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Summaries of Physical Research in the Geosciences

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Washington, DC 20545

DISCLAIMER

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FOREWORD

The Department of Energy supports research in the geosciences in order to provide a sound foundation of fundamental knowledge in those areas of earth, atmospheric, and solar-terrestrial sciences that are germane to the Department of Energy's many missions. The Division of Engineering, Mathematical and 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 the major Department of Energy laboratories, industry, universities, and other governmental agencies. Such support, formalized by a contract between the Department of Energy and the organization performing the work, provides 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 1982-1983. The Geosciences Research Program includes research in geology, petrology, geophysics, geochemistry, hydrology, solar-terrestrial relationships, aeronomy, seismology, and natural resource analysis, including the various subdivisions and interdisciplinary areas. All such research is related either directly or indirectly to the Department of Energy's technological needs.

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

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

The Geosciences Research Program is divided into five broad categories:

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

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

1. Geology, Geophysics, and Earth Dynamics

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

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

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

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

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

2. Geochemistry

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

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

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

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

3. Energy Resource Recognition, Evaluation, and Development

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

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

C. Magma Energy Resources. Field, laboratory, experimental, and 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.

4. Hydrologic and Marine Sciences

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

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

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

5. Solar-Terrestrial-Atmospheric Interactions

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

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

C. Solar Radiation. Research on the solar constant, spectral distribution, and characteristics of solar radiation 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

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

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

This program has as its objective accurate determinations of thermodynamic quantities of zeolites and related minerals. Calorimetric measurement techniques available for these studies include the following: enthalpy of combustion and reaction, low-temperature heat capacity, drop calorimetry, and differential scanning calorimetry. The temperature range of interest is from $T \to 0$ to the upper temperature limit of stability, typically about 500 K. The selection of substances to be studied is determined not only by their actual or potential technological importance but also by attempts to relate the thermodynamic results to aspects of structure and bonding in aluminosilicates.

In this connection, our recent results for the entropies of analcime (Si/Al=2), natrolite, mesolite, and scolecite (Si/Al=1.5) suggest that in some of the zeolites the structure of the zeolitic water is "ice-like," while in others it is somewhat closer to that of "liquid-water." Results of X-ray diffraction studies have been used to deduce the configurational entropy of our specimen of natrolite. Comparison of experimental equilibrium measurements with our thermodynamic calculations suggests that $\Delta_f H^\circ$ (albite) may be in error.

Our current studies are concerned with heulandite and mordenite and future work will deal with chabazite, clinoptilolite, and erionite. Because of doubts about the validity of currently accepted thermodynamic quantities for albite, we will determine the complete thermodynamic properties of a highly ordered specimen as functions of temperature.

B. Trace-Element Transport in Geologic Strata (M. G. Seitz)

Migration of elements in geologic bodies is important in many situations. For example, migration has produced ores of benefit to man. Understanding ore-forming processes can improve our exploration capabilities for valuable mineral resources. Because element migration can disrupt inadequate schemes of waste disposal, the understanding of migration obtained in this program can aid in developing technically sound plans for the safe disposal of nuclear and chemical wastes.

In this study, the transport of elements by aqueous flow through geologic media is being examined principally by hydrothermal infiltration experiments in which groundwaters are pumped through rock cores to cause the movement of trace elements. The experiments are done at elevated pressures and at temperatures from 20 to 325°C to investigate migration processes typical of those in the upper crust of the earth.

The infiltration experiments are used because they yield valuable information concerning reaction kinetics, reaction reversibility, and the behavior of different chemical species in rock formations. Migration is observed directly; thus, the uncertainty in extrapolating data on a wide variety of chemical reactions to predict element movement in geologic settings is avoided. The results of specific experiments are generalized to many geologic situations by our efforts to establish continuity between experimental observations and theoretical predictions from transport models.

Using methods similar to those employed in the infiltration experiments, we are extracting pore fluids from rock cores mined from various depths in the earth and analyzing the fluids to obtain profiles of groundwater composition vs. depth in cored rock structures. This infiltration-sampling method has been demonstrated to be an effective tool for analyzing water in nearly impermeable rock, with the chemical profiles complementing data from water pumped directly from the holes. Dense, nearly impermeable rock is attractive for use in the disposal of nuclear waste.

Being investigated are the characteristics of metasomatism caused by groundwater infiltration and the effects of fulvic and humic acids on the mobilization and concentration of heavy metals in natural geologic settings.

C. Migration of Heavy Element Chemical Species in Geologic Media (S. M. Fried, A. M. Friedman, and F. Schreiner)

Our purpose in this program is to understand what the chemistry of the heavy elements is under geological conditions and how this chemistry affects the mobility of actinide species in geologic strata. The important chemical properties under investigation include oxidation-reduction, the nature and stability of complexes formed, solubility of compounds in groundwaters, self-diffusion in rock strata, and hydrolysis reactions. We are using spectrophotometric techniques to determine the distribution of oxidation states and calorimetric methods to determine equilibrium constants for hydrolysis and equilibrium reactions. Since the migration of the actinide elements from a geological repository will have an obvious dependence on their geochemistry, the results of these studies may be expected to be relevant to the evaluation of the safety of a radwaste repository.

Because basalt is a prime candidate for the emplacement of radwaste in a mined repository, we have continued our study of the interaction of basalt with hexavalent neptunium. We have found that basalt and its accompanying olivine are separately capable of reducing hexavalent neptunium to neptunium (V) and neptunium (IV). Most of the neptunium (IV) was found to deposit on the surface of the containers or the basalt; surprisingly the neptunium (V) formed by this reaction was also deposited on the surface of the mineral. It is hypothesized that the immobilization of a substantial amount of the neptunium (V) is the result of the formation of insoluble neptunyl (V) salts with some of the cationic components of the basalt and olivine (such as Al and Mg). We plan to study the properties of salts of this type, as well as developing methods to identify the particular compound on the rock surfaces.

In order to monitor the progress of chemical reactions of Np and Pu in dilute solutions, a commercial titration microcalorimeter has been modified so that heats of reaction of the order of 4 kilojoules per mole on amounts of the order of 10 micromoles of reactant may be measured. With this improved capability, complexing and hydrolysis reaction constants will be determined.

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. Fundamental studies include the thermodynamic properties of silicate liquids and high-temperature brines, interactions between water and rock at elevated temperature and pressure, and the transport of fluid, heat, and chemically reactive solutes in groundwater systems. Geophysical activities encompass electromagnetic soundings of the crust, development and operation of a center for computational seismology, and an investigation of the effects of fracture characteristics on acoustic wave propagation in drill holes. The program is rounded out by hydrogeochemical studies in conjunction with the continental scientific drilling project and collection and evaluation of thermochemical data for use in assessment of the geologic disposal of nuclear wastes.

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

This project encompasses a wide range of fundamental studies in the fluid, heat and solute transport in underground formations. These studies have relevance to underground and other energy-related projects. The goal is to obtain a better understanding of various physical or chemical processes in porous or fractured media and their effects through analytic and numerical modeling.

More specifically, the following general topics are addressed:

1. Advanced well testing methods for fractured-porous media by means of coupled thermal, tracer and pressure measurements.

2. Development of a three-dimensional heat, fluid and solute transport code, based on the Integrated-Finite-Difference (IFD) technique. Generic studies of nonisothermal solute transport in idealized fracture or porous systems are made.

3. Continuation of the validation and applications of the LBL coupled thermo-hydromechanical model for fractured-porous media.

4. Development of a new integral form of the diffusion-type equation. This should make possible a reduction of mesh elements and the handling of moving boundary problems.

5. A fundamental study of the basis of the storage coefficient concept.

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

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

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

The theoretical work has yielded equations predicting the properties of mixtures based on the knowledge of the pure component solutions in water. In a number of cases, the calculated results for mixed brines are well verified by direct measurement. Phase equilibria can be predicted. Recent calculations have included a revised, general equation for all of the thermodynamic properties of aqueous NaCl to 300°C and 1 kbar as well as solubility calculations of Na_2SO_4 and several alkali halides in a variety of mixed electrolytes usually to about 250°C. 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^+, K^+, Mg^{++}, Ca^{++}, and Cl^-, $SO_4^=$, $HCO_3^=$, OH^-.

Other theoretical work concerns the properties of NaCl in high-pressure steam at temperatures to 800°C.

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

The objective of this project is to understand factors controlling albite solubility in aqueous solutions between 400°C and 0.1 to 50 MPa. The results are used in refining rock-water interaction models and data bases in order to model water-saturated rocks. The thermodynamic behavior of albite solubility measurements along the two-phase water saturation curve show that serious errors exist in the high temperature dissociation constants for the aqueous aluminum species, that current electrolyte models do not adequately account for ionic strength variations, and that the measurement of pH in quenched aqueous samples is subject to unpredictable error. Results are being evaluated to pinpoint the reasons for present difficulties.

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

The objective of this research program is to better understand the properties of silicate liquids and their metastable quench products, silicate glasses. Ultimately these data will be used to interpret the generation and subsequent thermal history of natural silicate liquids.

The ultrasonic velocity and attenuation of a variety of silicate liquids has been measured to obtain their adiabatic compressibilities. In many liquids of low viscosity, the ultrasonic velocity is independent of frequency in the 3-12 MHz range and the velocity only increases slightly with temperature. For liquids of higher viscosity, the ultrasonic velocity is frequency-dependent, particularly at low temperatures, and the ultrasonic period may be shorter than the liquid relaxation time.

Using high-temperature drop calorimetry, the heat of fusion of $NaAlSiO_4$ has been measured, and in combination with measurements in other silicate liquids including those containing substantial amounts of both FeO and Fe_2O_3, values of partial molar oxide Cp's have been calculated. Fifty-three sets of data have been used in the regression with an average error of 3.5% which is almost twice the error of measurement. This is much larger than analogous oxide heat capacities in the corresponding low-temperature glasses where the error in the regression of 35 compositions is only 1.0%, barely more than the individual measurement error.

As silicate liquids cool, they transform to glasses. It is not yet possible to predict this transformation temperature for multicomponent liquids, but we have noted that if Fe_2O_3 is substituted for Al_2O_3 or Na for K, then the transition temperature is reduced.

A wide variety of natural silicate liquids was equilibrated in air above their liquidus temperatures (1200-1450°C), then quenched to glass, and analyzed for ferric and ferrous iron and for their other components. Data for 46 experiments were added to those obtained in previous years at much lower oxygen fugacities to give a regression equation relating the ferric-ferrous ratio in silicate liquids to temperature, oxygen fugacity, and composition.

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

The movement of chemically reactive solutes in natural groundwater systems under the influence of gradients of composition, temperature, and pressure is being investigated theoretically and numerically. The principal focus of this research is a full accounting of the irreversibility of such systems through application of the thermodynamics of irreversible processes. This approach allows consideration of thermodynamically coupled processes such as thermal diffusion (Soret effect), thermal osmosis, chemical osmosis, and coupled diffusion which cannot be treated by the traditional methods of equilibrium thermodynamics. Conservation equations and linear phenomenological equations have been formulated for the motion of a solution of electrolytes in a porous or fractured medium. The resulting time-dependent transport equations must be solved numerically because of the nonlinear relationship between chemical potentials and mass concentrations of solution components.

The current emphasis is on the behavior of thermodynamically open systems which have evolved to, or near, a nonequilibrium steady state. This state is characterized by a quantifiable, minimum rate of entropy production which is analogous to the minimum total Gibbs free energy of an isolated system in a state of equilibrium. The assumption of the steady state allows formulation of linear transport equations for many reacting systems; these equations are susceptible to solution analytically and are providing results of considerable interest.

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

This project publishes critically evaluated thermochemical data for use in the disposal of nuclear wastes in subsurface repositories; and, thermophysical data for modeling heat transport by aqueous solutions. Tables of recommended values are generated from correlating equations using computerized methods. The data used by this database are obtained mainly from published experimental values. Major emphasis now is on nuclear waste disposal.

Thermochemical properties for nuclear waste disposal include stability constants, solubilities, adsorption equilibria and Nernstian potentials to high temperatures, These data are for use in predicting the solubility and speciation of waste metals in salt, basalt and tuff repositories. 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, solubilities and thermophysical properties to high temperatures; as well as computerized storage and retrieval of tables of data using desktop computers.

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

Variations in electrical conductivity within the crust are related mainly to the degree of connected porosity, saturation and salinity of pore fluids, as well as past or present thermal effects; e.g., temperature and hydrothermal alteration. Interpreted with thermal and seismic data, electromagnetic soundings might provide important information on thermal anomalies within the crust; including the existence of shallow magma bodies. The magnetotelluric (MT) method is the most common electromagnetic deep sounding method, but MT data from complex geological areas are often difficult to interpret accurately because distant inhomogeneities distort the electric fields at the point of measurement. To overcome this problem LBL developed a powerful controlled-source electromagnetic device for deep exploration. Because a dipole field is generated, depth of exploration is more limited than for MT, in which the excitation is provided by natural, ultra-low frequency plane waves. However, as the primary field strength of the dipole source decays according to an inverse cube of distance, the technique is less susceptible to distortions by inhomogeneities outside the region between the transmitter and receiver points.

Used together, MT and controlled-source EM methods provide a complementary data set. The LBL system is unique in that it has been designed for both types of soundings. Noise cancellation is achieved through use of a remote reference magnetometer, and in-field processing provides immediate reduction and display of data.

A mid-crustal conductor was detected and traced over a region of central Nevada between Winnemucca and Dixie Valley. This conductor is believed due to extension and heating of the crust beneath the Basin and Range province. In the Long Valley caldera, California, closely spaced stations in the south moat area delineated a shallow conductive feature that rises to within 2.5 km of the surface. The Long Valley caldera soundings were completed only days before the seismic swarm activity that began in mid-December 1982 and peaked in early January. Because there is a close spatial correlation between the conductivity anomaly and the earthquake hypocenters, the conductivity anomaly may be related to the magma injection that has been proposed to explain the seismicity. To test whether the conductivity anomaly is caused by a transient thermal pulse, we will carefully repeat selected soundings and perform numerical studies to relate conductivity changes to temperature changes caused by a simulated magmatic pulse.

H. 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 are being conducted in which digitized sonic log waveforms are obtained across single, horizontal, isolated fractures intersecting a borehole in a crystalline rock mass. The fluid flow characteristics of these isolated fractures are measured using conventional borehole packer techniques, and the results compared. The field tests 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. In this way it is anticipated that correlations will be established between such acoustic wave parameters as velocity and attenuation, and the permeability of the rock mass adjacent to the borehole.

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

CCS was established to aid the computational seismologist in such matters as program development, data processing and display (graphics), and data management. CCS operates within a large computational facility (LBL computer center) and utilizes their resources as well as the expertise within the computer science and mathematics group of the physics division. These groups provide CCS with a valuable resource in hardware and software support. A goal of CCS is to make a wide variety of seismological and basic computational software available to the seismological community to maximize research dollars and time and avoid unnecessary duplication.

Consistent with these aims, CCS has acquired and implemented a state-of-the-art seismic reflection package for studies in seismic imagery. To date this package has been used to process and analyze data from geothermal environments (The Geysers, California; Cerro Prieto, Mexico; Grass Valley, Nevada) and for waste isolation studies (Hanford, Washington).

Other areas of study have included:
1. Structure of the San Andreas fault zone,
2. Mammoth Lakes, California seismic activity,
3. Source mechanism study of the Geysers earthquakes,
4. Synthetic seismographs in layered lossy media,
5. Differential tidal gravimetry (microgravimetry) for time-stress changes,
6. Near-field studies for source discrimination, and
7. Deep earth structure from τ - p inversion.

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

The main focus of this program is to evaluate the active hydrothermal system beneath the Valles caldera and lend support to the CSDP site evaluation process by generating a complete body of data to define the hydrothermal chemistry of the Baca reservoir. The data are used to determine to what extent, if any, geochemical components are introduced into the reservoir from a deeper magma/hydrothermal source. The use of existing deep holes drilled by industry in the Baca geothermal field, a known geothermal resource, has provided an efficient means of investigating the system's deep thermal fluids. A wellhead sampling program was completed in the fall of 1982. New fluid and gas samples have been collected from five deep Union Oil Company wells located in the Redondo Creek area. Standard and trace chemical analyses of waters and gases and isotopic analyses of water have been obtained. A comparison of these data from deep geothermal wells with analyses from surrounding hot springs and local groundwater may reveal if a signature of deeper hydrothermal fluids is present. In addition to sampling of fluids, drill cuttings from the same wells are being analyzed in order to assess the nature and extent of the water/rock interaction in the hydrothermal systems. This study is in collaboration with A. H. Truesdell (USGS) and John Reynolds (UC Berkeley) who will obtain major dissolved gas and isotopic concentrations and noble gas analyses, respectively, on the same samples.

K. Asteroid Impacts and Mass Extinctions (L. W. Alvarez, 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 boundary, the one most closely linked to a large body impact, in order to predict the behavior expected in older boundaries.

Currently, a new widely distributed iridium horizon and its relationship to impact debris (microtektites) and extinctions are being studied in deep sea sediments 34 m.y. old near the Eocene-Oligocene boundary. Sediments from the Cretaceous-Tertiary (C-T) boundary (65 m.y. old), the Permian-Triassic boundary ($\sim$225 m.y. old), the Frasnian-Famennian boundary ($\sim$350 m.y. old) and the early Cambrian period ($\sim$550 m.y. old) are also being studied.

The correlation between the time of the C-T impact and floral and faunal extinctions which occurred on the continents is being examined in the Western United States and Southwestern Canada.

New techniques for sensitive, rapid and economical measurement of iridium in lithified sediments are being studied to determine the feasibility of a system capable of handling one kilometer of sediment in a few months of measurement time.

L. Fluid Flow in Stressed Rock (P. A. Witherspoon and Y. Tsang)

The objective of this project is to investigate how roughness in a fracture effects fluid flow and to develop the basic understanding of the deformation of the fracture under stress. This work is based on a theoretical model relating mechanical measurements on the rock to fracture geometry at different stress levels. Application of this model permits establishment of a valid fluid flow for a rough fracture over a wide range of stresses. Fluid flow in weathered, filled fractures is also being considered, and a model is being developed to describe this phenomenon under stress changes.

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

This work reproduces the chemical reactions of petroleum genesis, under conditions which closely resemble those under which petroleum is formed in nature. Emphasis is on the identification of possible water-soluble petroleum precursors. Kerogen-bearing rocks are reacted in an autoclave with brine at high temperature (200-350°C) and pressure, and the organic compounds evolved are separated and identified. Oil and gas field waters are analyzed for organic trace compounds, and laboratory results correlated with field data. The decomposition of water-soluble C-H-O compounds produced in the autoclave experiment will be investigated over a wide range of conditions expected in typical petroleum source beds, except that experimental temperatures will be higher to allow convenient reaction rates.

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 five projects: (A) Thermal and Creep Behavior of Generic Repository Rocks, (B) Diffusion in Silicate Materials, (C) Electrical Conductivity and Temperature in Upper Mantle, (D) Attenuation and Dispersion in Partially Saturated Sedimentary Rocks, and (E) Surface Wave Method for Determining Earthquake Source Mechanisms.

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 and W. B. Durham)

This laboratory program involves two sub-tasks: 1) determination of the thermal behavior of igneous rocks, and 2) measurement of the creep response of salt.

1. An experiment is being undertaken to measure the thermal diffusivity of igneous rocks to 400°C and 200 MPa lithostatic pressure. For use primarily on rock samples the order of 2.5 cm in diameter, the measurement technique produces precise and accurate measurements in a relatively short time, allowing detailed study 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.

2. This sub-task involves the exploration of the causes responsible for the significant disagreement in the parametric values for the constants in the steady-state flow equation describing the rheological behavior of polycrystalline halite (salt) at moderate temperatures and pressures. The effects of pressure, impurity content, and loading history are being investigated at pressures to 200 MPa and temperatures to 300°C.

B. Diffusion in Silicate Materials (A. J. Piwinskii, F. J. Ryerson, H. C. Weed)

Because oxygen and silicon are major constituents of the earth's crust, the diffusion of oxygen, silicon, and highly-charged cations is being studied over the temperature range of 1000°-1400°C. Compositions vary from almost pure silica (obsidian) to basalt from Halemaumau lava lake, Hawaii. The results of the study should be useful for evaluating the relative magnitude of diffusional and convective transport in geologic systems, and for modeling the thermal evolution of magmas. The results are also applicable to the kinetics of geologically and technologically important processes such as phase separation, crystal nucleation, and crystal growth.

C. <u>Electrical Conductivity and Temperature in Upper Mantle</u> (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.

D. <u>Attenuation and Dispersion in Partially Saturated Rocks</u> (R. C. Y. Chin, J. G. Berryman, B. P. Bonner, and G. W. Hedstrom)

We will combine theory and experiment to analyze attenuation and dispersion of waves in rocks containing liquid over a broad range of frequencies. The experiments will be carried out on rocks over a broad frequency range using ultrasonics, creep measurements, resonant bars, and impulse propagation. An anelastic long-wave, Pochhammer-Chree theory will be developed. This theory will be used to interpret the experiments, which show both geometric and anelastic dispersive effects. This combined theoretical and experimental approach will yield attenuation and dispersion results at frequencies which are inaccessible to present-day experimental methods. Interpretation and analysis techniques derived from this study will be applicable to a broad range of basic problems in energy recovery, particularly hydrocarbon and geothermal exploration and resource assessment.

E. <u>Surface Wave Method for Determining Earthquake Mechanisms with Applications to Regional Stress Field Studies</u> (H. J. Patton and K. K. Nakanishi)

We will use a method base on surface-wave excitation and seismic moment-tensor theories in order to obtain source mechanisms of remote western United States earthquakes. This method is particularly useful for studying the regional tectonic stress field in areas where there is poor coverage by dense seismic networks, and consequently the P-wave fault-plan solution technique has limited applicability. In the first year of study, we will test our methodology under "controlled" conditions to demonstrate consistency with other stress indicators and magnitude of errors. We will then apply the method to study the state of stress in the northern Basin and Range and its environs. The stress field will be characterized by (1) orientation, using directions of the principal stress axes determined from the focal mechanisms, and (2) magnitude, using the estimate of seismic moment (and field observations, when available) to calculate stress drop or apparent stress. Future work will concern interpretations of the observed stress field in terms of intra-plate sources of stress.

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

Contract: W-7405-ENG-48

Title: Geochemistry

Person in Charge: L. W. Younker

Scope of Work

The Geochemistry Program at Lawrence Livermore National Laboratory consists of two projects: (A) Thermodynamic and Transport Properties of Geochemical Systems, and (B) High-Pressure Kerogen Pyrolysis. Studies include laboratory measurements of diffusion coefficients and activity coefficients for mixed salts, and kerogen pyrolysis experiments up to 1kbar. 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 waste isolation and geochemical problems (including diagenesis and ore formation). Mutual diffusion data are needed to understand and model these processes. Osmotic/activity coefficient data are required to understand chemical equilibrium in these solutions (including speciation and solubility). Little diffusion data have been published except for single salts at 25°C, and almost no data are available for salt mixtures or for aqueous systems above 25°C. The situation is somewhat better for activity data, but experimental measurements are required for a wider variety of mixtures. Experimental diffusion and activity measurements, and the development of accurate approximation methods for mixed salts, are essential to fill these large data gaps.

The present task is to measure diffusion coefficients using Rayleigh or Gouy interferometry, and osmotic/activity coefficients using the isopiestic method. Diffusion data are currently being measured for aqueous $MnCl_2$ (ferromanganese nodule formation) and NaCl-$SrCl_2$ mixtures (waste isolation) at 25°C. If time permits, diffusion data will also be measured for NaCl at 50°C and approximation methods tested for estimating mixed salt diffusion coefficients. Isopiestic measurements will be completed for $MnCl_2$ and $MnSO_4$ at 250°C, and measurements started for NaCl-$MgCl_2$ mixtures to their solubility limits.

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

The specific goal of this project is to develop a chemical kinetic model for the conversion of kerogen to petroleum along with the associated diagnostic methods necessary to confirm its applicability in a geological setting. To obtain the required data, a series of pyrolysis experiments will be conducted using pressures up to 1 kbar. Pyrolysis products will be analyzed as a function of time to allow characterization of the chemical processes occurring. Time-temperature-pressure histories will be varied sufficiently to provide an improved basis for extrapolation to geological conditions and to develop the diagnostic methods. A detailed chemical model will be derived, and we will explore ways of interfacing chemical and geological models. These models will be valuable as an aid in geochemical exploration and could lead to improvements in extraction techniques for synthetic fuels.

The experimental parameters to be used in assessing the role of alternative reactions in controlling hydrocarbon composition include: organic source material, temperature, pressure, residence time of compounds in reactor vessel, sweep fluids, and mineral species in contact with migrating hydrocarbon phases. This set of parameters is designed to allow consideration of changes in composition of hydrocarbons related to the timing of primary migration, and will provide a better basis for linking the chemical evolution of hydrocarbons to changes in the geological environment.

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

Contract: W-7405-ENG-48

Title: 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 four projects, (A) Data Management, (B) Underground Imaging, (C) Viscosity Measurements, and (D) Thermal and Petrologic Studies of Silicic Systems. 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, and studies of fossil analogue systems.

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 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 (A. G. Duba and R. J. Lytle)

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 assess 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 or temperature). 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. This coordinated program involves a cooperative effort by LLNL and university researchers to achieve a balanced perspective. This balance requires efforts in fundamental studies, instrument development, data processing, data integration and interpretation, and field demonstrations.

C. Viscosity and Electrical Conductivity of Rock Melts: Continental Scientific Drilling Program (A. J. Piwinskii, F. J. Ryerson, and H. C. Weed)

In order to understand the transport of mass and energy in geological processes, we are determining viscosities and electrical conductivities for molten silicate systems. These include basalt from Kilauea Iki lava lake, Hawaii, and compositions corresponding to targets selected for deep continental drilling. The results should help clarify relationships between melt composition and viscosity, to model the evolution of magmatic systems, and to establish a correlation between transport and other properties for molten silicates.

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

Integration of petrologic studies and the thermal studies will eventually lead to an overall improved understanding of shallow silicic systems, and provide the basis for the development of predictive models which can be tested by deep drilling at a young system.

Petrologic Studies: We have identified three field sites which can contribute to the basic understanding of the petrologic evolution of silicic systems.

- Acidic-Basic complex of Ardnamurchan in Scotland.
- Black Mountain caldera in Nevada.
- Elkhorn Mountains/Boulder batholith complex in Montana.

Petrologic studies of these three systems are presently underway. Synthesis of the results of these studies will shed light on characteristics of both large-volume and small-volume silicic systems. These systems have been selected because they add critical information to augment the existing petrological models.

Thermal Studies: We are working to improve the present generation thermal models of shallow magma systems. Contact metamorphic aureoles provide a record of heat transfer mechanisms within and around shallowly emplaced igneous intrusions. We have used information from several exposed systems to constrain heat transfer mechanisms. This information will be used in conjunction with other constraints to improve the thermal modeling capabilities.

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

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-alone microcomputer using a conventional commercial data base management system. Information will be distributed in printed form on a semi-annual basis.

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 four subtasks: (A) Creep deformation of Rock; (B) Radiative Heat Transfer in Minerals, Glasses and Melts; (C) Electrical Conductivity and Temperature in the Upper Mantle; and (D) Nonlinear Generation of Acoustic Beams.

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

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

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

(D) The interactions of two high-frequency-sound beams are measured in fine-grained, dense rocks to determine the nonlinear acoustic properties of rock. If narrow-beam, difference-frequency sound can be propagated, numerous applications to problems in exploration geophysics, in situ monitoring, and rock property investigations are possible.

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

A. Creep Deformation of Rocks (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 its effect 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.

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

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

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

C. Electrical Conductivity and Temperature in the Upper Mantle
[T. J. Shankland and A. G. Duba (Lawrence Livermore National Laboratory)]

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

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

D. 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 uses 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.

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

Contract: W-7405-ENG-36

Title: II. Geochemistry

Person in Charge: R. W. Charles

Scope of Work

Research in geochemistry consists of seven subtasks: (A) Rock-Water Interactions, (B) Element Migration and Fixation in Rocks, (C) Physiochemical Basis of the NA-K-Ca Geothermometer, (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, and (G) Geochemistry of Technetium and Ruthenium and Geochemical Controls on the Redistribution of Multivalent Elements in the Lithosphere.

(A) Rock-water Interactions deals with hydrothermal experiments and theoretical calculations which model reactions in rock reservoirs using static, agitated, and dynamic (circulatory) systems. Theoretical approaches involve detailed chemographic relations and mass transport theory.

(B) Element Migration and Fixation in Rocks studies the location, mobilization, and deposition of trace elements in various rock reservoirs.

(C) The Physiochemical Basis of the Na-K-Ca Geothermometer seeks to define the phase equilibria underlying the Na, K, and Ca composition in solutions and will attempt to widen the geothermometer's usefulness.

(D) Cation Site Size and Coulomb Energy Calculations will contribute to the understanding of inter- and intracrystalline major and trace element fractionation trends and help define the effects of some accessory phases on whole-rock trace element distributions.

(E) Coal Maturation: Occurrence, Form, and Distribution of Sulfur and Mineral Matter in Peat will determine the botanical and depositional environment controlling the mineral matter found in peat, the precursor of coal.

(F) The Thermodynamic Properties of Aqueous Solutions of High Temperatures and Pressures studies the properties at aqueous electrolyte solutions by flow calorimetry.

(G) The Geochemistry of Technetium and Ruthenium and Geochemical Controls on the Redistribution of Multivalent Elements in the Lithosphere examines the mobility of these elements in nature in order to assess the effectiveness of potential geologic sites for nuclear waste repositories.

A. Rock Water Interaction in Geothermal Systems (R. W. Charles, T. M. Benjamin, and G. K. Bayhurst)

Rock and fluid are equilibrated in various hydrothermal systems in order to model reactions of interest to the Department of Energy concerning a number of rock reservoirs. Experimentation can involve reaction in static (cold seal), agitated (Dickson vessel), or dynamic (circulation) systems. The most advanced circulation system, constructed of titanium can examine reactions with chloride solutions in a temperature gradient. Maximum conditions are 350°C and one kilobar pressure for durations of up to nine months. Rock reactions and solution compositions are continually monitored by SEM and plasma emission spectroscopy, respectively.

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

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

Rocks and pure minerals are reacted with solution in order to learn more about the behavior of trace elements, some of which are of economic value. The questions asked are (1) Where is the element located in the crystal lattice?, (2) How is this element mobilized?, (3) What speciation is involved in transport?, and (4) How is the element precipitated? Experiments are conducted in agitated (Dickson vessels) and dynamic (circulation) systems. Solid phases are analyzed by proton microprobe, electron microprobe, and scanning electron microscope. Solutions are analyzed by ion chromatography and plasma emission spectrometry.

These studies can examine and help alleviate some of the cost of geothermal energy extraction, examine the origin of ore bodies, and examine the behavior of elements in a hazardous waste repository.

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

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

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

Calculations are underway to determine mean bond distances, volumes and distortion indices for coordination polyhedra, and coulomb potentials for all cation and anion sites using published crystallographic data for ordered end-members of the common rock-forming minerals. These calculations, together with some modeling of crystal structures, will improve our understanding of inter- and intracrystalline major and trace element fractionation trends. These data, not presently available, will enable us to predict the effects of accessory phases on whole-rock trace-element distributions, and the data will have wide application in predicting the distribution of minor and natural trace elements in natural and man-made materials.

We have completed calculations for the anhydrous rock-forming minerals and are beginning to work on hydrous minerals. This work will be aimed particularly at understanding and predicting the distributions of hydroxyl, fluoride, and chloride ions between minerals. Results of our calculations will be collected in a reference publication.

E. Coal Research: Occurrence, Form and Distribution of Sulfur in Peat (R. Raymond, Jr., A. D. Cohen, and R. Gooley)

Elemental, mineralogic, and petrographic compositions of peats, the precursors of coals, are controlled by a combination of botanical and depositional environments. Diagenic alterations occur within these various environments that will eventually affect the occurrence of sulfur and/or mineral matter in a coal deposit; one must understand the mechanisms for their 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 three distinct coal-forming regions: marine to brackish water environments (Everglades, SW Florida); salt marsh/freshwater complex (Snuggedy Swamp, South Carolina); and freshwater swamp-marsh complex (Okefenokee Swamp, Georgia). 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 distribution based on the first two objectives.

Our approach is to use electron probe microanalysis, scanning electron microscopy, bulk chemical analyses, and conventional sedimentological analyses to characterize the models 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 the relationship between sulfur and mineral matter occurrence and peak 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. Z. Rogers, T. M. Benjamin, R. W. Charles)

Knowledge of the thermodynamic properties of aqueous solutions is basic to an understanding of many geochemical systems. Hydrothermal alteration, element migration, geothermal activity, and integrity of waste repositories 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.

A flow calorimeter has been designed to measure the heat capacities of single and mixed electrolyte solutions over a temperature range from 25°C to 350°C and at pressures from saturation to 500 bar. 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 temperatures and pressures.

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

An understanding of the long-term stability of ^{99}Tc in a geologic environment is critical to evaluating the effectiveness of geologic sites for the disposal of nuclear wastes. Technetium exists in nature only as a fission product of the spontaneous fission of ^{238}U. This quantity is extremely small, below the detection limit of most analytical methods, and thus there have been no direct observations concerning the geochemistry of technetium. Nuclear waste site evaluations with regard to this element must be based upon inferences from laboratory and theoretical work.

The spontaneous fission product ^{99}Tc has a half life of $\sim 2.13 \times 10^5$ years. Because both the parent, ^{238}U, and the daughter are radioactive, in a closed chemical system these two nuclides establish a state of secular radioactive equilibrium. In such a state, the atomic ratio of the two elements is a well defined constant. Technetium-99 decays to the stable nuclide ^{99}Ru. This is one of four ruthenium isotopes produced by radioactive fission. The other three are produced instantaneously, while the rate of production of ^{99}Ru is slowed because of intervention of the long-lived precursor ^{99}Tc. In a closed chemical system the isotopic composition of spontaneous fission product ruthenium is fixed. In a system where ruthenium has been fractionated from technetium, the isotopic composition of ruthenium will be altered showing either an excess or deficiency of ^{99}Ru.

Measurements of the abundance of uranium, ^{99}Tc and the isotopes of ruthenium provide the means to evaluate the relative geologic stability of uranium and ^{99}Tc in recent times, and ruthenium, technetium and uranium during the period of time since the host rock was formed. We have developed procedures to measure ^{99}Tc and the isotopic composition of ruthenium in uranium-rich rocks by isotope dilution mass spectrometry. The methods will be applied to examine the geochemistry of these elements.

Previous work has demonstrated unexpected movement of technetium during the period of nuclear criticality of the natural fission reactors found in the Oklo mine in Gabon, Africa. We will measure ^{99}Tc abundances in rocks to determine the stability of the element in recent times. Samples for the analyses have been selected for these measurements and uranium abundances have been determined.

Contractor:	LOS ALAMOS NATIONAL LABORATORY University of California Los Alamos, New Mexico 87545
Contract:	W-7405-ENG-36
Title:	Thermal Regimes and Continental Scientific Drilling Program
Person in Charge:	J. T. Whetten

<u>Scope of Work</u>

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, and (D) Valles Caldera Information Base.

(A) The Polvadera Group of the Jemez Mountains is studied to determine its overall composition, the origin of its magmas, timing of eruptions, sequences of compositional variation, and its relations to older and younger volcanic units. The work is directed toward understanding the evolution of the magma chamber(s) beneath the Jemez Mountains.

(B) The location and extent of the buried portion of the Toledo caldera in the Jemez Mountains is to be determined. Geochronology, stratigraphy, and petrology of domes and volcanic and sedimentary deposits in the exposed part of the caldera will be studied.

(C) Teleseismic short-period P-wave delays and synthetic seismogram modeling of crustal transfer functions will be used to delineate regions of anomalous seismic wave propagation and attenuation beneath the Jemez Mountains (including Valles caldera).

(D) An information data base is being established for CSDP thermal regime studies of the Valles caldera.

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

The Jemez Mountains of northern New Mexico are a major basaltic-to-silicic, late Cenozoic volcanic field, lying at the intersection of the Jemez lineament and the Rio Grande rift. Volcanism in the Jemez Mountains began 12-13 m.y. ago. Caldera formation occurred 1.4 and again 1.1 m.y. ago with the eruption of the major ash flow sheets, followed by caldera collapse, resurgent domes, and additional small ash flows. The Jemez Mountains volcanic field is presently the focus of intense research interest for these reasons: (1) The Jemez Mountains are a major source of our information for understanding caldera formation, ash flow emplacement, and magma resurgence. (2) Data from the Jemez Mountains have contributed to what little is known about the complex magmatic evolution processes associated with high-level silicic magma chambers. (3) The Jemez Mountains are a focus of major hydrothermal activity and high heat flow.

The Polvadera Group (Tschicoma and Lobato Formations) northeast of Valles caldera is being studied to determine its overall composition, the origin of its magmas, the timing of eruptions, sequences of compositional variation, and the relationship to older and younger volcanic rocks. This project will be directed to understanding the magma chamber(s) that were active 2-10 m.y. ago, of factors governing changes in magma composition, and of the overall history of the Jemez Mountains.

B. Origin and Extent of the Toledo Caldera, Jemez Mountains, 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 in the Jemez Mountains formed during the eruption of upper and lower members of the Bandelier Tuff. The location and extent of the Toledo caldera is not well understood because most of the caldera has been masked by the younger Valles caldera. If a borehole is drilled by the Continental Scientific Drilling Program within the Valles caldera, one objective would be to choose a drill site located within the overlap of the Toledo and Valles calderas in order to gain maximum information on the history of the calderas and their geothermal systems. The principal objective of the project is to locate the area of overlap of the two calderas. We propose to do this through geochronologic, stratigraphic and petrologic study of the domes, and pyroclastic and sedimentary deposits located within the exposed remnant of the Toledo caldera. These data should provide information on source areas for these deposits within the Toledo caldera and, indirectly, its original location and extent.

C. Anomalous Lithospheric and Asthenospheric Structure Beneath the Valles Caldera/Rio Grande Rift of New Mexico (K. H. Olsen)

This project is to investigate lateral variations in crustal and uppermost mantle structure and the relationship of these variations to the major volcano-tectonic geothermal regimes of northern New Mexico. Specifically, we are using the techniques of (1) teleseismic short-period P-wave delays, together with (2) synthetic seismogram modeling of crustal transfer functions, to define the regions of anomalous seismic wave propagation and attenuation beneath the Jemez mountain volcanic field, which is one of the principal components of the Rio Grande Rift system of Colorado, New Mexico, Texas, and Mexico.

Our previous seismic studies in northern New Mexico have mainly used seismic waves from local and regional earthquakes and from available explosions to "illuminate" local structures from the side. CARDEX 81, for example, was the field-recording phase of a series of crustal refraction and fan shooting profiles in the Jemez Mountains/Rio Grande rift. The analysis and interpretation of this large data set continues and will be merged with future data to provide constraints in interpretation of future experiments. In contrast, the CARDEX 83 experiment will concentrate on "illuminating" structures from below, using seismic waves at nearly vertical incidence angles from distant (greater than 3000 km) earthquake sources. The data will complement those from previous studies, and the region of principal focus will shift from the shallow crust (depths less than 20 km) to the deeper crust and the uppermost mantle within approximately 50 km of the Moho.

D. <u>Valles Caldera Information Base</u> (N. L. Marusak and F. Goff)

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. We will establish an information base that 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; and (3) a brief summary of generalized plans for future research, including shallow, intermediate, and deep drilling.

The Information Base will be prepared on a stand-alone microcomputer using a conventional commercial data base management system. This computer system will be inter-Lab compatible and accessible. The formatting of Valles Caldera Information Base will be consistent with the Long Valley and Salton Sea Information Bases. Information will be distributed in printed form on a semi-annual basis.

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 Plasmas (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 result in 1982 came from a joint experimental and theoretical analysis of electron distributions within the earth's bow shock. Our data analysis, using data from high time resolution plasma analyzers on the ISEE spacecraft, demonstrated for the first time the existence of an electron beam aligned parallel to the magnetic field within the bow shock. Our theoretical analysis modeled such electron distribution functions and showed that they can generate an ion acoustic instability with properties similar to those observed for fluctuations within the shock. Since most previous theories of current-driven microinstabilities within the shock have concentrated on models driven by currents perpendicular to the magnetic field, our results offer a new approach to the study of wave-particle transport in collisionless shocks.

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

The interaction of the solar wind with the earth's magnetosphere is essentially electrical in character, very much resembling the working of a magnetohydrodynamic (MHD) electrical generator. Solar wind plasma, impinging on the earth's magnetic field, flows through its outer regions (the "boundary layer" and gives up its energy to the generator of electrical currents that flow into the ionosphere, depositing energy there. Currents also flow across and around the tail, creating the tail lobe magnetic field, a storehouse of magnetic energy that is drained away both continuously and intermittently during substorms. Much of the intermittent loss during substorms involves severance near the earth of a portion of the plasma sheet, forming a plasmoid which then drifts out of the tail and is lost.

We use data from satellites in the outer magnetosphere to seek quantitative understanding of at least some of the elements of this global system of energy exchange and conversion. Some important results of our research in the past year are:

(1) Further identification of plasmoids and their association with substorms.

(2) Further determinations of the properties of plasma vortices, the very large scale ($\sim$5 to 30 R_E) patterns of rotating plasma flow that drift tailward through the plasma sheet and that may be generated by an instability in the boundary layer.

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

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. Our initial approach is to study the loss of energetic electrons from the terrestrial magnetosphere. This work is done within the general framework of the Kennel-Petschek theory, with new features that we develop using a strong interplay between analytic and computer calculations in both linear and nonlinear theories. We test these results against the excellent Los Alamos particle measurements being made at geostationary orbit, and we compare available wave data with particle observations and theoretical estimates of wave energy densities. Our studies in this area bear on several problems of interest to DOE. Specifically, they bear strongly on (1) understanding plasma acceleration processes such as accompany the production of fusion plasmas, (2) understanding the relationship between plasma microinstabilities and the imperfect confinement of hot fusion plasma particles, (3) understanding the coupling between the terrestrial magnetosphere and troposphere (which possibly affects climate variability), and (4) assessing the hazards and economic viability of the near-earth environment with regard to space-based human activity (e.g., future energy generation and transmission technologies).

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

Contract: W-7405-eng-26

Title: Geochemistry of Crustal Processes at High Temperatures and Pressures

Person in Charge: R. E. Mesmer

Scope of Work

This program provides basic geochemical information on hydrothermal and magmatic processes involving both homogeneous and heterogeneous systems emphasizing the high temperature and high pressure regimes that promote transport and redistribution of materials in the crust. Special facilities are employed in experimental studies including a hydrogen service, internally heated vessel for studies to 1400°C and 500 MPa. Dickson type apparatus and emf cells, conductance, calorimetric and isopiestic facilities are utilized in hydrothermal work to conduct speciation, equilibrium and kinetics studies on selected model systems. Detailed thermodynamic and kinetic information on well chosen specific systems is needed to provide the data base for the quantitative modeling of the complex mixtures in natural rocks and fluids. The important geochemical questions addressed are magmatic and volcanic processes, element cycling, rock evolution and alteration, ore deposition, and the geochemical consequences of waste storage and extraction of geothermal energy.

Present research has provided information on phase equilibria, crystallization kinetics, redox reactions, chemical fractionation and element fractionation in certain magmatic systems. In hydrothermal systems speciation and equilibrium studies have been conducted on water, aqueous carbon dioxide, silicic acid, fluorosilicates, calcium and magnesium ions, and tungsten as well as solubility data on amorphous SiO_2 and quartz.

A. Silicate Melt Geochemistry

Olivine Nucleation and Growth Kinetics in Synthetic Basalt Magmas (M. T. Naney)

Crystal nucleation and growth experiments are conducted at 100 kPa to investigate nucleation delay and the crystal growth rate of olivine (Mg_2SiO_4) precipitating from two Fe-free model basaltic liquids. This study will provide data concerning: (1) the influence of viscosity on crystal nucleation, (2) initial olivine growth rates that may be compared with "average" growth reported for olivine in the literature, and (3) the influence of nucleation delay phenomena on growth rate values as calculated from isothermal crystallization experimental data.

Crystal nucleation and growth rate data to be obtained in this study are needed for the development of quantitative models of basaltic magma flow and consolidation.

Iron Redox Equilibrium Kinetics in Silicate Liquids (M. T. Naney, S. E. Swanson, Univ. of Alaska)

Controlled atmosphere experiments are conducted at 100 kPa to investigate iron redox reactions in silicate melts. Studies in progress are designed to test assumptions about the kinetics of these reactions made in recently published reports. We believe that assumptions about redox kinetics made by others have been too optimistic, with regard to silica-rich compositions. An important consequence of underestimating the time required for silicate melts to reach redox equilibrium is that ferrous-ferric iron ratios obtained from such samples would be non-equilibrium values. We believe that non-equilibrium data has been used to formulate functional relationships to calculate equilibrium oxygen fugacity of magmas in terms of temperature, bulk composition, and Fe^{+2}/Fe^{+3} ratios.

A series of timed experiments with each of three silicate liquids derived by melting natural volcanic rocks of widely varying composition (basalt, andesite and rhyolite) will be conducted at 1243°C and two redox conditions: log f_{O_2} = -6.05 and -7.83, (quartz-fayalite-magnetite buffer) in a CO/CO_2 gas mixing vertical tube-furnace. Additional studies of silicic calc-alkaline melts, using the previously obtained kinetic data, will be conducted to investigate the influence of redox conditions on crystallization. The goal of these studies is to understand the influence of redox conditions on chemical fractionation and crystallization of magmas in the crust.

Stability of "Magmatic" Epidote in Granitic Rock Systems (M. T. Naney)

The recently installed hydrogen-service internally heated pressure vessel will be used to investigate the stability of epidote [$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$], a common accessory mineral of silicic plutonic rocks. Experiments will be conducted to define the coexistence of epidote with hydrous granitic melts as a function of temperature (500-700°C), pressure (200-800 MPa), bulk composition, and oxygen fugacity. A pressure dependence for this coexistence has been demonstrated (Naney, in press) that may provide a single point "geobarometer" under favorable geologic conditions. This study will quantify the pressure dependence of epidote-melt coexistence in granitic systems and provide phase stability data that will be needed in a subsequent study of uranium and thorium chemical partitioning among coexisting silicic liquids, aqueous vapor, and crystalline phases.

B. Hydrothermal Geochemistry

Magnesium Hydrolysis and Brucite Solubility in High Temperature Aqueous Sodium Chloride Solutions (S. E. Drummond)

Recent estimates of the ΔH of the first hydrolysis step for magnesium (14.9 kcal/mole, Baes and Mesmer) along with the value of the equilibrium constant (K_1) at 25°C ($\sim 10^{2.5}$) corresponds to an estimated value for K_1 of $10^{7.7}$ at 300°C. This evidence indicates that magnesium is largely hydrolyzed in near neutral solutions at high temperature and suggests that about 10^{-4}m OH^- is freed when a neutral solution with 10^{-3}m total magnesium is cooled from 300° to 200°C. Consequently magnesium may play a more important role in influencing the pH of natural hydrothermal solutions than previously realized. The exact nature of this effect depends on the interaction of magnesium with OH^- and with other anions such as chloride at high temperature. Ongoing experiments on the hydrolysis of magnesium and the solubility of brucite [$(MgOH)_2$] in sodium chloride solutions will establish the role of magnesium in hydrothermal solutions.

Kinetics of the Thermal Decarboxylation of Acetate and the Role of Catalysis (S. E. Drummond, D. A. Palmer, F. W. Dickson)

This research is focused on the hypothesis that natural gas migrates as acetate from the source in a sedimentary basin and that the acetate decomposes at or near the reservoir to CH_4 and CO_2. The idea is attractive because acetate, unlike CH_4, is completely miscible in water and consequently is more mobile in water-laden sediments. The hypothesis is plausible if the time required to decompose acetate is compatible with the fluid migration time from source to reservoir. In order to address this point, experiments on the effects of temperature, composition, and catalysis on the thermal decomposition rates of acetate are in progress.

Hydrothermal Transportation and Deposition of Tin, Tungsten and Molybdenum (S. E. Drummond and D. Wesolowski)

Hydrothermal tungsten ores are commonly associated with relatively high concentrations of either tin or molybdenum but rarely both. Tungsten and molybdenum are usually associated in relatively oxidized porphyry systems whereas the tin-tungsten association is most common in reduced environments. Recent experimental work has shown that tungsten is transported in the +6 state as HWO_4^-, even in extremely reducing conditions. These observations suggest that, like tungsten, molybdenum is transported in the +6 state but over a more limited range of f_{O_2}. Tin, however, is probably mobile only in the +2 valence state and only is reduced systems. Experimental studies of the hydrolysis of tin and molybdenum and the solubilities of cassiterite (SnO_2), powellite ($CaWO_4$) and molybdenite (MoS_2) are planned in order to test this hypothesis and quantitatively evaluate the mineralization processes associated with granitoids.

Reaction of Silica Phases with Aqueous Solutions (F. W. Dickson)

Scientific studies on the shallow earth's crust and practical uses as well commonly need data on modes of interaction of the common silica minerals (quartz and amorphous silica) with aqueous solutions that range from dilute, recently injected, meteoric waters to concentrated brines. Crustal processes from 20°C to 300°C and 0.1 to 50 MPa follow reaction paths that may depart substantially from equilibrium, which requires detailed knowledge of kinetic steps as well as the equilibria among the involved phases. The reactions of quartz, and to a lesser degree of amorphous silica, with H_2O, $NaNO_3$ solutions, NaCl solutions and buffered NaCl solutions are being determined at temperatures in the interval 125°C-275°C. For quartz reactions, stationary and rocked titanium alloy vessels filled with coarse Ottawa quartz sand are being used. Samples of reacted fluid are removed from the top of pressure vessels while fresh fluids are injected at the base. Quartz solubilities are being determined reversibly and the kinetics of the reactions are being outlined.

Ionization Equilibria in High Temperature Aqueous Electrolyte Solutions by Electrical Conductance Measurements (W. L. Marshall, J. D. Frantz, Geophysical Laboratory of Washington, DC)

Salts and other electrolytes in aqueous solutions are known to associate strongly at extremes of temperature (to 800°C) and at moderate to high pressures. The quantitative representation of this association and the determination of any possible hydrolysis of these electrolytes in high temperature aqueous solutions and supercritical fluids is of great importance for a full description in terms of the actual species present. The attainment of accurate ionization constants at extremes of temperature and pressure for particular acids and bases together with already available values for the ion-product of water and ionization constants for many salts previously obtained at ORNL will allow the above descriptions.

C. Geochemical Modeling

Stable Isotope Exchange in Mineral-Fluid Systems (D. R. Cole)

The isotopic ratios of $^{18}O/^{16}O$ and D/H have been increasingly used to resolve reaction paths of mineral-fluid reactions occurring both in the laboratory and in nature. This study is being undertaken to develop a basis for oxygen and hydrogen isotopic reaction kinetics in mineral-fluid systems undergoing mineralogic change. In addition, a detailed examination is made into factors that control diffusional isotopic exchange. Application of surface-controlled and diffusion models to well-studied geologic systems should prove useful in quantifying either time or water/solid mass ratios regardless of the degree of isotopic equilibrium.

Boiling and Mixing: Mechanisms for Self-Sealing in Geothermal Systems (S. E. Drummond and D. R. Cole)

Self-sealed zones are characteristic of many liquid-dominated geothermal systems and tend to occur at or near the margins of the reservoir. The processes of mineral deposition and rock alteration that lead to self-sealing have been attributed to the change from isothermal convection to a conductive gradient producing rapid temperature decreases, increased thermal fluid-groundwater mixing, boiling, and/or increasingly oxidizing conditions. Numerical models are being constructed to predict mineral solubilities in boiling and mixing hydrothermal solutions. These models are used to test the effectiveness of boiling or mixing as self-sealing mechanisms for a variety of well-documented geothermal systems. Results of these computations provide a quantitative understanding of the specific nature of natural boiling and mixing hydrothermal systems, ultimately leadinq to the development of better exploration criteria.

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

Contract: EY-76-C-06-1830

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 basic research in areas of remote sensing and image processing most relevant to the geoscientific research and development responsibilities of the Department of Energy. The basic purpose is to develop and test new interactive computer techniques for processing and using combinations of remote sensing and geosciences data so that geoscientists can analyze more complex data combinations, more completely and more rapidly.

The current scope and emphasis of activities involve:

1. Maintaining cognizance and acquiring appropriate remote sensing and geoscience data sets to support energy-related application efforts. Current emphasis is on acquiring Landsat-4 thematic mapper data and shuttle imaging radar data.

2. 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. Near-term emphasis is on software development required to transfer existing interactive programs to the VAX 11/780.

3. Demonstrating, evaluating and transferring advanced computer techniques for processing and combining remote sensing and geoscience data of energy-related relevance. Current efforts involve cooperative assessments of potential utility to national security technology (with DOE/ISA), to Continental Scientific Drilling Program (with Sandia, Los Alamos and Livermore Laboratories), and to rock microstructure analysis (with Universities of Washington and Wisconsin).

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

Each year, new data -- national, regional and local (Hanford) -- are acquired and digitized as appropriate to support the development and demonstration of interactive computer procedures for merging remote sensing and geoscience data sets. As a Landsat-4 Principal Investigator, PNL is currently emphasizing the early acquisition and evaluation of the 7-band thematic mapper data over several geographic regions wherein DOE has geoscientific interests. These include several major operating facilities, such as Hanford and Savannah River Plants, sample nuclear waste repository locations and selected candidate Continental Scientific Drilling Program (CSDP) sites. PNL will be acquiring and processing Shuttle imaging radar data for geologic applications as they become available for selected areas of DOE interest. Also, acquisition of relevant geologic and geophysical data sets to support the preparation of CSDP demonstration products remains a high priority.

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

Numerous specialized computer programs exist at PNL for interactively processing, enhancing and displaying remote sensing and geoscientific data. Current emphasis is on using these experimental programs to support other priority R&D interests of the DOE including the CSDP, expanded multispectral data use by ISA and potential contributions to geologic nuclear waste isolation activities.

Current work is underway to develop new programs to more effectively process and utilize the Landsat thematic mapper data being acquired for DOE by NASA, especially the new thermal band data. Research is also in progress to develop appropriate image processing techniques for analysis of microscale and macroscale geologic features. This work included a study of sandstones from the Illinois deep drill hole in which petrofabric data derived from image analysis will be compared with data derived using conventional methods in order to evaluate performance of the image processing technique. In addition, potential techniques for automatic grain classification such as multiband analysis will be evaluated.

C. <u>Application and Transfer and Geodata Capabilities</u> (H. P. Foote and G. E. Wukelic)

Previous demonstrations, reciprocal visits and data exchanges between PNL and other DOE National Laboratories involved in OBES geosciences programs have shown that PNL-developed geoscience computer processing (geodata) techniques could be beneficially applied to a variety of ongoing research and programmatic activities. More serious considerations and discussions are in progress to explore and develop procedures for accomplishing the transfer of appropriate capabilities.

Contractor:	PACIFIC NORTHWEST LABORATORY Battelle Memorial Institute Richland, Washington 99352
Contract:	EY-76-C-06-1830
Title:	II. DOE Insolation/Aeronomy Observatory 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 atmospheric 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 including photovoltaics and biomass and to passive 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, G. J. Schuster, G. M. Stokes, and E. W. Kleckner)

The emphasis of the aerosol portion of the trace species work was intended to be an assessment of the human influence, including fossil energy technologies, on the environment. However, through volcanic activity, nature has masked any anthropogenic effects in the last three years. A study of the short-term tropospheric and longer-term stratospheric effects of the neighbor volcano Mount St. Helens has been completed and published in the Journal of Climate and Applied Meteorology. The major conclusion of this work was that the 1980 eruptions had no long-term climatic impact. Of greater consequence are the 1982 eruptions of El Chichon. Aerosol data have been collected at PNL radiometer sites in the northern hemisphere since the spring of 1978. Based on this data set which establishes background levels, it is easily determined that El Chichon continues to significantly perturb the stratosphere ten months after its eruption. From the attenuation of direct sunlight as a function of wavelength and from the breadth and displacement from the sun of the corona caused by diffraction by these stratospheric particles, a size distribution is to be determined. This result along with global distribution of the aerosols will ultimately determine the climatic impact of this volcano.

The extraction of information on trace gases depends on deviations from the expected smooth wavelength dependence of aerosol attenuation. Work continues on the validation of the PNL ozone extraction technique using the nearly colocated Boulder, Colorado, radiometer and the NOAA ozone network Dobson photometer. Several existing methods are being scrutinized to determine water vapor abundance.

Spectral data in seven broadband filters which span a silicon PIN diode's sensitivity are made every five minutes with a 1.5° field of view centered on the sun's disk. Less often scattered light measurements of the entire sky are made with approximately 10° between samples. Two mathematical approaches have been used to obtain continuous spectral distributions from these seven samples. Very good agreement with simulated, but realistic, spectra generated by the AFGL's LOWTRAN5 model has been obtained. Total irradiance values within one percent are obtained and reasonable averaging over spectral features yields spectra which should prove useful to materials, biological, and solar technologies. Validation using actual PNL radiometer measurements compared to LOWTRAN5 and absolute spectroradiometers at DSET Labs and SERI is in progress. A spectrometer for precision measurement of the transmission of optical elements has been interfaced to a computer. This transmission measurement is crucial in applying the mathematical inversion schemes.

B. <u>Aeronomy Studies</u> (E. W. Kleckner, D. W. Slater, and N. R. Larson)

The importance of mid- to high-latitude auroral and ionospheric phenomena has gained greater appreciation as evidence regarding the wide ranging and complex interactions has become available. The Stable Auroral Red arc (SAR arc) is among the variety of auroral emission patterns which occur frequently but are not visible to the naked eye. This phenomenon has been the subject of investigation for several years. As a result of this effort, PNL has produced the most comprehensive catalog of SAR arc events available to researchers. Dissemination of this unique archive has been achieved through publication in the open literature, and as continuing updates (through 1982) available as PNL reports.

SAR arcs are spatially associated with the equatorial plasmapause region of the magnetosphere and constitute the optical manifestation of energy flux to the ionosphere from that region. We have found that the energy dissipation within the ionosphere appears to be reasonably well explained; however, the energy transfer mechanism within the magnetosphere responsible for the maintenance of SAR arcs is yet to be adequately defined and, at the present time, is under active study. A cooperative study led to calculations of electron heating rates and temperatures within the body of a SAR arc. The results were then compared to our absolute photometric observations of integrated emission intensity. Good agreement was found between the calculated and observed emission rates.

A second study used the photometric network data in conjunction with Fabry-Perot interferometer measurements, the objective being a determination of the thermospheric response to energy input from both SAR arcs and the more poleward aurora. This has led to the first report of thermospheric winds resulting from SAR arc heating exclusive of competing aurorally generated circulation. In accordance with model predictions, measurements both North and South of the arc showed flow patterns consistent with areas of subsidence of the thermospheric neutral oxygen, indicating that a thermal convection cell had indeed been generated. The modeled and observed behaviors in the vicinity of the arc were in close agreement.

In perhaps the most surprising and consequential study, in situ measurements by satellite above the locations of several SAR arcs have allowed identification of the low energy thermalized electron population believed responsible for the creation of the features. Analysis of the available data sets reveals a 1-to-1 correspondence in the occurrences of low energy electrons (<8 eV) and the locations of SAR arcs. The electron populations thus far examined exhibit field aligned convective velocities of 200-300 km/sec. Viewed from the plasma rest frame, calculations show that the convecting electron population above the arcs is well described by a Maxwellian thermal distribution with a characteristic temperature of ≈10,000 K.

A goal of the aeronomy program is to develop a capability to model the physics of the F-region in the ionosphere. This model, together with the extensive observational base, will provide a tool for detailed study of energy transport within this region. As a supplement to existing instrumentation, a compact and portable, 4-color meridian scanning photometer is under construction. This instrument will allow the acquisition of simultaneous absolute emission intensities at a number of auroral wavelengths. These ratios, in turn, will allow very specific particles within this region. A "core" network of three photometer sites located near PNL will continue to be operated so as to provide the high spatial resolution needed for studies of D- and E-region phenomena (≈100-km height).

Contractor:	PACIFIC NORTHWEST LABORATORIES Battelle Memorial Institute Richland, Washington 99352
Contract:	DE-AC06-76RL0 1830
Title:	III. Chemical Migration by Contact Metamorphism in Granite - Carbonate 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 and silt/carbonate rocks and granite pegmatite and 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 radionuclides in geologically confined nuclear waste.

The first geological site has been the granite intrusion at Notch Peak, Delta, in western Utah. The intrusion was emplaced in a Cambrian limestone interbedded with silt and carbonate layers. Samples of silt and carbonate, ranging from highly metamorphosed (near contact) to unmetamorphosed, were collected along horizontal and vertical traverses away from the granite intrusion in the Big Horse, Weeks, and Marjum formations. Analyses on some 40 major, minor, and trace elements is obtained by neutron activation analysis and x-ray fluorescence. A comparison of trace element signatures from metamorphosed to unmetamorphosed samples, ranging from granite to silt/carbonate in the Big Horse formation, indicate that some elements -- Na, K, Rb, Ba, Sr, Cs, As, Sb and Pb -- in the silt have migrated over distances of 5-40 meters, whereas there is virtually no migration of REE, V, Cr, Sc, Zr, Hf, Al, and Th. Carbonate rocks are impermeable to fluids relative to silt. The chemical systematics of the Weeks and Marjum formations are under study.

The second geological site is pegmatite country rocks in the Black Hills, South Dakota. The five different pegmatites chosen will enable us to address (a) composition of fluids (b) capability of dispensing fluids into country rocks and (c) partitioning of mobile elements between minerals phases and fluids derived from pegmatites. Preliminary study on the Tin Mountain pegmatite suggests that K, Rb, Cs, and Sb have migrated to distances of $\sim$5 meters from the pegmatite/amphibolite contact. There is virtually no migration of REE, Al, V, Cr, Sc, Hf, and Th. The chemical study of mineral separates biotite and muscovite and concentration profile as a function of distance in other pegmatites is under progress.

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

Contractor:	SANDIA NATIONAL LABORATORIES Albuquerque, New Mexico 87185
Contract:	DE-AC04-76DP00789
Title:	I. Magma Energy Research
Person in Charge:	W. C. Luth

Scope of Work

The Magma Energy Research Project has been assessing the scientific feasibility of directly extracting energy from buried magma sources and has been divided into five major research tasks: magma source location and definition, magma source tapping, magma characterization, magma-material capability, and energy extraction. Magma Energy was judged to be scientifically feasible last year. Continuing research is following on the task of locating and defining specific shallow crustal magma bodies for future scientific/engineering experiments. Sites are being studied for future shallow magma experiments, and geophysical techniques for detecting shallow magma sites are being evaluated.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: II. Continental Scientific Drilling Program
Thermal Regimes

Person in Charge: W. Herrmann

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 IV (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 research 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 in permeable convecting geologic media. Such thermal geophysical techniques are based on the measurement and analysis of thermal and fluid transfer, but particularly in regions where natural convection heat transfer and/or ground water flow in aquifers significantly alter subsurface temperature profiles. Current research is concentrating on the design of a convective heat flow sensor for use in permeable convecting surface zones. Initial tests were run at Long Valley and additional tests of an improved tool are planned later this year at Long Valley.

B. Magmatic Emplacement (C. R. Carrigan)

A primary objective of the CSDP is the characterization of the geology and physics of a geothermal system. A study is in progress to utilize the surface evidence of geothermal systems such as heat flow, gravimetric and tilt data to provide assessments of the present state and evolutionary track of these systems. This study is evaluating the effect of the coupled magma/wall rock and magma/hydrothermal interaction on surface observables. Numerical codes are being used to investigate evolutionary models of both resupplied and isolated magmatic structures such as dikes, sills, conduits, and chambers.

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

In view of its long and intense history of volcanism and current seismic, tectonic, and fumarolic activity, the Mono Craters-Long Valley area is an important potential site for deep exploration of crustal thermal regimes. To assess this potential and to gain a basic understanding of magma/ hydrothermal systems, a coordinated program of geophysical and geochemical observation and modeling is being conducted. Intersecting refraction profiles have been completed across western Long Valley caldera and the Mono vent chain to define upper crustal structure. High precision gravity measurements, repeated over a network of benchmark stations, have recorded changes associated with recent seismic events. These events, possibly reflecting shallow intrusion of magma, were also observed through rapid deployment of seismic arrays. Analysis of carefully sampled suites of recently ($\leq 10^3$y) erupted glasses indicates important chemical and isotopic changes during magmatic intrusion and eruption, apparently as a consequence of degassing. Modeling efforts are underway to relate these surface observations to behavior of magma and hydrothermal systems at depth.

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°C) thermal probes and associated cables and handling equipment are being developed for logging high temperature holes. Initial instrumentation work has concentrated on the development and testing of downhole periodic seismic sources. Both compressional-wave and shear-wave (P and S) sources have been developed. A swept-frequency periodic source is currently under development.

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 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 caldera, 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 composition and circulation pattern of hydrothermal fluids. An interdisciplinary and interlaboratory program of investigations in shallow holes is underway at these three candidate Continental Drilling sites as a necessary step toward deep drilling at these sites. Dr'lling targets are the conduits beneath the youngest vents at Long Valley and Valles calderas, and an unexplored region of the Salton Sea thermal anomaly. Laboratories participating in this proposal are Lawrence Berkeley, Lawrence Livermore, Los Alamos and Sandia National Laboratories. Sandia will have responsibility for drilling the vent at Long Valley and for interpreting petrologic data from the Long Valley and Valles holes in terms of the degassing of rhyolitic intrusions. Measurement of material properties of core and downhole geophysical experiments will be conducted in collaboration with the other laboratories in order to determine mechanism and rate of heat transfer and define conduit geometry.

F. Thermal Regimes Research Drilling Office (R. K. Traeger)

This activity will provide logistical support for research drilling programs in the CSDP-Thermal Regimes area. The support functions include consultation with principal investigators (P.I.'s) and program officers regarding budgetary and technological constraints on research drilling and aiding in the formulation of detailed drilling, logging and experimentation plans. The drilling office, if requested, will assume responsibility for environmental, safety, legal, and insurance activities associated with drilling programs, issue and monitor contracts for site preparation and field activities associated with drilling, provide (if necessary) a site engineer, and generally support the scientific activities of the P.I. and co-workers. The drilling office will provide support for a Scientific and Technical Review Panel which is charged with overall review of the research drilling activities.

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

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-alone 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: III. 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 purpose of the crustal strain program is the development of methods and techniques for interpreting time-dependent deformation of the earth's surface. 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 notions 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 work model. Gravity gradient data associated with the 1975-1977 Kilauea inflation-deflation episodes have been interpreted by use of these techniques. Work using these codes is underway with collaborators at the U. S. Geological Survey and at the Earthquake Research Institute, Tokyo, Japan. Seismicity data, waveform modeling and laboratory studies of rock deformation and slip suggest that shear stress is distributed inhomogeneously on fault planes. A model consisting of a finite fault embedded in an elastic medium has been constructed to explain these data.

B. Time-Dependent Deformation and Fracture of Brittle Rock (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 theory. Stress-strain curves for various loading histories are being predicted and compared with experimental results.

Currently efforts are concentrated on applying the model to long-term creep problems and experimentally verifying the results, extension of the model to a fully three-dimensional description and definition of damage accumulation inferred from acoustic emissions.

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

The objective of this program is to investigate the creep mechanisms of sodium chloride at low temperatures and stresses. The creep response of sodium chloride has been studied 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.

D. Natural Convection in Double-Diffusive Counter-Buoyant Systems (D. B. Hayes and J. C. Eichelberger)

In double-diffusive counter-buoyant fluid systems, gradients in temperature and composition produce opposing buoyancy forces, resulting in complex patterns of circulation. For example, heat is lost from the margin of a magma body but water may diffuse inward, resulting in opposing buoyancy forces within chemical, and thermal boundary layers of greatly differing thicknesses. The equations describing non-equilibrium flow of fluid (gas) - magma mixtures in conduits have been developed for the case involving low volume fraction of gas. Numerical solutions for these integro-differential equations, expected to be stiff because of disparate length scales, are being sought.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: IV. 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 contents are being determined for a large number of obsidian samples from explosively and effusively erupted young volcanic units at Mono Craters/Inyo Domes, Katmai, 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 small plates cut from the same obsidian samples. Field, analytic, and computer-based studies of volcanic gases are being performed for Mount St. Helens 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 number of geochemical, geophysical and energy related problems and to a large degree depends on a knowledge of the kinetic and thermodynamic constraints governing clay mineral dissolution. To approach the problem experimentally, a hydrothermal Dickson Apparatus has been brought on line and the requisite solution analytic equipment purchased and installed. Preliminary experiments using Wyoming bentonite demonstrated the desirability of eliminating exchangeable potassium and magnesium as well as amorphous silica in order to obtain readily interpretable changes in fluid composition. A theoretical methodology for dissolution data interpretation has also been located and a data base containing the appropriate thermodynamic values identified. Currently preparations are underway to program this theoretical model and for starting in earnest the hydrothermal experiments using the reference montmorillonite clay SWy-1.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: V. 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. Field Portable Gas Chromatograph (R. O. Woods)

Efforts to characterize fumarolic gases by bottle sampling are perturbed by the reactive natures of the species involved. These cause deterioration of samples between the time of their being taken and their later analysis in the laboratory. *In situ* analysis using portable instrumentation avoids this problem. A field gas chromatograph, configured to analyze the gases commonly found in volcanoes and constructed of materials capable of surviving in a corrosive atmosphere, is being developed. To date the analytic instrumentation has been built and partially tested. The ongoing effort involves assembling a supporting electronics package and calibrating the overall system.

B. Mapping Damage Space in Rocks Using Acoustic Emission (D. J. Holcomb)

A technique is being investigated for studying the local failure processes that lead to macroscopic failure of polycrystalline materials, such as rock. Failure of brittle rock is the end point of a process of accumulating local failures which can be characterized with the concept of damage. If damage is a state variable, then it should be possible to map damage-stress space with acoustic emissions (AE) in a manner analogous to mapping yield surfaces for a plastic material. To show this, surfaces of constant damage are being mapped by approaching the surface along different stress paths, using the onset of acoustic emission activity as an indicator that the surface had been reached.

Preliminary results indicate that for the simple triaxial stress state, there are indeed "damage surfaces" that are detectable using acoustic emissions. An unexpected development was the realization that the same approach could be used to determine *in situ* stresses without the drawbacks inherent in other methods.

Continued development and generalization of the techniques is planned, applying the damage mapping methods to several rock types, using sufficiently general stress states that the full damage surfaces are delineated and integrating the results into existing failure models that are based on the concept of damage as a state variable.

C. Noble Metals (H. W. Stockman)

This study is directed toward defining the distribution of noble metals in the mantle. It is generally agreed that the distribution of noble metals among sulfide, oxide, and silicate phases in the mantle is an important factor in the production of noble metal-rich magmas, hence in the production of magmatic platinum-gold deposits. Work in progress involves both chemical analyses of natural materials and experimental studies of phase equilibria. A homogeneous, contamination-free and alteration-free peridotite standard has been prepared to test noble metal analysis techniques. Methods have been developed for separation of sulfides from mantle-derived rocks, and the sulfides will be analyzed to assess their contribution to whole-rock noble metal content. Experimental work includes determination of noble metal solubility in Fe-Ni sulfides, and redetermination of the Ru-RuS_2 sulfur buffer.

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, without complexities associated effects of the wall of fusion devices. One can also learn basic processes associated with the natural dynamo (consisting of the solar wind and the 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.

University of Alaska researchers are also interested in energy-related geophysical problems in the Arctic region. In particular, they are studying the electric current induced by auroral activity in power transmission lines and in oil/gas pipelines. We have successfully demonstrated that auroral activity causes surges in the protective relay system in power transmission lines. An intense surge will open the protective relay, causing a system blackout; 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. Intense electric currents (as much as 1000 A at times) in an oil pipeline, induced by the aurora, may cause serious corrosion of the pipe. Geomagnetic disturbances at Prudhoe Bay also cause serious problems in the operation of various drilling sensors which are oriented by a magnetic compass. We plan to develop a feedback system to make necessary corrections automatically.

In the 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 plan to cross-calibrate these instruments at locations where permafrost thickness and distribution are known by developing numerical methods to handle the data from all the radar and EM devices.

Contractor:	UNIVERSITY OF ARIZONA Department of Geosciences Tucson, Arizona 85721
Contract:	DE-AC02-81ER10842
Title:	I. Rock Deformation in Magma Hydrothermal Systems
Person in Charge:	Denis Norton

Scope of Work

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

We have developed a mapping method for accumulating information on the geometry of fracture surfaces found in fossilized magma-hydrothermal systems. The mapping system prepares three-dimensional models of outcrops and information contained within outcrops. These geometric images are then used to reconstruct the geologic history of a system by comparative analysis with mathematical models of the processes believed to have formed the system.

The data required for these studies are collected in steps: First, a preliminary geometric model of the important geomorphic land forms and structural elements is generated, using at least two high-quality photographic perspective images and a precisely surveyed control network of object coordinates. Second, this model becomes a base map on which the relative age, mineralogy, detailed fracture characteristics, and location of hand samples are annotated. Last, the preliminary model is refined using the new information above and extrapolating the fracture surfaces into the interior of the outcrop.

We are now applying this mapping system to studies of fossil magma-hydrothermal systems. This work has progressed to the stage of final computation and production of computer images in the field data. Preliminary images of topographic surfaces have been digitized; these will be used as the base surfaces on which outcrop information will be depicted.

The imagery ultimately collected from field sites contains numerous features of interest that will be transformed into computer images. Although the computer processing is as yet incomplete, there are many qualitative aspects of the images relevant to the academic and engineering goals of our research.

Contractor: UNIVERSITY OF ARIZONA
Tucson, Arizona 85721

Contract: DE-AC02-80ER10753

Title: II. Solar Variability: Figure and Mean Diameter

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

Scope of Work

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

A. Technical Developments

A system is now being constructed to calibrate the telescope field absolutely to potential accuracies of 10^{-3} arcsec. The calibration is performed by interferometrically measuring angles between images in the telescope field produced by a single mode laser and a reflecting grating. The interferometer is also being used to monitor the shape of the limb scan, a modification which will reduce systematic errors below the level obtainable with the CID camera formerly scheduled for this purpose. Sophisticated lightning protection devices have been installed at the telescope site in order to minimize the possibility of future lightning damage.

B. Observations

A preliminary analysis has been completed of data taken in 1981, prior to the extensive damage caused by lightning. Analysis of these observations is continuing. The current observational run began in mid-May 1983. The new program utilizes four diameter measurements, a procedure which facilitates corrections for effects due to the earth's atmosphere. To minimize bias caused by rotation of the detector between the four different diameters, the data are to be Fourier analyzed as one linked set. The signal-to-noise ratio obtained using this technique has been found to be satisfactory.

C. Theoretical Work

A theory has been developed to treat properties of long and short period oscillations. The theory includes effects due to the mean intensity's nonlocal nature, deviations from radiative equilibrium, and a nongray atmosphere. For the long period oscillations of interest in studies of variability in the solar constant, the nonlocality of the mean intensity is the most important effect, producing percentage temperature changes 10^3-10^4 times larger than those occurring in the diameter. This theory has been used to intercompare results of diameter, Doppler, and radiometric studies of the 160 min period oscillation; agreement is found to be approximately within the limits of observational error. The 1979 observations also produced the discovery of rapid internal solar rotation, a finding with important implications for Einstein's general theory of relativity and other theories of gravitation.

Contractor:	ARIZONA STATE UNIVERSITY Department of Chemistry Tempe, Arizona 85287
Contract:	DE-AC02-80ER10765.A000
Title:	Silicate, Aluminosilicate and Borosilicate Melts: Thermochemical Studies by High Temperature Calorimetry
Person in Charge:	A. Navrotsky

Scope of Work

High temperature solution calorimetry is used to determine heats of mixing in aluminosilicate glasses and melts. We are focusing on the role of oxide basicity in determining mixing properties along the joins $MAlO_2$-SiO_2 (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. 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.

A pressure vessel for the study of heat contents of hydrous melts in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Si_4O_8 up to 1000°C and 1 kbar 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. Calibration and testing of the equipment is underway. In addition, solution calorimetry of hydrous glasses may be feasible.

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

Contractor:	BROWN UNIVERSITY Department of Geological Sciences Providence, RI 02912
Contract:	DE-AC02-79ER10401
Title:	Major Volcanic Centers: Magnetotelluric Studies
Person in Charge:	John F. Hermance

Scope of Work

The focus of activity at this laboratory is on applying geophysical and electromagnetic techniques to detecting and characterizing geological features and physical processes within the earth that are related to energy sources. Presently attention is being directed toward acquiring an understanding of dynamical processes and thermal regimes associated with centers of major volcanic activity, particularly the Long Valley/Mono Basin volcanic complex. This work is related to questions of basic scientific importance, as well as to national priorities in resource related areas such as geothermal energy, chemical transport of minerals in the crust, the emplacement of economic ore deposits, and deep drilling for scientific purposes. It is felt that to understand the dynamic evolution of intraplate volcanic centers in the western United States, it is necessary to understand the segregation of basaltic magma from parent mantle material at depth (30 to 100 km) and its migration to higher levels in the crust (5 to 15 km). The physical transport of molten material offers an effective mechanism for transferring heat from deep sources to shallow depths in the crust, leading in turn to episodes of crustal melting at shallow depth and silica volcanism at the surface. In addition, combined electromagnetic and seismic studies of the crust at depths less than 5 km can play an important role in characterizing the porosity and permeability of the crystalline basement above possible magma chambers. This information is important to understanding the manner in which active hydrothermal systems are dynamically coupled to magma sources at high levels in the crust; we need to identify whether the mechanisms for heat transport is through simple conduction or if it is through fluid-transport (advection or convection). In addition, geophysical constraints on the permeability of crystalline basement are important for characterizing the transport of chemical species in the crust (via ore-bearing fluids, for example).

A. Thermal Processes Associated with Major Volcanic Centers

Geophysical investigations of the major rift zones of the world typically indicate that all of these regions exhibit anomalously low values of electrical resistivity, density and seismic velocity, either within the crust itself or at high levels of the mantle. Beneath intraplate rifts such as the Basin and Range or the Rio Grande rift in the western U.S., the emplacement of basaltic magma at mid-levels in the crust may lead to extensive remelting, triggering eruptive episodes of silica magmatism, such as associated with the Valles caldera or the Long Valley/Mono Basin complex. However, the interpretation of magnetotelluric measurements made by our group in these two areas does not indicate a profound geophysical anomaly such as would be expected to be encountered if a major magma body were present. We feel, therefore, that silica magma centers, beneath resurgent calderas of this type, solidify very quickly after eruption. This requires a mechanism for renewing thermal activity at depth in the crust. We are pursuing this question through geophysical field work in the Long Valley/Mono Basin area, as well as in the Valles caldera. Preliminary inspection of data obtained during the 1981-82 field seasons suggests the presence of an anomalous conductor associated with the Eastern Sierra Front, but does not indicate the presence of a high level magma body associated with Mono Craters.

B. Physio-chemical Processes Associated with the Genesis of Primitive Crust

We are continuing our interpretation of geophysical/electromagnetic experiments on Iceland and adjacent areas of the Mid-Atlantic Ridge. A magnetotelluric field experiment was mobilized in collaboration with the Icelandic National Energy Authority during the summer of 1982. It verifies that crustal thickening due to underplating provides a significant contribution to mechanisms of crustal genesis in this region. According to this model, mantle derived melt accumulates in a thin layer at the base of the crust beneath the neovolcanic zone. With time, this melt cools, solidifies, and accretes to the base of the crust leading to crustal thickening. The crust increases in thickness from 8-10 km directly beneath the neovolcanic zone to an average value of 10 km for the generally older ($\sim$ 10 m.y.) Iceland plateau. Hence, segregation of material from a significant volume of the mantle and continued crustal underplating may persist well beyond the boundaries of surface manifestations of volcanic activity. There is a strong possibility that such a process may be operational beneath the Basin and Range Province and the Salton Trough in the western U.S.

C. Magnetotelluric/Magnetic Variation Field System

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

D. Theoretical Models of Electromagnetic Induction Phenomena

General

The application of geophysical techniques to problems in the field are often constrained by the adequacy of modeling algorithms necessary to interpret the actual data. Because of this we have devoted a significant part of our research effort to developing models to simulate the electromagnetic response of representative geologic structures.

Modeling Three-Dimensional Induction Effects

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

Bias of Long-Period Magnetotelluric Response Parameters Due to Lateral Heterogeneities

A simple three-dimensional model has been used to evaluate the bias of long-period magnetotelluric principal resistivity values in the presence of modest current channeling at shallow depth. It was shown that conventional MT parameters are not always good indicators of the degree to which the observed resistivities depart from a quasi one-dimensional response function. Large skew is sometimes associated with minimal bias. But unfortunately, small skew is sometimes associated with maximal bias. Also it appears that the geometric mean of the maximum and minimum principal resistivity values at a site may be regionally biased in a statistical sense for a large number of sites. A smaller bias can be achieved if one can identify the class of conductivity structures associated with local perturbations of the long period response parameters.

Finite Source Fields Coupled to Lateral Conductivity Heterogeneities: Effects on Magnetotelluric and Magnetic Gradiometric Deep-Sounding Experiments

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

Contractor:	CALIFORNIA INSTITUTE OF TECHNOLOGY Seismological Laboratory, Division of Geological and Planetary Sciences Pasadena, CA 91125
Contract:	DE-AT03-83ER13120
Title:	<u>In</u> <u>Situ</u> Stress in Deep Boreholes
Person in Charge:	T. J. Ahrens

<u>Scope of Work</u>

Knowledge of the <u>in</u> <u>situ</u> stress field 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 attempting to turn it into a useful geophysical tool. However, we have not yet used it as it is finally intended to be used; that being to determine the six independent values of the stress tensor at one point and to routinely log many data points along a narrow (e.g., 6" diameter) borehole. We are currently carrying out tests with the present instrument in the laboratory and in a Colorado oil shale mine. We expect in the next year to design, construct and test a smaller 6" version of the present experimental apparatus and test it in the laboratory as well as a series of scientific drill holes near the San Andreas fault in Southern California.

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.

Our current work for DOE is focused on the RARGA system, which is a self-contained, mobile laboratory designed to make precise elemental and isotopic abundance measurements of the noble gases in terrestrial fluids. Recently road tested, the lab will be deployed from July 1 to late October 1983 in Yellowstone National Park for a detailed study of the noble gases from hot springs in that important tectonic hot spot. Our preliminary work on Yellowstone samples has identified a radiogenic argon component that is closely correlated with mantle derived helium of high $^3He/^4He$ ratio. The use of such correlation techniques to identify gas components from the mantle or other well-characterized sources is an important thrust of our research. After the intensive study planned for mid-1983 at Yellowstone, we hope to have improved greatly our understanding of the various geothermal basins at Yellowstone, i.e., how they are related to one another and how they are coupled to mantle sources.

Another project (now in press) with RARGA concerns noble gas solubilities in brines. Those studies have provided thermodynamic data that can place constraints on the physical structure of gas-bearing solutions and help to model the transport of noble gases in natural hydrothermal circulation systems.

A RARGA manuscript in preparation concerns noble gases in water and steam samples from the Lardarello geothermal field in Tuscany, Italy. Helium isotopic, argon isotopic, and elemental data from all the noble gases vary considerably from sample to sample, with trends beginning to develop when the data are plotted versus position in the field.

Turning to other projects, we are studying the solubility of noble gases in silicate melts as a function of their temperature and composition. An isotopic dilution technique affords considerable precision in these measurements, which are being made in collaboration with the Carmichael group at LBL.

A study of noble gases in diamonds of two types and from a number of geographical locations is well underway, with numerous samples now on hand and a new furnace, for outgassing the diamonds without generating excessive blanks, under construction.

A collaboration with Craig's lab at UCSD has made definitive measurements, which are being readied for publication, on the isotopic composition of neon from submarine basalts.

A number of other projects are in preliminary stages, including work on samples from the Baca geothermal field in the Valles caldera, New Mexico.

Contractor: UNIVERSITY OF CALIFORNIA
Department of Geology and Geophysics
Berkeley, California 94720

Contract: DE-AM03-83ER13100

Title: Advective-Diffusion/Dispersion Transport of Chemically Reacting Species

Person in Charge: H. C. Helgeson

Scope of Work

This project is aimed at development of a comprehensive transport model for hydrothermal systems. The model will be used to describe mass transfer using an advection-diffusion/dispersion equation coupled to mass action equations representing reversible chemical reactions including aqueous complexing, oxidation/reduction equilibria, ion-exchange with stationary minerals, and precipitation/dissolution reactions. The numerical approach is based on an implicit finite difference scheme which provides for simultaneous coupling of fluid flow, diffusion, and chemical reactions. This method is superior in numerical stability and accuracy to its explicit analogs. The model will be used to interpret phase relations in hydrothermal/geothermal systems, weathering profiles, and altered sediments where quantitative comparisons can be made between the predicted and observed spatial distribution of secondary mineralization. More accurate calculations can then be carried out to evaluate the geochemical and environmental consequences of acid rain, reservoir flooding, and toxic waste disposal.

Contractor:	UNIVERSITY OF CALIFORNIA LOS ANGELES Institute of Geophysics and Planetary Physics Los Angeles, California 90024
Contract:	DE-AT03-81ER10965
Title:	Adiabats and Grüneisen Parameter at High Temperatures and Pressures
Person in Charge:	R. Boehler

Scope of Work

It is generally accepted that the removal of heat produced by radioactive sources from the earth's interior is only possible by a convecting mantle. Since the earth's mantle is convecting at a high Rayleigh number, a representative temperature profile for the mantle as a function of depth is probably following the adiabatic temperature profile closely over most of its extent.

We have calculated a thermal model for a three-layer mantle of a self-gravitating earth. The model is based on measurements of the adiabatic gradient at high pressure and high temperature of olivine and MgO and the empirical law $(\partial T/\partial P)s = (\partial T/\partial P)_{s,O} \exp(m(^{V}/V_{O}-1))$ found from recent measurements on compressible materials, such as the alkali metals lithium, sodium, potassium, and cesium. The volumes were calculated from a first order Birch equation using laboratory data of B, the bulk modulus, and its pressure and temperature derivatives. $(\partial T/\partial P)_{s,O}$ was calculated from laboratory data on the density, specific heat, and the thermal expansion coefficient. The model yields the pressure, the acceleration due to gravity, the density, the adiabatic temperature, the Grüneisen parameter, the thermal expansion coefficient, and the isentropic bulk modulus as a function of depth. The temperature at 100 km depth is taken as 1600 ± 100K. From our calculations the adiabatic temperature gradient at the top of the upper mantle is 0.45 Kkm^{-1} and decreases to 0.21 Kkm^{-1} at the bottom of the lower mantle. The adiabatic temperature difference across the whole mantle is 780 ± 100 K. The Grüneisen parameter decreases from 1.17 to 0.92 in the upper mantle and from 1.44 to 1.00 in the lower mantle.

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 attempting to develop 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 crystals 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. So far we have made a few analyses of the glasses for both H_2O and CO_2 which suggest pressures of entrapment above 2 kbar (2×10^8 Pa). We are struggling to make these analyses more accurate (to about 0.1% H_2O and 0.01% CO_2). The principal problems are the difficulty of getting the gases completely out of the viscous melt in a way that yields a small enough blank. Results on two samples of the Bishop Tuff from California, suggest variable concentrations of H_2O and CO_2 in melt inclusions in quartz phenocrysts from different samples of the Plinian ash fall. We are checking our extraction techniques further in the light of this apparent, and unexpected variability. We hope to be able to confirm or improve Hildreth's estimates of the range of vapor pressures within the body of magma before its extrusion. Future studies may reveal the change in magmatic vapor pressures with time as the body of magma developed prior to the cataclysmic eruption. Comparison of such data with similar data on recent rhyolites from Mono Craters and the Inyo Domes may help assess the current state of the (Mammoth Lakes) magma body.

Contractor:	COLUMBIA UNIVERSITY Lamont-Doherty Geological Observatory Palisades, New York 10964
Contract:	DE-AS02-76ER03134
Title:	I. Tectonics of the Eastern Aleutian Arc
Person in Charge:	K. Jacob, E. Hauksson, and L. Sykes

Scope of Work

The physical processes associated with the tectonics of a classic, subducting plate margin and its volcano-magmatic arc are studied mostly by seismological methods. A 12-station telemetered seismic network with one- and three-component, short-period high-gain, and broad-band medium-gain sensor combinations with digital event-detection and digital recording provides the data for this basic tectonic study. The data are analyzed for velocity and attenuation structures in the crust and upper mantle from travel time and waveform information, for spatial distributions of seismicity in the subduction zone and volcanic arc using hypocenter locations, for deformation and stress patterns using focal mechanism solutions, and for the distribution of magma and its migration in the volcanic arc using all of the above methods. The seismic network is centered on the Shumagin Islands Seismic Gap, a >300 km-long arc sediment that has a 30 to 99% probability for a great ($M_W \sim 8$ or larger) earthquake to rupture the plate boundary during the next two decades.

Recent results have shown a northward dipping Moho structure in the forearc region; a systematic increase of stress drop with seismic moment of thrust zone earthquakes with magnitudes $M_L = 2$ to 6; a slightly enhanced seismicity at shallow depths (~ 25 km) and in the Benioff-zone (<250 km), that in time coincided with a geodetically detected, mostly aseismic slip event (amplitude 80 cm!) between the descending Pacific slab and the overriding mantle of the North American plate; the slip was restricted to depths between ~ 20 and ~ 120 km, and in time also coincided (1978-1980) with a two-year eruptive quiescence of the otherwise active Pavlof Volcano whose seismicity we monitor. The deep slip event further stressed the presently locked, shallow thrust zone and thus should have brought it closer to failure.

Although this study is focused on basic tectonic processes, important results concern the seismic, volcanic and tsunami hazards to offshore structures for oil exploration in outer continental shelf regions within and directly adjacent to the Shumagin seismic gap and network.

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

Contract: DE-AC02-76ER04054

Title: II. Fluid Transport Properties of Rock Fracture

Person in Charge: T. Engelder and C. Scholz

Scope of Work

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

The initial time-dependent transmissivity experiments have been run using Barre Granite and a pelagic limestone. The experimental conditions include confining pressure of 50 MPa, a pore pressure of 20 MPa, and a variety of temperatures to 150°C. The experiments have lasted up to eight days with flow rates driven by a pressure difference of about 0.5 MPa for the granite with a rough surface and 5 MPa for a limestone with a smooth surface. Flow rate for the granite increased with time whereas the flow rate within the limestone slowed with time. Surfaces were examined with a profilometer showing that the grain boundaries of the granite eroded with time thus increasing the aperture of the joint. Erosion of contact points on the limestone allowed the limestone to close in time. Chemical analyses showed that solubility of the granite increased with temperature.

As a continuation of our work on the time-dependent transmissivity of joints, we propose experimental and analytical investigations in five areas. The principal work is to document the effect of water rock interaction on joint transmissivity at various pressures and temperatures within the upper crust. Associated projects include analyzing the pore-fluid for major elements in solution as a result of the rock-water interaction as well as x-ray analyses of the minerals deposited on the joints. The surface topography of joints will be studied to understand the effect of topography of joint stiffness and the effective stress law of joints. In another study the effective stress law and the cubic law will be reexamined using nonreactive pore fluids. Finally we plan a study of the retention of radionuclides on rock fractures to assess the flow paths along joints of various roughnesses.

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

Contract: DE-AC02-83ER13096

Title: Energetics and Thermochemical Properties of Rocks and Minerals

Person in Charge: J. B. Thompson, Jr.

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 heat capacities, and enthalpies and entropies of transformations. Some of the transformations of concern are homogeneous (structural changes within single mineral grains), others are heterogeneous, involving the appearance or disappearance of mineral phases of a given phase assemblage. Heating of many minerals results in the release of volatile species that may either create a fluid phase or add substance to a pre-existing one.

Much of the requisite thermochemical data to handle the above problems are unknown or inadequately known. We propose to augment the thermochemical data base for rocks and rock-forming minerals by high-temperature (25 to 1700°C) differential scanning calorimetry, coupled where appropriate with simultaneous controlled-atmosphere thermogravimetry. We also intend to investigate the energetics and kinetics of homogeneous transformations in important rock-forming minerals. In addition, the high-temperature heat capacities and heats of fusion of minerals and mineral series comprising certain igneous rocks will be investigated. The thermodynamic data and models generated from them not only are of concern to metamorphic and igneous petrologists, but have potential application in such fields as the extraction of geothermal energy, nuclear waste disposal, terrestrial heat-flow studies, and the geochemistry of ore deposits.

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

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

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 the two groups headed by W. C. Luth and M. J. Davis at the Sandia National Laboratories. One of the motivations of the proposed cooperative research is the availability of the unique Magma Simulation Facility at the Sandia National Laboratories.

The 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 now in progress. For a few of these core samples and the other basalts obtained from the Hawaii Geothermal Project-A (HGP-A hole), both thermal diffusivity and C_p have been determined as function of temperature to 750°K. Analysis of the thermal data will be made in terms of chemistry, glass content and mineralogy of these core samples.

Compressional wave velocity (V_p) and attenuation (Q^{-1}) measurements are proceeding on melts of two plagioclase compositions: $Ab_{80}An_{20}$ and $Ab_{50}An_{50}$, where Ab stands for albite ($NaAlSi_3O_8$) and An stands for anorthite ($CaAl_2Si_2O_8$). Plagioclase is among the major constituents of Hawaiian basalts. Ultrasonic measurements on $Ab_{80}An_{20}$ have been carried out at 1500°C over the frequency range 5-20 MHz. Measurements on $Ab_{50}An_{50}$ have been carried out at 1475 and 1500°C, over the same frequency range. The data indicate that for both samples the relaxation times are on the order of 10^{-7} second near 1500°C.

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

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

Contract: DE-AC02-76ER02534 A008

Title: Seismology of Crack Formation

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 Tap 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 research program, we are interested in both passive and active seismology. We constructed 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.

Our study areas include the hot dry rock fracture system at Fenton Hill, magma lens in Kilauea Iki, deep and shallow volcanic tremor sources under Kilauea, inside Mt. St. Helens, and Long Valley. We obtain data from our own event recorders as well as those collected by other universities and government agencies in the U.S. We are also collecting data from Mexico, Japan, New Zealand, and France through cooperation with universities and research institutions in these countries. We are also developing a borehole seismograph which can be operated at high temperature.

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

Contract: DE-AC02-78ER04972

Title: Microcrack Technology

Person in Charge: G. Simmons

Scope of Work

The objective of this project is to demonstrate the usefulness to the DOE energy programs of various aspects of microcracks in rocks. Open microcracks control such important properties as permeability, electrical conductivity, and velocity of elastic waves. Healed microcracks provide data on the history of the rock and evidence that may be useful for predicting future physical and chemical characteristics. Potential practical applications include site characterization for waste repositories, estimation of changes of permeability of rock in situ due to changes of temperature associated with production in a hot-dry-rocks geothermal system, prediction behavior of certain isotopes from radwaste in granitic rocks, and improvements in 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).

At the present time, we are emphasizing studies on the geographical extent and physical conditions of the mobilization and migration of rare earth elements and uranium through microcracks in granitic rocks. In core from the Redstone Quarry (New Hampshire) uranium is present in sealed microcracks throughout 3000 feet and in altered mafic minerals within 2 cm of the cracks. In cores of the Sherman granite (Wyoming) U and REE's occur in minerals in partially sealed microcracks in cores separated 30 km; the minerals appear to be identical over the distance. In wall rock of the Geevor (tin) Mine in the Cornwall district of southwest England, U occurs in microcracks and was apparently deposited from hydrothermal fluids after the main tin mineralization. In a reconnaissance examination of a few borrowed samples of the granites near Bangor, Maine, we observed that several minerals that typically contain U are present in microcracks. On the basis of these observations, it appears that transport of U in granitic rocks occurs in microcracks and may be controlled largely by the characteristics of the cracks when they are open.

We plan to examine further the microcracks in the granites near Bangor, Maine, for evidence of REE- and U-mobility. John Ferry has shown previously that a widespread hydrothermal system operated in these granites and has estimated total water flux, pressure, and temperature. We plan also to begin work on microcracks (both open and healed) in eastern black shales.

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 is to determine what chemical and physical changes occur during the diagenetic transformation of calcareous ooze to chalk.

Chalk comprises a large part of the marine carbonate record and has been found, in the North Sea, to host recoverable quantities of oil. Chalk deposits hold the promise of future oil fields; thus, an understanding of the formation of chalk is essential to understanding and exploiting its capacity to produce oil.

Marine chalks occur in many stages of diagenesis, from plastic to hard, impermeable limestone. The seemingly haphazard interlayering and localized occurrence of different types of chalks affects the extent and productivity of hydrocarbon pools. The question of why the diagenetic stage of contiguous layers is so variable has yet to be answered.

At the University of Minnesota we have developed a hydrothermal reaction system in which we can expose soft calcareous sediment to elevated temperatures and differential pressure. Samples of tropical South Atlantic calcareous ooze containing differing amounts of low-Mg calcite, aragonite, biogenic opal, and detrital silicates are subjected to accelerated diagenetic conditions in the laboratory. The sediment pore fluids are sampled by a constant-head flow-through technique which allows us to monitor changes in both fluid chemistry and permeability over the course of an experiment. Thus, we can observe the interaction of in situ chemical and physical changes during diagenesis.

Recently we formed a very hard and pure chalk. After initial compaction and dewatering, heating caused further compaction and an increase in permeability. Pressure solution and recrystallization of biogenic high-Mg calcite to low-Mg calcite was indicated by a decrease in pore fluid calcium concentration accompanied by a release of strontium and magnesium from the rock to the pore solution.

The uptake and release of such elements as magnesium will be greatly affected by the percentage and types of clays present in the sediment, the initial pore fluid chemistry, and the diagenetic conditions. We shall examine the differences in chalk diagenesis caused by varying clay percentages and pressure-temperature conditions. We hope to be able to associate natural chalk textures and compositions with differing diagenetic conditions and initial compositions. The changes which occur during laboratory diagenesis also indicate what types of changes should occur in reservoir chalks subjected to fluid injection to enhance petroleum recovery.

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

Contract: DE-FG01-82ER12018

Title: I. Studies in Geophysics

Person in Charge: T. M. Usselman

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

The studies include: (1) problem-oriented studies such as demands on geophysical knowledge in connection with climatic variations, fresh water resources, mineral resources, geothermal and other energy sources, 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 Bull, John C. Crowell, Nicholas C. Matalas, J. Murray Mitchell, V. Rama Murthy, Raymond G. Roble, and Ferris Webster; and Thomas M. Usselman, staff officer.

Studies Completed

- ENERGY AND CLIMATE (Roger R. Revelle, panel chairman). Publisher in 1977 (158 pp.).
- ESTUARIES, GEOPHYSICS AND THE ENVIRONMENT (Charles B. Officer, panel chairman). Published in 1977 (127 pp.).
- CLIMATE, CLIMATIC CHANGE, AND WATER SUPPLY (James R. Wallis, panel chairman). Published in 1977 (132 pp.).
- THE UPPER ATMOSPHERE AND MAGNETOSPHERE (Francis S. Johnson, panel chairman). Published in 1977 (169 pp.).
- GEOPHYSICAL PREDICTIONS (Helmut E. Landsberg, panel chairman). Published in 1978 (215 pp.).
- IMPACT OF TECHNOLOGY BN 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 ESTUARIES (L. Eugene Cronin and Charles B. Officer, panel co-chairmen). In press: expected to be available in Spring 1983.

Studies in Preparation

- <u>Explosive volcanism: Inception, evolution, and hazards</u> (Francis R. Boyd, panel chairman). Publication is expected in 1983.
- <u>Groundwater contamination</u> (John D. Bredehoeft, panel chairman). Publication is expected in 1983.
- <u>Geophysical data and public policy</u> (Michael A. Chinnery, panel chairman). Publication is expected in 1983.
- <u>Atmospheric electrical environment</u> (E. Philip Krider and Raymond G. Roble, panel co-chairmen). Symposium scheduled for May 1983.

Studies Under Active Consideration

- Recent Crustal Movements

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, nonrenewable 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 to the scientific community a basis for judgments with respect to the development of the basic science of geophysics in the broad sense and with respect to the relative importance to society of the developments within various branches of geophysics.

Contractor:	NATIONAL ACADEMY OF SCIENCES/ NATIONAL RESEARCH COUNCIL Washington, DC 20418
Contract:	DE-FGO1-82ER12018
Title:	II. Committee on Seismology
Person in Charge:	J. W. Berg, Jr.

Scope of Work

The Committee on Seismology meets twice a year to discuss current topics of major importance relevant to seismology, to review with government agency personnel, in particular, the actions that have resulted from recommendations of the committee and its panels, and to take actions to assure a healthy science which is in a position to provide maximum benefits to the nation and to society. These activities are directed at fulfilling the fundamental mission of the committee, as follows: to maintain an active surveillance of major trends in seismology and of developments related to seismology in allied 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 seismological-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.

Current Activities

A workshop on seismographic networks was held in March 1982, to address problems associated with the global, regional, and national networks. The report is currently in the process of publication and was distributed by July 1, 1983.

A report on data problems in seismology has been written and is being revised. The revised draft was submitted to the Committee on Seismology for discussion at the next meeting on April 14-15, 1983.

The Panel on Seismological Studies of the Continental Lithosphere is revising its report. The subject matter corresponds with the International Program on the Lithosphere.

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

Contract: DE-FG01-82ER12018

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

Person in Charge: W. L. Petrie

Scope of Work

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

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

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

The committee represents both the National Academy of Sciences, which is the U.S. voting corporate member of IAGC, and geochemists of the United States. The committee supports the IAGC and its council with annual dues, active participation in nominations for IAGC and council offices, the nomination of NAS delegations to IAGC general assemblies and council meetings, and organizing and administering travel grant programs to help our ablest young geochemists attend and present their papers at the concurrently convening quadrennial International Geological Congress. The IAGC met in Paris in 1980: the next meeting is scheduled for Moscow in August 1984.

The committee, which informs members of activities and advances in geochemistry, sponsors symposia and scientific meetings and establishes ad hoc subcommittees or panels, as appropriate, to report on timely topics concerning geochemists both in the United States and abroad. For example, the committee interacts with the U. S. Geodynamics Committee via geochemists assigned to report on specific topics of interest, reviews documents related to radioactive-waste disposal, and arranges workshops, such as that entitled "Basic Research in Organic Geochemistry Applied to National Energy Needs," held at the University of South Florida, St. Petersburg, in December 1980 (gratis copies are available from Mr. W. L. Petrie, NAS-NRC 2101 Constitution Ave., Washington, DC 20418). A study entitled the "Future of Geochemistry" is planned as a sequel to "Orientations in Geochemistry" (1973) by the Panel on Orientations for Geochemistry under the chairmanship of R. M. Garrels.

M. L. Crawford is currently organizing a symposium on fluid migrations in the lithosphere. A major international activity was the Fifth International Conference on Geochronology, Cosmochronology, and Isotope Geology, June 27-July 2, 1982, in Nikko National Park, Japan; the chairman of the committee attended this conference.

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

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

Contract: DE-FG01-82ER12018

Title: IV. U.S. Geodynamics Committee

Person in Charge: P. J. Hart

Scope of Work

The United States Geodynamics Committee (USGC) was established in 1969 to foster and encourage studies of the dynamic history of the earth, with appropriate attention to both basic science and applications. The USGC work is based largely on the recommendations developed by its 16 reporters and their associated groups. In 1976, at the request of the Geophysics Research Board, the USGC began planning U.S. research activities in solid-earth studies in the 1980's. In the years following, the committee devoted a considerable effort to the program, leading to the report, Geodynamics in the 1980's, published in April 1980. This report urges that research emphasize the origin and evolution of continental and oceanic crust, the continent-ocean transition, the relation of mantle dynamics to crustal dynamics, and a geodynamic framework for understanding resource systems and natural hazards.

Members of the committee are John C. Maxwell (chairman), Don L. Anderson, Bruce A. Bolt, Francis R. Boyd, B. Clark Burchfiel, William C. Kelly, David L. Mackenzie, Prank Richter, Jack E. Oliver, 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 February 1983, the list is as follows:

Fine structure of the crust and upper mantle	J. E. Oliver
Evolution of oceanic lithosphere	J. R. Heirtzler
Large volume experimentation	R. C. Liebermann
Application of isotope geochemistry to geodynamics	R. E. Zartman
Geodynamic modeling	D. L. Turcotte
Drilling for scientific purposes	E. M. Shoemaker
Magnetic problems	C. E. Helsley
Plate boundaries	J. C. Maxwell
Geodynamic data -- users' 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
Celebration of Polar Years and IGY; and Geophysics Film Series	C. L. Drake

The results of the work of the USGC and reporters have been issued In annual reports (published or unpublished). 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 also recommended that a national Continental Scientific Drilling Program be organized to facilitate the necessary communication and coordination. As a result of the response by federal agencies to the report recommendations, a Continental Scientific Drilling Committee was created in January 1980 under the Geophysics Research Board. The committee actively encourages the development of this drilling program, including add-on investigations in mission-oriented holes and holes dedicated to basic scientific objectives.

The reporter for plate boundaries organized cross sections across ancient plate boundaries. Eighteen such cross sections are in preparation of which 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 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. Preparation of the maps and cross sections was essentially complete at that time. Publication of the results will begin in 1983.

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. It is likely that this effort will lead to 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.

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 Interunion Commission on the Lithosphere. The secretariat of that commission is located in the United States; basic support for the practical operations of the secretariat is provided through the USGC. The international program is developing in a manner partly analogous to the new plans of the USGC. In particular, the emphasis has shifted toward the continents and the continent-ocean transition for reasons of scientific and societal relevance, especially in the areas of resources and natural hazards. The USGC will serve as the U. S. counterpart to the Interunion Commission on the Lithosphere.

The USGC organized a workshop on problems of the lithosphere which was held in March, 1982, in Austin, Texas. The workshop focused primarily on areas of scientific controversy in connection with the lithosphere with the expectation that this will provide guidance regarding the most productive areas for research in the coming years. Proceedings of this workshop are expected to be published in 1983.

Future Work of the USGC

1. Identify actions that can be taken in response to recommendations of the reporters.

2. Identify new priority topics to which the committee can react directly or via a reporter.

3. Address actions to be taken in response to the discussions at the workshop on the lithosphere.

4. Address the program of the International Lithosphere Commission what action should the USGC take? 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: V. Continental Scientific Drilling Committee

Person in Charge: R. S. Andrews

Scope of Work

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

Members of the CSDC are the following: Eugene Shoemaker (Chairman), Lawrence Bonham, Lawrence Cathles, William Dolan, Charles Drake, James Eidel, Howard Gould, Bob Greider, John Hermance, Charles Mankin, L. J. Patrick Muffler, 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 Committee, five of which currently exist: Thermal Regimes; Basement Structures and Deep Continental Basins; Mineral Resources; Drilling, Logging, and Instrument Technology; and Sample Curation and Data Management. The CSDC established three ad hoc task groups to address specific research drilling targets: the Salton Sea Geothermal Field in California, the Valles caldera in New Mexico, and the Creede Mining District in Colorado.

A DEW (Drilling Early Warning) NEWSLETTER was established by the Committee as its mechanism for communicating with the scientific community. This aperiodic newsletter is distributed to approximately 1700 researchers in universities and other academic institutions, industry, government laboratories and geoscience administrators, geoscience societies, and 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 efforts to the benefit of all concerned. It also provides information on the Committee's activities and scientific objectives, announces important meetings and publications, and serves as a forum for interested scientists to exchange information related to drilling. Five newsletters have been distributed to date.

In 1980, the CSDC reviewed the scientific plan for add-on investigations to a drilling activity by industry in northern Illinois and issued a report entitled Comments of the Continental Scientific Drilling Committee on the Document "Illinois Deep Hole Project -- Preliminary Plan". The research proposed in this plan has been completed by the investigators, was reported at 1981 annual meetings of the AGU and the GSA, and will be published in a special issue of the AGU's Journal of Geophysical Research.

The Panel on Thermal Regimes has completed a report to CSDC recommending initiation of a new, highly focused scientific drilling program aimed at understanding the roots of hydrothermal systems related to young magmatic intrusions. Primary targets are high level silicic caldera systems of the Valles caldera and the Long Valley-Inyo-Mono region. The importance of the Yellowstone system is discussed in this report; further considerations will be made concerning the viability of this target for the future. The report also recommended making use of add-on investigations wherever possible to further the understanding of the thermal regime of the Salton Trough. It is anticipated that the report will be issued by the CSDC by the Summer of 1983. A discussion of the targets identified by this Panel, as well as those identified by the Panel on Mineral Resources, will be presented at a symposium in May 1983 during the GSA joint Cordilleran-Rocky Mountain Section meeting in Salt Lake City, Utah.

The CSDC learned of an industry drillhole in the Salton Sea Geothermal Field that may provide an opportunity for add-on investigations, including deepening it from its planned total depth of 12,000 ft to about 18,000 ft. 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 panel on Mineral Resources presented a report to the CSDC recommending major emphasis on drilling to study stacked hydrothermal mineral deposits in four mining districts: Creede, Red Mountain, Tonopah, and Butte. The report is being reviewed for issuance by CSDC, probably in mid-1983.

The Panel on Sample Curation and Data Management developed a report concerning curation of drilling samples and ancillary data and recommended means for the formation of an initial organization to handle such activities. 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 1983.

The Panel on Basement Structures and Deep Continental Basins has addressed dedicated drilling based on the U. S. Geodynamics Committee Workshop on Problems of the Lithosphere, the COCORP seismic profiling program, and ocean-continent and ocean margin transect projects, as well as other compilations of geological and geophysical data. The Panel proposed a deep research hole in the Appalachians for its highest priority target; it is preparing a report on its findings for the CSDC. The Panel will also hold special information sessions on research drilling at various future sectional meetings of the GSA.

The Panel on Drilling, Logging, and Instrument Technology is developing plans for a workshop in late 1983 on diagnostics and drilling to develop dialogue between scientists and the drilling/logging community. Focus for the workshop will be on scientific measurements required for research drilling projects recommended by the other panels. The Panel is studying the state of the art in slim-hole drilling and logging and will identify advanced technology required to meet scientific needs. The efficacy of turbine drilling in crystalline rocks is also being addressed by the Panel.

Contractor:	NATIONAL ACADEMY OF SCIENCES/ NATIONAL RESEARCH COUNCIL Washington, DC 20418
Contract:	DE-FG01-82ER12018
Title:	VI. Geological Sciences Board
Person in Charge:	J. W. Berg, Jr.

Scope of Work

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

The Board maintains an awareness of the national, societal, scientific, and technological demands that geological 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 of the Board will include the following:

1. Identify basic research opportunities and applied research needs.

2. Review new technology and recommend ways by which the geological 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 geological sciences.

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

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

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

7. Provide advice to governmental 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.

Current Activities

1. Committee on Geological Mapping (formerly Working Group on Mapping)

The Working Group supported by the Board has been transformed to a committee. The types of maps that are needed by users are being determined by a questionnaire that has been sent to a statistical sample (3 percent of a population estimated at 70,000 users). Separate funding has been sought for committee activities, but supporting services are provided by the core support of the Board. The data base provided by the questionnaire will be analyzed by the committee and a report will be published. The raw data will be made available to other organizations on request.

2. Ad Hoc Committee on Public Education and Information

• The ad hoc committee has met twice and will recommend to the Board that a committee be established to report on needed improvements in geological education in elementary and secondary schools, primarily.

A workshop may be organized by the committee to identify problems, to compile information, and to make some recommendations pertinent to education in the geological sciences.

3. Working Group on Instrumentation

The working group was formed in October 1981, and members are from the Geological Sciences Board, the American Geophysical Union, the Geological Society of America, and the Mineralogical Society of America. This group investigated the needs for geochemical instrumentation, but it was recognized that the needs for instrumentation are acute in all the geological sciences. An interim report has been submitted to the Board, and the information will be submitted to the involved professional societies. This information will be included in reports of the Board. The working group will be disbanded during this year.

4. Committee on Global and International Geology

A committee has been appointed to study and to report on the role that U.S. scientists can play in helping to meet national, societal, and scientific requirements for international information. The study will include an examination of the policies that control the flow of international information.

5. Geological Sciences Board Workshop (June 1981)

The workshop was supported by core support of the Board. The purpose was to report on the status and outlook for the geological sciences. The report has been condensed and is in the process of preparation for publication.

The following committees are funded separately from core support of the Board:

6. Committee on Opportunities for Research in the Geological Sciences

The Board was requested by the Director of the Division of Earth Sciences, National Science Foundation, to prepare a report on the state of the science and to recommend policy for the decade of the 1980s relevant to the academic community and the National Science Foundation. A committee was appointed which has met twice. An interim report was submitted to NSF in November 1982 and a final report has been drafted. It will be submitted to NSF in July 1983.

7. Committee Advisory to the U.S. Geological Survey

   A committee has been appointed to provide advice to the Director of the U.S. Geological Survey on the geological programs of that agency.

8. Committee on Seismology, U.S. National Committee for Geochemistry, and Committee on Geodesy.

   These committees are active and reports in seismology and geodesy are in progress.

Products

The standard product is a report. There have been five reports either published during the past year or in press. Two of these reports have been funded by core support of the Board.

1. Geological Aspects of Industrial Waste Disposal, National Academy Press, 1982. (NAS Program Initiation funds and core support.)

2. Geological Research Applicable to Major Scientific and Societal Problems (in preparation).

Three reports have been supported by external funds to committees operating under the purview of the Geological Sciences Board.

3. Fostering Increased Cooperation Between Geological and Materials Sciences, National Academy Press, 1982.

4. Options for Scientific Ocean Drilling, National Academy Press, 1982.

5. Seismographic Networks: Problems and Outlook for the 1980s (in press).

Contractor:	UNIVERSITY OF NEVADA SEISMOLOGICAL LABORATORY Reno, Nevada 89557-00180
Contract:	DE-AS08-82ER12082
Title:	Studies of Magma Chambers in the Western Great Basin
Person in Charge:	A. Ryall

Scope of Work

This research is in support of the Continental Scientific Drilling Site Assessment Program and is aimed at defining the configuration of the magma chamber in Long Valley caldera, California; characterizing seismicity associated with magma injection in the caldera; searching for evidence of a possible buried cauldron complex in the Adobe Hills area; 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 1982 we deployed five additional seismic stations in the southwest part of the Long Valley caldera, in an area where spasmodic tremor has been observed on at least eight occasions. The US Geological Survey has since reinstrumented seven of the caldera stations, and we are redeploying our equipment at sites north of the caldera. 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 ten readings for the location of earthquakes in the Mammoth Lakes area with magnitude $M_L<1.5$.

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 broadband (0.05-30 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 one station is operating at a mine-tunnel station south of Reno. A second station will be installed in a mine at Mina and 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 February 1983 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 is being assembled that will provide for event detection and conversion to digital format of the analog data transmitted to the Reno data facility. This will facilitate analysis of large numbers of earthquakes and will make possible some limited waveform analysis of the network data.

C. Interpretation

1. Geometry of the Magma Chamber

In order to outline the three-dimensional geometry of the Long Valley magma chamber, we are studying propagation effects for more than a 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. Current efforts are focused on determining the depth to the top of the main magma body in the central part of the caldera and defining the shape of an apparent tongue of magma in the southern ring fracture system. We are also investigating anomalous propagation effects that suggest the presence of magma bodies in areas outside Long Valley caldera.

2. Magma Injection

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. A detailed study is in progress of a major burst of activity that occurred in this area in early January 1983.

3. Focal Mechanisms

In a paper completed for publication, 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: STATE UNIVERSITY OF NEW YORK
Albany, New York 12222

Contract: DE-AC02-82ER13013

Title: I. Thermal Evolution of Sedimentary Basins

Person in Charge: T. M. Harrison

Scope of Work

This investigation utilizes the ability of the $^{40}Ar/^{39}Ar$ thermochronological approach to resolve the age, temperature, and, in some cases, the duration of thermal events experienced by microcline-bearing sedimentary rocks. We have determined that detrital microcline grains in sedimentary strata preserve a record of thermal events in the temperature range 100°C to $\sim$ 200°C, depending on length of heating and several mineralogical variables.

Having shown the utility of this approach in a study of a basin formed in a compressional environment (southern San Joaquin Valley, California), we intend to turn our attention to the evolution of basins formed in extensional environmental with an eye to testing existing hypotheses of basin development.

Our initial study will focus on the Albuquerque Basin in the Rio Grande Rift. Microcline separates obtained from both deep drill holes and surface samples will be analyzed by the $^{40}Ar/^{39}Ar$ age spectrum approach. Analysis of the coexisting apatites by fission track dating may also prove useful. A field program will relate the samples at depth with the structural history of the basin. This data should allow resolution of the time-temperature history of various portions of the basin providing sufficient information to assess the validity of simple mathematical models of rifting and subsequent subsidence.

A companion study will be directed at learning more about the transport kinetics of Ar in microcline over geological periods. $^{40}Ar/^{39}Ar$ analyses of microcline separates from the Fenton Hill deep drill holes will further constrain paleo-temperature estimates based on microcline thermochronology.

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

Contract: DE-ACO2-81ER0933

Title: II. Crustal Stretching and Subsidence in Sedimentary Basins

Person in Charge: J. F. Dewey

Scope of Work

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

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

The Austro-Alpine nappe complex of eastern Switzerland, together with the southern Alps, represents the thinned continental crust of the southern margin of the Alpine trough whose demise led to the growth of the Alps. Both the continental basement and the cover are exceedingly well exposed in eastern Switzerland. By detailed and systematic structural mapping in parts of the Austro-Alpine Nappes, it will be possible to reconstruct, with great precision, the stretching factor, β, and its variability across the basin margin from which the subsidence and thermal history of a large rift complex can be deduced. From the results of this analysis it will be possible to derive a basic picture of the mechanical behavior of the stretched crust-lithosphere during the attenuation process and a knowledge of lithospheric behavior during the prolonged period of Jurassic-Cretaceous cooling. A systematic and very detailed study is also being made of the stratigraphic-structural-thermal maturation history of the intracontinental Pennsylvanian-Permian basins and troughs of Colorado, Texas, and Oklahoma and will be integrated with the Alpine results.

Contractor: 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 will be 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, Sr, U, REE) and stable (C, 0) and radiogenic isotopes (Sr, Nd, Pb) within a framework of well-established dolomite and calcite cement zonal stratigraphies. 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°C and greater may have been involved in dolomitization. Preliminary solid inclusion work has identified calcite and iron sulfides within the dolomites. Research on major and trace elements has shown that there are at least two major dolomite types which differ from one another 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. Studies are just beginning on extension of the zonal stratigraphies and geochemistry from Iowa southward into Missouri and eastward into Illinois.

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

Contract: DE-AC02-81ER10921

Title: Deep-Burial Diagenesis in Carbonates

Person in charge: G. M. Friedman

Scope of Work

This research program emphasizes the effects of deep burial on creation and elimination of porosity with depth and on changes in textures of carbonate rocks. Two parallel lines of investigation have been employed: (1) experimental compaction tests at various temperatures, pressures and interstitial fluid compositions on natural carbonate sediments and (2) petrographic and mechanical-log analysis of carbonate rocks from boreholes of some of the world's deepest carbonate hydrocarbon (gas) reservoirs.

In the experimental compaction tests we have obtained a breakthrough: in compacted ooids in the presence of distilled water neomorphic microspar of calcite pseudomorphically replaced aragonite, with survival in places, in the ooids of parts of their original fabric. Most of the ooids, replaced neomorphically, retained concentric rims however.

Ooids and skeletal particles compressed at 150°, 200° and 250°C and at 1.5 and 2.4 kilobars, consistent with burial depth of 6 and 9 km, showed appreciable volume reduction. Skeletal particles showed greater response to pressures than ooids and coarser particles lost more void space than finer ones. Skeletal particles become parallel oriented and horizontal as a result of compaction. At a burial depth of 6 to 9 km oolitic facies are likely to retain greater porosity than skeletal facies. Compaction of ooids is greater in distilled water than in marine water. Experimentally compacted ooids develop the same kinds of particle breakage as observed in naturally compacted oolite facies: buckled, spalled, crushed, split, and diagonal fractures. Except for crushed and split particles which increase at higher temperatures, other kinds of breakage are unrelated to temperature effects. At higher temperature ooids develop a higher concentration of longitudinal contacts than other kinds of contacts. By contrast skeletal particles give way from concavo-convex to sutured/fused contacts.

Our study of boreholes reveals that among the world's deepest producing hydrocarbon (gas) reservoirs in the Anadarko Basin of Oklahoma porosity in carbonates is chiefly confined to dolomites. Gas is produced from intercrystal and moldic porosity in Hunton (Ordovician to Devonian) strata at a depth of 25,000 feet. Porosity has been calculated from logs; correcting for the presence of ferroan dolomite indicates porosity greater than previously expected. Our corrections lead us to believe that many productive intervals have been missed. Circumstantial stratigraphic evidence suggests ferroan dolomite to form under conditions of deep burial. The smectite-illite transition has been inferred as a source of sufficient Mg and Fe to form ferroan dolomite; temperature may control this transformation.

Contractor:	RICE UNIVERSITY Houston, Texas
Contract:	DE-AS05-83ER13124
Title:	Structural Evolution of Central Brooks Range, Alaska
Person in charge:	H. Ave-Lallemont

Scope of Work

The main objective of this effort deals with the Jurassic/Tertiary structural evolution of the Brooks Range fold-thrust belt. We apply structural and strain analysis to unravel the sequential development of folds and faults and the kinematics of thrusting. The timing and regional age relations are established by paleontologic and $^{40}Ar/^{39}Ar$ dating. This work centers on the deformation of Upper Devonian to Triassic rocks in and adjacent to the Doonerak Window in the central Brooks Range and of Cretaceous rocks in the northern foothills of the Brooks Range. We test the alternative hypotheses that: (1) the thrust belt experienced continuous northerly transport, or that it underwent a complex transport history involving both north and south motions, and; (2) that development of Mesozoic and Tertiary thrusts are the product of two or more discrete tectonic events, or alternatively are the result of continuous deformation over the last 150 m.y. we also will analyze available seismic reflection lines of the Brooks Range and Arctic Slope. The integration of these studies will allow us to construct balanced cross sections, which are critical for paleogeographic reconstructions of northern Alaska and which may yield important constraints for future hydrocarbon exploration in the region.

Another objective of this work is to test the hypothesis the pre-Upper Devonian rocks were involved in mid-Devonian tectonism related to the development of the Innuitian fold-thrust belt of northern Canada. Studies of pre-Upper Devonian rocks in and south of the Doonerak Window and of rocks in the Schist Belt bordering the southern Brooks Range augmented by metamorphic and $^{40}Ar/^{39}Ar$ studies, will not only constrain models for the mid-Devonian tectonic event, but also for the involvement of these rocks in the younger fold and thrust event of the Brooks Range.

A third objective of ophiolitic rocks south of the Schist Belt, both geochemically and structurally, as similar rocks were involved in the thrusting of the western Brooks Range.

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

Contract: DE-AC01-82ER12050

Title: Thermally Induced Chemical Migration in Carbonate Rocks

Person in Charge: J. J. Papike

Scope of Work

The main objective of this research continues to be to gain a quantitative understanding of the extent and mechanisms of chemical migration in diverse geological media. The prime site for this study has been the Notch Peak locality in Southwest Utah. Some of the important conclusions resulting from this work so far are: (1) The Notch Peak granitic stock is comprised of three concentric sequentially intruded rock types. They were all derived from the same parent (greywacke) by different degrees of partial melting. (2) Maximum temperature near the contact between the quartz monzolite intrusion and the Cambrian sediments was 575-600°C. (3) Mineral compositions and assemblages in the limestones (as opposed to the argillites) show that fluids were buffered by metamorphic reactions, that domains of equilibrium are small, and that the limestones behaved as a closed system during metamorphism. $^{18}O/^{16}O$, $^{13}C/^{12}C$, and D/H ratios have been determined and show that little or no interaction between the limestone and the intrusion has taken place. (4) In contrast to the behavior of the limestones, extreme depletion of $\delta^{18}O$ in the argillites close to the intrusion indicates fluid/rock ratios $\nmid 1$ and X $(CO_2) = CO_2/(H_2O+CO_2)$ of the fluid approaching 0. (5) The different behavior of the stable isotopes between limestones and argillites indicates that the limestones were impermeable to fluids relative to the argillites. Thus the flow of fluids was confined to the argillite beds and fractures. (6) In the argillites, migration of Na, K, Rb, Ba, Sr, and Cs has taken place over tens of meters. In contrast, there is no detectable migration of REE, V, Cr, Sc, Zr, Hf, and Al.

New, follow-up, analog sites for chemical migration studies are now being considered. Ideally, such sites include a variety of chemical compositions for the heat and trace element source (the igneous intrusion) which, in turn, intrude a variety of country rock types. In addition, the igneous intrusion should be "spiked" with certain elements of interest (e.g., Cs, Rb) that are in low concentrations in the country rock. This allows the chemical migration path to be monitored effectively. The situation described is probably best represented by the intrusion of a variety of granitic pegmatites into diverse country rock types. Five pegmatite/wallrock interaction sites in the Black Hills, South Dakota, have been selected for detailed study. The purpose of selecting these five pegmatites which exhibit contrasting characteristics is to identify and quantitatively define variables in chemical migration. The variables addressed are: (1) composition of solutions, (2) capability of dispensing solutions into the country rocks and (3) partitioning of mobile elements between mineral phases and solutions derived from pegmatites.

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-AT03-76ER71045

Title: I. Porosity with Fluids

Person in Charge: A. M. Nur

Scope of Work

The objectives of this project are (1) to advance our basic understanding of porous or 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 Mechanism. Systematic measurements of wave attenuation in rocks vs pore fluid saturation, pore fluid compressibility, pore fluid viscosity, overburden pressure, strain amplitude temperature and frequency have proven that wave induced fluid flow in the pores is the dominant mechanism of attenuation in rocks at shallow crustal conditions. The results have been applied to the interpretation of deep crustal reflection data and to seismic models of overpressure zones.

2. Network models of porous rocks with fluids. We have developed a general framework to describe all the petrophysical properties of rock, and their dependence on overburden pressure, pore pressure and other variables. The models correctly and accurately predict the hydraulic, electrical and elastic properties of a wide range of porous sedimentary rocks. Results suggest that successful models require that the pore space be characterized as flat grains in contact, rather than cracks with various aspect ratio. The results will provide an order of magnitude improvement in well log interpretation and will allow the development of rigorous petrophysical reservoir models.

3. Velocity and attenuation in heavy oil sands. We have measured the velocities and amplitudes of compressional and shear waves in heavy oil sand sample from Canada and Venezuela as a function of pressure and temperature. The results reveal a 25%-50% decrease in velocity and a 6-7 fold decrease in amplitude upon heating to 125°-150°C. These large changes suggest that seismic methods may be useful in monitoring in situ thermal recovery processes, e.g., steam flooding for enhanced oil recovery.

4. Pore pressure in the crust. We have developed a numerical model which incorporates hydraulic diffusivity, pressure solution and solution transfer, rock and pore deformation, and tectonic strain rate. The model is used to estimate the tectonic and mechanical conditions under which a portion of the crust will develop pore pressure greater than hydrostatic, and as great as lithostatic, and the conditions under which it will drain. The results show that a critical factor—the ratio between permeability and pore volume strain rate—control the fate of pore fluids in the shallow and mid crust. The results of this study will be used to guide exploration efforts to determine the distribution of permeability and pore pressure in the crust, which are particularly important for the evaluation of radioactive waste disposal sites.

Contractor:	STANFORD UNIVERSITY Stanford, California 94305
Contract:	DE-AT03-82ER12051.000
Title:	II. Mechanism of Zeolite Crystallization and Alteration in Silicate Gasses
Persons in Charge:	J. G. Liou and R. J. Donahoe

Scope of Work

The importance of zeolites as a mineral group is well documented, both in natural environments and with respect to their utility in a wide variety of commercial applications. Despite their importance geologically and industrially, relatively little is known about the physiochemical properties which control zeolite formation. It is the purpose of this project to investigate physical and chemical controls on the formation of some Na-K synthetic zeolites.

A. Precipitation Experiments

Phillipsites of varying Si/Al ratio, faujasite, and some low-silica zeolites of unknown structure have been synthesized from clear solutions in the system Na_2O-K_2O-Al_2O_3-SiO_2-H_2O-Cl,NO_3. Chemical controls on phillipsite structure, composition, crystallization process, and growth kinetics were studied. These experiments have shown that the composition of synthetic zeolites can be precisely controlled through varying solution composition parameters. Conversely, the composition of zeolites can give information about the solutions from which they formed. This data has application to zeolite synthesis as well as modeling the chemical evolution of diagenetic and low-temperature hydrothermal fluids.

B. Calorimetric Study of Synthetic Zeolites

Low-temperature heat capacities and heats of solution have been determined for three mixed, Na-K synthetic phillipsites of different Si/Al ratios. Through ion exchange in saturated NaCl and KCl solutions, nearly end-member Na- and K-phillipsites are obtained 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 materials.

C. Nuclear Magnetic Resonance Study of Solutions and Zeolites

Solid MAS^{29}Si and ^{27}Al NMR has been used to investigate the structures of some of the synthetic zeolites. The spectra may help determine the Si-Al order-disorder in the phillipsites and thereby aid in the calculation of free energies of formation from the calorimetric data. High resolution ^{29}Si NMR has been used to study the distribution of aluminosilicate species in solutions from which zeolites precipitate, as a function of solution composition. These observations, together with those from the precipitation experiments, have laid the basic framework for a comprehensive theory of zeolite crystallization.

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

Contract: DE-AT03-82ER12018

Title: III. The Hydrothermal Solubility of Uraninite

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

Scope of work

Uranium dioxide is a major component in many high-level radioactive waste forms which are slated for long-term remote storage in geologic repositories. Prevention of environmental contamination by radionuclides requires careful assessment of the rate, geographic extent and degree of dispersal of radionuclides from breached repositories or waste disposal sites which in turn depends on complex and sophisticated geochemical and mass transport modeling. Solution mining of in situ uranium deposits which also have uranium dioxides as their major ore presents a similar, though inverse problem. The equilibrium solubility of uranium (IV) dioxide (UO_2)in aqueous solution is a function of many factors such as solution composition (pH, ligand concentration, and ionic strength), oxidation-reduction potential, temperature, and to a lesser degree pressure. The limiting concentration of uranium in natural aqueous systems is dependent on the above factors as well as absorption and complex chemical interaction of the solutions with solid components with which the solution comes into contact.

These constraints must be recognized and accounted for in solution transport and fixation models. The thermodynamic data required to compute these models and limiting solubilities of uranium exists for near-surface conditions of low temperature and high oxidation potential but data for higher temperature and pressure conditions is limited both in extent and precision. This is especially true for reduced 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 fO_2 conditions at sufficiently low levels to maintain the U(IV) valence state both in the solid and solution. The temperature range of the experiments is from 100 to 400°C at 500 bars total pressure. We will also attempt to investigate the effect of carbonate and chloride ligands on UO_2 solubility under similar conditions. From the data we may be able to extract equilibrium solubility products as well as hydrolysis and complexation constants.

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 experiment. 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 has been found to be 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.

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

Contract: DE-AS05-79-ER10361

Title: Mechanical and Transport Properties of Rocks

Person in Charge: M. Friedman

Scope of Work

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

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

The effect of the α-β quartz transition on the creep properties of Sioux quartzite and Westerly granite has been determined dry at 200 MPa confining pressure. The effect is profound for both materials with the creep rate at constant stress decreasing appreciably in the β- field, as it does for synthetic quartz. The deformation is semibrittle and entirely within the transient creep regime. Activation energies in the β- field are 16.5 and 16. 1 Kcal/mole for quartzite and granite, respectively, and 38.7 and 35. 7 in the α-field. Transition temperatures are different for the two materials, but the virtually identical creep behavior confirms our earlier contention that quartz controls the creep rate in granite deformed to low strains.

We are also investigating the effect of strain rate on stress at failure of Westerly granite deformed at 100 Mpa confining pressure and temperatures to 500°C. As expected, the strength of the material decreases both with increasing temperature and decreasing strain rate. However, the form of the dependencies and the flow processes have not yet been determined in these transient creep experiments as the data are currently insufficient.

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

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

The elevated-temperature, corrosive fluid permeability system is completed and under initial shakedown testing. During the construction of this system two complementary topics were investigated, namely: (1) experimental study of the evolution of surfaces undergoing dissolution, with specific emphasis on the changes of surface roughness and asperity shape; and (2) an exploratory experiment to assess whether measurable pressure solution could occur in the time constraints typical of our proposed permeability experiments. For (1) we found that dissolution increases surface roughness and is surface reaction controlled. Defects, such as grain boundaries and microcracks or pores are more important than the crystallographic orientation of the grains. For (2) we found ample evidence of pressure solution in a water-saturated monolayer of quartz grains between surfaces of quartzite with SEM for tests at 300°C for 2-3 days under 10 to 15 MPa effective normal stress across the layer.

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

Having acquired a good understanding of the deformation of wet and dry intact crystalline rocks under short-term triaxial compression at the conditions of low effective confining pressures (0-200 MPa) but high temperatures (to partial melting, about 1000°C), we turned our attention to the effects of time of loading and of discontinuities like joints.

In an effort to characterize the time-dependent rheology and flow processes (mechanisms of deformation) operative for presupposed semibrittle behavioral conditions we have conducted a series of drained constant stress creep tests on 2 x 4 cm specimens of dry and water-saturated (Pp = 100 MPa) Westerly Granite at 100 MPa effective confining pressure and temperatures of 300°C to in excess of Tm (1000°C).

Available equations of flow and time to failure are used as response models to characterize the experimental data. Data for 600°C and below (the brittle field) are well fit by an equation of the form: $t_{failure} = t_0 P^{-\alpha} \exp(E/RT-K\sigma)$, which has been shown to predict the static time for rock. Using this expression, the calculated apparent activation energies for the summed fatigue processes in the quartz field is 7.5 kcal/mole (300°-400°C dry) and 21. 6 kcal/mole (400-600°C, wet, Pp of 100 MPa). Quasi-steady state flow is observed in the β-quartz field (700-800°C) and the flow behavior is described by $\dot{\varepsilon} = A\exp(-Q/RT)\sigma^n$ where Q = 68 kcal/mole, n = 2.7, and A=25.2.

The deformation is multimechanistic; microfracturing of apparent extensile and shear origin, glide in quartz and biotite, microfracture healing, dissolution, mineral alteration, incipient and partial melt are mechanisms observed and evaluated as functions of temperature and strain. The bulk specimen deformation is partitioned into that contributed by the individual mineral species in the analysis. The systematic change in micromechanisms observed with increasing temperature is compatible with the origin of the gradational succession of macroscopic deformation modes from a single narrow fault ($T/Tm \leq .5$), to a shear zone ($T/Tm \cong .6$), to multiple shear fractures ($T/Tm \cong .75$), to uniform flow ($T/Tm \geq .9$). These observations are being accompanied by finite element models of polyphase aggregate deformation.

We have completed preliminary studies of the frictional strengths of artificial joints in Westerly granite at confining pressures of 25 to 200 MPa and temperatures of 400° to 800°C. These are to be compared with the strengths of the intact rock to discover under which conditions the bulk strength of the rock mass is likely to be significantly lowered by the presence of pre-existing fractures; that is, where would frictional and intact-rock strengths become about equal?

We tentatively conclude that the jointed rock is substantially the weaker under all these test conditions and hence that the deformation of the rock mass probably cannot be modeled as a continuum at these physical conditions. Our purpose now is to acquire enough experimental data to allow a good estimate of the errors in predicting rock-mass deformations if the influence of joints is neglected.

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-dacite stratovolcano has been segmented by strike-slip and normal faults. Erosion and faulting have exposed the entire volcanic succession, a radial dike system, and sedimentary and volcanic rocks predating and postdating the stratovolcano. Geologic mapping on a scale of 1:12,000, completed before this contract began, permits estimates of the proportions of igneous material that formed sills, dikes, lava flows, and reworked debris during growth of the cone. Rock and mineral major-element and trace-element analyses are being used to test models of magmatic differentiation and magma mixing. An unusually complete record of magmatic evolution can be documented.

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 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. Mineralogical and trace-element changes, and variations in isotopic ratios of oxygen, hydrogen, and carbon, will be related to permeability and porosity variations as well as to sample locations, permitting reconstruction of flow patterns and temperature gradients in this geothermal system.

Contractor: UNIVERSITY OF TULSA
Tulsa, Oklahoma 74104

Contract: DE-AS05-79ER10400

Title: Stability of Natural Gas in the Deep Subsurface

Persons in Charge: C. Barker, N. Takaoh and K. A. Kuenhold

Scope of Work

As average well depth continues to increase and drilling rigs with 50,000 ft. capability are built, considerations of methane survival at depth become important. 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 50), multiphase (up to 30) systems for conditions corresponding to temperatures and pressures down to 40,000 ft (12 km). In the last year this program has been restructured and completely rewritten in more modern code. This has optimized the convergence, improved convenience in handling major versus trace components, and provided much better documentation. The calculations show that methane stability varies widely and that reservoir lithology is an important factor influencing natural gas stability. In particular sulfur, or sulfur-bearing minerals such as anhydrite, reduce methane stability and convert it to hydrogen sulfide. However if iron content is high, pyrite forms and the methane may survive. In many deep carbonates methane remains stable but is diluted with thermally-produced carbon dioxide to give a gas composition that would be uneconomical to produce.

Deep rocks containing gases (in either commercial or non-commercial amounts) are being analyzed and the rock mineralogy determined. 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, fast scanning mass spectrometer. When each individual inclusion ruptures, it produces a burst of gas lasting about 0.5 sec. Software recognizes the burst, retains the previous spectrum as background and records the next six spectra at 1 spectra per 75 msec. The compositional data from these six spectra can be extrapolated back to the time of rupture to give the original gas composition. Analyses of gases in up to 200 inclusions have been made in a single heating experiment with a 10 mg sample of carbonate cement. Gas compositions analyzed so far have ranged from dominantly methane to those with major water, carbon dioxide or hydrogen sulfide, while some low-grade metamorphic samples produced a nitrogen-hydrogen mixture. The gas compositions are being compared with those calculated using the thermodynamic program.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, MA 02543

Contract: EG-77-S-0204392

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

Person in Charge: J. Hunt

Scope of Work:

The overall objective of this program is to examine the processes of hydrocarbon formation and migration in deeply buried sedimentary rocks. Fine grained shale and carbonate well cuttings from three areas are being studied: (1) the North Slope of Alaska, (2) the U. S. Gulf Coast and (3) continental rises and slopes drilled by the International Program of Ocean Drilling. Pattern recognition of kerogen cracking products obtained at various levels of natural maturation is showing significant changes in the kerogen as it generates oil, condensate, or gas. If these patterns are reproducible in different basins, it could lead to the ability to predict more quantitatively the oil, condensate or gas that has been generated from a particular stratigraphic sedimentary sequence.

A photo-ionization detector is being used to identify individual alkenes, aromatics and heterocyclics in kerogen breakdown products as these are giving clues to both the type and maturation state of the kerogens. Also, cryogenic attachments have been added to the capillary GC columns on the pyrolysis apparatus for more definitive identification and quantitation of C_5 through C_8 compounds.

The oil and gas generation windows plus evidences of hydrocarbon migration are being monitored in six wells from the North Slope of Alaska and four wells from the U.S. Gulf Coast. Samples also are being obtained from two wells targeted for 26,000 and 30,000 feet in the Gulf Coast. Vitrinite reflectance data will be available for all of these wells so that we will be able to determine how pyrolysis maturation indicators vary with the more conventional measurements. In addition, we will have enough wells on the Alaskan Slope so that it may be possible to get a rough idea of three-dimensional formation and migration patterns of both gas and oil over a fairly wide region.

In the coming year, the headspace analysis for light hydrocarbons will be modified by changing to a 100 m fused silica glass capillary column. Studies are currently underway to find the proper liquid phase to give 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 would enable the detailed hydrocarbon analyses to extend to a higher range.

It also is planned to equip the pyrolysis apparatus with a CO analyzer for identifying kerogen type. Studies by Chevron scientists have indicated that this technique is more suitable for rapid screening than conventional procedures.

Contractor: WOODWARD-CLYDE CONSULTANTS
Pasadena, California 91104

Contract: DE-AC03-82ER13014

Title: Earthquake Analyses: Long Valley/Mono Crater

Person in Charge: L. J. Burdick

Scope of Work

During the past year, substantial progress has been achieved in the Continental Scientific Drilling Program toward identifying potential geothermal drilling sites in the Mono Craters/Long Valley area. Recent results have shifted interest from the area of recent volcanics (Mono Craters) to the southern moat and resurgent dome area of the Long Valley caldera. However, the present location resolution and constraint on material properties of the inferred magma body beneath this part of the caldera are both limited. The purpose of the program of research discussed here is to apply sophisticated techniques to high-quality seismic data sets and to integrate the results with interpretations of complementary geophysical data sets.

A. Reflected and Converted Phases from the Long Valley Magma Body (L. J. Burdick and W. Savage)

The S-wave screening effect observed by Ryall and Ryall (1982) is constrained to an anomalous path region in the southern Long Valley. Locally recorded data are being used to further resolve the location and nature of the anomalous region. Excellent-quality three-component digital data have been collected (using the January 1983 swarm events) for ray paths crossing the western side of the southern moat. During the summer of 1983, additional data will be recorded from both explosions and earthquakes in conjunction with the planned refraction experiment in Long Valley. These data will be combined with other available records, and polarization filtering will be used to search for secondary S-wave arrivals. Forward models will be developed for S_xS and S-wave screening to interpret the observations in terms of magma bodies.

B. Source Mechanics of the Larger Earthquakes in the Long Valley Region (T. Wallace)

There has been considerable controversy over the exact nature of the earthquake source mechanisms of the largest events in the 1980 Mammoth Lakes sequence, whether they are double couples produced by slip on faults or injection sources best described by compensated linear-vector dipoles (CLVD). The CLVD source model is being evaluated for the 1980 and 1983 Mammoth Lakes earthquakes using synthetic seismograms matched to observed records. A critical analysis of moment tensor inversion will also be carried out. The similarities in source mechanics for the 1941 and 1980-83 events will be studied using relative waveform inversion. The results of these studies should clarify the applicability of the CLVD interpretation and assess the long-term similarity of earthquake sources in the region. The best source models will be used to investigate the sensitivity of teleseismic short-period body waves to the presence of a magma body.

C. Analysis of Local Seismicity Data (K. McNally)

During the January 1983 swarm, close-in recordings were obtained from stations directly above the swarm. These data are being used to refine hypocentral locations and focal mechanisms for selected swarm events. The space-time microearthquake processes will be assessed in comparison with the 1980 sequences, the large-event source models, and the other geophysical data sets available in the region. The stability of the swarm patterns is important in evaluating the tectonic changes that might be associated with the recent seismicity. These results will be used to assess the degree of uncertainty associated with this apparent change.

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. Previous efforts have concentrated on developing the method of geophysical transmission tomographic imaging using cross-borehole electromagnetic measurements. This technology has been successfully refined and implemented for use in the field. The major goal for the current phase of work is to determine the feasibility of extending this technology for imaging by using data obtained from reflected signals. Near-surface acoustic/seismic imaging situations are of greatest interest, where the region can be probed from the surface or a single borehole.

The scope of work encompasses the development of theoretical models and data processing methods. Computer models are being developed for backscattered measurements obtained by arrays of sources and receivers. Image reconstruction methods based on computer-aided reflection tomography will then be applied to the simulated data to obtain images of reflectivity. The approach is applicable to situations where impedance variations in the medium are of primary diagnostic significance.

This effort is aimed at providing imaging techniques for applications such as the characterization and monitoring of nuclear waste isolation sites, monitoring of underground processes, and evaluation of subsurface resources.

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 interpretation of fractures observed in the field. The fracture energy for crack initiation and crack propagation in nine different types of rock was measured with a standardized test procedure. The fracture toughness is found to depend primarily on the preexisting microcrack network in the crystalline rocks and is influenced much less 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 experimental results show that fracture energy depends on cracking rate and on chemical environment. It also depends on the distance a crack has run through a given rock. A most important result of the tests is the demonstration that the fracture energy depends on the state of stress in the test specimen. For example, the presence of compressive stress parallel to the crack plane can cause large changes in fracture energy. Hence, the fracture energy (or fracture toughness) is not a true material property that can be tabulated for different kinds of rock; it must be evaluated for the conditions of loading present in any given problem.

The focus of the research is now on determination of the mechanism by which cracking occurs and by which the "process zone" that surrounds a fracture develops. Knowledge of the mechanisms that control fracture in rock is needed if laboratory results are to be applied in the field or in engineering designs. Conditions in the field or in service cannot usually be duplicated in the laboratory, and a basis for extension or extrapolation of the laboratory data is best found in the physical processes that control crack growth.

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

ON SITE	FY 1969	FY 1970	FY 1971	FY 1972	FY 1973	FY 1974	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982	FY 1983
ANL	$ 0	$ 0	$ 50	$ 50	$201	$ 60	$ 98	$ 60	$ 50	$ 100	$ 140	$ 240	$ 310	$ 330	$ 330
BNL	—	—	—	—	65	41	0	—	—	—	—	—	—	—	—
LANL	0	0	0	0	95	291	630	906	750	810	1,084	1,420	1,600	1,375	1,684
LBL	—	—	—	—	—	295	315	816	620	660	735	995	1,075	1,180	1,405
LLNL	—	—	—	—	—	—	75	135	130	250	630	910	1,060	1,110	1,280
ORNL	195	195	180	145	0	0	50	140	150	180	240	280	380	430	430
PNL	75	105	76	85	100	123	175	265	250	280	450	565	680	520	520
SNL-A	—	—	—	—	—	—	245	500	450	500	800	1,165	1,310	1,546	1,682
On-Site Total	$270	$300	$306	$280	$461	$ 810	$1,588	$2,822	$2,400	$2,780	$4,079	$5,575	$ 6,215	$ 6.491	$ 7,331
Total Off-Site	$483	$565	$410	$375	$319	$ 526	$ 672	$ 842.75	$ 898.3	$1,150.4	$1,894.31	$2,507.035	$ 3,025.528	$ 3,140.71	$ 4,519
TOTAL OPERATING	$753	$865	$716	$655	$780	$1,336	$2,260	$3,664.75	$3,298.3	$3,930.4	$5,973.310	$8,082.035	$ 9,240.528	$ 9,631.71	11,850
TOTAL EQUIPMENT	—	—	—	—	—	—	—	—	—	—	$ 355.000	$ 560.000	$ 923.000	$ 900.000	890
TOTAL GEOSCIENCES	$753	$865	$716	$655	$780	$1,136	$2,260	$3,664.75	$3,298.3	$3,930.4	$6,328.310	$8,642.035	$10,163.528	$10,531.71	12,740

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

Institution	FY 1969	FY 1970	FY 1971	FY 1972	FY 1973	FY 1974	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982	FY 1983
U/Alaska (Akasofu)	$ 21	$ 20	$ 21	$ 25	$ 22	$ 45	$ 41	$ 92.4	$ 78.8	—	$ 85.4	$ 84.3	$ 108.055	$ 113.141	$ 117.000
U/Alaska (Pulpan)	39	40	40	44	0	102	79	31.5	41.8	58.6	112.7	86.6	70	—T	—
U/Alaska (Kienle)	—	—	—	—	—	—	90T	—	—	—	—	—	—	—	—
U/Arizona (Hill)	—	—	—	—	—	—	—	—	—	—	—	90.698	95.518	98.541	100.669
U/Arizona (Norton/Bird)	—	—	—	—	—	—	—	—	—	—	—	—	65.855	69.757	48.219(T)
Arizona State (Navrotsky)	—	—	—	—	—	—	—	—	—	—	—	34.96	61.532	66.453	123.190
Aspen Institute (Roberts)	—	—	—	—	—	—	—	—	—	47.6	57.2	70.5T	—	—	—
Brown U. (Hermance)	—	—	—	—	—	—	—	—	—	—	94.7	140	613.916	165	333.199
Cal Tech (Ahrens)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	72.159
U/California (B) (Reynolds)	70	75	61	61	61	60	63	130	127	148	127	167.8	144.06	150	165.000
U/California (B) (Price)	0	30	37	65	—	—	—	—	—	—	—	—	—	—	—
U/California (B) (Helgeson)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	203.527
U/California (D) (MacGregor)	—	—	—	—	—	—	—	—	—	71.2	61.4	23.04	—	—	—
U/California (LA) (Knopoff)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
U/California (LA) (Anderson/Warren)	—	—	—	—	—	—	45	55	41	50	103.3	107	121	NFXT	—
U/California (LA) (Boehler)	—	—	—	—	—	—	—	—	—	—	—	—	45.554	NFX	60.000
U/California (LA) (Kennedy)	62	60	60	60	60	60	60	60	60	60	72	72T	—	—	—
Carnegie-Mellon (Kohman)	—	—	—	—	40	38T	—	—	—	—	—	—	—	—	—
U. Chicago (Anderson)	—	—	—	—	—	—	—	—	—	—	—	54.036	NFX	37.618	97.636
Columbia U. (Fairbridge)	—	—	—	—	—	30	75T	—	P	—	—	—	—	—	—
Columbia U. (Sykes/Jacobs)	0	70	70	66	60	137	180	200	240	256	274	311.8	317.953	318.001	337.204
Columbia U. (Scholz/Engelder)	—	—	—	—	—	—	—	65	62.1	75	100	140	160	155.869	266.706
Ft. Lewis College (Ellington)	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—
Harvard Univ. (Thompson)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	372.013
U/Hawaii (Manghnani)	—	—	—	—	—	—	—	—	—	—	—	—	—	88.109	95.88
Headquarters Services	—	—	—	—	—	—	—	—	—	—	—	—	—	6.1	1
Indianapolis Center for Advanced Research (Dines)	—	—	—	—	—	—	—	—	—	—	—	80	63.924	T	—
U/Minnesota (Johnson/Seyfried)	—	—	—	—	—	—	—	—	—	—	—	—	66.175	58.758	NFX
MIT (Grodzins)	170	164	94	50	0	—	—	—	—	—	—	—	—	—	—
MIT (Aki)	44	25T	—	—	—	—	35	100	130	112.6	142	152	160.375	151	168.260
MIT (Simmons)	—	—	—	—	—	—	—	—	—	100	100	90	100	105.561	105.0
NAS/NRC (Petrie: Alaskan Earthquake)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
NAS/NRC (Petrie: U.S. National Committee in Geochemistry)	—	—	—	—	—	—	—	—	—	—	—	—	18.6	21.8	—
NAS/NRC (Usselman: Studies in Geophysics)	1	16	11	4	2	3	4	4	4	—	6	27	29	56	—
NAS/NRC (Berg: Committee on Seismology)	—	—	—	—	—	—	—	8.8	9	8.8	8.8	8.8	10.296	16.130	—
NAS/NRC (Berg: Geological/Materials Sciences Study)	—	—	—	—	—	—	—	—	—	—	14.17	—	9.624T	—	—
NAS/NRC (Berg: Geological Sciences Board)	—	—	—	—	—	—	—	—	—	—	—	—	—	12.5	—
NAS/NRC (Hart: Geodynamics Committee)	—	—	—	—	—	—	—	—	—	—	16	20	29.5	79.96	—
NAS/NRC (Andrews: Continental Scientific Drilling Committee)	—	—	—	—	—	—	—	—	—	—	—	60	70	93.3	—
Naval Weapons Support Center (Tanner)	—	—	—	—	—	—	—	5.5	—	—	—	—	—	—	—
U/Nevada (Ryall)	—	—	—	—	—	—	—	—	—	—	—	—	—	75	86.709
NOAA (Donnelly)	—	—	—	—	—	—	—	—	—	5	—	—	—	—	—
Univ. of Oregon (Weill)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	103.088
Oregon State (Fehler)	—	—	—	—	—	—	—	—	—	—	—	—	—	38.46	—
U/Pennsylvania (Faul)	19	25T	—	—	—	—	—	—	—	—	—	—	—	—	—
Pennsylvania State University (Martin)	—	—	—	—	—	—	—	—	—	—	—	81.846	83.278	NFX	T
Princeton U. (Hollister)	—	—	—	—	—	—	—	22.9	—	—	—	—	—	—	—
Queens College (CUNY) (Schreiber)	—	—	—	—	—	—	—	—	—	—	—	—	83	81.3	48.570
Rice U. (Baker)	—	—	—	—	—	—	—	—	—	—	—	16.6	—	0.193	—
Rice University (Ave-Lallemant)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	119.777
RPI (Friedman)	—	—	—	—	—	—	—	—	—	—	—	—	91.695	99.275	149.954
SMU (Blackwell)	—	—	—	—	—	—	—	—	—	—	—	—	54.39	69.57T	—
So. Dakota School of Mines (Papike)	—	—	—	—	—	—	—	—	—	—	—	—	—	67.295	109.334
U/So. Florida (Sackett)	—	—	—	—	—	—	—	—	—	—	—	—	34.634T	—	—
Stanford U. (Liou)	—	—	—	—	—	—	—	—	—	—	—	—	—	33.937	45.224
Stanford U. (Nur/Kovach)	—	—	—	—	—	—	—	59.6	65	103.6	146.6	140	140	125	169.860
Stanford U. (Parks)	—	—	—	—	—	—	—	—	—	—	—	—	—	57.692	65.535
SUNY, Albany (Dewey)	—	—	—	—	—	—	—	—	—	—	—	—	66.193	—	NFX(T)
SUNY, Albany (Harrison)	—	—	—	—	—	—	—	—	—	—	—	—	—	39.21	135.714
SUNY, Stony Brook (Schaeffer)	—	—	—	—	54	81T	—	—	—	—	—	—	—	—	—
SUNY, Stony Brook (Papike)	—	—	—	—	—	—	—	—	—	—	59.7	59.1	64.603	T	—
SUNY, Stony Brook (Hanson/Myers)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	111.618
Univ. of Texas at Austin (Barker)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	94.450
Texas A&M (Friedman)	—	—	—	—	—	—	—	—	—	—	62.5	208.495	202.414	200	201.295
U/Tulsa (Barker)	—	—	—	—	—	—	—	—	—	—	59.7	NFX	74.958	71.478	74.800
USGS (Hess)	—	—	—	—	—	—	—	—	9.1	54	54	—	—	—	—
U/Wisconsin (Wang)	—	—	—	—	—	—	—	—	—	—	—	57.39	37.8	—	—
Woods Hole (Hunt)	—	—	—	—	—	—	—	—	30.5	—	102	140.68	138.661	150	150.000
Woodward-Clyde, Pasadena (Cole/Burdick)	—	—	—	—	—	—	—	—	—	—	—	—	—	99.72	99.611
XDATA (Dines)	—	—	—	—	—	—	—	—	—	—	—	—	—	84.235	65.917(T)
Yale U. (Gordon)	—	—	—	—	—	—	—	—	—	—	45.14	3.6	34.525	25.837	39.330
Yeshiva U. (Cameron)	41	36	16T	—	—	—	—	—	—	—	—	—	—	—	—
Off-Site Total	$483	$585	$410	$375	$319	$526	$672	$842.75	$898.3	$1,150.4	$1,594.31	$2,507.835	$3,025.528	$3,140.710	$4,516.942

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