determine if ray paths through proposed regions of magma show anomalously high shear wave attentuation.

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 at Los Alamos National Laboratory presently consists of three subtasks: (A) Electrical Conductivity and Radiative Transport in the Earth; (B) Nonlinear Generation of Acoustic Beams; and (C) Creep Deformation of Rock. These research tasks apply importantly to technology needs in waste isolation and geothermal energy.

A. Electrical Conductivity and Radiative Transport in the Earth (T. J. Shankland and A. G. Duba (Lawrence Livermore National Laboratory))

We are measuring the thermoelectric effect in the mantle minerals olivine and pyroxene as a function of temperature, orientation, oxygen fugacity, and iron content and are investigating the effect of magnesium/silicon nonstoichiometry on mineral conductivity from radiative heat transport in a variety of materials that figure in geothermal studies, nuclear waste isolation, and solid-earth geophysics. The results of both of these efforts apply to inferences of the temperature distribution in the upper mantle and lower crust of the earth.

Because temperature differences in the earth drive tectonic motions on the earth's surface and interior, improved knowledge of thermal patterns is a requirement for evaluating seismic and volcanic hazards. Further, knowledge of the thermal state of the crust and upper mantle is essential for regional geothermal prospecting, particularly for the Continental Scientific Drilling Program.

B. Nonlinear Generation of Acoustic Beams (T. J. Shankland and J. N. Albright)

We are using the nonlinear elastic properties of rocks to generate low-frequency, long-wavelength acoustic beams in analogy with the case in laser optics. Two narrow beams of high-frequency sound can interact in a nonlinear medium to produce a narrow beam at their much lower difference frequency. The lower frequency beam has the narrow width of the generating beams, but it can travel much farther because of lower attenuation. Such a narrow beam would permit examination of acoustic interfaces from mine interiors and wellbores without the ambiguities of conventional seismology that

use undirected sources, for example, transducers or explosives that broadcast energy in an almost spherical pattern. Should beam formation prove possible, there would be numerous applications to problems such as mapping fractures, the boundaries of ore and coal bodies, burn fronts in underground retorts, and fluid locations in oil, gas, and geothermal reservoirs. Of more interest to basic research in rock physics is the investigation of nonlinear properties of rocks and frequency dependence of elastic properties.

Nonlinear acoustic beams have previously been observed in homogeneous materials and fluids; however, rocks have the advantage of much greater nonlinear coefficients owing to the strong effect of crack closure on elastic properties. In preliminary results we have observed difference frequency generation from vibroseis transducers operating in the field and from piezoelectric transducers on laboratory specimens at high frequencies.

C. Creep Deformation of Rock (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 study creep deformation of basalt, granite, and tuff at simulated in situ conditions of temperature, pressure, pore pressure, and differential stress. Emphasis is placed on evaluating effects of water on time-dependent brittle deformation of intact vs. fractured samples and the effect of creep on fluid permeability. Results of the experiments will be formulated into creep constitutive relations in a form amenable to predictive computer models of repository designs.

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

Geochemistry research consists of eight subtasks: (A) Rock-Water Interactions in the Jemez Geothermal System; (B) Element Migration and Fixation in Rocks; (C) Physicochemical Basis of the Na-K-Ca Geothermomemter; (D) Cation Site Size and Coulomb Energy Calculations for the Principal Rock-Forming Minerals; (E) Coal Maturation: Occurrence, Form, and Distribution of Sulfur and Mineral Matter in Peat; (F) Thermodynamic Properties of Aqueous Solutions at High Temperatures and Pressures; (G) Geochemistry of Technetium and Ruthenium and Geochemical Controls on the Redistribution of Multivalent Elements in the Lithosphere; and (H) Geologic, Geochemical, and Sr, Nd, and Pb Isotopic Studies on the Anomalous Late Cenozoic Basalt Province in the Southwestern Great Basin.

A. Rock-Water Interactions in the Jemez Hydrothermal System (R. W. Charles, R. J. Vidale, and F. Goff)

Experimental and theoretical studies are coordinated with field work to investigate rock-water interactions in the Jemez geothermal system, Northcentral New Mexico. The Jemez hydrothermal system includes at least three major hot circulating aqueous fluids, each of which has a characteristic major and minor element chemistry and is associated with characteristic rock alteration. Experimental studies will be coordinated with field work in order to define the principal variables as the system changes or has changed with time.

The approach is to define the stable mineral assemblages for a given set of variables by equilibration in agitated and, later, in circulating systems. Thermodynamic calculations will help fix these mineral assemblages in $f(O_2)$, $f(CO_2)$, $f(S_2)$, and pH space and, if thermodynamic data is not available, in chemical potential space. The experimental observations allow us to interpret the occurrence of natural alterations in portions of the Jemez system and to model the progress of such alteration through time, especially, in relation to known and proto-ore deposits.

B. Element Migration and Fixation in Crustal Rocks (T. M. Benjamin, R. W. Charles, and G.K. Bayhurst)

Acquiring an understanding of trace element migration and fixation in rocks requires a multifaceted experimental effort. Studies include: 1) the determination of the trace element concentrations and distribution in discrete mineral phases; (2) the conditions and mechanisms of element mobilization; and 3) the incorporation in secondary, precipitated, phases. Determining the major element compositions and spatial distributions in the solid phases utilizes well known electron microprobe and scanning electron microscopy techniques. The trace elements analyses are obtained from improved instrumental neutron activation analysis of bulk samples and our newly developed nuclear microprobe. The nuclear microprobe uses MeV energy protons, focused to micron size spots by a super conducting solenoid final lens, to yield characteristic x-rays resulting in elemental sensitivities, in favorable circumstances, in the 5 ppm range. The hydrothermal experiments are conducted in static Dickson vessels and dynamic fixed temperature circulating systems. The rock-aqueous fluid equilibration experiments are run at controlled pressure, temperature, and complexing anion composition. Solution samples are obtained at pressure and temperature allowing the experimental run to continue uninterrupted while obtaining unfractionated aqueous fluid. These solutions are analyzed by ion chromatography and plasma emission spectrometry.

This work can be used to examine economic recovery of metals in a geothermal energy extraction system, the origin of ore bodies, and the behavior of elements in a hazardous waste repository.

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

The Na-K-Ca geothermometer uses these cation concentrations in the emergent aqueous fluid from geothermal systems to deduce the temperature of equilibration of the subterranean hot rock and coexisting fluid. Fournier and Truesdell (USGS) utilized surface water samples and temperature measurements to derive empirical constants for a feldspar controlled system. This form of the Na-K-Ca geothermometer has been successfully applied, with limitations, to many reservoirs and has undergone some modification to take into account, where necessary, other elements in the solutions.

A series of experiments is underway to address the two primary limitations of the empirical geothermometer, temperature calibration and the chemical basis of the geothermometer. Temperature calibration is required because although the solution cation concentrations tend to preserve the highest temperature of equilibration the emergent fluid may be significantly cooler so that the empirical geothermometer will yield temperatures below the

true temperature of equilibration. The physicochemical basis needs to be understood so that the applicability of a given geothermometer, or which of a series of distinct geothermometer formulations, are appropriate in a given geochemical setting. We have observed that the activities of Na-K-Ca are fixed by secondary phases produced by reaction of the feldspars (± quartz) with water. Characterization of these secondary overgrowth is the thrust of the experimentation. Because granites provide the thermal source in many geothermal systems, granite plus aqueous fluid (± complexing anions) is reacted in both static Dickson and dynamic circulating systems.

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

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.

Computer program development and modification are largely completed, and data compilation is completed. Loading of crystallographic data onto computer disk files has been completed. We will continue our calculation 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 and Mineral Matter in Peat (R. Raymond, Jr. and A. D. Cohen)

Elemental, mineralogic, and petrographic compositions of peats, the precursors of coals, are controlled by a combination of botanical and depositional environments. Diagenetic alterations occur within these various environments that will eventually affect the occurrence of sulfur and/or mineral matter in coal deposits. To evaluate the occurrence of sulfur and/or mineral matter in a coal deposit, one must understand the mechanisms for the introduction into the original peat deposit and the alterations they go through during stages of peatification.

We are investigating sulfur and mineral matter emplacement, distribution, and alteration in four distinct coal-forming regions: marine to brackish water environments (Everglades, SW Florida); salt marsh/freshwater complex (Snuggedy Swamp, South Carolina); freshwater swamp-march complex (Okefenokee Swamp, Georgia); and a freshwater complex with late stage marine incursion (Cranberry Island, Maine). The objectives of our research are: (1) to identify and correlate sulfur forms, authigenic minerals, and detrital minerals found in different peat types; (2) to identify the processes that enhance and/or inhibit distribution and preservation of sulfur and mineral matter in the initial coal-forming environment; and (3) to construct geochemical models for their formation, preservation, alteration, and distributuion based on the first two objectives.

Our approach is to use scanning electron microscopy, x-ray diffraction, fluorescent, and plain optical microscopy, bulk chemical analyses, and conventional sedimentological analyses to characterize the modes of occurrence and content of both sulfur forms and biogenically and non-biogenically derived mineral matter in peat types. We will thereby be able to establish relationships between sulfur and mineral matter occurrence and peat types, and also to correlate the concentration and forms of their occurrence with specific environments of deposition.

F. Thermodynamic Properties of Aqueous Solutions at High Temperatures and Pressures (P. S. Z. Rogers and C. E. Holley)

Knowledge of the thermodynamic properties of aqueous solutions is basic to an understanding of many geochemical systems. Hydrothermal alteration, element migration, and geothermal activity, are a few examples of processes largely dependent on the properties of the associated aqueous fluid. Studies of these processes require information on the heat content and ion activities of mixed electrolyte solutions over a wide range of composition and temperature.

Construction of a flow microcalorimeter, designed to measure the heat capacities of aqueous solutions, has recently been completed. The calorimeter has several features that make it a unique and powerful tool for determining the properties of electrolyte solutions. The most important of these is that the fluid flows through the calorimeter, allowing measurements along isobars (rather than along the saturated vapor pressure curve) and allowing sample changes without disturbing the temperature equilibration of the calorimeter. All parts of the calorimeter that contact the aqueous solutions are constructed of a special platinum alloy, providing corrosion resistance over the operating temperature range

of 25°C to 350°C. The calorimeter also has been completely automated for nearly continuous operation.

The number of different electrolyte solutions of interest at high temperatures is large, so a method of obtaining thermodynamic properties from a minimum amount of experimental data is desirable. Heat-capacity measurements are ideal for this purpose because the heat capacity data can be integrated as a function of temperature to determine solution enthalpies and the ion activities of solution species. These thermodynamic properties will be used to provide an accurate model for electrolyte solutions at high temperature and pressures.

G. The Geochemistry of Technetium and Ruthenium and Geochemical Controls on the Redistribution of Multivalent Elements in the Lithosphere (D. B. Curtis, R. E. Perrin, D. J. Rokop, and K. Daniels)

Methods of isotope geochemistry provide powerful tools for studying the alteration of rocks: nuclear processes change the chemical and isotopic composition of natural materials in situ. The relative abundance of these natural nuclear products in a chemically isolated system can be predicted, usually by rather straightforward models of the nuclear processes. Discrepancies between predicted and actual abundances manifest the effects of chemical processes in the lithic environment.

Commonly these methods involve radioactive nuclides and their decay products (^{238}U-^{234}U, ^{87}Rb-^{87}Sr). However, the number of chemical elements represented by radioactive parent-daughter pairs is limited. In contrast, spontaneous fission produces nuclides that represent roughly one third of all the elements on the periodic table. However, the rate of element production by this process is so slow, the rate constant is 8.5×10^{17}/year, that the quantities of most elements produced in the entire history of the earth are imperceptible relative to those found "naturally" in geologic materials. In the case of a few elements, the "natural" component is sufficiently small that the spontaneous fission product can be detected. Ruthenium and technetium are two such elements. Because the abundances of these spontaneous fission products are so small there have been few efforts to develop the sophisticated analytical techniques and information required to use them as geochemical tools. We are using the unique capabilities of the Los Alamos National Laboratory Isotope Geochemistry Group to make the measurements. The ability to do so permits us to address several matters of importance. Both ruthenium and technetium are multivalent elements. Studies of their stability will provide information about the effects of redox conditions on the long term

retention of multivalent elements in a geologic environment. Our work is one of the first attempts to explicitly examine the geochemistry of this rare element. Ruthenium is one of six geochemically similar elements termed platinum group metals. Some of these are important components of critical industrial processes. Studies of the geochemistry of ruthenium will contribute to our understanding of processes that enrich platinum group metals and thus enhance the ability to assess the reserves of these critical resources.

H. Geologic, Geochemical and Sr, Nd, and Pb Isotopic Studies on an Anomalous Late Cenozoic Basalt Province in the Southwestern Great Basin (B. M. Crowe, D. B. Curtis, and G. L. Farmer)

Field investigations are being undertaken to study the age, and geochemical and isotopic patterns of basaltic volcanism in a narrow strip extending from the western edge of the Nevada Test Site westward to the eastern edge of the Sierra Nevada range. This strip crosses several major structural features including: 1) the Death Valley-Pancake Range volcanic zone; 2) the western edge of the North American craton; and 3) an east-to-west transition in the degree of activity of basin-range tectonism. Associated with these structural features are: 1) a petrological transition in the composition of basaltic rocks from hawaiites to potassium-rich alkali basalts; and 2) a transition in the isotopic composition of neodymium and strontium ranging from mantle array basalts (Sierra Nevada edge) to highly anomalous basalts (Nevada Test Site region). Lead isotopic data for basalts are available only for the eastern and western edges of the strip. These data define a linear array on a $^{207}/^{206}Pb$ versus $^{204}/^{206}Pb$ diagram indicating a common aspect to the geochemical history of the rocks. The lead isotopic compositions of individual samples does not show a recognizable covariance with the neodymium-strontium isotopic composition , with variations in trace element contents or with geographic location of the studies basalts. It is not presently known whether differences in the lead isotopic composition of the basalts reflect a heterogeneous source region or differing degrees of contamination. Selected basalts, rhyolites, and Cretaceous granites will be mapped and sampled in the field and analyzed for age, major and trace element chemistry, and the isotopic composition of lead, neodymium, and strontium. The primary thrusts of the work are: 1) To determine if isotopic covariation exists between the basalts and crustal rocks and if such covariation is consistent with models of crustal contamination; 2) To attempt to relate the isotopic compositions of lead to strontium and neodymium isotopic variations for the basalts, the rhyolites, and the granites; and 3) To attempt to related the lead isotopic compositions of studied basalts to lead isotopic data for basalts from larger region of the southwestern United States.

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

Contract: W-7405-ENG-36

Title: III. Thermal Regimes and Continental Scientific Drilling Program

Person in Charge: J. T. Whetten

Scope of Work

Research in Thermal Regimes and the Continental Scientific Drilling Program at Los Alamos National Laboratory consists of four items: (A) Studies of the Polvadera Group; (B) Origin and Extent of the Toledo Caldera; (C) Anomalous Lithospheric Structure Beneath Valles Caldera; (D) Shallow Hole Investigation of Long Valley, Valles, and Salton Sea Thermal Regimes; and (E) Valles Caldera Information Base.

A. Field, Petrologic, and Geochemical Studies of the Polvadera Group, Jemez Mountains, New Mexico (W. S. Baldridge and D. T. Vaniman)

The Polvadera Group consists of basalts, andesites, dacites, and rhyolites erupted between 10 and 2 m.y. ago on the northern, northeastern and eastern sides of the Jemez volcanic field. Basalts, comprising the Lobato Formation, were erupted earliest during Polvadera volcanism--between 10 and 7 m.y. ago. They range in composition, but at least two distinct groups are present based in both major- and minor-element characteristics. Field relations in the Lobato are complex, possibly indicating that systematic differences in composition occurred with time, or perhaps that different vents erupted different compositions simultaneously. Detailed mapping is underway to resolve these chemical-stratigraphic relations.

Andesitic and dacitic lavas (Tschicoma Formation) occur both as domes and flows. Dome distributions are being studied to the north and east of the Toledo caldera, where extensive vertical sections are exposed. Forth new chemical analyses are helping to define variability within and between the Tschicoma domes and flows to examine magma chamber processes.

Rhyolitic lavas (El Rechuelos Formation) were erupted late in the Polvadera cycle. These lavas may be early derivaties from a magma parental to the Valles (Bandelier) eruptions, or they may have oeveloped by parallel processes from other magma sources. New potassium-argon ages are currently being obtained to constrain stratigraphic relations within the Polvadera Group.

This work will lead to a more complete understanding of the magma chamber or chambers active 2-10 m.y. ago, of processes governing changes in magma compositions, and of the overall petrogenetic history of the Jemez volcanic field. It will also lead to an understanding of the ages, forms, and volumes of volcanic constructs that border the Valles caldera, and thus, will be important in interpreting results obtained in Continental Scientific Drilling Program drill studies.

B. Origin and Extent of the Toledo Caldera, Jemez Mountain, New Mexico, and its Relation to the Valles Caldera (G. H. Heiken and F. E. Goff)

The Toledo caldera is the older of two large calderas formed during the eruption of upper and lower members of the Bandelier Tuff. It is a major volcanic structure within the Jemez Mountains volcanic field, New Mexico, but its location and extent is poorly understood because much of the caldera has been masked by overlap of the younger Valles caldera. If a borehole is to be drilled by the Continental Scientific Drilling Program within the caldera complex, one option would be to choose a drill site located within the overlap of both calderas; this will provide maximum information on their history, structure, and geothermal systems. To this we must learn the extent and original position of the Toledo caldera. We propose to locate the buried portions of the Toledo caldera through geochronologic, stratigraphic, and petrologic study of domes, pyroclastic and sedimentary deposits located within the exposed remnant of the Toledo caldera, along the northern edge of Valles caldera and along the eastern flanks of the caldera complex, where the tuffs are interbedded between the upper an lower members of the Bandelier Tuff. These data should provide information on source areas for these deposits within the Toldeo caldera and, indirectly, its original location and extent.

We have nearly completed geologic mapping of most of the domes, tuffs, and sediments of the Cerro Toledo Rhyolite at a scale of 1:24,000. We have identified six eruption sequences within the Cerro Toledo Rhyolite. All consist of rhyolitic tephra and most contain Plinian pumice-falls and thin beds of very fine-grained ash of phreatomagmatic origin. Most Toledo deposits are thickest in paleocanyons and generally absent on pre-upper Bandelier ridges. Some of the phreatomagmatic tuffs flowed down canyons from the caldera and were deposited as base surges.

The tuffs are limited to two zones: 1) a 200-km-wide band that trends E to NE of the Toledo caldera (from the north edge of the Valle Grande to the north rim of the Toledo caldera); and 2) a SE-trending, 4-km-wide tuff blanket from Rabbit Mountain. There are no Cerro Toledo tuffs exposed elsewhere around the Jemez Mountains.

All of the major tuff sequences from Toledo intracaldera activity are separated by epiclastic sediments that represent periods of erosion and deposition in channels.

A study of the gravity data and drillhole data indicates that caldera resurgence is not reflected in the basement structure below Redondo Peak. On the basis of these observations, we are now evaluating models of resurgence associated with the Jemez caldera complex.

C. Lithospheric Structure and Volcanotectonic Evolution Beneath the Jemez Mountains and Rio Grande Rift Using Techniques of Seismic Tomography (K. H. Olsen)

The objective of this project is to investigate lateral variations in earth structure and rock properties (elastic wave velocities, densities, inferred temperature, etc.) beneath a complex volcanotectonic regime in northern New Mexico. We employ mainly geophysical techniques to characterize earth structure from depths of about 1-2 km to the level of the Mohorovicic discontinuity (approximately 35 km), which are beyond access by conventional surface geological techniques, although we incorporate geological and geochemical data by other investigators in our interpretations.

Our principal techniques are seismic: 1) time delay and synthetic modeling of amplitudes and waveforms of seismic waves from local and regional sources (mainly explosions); 2) merged common-depth-point (CDP) reflection and wide-angle-refraction profiling for high-resolution studies of stratigraphy of near-surface (less than 5 km) layers; and 3) time-delay observations from teleseismic (distances beyond 2000 km) sources, which are best suited for delineating mantle-level anomalies at comparatively low resolution. We combine these seismic data with gravity, aeromagnetic, and local earthquake location data derived from other Los Alamos programs to form an integrated geophysical picture of the study area.

This study deals, in general, with broad tectonic and evolutionary questions concerning the Rio Grande rift, one of the major active continental rift systems of the world. However, the principal focus of this ongoing study since 1981 has been the Jemez Mountain Volcanic Zone, which is one of the keystone elements of the rift. The Jemez region is a 100-km x 100-km x 50-km-deep block of the earth's crust that will be intensively studied using many geoscience disciplines (including deep research drilling) during the coming decade in order to clarify fundamental scientific questions pertaining to structure and evolution of large volcanic complexes and related hydrothermal geothermal systems.

D. Shallow Hole Investigation of Long Valley, Valles, and Salton Sea Thermal Regimes (F. E. Goff and J. C. Rowley)

The intrusion of magma into the upper crust, the release of heat and volatiles from these intrusions, and the development of associated hydrothermal systems are problems central to understanding the evolution of continental crust and its resources. Recent research into magma/hydrothermal systems under the continental Scientific Drilling Program (CSDP) has concentrated on Long Valley caldera, Valles caldera, and the Salton Sea. All three areas contain major, recently active magmatic systems and currently active hydrothermal systems. An interdisciplinary and interlaboratory program of investigations in shallow holes is underway for the three candidate CSDP sites as a necessary step toward deep drilling at these sites. Drilling targets are the youngest volcanic vents at Long Valley and Valles caldera and an unexplored region of the Salton Sea thermal anomaly.

Los Alamos has begun the contracting and coordination activities necessary to core a 650-m-deep hole down the Banco Bonito vent. Various geophysical logs will be obtained from the well during the later part of FY84. Strain rates will be measured on cores at Valles and on those obtained from Long Valley. Los Alamos is conducting petrologic studies of phenocryst phases as functions of depth in the rhyolite cores from the two sites and will continue with these investigations during FY85. Hydrologic tests will be performed on several aquifers of interest in the Banco Bonito corehole during FY85. Investigations of aquifer geochemistry and hydrothermal alterations will be conducted in collaboration with the other laboratories in order to help determine the characteristics of hydrothermal systems in the ring-fracture zone of Valles. Los Alamos will coordinate additional scientific efforts in the Valles corehole by the other laboratories and other interested research groups.

E. Valles Caldera Information Base (N. Marusak and F. Goff)

This is a continuation of an integrated information base containing references to published geologic, geophysical, and geochemical data and interpretations for considering detailed site selection for CSDP-Thermal Regimes. This task involves coordination with LLNL and Sandia with the objective of selecting a conventional commercial data base management system and compatible computer hardware for this project. Los Alamos has selected appropriate bibliographic titles for the assigned task from the Georef data base and DOE Energy data base. We have received these titles on tapes and are in the process of loading them into the computer for producing the hard copy listing of references.

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 objective of this program 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 and to understand sources of free energy in these plasma particle velocity distributions. Since 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, these studies help us understand the coupling of solar variations to the near-earth environment. 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 Transport in Space Plasma (S. P. Gary and W. C. Feldman)

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

Our most important research of 1983 has been a comprehensive survey of electromagnetic ion beam instabilities near collisionless shocks such as the earth's bow shock and interplanetary shocks. Our work has shown there are four different kinds of beam driven instabilities, and has demonstrated the parameter regimes in which each is important. These results have important implications for understanding how collisionless shocks accelerate ions to high energies, and may bear on the important astrophysical question of cosmic ray acceleration by interstellar shock generated by supernovae.

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

The interaction of the solar wind with the earth's magnetosphere is in the nature of an electrical generator, i.e., a conducting medium (in this case the solar wind plasma) moves through a magnetic field (in this case the earth's magnetic field), giving up its momentum in the generation of electrical currents. The solar wind-magnetosphere system is much like an MHD generator of unusual geometrical design. But it has the additional feature that it can store the electrical energy that it creates in the form of magnetic fields and this it does in the geomagnetic tail. Unlimited energy cannot be stored in the tail and excess energy is released intermittently in spasmodic fashion which part of the tail plasma sheet is severed from earth by magnetic reconnection. This process occurs during (and is the cause of) a magnetospheric substorm in which some energy is deposited in the polar ionosphere and a comparable or greater amount is returned to the solar wind as the severed plasma sheet in the form of a plasmoid (a plasma structure threaded with closed magnetic loops) flows downstream out of the tail.

There are two major results of our work during this year: 1) Working with data from the ISEE-3 satellite for (~ 1.5 million kilometers) down the tail we identified the substorm-generated plasmoids passing that distant location; and 2) We held a Chapman Conference on Magnetic Reconnection at the Los Alamos National Laboratory. The Conference was hailed as an outstanding success and most of the papers will be published in an American Geophysical Union Geophysical Monograph entitled Magnetic Reconnection in Space and Laboratory Plasmas. The book will be available in May 1984.

C. Theory of Energetic Acceleration and Precipitation from the Terrestrial Magnetosphere (D. N. Baker and M. F. Thomsen)

In this research effort we address the details of fundamental acceleration processes and resonant wave-particle interactions in the earth's outer radiation zone. These aspects of energetic particle studies deal specifically with the problem of how energetic electrons are generated and subsequently lost from the magnetosphere into the auroral ionosphere.

During this year we re-examined recent theories which ascribe banded chorus emissions to whistler instabilities driven by the presence of an energetic electron loss cone feature. We have improved this theory by using realistic observed distribution functions and by solving the dispersion relation exactly for the case of parallel propagation. We have also used concurrent data from the Los Alamos geostationary orbit energetic electron particle

sensors and ISEE-1 instruments to determine those cases where high fluxes of trapped electrons were present and ISEE was within ±1 hour of local time of a synchronous orbit spacecraft. Several candidate events have been identified and analyzed.

We have further extended our understanding of solar wind-magnetosphere interactions through the use of statistical studies. In one class of investigations using the method of linear prediction filtering, we found that the magnetosphere responds to solar wind changes on two characteristic time scales: 20 minutes and 60 minutes. The 20 minute scale represents direct driving of magnetospheric currents by the solar wind while the 60 minute response is due to storage of energy in the magnetotail (for ~ 1 hour) followed by a sudden release of this energy through substorm reconnection.

Much of the work during the past year has been directed toward a determination of where, when, and how magnetospheric reconnection occurs and how energetic particles are accelerated in this process. In one such study we have examined very detailed plasma, energetic particle, and magnetic field reconnection signatures at ~ 30 R_E geocentric distance in the plasma sheet. We find good direct evidence of strong electron acceleration and heating in many of our reconnection events. In other studies we have used plasma composition and energetic particle drifts in the earth's magnetic field to identify the location and spatial extent of substorm reconnection. We have also used these results to determine whether the plasma in the outer magnetosphere during each event originated in the solar wind or the ionosphere. Our geostationary orbit particles are accelerated and shy plasma sheet instabilities develop in certain regions.

All of these sorts of substorm-related topics have been reviewed by us in a major solar-terrestrial physics document called Solar Terrestrial Physics - Present and Future to be published by NASA. Our contribution on substorms constitutes one of the chapters of this book and summarizes the present understanding of substorm processes.

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: Robert E. Mesmer

Scope of Work

The major goal of the program is to better understand the chemical and physical processes operating in the aqueous and molten silicate fluids that are responsible for the distributions of elements in the earth's crust. Our principal avenue to this goal is experimental studies of selected natural and analogue chemical systems at temperature and pressure conditions simulating crustal environments to depths of 18 km.

Experiments are conducted on the phase equilibria, crystallization kinetics, and elemental/isotopic partitioning of rock-forming silicate systems over temperatures ranging from 500 to 1400°C and pressures to 500 MPa under controlled redox conditions to develop understanding of magmatic/hydrothermal processes. Homogeneous and heterogeneous hydrothermal experimental studies of major and minor crustal components are used to derive the thermodynamic and kinetic data required to develop models for the distribution and mobilities of elements in the upper few kilometers of the crust. This research provides insight into problems associated with energy transfer in magmatic/hydrothermal systems, volcanic processes, mineral resource exploration, enhanced techniques for oil and ore recovery, nuclear waste isolation, geothermal energy and development of ceramic structural materials.

A. Silicate Melt Geochemistry (Naney)

Iron Redox Equilibration Kinetics in Silicate Liquids (with S. E. Swanson, University of Alaska).

A series of experiments with three silicate liquids derived by melting natural volcanic rocks (basalt, andesite, and rhyolite) were conducted at 0.1 MPa (1 atm), 1243°C and two oxygen fugacities: $\log f_{O_2} = -6.08$ and -7.83 (QFM) in a CO/CO_2 gas-mixing vertical tube furnace. Minimum equilibration times are 500 and 1000 min for the basalt and andesite respectively. Equilibrium times reported here are comparable to durations cited in the literature for experiments with basalt and andesite.

Ferrous/ferric ratios in samples of rhyolite showed no indication of reaching equilibrium with furnace oxygen fugacity in experiments of up to 5900 min duration. Experiments with crushed rhyolite showed oxidation of the melt related to the interaction of liquid formed during heating with air trapped between the grains of the original sample pellet. This phenomenon was also observed in the andesite and basalt experiments. However, unlike the basalt and andesite melts, the ferrous/ferric ratios of rhyolites showed no further changes following initial oxidation. Iron redox behavior in natural rhyolites is similar to that observed in experiments with rhyolites. Oxidation of rhyolite ash-flows is probably related to high temperature air-ash reaction during or immediately following eruption. In contrast, massive glassy rhyolites (flows and domes) show little variation in bulk ferrous/ferric ratio--despite the fact that constituent Fe-Ti oxides may show a wide range of compositions--which suggests that these massive rhyolites are insensitive to external changes in oxygen fugacity.

Stability of "Magmatic" Epidote in Granitic Rock Systems. The stability of epidote [$Ca_2Al_2FeSi_3O_{12}(OH)$] is being investigated in synthetic analogs of natural granite and granodiorite compositions. Experiments are currently being conducted between 400°C and 600°C, over the pressure range 200-400 MPa to define the stability limits of epidote under subsolidus conditions. The hydrogoen-service internally heated pressure vessel, which permits control of redox conditions over a wide range of f_{O_2}-T conditions, is being used for this study. Results of recent experiments indicate that epidote is stable to at least 500°C and 400 MPa at relatively oxidizing conditions (Ni-NiO < f_{O_2} < Mt-Hm) in the composition investigated. However, under more reducing conditions (f_{O_2} < Ni-NiO) epidote is unstable at 550°C and 400 MPa. These experiments are doped with uranium to permit simultaneous investigation of the chemical partitioning of this actinide.

Geochemistry of Silicic Magma Systems (with W. C. Luth and J. C. Eichelberger, Sandia National Laboratories). A suite of hydrous rhyolitic glasses from tephra depostis of Little Glass Mtn., California, were analyzed at ORNL for ferrous and ferric iron using a colorimetric method adapted to analyze micro-sample (10-30 mg). These samples which contained H_2O contents ranging from 0.15 to 1.79 wt. pct. showed no significant variation in ferrous and ferric iron contents. This is an interesting finding in light of the commonly held opinion that hydrous volcanic glasses tend to be more oxidized than anhydrous glasses.

B. Hydrothermal Geochemistry - Homogeneous Equilibria (Wesolowski, Drummond)

Second Dissociation Constant of Sulfuric Acid in 1.0 m NaCl from 75-295°C. These experiments were performed in a hydrogen electrode emf cell and they demonstrate that sulfate species will persist metastably in a hydrogen atmosphere long enough to make precise measurements of the sulfate/bisulfate equilibria to 300°C. The present results represent the only direct measurements of sulfate hydrolysis in chloride media at elevated temperatures and are the first of a series of such experiments that will extend over a wide range of salinity (0.1 to 5 m) and include NaCl-$MgCl_2$ mixtures.

Above 200°C the equilibrium quotients of Marshall for the reaction HSO_4^- $SO_4^{2-} + H^+$ in Ca^{2+}-H^+-HSO_4^--SO_4^{2-} media match those in NaCl media. These two data sets differ by as much as 50% at lower temperatures suggesting important media effects.

C. Hydrothermal Geochemistry - Heterogeneous Equilibria (Drummond, Dickson)

Hydrolysis of Magnesium and Brucite Solubility in Aqueous Sodium Chloride Solutions at Elevated Temperatures by EMP (with P. Brown, Western Australia University). A series of potentiometric titrations in the hydrogen electrode emf cell have been carried out to measure the solubility of brucite ($MG(OH)_2$) and the hydrolysis of Mg^{2+} in aqueous sodium chloride solutions from 60 to 200°C. Most of the titration data were taken subsequent to brucite precipitation. These data were analyzed by least squares regression in terms of the solubility product of brucite and many of the possible $Mg_x(OH)_y$ hydrolysis products. Separate solubility experiments in strong base (at both 60° and 200°C) gave no indication of amphoteric solubility and hence negate the possibility of the formation of even minute quantities of negatively charged $Mg_x(OH)_y$ species in the titration experiments. Consequently, the titration data are described solely in terms of the solubility product of brucite. For the entire data set of solubility quotients 3 was about 0.05 log units. The enthalpy for the reaction $MG(OH)_2(s) + 2H^+$ $Mg^{2+} + 2H_2O$ in both 0.1 and 1.0 m NaCl media is 26.2 kcal/mole which agrees favorably with the estimate of 27.3 by Baes and Mesmer (1981).

Thermal Decarboxylation of Acetate: Boundary Conditions for the Role of Acetate in the Primary Migration of Natural Gas. In and effort to understand the kinetics of the thermal decarboxylation of acetate and the role of catalysis, a series of laboratory experiments were conducted to measure the rate constant for the decomposition of acetic acid in the presence of a variety of materials including gold, titanium, stainless steel, silica, montmorillonite and magnetite. Activation energies for decarboxylation range from about 8 kcal/mole in stainless steel to 57 kcal/mole in treated titanium vessels. Extrapolated rate constants at 100°C differ by more than thirteen orders of magnitude between the stainless steel and the least catalyzed titanium experiments. Methane and carbon dioxide were the predominant reaction products of these experiments but mass spectrometric analysis revealed concentrations of carbon monoxide, hydrogen, and hydrocarbons (apparent masses range from 29 to 56) amounting to as much as 40 mole percent of the total volatile products, depending on the catalyst. Gold, titanium, and pure montmorillonite were the least active catalysts while stainless steel, silica, and magnetite showed marked catalytic effects. The reactions were first order in acetate except for the experiments with silica and magnetite which were zero order. With this recent advance in the understanding of the chemical kinetics of acetate decarboxylation, it is possible to assess the role of acetate in the primary migration of natural gas. The appropriate physical, chemical, and geological constraints on this process were considered and integrated via a computer model that couples basin subsidence, compaction and fluid flow parameters with the chemical constraints dictated by the experimental kinetic data. This analysis shows that acetate can account for substantial gas migration from source rocks in the early catagenic stages of kerogen degradation at depths around 3 km and temperatures of 110 + 20°C.

Quartz Solution/Dissolution. The reaction of quartz grains with H_2O and NaCl were studied at 200, 220, and 250°C, 20 MPa and over times ranging from 20 to 200 hrs (av. 144 hrs). Some experimental difficulties that were encountered early in the year were worked out. A total of 15 experiments were done which involved 182 samplings and analyses for SiO_2. Experiments used double titanium alloy reaction vessels held in one furnace that were connected to permit transfer of fluid from the top of one vessel (reservoir vessel) to the bottom of the other (reaction vessel) during sampling. Experiments were done at several mass-ratios of quartz to solution: 5.0, 1.2 and 0.22 in g·Qtz per g·H_2O. Two grain size ranges (+80 and 35-80 mesh) and 3 total surface areas of the quartz were used (0.415, 0.177, and 0.0445 M^2). Part of the experiments

with quartz-filled vessels were static; all other were rocked through vertical several times per minute. The experimental data have been processed to determine equilibrium solubilities and kinetic reaction steps and rates. Rates of reactions of initially undersaturated solution with quartz are rapid compared to reactions of supersaturated solutions. The behavior of quartz-solution systems reflects the prior events (sequences of variations in time, temperature, pressure, and concentrations). Apparently a new solid phase, probably metastable, forms as layers of the quartz, as has been reported also by other workers. The surface coatings evidently are pervasive and tenacious. They prevent quartz surfaces form interacting directly with solution so long as they are present. Apparent orders calculated for quartz reactions range from 1.00 to 1.50 for undersaturated solution and to 10 and above for supersaturated ones.

D. Hydrothermal Geochemistry - Modeling (Cole, Wesolowski, Drummond)

Geochemistry of Tungsten in Hydrothermal fluids Experimental studies of the hydrolysis of tungsten (VI) in NaCl solutions to 300°C conducted at this laboratory have enabled us to develop a quantitative model for the transport and deposition of scheelite ($CaWO_4$) in ore and geothermal systems as a function of temperature, pressure, ionic strength and acidity. The model has been demonstrated to adequately explain the occurrence of ore grade levels of this important strategic and industrial commodity in several types of ore systems ranging from 0.1 to >10 MPa and 100 to 500°C. The important variables controlling solubility have been identified as temperature and ionic strength in low P-T regimes and proton concentration at higher pressures and temperatures. However, the interplay of these variables is complex and the physicochemical conditions of the depositional system must be well characterized.

Modeling Activity Coefficients in Hydrothermal Solutions. Recently, largely through the efforts of researchers at ORNL, a fairly complete body of stoichiometric activity coefficient data has become available for the major components of natural hydrothermal solutions in NaCl media to 300°C. It is clear from these data that, up to 300°C, the salts in natural hydrothermal solutions behave as if they are predominantly ionized and that NaCl is a good model substance for the activity coefficients of these components. As a consequence, it has been possible to systematize these data via a computer program that, in contrast to the ion-pair approach used historically by most geochemists, allows the activity coefficients of these components to be computed accurately, unambiguously and simply.

Oxygen Isotopic Exchange Accompanying Surface Reactions and Diffusion (in collaboration with H. Ohmoto and A. C. Lasaga, Penn State University).

Oxygen isotopic exchange between minerals and fluids proceeds through two mechanisms: (1) surface reactions (dissolution, precipitation) and (2) diffusion of oxygen-bearing species along lattice planes or crystal imperfections. The rate constants for the first type of mechanism are related as follows: $r = -\ln (1-F)(WS)/(W + S)(A)(t)$ where W and S are the moles of oxygen in the solution and mineral, respectively, A is the surface area of the mineral (m^2), t is time (sec) and F is the fraction of isotopic exchange. Examination of the published experimental data on oxygen isotopic exchange reactions between various phases (e.g., silicates, carbonates, sulfates) and aqueous fluids using the above equation yields rate constants of between 10^{-4} and 10^{-8} moles m^{-2} sec^{-1} in the temperature range of 800 to 250°C, and activation energies of between 8 and 22 kcal mol^{-1}. Rates of oxygen isotopic exchange accompanying diffusion of oxygen-bearing compounds through mineral lattices are also calculated from published experimental data using equations that take into account fluid/mineral mass ratios of the systems. These data suggest that oxygen isotopic exchange reactions between fluids and rocks in natural systems may proceed in two steps: the first through a surface-controlled mechanism when the fluids and minerals are out of chemical equilibrium, and then through a diffusional mechanism once the systems attain chemical equilibrium.

Partitioning of Hydrogen and Oxygen Isotopes between Aqueous Electrolytes and Coexisting Vapor. The existing experimental data on the fractionation of oxygen and hydrogen isotopes between liquid and vapor in pure fluids and in electrolyte solutions have been critically reviewed. D/H and $^{18}O/^{16}O$ fractionations between pure liquid and vapor at near infinite dilution in $H_2{}^{16}O$ from 0-200°C can be accurately modeled by the measured vapor pressure ratios of the isotopic liquids $D_2{}^{16}O$ and $H_2{}^{18}O$ relative to pure $H_2{}^{16}O$, assuming ideal mixing in both phases and accounting for the disproportionation reaction $H_2{}^{16}O + D_2{}^{16}O \quad 2HD{}^{16}O$. Above 150°C, the calculated fractionations for D/H partitioning are significantly improved by correcting the vapor pressures for gas of liquid D_2O in liquid H_2O. At temperatures above 300°C, additional corrections are necessary for nonideal mixing and molar volume effects. At geothermal temperatures (~ 100-300°C) large

liquid-vapor isotope fractionations occur, and thus phase separation (i.e., boiling, condensation) must be considered in quantitative modeling of fluid-rock isotopic exchange in dynamic systems. Data on fractionation of oxygen and hydrogen between vapor and high salinity brines at elevated temperatures are sparse and conflicting. This information is necessary for the interpretation of geochemical processes based on isotope measurements.

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

Contract: DE-AC06-76RLO 1830

Title: I. Remote Sensing: Geoscience Data Analysis and Integration

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

Scope of Work

Since 1976, PNL has been conducting research in areas of remote sensing, image processing, and computer graphics most relevant to the geoscientific interests of the Department of Energy. The goal of this task is to develop practical interactive computer techniques for processing and analyzing combinations of remote sensing and geoscience data so scientisits can interpret more complex data combinations more completely and more rapidly. Successful techniques are being integrated into basic research and technology programs involving resource discovery, national security, energy development and utilization, conservation of the environment, and the safety objectives of the Department of Energy.

The current scope of research responsibilities involves:

(A) Maintaining cognizance and acquiring appropriate remote sensing and geoscience data sets to support continuing research efforts;

(B) Upgrading computer capabilities (hardware and software), as required, to advance the state of the art in digital processing, analysis, and display of remote sensing (imagery) and geoscience (point, line, and map) data;

(C) Demonstrating and integrating experimentally developed techniques within basic research and technology programs internal and external to DOE.

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

Several new data sets have recently been acquired and processed. Remote sensing examples include day and night Landsat seven-band thematic mapper (TM) scenes, Heat Capacity Mapper Mission (HCMM) data, and Thermal Infrared Mapping Spectrometer (TIMS) data from selected areas of DOE research and development interests. Current emphasis is on acquiring and experimenting with the shuttle imaging radar (SIR) and the

French (high-resolution stereo) SPOT data to be acquired in the fall of 1984.

Additional geologic and geophysical data items and maps to support primarily the preparation of more advanced CSDP demonstration products were acquired and selectively digitized. Digital ocean bottom topography (bathymetric) and ocean surface (radar altimetry) data for the coastal region of Washington State have been acquired to test ocean data analysis software programs under development.

B. Image Processing/Computer Graphics Software Developments
(H. P. Foote, S. C. Blair, and G. M. Petrie)

1. Image Enhancement, Data Integration/Analysis and Classification Programs. New and/or improved programs (e.g., Principal Component, Intensity-Hue-Saturation, etc.) have been added to upgrade the system's image enhancement, spectral classification, and change detection functions for general usage. Current emphasis is on upgrading interactive analysis programs to maximize the usefulness of the Landsat seven-band thematic mapper data capability for energy related applications, both qualitatively and quantitatively.

2. Transition to VAX 11/780 Operations. We are currently involved in transferring computationally intensive programs to the VAX 11/780 - array processor combination and incorporating additional NASA image-processing software developed at Goddard specifically for manipulating Landsat thematic mapper data.

3. Computer-Generated Shaded Relief Maps. During 1983, a software program was developed and tested for generating gray-scale and color-coded relief maps for both large and site-specific areas using various resolution levels of available terrain data. The program is capable of generating a variety of shading options simply by altering the solar illumination angle and of emphasizing area of lower topographic relief; both of which have potential for inexpensively enhancing surface features of geologic interest not normally seen in standard satellite images. This program was used to prepare a series of shaded relief maps for the 1983 CSDP Long Valley, CA Workshop.

4. Oblique-Multiparameter Stereo Graphics. A computer program has been successfully developed for improving 3-D integrated (remote sensing and geoscience) data displays by incorporating the capability to generate a variety of viewing perspectives other than vertical. This results in multiparameter stereo graphics, which more closely resemble on-the-surface viewing and this should improve the interpretation value of such

products. This program was also used to prepare a series of combined Landsat, topography, and geology stereo graphics for the 1983 CSDP Long Valley, CA Workshop.

C. Demonstration and Application of Task-Developed Capabilities (H. P. Foote, G. E. Wukelic, S. C. Blair, and G. M. Petrie)

1. Evaluation of Landsat Thematic Mapper Geoscience Data-Use Implications. Initial processing, analysis, and evaluation of Landsat TM data started in FY83 as part of a cooperative PNL-NASA GSFC agreement and will continue until April 1983 with the successful launch of Landsat-5 on March 1, 1984. Efforts to date have emphasized the qualitative potentialities of single band, multiband (composited), and ratioed TM products. Published results to date have emphasized the qualitative potentialities of single band, multiband (composited), and ratioed TM products. Published results to date have demonstrated and documented the utility of the increased spectral and spatial capabilities of the thematic mapper for siting and monitoring major energy facilites. Future research will stress the quantitative uses of TM radiometric data and associated error factors (e.g., data processing, atmospheric, and sub-pixel effects) and how they can be modeled to improve TM use for surface-temperature determinations.

2. Application to Midscale Geologic Features. The use of PNL computer image processing and manipulation techniques for analyzing rock features are being examined. Thirteen rock samples were sectioned, photographed, and digitized into 512 x 512 picture elements (pixels). Existing image processing programs were then used to classify each pixel as either grain or pore space. Further software development allowed the number of distinct grains (or pores) contained in each image to be determined and to associate each pixel with the parent grain (or pore) space. Each pore could then be characterized by its area, shape, and direction. Plans include extending this 2-D test to a 3-D representation of the rock structure.

3. Application to Geoscience Studies in the State of Washington. We have recently completed a digital, high-resolution topography mosaic for the state of Washington to use in preparing a series of integrated geoscience data products. In this demonstration, 36 one-degree-square DMA digital elevation files were resampled to form one file in a Lambert conic projection. The file covers the region from longitude 125°W to 116°W and latitude 45°N to 49°N. The grid spacing for the file is 154 m, resulting in array dimensions of 4608 by 3000 pixels. Thus, the file contains about 13.8 million elevation values. The ground resolution of the file is approximately

five times greater than any other single elevation file for the State. The new elevation file will find application in several geologic and geophysical studies within the State. Shaded relief maps can be computed from the elevation data from any desired illumination angle. We are in contact with the geology department at Washington State University, where somewhat similar work is being done with physical relief models. We will prepare digital relief maps from several lighting directions for comparison with the physical models.

4. Application to CSDP. The CSDP represents an ideal opportunity to obtain expert opinions as to the geoscientific interpretation significance of the experimental geodata analyses and display techniques being developed and tested under this task. Accordingly, an initial series of geodata demonstration products were prepared in support of the Valles Caldera Workshop (1982) and the Mono Craters-Long Valley Workshop (1983). These products were well received by the participants, and we are currently emphasizing 1) the acquisition of Landsat thematic mapper data for these and other CSDP sites (under the NASA-PNL LIDQA Program Agreement) and 2) the interaction with CSDP participants to acquire more geoscientific data for preparation of more extensive data integration products in the near future.

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

Contract: DE-AC06-76RLO 1830

Title: II. DOE Insolation/Aeronomy Studies

Person in Charge: G. M. Stokes and E. W. Kleckner

Scope of Work

The current program concentrates on the areas of aeronomy in the upper atmosphere and on insolation and radiative properties of the lower atmosphere. In particular, the aeronomy program is concerned with energy transport and interactions within the complex interface between the plasmasphere/magnetosphere regions and the ionosphere/upper atmosphere regions. Significant advances have been achieved over the past two decades in expanding our basic knowledge of the earth's atmosphere and magnetosphere and the sun as an interacting system. It is important that the physics of this coupling region be well understood in order to obtain definitive solar-terrestrial cause-effect relationships.

The insolation program relies on a data base of direct and diffuse solar radiation measurements made in visible and near-infrared spectral passbands. The research focuses on two goals. One is to quantify the spectral characteristics of scattered and direct sunlight. This is germane to energy generation solar technologies such as daylighting. The primary emphasis of the insolation task is on the characterization of the influence of trace species in the troposphere and lower stratosphere on solar radiation. These man-made or naturally produced trace species include aerosols, molecules, and clouds.

A. Insolation Studies
(J. J. Michalsky, N. R. Larson, and E. W. Kleckner)

Significant progress was made in the characterization of the continuous solar spectrum from discrete sampling of that spectrum. One goal of the insolation work is to develop low-cost instrumentation and data reduction techniques which can be used to provide adequate spectral information for technologies which are sensitive to a broad, continuous spectrum. These include materials research, biomass, daylighting, and photovoltaics among others. Two mathematical methods for using discrete filter measurements to generate continuous spectra are described in a paper accepted for publication in Solar Energy. The effectiveness of the procedures are demonstrated to some degree by using the technique on simulated filter measurements. A second paper has been drafted which extends the validation effort by comparing modeled spectra using measured

or estimated aerosol, water vapor, and ozone data. The estimated spectrum based on filter measurements is also compared to simultaneous spectroradiometric measurements in that paper. The agreement is within the error bounds for the spectroradiometric measurements and for the modeled spectra.

The major activity in the insolation work this past year had been on volcanically produced aerosols. A data base which extends to the Spring of 1978 at PNL has been used to establish a non-volcanically perturbed background aerosol data base. From these measurements it has been found that monthly-averaged aerosol optical depths are reproducible from year-to-year when there is no volcanic perturbation of the aerosol burden of the troposphere or stratosphere. These background measurements helped establish the non-significance of the climatic impact of the Mount St. Helens eruptions in earlier work. The past two years it has been used to monitor the evolution during the Spring of 1982. The first year's data (following El Chichon's eruption) which consist of differences between pre- and post-eruption optical depths as a function of wavelength have been inverted for size distribution in a collaboration with University of Arizona scientists. A publication on these results appeared in the January issue of Geophysical Research Letters. We are about to complete the reduction of a second year's data set. The influence of the El Chichon cloud is quite easy to discern through 1983. The interest of this volcano is not only the attenuation of sunlight by the cloud, but more importantly, the inferred sizes of the stratospheric aerosols. In the first year they evolved to sizes that were much larger than modeled volcanic size distributions. These larger sizes may affect the surface temperature in an unexpected manner. This unexpected behavior in size evolution should warn us about how we regard historical volcanoes and our models of those eruptions' influence on climate.

B. Aeronomy Studies (E. W. Kleckner, D. W. Slater, N. R. Larson)

Solar-terrestrial interactions shape and link the three major regions of near earth space: the magnetosphere, the ionosphere, and the atmosphere. A major goal of the aeronomy program is to investigate the coupling of the ionosphere, plasmasphere, and magnetosphere. To accomplish this, a network of computer-controlled, automated photometers has been maintained to acquire synoptic observations of the aurora and airglow. These, in turn, provide valuable information concerning the complex question of energy transport within this system, and the system's response to ever changing conditions.

One type of phenomenon, Stable Auroral Red (SAR) arcs, has been the subject of extensive investigation during the past year. These midlatitude features constitute the ionospheric response to energy

influx from the equatorial plasmapause region. Such energy input distributed on a global scale can be expected to have significant effects within the ionosphere, effects which are currently being investigated. Work in this area has proceeded from analysis started last year which suggested an association of SAR arcs with precipitating suprathermal (< 10ev) electrons as detected by the Dynamics Explorer -1 and -2 spacecraft. In cooperation with Southwest Research Institute, we have identified a one-to-one correspondence of these precipitating electrons and SAR arcs for approximately 30 individual events. As shown by earlier analysis, heating of the ionosphere/thermosphere within SAR arcs by this energy influx can lead to a "fountain effect," i.e., a thermally driven convection cell capable of injecting enhanced densities of N_2 from low altitudes into regions within the above SAR arcs. We have initiated study of satellite measurements of atmospheric neutral species within these locations for comparison with empirically derived atmospheric models. Initial results indicate significant compositional perturbations due to these localized heat sinks.

The comprehensive catalog of SAR arc events as detected by the PNL photometer network has been made available to researchers as a PNL report.

Final construction, software development, and testing of a multichannel, meridian scanning photometer is nearing completion. The instrument is capable of parallel processing four independent photometric channels at the high speed needed for time-resolved of the aurorae and airglow. The parallel acquisition feature will allow direct use of intensity ratios in the determination of the energy spectrum of precipitating particles. An additional system, centered around a high resolution spectrometer, is also being brought on line. This will allow observation of OH temperatures and densities. In particular, we are focusing on measurements of processes in the 80-95 km region near the mesopause.

Data processing is current with all units, and archival quality magnetic tapes containing the data are routinely prepared. Access by researchers to this data base has been facilitated by the introduction of an easy-to-use retrieval system.

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

Contract: DE-AC06-76RLO 1830

Title: III. Chemical Migration by Contact Metamorphism in Granite - Country Rocks

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 pegmatites and surrounding country 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 radionuclide in diverse geologically confined nuclear waste.

The first geological site was the granite intrusion at Notch Peak in Southwest Utah. Some of the important findings were: 1) the granite stock is composed of three concentric sequentially intruded rock types, 2) maximum temperature near the contact between the quartz monzonite intrusion and the Cambrian sediments was 575-600^{o}C, 3) relative to silts, limestones were impermeable to fluids and the flow of fluids was confined to silt beds and fractures, and 4) in silt, elements Na, K, Rb, Ba, Sr, As, Sb, Pb, and Cs have migrated over tens of meters, while there is no detectable migration of REE, V, Cr, Sc, Zr, Hf, and Al.

The second geological site is pegmatite - country rocks in the Black Hills, South Dakota. Five different pegmatites have been chosen to address (a) composition of fluids, (b) capability of dispensing fluids into country rocks, and (c) partitioning of mobile elements between mineral phases and fluids derived from pegmatites. Preliminary studies of the Tin Mountain, Etta, and Bob Ingersoll pegmatites show that there is virtually no migration of REE, Al, V, Sc, Cr, Hf, and Th elements. On the other hand, elements K, Li, Rb, Cs, As, Sb, Zn, and Pb have migrated 4 to 90 meters. The degree of migration varies depending on the element. Minerals biotite and muscovite are effective trace element traps for Li, Rb, and Cs. However, biotite has a greater affinity for Li, Rb, and Cs than muscovite and their relative affinities can be explained in terms of crystal chemistry. The REE concentrations in biotite and muscovite are high and indigenous. Similar types of chemical studies in other pegmatites emphasizing minerals such as

apatite and tourmaline as a recorder of melt/fluid evolution are under progress. The chemical data on some 40 major and minor trace elements are obtained by neutron activation analysis and x-ray fluorescence.

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

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: I. Continental Scientific Drilling Program
Thermal Regimes

Person in Charge: W. C. Luth

Scope of Work

Research conducted under the auspices of the Continental Scientific Drilling Program (CSDP) - Thermal Regimes sub-program at Sandia involves both generic and site specific activities as well as technology development and operation of a Thermal Regimes Research Drilling Office. Generic supportive research efforts include: development and testing of advanced thermal geophysical techniques; analysis of surface manifestation of subsurface magmatic emplacement; and a portion of the research conducted under III (Geochemistry Research) bearing on energy and mass transfer within, and between, hydrothermal and magma systems. Site specific research is concentrated at the Mono Craters-Long Valley, California, site and involves a number of non-Sandia participants. Recognition of the need for advanced technology to obtain scientific data in the hostile hydrothermal-magma transition zone resulted in a research program in drilling, logging, and instrumentation to provide the base for technology development. A Research Drilling Office has been established to implement the drilling activities of the CSDP-Thermal Regimes sub-program. The first major activity of the Research Drilling Office will be to provide support for the joint laboratory (SNL, LANL, LBL, LLNL) shallow drilling program.

A. CSDP - Thermal Geophysical Techniques (J. C. 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 near high temperature heat sources in the crust. Such thermal geophysical techniques include measurement and analysis of thermal and fluid transport in regions where natural convection heat transfer and/or ground water flow in aquifers significantly alter subsurface temperature profiles. Current research is presently concentrated in two areas:

(1) A convective heat flow sensor is being developed for use in permeable subsurface zones. A prototype downhole instrument was used to measure ground water velocities and convective heat flow in Long Valley, California. An improved downhole instrument has been calibrated in a permeable test bed at velocities as low as 10^{-7} m/s. Several small scale versions

of the instrument have been constructed to test improved methods of velocity measurement in a permeable medium.

(2) Thermopile heat flux sensors are being used in regions where surficial heat flow is relatively high. In such regions, normal surface temperature variation effects become unimportant at very shallow depths. The sensors can, therefore, be emplaced by simple digging as opposed to the normal requirement of drilling heat flow holes. In addition to speed of measurement, the thermopile method of heat flow measurement gives a direct measurement of vertical heat flow essentially at a point. This eliminates the need to obtain gradients from temperature measurements over a finite vertical extent. The sensors have been used to obtain heat flow profiles over a suspected intrusion in the East Rift Zone of Kilauea volcano, Hawaii. Here 20 heat flow measurements were taken with 4 thermopile sensors in a time period of two days.

B. Magmatic Emplacement (C. R. Carrigan)

The characterization of the geology and physics of a geothermal system requires treating the problem of both the thermal and dynamical evolution of magmatic reservoirs. How such reservoirs evolve is dependent in part upon heat transfer processes in the country rock exterior to a magma body. A model for estimating heat transfer and infiltration within a two-phase (liquid/vapor) hydrothermal zone adjacent to a dike has recently been developed using an engineering type heat transfer analysis. The model is best applied to shallow geothermal zones which are most accessible to drilling and which are of interest from a hazards perspective. The model predicts maximum dike solidification rates of about 1 meter/yr for reasonable permeabilities.

The interior problem of thermal convection in a cooling reservoir is being studied using both finite element and parameterized schemes. For 100 M rhyolite sills, the more approximate parameterized models are found to be in reasonable agreement with the more rigorous 2-D finite element models. The parameterized models can in principle be extended to model the thermal regimes of cooling magma bodies which are beyond the parameter ranges treated by finite element or difference formulations. In terms of computer resources, they are also much less costly to produce.

C. CSDP Mono Craters-Long Valley (CA) Site Assessment (J. C. Eichelberger and J. B. Rundle)

With its long history of active volcanism, and its current tectonism and seismicity, the Mono Craters-Long Valley region is important as a potential site for deep continental drilling. For

the past two years, assessment of this site as a crustal thermal regimes target for drilling has been conducted using a variety of geophysical, geochemical and petrologic techniques. Investigations under this program are being conducted by a variety of National Laboratories, the U.S. Geological Survey, Academic Institutions, and private industry.

Specific investigations include a high resolution seismic refraction profile covering the entire Long Valley caldera and the Mono Craters-Inyo Domes chain of recent extrusions; establishment and reobservation of a dense network of high precision gravity benchmarks throughout the entire Long Valley-Mono Craters area; passive seismicity recording; temperature and heat flow observations; and geochemical and isotopic analyses of carefully sampled young ($< 10^3$ yr) volcanic glasses. Data examined and analyzed to date indicate the probable existence of shallow magma within the caldera, and that surface samples show a pattern of degassing of volatiles indicative of the physics of emplacement of the recent extrusives.

D. CSDP - Drilling, Logging, and Instrumentation (H. C. Hardee and J. C. 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. Shallow test holes were drilled at Long Valley for the purpose of evaluating these logging instruments.

High temperature ($1200^{\circ}C$) thermal probes and associated cables and handling equipment are being developed for logging high temperature holes. A high temperature logging system for measuring drillhole temperatures to $800^{\circ}C$ is in the final stages of development. This system uses a platinum RTD in a special probe assembly attached to a 2 km length of high temperature, stainless steel sheathed cable. The cable is mounted on a microprocessor controlled winch assembly and cable operation and data collection is computer controlled.

E. CSDP-Shallow Hole Investigation of Long Valley, Valles, and Salton Sea Thermal Regimes (J. C. Eichelberger)

The intrusion of magma into the upper crust, the release of heat and the development of associated hydrothermal systems are problems central to understanding the evolution of continental crust and its resources. Recent surface research into magma/hydrothermal systems under the Continental Scientific Drilling Program has concentrated

on Long Valley Caldera, Valles Caldera, and the Salton Sea. All three areas contain recently active magmatic systems and currently active hydrothermal systems. A shallow drilling phase of research began at Long Valley and Valles in FY84 and will begin at Salton Sea in FY85. These holes will answer specific questions about the thermal, chemical, and mechanical behavior of magma at shallow depth, and the composition and circulation pattern of hydrothermal fluids. They will also provide a necessary step toward deeper drilling. Targets are the youngest rhyolite flow (Obsidian Dome) and its feeder conduit at Long Valley, the youngest rhyolite flow (Banco Bonito) and a hydrothermal outflow zone at Valles, and an unexplored region of the Salton Sea thermal anomaly. Laboratories participating in this program are Lawrence Berkeley, Lawrence Livermore, Los Alamos, and Sandia National Laboratories. Sandia has responsibility for drilling operations at Long Valley and the Salton Sea and for interpreting petrologic data from the Long Valley and Valles holes in terms of the degassing of rhyolitic magma. A 150 m hole was cored through Obsidian Dome and demonstrated nearly complete degassing of magma comprising the flow. Preparations are underway for the conduit hole, which will investigate vent structure and the degassing and crystallization behavior of magma emplaced under substantial (10 MPa) load. Shallow drilling at Long Valley will be succeeded by intermediate depth drilling late in FY84 under the Inyo program, which involves USGS and university participation in addition to the DOE labs.

F. Geoscience Research Drilling Office (R. K. Traeger).

The Drilling Office supports geoscientists by providing field logistics, generic hardware, drilling plan developments, and consultation for CSDP--Thermal Regimes research. In the last year, permits were obtained and contracts let to provide research holes in Long Valley, CA and the Salton Sea, CA. A limited instrumentation capability for borehole diagnostics is being developed and maintained. The Office is available for planning and other consultation related to drilling and instrumentation for the CSDP--Thermal Regimes.

G. Long Valley-Mono Craters (CA) Information Base (W. C. Luth and J. C. Eichelberger)

An integrated information base containing references to published geologic, geophysical, and geochemical data and interpretations is essential in considering detailed site selection for CSDP-Thermal Regimes. The information base will contain:

(1) Bibliographic information in standard reference format with keyword-based identification of data presented in the reference.

(2) A listing of researchers who are currently engaged in active research in this area, with a brief statement of type, nature, extent, and objectives of the research.

(3) Brief summary of generalized plans for future research, including shallow, intermediate and deep drilling.

The Information Base will be prepared on a stand-along microcomputer using a conventional commercial data base management system. Information will be distributed in printed form on a semi-annual basis.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: II. Geophysics Research

Person in Charge: W. C. Luth

Scope of Work

Research in geophysics under this program involves modeling, experimental, and field activities leading to a more soundly based understanding of physical and mechanical processes in the earth's crust and upper mantle.

A. Crustal Strain (J. B. Rundle)

The crustal strain program has as its objective the development of methods and techniques for modeling time-dependent deformation of the earth's surface, and interpreting these data in terms of possibility of tectonic instability in a given area. Motions of a few centimeters a year, commonly observed in tectonically active areas such as the western United States, have been interpreted as due to subtle stress relaxation processes deep within the earth. These motions provide clues to the occurrence of a future event.

Computer codes have been developed which compute time-dependent surface deformation due to various sources in a layered, inelastic earth model. Additionally, other codes compute gravity, sea level, potential, and surface deformation changes due to volcanic loading of the crust; and heat flow, fluid flow and deformation due to sources of fluid pumping in a fluid-infiltrated earth model. Physics of the earthquake rupture process has also been examined using simple models of inhomogeneous faults, together with friction laws derived from laboratory failure experiments.

Gravity gradient data associated with the 1975-1977 Kilauea inflation-deflation episodes, as well as gravity change data from Long Valley have been interpreted by the use of these techniques. Work is also underway on understanding the mechanics of the earthquake cycle, both at convergent plate boundaries (subduction zones) and at transform faulted boundaries. Collaborators have included scientists at University of Tokyo, Japan, the U.S. Geological Survey, the California Institute of Technology, and the University of California, Santa Cruz.

B. Time-Dependent Deformation and Fracture of Brittle Rock (L. S. Costin and D. J. Holcomb)

This research is directed toward a basic understanding of the mechanics of microcrack growth and how this is reflected in the continuum response of the material. Both experimental and analytical efforts are in progress. An experimental determination of the relationship between applied stresses and the time-dependent growth of cracks in granite and marble has been established and shown to be consistent with the notion that time-dependent crack growth occurs by the mechanism of stress corrosion. In these experiments, both temperature and moisture were varied.

To apply the experimental results to the problem of time-dependent deformation of brittle rock, a relationship between microcrack behavior and continuum behavior was established through an analytical model based on fracture mechanics and damage theory. The response of rock to various loading histories are being predicted and compared with experimental results.

Current efforts are concentrated on developing a proper definition of damage evolution that includes the interaction of microcracks which occurs when microcrack density becomes large. It is this interaction that results in fault and joint formation prior to failure. Damage rates will be based on test data where the damage accumulation is inferred from acoustic emissions.

C. Creep Response of NaCl at Low Stresses and Temperatures (D.H. Zeuch and W. R. Wawersik)

The objective of this program is to investigate the creep mechanics of sodium chloride at low temperatures and stresses. The creep response of sodium chloride has been studies extensively at temperatures above approximately one-half the absolute melting point, where it appears that dislocation climb is the creep mechanism; however, relatively little work has been carried out at lower temperatures. Such results as are available suggest that the dominant creep mechanism under lower-temperature conditions may be a thermally activated glide or cross-slip process. This in turn implies that creep history and initial substructure may exert a profound influence on the creep behavior of sodium chloride, because recovery is (implicitly) slow.

Work is in progress to conduct creep experiments on sodium chloride single crystals under low stress, low temperature conditions outside the range of any previous testing. Single-stage creep tests will be performed to assess the basic creep properties and substructural evolution of the single crystals. In addition, multistage temperature and stress-changing experiments will be carried out to determine the activation parameters and stress

dependence of creep in order to: (1) identify the deformation mechanism(s); (2) quantify the kinetics of recovery; and (3) determine the influence of initial substructure on creep.

A specialized creep frame has been constructed to perform the tests, and a series of cold-working/annealing tests have been carried out in order to develop techniques for the alteration of the initial substructure of the synthetic single crystals. The substructural modification tests also provided preliminary results on the kinetics of recovery of chloride; the apparent activation energy associated with the recovery process is consistent with a cross-slip mechanism at lower temperatures.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: III. Geochemistry Research

Person in Charge: W. C. Luth

Scope of Work

Research under this program involves experimental, analytical, and theoretical geochemistry relating to magmatic and hydrothermal processes taking place within the earth's crust.

A. Hydrothermal-Magma Systems (W. C. Luth, T. M. Gerlach, J. C. Eichelberger, and H. R. Westrich)

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, and modeling approaches. The research includes electron microprobe analysis of quenched in situ samples of basaltic magma obtained from drilling programs at Kilauea Iki Lava Lake in 1978 and 1981 as part of the Magma Energy Research Program, experimental studies of bubble nucleation and growth in silicic melts, studies of the amounts and kinds of volatiles in young silicic volcanic suites, and the chemistry of volcanic gases including sublimate and condensate fractions. Advanced methods are being developed for use of the fully automated electron probe in geochemical analysis of drill core samples. Computer software is also under development for processing and evaluating large data bases of automated probe analyses with complete propagation of error capabilities. Water CO_2, S, Cl, and F are being determined for a large number of obsidian samples from explosively and effusively erupted young volcanic units at Mono Craters/Inyo Domes and the Cascade Range. These studies have focused on the isotopic composition and amount of water in the obsidian samples as a function of time. The rates of bubble nucleation and growth as a function of water content are being investigated in rhyolitic melts up to 0.5 kbar. Field, analytic, and computer-based studies of volcanic and fumarolic gases are being performed for Vulcano, Usu Volcano, Long Valley, and Kilauea Volcano in an effort to better understand chemical trends during magma degassing.

B. Clay-H_2O Interactions (J. L. Krumhansl)

The ability to predict the course of rock-water interactions at temperatures up to 350°C is critical to a large number of geochemical, geophysical, and energy related problems. To a large degree these predictions depend on a knowledge of the kinetic and thermodynamic constraints governing clay mineral dissolution. This problem has been approached through the use of a Dickson hydrothermal apparatus, and by employing standardized clays. To date the Wyoming bentonite SWy-1 has been subjected to tests of at least two months duration at 200 and 300°C, and in both acidic (pH = 2.1) and neutral solutions. The results of these tests indicate that clay dissolution is highly incongruent, that hydroxide complexing of both aluminum and iron is an important factor in governing the overall solubility, and that when compared to theoretical estimates derived using a Tardy-Garrels type approximation, the clay is somewhat more stable than would have been anticipated. It was also found that run times of at least six weeks were required for the system to achieve steady state; consequently, evaluation of a wide range of clays (of differing compositions) will proceed somewhat more slowly than had been anticipated in the original proposal.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, NM 87185

Contract: DE-AC04-76DP00789

Title: IV. Advanced Concepts

Person in Charge: W. C. Luth

Scope of Work

Research conducted in this program involves exploratory research in several geoscience areas. Typically such research efforts are of a short-term nature and may be oriented toward assessing feasibility of a particular research task.

A. Noble Metals (H. W. Stockman)

The noble metals are designated as strategic and critical minerals by the U.S. government because of their unique properties and energy and defense applications. The goal of this project is to develop an understanding of how noble metals are concentrated and transported by geologic processes. Work has been concentrated on: (1) development of techniques for obtaining high quality analyses of noble metals in rocks and minerals; and (2) experiments with synthetic, noble metal-containing systems, used to interpret noble metal distributions in natural rocks and minerals. Work on analytical methods has involved development of techniques for separation of noble metal-rich Fe-Ni-Cu sulfides from rocks, SEM and electron microprobe analyses of mineral separates and in situ platinum minerals, and development of computer codes for correcting electron microprobe analyses of minute platinum-group minerals. Experimental studies have involved determinations of the solubilities of platinum elements in solid and liquid Fe-sulfides at 1000-1250^{o}C, determination of the Ru-RuS_2 and Ir-Ir_2S_3 sulfur buffers, and investigations in the Pt-S and Os-S systems at high temperatures.

PART II

OFF-SITE

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: DE-AT06-76ER70005

Title: I. Magnetosphere Annihilation and Applications

Person in Charge: S.-I. Akasofu

Scope of Work

Plasmas in thermonuclear fusion research devices and in space around the earth have much in common. The earth's magnetosphere provides a unique opportunity to study some of the basic characteristics of plasmas. We have learned basic processes associated with the natural dynamo (consisting of the solar wind and magnetosphere) which can generate as much as one million MW. Specifically, University of Alaska researchers are working with thermonuclear fusion groups at the University of Texas, Austin, and the Plasma Physics Laboratory, Princeton University, in applying computational methods developed by them to learn some of the basic characteristics of plasmas in nature. During he last 12 months we have used extensively the electromagnetic codes developed by the fusion researchers in simulating various magnetospheric and solar processes. So far, we have not found any indication that magnetic reconnection can occur explosively (namely, explosive magnetic field annihilation), supplying energy for magnetospheric substorms and solar flares.

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 systematic blackout; blackouts caused by auroral activity are fairly common in Canada where many power transmission lines are rather long. 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. We have obtained excellent data to study the relationship between the induced current and the protective relay and thus are analyzing them in detail.

In the arctic 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 made an extensive survey of permafrost in the Prudhoe Bay area last summer and are analyzing the data.

Contractor: ARIZONA STATE UNIVERSITY
Department of Chemistry
Tempe, Arizona 85287

Contract: DE-AC02-80ER10765.A000

Title: Silicate, Aluminosilicate and Borosilicate Melts: Thermal-Chemical 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 (M = Li, Na, K, Rb, Cs, Mg, Ca, Ba, Sr, Pb) and in determining heats of vitrification and of fusion. These systematics lead to an understanding of effective heats of fusion of diverse components in an aluminosilicate framework. The enthalpies of the substitution $Si^{4+} \rightarrow Al^{3+} + 1/nM^{n+}$ correlate with the field strength z/r of the substituting cation and with the trends shown in TO bond length variations obtained from ab initio molecular orbital calculations. In addition, we have completed study of the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Si_4O_8 and are continuing the modeling of phase equilibria in silicate systems, using experimental heats of mixing and of fusion and models for entropies of mixing. The emphasis is on ascertaining the usefulness of the two-lattice model for the entropy of mixing and in developing more appropriate complex structural entropy models.

In addition, we are beginnning to study other coupled substitutions, especially $Si^{4+} \rightarrow B^{3+} + Na^{+}$ and the substitution of nitrogen for oxygen by reactions such as $O^{2-} \rightarrow N^{3-} + 1/nM^{n+}$. The system Na_2O-B_2O_3-SiO_2 is receiving detailed calorimetric study. These glasses differ from the corresponding aluminosilicates in a systematic fashion.

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 1000°C and 1 kbar has been constructed. It will permit direct study of the thermodynamic properties of glasses and melts containing up to 50 mol% H_2O by drop calorimetry under high pressure.

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

Contractor: UNIVERSITY OF ARIZONA
Tucson, Arizona 85721

Contract: DE-AC02-80ER10753.A001

Title: I. Solar Variability: Changes in Figure and Mean Diameter

Person in Charge: Henry A. Hill

Scope of Work

The objective of this program is to develop and use an indirect diagnostic of changes in the solar constant by monitoring the figure and diameter of the sun over long periods of time. Obtaining reproducible radiometer data over the period of years to decades necessary for a significant study of the changes in solar luminosity constitutes a serious problem; this problem motivated the search for an indirect diagnostic. Such indirect diagnostic of luminosity is offered by measures of changes in the solar shape and mean diameter. Techniques measuring fractional solar diameter changes over approximately 9 hr observing runs to accuracies of $D/D \tilde{=} 10^{-5}$ to 10^{-6} are being used to measure changes over longer, climatically significant time periods. The relationship between this indirect diagnostic and solar constant is being examined.

A. Technical Developments

The success of the program to monitor long term variation in the figure and diameter of the sun depends in large measure on maintaining the stability of the telescope over similarly long periods. To meet this requirement, a focal plane distance calibrator has been designed for the SCLERA astrometric telescope, and its construction and installation is nearly complete. This device consists of a pre-lens diffraction grating; a focal plane stabilized light source; light detectors on the solar detector; and necessary computer and computer related equipment. Hardware is now being installed, and software is starting to be developed. The grating, on low expansion glass, can be placed on the stop of the primary lens and is designed to produce first order diffraction images in the focal plane with the approximate angular diameter of the sun. The light source is a single mode stabilized helium-neon laser. The first order diffraction maxima are imaged on the solar detector and are used to calibrate the angular field. This device will coexist with the Michelson measuring interferometer that measures distances in the focal plane. The Michelson interferometer has been designed and constructed so that the white light fringe can be detected, thus providing a fiducial for day to day comparison of measurements. This system to detect the white light fringe has been in operation since the summary of 1981.

B. Observations

Nearly seventy days of solar diameter measurements have been collected during 1983 with the white-light fringe detecting system in place. Analysis is continuing on the unprecedented quantity of this type of astrometric data. It is expected that these observations contain information on the variation in time of the solar figure and mean diameter and should yield a new measurement of the visual solar oblateness.

C. Theoretical Work

Our ability to infer a particular luminosity change from, for example, an observed change in the mean solar diameter has been quite limited. At present there is a difference of approximately three orders of magnitude between the least and the greatest sensitivity that has been suggested. This large range in the estimates of the sensitivity is, in part, a reflection of the several different physical processes that have been considered potentially important in producing luminosity changes. However, of equal importance have been differences in the treatment of the boundary conditions in the solar envelope. Considerable success has been achieved in refining the treatment of the boundary conditions. Testing of the new theoretical work is currently underway. In addition to the new developments in the theory, information on the ratio of fractional change of luminosity to the fractional change in the solar diameter has been obtained from recent work on global oscillations of the sun. This ratio is found to be about two for variations in the sun that occur over a time scale of hours. To the extent that this ratio is characteristic of the lower frequency, climatically significant variations, these new findings should be quite valuable. These findings will aid interpretation of the results of the solar diameter observations and will aid the testing of SCLERA's theoretical studies know in progress.

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

Contract: DE-AC02-81ER10842

Title: II. Rock Deformation in Magma-Hydrothermal Systems

Person in Charge: Denis Norton

Scope of Work

The goal of this project is to obtain a better understanding of the evolution of stress and strain in fossil magma-hydrothermal systems through the investigation of fracture systematics. Our main objective has been to obtain a data base on the nature of fractures that is sufficient to (a) test previous theoretical studies on the evolution of stress around cooling magmas, and (b) improve techniques for numerical modeling of coupled transport processes around thermal perturbations in the Earth's crust. In establishing this data base, we have discovered several new aspects of fracture topology:

1. In the approximately 30 fossil magma chambers we have studies, which represent a broad spectrum of compositions, ages, exposure levels, and chamber sizes, fractures are oriented with respect to what we infer to have been local stress trajectories present when the magma was emplaced and cooled.

2. Fractures observed in outcrops and shallow drill holes can be used to predict fracture characteristics that will be encountered at greater depths because variations in the abundance and character of fractures as a function of depth are caused by magma-hydrothermal conditions. Weathering processes accentuate the fracture patterns but do not generally cause fractures.

3. Fractures are present today that formed subsequent to the cooling event. Even in one b.y. old systems, these fractures can be readily differentiated from those formed by the thermal event.

4. Fracture extents are much more limited than previously assumed. In addition, the shapes of individual fractures are directly related to fossil stress orientations and relative stress magnitudes.

5. Substantial evidence exists to suggest that fracture topology is a direct consequence of H_2O-rich fluids responding to nonhydrostatic stress conditions.

Because fractures control the response of a rock mass to thermal, chemical, and mechanical perturbations, our research is relevant to engineering design problems related to waste disposal and both natural geothermal and hot-dry-rock reservoirs. We have concluded the following: (1) Thermal perturbations (e.g., waste disposal) embedded in crystalline rocks will very likely cause fractures to propagate away from the heat source at a rate similar to the rate of heat dispersion; (2) Production of fluids from geothermal reservoirs will inevitably lead to deleterious chemical reactions that will ultimately seal the productive wells. This problem can be avoided only by utilizing methods that produce fluids within the constraints imposed by the natural feedback conditions; and (3) H_2O-rich fluids are distributed in virtually all fractures. The intrinsic properties of these fluids and the shapes of the fractures that contain them exert a dominant effect on the bulk modulus of rock. Therefore, the seismic prospecting technqiues used to detect magmas and geothermal resources are inadequate for discriminating between the sheath of fractures around a magma chamber and the magma itself.

Contractor: CALIFORNIA INSTITUTE OF TECHNOLOGY
Seismological Laboratory, Division of
Geological and Planetary Sciences
Pasadena, California 91125

Contract: DE-AT03-83ER13120

Title: In Situ Stress in Deep Boreholes

Person in Charge: T. J. Ahrens

Scope of Work

Knowledge of the in situ stress in the earth is important to our understanding of contemporary tectonic, geothermal, and rock-forming processes, and provides information which is required to exploit energy resources and store waste in the earth.

We are developing a new type of stressmeter which employs interference holography and by means of laboratory and field measurements, we are attempting to turn it into a useful geophysical tool.

This development was carried out with a 12" diameter device which is lowered into boreholes and first locks in place. Then a holographic exposure is taken of the borehole wall, a side-core hole is drilled which relieves in situ stress and a second hologram is taken. The resulting interference hologram yields a map of displacement, which is inverted to obtain the 6 components of the in situ stress tensor.

Current Activities (J. Bass, D. Schmitt, and T. J. Ahrens)

We have completed laboratory and initial field tests of this new device, which we believe will become a useful tool in borehole geophysics. Laboratory tests included carrying out measurements on samples, under known prestress, and developing the numerical methods for calculating synthetic interference holograms for inverting field data. In 1983, we carried out a successful series of field tests of the holographic tool at depth in the Union Oil Co. oil shale mine in a series of 12" holes especially drilled for us. We obtained an outstanding set of good results. We have performed a preliminary analysis of these data to yield values of maximum and minimum horizontal stress and stress orientation which agrees well with values obtained by other methods (hydrofracture) in this region by Bredehoeft et al. (1978). These results and the description of the operation of the instrument are currently being described in a scientific paper, "In situ stress measurements with borehole interference holography."

Because most uncased scientific drillholes in the U.S. are 6" or less in diameter, we are currently developing a 5 1/2" diameter field

version of the earlier instrument. We expect that this instrument will be compatible with both standard and high temperature 7-conductor borehole logging cable. Many details of design include film transport, optical systems, rotation, locking, orientation transducing, internal pressurization, mud-filtering, and side-hole coring, are being improved as a result of our experience with the 12" "laboratory-field" apparatus. We expect this device could operate initially at depths of several hundred meters using film. With a new indium-oxide coated photoconductor polyvinylcarbozole film which is erasable, and an electronic-optic scanner on-board the apparatus, we expect to eventually provide a television-like display of interference fringes on the surface. With this remote read-out device, we expect that the apparatus will have a depth capability of several km.

A final series of tests of the 12" apparatus is now scheduled for June 1984. After this point we will put all our effort into fielding a 6" device in existing scientific boreholes in S. California and other holes of opportunity.

Contractor:	UNIVERSITY OF CALIFORNIA Department of Geology and Geophysics Berkeley, California 94720
Contract:	DE-AM03-83ER13100
Title	Advective-Diffusive/Dispersive Transport of Chemically Reacting Species in Hydrothermal Systems
Person in Charge:	H. C. Helgeson

Scope of Work

A phenomenological transport code based on continuum theory is being developed to describe fluid flow and simultaneous chemical reactions representing ion association, oxidation/reduction, ion exchange, and mineral hydrolysis in hydrothermal systems. Mass and heat transfer coupled to reversible reactions by the law of mass action and irreversible reactions described by kinetic rate laws are included in the code. Transport equations representing conservation of mass and energy are solved numerically for transient conditions of fluid flow in porous and fractured media. The fluid flux equation contains an advective term corresponding to Darcy's law and a diffusive/dispersive term based on Fick's first law.

Preliminary tests of the code so far developed include validation of the chemical algorithms used in the code by comparison with the equilibrium speciation and mass transfer program package EQ3/EQ6 developed by Wolery (1979), as modified by Helgeson and Murphy (1983) to include mineral dissolution kinetics. The results of calculations for reaction paths in a closed system obtained by considering a single node in the transport code with appropriate boundary conditions for complex systems involving activity coefficients, aqueous complexes, and reaction products compare favorably with the partial equilibrium model. Furthermore, the computation time is considerably faster, which is indispensible for integrating chemistry with fluid flow. The transport code has also been tested for the case of diffusional mass transfer coupled to reversible precipitation/dissolution reactions by comparing numerical results with the analytical steady-state limit obtained by Helfferich and Katchalsky (1970) for a two-component system. In the transient case considered, the calculations indicate that the zone of mineral precipitation first oversteps the steady-state limit and then dissolves at its boundaries, shrinking in size until steady-state is reached. Multi-mineralic zones were found to move in a complicated fashion before reaching steady-state.

Contractor: UNIVERSITY OF CALIFORNIA
Department of Physics
Berkeley, California 94720

Contract: DE-AM03-76SF00034

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.

A. The RARGA Project

The Roving Automated Rare Gas Analysis (RARGA) system is a self-contained, mobile laboratory designed to make precise elemental and isotopic abundance measurements of the noble gases in terrestrial fluids. In 1983 the laboratory was deployed at Yellowstone National Park from late June until early November, acquiring a large data set consisting, for each sample, of an elemental run (He, Ne, Ar, Kr, and Xe concentrations) plus isotopic runs on He, Ne, and Ar. Additionally enough isotopic runs on Xe were carried out to establish that there are no significant ^{129}Xe anomalies in Yellowstone samples and enough calibration runs on air Ne to monitor mass fractionation occurring in the mass spectrometry.

B. Yellowstone Projects

The first completed report on the Yellowstone work is an overview of the November 1983 data set (approximately 80 samples), with emphasis on correlations among the measured parameters in the whole set. The helium-argon data conform well to a plane in $^{3}He/^{40}Ar$, $^{4}He/^{40}Ar$, $^{36}Ar/^{40}Ar$ space, indicating that all samples can be explained as mixtures of three components -- an air component, a crustal component with a $^{4}He/^{40}Ar$ ratio of 4.1, and a magmatic component which is as yet not well constrained beyond knowing that

$^3He/^4He$ exceeds 16 times the air value and that $^{40}Ar/^{36}Ar$ exceeds 500, in agreement with previously determined limits. The report presents an overview of the neon anomalies (more below), the elemental fractionation patterns (well correlated but not explained), and regional behavior of the quantity $(^3He/^4He)_{local\ maximum}$ which falls off quickly to air-like values outside the caldera and has a structure inside the caldera which is reasonably well defined but does not correlate in any simple way with other geophysical parameters.

A brief report is in preparation of an experiment we performed in measuring $^3He/^4He$ ratios in soil samples at Yellowstone by the simple practice of inserting the lower, open end of a copper tube, closed at the top, in the soil and leaving it there for two weeks before closing off the air sample it contained. This simple technique detects excess ^3He and might be useful in the future for studies of vertical heat flow in Yellowstone.

A project which is well along, but requires analyses of about a dozen more samples collected in 1983 but not yet analyzed, is a study of the noble gas dynamics in Horseshoe Spring, in the Norris Geyser Basin. That spring was sampled extensively at various depths and at various lateral positions in order to understand how convection in that spring, which dissolves air gases at the surface and is fed with subterranean gases at a vent at the bottom, affects the elemental and isotopic ratios observed in the samples. This study, together with some measurements we have made on cold springs in Yellowstone, is a start towards understanding the elemental patterns mentioned above.

Another project which requires additional analyses, currently being carried out with the RARGA equipment, concerns a detailed study of the helium isotopes in Lower Geyser Basin at Yellowstone. Preliminary results indicate varying $^3He/^4He$ ratios but correlations with the HCO_3^-/Cl^- ratios in the fluid phase, as might be a reasonable outcome of varying degrees of boiling and steam separation in the fluid there. This work will be reported at the May 1984 meeting of the AGU in Cincinnati.

RARGA obtained the first extensive data set for neon isotopes in Yellowstone and the results are being examined in more detail than was possible in the report on the overview of the data as a whole. There is evidence for both mass fractionation of neon isotopes and occurrence of nuclear anomalies in the isotopic ratios. In our present scrutiny of the data we are concentrating, with some

success, on seeing how the isotopic ratios correlate for measurements within given regions in Yellowstone.

C. Well Samples from the Valles Caldera

The RARGA equipment has been used to measure the noble gases from four wells in the Baca field at the Valles caldera and a paper has been completed on the rather simple story those measurements reveal. The sampling was carried out in such a way that the absolute concentrations of the noble gases in the steam were determined quite precisely in addition to the relative elemental and isotopic ratios. We were thus able to show conclusively that the fluid in the Baca wells we sampled are two component mixtures. The origin of these components, and how they correlate with chemical measurements made on these fluids, is discussed in the paper.

D. Noble Gases in Silicate Melts

Data are now being collected in our study of solubilities of noble gases in silicate melts of various compositions and at various temperatures. One of our spectrometer systems has been dedicated to this study and equipped with a pipette of isotopically anomalous He, Ne, Ar, and Xe for precise isotopic dilution measurements on the quenched glasses which are prepared in Carmichael's lab at LBL. Preliminary measurements indicate that there may be surface as well as volume solubilities involved. We are well equipped to check such a possibility with the sensitive laser-microprobe rare gas spectrometer which has been constructed in our laboratory and is now in operation. That instrument is part of our NASA research on extraterrestrial samples, but is available for a few key measurements in this study.

E. New Starts for 1984

We are planning to maintain the momentum in our RARGA project by an annual field deployment. We are beginning to formulate plans for the 1984 expedition. It is important to extend our studies to natural gases so that it is likely that a detailed study of a gas field will be the eventual plan. We will have to add a Cu/CuO furnace to our inlet system for conversion of methane and hydrogen to carbon dioxide and water, but we anticipate that this change in the equipment will be easy to accomplish. Otherwise we are ready to apply RARGA to this new class of problems.

Contractor:	UNIVERSITY OF CALIFORNIA Department of Earth and Space Sciences Los Angeles, California 90024
Contract:	DE-FG03-84ER13203
Title:	Determination of Thermodynamic Functions of Minerals at High Temperature
Person in Charge:	Orson L. Anderson

Scope of Work

We are continuing work done in our laboratory for the past three years, measuring the thermal expansivity and elastic constants of certain minerals at high temperature (e.g., well above the Debye temperature of the mineral θ). The new minerals to be measured are NaCl, α-quartz, vitreous silica, TiO_2 and possibly iron (α-phase).

It is proposed to use these new data and the corresponding existing data already measured for MgO, Mg_2SiO_4, and Fe_2SiO_4 to calculate the thermodynamic functions of these minerals into the high temperature range $600^{\circ}K$ - $1300^{\circ}K$. These include the entropy, the internal energy, the enthalpy and the free energies.

The thermodynamic functions thus determined would be applicable to a large range of DOE projects including geochemistry, magma energy generation, nuclear waste disposal, and the continental scientific drilling program.

Contractor: UNIVERSITY OF CALIFORNIA AT LOS ANGELES
Department of Chemistry and Biochemistry
Los Angeles, California 90024

Contract: DE-AT03-81ER10965

Title: Adiabats and Gruneisien Parameter at High Temperatures and High Pressures

Person in Charge: R. Boehler, M. Nicol

Scope of Work

The high temperature equation of state may be described by a Gruneisen model for the finite-temperature pressure,

$$P(V,T) = P_o(V) + 3N\,\gamma\,(V)\,\frac{k_B T}{V},$$

where $T_o(V)$ is the T=0 static lattice pressure. The second term is the high-temperature quasiharmonic approximation to the thermal lattice pressure. The Gruneisen parameter λ (V) is related to the volume change of lattice frequencies. The knowledge of its pressure dependence is of great importance in studies involving high pressures and high temperatures, for example geophysical modeling and shock wave experiments.

Various forms of the volume dependence of γ have been deduced in the past and are frequently used such as for example the Slater model

$$\gamma(V) = -\frac{2}{3} - \frac{V}{2}\,\frac{\partial^2 Po}{\partial V^2}_T \Big/ \frac{\partial Po}{\partial V}_T$$

or simpler forms such as $\gamma\cdot\rho$ = constant. The purpose of our study was to measure the Gruneisen parameter γ at very high compressions (over 50%) and to compare its functional dependence with those shown above. the study includes effects of solid-liquid and solid-solid phase transitions on the volume dependence of γ.

Adiabatic compression measurements were carried out on the highly compressible alkali metals in both the solid and the liquid state. This yields directly the Gruneisen parameter as a function of pressure and temperature. The results for Li, Na K, Rb, and Cs can be generalized in the following form: 1) γ rapidly decreases with compression approaching an asymptotic value of 0.5 at compressions above 30%. This behaviour is significantly different from the Slater or free volume relationships; 2) the pressure dependence of γ in the liquid is essentially the same as in the solid. 3) γ increases by several percent at the liquid-solid

transition; 4) at constant volume, γ decreases with temperature. For Cs, both experiment and theory indicate that γ becomes very small as the isostructural electronic transition at 42 kbar is approached and shows a strong increase after the transition.

Contractor: THE UNIVERSITY OF CHICAGO
Chicago, Illinois 60637

Contract: DE-AC02-80ER10763

Title: Water and Magma Bodies

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

Scope of Work

The emplacement, crystallization and eruption of silicic magmas are important both for the compositional evolution of the crust as a whole as well as for the formation of a variety of ore deposits and geothermal fields. We are continuing development of a new way to determine the pressures of crystallization within such bodies of magma. The new method relies both on the increased solubility of H_2O and CO_2 in silicate melts with pressure and on the preservation of samples of the natural high pressure environment of crystallization as tiny inclusions within virtually rigid crystals. We make wafers of the phenocrysts found in silicic volcanic rocks to expose inclusions of glass for analysis both by the electron microprobe for major elements and by a special vacuum fusion device for H_2O and CO_2. That device has been completely rebuilt with modifications intended to reduce uncertainties in results. A quadrupole mass spectrometer (residual gas analyzer) will be incorporated into the system in order to allow more certain confirmation of the nature of each of the gases present. Uncertainty concerning possible H_2S contribution to apparent CO_2 concentration will be removed. We are also investigating possible use of laser heating of melt inclusions which might help to drastically reduce blanks and sample analysis time. Current work centers on a suite of samples of the rhyolitic Bishop Tuff which includes pumice from the plinian phase as well as each of the major ignimbrite lobes. Analysis of this suite may help reveal change in magmatic vapor pressures with time as the magma body developed prior to the cataclysmic eruption. It may also aid in understanding of dynamic mixing processes within the erupting magma body. The data will also be used to help assess the current state of the magma body(ies) beneath the Inyo domes and Mammoth Lakes.

Stanley Williams joined the project in January of 1984, and the rate of progress increased dramatically.

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

Contract: DE-AS02-76E03134

Title: Tectonics of the Eastern Aleutian Arc

Person in Charge: K. Jacob, J. Taber, and L. Sykes

Scope of Work

The geophysical processes associated with subduction and arc-magmatism are investigated in one of the world's major active arc-trench systems. We use primarily seismological methods for this purpose. On an arc-wide basis we compare and synthesize globally recorded seismotectonic information for most of the Aleutians. In the Shumagin Islands section of the Aleutian arc we carry out a very detailed study of this 300-km long arc segment. This in-depth study relies on high-quality data from a digital seismic network for which we operate 14 remote stations linked by telemetry to a central, digital-recording site. This arc segment is a seismic gap for which a 30 to 99% probability has been determined that a great earthquake ($M \geq 8$) will occur within the next two decades. Major research topics presently concern: accurate determination of the geometry and velocities of the interface of the descending Pacific slab against the upper mantle and crust of the overriding North American plate by means of three dimensional seismic ray tracing of direct and converted body wave phases; relative location of the dipping seismic (Benioff-) zone with respect to the slab surface; inversion of local and teleseismic travel time residuals for determination of two- and three-dimensional velocity perturbations associated with the volcanic arc and its magmatic root zone; monitoring of seismic and eruptive activity of Pavlof Volcano and other structures along the volcanic arc, and integration of these results with those from geodetic crustal deformation data to investigate plate coupling and to update the existing estimates of long term probabilities for the occurrence of future great earthquakes by medium- to short-term precursors. Although the study focuses on basic research of the subduction process, immediate applications concern the geothermal energy potential of the Aleutian arc; seismic, volcanic and tsunami hazards reduction to off shore oil lease sale areas that are located directly adjacent to the Shumagin seismic gap and network; other spinoffs concern earthquake engineering, and - perhaps - earthquake prediction. Technical long-term objectives are the sensing and - eventually digital - transmission of high fidelity, wide-dynamic range, seismic ground motion data to the central network recording site capable of resolving the motions of both small and the large earthquakes.

Contractor: HARVARD UNIVERSITY
Department of Geological Sciences
Cambridge, Massachusetts 02138

Contract: DE-AC02-83ER13096

Title: Energetic and Thermochemical Properties of Rocks and Minerals

Person in Charge: J. B. Thompson, Jr. and S. K. Dobos

Scope of Work

Any thorough understanding of the earth's crustal processes and energy budget must take into account the energetics and thermochemical properties of rocks and their constituent minerals, notably their heat capacities and their enthalpies and entropies of transformations. Such thermodynamic data, and physico-chemical models derived from them, are of direct concern in such fields as the extraction of geothermal energy, nuclear waste disposal, terrestrial heat-flow studies, the geochemistry of ore deposits and igneous, metamorphic and sedimentary petrology.

Much of the requisite thermochemical data to handle problems in the above fields is unknown or poorly characterized. We propose to augment the data base for the thermochemical properties of rocks and rock-forming minerals, as well as heterogeneous transformations in rocks involving the appearance or disappearance of mineral phases of a given phase assemblage. Such studies comprise one of the most basic energy-related branches of scientific investigation in the geosciences, and are fundamental to our understanding earth processes and earth materials.

Our calorimetry lab is now complete and fully equipped with three thermoanalytic instruments: (i) a power-compensated differential scanning calorimeter for the temperature range -170 to 725°C, (ii) a heat-flux differential scanning calorimeter for the range 25 to 1700°C, and (iii) a thermogravimetric analyzer for the range 25° to 1200°C, capable of operation with controlled atmospheres from a moderate vacuum to ambient pressure. The instruments may be run semi-automatically, and are interfaced to computers for real-time monitoring, data collection and data reduction.

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

Contract: DE-AT03-80ER12099

Title: Physical Characterization of Magma Samples

Person in Charge: M. H. Manghnani

Scope of Work

This program involves 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 and (2) viscosity, electrical conductivity, and V_p, V_s, and Q^{-1} of magmatic fluids at elevated temperatures and pressures 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.

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) are being conducted in cooperation with W. C. Luth at the Sandia National Laboratories.

The physical, seismic, electrical, and thermal properties (diffusivity, conductivity and specific heat) of selected Lava Lake core samples, for which chemical composition and mineralogy have been determined by the Sandia Laboratories (Dr. W. C. Luth), are being interpreted in terms of chemistry, glass content, and mineralogy of these core samples.

We are currently focusing our efforts on the elastic, anelastic, and electrical properties of melts of basaltic and related composition. The temperature and frequency dependence of ultrasonic compressional velocity (V_p) and attenuation (Q_p^{-1}) measurements for various melt

compositions are interpreted in terms of viscosity, relaxation time and structure of melt.

The temperature dependence of the melt conductivity of the eight samples from Kilauea Iki samples from different depths is almost the same and follows the Arrhenius equation.

The proposed research, involving close cooperation between the University of Hawaii and the Sandia National Laboratories, provides an impetus to basic energy research needed for acquiring a better knowledge of the fundamental in situ physical properties of rocks relevant to geothermal exploration and to planned projects such as the U.S. Continental Scientific Drilling Program.

Contractor: LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
Palisades, New York 10964

Contract: DE-AC02-76ER04054

Title: Fluid Transport Properties of Rock Fracture

Person in Charge: T. Engelder and C. Scholz

Scope of Work

Our problem is to understand the parameters that limit fluid flow within the crust of the earth. Because the major flow paths are through joints within the crust the rock-water interaction along joints is of most interest to our project. This problem is important to the DOE because the extraction of hydrocarbons and geothermal energy is critically dependent on flow along fractures toward well bores. Yet, the burial of nuclear waste requires conditions which limit or stop the flow of fluid away from the waste repository.

Flow is governed by the mechanical closure of joints as well as the dissolution and precipitation of components within the joints. During the past year our attention has been divided between two projects: 1) the correlation between flow rate and the change in water chemistry along joints; and 2) the closure of random surfaces in contact.

A. Chemistry

Experiments on the correlation between flow rate and the change in water chemistry were run in a triaxial testing machine with confining pressures up to 100 MPa and pore fluid pressures some predetermined fraction of 100 MPa. Temperatures were up to 100 C. The experiments were accomplished by recycling an 80 cc charge through the rock sample (primarily) a quartzite with some impurities and a granite). Usually the sample consisted of a split cylinder to simulate a joint. Samples were taken at predetermined intervals until the 80 cc charge was exhausted.

For very rough joints the flow rate did not change with time as the fluid chemistry approached equilibrium values. At room temperature, 14 days were required for equilibrium between the water and rock. For chemical components such as Ca, Na, K, and Mg equilibrium was approached asymptotically. For a polished joint with smaller apertures equilibrium was established at about the same rate, but the flow rate decreased with time with the rate of decrease slowing after a couple of days. Future work includes identifying the mechanism for this time-dependent flow rate.

B. Closure

The Greenwood-Williamson-Walsh-Grosenbaugh theory describing the elastic deformation of joints has been written in a more general form. We have tested this theory quantitatively in the laboratory. This has been done by comparing joint closure from experiment with joint closure predicted by the theory. These comparisons were made using actual topography data from the surfaces of the joints used in the experiments.

Joint closure experiments were done using fused silica glass as a materials because of its isotropy and its well-known elastic moduli. Joints consisted of saw-cuts whose faces were ground with #220, #120, #80, and #60 polishing grits. Experiments were done where one rough surface was in contact with a flat surface and where two similar rough surfaces were in contact. Maximum stresses reached in these experiments ranged from 7.5 MPa to 10 MPa.

The maximum joint closure at a given normal stress does not, in general, depend solely on the rms height of the surfaces in contact. The amount of joint closure depends more strongly on the shape of the uppermost tail of the probability density function for summits (local maxima) on the surfaces. To compute the surface topography parameters in the joint closure theory using one-dimensional profiles, a model for surface topography must be assumed. The best agreement between theory and experiment is obtained with a model that includes the true skewed nature of the probability density functions associated with the surfaces in contact. For these experiments, the inverted chi squared model for surface topography of Adler and Firman (1981) shows much better agreement with experiment than does the gaussian model of Nayak (1971).

Contractor:	MASSACHUSETTS INSTITUTE OF TECHNOLOGY Department of Earth, Atmospheric, and Planetary Sciences Cambridge, Massachusetts 02139
Contract:	DE-AC02-76ER02534 A0010
Title:	Continental Scientific Drilling Program: The Seismology of Continental Thermal Regimes
Person in Charge	K. Aki

Scope of Work

This program was started as an involvement in two major geothermal projects, namely the Hot Dry Rock Geothermal Energy Development Project of the Los Alamos National Laboratory and the Magma Energy Project of Sandia National Laboratories. The theory and methods developed for interpretation of various seismic experiments conducted at Fenton Hill, New Mexico, and Kilauea Iki, Hawaii, however, found a variety of applications to other geothermal areas and volcanoes, and our research has been evolving into what might be called Volcanic Seismology.

In this program, we are applying the methods of both passive and active seismology to the candidate sites for CSDP, such as Long Valley, Jemez Mountains and Imperial Valley in order to delineate the geometrical and mechanical properties of the geothermal system. We use a set of digital event recorders for collection of high quality data as used in our study of Mt. St. Helens. Our interpretation methods for observed seismic signals from volcanoes and geothermal areas include the effects of seismic wave generation, transmission, scattering, and attenuation in a medium containing fluid-filled cracks.

Major accomplishments in the past year include (1) Development of theory of magma intrusion and volcanic tremor and application to the Mammoth Lakes seismic events, and (2) Determination of frequency dependence of attenuation in the Long Valley. We discovered that Q's and S waves and coda waves in the Long Valley show a unique frequency dependence, which is similar to the Kilauea, Hawaii, region but distinctly different from all other areas so far studied.

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

Contract: DE-AC02-78ER04972

Title: Microcracks and Energy

Person in Charge G. Simmons

Scope of Work

The objective of this project is to develop the scientific basis for the practical utilization of microcracks in DOE energy programs.

Open microcracks control such important properties as hydraulic permeability, electrical conductivity, compressibility, thermal expansion, and the velocities of elastic waves. Healed microcracks provide data on the pressure-temperature-stress history of a rock and may be useful in estimating the properties at the time the healed cracks were open. The potential applications include (1) site characterization for waste repositories; (2) estimation of the changes of permeability of rock in situ due to changes of temperature associated with production in a hot-dry-rocks geothermal system; (3) prediction of the behaviour of certain isotopes in radioactive waste emplaced in granitic rocks; and (4) improvements in the exploration techniques for uranium in crystalline rocks.

We use the petrographic microscope, the scanning electron microscope (SEM) equipped with both high energy 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).

We have examined the mobilization of uranium and rare earth elements in several igneous rocks: Conway and Mount Osceola granites of New Hampshire, Sherman granite of Wyoming and Colorado, the Carnmenellis granite of southwest England, and various granites and contiguous metasedimentary rocks near Augusta, Maine. Several different uranium-bearing and REE-bearing minerals occur in the microcrack in these rocks over extensive geographical areas and vertical depths - at least 250 square kilometers and a vertical extent of one kilometer for the New Hampshire granites. Because thorium-bearing secondary minerals also

occur in the same microcracks, it now appears that thorium may have been mobilized along with U and the REEs.

Uranium and REEs were mobilized in the Sherman granite over distances of at least 50 kilometers and vertical extent of 350 meters. They have remained immobile for one billion years. It would appear that this granite provides a guide to the type of crystalline rock for use as a high level rad-waste repository: namely, a granite pluton that has been altered and in which the microcracks are sealed.

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

The purpose of this project was to determine the chemical and physical changes which occur during the transformation of ooze to chalk. Chalk comprises a large part of the marine carbonate record, and oil is presently being produced from chalk reservoirs. An understanding of the mechanism of chalk diagenesis has implications pertinent to a broad range of problems in geology.

Hydrothermal experiments on three calcareous oozes of different compositions were performed at low water to rock ratios in a flow-through apparatus and a pore fluid sampler apparatus developed at the University of Minnesota. These facilities allow unconsolidated sediment to be compacted and dewatered in the experimental cell. Sediments in the flow-through system were exposed to 300 bars differential pressure, 100 bars pore pressure; those in the squeezer assembly were exposed to 400 bars confining pressure and little pore pressure. Experiments lasted two weeks at 150 C.

The sediments were chosen to reflect the changes in carbonate sediment composition through the Calcite Compensation Depth. The original pore fluid in the oozes was replaced with Mg and $SO_4^=$ free artificial seawater similar to that inferred to exist in chalk formations at depth. The presence of Mg and Sr in the reacted pore fluid and the decrease in pH and Ca concentration reflected Ca-X exchange and the replacement of less stable carbonate phases, while exchange reactions with clays introduced elements such at Si and Fe into the pore fluid. Initial porosity reduction due to compaction was furthered by pressure solution; fragile coccoliths dissolved while solution-resistant forms became more abundant. The sediments in the pore fluid sampler which were exposed to little pore pressure experienced a slightly greater reduction in porosity.

The following conclusions are relevant: 1) The porosity decrease due to compaction and dewatering of calcareous oozes is reinforced by high confining pressure and elevated temperature which produce welded contacts and lithified sediment. 2) The elimination of unstable phases, as reflected by the Ca-Mg exchange and trace element abundances,

increases the preservability of the sediment. 3) Trace element abundance in reacted pore fluids can be traced to Ca=X exchange in carbonate phases and exchange reactions with clays. The trace element compositions of reservoir pore fluids and sediments may be useful in the determination of conditions of lithification and diagnetic pathways. 4) Experiments on chalk diagenesis illuminate mechanisms of lithification and porosity retention in chalk reservoirs.

Contractor:	NATIONAL ACADEMY OF SCIENCES/ NATIONAL RESEARCH COUNCIL Washington, DC 20418
Contract:	DE-FG01-82ER12018
Title:	I. Studies in Geophysics
Person in Charge:	Thomas M. Usselman

The Geophysics Research Forum (GRF) 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, natural hazards, and environmental 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 Arthur E. Maxwell (chairman), Colin B. Bull, John C. Crowell, Devrie S. Inriligator, Nicholas C. Matalas, J. Murray Mitchell, V. Rama Murthy, and Ferris Webster; and Thomas M. Usselman, staff officer.

Studies Completed

ENERGY AND CLIMATE (Roger R. Revelle, panel chairman). Published in 1977 (158 pp.).

ESTAURIES, 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 PREDICTIONS (Helmut E. Landsberg, panel chairman). Published in 1978 (215 pp.).

GEOLOGICAL PERSPECTIVES ON CLIMATIC CHANGE (Preston Cloud, ad hoc committee chairman). Published in 1978 (46 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 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). Published in July 1982 (104 pp.).

CLIMATE IN EARTH HISTORY (Wolfgang H. Berger and John C. Crowell, panel co-chairmen). Published in December 1982 (198 pp.).

FUNDAMENTAL RESEARCH ON ESTAURIES (L. Eugene Cronin and Charles B. Officer, panel co-chairmen). Published May 1983 (79 pp.).

EXPLOSIVE VOLCANISM: INCEPTION, EVOLUTION, AND HAZARDS (Francis R.Boyd, panel chairman). Published January 1984 (192 pp.).

GROUNDWATER CONTAMINATION (John D. Bredehoeft, panel chairman). Published February 1984 (179 pp.).

Studies in Preparation

Geophysical Data and Public Policy (Michael A. Chinnery, panel chairman). Publication is expected in 1984.

Atmospheric Electrical Environment (E. Philip Krider and Raymond G. Roble, panel co-chairmen). Symposium held June 1983, publication is expected for 1984.

Active Tectonics (Robert E. Wallace, panel chairman). Symposium held December 1983, publication is expected in 1985.

Sea-Level Change (Roger R. Revelle, panel chairman). Symposium is scheduled for December 1984.

Scope of Work

The modular pattern for the Studies in Geophysics was designed to permit selection of the most timely topics 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, non-renewable resources, and the environment;

(2) to provide government officials with technological and scientific evaluations that can serve as a basis to assist in decision making in matters involving geophysical research and knowledge, both in policies and programs;

(3) to provide 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, DC 20418

Contract: DE-FG01-82ER12018

Title: II. Committee on Seismology

Person in Charge: Joseph 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 scientific 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 seismologically related activities within the National Research Council, particularly in the fields of earthquake engineering, rock mechanics, geodesy, geodynamics, and geology. Panels are established to conduct ad hoc studies on topics specified by the committee.

Members of the committee are Paul W. Pomroy (chairman), Lawrence W. Braille, C. Allin Cornell, Robert S. Crosson, Ricardo Dobry, Robert B. Herrmann, Thomas H. Jordan, Hiroo Kanamori, Franklyn Levin, David W. Simpson, and Robert E. Wallace; and Joseph W. Berg, Jr., staff officer.

Products

The Committee issued three reports during the contract period as follows: Seismograph Networks: Problems and Outlook for the 1980s (1983); Effective Use of Earthquake Data (1983); and Seismological Studies of the Continental Lithosphere (1984).

Current Activities

The Committee on Seismology is planning to conduct a study and to write a report on Seismic Hazard Analysis which will provide an in-depth review of the statistical and deterministic approaches to the problem.

Contractor: NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
Washington, DC 20418

Contract: DE-FG01-82ER12018

Title: III. U.S. Geodynamics Committee

Person in Charge: Pembroke J. Hart

Scope of Work

The U.S. 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 17 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 following years, the committee devoted a considerable effort to this task; this led to the report, Geodynamics in the 1980's, published in 1980. This report emphasizes 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.

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

The list of topics and respective reporters has been subject to continual review and revision, as appropriate. As of December 1983, the list was as follows:

Fine Structure of the Crust and Upper Mantle J. E. Oliver
Evolution of Oceanic Lithosphere J. R. Heirtzler
Large Volume Experimentation R. C. Liebermann
Application of Isotope Geochemistry to Geodynamics R. E. Zartman
Geodynamic Modeling D. L. Turcotte
Drilling for Scientific Purposes F. G. Stehli
Magnetic Problems C. E. Helsley
Plate Boundaries J. C. Maxwell
Geodynamic Data -- User's Needs W. J. Hinze
Geodynamic Data -- Archiving Problems M. A. Chinnery
Lithospheric Properties T. H. Jordan
Comparative Planetology J. W. Head
Continent-Ocean Geodynamic Transects R. C. Speed
Electrical Properties of the Asthenosphere C. S. Cox
Coordination of Major Geodynamics-Related Programs A. R. Palmer
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). Highlights are outlined below.

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 (COCORP) began applying this technique. That group has now completed profiles totalling more than 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 recommended that a national Continental Scientific Drilling Program be organized to facilitate the necessary communication and coordination. As a result of the response by the federal agencies to the report recommendations, a Continental Scientific Drilling Committee was created in January 1980 under the Geophysics Research Board. The USGC actively encourages the development of this drilling program, including add-on investigations in mission-oriented holes and the drilling of 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 sixteen have been published; two are in press.

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 corridors around the North American coast -- from the continental craton across the transition zone to oceanic lithosphere. The transect project began in 1980. 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 (poster session) and symposium were held at the meeting of the Geological Society of America in November 1982. Preparations of the maps and cross sections was essentially complete at that time. Publication of the resultant maps and section is under way; completion is expected in 1984 or 1985.

The USGC has endeavored to address two main issues regarding geodynamic data: the needs of users and archiving problems. The USGC convened a group in the early seventies to develop new sections of the Guide to International Data Exchange Through the World Data Centers and collaborated with the Committee on Geophysical Data in preparing the solid-earth section of the CGD report issued in 1979. The two USGC reporters for geodynamic data are actively involved with the current study on geophysical data and public policy and the task of modernizing the international Guide.

The USGC took initiative in the mid-seventies to encourage and assist the production of gravity and magnetic maps of the United States; the effort expanded to include North America. Preparation of these maps was strongly supported by the Society of Exploration Geophysicists and federal agencies. The gravity and magnetic maps for the United States were published in 1982 and were the subject of special symposia on applications at the fall 1982 meeting of SExG. Publication of the maps for North America is expected within the next year.

The reporter for electrical properties of the asthenosphere has worked closely with the international committee for a program of the same title. Several meetings have been held with the objective of developing a specific cooperative program between the United States and Canada.

In 1980, the USGC appointed a reporter and associated working group to ensure coordination among major geodynamics-related programs, especially the Circumpacific Map Project, Consortium for Continental Reflection Profiling (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. An important result: agreement was reached that the major maps will be published on the same projection and at the same scale.

International Lithosphere Program. The International Union of Geodesy and Geophysics and the International Union of Geological Sciences have organized the International Lithosphere Program -- an international program of geodynamics for the 1980's as a successor to the Geodynamics Project, which formally ended in December 1979. The full title of the new program is "Dynamics and Evolution of the Lithosphere: The Framework for Earth Resources and the Reduction of Hazards." International guidance is provided by the Inter-Union 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 serves as the U.S. counterpart to the Inter-Union Commission on the Lithosphere.

Workshop 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 were published in The Lithosphere: Report of a Workshop (1983).

Future Work of the USGC

1. Identify actions that can be taken in response to recommendations of the reporters.
2. Assess new directions for the committee and new priority topics to which the committee can react directly or via a reporter. This assessment will take especially into account Geodynamics in the 1980's, the discussion at the Workshop on the Lithosphere, the Continental Scientific Drilling Program, the International Lithosphere Program, and recommendations of reports of the Board on Earth Sciences (e.g., Seismological Studies of the Continental Lithosphere; and report of the Committee on Global and International Geology).
3. Address the program of the International Lithosphere Commission (ICL). What action should the USGC take in response to recommendations of the ICL? Can the USGC provide guidance and recommendations for the Lithosphere Commission?

Contractor:	NATIONAL ACADEMY OF SCIENCES/ NATIONAL RESEARCH COUNCIL Washington, DC 20418
Contract:	DE-FG01-82ER12018
Title:	IV. Continental Scientific Drilling Committee
Person in Charge:	Robert S. Andrews

Scope of Work

The Continental Scientific Drilling Committee (CSDC) was established in January 1980 at the National Academy of Sciences-National Research Council to work toward implementation of the recommendations in the report of the July 1978 Workshop on Continental Drilling for Scientific Purposes held at Los Alamos, New Mexico. This report, Continental Scientific Drilling Program (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 thrcugh add-on experiments, and supplementing these efforts with "dedicated" holes drilled for scientific purposes. In 1983 the CSDC became an activity under the newly-established Board on Earth Sciences.

Members of the CSDC are: Francis Stehli (chairman), Charles Bacon, Lawrence Cathles, Charles Drake, James Eidel, Howard Gould, Kate Hadley, John Hermance, William Hinze, Charles Mankin, Jack Oliver, Elburt Osborn, C. Barry Raleigh, 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 CSDC, six of which currently exist: Thermal Regimes; Basement Structures and Deep Continental Basins; Mineral Resources; Downhole Physical Property Measurements and Fault Zone Drilling; Drilling, Logging, and Instrument Technology; and Sample Curation and Data Management. The CSDC established eight ad hoc task groups to address specific research drilling targets and objectives: Salton Sea Geothermal Field (CA); Valles Caldera (NM); Yellowstone (WY); Creede Mining District (CO); Tonopah Mining District (NV); Red Mountain Mining District (AZ); Southern Appalachians; and Sample Curation Facilities.

A DEW (Drilling Early Warning) NEWSLETTER was established by the CSDC as its mechanism for communicating with the scientific community. This newsletter is distributed on occasion to approximately 2500 researchers in universities and other academic institutions, industry, government laboratories and geoscience administrators, and geoscience societies, and to interested foreign scientists. 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 research efforts. It also provides information on the committee's activities, announces important meetings and publications, and serves as a forum for interested scientists to exchange information related to drilling. Nine newsletters were distributed by mid-1984.

In 1980, the CSDC reviewed the scientific plan for add-on investigations to an industry drilling activity in northern Illinois and issued a report entitled Comments of the Continental Scientific Drilling Committee on the Document "Illinois Deep Hole Project -- Preliminary Plan." Research results from this project were published in the 10 September 1983 issue of the Journal of Geophysical Research.

Current Activities

Since the summer of 1983, the CSDC has greatly accelerated its activity. This took place as the result of high interest expressed by the White House Office of Scientific and Technology Policy (OSTP) in providing major incremental funding for a National Continental Scientific Drilling Program for FY 85. Important factors that led to this situation were the publication of the Board on Earth Sciences' report Opportunities for Research in the Geological Sciences and the research briefings to OSTP and other relevant government agencies by the Panel on the Solid Earth Sciences of the Committee on Science, Engineering, and Public Policy.

The CSDC has the goal of fostering the development of a program of maximizing the scientific value of current and planned drilling activities of industry and government agencies through add-on experiments, supplementing these efforts with holes drilled solely for scientific purposes. This goal has been accomplished through newsletters, meeting, and symposia which attempt to inform the scientific community as to the nature of a planned national research drilling program, opportunities for scientists to become involved in drilling efforts that come to the committee's attention, initial primary scientific objectives and highest priority targets for a research drilling program, and providing for an exchange of ideas.

The Panel on Thermal Regimes completed a report (mid-1984) to the 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 and the Long Valley-Inyo-Mono region. The importance of the Yellowstone system is discussed in that report; further considerations are being made by a new CSDC task group concerning the viability of this target for the future. The report also recommends making use of add-on investigations wherever

possible to further the understanding of the thermal regime of the Salton Trough.

The CSDC learned of an industry drill hole in the Salton Sea Geothermal Field that may provide an opportunity for add-on investigations. The Panel on Thermal Regimes held an open meeting of interested scientists to discuss this opportunity with the principal investigators; the consensus of the group was enthusiastic endorsement of the scientific merit of the plan. The CSDC issued a letter report, Opportunity for Add-on Scientific Experiments in a Republic Geothermal, Inc., Drill Hole in the Salton Sea Geothermal Field, in October 1982. Since that time, the CSDC has followed this project with keen interest and has supported several activities to develop experimental research for this project as it has evolved.

The Panel on Mineral Resources presented a report to the CSDC (mid-1984) recommending major emphasis on drilling to study stacked hydrothermal mineral deposits in four mining districts: Creede, Red Mountain, Tonopah, and Butte.

The Panel on Sample Curation and Data Management prepared a report concerning curation of drilling samples and ancillary data. The impetus for this panel was based in part on results of a DOE-OBES workshop on core curation at Los Alamos in 1981. The report is presently being reviewed by the CSDC for issuance later in 1984. In addition, the CSDC established a task group to outline the specifications necessary for a national drilling sample curation facility. This task group has met, and its report is being prepared for issuance in June 1984.

The Panel on Basement Structures and Deep Continental Basins addressed dedicated drilling based on a number f scientific reports and projects, as well as various compilations of geological and geophysical data. The panel proposed a deep research hole in the southern Appalachians as its highest priority target; a report on its findings is ready for Academy review. The report should be issued by the CSDC in the Summer of 1984. The Panel has held several special information sessions on research drilling at various sectional meetings of the GSA.

The Panel on Drilling, Logging, and Instrument Technology co-sponsored a workshop in late 1983 on diagnostics and drilling to develop dialogue between scientists and the drilling/logging community. Focus for the workshop was on scientific measurements required for research drilling projects recommended by the CSDC. The panel is studying the state of the art in drilling and logging, and will identify advanced technology required to meet scientific needs identified by the other panels of the CSDC.

The Panel on Downhole Physical Property Measurements and Fault Zone Drilling prepared a report identifying the San Andreas fault as the highest priority target to study the processes of active faulting. The

panel held a formal symposium on this subject at the AGU 1983 Fall Meeting in San Francisco. This report should be ready for issuance by the CSDC in Summer 1984.

International cooperation and coordination in continental scientific drilling receives continuing attention of the CSDC. The chairman, staff officer and other members of the CSDC are directly involved in the activities of the International Lithosphere Program related to continental drilling, and in discussions regarding bilateral cooperative studies. The CSDC was a cosponsor of the International Symposium on Observation of the Continental Crust through Drilling, held in Tarrytown, NY, 20-25 May 1984. Members of the CSDC participated in the continental drilling activities at the International Geological Congress in Moscow, August 1984.

Future Activities of the CSDC

The goal of the CSDC will probably change as a national program becomes a reality, with major incremental funding. A group of universities is in the process of forming an organization to manage a national program. Many of the activities of this corporation will be operationally oriented, including decisions on individual projects and funding. Some of the operational activities may be inappropriate for an Academy committee. The future of the CSDC will depend in large part on two factors: (1) the needs of the supporting federal agencies to have an Academy group for oversight of a management organization and for addressing long-term objectives and targets for a national program; and (2) the CSDC's perspective on the ability of the planned management organization to implement the type of the national program called for at the time of the CSDC's establishment.

Contractor: NATIONAL ACADEMY OF SCIENCES/
NATIONAL RESEARCH COUNCIL
Washington, DC 20418

Contract: DE-FG01-82ER12018

Title: V. Board on Earth Sciences

Person in Charge: Joseph W. Berg, Jr.

Scope of Work

The fundamental mission of the Board on Earth Sciences of the Commission on Physical Sciences, Mathematics, and Resources is to provide oversight of the solid-earth science activities with the National Research Council, to provide a review of research and public activities in the solid-earth sciences, to assess the health of the disciplines, and to identify research opportunities. This group is to take a leading role in helping to establish scientific policy bearing on larger earth science programs in and on behalf of the United States. A major charge of the Board and its committees is to assess and recommend basic reasearch and its applications to meet national and societal needs.

Members of the Board are William R. Dickinson (chairman), Don L. Anderson, Paul A. Bailly, Thomas D. Barrow, Lloyd S. Cluff, W. Gary Ernst, Michel T. Halbouty, Melvin J. Hill, Carroll Ann Hodges, John Imbrie, V. Rama Murthy, Jack E. Oliver, Stephen C. Porter, C. Barry Raleigh, J. William Schopf, and E-an Zen; and Joseph W. Berg, Jr., staff officer.

The committees of the Board are: Committee Advisory to the U.S. Geological Survey, Committee on Cartography, Committee on Geodesy, Committee on Geological Mapping, Committee on Global and International Geology, Committee on Seismology, Continental Scientific Drilling Committee, U. S. Geodynamics Committee, USNC/Geochemistry, USNC/Geology, USNC/International Geographical Union, USNC/International Union of Geodesy and Geophysics, USNC/International Union for Quaternary Research, and USNC/Rock Mechanics.

Current Program

The Board maintains an awareness of the national, societal, scientific, and technological demands that solid-earth sciences will be expected to meet in the future and takes actions which help to meet the demands. Such actions are taken using existing National Research Council activities where possible. The functions include the following:

1. Identify basic research opportunities and applied research needs.

2. Review new technology and recommend ways by which the earth sciences can best utilize technological advances to provide maximum benefits to society and to the sciences.

3. Assess educational and manpower requirements relating to future national and societal demands on the earth sciences.

4. Provide a mechanism to enhance interrelationships between domestic and international programs, policies, and problems based on the need to recognize that the earth sciences are intrinsically global in nature.

5. Identify problem areas and help provide a means for the dissemination of information to governmental policy makers and the general public on the implications of geological data pertinent to many of our major societal problems.

6. Coordinate activities in the earth sciences with other National Research Council groups having related responsibilities.

7. Provide advice to government agencies on request and at the initiative of the Board.

8. Initiate tasks that stem from and are relevant to the functions given above. The conduct and completion of specific tasks will be achieved through the use of workshops, the appointment of subunits, and/or any other means deemed appropriate and expeditious.

The committees of the Board on Earth Sciences are engaged in all of the functions listed above.

Products

Several reports have been issued by committees of the Board on Earth Sciences. They are: (1) Opportunities for Research in the Geological Sciences; (2) Geology and Our Future: Summary of a Workshop Report; (3) The Lithosphere: Report of a Workshop; (4) Seismographic Networks: Problems and Outlook for the 1980s; (5) Effective Use of Earthquake Data; (6) Seismology of the Continental Lithosphere; (7) Annual Review of U. S. Progress in Rock Mechanics - Rock Mass Characterization; and (8) Hydraulic Fracturing Stress Measurements. The reports are being used by government agencies and the scientific community. One measure of success is that new incremental funding for site selection of continental drilling has been specified by the Office of Science and Technology Policy for FY 1985. This was a recommendation in Opportunities for Research in the Geological Sciences, as well as one of the five research areas identified by the Committee on Science, Engineering, and Public Policy which briefed officials of OSTP and federal agencies.

Contractor: NATIONAL ACADEMY OF SCIENCE/
NATIONAL RESEARCH COUNCIL
Washington, DC 20418

Contract: DE-FG01-82ER12018

Title: VI. Geophysics Film Committee

Person in Charge: Pembroke J. Hart

Scope of Work

The Geophysics Film Committee was established in the National Academy of Sciences to provide scientific guidance for, and to ensure the scientific integrity of, the film series entitled "Planet Earth" that is being produced by PBS station WQED/Pittsburgh in cooperation with the National Academy of Sciences. The series is scheduled for public broadcasting in the 1985-86 season.

The series will include seven one-hour films for broadcasting; the films can be adapted for telecourse and other educational purposes.

The Film Committee's responsibilities include the following tasks:

1. Selection of specific topics and titles for the films in the series. The subject areas for the seven one-hour films are: comparative planetology, solid earth, mineral and energy resources, oceanography and hydrology, climatology and meteorology, solar-terrestrial relations, and a concluding segment on man's impact on the earth.

2. Appointment of a panel for each one-hour film. The basic responsibility of each panel is to assist the Committee and WQED in identifying appropriate scientific topics, scientific activities, opportunities for new filming, and opportunities to utilize existing footage, and to review the film and script as production advances. Thus, each panel will require meetings of the entire panel and of selected subgroups of the panel to accomplish its tasks:

   Each panel (a chairman and approximately five members) will work closely with WQED to explore subtopics for its film and to identify scientists who are at the frontiers in their respective field of study and whose experiments are expected to have a major impact in science.

   The panel will assist in the preparation of the film script.

   Members of the panel may be asked to participate in arrangements for the actual filming.

Each panel will review the film and its script as production progresses.

3. At appropriate stages of production, the Committee will meet to screen and review the seven films for scientific content and accuracy, as well as to confirm that the overall theme of the series has been addressed.

4. The Committee and panels will assist in developing written material to facilitate use of the films for educational purposes.

5. Meetings of the Geophysics Film Committee and its panels have been held or are scheduled during the eighteen-month period of development of themes, and production of the films. In addition, travel by the chairman and staff of the Committee, and by subgroups of the panels, is required.

In 1983, the Committee established a panel to provide guidance in topic selection and production aspects of the solid-earth film. That film entered editing in mid-1984. Corresponding panels for the remaining films have been established; production of those films and associated written material is proceeding in parallel.

Members of the Geophysics Film Committee are: Roger R. Revelle (chairman), G. Arthur Barber, Charles L. Drake, Herbert Friedman, Laurence M. Gould, Thomas F. Malone, John P. Schaefer, Alan J. Shapley, Eugene M. Shoemaker, Walter S. Sullivan, Verner E. Suomi, James A. Van Allen, J. Tuzo Wilson, and Stanley Ruttenberg (senior consultant); and Pembroke J. Hart and Barbara Valentino, staff.

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

Contract: DE-AS08-82ER12082

Title: I. Investigation of Magma Chambers in the Western Great Basin

Person in Charge: A. S. Ryall

Scope of Work

This research is in support of the Continental Scientific Drilling Site Assessment Program, and is aimed at defining the geometry of magma bodies in Long Valley caldera, California; characterizing seismicity associated with magma injection in the caldera; searching for evidence of other magma bodies in the surrounding region; and supporting complementary investigations by other agencies involved in the Site Assessment Program. Subtasks are described below.

A. Seismic Network Operation

During the last half of 1983 we deployed eight additional seismic stations north and east of Long Valley caldera. The US Geological Survey has concurrently installed 12 new stations in the caldera region. This brings to 33 the number of seismographic stations recording in and around the Long Valley caldera. All of the University of Nevada stations and many of the USGS stations are being recorded on analog magnetic tape at Reno. Station spacing in the southwest part of the caldera is less than 10 km; north of the caldera it is 15-20 km. This network is sufficient to provide at least 20 readings for the location of all earthquakes in the Mammoth Lakes area with magnitude greater than 1.5 ML.

The University of Nevada has developed and tested a digital seismographic system for remote operation. The digital station is a data acquisition system that provides broad-band (0.05-20 Hz), wide dynamic-range (96 dB) digitization of signals from a three-component set of seismometers, and telemeters the data to a central facility where it is continuously recorded. This system has been tested in an experiment in Hot Creek Valley, central Nevada, and three stations are now operating in mine-tunnels at Mina, Bodie, and Washoe Lake. A fourth station is to be installed in the Las Vegas area in the near future. The Bodie and Mina stations will be used to determine spectral characteristics of seismic signals affected by attenuation in Long Valley caldera.

B. Data Analysis

Routine analysis efforts have provided a detailed picture of earthquake distribution through early 1984 and work is in progress to develop a master-event algorithm that will enable us to reanalyze data collected before the dense network was installed in

1982. A New system has been installed that will provide on-line event detection and digitization of the analog seismic signals transmitted to the Reno data facility. This will facilitate analysis of large numbers of earthquakes and will allow waveform analysis of the network data.

C. Interpretation

1. Geometry of the Magma Chamber (C. O. Sanders and F. D. Ryall)

In order to outline the three-dimensional geometry of the Long Valley magma chamber, we have studied propagation effects along 1200 ray paths for nearly three hundred small events around the southern caldera boundary and within the caldera. The primary discriminant for paths through magma appears to be anomalously low (2-3 Hz) signal frequencies combined with the lack of an S-wave. Signal characteristics have been tabulated and mapped for a variety of paths through the caldera and a range of event depths. Two massive magma bodies have been identified in the Long Valley caldera and their geometries have been mapped out in detail in a paper by Sanders soon to be published in the Journal of Geophysical Research. We are also investigating anomalous propagation effects that suggest the presence of magma bodies under Lake Crowley and along the frontal fault system south of the caldera.

2. Magma Injection (A. S. Ryall and F. D. Ryall)

Earthquakes in one small area just east of the town of Mammoth Lakes have tended to occur as intensive swarms having the appearance of spasmodic tremor observed in volcanic regions. Current research is aimed at explaining the localization of this type of activity in the southwestern part of the caldera, and determining the extent to which swarm activity along the southern caldera boundary may represent dike formation.

3. Focal Mechanisms (U. R. Vetter and A. S. Ryall)

In two papers we have concluded that focal mechanisms of earthquakes in the western Great Basin, including the area around Long Valley caldera, vary systematically with depth. Shallow events have strike-slip mechanisms and events at mid-crustal depth have a strong component of normal slip. This variation, taken together with different fault geometries at different depth, is consistent with a process of lithospheric extension involving normal movement on primary faults and the formation of clusters of fissures or dikes due to crustal spreading at shallow depth. We are now reanalyzing regional and worldwide data for several large earthquakes in 1980, to determine whether those events can be explained by a multiple rupture process rather than the fluid injection model recently proposed by US Geological Survey scientists.

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

Contract: DE-AC02-81ER10921

Title: Deep-Burial Diagnesis in Carbonates

Person in Charge: G. M. Friedman

Scope of Work

The objectives of this research are (1) to gain an understanding of what makes or breaks porosity in carbonate rocks as a result of deep burial, (2) to relate changes in textures of carbonate rocks to depth, and (3) to develop criteria for interpretation of former depth of burial and paleotemperature in strata now at shallower depth. We have adopted three parallel lines of investigation: (1) experimental compaction tests, (2) study of cores, samples, and wireline logs from boreholes of some of the world's deepest hydrocarbon reservoirs, and (3) study of samples from strata now exposed that were formally subjected to great depth of burial and high paleotemperatures.

Compaction tests reveal that ooid samples show appreciable reductions of bulk volume and porosity when squeezed at temperatures and pressures equivalent to overburdens of over 3 to 6.5 km. Ooids develop pressure-solution contacts during experimental compaction. This is consistent with earlier experience that pressure solution is one of the important processes in the overall diagenesis of carbonate sediments. Scaling down of the time factor from millions of years to just a few days of rapidly rising pressures and temperatures might explain the relatively small magnitude of pressure-solution effects that give way to more mechanical grain adjustments through different types of grain breakage. Besides pressure solution, ooids have been deformed plastically developing both longitudinal and concavo-convex contacts. Temperature and salinity of water that saturated the experimentally compacted ooid samples have effects on the nature of grain contacts and styles of grain breakage. Marine water appears to suppress pressure solution and enhances plastic deformation when other experimental conditions remain constant. Higher temperature appears to enhance pressure solution. Change in temperature appears to have little effect on styles of over-burden breakage, but salinity of water has. These changes in ooid grain contacts and ooid breakage are subtle, but consistent in all experiments that have been run and are considered to be significant.

In the deep Anadarko Basin of Oklahoma and Texas carbonate rocks of the Hunton Group (upper Ordovician to Lower Devonian dolostones alone provide porosity (both intercrystalline and moldic). Bulk densities determined by measuring proportions of major minerals (x-ray diffraction) and iron concentration (x-ray fluorescence) permit improved estimates of true porosities and water saturations. We have calculated more porosity and hydrocarbons than expected for select zones. Intervals with less than 4% apparent porosity before correction for iron, actually have 4-10% porosity. Potentially productive intervals

have been missed. At depths exceeding 3 km ferroan dolomite and calcite in the Hunton Group carbonates are predictably associated with interbedded argillaceous zones and with the underlying marine Sylvan Shale. The Sylvan Shale is inferred as the source for Mg^{2+} and Fe^{2+} in generating iron-rich dolomite. Increased temperature with depth has been inferred as the predominant factor for dolomitization.

Lower Ordovician carbonate strata in undeformed belts of the northern Appalachian Basin yield depth of burial and paleotemperature data implying a former depth of burial which has not been usually inferred for this area. A study of liquid inclusions in carbonate crystals puts the paleotemperature into the anchizone suggesting a burial depth of several kilometers. In this continuing study we plan to define the depth of burial/orogenic transition zone.

Contractor:	RICE UNIVERSITY DEPARTMENT OF GEOLOGY Houston, Texas 77251
Contract:	DE-AS05-83ER13124
Title:	Structural Evolution of Central Brooks Range, Alaska
Person in Charge:	H. G. Ave' Lallemant

Scope of Work

The objective of this research program is to acquire a thorough understanding of the evolution of the EW-trending Brooks Range fold and thrust belt in northern Alaska. A NS-trending transect along the Alaska Pipe Line is being mapped in detail at a scale of 1:30,000 and locally at 1:15,000. Available seismic reflection lines and bore-hole data of the northern foothills and the foreland basin are being analyzed to get better vertical constraints.

The Brooks Range consists of Lower Paleozoic rocks which generally are metamorphic and exposed mostly in the southern part of the range, and Upper Paleozoic clastics and limestone and Mesozoic clastic rocks in the northern Brooks Range. The source area of all pre-Middle Jurassic sediments lies to the north: Middle Jurassic and younger sediments have sources to the south. This change of course area has been related to the emergence of the Brooks Range fold and thrust belt in the Middle Jurassic. An older Devonian deformation has been proposed to have affected the Lower Paleozoic rocks and this deformation is related to the Innuitian event of the Canadian Arctic Islands.

In the central Brooks Range lies the so-called Donnerak window. Two models have been proposed to explain the north-dipping thrust faults, north of the window, and south-dipping ones, south of Doonerak. In one model two thrusting events were proposed: the first one south-directed and the second one north-directed. The second model proposes only a north-directed thrusting event. The Doonerak window was supposed to be a basement high in the first model and a basement uplift in the second one.

Detailed mapping during 1983 has shown that only one north-directed thrusting event had occurred, but that the Doonerak window is not a basement uplift, but an exhumed duplex structure. Fieldwork has also shown that the Lower Paleozoic rocks have undergone exactly the same deformational history as the younger rocks; no pre-Upper Devonian structures were found. This may indicate that the Upper Devonian clastic rocks were deposited on the southern flank of a foredeep, too far away from the Innuitian fold and thrust belt to be deformed penetratively.

Structures in the metamorphic rocks of the southern Brooks Range are all correlatable to the ones in the Doonerak window and thus have formed also during the Juro-Cretaceous Brookian event. Slices of

ophiolitic rocks are much less penetratively deformed but have also been emplaced by northward thrusting.

Preliminary balanced cross sections incorporating our field data, seismic reflection, and bore-hole data show that it is possible that major structural traps may occur in the central Brooks Range, but that because of their depth would hold only gas.

Contractor: SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY
Rapid City, South Dakota 57701-3995

Contract: DE-AC01-82ER-12050

Title: Thermally Induced Chemical Migration: A Natural Analog Approach

Person in Charge: J. J. Papike

Scope of Work

The major objective of this research is to gain a quantitative understanding of chemical migration in the geologic environment over a range of temperatures and pressures and in diverse geologic media. Contact metamorphic occurrences serve as geologic analogs with the igneous intrusion providing the neat and trace element source, and the country rock the medium through which migration takes place. The specific sites for this study are pegmatite/wallrock interaction zones in the Black Hills, SD. This type of study provides information on chemical migration over geologic times; a time span that cannot be duplicated in laboratory experiments or with presently available calculation procedures.

Key Questions Being Addressed

1. What is the extent of chemical migration under differing geologic conditions, e.g., P, T, composition of solutions, and nature of country rock?
2. What are the relative mobilities of elements of interest, e.g., Cs, Rb, Li, Sr, etc.?
3. What are the mechanisms of migration, e.g., nature of fluid phase, speciation, etc.?
4. What are the mechanisms of retardation, e.g., sorption, equilibrium cation exchange, etc.?
5. What is the partitioning behavior of the elements of interest among the mineral phases in the host rock and migrating fluid phase?
6. What are the mechanisms of fluid and chemical migration through granite complexes? How does this migration manifest itself?

Some Initial Findings from Pegmatite/Wallrock Studies

1. Maximum temperature of country rock was approximately 510-540^{o}C.
2. The migration of Li and Cs has taken place to distances greater than 90 meters. Rb has migrated up to 10 meters.
3. The relative mobilities of Li, Cs, and Rb are: Li > Cs >> Rb.
4. There is no detectable migration of REE, Al, V, Sc, Cr, Hf, U, Th.
5. Sheet silicates are effective trace element traps. Biotite is a much more effective trap as indicated by Kd's for biotite/muscovite pairs: Cs-12.3, Rb-2.5, and Li-4. These partition coefficients agree with experimentally determined coefficients for phlogopite and muscovite and can be rationalized in terms of the crystal chemistry of these sheet silicates. This work is being done in collaboration with J. C. Laul (Pacific Northwest Laboratories), who is conducting the INAA and RNAA analyses.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: DE-AT03-82ER12051.000

Title: I. Mechanism of Zeolite Crystallization and Alteration in Silicate Glasses

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

Scope of Work

The mechanism of zeolite crystallization is important not only from a theoretical viewpoint, but also in reference to the large field of industrial applications. Despite the importance of zeolites geologically and industrially, relatively little is known about the physiochemical controls on zeolite formation or about thermodynamic properties of zeolites. This project includes the following three major tasks:

A. Experimental Study on the Processes of Zeolite Formation
Our experimental study attempted to 1) examine the effect of solution composition on the composition and structure of some synthetic zeolites in the system Na_2O-K_2O-Al_2O_3-SiO_2-H_2, 2) study the effect of solution composition on the crystallization path of these zeolites, and 3) interpret these observations within the framework of a theory for the crystallization mechanism of zeolites. Three sets of experiments in which phillipsite or merlinoite precipitated from clear solutions were completed. The results showed that at a fixed activity of silica, zeolite Si/Al ratio is a linear function of pH. This dependence is examined in the light of ^{29}Si NMR spectra of the initial solutions. The results are applied to natural zeolite paragenesis and serve to delineate the framework of a comprehensive theory for the mechanism of zeolite crystallization.

B. Synthesis and Characterization of Alkali Zeolites
Zeolites having the structures of phillipsite, merlinoite and gismondine were synthesized from clear solutions at 80°C. Their morphologies, cell parameters and composition were determined and the chemical controls (pH, Na/(Na + K) ratio) on their formation were delineated. Using the experimental results, the occurrence of merlinoite together with phillipsite in saline, alkaline sediments from Searles Lake, California was predicted and confirmed by SEM

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observation of selected core samples. Because of their close similarities in physical properties, it is suggested that merlinoite is much more common as an authigenic mineral then is currently realized.

C. Calorimetric Study of Synthetic Zeolites

Low-temperature heat capacities and heats of solution were determined for nine synthetic merlinoites of various Si/Al and Na/(Na + K) ratios. Eleven additional merlinoites will be prepared and their thermochemical properties will be measured. In this way, variation of thermochemical properties as a function of both Na-K and Si-Al mixing can be studied, facilitating the application of the data to natural zeolites.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: DE-AT03-76ER71045

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

Person in Charge: A. M. Nur

Scope of Work

The objectives of this ongoing project are (1) to advance our understanding of physical processes in cracked rocks with fluids; and (2) apply the results to geophysical exploration, reservoir evaluation and the study of shallow crustal processes. Specific current studies are:

1. Seismic Attenuation in Rocks. Measurements of wave attenuation in rocks vs temperature and frequency have revealed that the rheology of the pore fluid, and surface interactions between fluid and solid control wave induced fluid flow in the pores. It appears that these processes dominate mechanism of attenuation in rocks at shallow crustal conditions. The results are being applied to the interpretation of reflection data in oil and gas fields, hydrological exploration, and to seismic models of overpressure zones.

2. Network models of porous rocks with fluids. We have utilized our network model to describe the petrophysical properties of about 50 rocks, and their dependence on overburden pressure, pore pressure, and other variables. The model correctly and accurately predicts the hydraulic, electrical and elastic properties of all the rock studies. Results suggest that the pore space can be characterized as a mix of flat grains in contact, with a wide range of contact shapes. The results are used already in the development of rigorous petrophysical reservoir models, utilizing seismic, core, and log data.

3. Velocity and attenuation in heavy oil sands. We have by now measured the velocities and amplitudes of compressional and shear waves in heavy oil sand sample from the U.S., Canada, and Venezuela as well as sandstones with various hydrocarbons as a function of pressure and temperature. The new results confirm the large decreases in velocity and amplitude upon heating to 125°-150°C. These large changes have been found to be controlled by wave induced phase transformation and/or chemical reactions in the pore fluid. The results are being applied at present in tracking an in situ steam flood for enhanced oil recovery.

4. Pore pressure in the crust. Our numerical model which incorporates hydraulic diffusivity, pressure solution and solution transfer, rock and pore deformation, and tectonic strain rate, is being used

to estimate the tectonic and mechanical conditions under which super pore pressure zones develop in the accretionary wedge in subduction zones; in active fault zones; and during the migration of hydrocarbons from their source rocks to their reservoir rocks. The results show that the main factors which control pore pressure in these situations are the ratio between permeability and pore volume strain rate and the geometry of permeable and impervious zones in the crust. The results of this study will also be used in the evaluation of radioactive waste disposal sites.

Contractor: STANFORD UNIVERSITY
DEPARTMENT OF APPLIED EARTH SCIENCES
Stanford, California 94305

Contract: DE-AT03-84ER12016

Title: III. The Hydrothermal Solubility of Uraninite

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

Scope of Work

The equilibrium solubility of uranium (IV) dioxide (UO_2) in aqueous solution is a function of solution composition (pH, ligand concentration, and ionic strength), oxidation-reduction potential, temperature, and pressure. The limiting concentration of uranium in natural aqueous systems depends on these factors as well as adsorption and more complex rock- and soil-water interactions. These constraints must be recognized and accounted for in solution transport and fixation models. The thermodynamic data required to utilize these models and to compute the solubility limit of uranium exist for near-surface conditions of low temperature and high oxidation potential, but data for higher temperatures and pressures is limited both in extent and precision. This is especially true for tetravalent uranium species.

The major thrust of this work is to obtain equilibrium solubility data for stoichiometric UO_2 in the system UO_2-H_2O while varying pH but while maintaining f_{02} conditions at sufficiently low levels to maintain the low oxidation state both in the solid and solution. The temperature range of the experiments is from 100 to 400°C at 500 bars total pressure.

The experimental approach involves reacting spherical, uranium dioxide pellets with solution in Dickson-Gordon hydrothermal apparatus which permits solution samples to be withdrawn into gastight containers at ambient P/T conditions of the experiement. Equilibrium is approached both from over-saturated and under-saturated conditions. The UO_2 solid is characterized both before and after each experiment. The oxygen fugacity (redox potential) is controlled in the experimental apparatus by maintaining a fixed partial pressure of hydrogen within the reaction cell. Attempts to monitor in situ pH at ambient P/T conditions of the experiment have not been successful as it proved impossible to maintain stable electrode potentials for the duration of the experiments. Hydrogen ion activity is now measured at 20°C and extrapolated to the P/T conditions of the experiment by computer.

We have completed a series of fifteen solubility experiments from pH 1 to pH 7 at 200 and 300°C and eleven in the range from 100 to 400°C. Preliminary analysis of the results indicates that total uranium in solution is at least an order of magnitude higher than predicted from

thermodynamic calculations using the data base of Lemire and Tremaine (1980) and EQ3/6 (Wolery, 1978). The results show only a very slight increase in solubility from 100 to 300°C.

Our UO_2 is pre-reduced in H_2 at 900°C and NiO in crimp-sealed Pt capsules included in some runs is reduced to Ni metal, verifying that the low f_{O2} desired, is achieved. Other investigators have had difficulty in achieving reduction of uranium to U(IV) in solution. We are concerned that persistent surface oxidation of our samples may be responsible for the high solubility and scatter observed.

Because the predicted and measured uranium solubility of UO^2 approaches or falls below the limit of detection of our analytical method (2×10^{-10}M) near neutral pH, we hope to complete the UO_2-H_2O (NaCl - NaOH) system experiments by conducting experiments at high pH to extend and confirm the high temperature solubility data of Tremaine et. al., 1981.

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

Contract: DE-AC02-83ER13013

Title: Thermal Evolution of Sedimentary Basins

Person in Charge: T. M. Harrison

Scope of Work

Our research objective is to assess the usefulness of $^{40}Ar/^{39}Ar$ age spectrum analyses of detrital microcline in providing thermochronological information necessary for reconstructing the thermal evolution of sedimentary basins. Detrital microclines preserve a record of thermal events in the temperature range ~ 100°C to 200°C, depending on length of heating and several mineralogical variables.

During 1983, a study of deep drill core material from the San Joaquin Basin (California) illustrating the feasibility of this approach was brought to completion. We are presently investigating two extensional basins, the Albuquerque Basin (Rio Grande Rift) and the North Sea. Microcline has proved to be very abundant in both areas above depths of ~ 6 km, and $^{40}Ar/^{39}Ar$ analyses reveal small ^{40}Ar diffusion loss gradients in samples from both terranes. Improvements in analytical techniques, especially temperature monitoring, allow very precise diffusion parameters to be calculated from the laboratory Ar loss data and indicate a slightly higher range in activation energy (31-35 kcal-mol^{-1}) than previously thought (~ 30 kcal-mol^{-1}). Temperature histories inferred from these preliminary analyses are generally compatible with the known thermal history giving us confidence that this approach may be used to extract temperature-time information from samples with poorly known burial histories.

In the hope of better understanding the behavior of K-feldspar during a geological heating, we analyzed a suite of samples from the Fenton Hill deep drill holes, thought to have been at temperature for about one million years. However, it appears from our analyses and simple heat flow calculations, that the heating is very recent, on the order of perhaps 100,000 years.

Contractor: STATE UNIVERSITY OF NEW YORK
DEPARTMENT OF EARTH AND SPACE SCIENCES
Stony Brook, NY 11794

Contract: DE-AC02-83ER13112

Title: Geochemistry and Origin of Dolomites

Persons in Charge: G. N. Hanson and W. J. Meyers

Scope of Work

The prime objective of this research is to investigate the geochemistry and petrology of regionally extensive dolomites using radiogenic and stable isotopes, trace elements, and a variety of petrographic approaches. We are applying these approaches to the regionally dolomitized Burlington and Keokuk Formations (Mississippian) in Iowa, Illinois, and Missouri. These data will be the basis for testing detailed quantitative geochemical models, including chemical mass transfer models, to constrain the source(s) and migration path(s) of dolomitizing fluids. A general understanding of dolomites is important because they are significant reservoirs for hydrocarbons and in many regions have acted as conduits for migration of petroleum, brines, and ore-forming fluids.

We are using a wide range of high precision major and trace element analyses (Ca, Mg, Fe, Mn, REE) and stable (C, O) and radiogenic isotopes (Sr, Nd,) within a framework of well-established dolomite and calcite cement zonal stratigraphies as established by cathodoluminescence petrography. In addition, we are investigating fluid inclusions, solid microinclusions, and crystal defect structures in the dolomites. Fluid inclusion work to date has indicated that highly saline fluids and temperatures of 100^{o}C and greater may have been involved in dolomitization. Preliminary solid inclusion work has identified calcite and iron sulfides within the dolomites. The petrographic framework has been extended southward into Missouri and Illinois and shows that the calcite cement stratigraphy and dolomite zonal stratigraphy are regionally consistent over at least 10's of thousands of square miles. Research on petrography and major and trace elements has shown that there are at least three regionally extensive dolomite types which differ from one another in luminescence signatures and in stoichiometry, Fe, and Mn. The REE data for the dolomites show that non-carbonate components have a major effect on bulk samples, and on acid soluble portions. This indicates that dolomite, or diagenetic calcite, must be physically separated from non-carbonates in order to analyze the REE within the carbonate lattice. Results of the REE analyses of dolomites show regional and stratigraphic consistency in absolute amounts and REE patterns. These suggest that REE are essentially immobile during diagenesis. Similarly Nd isotope analyses of dolomites show great consistency whereas Sr isotopes show wide variation, the latter indicating a probable allochthonous source for some Sr. Studies on Sr isotopes and REE on the host limestones are just beginning.

These studies have the potential of developing an integrated approach that could be widely applied to fluid-rock systems, not only for studies of dolomitization, but also for cementation of carbonates and sandstones, for migration of elements related to waste disposal and for the chemical evolution of ore fluids.

Contractor: TEXAS A&M UNIVERSITY
CENTER FOR TECTONOPHYSICS
College Station, Texas 77843

Contract: DE-AS05-79-ER10361

Title: I. Mechanical and Transport Properties of Rocks

Person in Charge: M. Friedman

Scope of Work

Geothermal-energy exploration and exploitation, safe underground isolation of toxic waste, siting of stable nuclear power plants, continental scientific drilling and the problems of earthquake prediction and hazard reduction all require a better understanding of the mechanical and transport properties of rocks and rock masses under confining pressure at high temperature. Our objectives continue to be to learn more about these properties in the brittle and semi-brittle regimes through experimental and observational studies. Our goal is to predict the behaviors of rock masses in which heat is stored naturally or artificially.

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

Having shown that the α - β quartz transition affects profoundly the creep rate of Westerly Granite in the transient regime at 200 MPa confining pressure (Ross et al., 1983), we chose to complete our investigations of low pressure static fatigue of the granite by investigating the effects of strain rate. We have thus conducted a series of constant strain rate tests on dry Westerly Granite at 100 MPa argon confining pressure, temperatures from 24 to 500°C, and strain rates ranging from 10^{-4} to $10^{-7} s^{-1}$ (Harris, 1984). As expected, the fracture strength is sensitive to both temperature and strain range over this rate, the failure stress in these brittle and slightly transient tests decreasing with increasing temperature and decreasing strain rate. Strains at failure show a slight decrease with decreasing strain rate at constant temperature. The activation energy estimated for failure processes in the temperature range 24 to 300°C is 14 $\pm$ 5 kcal/mole and these are shown to be dominatedly brittle although a combination of rate processes (semibrittle) operate at 500°C. Log time to failure is directly proportional to -log strain rate, virtually independent of temperature in the 24 to 500°C range studied. An analysis of the creep results of Kranz et al. (1982) and Bauer (1983) over the temperature interval 200 to 600°C reveals an identical result.

Having completed our work on low pressure-moderate temperature static fatigue of Westerly Granite in the dominantly brittle range and on high-pressure-moderate-to high-temperature deformation, in

the solid pressure medium equipment dominantly in the steady-state-semibrittle to ductile regime, we are currently beginning an investigation of the creep behavior at intermediate physical conditions, supported by DOE/BES, Contract DE-F605-84-ER13216. These experiments, to be conducted at constant strain rates in the range 10^{-4} to $10^{-8}s^{-1}$ at 400 to 800°C at argon confining pressures of 800 MPa (entirely in the α-quartz stability field) on both nominally dry and induced seawater pore pressures to 500 MPa, will permit a thorough physical understanding of the evolution from elastic-brittle, through transient (work-hardening)-semibrittle to steady-state-semibrittle-ductle flow.

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

The long-term objective is to measure and understand the variation of fracture permeability of several typical crustal crystalline rocks as a result of hydrothermal reaction with through-flowing aqueous fluids at temperatures to 300°C, fluid pressures to 20 MPa, and confining pressures to 100 MPa. Experiments are designed to evaluate the relative importance of dissolution and secondary mineral formation on permeability changes. Complementary experimental and theoretical studies aim at assessing the role of elastic and inelastic deformation of fracture-surface asperities upon changes of fracture permeability.

A servo-controlled permeability system has been designed and built that allows measurement of permeability using either a continuous flow method or transient pulse method with highly corrosive aqueous fluids at elevated temperatures. In a continuous flow mode, one can control either the flow rate (to 1 ml/day) or differential fluid pressure.

Early experiments have focused on determining how dissolution modifies fracture surfaces of quartzite and hence changes fracture permeability. Experiments indicate pronounced changes occur and that intragranular and intergranular (grain boundary) cracks, pores, and tubules play the dominant role in the dissolution modification of surface roughness, with grain-boundary widening being especially prominent. The experiments also clearly show that cutting and grinding induced microcracks markedly influence the early stage of fracture-surface modification and that one must give careful consideration to their influence when performing permeability experiments on "artificial" fracture surfaces (e.g., saw cuts) in a chemically reactive fluid environment.

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

The deformation of room-dry and water-saturated Westerly Granite is being investigated at confining pressures between 20 and 200 MPa and temperatures between 25 and 900°C, in order to evaluate (1) time-dependent effects of strength and strain to failure, (2)

frictional strength of bare-rock surfaces, and (3) effect of temperature on tensile strength, i.e., the possible thermal activation of the tensile fracture process.

With regard to our preliminary conclusions about borehole stability in crystalline rocks at low confining pressures but high temperatures, we note that (a) the creep-rupture strength of granite is only about 20 percent below the short-time triaxial strength so that for geotechnical applications and failure in compression the effect of time may be ignored; (b) results from twenty-four frictional sliding tests indicate that the frictional strength of smooth surfaces of granite is only about 50 percent of the intact strength; and (c) results from twenty-two triaxial extension tests show that the tensile strength of granite drops from about 10 MPa at 25°C to sensibly zero at 800°C. This suggests that fracture is in fact a thermally activated process and it emphasizes the necessity to keep borehole-pressures during drilling less than the least compressive principal stress in the rock mass to avoid hydraulic fracturing. The next steps in this study are to (1) study the textures and fabrics of tensile fracture surfaces and of precursive side cracking in Westerly Granite specimens to detect changes, if any, with increasing temperature (and decreasing strength), (2) extend our triaxial-extension testing to other rock types (e.g., basalt and pure quartzite) to further study tensile strength changes with temperature and the thermal activation of fracture, (3) extend our sliding friction work to these same rocks, and (4) look into the effects of water, surface roughness, and mineralization on the frictional properties of pre-existing fractures (joints). With regard to (3), we would expect the strength reduction observed for smooth rock surfaces to decrease, perhaps vanish, when rough and mineralized natural fracture surfaces are tested. If so, we may still find a pressure and temperature regime in which a jointed rock mass can be modeled solely as a continuum.

Contractor: UNIVERSITY OF TEXAS AT AUSTIN
DEPARTMENT OF GEOLOGICAL SCIENCES
Austin, Texas 78712

Contract: DE-AS05-83ER-13119

Title: Investigation of a Fossil Geothermal System, Hamblin-Cleopatra Volcano, Clark County, Nevada

Person in Charge: D. S. Barker

Scope of Work

In the Lake Mead area, Southern Nevada, a Miocene high-potassium andesite-quartz latite stratovolcano was segmented by strike-slip and normal faults. Erosion and faulting have exposed the entire volcanic succession, the intrusive core, a radial dike system, and sedimentary and volcanic rocks predating and postdating the stratovolcano. Mapping at a scale of 1:12,000, completed before this contract began, permits estimates of the proportions of igneous material that formed intrusive bodies, lava flows, and reworked debris during growth of the cone. Such data are essential in constructing better models of subvolcanic geothermal systems.

Mineralogical and chemical changes were imposed on the volcanic and intrusive rocks by convecting groundwater. The exhumed core of hydrothermally altered rocks represents a fossil geothermal system. Alteration increases toward the focus of the radial dike system, and most rock units can be sampled in fresh as well as in variously altered states; thus the compositional changes induced by alteration can be distinguished from those produced by magmatic processes. Field observations of fracture aperture and spacing, and laboratory measurements of porosity, are being used to quantify the hydrologic characteristics of the rock units. Mineralogical and trace element changes, and variations in isotopic ratios of oxygen, hydrogen, and carbon, will be related to permeability and porosity, as well as to sample locations, permitting reconstruction of flow patterns and temperature gradients in this geothermal system.

The first stage of this contract has been to investigate the magmatic processes that accompanied and powered the hydrothermal convection. Major-element and trace-element (Rb, Sr, Y, Zr, Nb, Ni) analyses have been completed on 24 whole-rock samples from stratigraphically well-located lava flows, to document changes in magma composition through time. More than 800 electron probe analyses have been made on phenocryst phases. Bimodalities in compositions of orthopyroxene, clinopyroxene, plagioclase, magnetite, and ilmenite, as well as reverse zoning in plagioclase and cyclicity in trace element concentrations, indicate magma mixing during repeated replenishment of the shallow magma chamber that fed the Hamblin-Cleopatra Volcano. The most highly fractionated liquid (quartz latite) was erupted early in the history of the volcano, and was followed by an oscillatory trend toward more mafic liquids (andesites).

Contractor:	UNIVERSITY OF TULSA Tulsa, Oklahoma 74104
Contract:	DE-F605-84EF13220
Title:	Stability of Natural Gas in the Deep Subsurface
Persons in Charge:	C. Barker and N. Takach

Scope of Work

We have continued to investigate the stability of natural gas in the deep subsurface 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 70), multiphase (up to 30) systems for conditions corresponding to temperatures and pressures down to 40,000 ft (12 km). Equilibrium compositions have been computed for low, average, and high geothermal gradients; hydrostatic and lithostatic pressures; and with or without graphite. Graphite is present when deep gases are generated by cracking oil but is absent if reservoirs were originally filled with methane alone. Calculations have been made for sandstone reservoirs with various amounts and combinations of feldspars, clays, carbonate cements and iron oxides, with and without graphite; and for limestone and dolomite reservoirs with various combination of clays, iron minerals, anhydrite, and sulfur, again with or without graphite. Natural gas shows considerable stability in sandstone reservoirs under most conditions, but its concentration in deep carbonates is much more variable and tends to a hydrogen sulfide-carbon dioxide (H_2S-CO_2) mixture, except when an appreciable concentration of iron is present. Hydrogen is present at the one to two percent level for most lithologies. Preliminary calculations have been made for igneous reserviors.

The thermodynamic predictions can (in principle) be checked by direct analysis down to the depth limit of available samples. To avoid the severe problems of contamination and gas loss during sample retrieval, the gas trapped in fluid inclusions in late stage cements is being used. The fluid inclusions are opened by heating in a vacuum system that forms the inlet to a computer-controlled, gas scanning mass spectrometer. In the past year the analytical system was moved to a new building and rebuilt with an improved configuration. A signal conditioner has been added to the computer hardware so that the mass spectrometer response for minor components can be preferentially amplified. In addition, improved software plus additional memory now allows evolution of several individual gases (H_2O, CH_4, H_2S, etc.) to be monitored continuously while at the same time analyzing gases from bursting individual fluid inclusions. Up to 400 inclusions can be analyzed in a single run with a typical sample size of 10 mg. Inclusions have been analyzed in both silica and carbonate cements and show a variety of compositions depending on environment. Often different generations of inclusions in the same sample will show quite different compositions. While shallow samples often show a range of

hydrocarbon samples from below 20,000 feet have only methane. This may range from a major component to traces in inclusions with significant hydrogen sulfide. The gas compositions are being compared with those calculated using the thermodynamic program.

Contractor: UNIVERSITY OF WISCONSIN
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
Madison, Wisconsin 53706

Contract: DE-FG02-84ER13184

Title: Thermal Stress Microfracturing of Granite

Person in Charge: H. F. Wang

Scope of Work

The mechanical and hydrologic response of rock masses to heat is an important basic research area especially relevant to predicting the long-term behavior of a geologic repository for radioactive waste. Such research also has applicability to natural heat sources such as the effect of a magmatic intrusion on the hydrothermal system in country rock, or to the production of geothermal energy.

High temperatures dramatically reduce the elastic moduli of granites, even under high confining pressures. This effect is attributed to microcracks created by internal thermal stresses. A spherical inclusion model has been used to predict whether a given change in temperature or pressure will introduce a tensional crack between a mineral constituent and the rock matrix. We are able to predict crack densities, and hence elastic moduli as a model rock is subjected to changes of P and T. The results are critically dependent upon the P,T path to which the rock is subjected. Comparisons are made for the case in which the rocks are heated only at maximum pressure, then compressed isothermally. The comparisons are quite close for three granitic rocks, but underestimate the crack densities of quartz-free gabbro and basalt.

A detailed description of thermally-produced crack porosity is important to improvement of the crack model. High resolution crack porosity data will be obtained for several granites which have been heated to high temperatures at high confining pressures. The crack characterization will be by differential strain analysis and by direct observation with the optical microscope and the scanning electron microscope. Given the crack porosity data, it should be possible to refine a differential thermal expansion model to reflect the observed distributions and types of cracks within different minerals.

This project is joint with Lawrence Livermore National Laboratory. The microcrack data and modeling described above will be related to physical property measurements made there. These data will include elastic wave velocities, electrical conductivity, and permeability as functions of pressure and temperature. Consideration will be made of different pressure, temperature paths.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, MA 02543

Contract: EG-77-0204392

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

Persons in Charge: J. M. Hunt and J. K. Whelan

Scope of Work

The objective of this program is to develop a better understanding of the processes of hydrocarbon generation and migration in coastal and offshore sedimentary basins as an aid in predicting favorable exploration areas for petroleum. Our research is concentrating on the light hydrocarbons in the C_1 through C_{15} range since these hydrocarbons are not formed by living processes except for methane and possibly some ethane. Also, these are the hydrocarbons that migrate most easily by diffusion, solution in pore waters or in the oil and gas phases.

The stratigraphic intervals generating the C_1- C_{15} hydrocarbons have been identified in shale sections of four wells in the Gulf of Mexico and four wells on the North Slope of Alaska. Migration of these hydrocarbons has been followed through sediments of varying lithologies and organic richness. Methane and ethane were found to migrate over far greater vertical distances from their source beds than the C_{3+} hydrocarbons over tens of meters in 80 million years in fine-grained sediments. Lateral and vertical migration does appear to occur within the oil generation interval (~100°C) with the smaller molecules migrating first.

An ion trap detector is being added to the pyrolysis apparatus in order to monitor evolution of various gases during the pyrolysis process. It is hoped that specific gases will give clues as to both the type and maturation state of the kerogens. The headspace analysis for light hydrocarbons has been modified by changing to a 100 m fused silica glass capillary column. It has been found that 10% PhMe silicone gives as good separation as the standard HHK column in the C_5-C_8 range. The advantages of the fused silica column over HHK are due to its much higher temperature capability (350°C as compared to 50°C for HHK). This will enable the detailed hydrocarbon analyses to extend to a higher range.

We are also analyzing gases of Deep Sea Drilling Project sediments from the Gulf of Mexico in order to learn more about the initial stages of light hydrocarbon migration in sediments.

Future work on this project will concentrate on mechanisms, directions, and distances of oil and gas migration, the depth and extent of gas generation and the potential hydrocarbon resources of the outer continental slopes and rises.

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

The general aim of this work is to develop computer-aided imaging techniques for visualizing the subsurface geology. Work is currently centered on the investigation of computed reflection tomography for application to underground imaging. The imaging technique is based on a line-integral measurement model for incoherent acoustic backscattering from elliptical integration paths through a two-dimensional underground cross section. Computer simulation results have been produced illustrating the image quality obtainable for the case of a linear surface array of sources and receivers. Test results include images of layered structures, lines, and point reflectors obtained by an iterative reconstruction technique applied to simulated data.

The method is aimed at near surface imaging situations in which high resolution is required for the detection of buried objects, fractures or other signficant scattering features.

Computer software has been designed, implemented, and tested for the forward (data generation) problem and the inverse (reconstruction) problem in computed reflection tomography using a linear array. The initial results indicate that good depth and lateral resolution is obtainable for depths up to one half of the total array (aperture) width. Below this depth, the lateral resolution deteriorates rapidly so that only a horizontally layered representation can be obtained.

The reflection tomography model, as implemented for the general case, does not assume any particular center frequency for pulse-echo probing, and can therefore be scaled to fit particular array lengths and compatible frequencies. The basic data collection and reconstruction model is strictly valid only under simple assumptions for the backscattering process. These assumptions are: (1) the velocity of sound in the medium is essentially constant, so that errors in round-trip delay time and the departure of the wavefronts from circular arcs are small compared to the desired image resolution; (2) attenuation due to adsorption in the medium is either known or is negligible; (3) attenuation due to scattering is neglected, and there are no second-order scattering effects; and (4) the scattering is assumed to be isotopic.

Continued work on this problem is aimed at investigating the effects of noise and quantifying the relationship between array parameters and resolution as a function of position in the image plane.

Contractor: YALE UNIVERSITY
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
P. O. Box 6666
New Haven, Connecticut 06511

Contract: DE-AS02-76ER10455

Title: Opening Mode Crack Growth in Rock

Person in Charge: Robert B. Gordon

Scope of Work

The objective of this research is to develop an understanding of the fracture strength of brittle rock that can be used in the solution of engineering design problems and in the field. The specific energies for crack initiation and propagation in nine different types of rock have been measured in the laboratory. The experiments show that, because of the non-linear elasticity of rock, the measured fracture energy depends on the way in which the test specimen is loaded. Hence, a standardized test procedure is needed to obtain data that show the differences in fracture energies that are due to differences in structure and composition of rock. The fracture toughness is found to depend primarily on the preexisting microcrack network in the crystalline rocks and is less influenced by mineralogical makeup and texture. Rock which is relatively free of microcracks (such as quartzite), or in which cracked or porous material is organized in nearly continuous sheets (such as limestone), or which has a very high concentration of microcracks (such as marble), tends to have a low fracture energy. High fracture energy is found when rock contains a microcrack network that permits development of multiple, partially completed, fracture paths.

The micromechanical processes that control the fracture energy and the structure of the fracture surfaces in rock are being studies by direct observation of crack growth under the microscope. Highly polished specimens are used in a small but stiff loading frame that permits stable crack growth. Successive loading-unloading curves are recorded and used to compute the energy consumed in each observed increment of crack extension. The size and structure of the process zone formed by the advancing crack is found to be sensitive to the microstructure of the rock. The results are being used to interpret the dependence of fracture energy on crack length and rock structure which was observed in the tests on large specimens.

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

Institution (PI)	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982	FY 1983	FY 1984
U/Alaska (Akasofu)	$ 41	$ 92	$ 79	–	$ 85	$ 84	$ 108	$ 113	$ 117	$ 120
U/Alaska (Pulpan)	79	32	42	59	113	87	70T	–	–	–
U/Alaska (Kienie)	90T	–	–	–	–	–	–	–	–	–
U/Arizona (Hill)	–	–	–	–	–	91	96	99	101	90
U/Arizona (Norton)	–	–	–	–	–	–	66	60	48T	–
Arizona State (Navrotsky)	–	–	–	–	–	35	62	66	123	–
Aspen Institute (Roberts)	–	–	–	48	57	71T	–	–	–	–
Brown U (Hermance)	–	–	–	–	95	140	164	165	333	–
Cal Tech (Ahrens)	–	–	–	–	–	–	–	–	72	81
U/California-B (Reynolds)	63	130	127	148	127	168	144	150	165	196
U/California-B (Helgeson)	–	–	–	–	–	–	–	–	204	–
U/California-D (MacGregor)	–	–	–	71	61	23	–	–	–	–
U/California-LA (Warren)	45	55	41	50	103	107	121	NFXT	–	–
U/California-LA (Boehler)	–	–	–	–	–	–	46	NFX	60	66
U/California-LA (Anderson	–	–	–	–	–	–	–	–	–	60
U/California-LA (Kennedy)	60	60	60	60	72	72T	–	–	–	–
U/California-SD (Craig)	–	–	–	–	–	–	–	–	–	35
U/Chicago (Anderson)	–	–	–	–	–	54	NFX	38	98	NFX
Columbia U (Fairbridge)	75T	–	–	–	–	–	–	–	–	–
Columbia U (Jacob)	180	200	240	256	274	312	318	318	33F	359
Columbia U (Engelder)	–	65	62	75	100	140	150	156	289	–
Columbia U (Walker)	–	–	–	–	–	–	–	–	–	73
Ft. Lewis College (Ellington)	–	2	–	–	–	–	–	–	–	–
Harvard U (Thompson)	–	–	–	–	–	–	–	–	372	–
U/Hawaii (Manghnani)	–	–	–	–	–	–	–	88	96	99
Headquarters Services	–	–	–	–	–	–	–	6	1	3
Indianapolis Ctr. for Adv. Research (Dines)	–	–	–	–	–	80	64T	–	–	–
U/Minnesota (Johnson)	–	–	–	–	–	–	68	57	NFXT	–
MIT (Aki)	35	100	130	113	142	152	160	151	158	147
MIT (Simmons)	–	–	–	100	100	90	100	106	106	110
NAS/NRC (U.S. National Comm. Geochemistry)	–	–	–	–	–	–	19	22T	–	–
NAS/NRC (Studies in Geophysics)	4	4	4	–	6	27	29	58	–	30
NAS/NRC (Comm. on Seismology)	–	9	9	9	9	9	10	16	–	10
NAS/NRC (Geol/Materials Sci. Study)	–	–	–	–	14	–	10T	–	–	–
NAS/NRC (Geol. Sci. Board)	–	–	–	–	–	–	–	13	–	10
NAS/NRC (Geodynamics Comm.)	–	–	–	–	15	20	30	80	–	50
NAS/NRC (Cont. Sci. Drilling Comm.)	–	–	–	–	–	60	70	93	–	80
NAS/NRC (Geophys. Film Comm.)	–	–	–	–	–	–	–	–	–	20
Naval Weapons Support Center (Tanner)	–	6	–	–	–	–	–	–	–	–
U/Nevada-R (Ryall)	–	–	–	–	–	–	–	75	87	95
CUNY-Q (Schreiber)	–	–	–	–	–	–	83	81	49	–
SUNY-A (Dewey)	–	–	–	–	–	–	86	–	NFXT	–
SUNY-A (Harrison)	–	–	–	–	–	–	–	39	136	–
SUNY-SB (Papike)	–	–	–	–	51	59	65T	–	–	–
SUNY-SB (Hanson)	–	–	–	–	–	–	–	–	112	118
NOAA (Donnelly)	–	–	–	5T	–	–	–	–	–	–
U/Oregon (Weill)	–	–	–	–	–	–	–	–	103	95
Oregon State (Fehler)	–	–	–	–	–	–	–	38T	–	–
Pennsylvania State U (Martin)	–	–	–	–	–	62	83	NFXT	–	–
Pennsylvania State U (Given)	–	–	–	–	–	–	–	–	–	100T
Princeton U (Hollister)	–	23T	–	–	–	–	–	–	–	–
Rice U (Baker)	–	–	–	–	–	16	–	T	–	–
Rice U (Ave-Lallemant)	–	–	–	–	–	–	–	–	120	121
RPI (Friedman)	–	–	–	–	–	–	91	99	150	–
SMU (Blackwell)	–	–	–	–	–	–	54	70T	–	–
S. Dakota Sch. M & T (Papike)	–	–	–	–	–	–	–	67	100	130
U/S. Florida (Sackett)	–	–	–	–	–	–	34T	–	–	–
Stanford U (Liou)	–	–	–	–	–	–	–	34	45	NFXT
Stanford U (Nur)	–	60	65	104	147	140	140	125	160	172
Stanford U (Parks)	–	–	–	–	–	–	–	57	56	56T
U/Texas-A (Barker)	–	–	–	–	–	–	–	–	54T	–
Texas A&M (Friedman)	–	–	–	–	63	208	202	200	201	93
Texas A&M (Carter)	–	–	–	–	–	–	–	–	–	70T
U/Tulsa (Barker)	–	–	–	–	60	NFX	75	71	75	80
USGS (Haas)	–	–	9	54	54T	–	–	–	–	–
U/Wisconsin (Wang)	–	–	–	–	–	57	38	–	–	48
Woods Hole (Hunt)	–	–	31	–	102	141	139	150	190	208
Woodward-Clyde, Pasadena (Burdick)	–	–	–	–	–	–	–	100	100	100
XDATA (Dines)	–	–	–	–	–	–	–	54	66T	–
Yale U (Gordon)	–	–	–	–	45	4	35	26	39	184
Off-Site Totals	$672	$838	$899	$1,152	$1,895	$2,509	$3,030	$3,141	$4,523	$3,309

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

ON-SITE	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982	FY 1983	FY 1984
ANL	$ 98	$ 60	$ 50	$ 100	$ 140	$ 240	$ 310	$ 330	$ 330	$ 360
LANL	630	906	750	810	1,084	1,420	1,500	1,375	1,684	2,343
LBL	315	816	620	660	735	995	1,075	1,180	1,405	1,485
LLNL	75	135	130	250	630	910	1,060	1,110	1,280	1,815
ORNL	50	140	150	180	240	280	380	430	430	470
PNL	175	265	250	280	450	565	580	520	520	578
SNL/A	245	500	450	500	800	1,165	1,310	1,546	1,682	2,087
On-Site Totals	$1,588	$2,822	$2,400	$2,780	$4,079	$5,575	$ 6,215	$ 6,491	$ 7,331	$ 9,138
Total Off-Site	$ 672	$ 838	$ 899	$1,152	$1,895	$2,509	$ 3,030	$ 3,141	$ 4,523	$ 3,309
TOTAL OPERATING	$2,260	$3,660	$3,299	$3,932	$5,974	$8,084	$ 9,245	$ 9,632	$11,854	$12,447
TOTAL EQUIPMENT	—	—	—	—	$ 355	$ 560	$ 923	$ 900	$ 890	$ 960
TOTAL GEOSCIENCES	$2,260	$3,660	$3,299	$3,932	$6,329	$8,644	$10,168	$10,532	$12,744	$13,407

SUBJECT INDEX

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