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Summaries of Physical Research in the Geosciences

October 1981

U.S. Department of Energy
Office of Energy Research
Division of Engineering, Mathematics & Geosciences
Washington, DC 20545

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FOREWORD

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

The summaries in this document, prepared by the investigators, describe the scope of the individual programs and detail the research performed during 1980-81. The Geosciences Research Program includes research in geology, petrology, geophysics, geochemistry, hydrology, solar-terrestrial relationships, aeronomy, seismology, and natural resource analysis, including the various subdivisions and interdisciplinary areas. All such research is related either directly or indirectly to the Department of Energy's technological needs.

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

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

The Geosciences Research Program is divided into five broad categories:

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

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

1. Geology, Geophysics, and Earth Dynamics

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

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

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

   D. Rock Flow, Fracture, or Failure. Research related to response of minerals, rocks, and rock units to natural or artificially

induced stress, including the strain rates that range from those appropriate to drilling to viscoelastic response.

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 of 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 Utilization

A. Resource Definition and Utilization. The principal goal of this research is to develop new and advanced techniques

that are physicaly, 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 reinjec tion) 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 on the earth, including the long-term effects of solar radiation on the climate.

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

PART I

GEOSCIENCES

ON-SITE

Contractor: ARGONNE NATIONAL LABORATORY
Argonne, Illinois 60439

Contract: 109 ENG 38

Title: Geosciences Program - Geochemical Research

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

Scope of Work

Research in Geosciences at Argonne National Laboratory involves experimental studies of the thermodynamic properties of natural and synthetic minerals and of the chemical migration of trace elements and radionuclides in geomedia. Currently, emphasis is on zeolite minerals and on fission product and actinide elements in the thermodynamic and migration programs respectively.

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

In this program, several calorimetric techniques (e.g., fluorine combustion, solution, high-temperature drop, and low-temperature adiabatic) are being used to determine the thermochemical properties of those zeolites that are of interest in the exploitation of vapor-dominated hot-dry-rock geothermal systems and that may be of interest in nuclear waste technology.

Measurements have been completed on analcime ($NaAlSi_2O_6 \cdot H_2O$), dehydrated analcime, and natrolite ($Na_2Al_2Si_3O_{10} \cdot 2H_2O$). The studies have yielded complete and precise thermodynamic quantities as a function of temperature for the technologically important equilibrium between albite, water, analcime, and quartz. Further zeolites being investigated include scolecite ($CaAl_2Si_3O_{10} \cdot 3H_2O$) and mesolite ($NaCa_{0.5}Al_2Si_3O_{10} \cdot 2.7H_2O$) both of which are isostructural with natrolite, the analcime analog, and pollucite ($CsAlSi_2O_6$). Our results for these materials will indicate how the thermodynamic properties vary with metallic substituent and may provide guidelines for the establishment of predictive schemes. There is also current technological interest in pollucite because it forms when aluminosilicate phases in basalts (some of which are being considered for nuclear waste storage) react with fission-product cesium.

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

Infiltration experiments in this program are used to study mass transport, especially of trace elements, through rocks and minerals at ambient and hydrothermal temperatures. In these experiments, aqueous solutions are pumped through rocks, and the reactions between solutions and rocks are monitored by chemical and radiochemical analyses. These experiments are capable of

taking into account many factors, including reaction rates, reaction equilibria, chemical speciation of solutes, incorporation of trace elements into surfaces, and fracture geometry, all of which affect mass transport.

Infiltration experiments are used to study the movement and genesis of pore water in Precambrian granite from the margins of the Canadian Shield and to investigate infiltration metasomatism that accompanied the intrusion of magma into carbonate rocks.

C. Migration of Heavy Element Chemical Species in Geological Strata (S. M. Fried, A. M. Friedman, J. C. Sullivan, and K. Nash)

The oxidation state of multivalent actinide ions and technetium makes a profound difference in the ability of these species to migrate through porous rocks, soils, and sediments. For example, it has been reported that PuO_2^{2+} migrates through porous rocks approximately 250 times faster than Pu^{4+}. Therefore, it is quite important to know the stable oxidation state of these metal ions in typical environmental solutions. Several factors are associated with the disposal site and surrounding media which may modify the oxidation states of these metals and thus promote or inhibit environmental mobility. This program deals specifically with the effect of radiolysis on the adsorption behavior of humic materials and clays, complex formation with carbonate anions ($CO_3^{=}/HCO_3^{-}$). the rates of the above processes at near neutral and alkaline pH.

- Effect of radiolysis on the speciation of actinides and technetium. Radiolysis effects on the oxidation states of actinides and technetium in near neutral solutions are being studied by including high specific activity nuclides in solutions, and by pulsed radiolysis. These studies evaluate the gross oxidation or reduction effects on the subject metal ions and the rates of specific reactions between the metal ions and various radiolysis products.

- Reduction and adsorption of actinides by humic acids and clays. In this set of studies, the considerable reducing power of humic acids and selected clays for high valent species of Np and Pu are determined. In addition, reduction of these actinides by simple humic acid model compounds and mineral constituents are under investigation.

- Carbonate complexing of actinides. Carbonate and bicarbonate are prevalent species in many natural waters, occurring in concentrations up to 1.0 M. The stability and rates of complex formation of actinide carbonates (and bicarbonates), and the relative effectiveness of carbonate vs. humate, citrate, tartrate, etc., as complexants for actinides are also being investigated.

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

Contract: EY-76-C-06-1830

Title: I. Remote Sensing and Geoscience Data Analysis Methodology

Persons in charge: G. E. Wukelic, H. P. Foote, and S. C. Blair

Scope of Work

The objective of this program is to conduct basic research in remote sensing most relevant to the Department of Energy's objectives in the geosciences. The current goal is to develop and test advanced computer techniques for processing, integrating, displaying and using combinations of remote sensing and geoscience (geophysical and geologic) data so that geoscientists can analyze more complex data, more completely and more rapidly. Successful techniques will become valuable tools in geoscience-related activities involving resource discovery, energy development and utilization, energy conservation, and environmental assessments.

This continuing project encompasses a range of research activities including updating and expanding the relevant digital data bases at the Pacific Northwest Laboratory (PNL), developing capabilities (software and hardware) for integrating and displaying remote sensing and geoscience data sets in common map formats and geographic projections, and demonstrating the potential utility of the developed computer analysis programs to the Department of Energy's technological needs.

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 directly, in digital form or digitized as appropriate, to support the development and demonstration of interactive procedures for merging remote sensing and geoscience data sets. Current emphasis is on satellite data (mainly Landsat data); topographic data; borehole geophysical data; and regional geologic, gravity, seismic, and magnetic data.

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

1. Remote Sensing and Geoscience Data Integration

This continuing activity involves the development of software for reformatting and geographically registering remote sensing and geoscience data sets, producing stereo pairs, and manipulating data for color display and speciality product generation. Integrated map products currently being prepared and evaluated include

- Color-coded combinations of geologic, topographic, and fault data sets for the Los Angeles USGS Quadrangle. (Rock types are color coded with topographic relief presented in stereo.)

- Landsat false-color imagery for the Santa Barbara region registered with topographic and geologic fault data sets. (Topographic relief is presented in stereo.)

- Various combinations of aeromagnetic, geologic, topographic, and cultural data sets for the Hanford, Washington, area. (Color and stereo relief display the magnetic field intensity.)

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

PNL's capabilities for processing geophysical data are continually extended and improved. Dynamic earthquake data displays are further advancing, including a computer-generated three-dimensional movie of earthquake swarms occurring in time and a flyby of selected seismically active zones, such as the San Andreas Fault and the Aleutian Trench. This type of display will create a three-dimensional effect without stereo viewing equipment.

Digital data base integration methodologies are expanding to include data on the micro as well as macro scales by means of a recently acquired drum digitizer that digitizes photomicrographs, and possibly electronmicrographs, of rock fabrics. Analytical software, based on the present image analysis software at PNL, will be developed to provide versatile high speed analysis of rock properties required for some geochemical studies.

Work continues on a display and analysis package for the display and analysis of borehole geophysical data. This software will rapidly recall and display digitized geophysical logs and will include quantitative analysis routines for evaluating borehole logging data.

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

The basic requirement of this task is to develop and test advanced computer techniques for integrating and mapping remote sensing, geophysical, and geologic data. This task, however, also aims to produce sample products for evaluation by appropriate basic and applied researchers in the geosciences community. This potential interaction with geoscience users is achieved by combining resources, such as personal communications, publications, laboratory visits, and workshops. These techniques are also being tested in several programmatic areas at PNL in which hydrological and geological data sets are utilized.

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

Contract: EY-76-C-06-1830

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

Person in Charge: R. A. Stokes

Scope of Work

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

Information acquired in the insolation task has direct applicability to solar power site evaluations, and photovoltaic and photobiological programs. Insolation research currently provides detailed information about the atmospheric effects of the 1980 Mt. St. Helens volcanic eruptions and their effects on radiation transfer within the atmosphere. Due to the size of the data base and availability of measurements both before and after the eruptive events, a baseline can be established from which deviations resulting from volcanic activity can be measured.

The aeronomy program uses nighttime optical emissions as a prime diagnostic tool to investigate the state of the upper atmosphere and the sources of energy flowing into this region.

Significant quantities of energy are transferred into this region by processes within the magnetosphere, notably from the plasmasheet and the plasmasphere/magnetosphere interface region. Such energy fluxes can have profound effects on the upper atmosphere. The optical manifestations of these effects are monitored by this program.

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

Analysis of insolation data occurs in several subtasks: building a quality data archive, and studies of volcanic effects, atmospheric aerosols, and cloud physics. For the purpose of an archival data base, calibrated spectral measurements in the range of 300 to 1100 nm are assembled. A major service is to provide direct solar measurements to the National Climatic Center for access by interested users. The Pacific Northwest Laboratory (PNL) also maintains high spatial resolution measurements of the diffuse component of solar radiation. The direct radiation data

are utilized in volcanic effect studies, from which turbidity values in 12 spectral bands can be obtained every 5 minutes throughout the day. This represents an extremely dense data set from the nine sites. The length of the historical record allows seasonal effects to be recognized and corrected when analyzing a single event such as a volcanic eruption or power plant introduction. The distribution of stations in the PNL network allows effective observation of continental effects due to the increased turbidity from these events. Routine data collection also includes high spatial resolution solar-zenith and solar-almucantar scans at half-hour intervals. On clear days, these data as well as the direct measurements can be used to derive aerosol properties, including average size, size distribution, index of refraction, and quantity.

The above goals are achieved using a Mobile Automatic Scanning Photometer (MASP). The MASP system measures insolation in spectral bands centered at 395 nm, 470 nm, 570 nm, 680 nm, 785 nm, 900 nm, and 1010 nm. The field of view is 1.5^{o}, with a basic instrument stability of $\pm$ 2%. The MASP units were designed and built to be portable and operate routinely at remote sites; presently these include Hinsdale, Montana; Ely, Nevada; Richland, Washington; and Ft. Providence, Northwest Territories, Canada. Additional archival data are acquired from cooperative programs which have instruments sited at Iron Mountain, Michigan; Boulder, Colorado; Eureka, Montana; Albuquerque, New Mexico; and Leduc, Alberta, Canada.

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

A primary resource of the aeronomy studies is the nighttime optical data acquired by the instrument network mentioned previously. Upper atmospheric emissions centered at 557.7 nm, 630 nm, 427.8 nm, and 486.1 nm are routinely recorded by the MASP instrumentation. The observing technique consists of scanning the sky in a series of zenith-centered concentric circles at elevation angles of 10^{o}, 15^{o}, 20^{o}, 30^{o}, 50^{o}, and 90^{o}. Since the photometric field of view is 2.5^{o}, these scans cover adequately the entire hemisphere. Total energy introduction into the thermosphere and energy spectra of incident particle populations may be derived by using the absolute values and ratios of the emission intensities. The extent of the MASP network thus, allows details of particle precipitation and energy deposition to be studied simultaneously over a range of 6 hours. This type of coverage is unique to PNL's operation. The utility of global coverage thus obtained is greatly enhanced by highly localized and detailed measurements made with various satellite experiments. To this end, PNL has aggressively pursued a program of collaborative research with many principal investigators having satellite-borne experiments.

Most detailed investigations to date have involved single ground stations, with the result that our understanding of large-scale auroral phenomena has tended to be restricted. Synthesizing

observations by the PNL network is a major research focus. Principal study areas include solar cycle control of energy deposition and frequency of mid-latitude upper energy deposition and atmospheric phenomena, analysis of the mechanisms of energy transport from magnetospheric source regions to energy sinks within the upper atmosphere, and the effects of this energy input on the dynamics of the upper atmosphere. The MASPs have benefited investigations of diffusion rates and atmospheric electric fields through the monitoring of high-altitude chemical releases. Further cooperative tasks of this type are planned.

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

Contract: DE-AC06-76RLO-1830

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

Person in Charge: D. Rai

Scope of Work

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

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

The basic experimental approach involves preparation of metal-organic complexes and the subsequent use of these in batch and column experiments to determine their mechanisms of sorption. Initially, technetium (Tc) was selected for these experiments. Technetium is capable of exhibiting multiple oxidation states (Tc(-I) through (VII)) depending on the chemical environment. All states from TC(I) through TC(VII) are capable of undergoing complex formation with organics. Methods of preparing organic complexes (EDTA, DTPA, citrate) of Tc(III), Tc(IV), and Tc(V) were developed. Crystalline products of Tc organic complexes have been isolated and are being characterized. This includes determining formation constants for these complexes.

B. Investigation of Mechanisms that Control the Concentration of Radionuclides in Ground Waters (D. Rai and R. G. Strickert)

The purpose of this investigation is to determine the mechanisms and the effects of various factors (such as pH, Eh, complexing and competing ligands, tracer concentration, oxidation state of the element, solid phases) in controlling the concentration of elements in solutions in equilibrium with different geomedia. Initially, plutonium (Pu) and americium (Am) were selected for these studies. Contaminated Hanford soils were used to determine the factors or mechanisms controlling the concentration of Pu and Am in solutions contacting these soils. The concentrations of Pu in solutions equilibrated with these soils were found to be controlled by crystalline PuO_2. The concentration of Am in solutions appeared to be controlled by an Am solid phase. Although the nature of the

Am solid phase is not known, it does have very low solubility ($\sim 10^{-11}$ M at pH 7). The results indicate that very high Am sorption by different minerals (reported in the literature) is due to the precipitation of Am solid. In an effort to identify this Am solid and the Am solution species, studies on solubility of AmO_2 and $Am(OH)_3$ are being conducted. Studies are also underway to check whether the Am solid phase controls the Am solution concentrations from different rocks and sediments in other ground waters.

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

Contract: EY-76-C-06-1930

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

Person in Charge: J. C. Laul

Scope of Work

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

The geological site under study is the porphyritic quartz monzonite intrusion at Notch Peak, near Delta in western Utah. The intrusion was emplaced in a Cambrian limestone interbedded with argillaceous layers. The Notch Peak granite intrusion discordantly intersects nearly all depositional environments of a carbonate platform edge and outer shelf of Cambrian age. The metamorphic temperatures near contact are $\sim 500^{o}C$ for the highest grade rocks (calcite, dolomite, diopside, forsterite, mite, quartz, talc, tremolite). 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.

Several samples were analyzed for some 35 major, minor, and trace elements by neutron activation analysis and x-ray fluorescence. A comparison of trace element signatures from metamorphosed to unmetamorphosed samples, ranging from granite to silt/carbonate, as a function of distance should reveal the degree and importance of transport of various elements. It should also disclose any chemical fractionation and partitioning trends among minerals. Preliminary results lend evidence of chemical migration of some elements during contact metamorphism between the granite and silt/carbonate system on a scale of several meters. This study is in collaboration with J. J. Papike of the State University of New York at Stony Brook, whose responsibility is to obtain petrographic and petrologic information on the same samples.

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

Contract: W-7405-ENG-48

Title: Geosciences Program

Person in Charge: P. A. Witherspoon

Scope of Work

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

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

This project encompasses a wide range of fundamental studies in fluid, heat, and solute transport in underground formations. These studies have relevance to underground thermal energy storage, geological isolation of nuclear waste, chemical waste disposal, and other energy-related projects. The goal is to better understand the various physical or chemical processes in porous or fractured media and their effects through analytic and numerical modeling. At the same time, a number of graduate students and post-doctoral fellows are trained in the expertise and experience necessary to participate in developments in this field.

The following general topics are addressed:

- Hot and cold water injection into a one- or two-phase porous system. In the area of thermal energy storage in aquifers, a number of basic problems need to be solved in order to understand the thermohydraulics of a reservoir under injection or production. Among these are the areas of thermal dispersion, nonisothermal pressure transient behavior, and buoyancy flows in a liquid or steam-liquid reservoir.

- Thermally induced flows in a fractured medium. Such a process is significant to nuclear waste underground repository problems. Regional, thermally-induced convection around and above an extended heat source in the presence of one or more fractures will be analyzed. Interaction of flows in one fracture with those in another has to be understood.

- o Transport in a fractured porous medium. Most underground formations are fractured porous media. The interaction between fracture flow and porous medium flow of heat, fluid, or solute is a most interesting and open issue to be studied.

- o Development of new directions. As more experience is gained in field and modeling studies, new directions of energy research and development emerge. Initial investigations are being made to determine the significance and feasibility of these ideas.

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

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

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

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

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

The experimental program involves measuring the heat capacity and the density of solutions in the range 0 to 300°C and 0 to

1 kbar. These measurements suffice to give a comprehensive equation of state, provided that other thermodynamic properties are known for a particular system at room temperature and pressure.

The theoretical work has yielded equations predicting the properties of mixtures based on the knowledge of the pure component solutions in water. In a number of cases, the calculated results for mixed brines are well verified by direct measurement. Phase equilibria can be predicted. New results for sodium sulfate (Na_2SO_4) and revised equations for sodium chloride (NaCl) are essentially complete. Other experimental work includes measurements for magnesium sulfate ($MgSO_4$). Calculations for solutions of Na^+ with $CO_3^=$, HCO_3^-, and OH^- also are well advanced; these results are important for the treatment of phase equilibria involving carbonates.

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

The objective of this project is to further the understanding of ground water chemistry and the factors that control its composition. This is accomplished by measuring the solubility of common rock-forming minerals in aqueous solutions at temperatures ranging from 25°C to 400°C and at pressures ranging from 0.1 to 50 MPa. The results of the measurements are used to test rock-water interaction models. Refinement of the existing rock-water interaction computer codes and data bases is needed before chemical transport can be accurately modelled in water-saturated rocks.

Measurements of albite solubility along the water saturation curve indicate that serious errors exist in the high temperature dissociation constants for the aqueous aluminum species. Experiments to measure the solubility of diaspore α-Al(O)OH as a function of pH at 175°C, 250°C and 350°C are being conducted to determine dissociation constants for the principal aluminum species so that these errors may be rectified and evaluation of the solubility of albite may be completed.

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

This project is designed to investigate silicate liquids for two general purposes--to allow the approximation of the properties of naturally occurring melts of a wide compositional range, and to examine more specifically the effect of composition in simpler systems in order to understand more details of the mechanisms of solution chemistry.

Measurements of density as a function of temperature (1000°C to 1600°C) have allowed partial molar volumes of eight oxide components to be calculated, and these values give excellent agreement with values measured on natural liquids. Within the temperature and compositional span of the experimental data, silicate liquids mix ideally with respect to volume.

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

The heats of fusion at 1 bar for $NaAlSi_3O_8$, $CaAl_2Si_2O_8$, and $CaMgSi_2O_6$ (three of the most prominent components in rock-forming minerals and in natural melts) have been determined, based on measurements of the liquids by high temperature drop calorimetry and measurement of the glasses by differential scanning calorimetry. Data has also been collected on intermediate compositions on the ternary system to investigate mixing properties. This work is being extended to cover a much wider compositional range.

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

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

Fundamental aspects of transport phenomena accompanied by chemical reactions in ground water flow systems are being studied theoretically. The approach is derived from the thermodynamics of irreversible processes, and allows consideration of nonequilibrium states of chemical reactions, the study of systems which have evolved to nonequilibrium steady states, and the inclusion of thermodynamic coupling of vector transport processes.

Initial work has provided analytical solutions to three idealized solute transport problems, formulated in the context of classical transport theory, in which nonequilibrium chemical reactions are described by linear rate expressions. These solutions serve as references for comparing results obtained from systems with nonlinear reaction kinetics and from steady-state or time-dependent systems with thermodynamic coupling between transport processes. The analytical solutions are applicable to systems in which the concentration of solute sorbed on the solid phase is small compared to the sorptive capacity of the solid phase, and in which solute mass is introduced at a single point within the system. The resulting point-source solutions have two immediate applications. First, they are useful approximations to time-dependent solute concentration histories in the far field where source dimensions are small relative to source-to-observer distances. Second, they can be used as kernels of finite spatial integrals to derive solutions for sources occupying finite regions of space; the derived solutions are then descriptive of near-field problems in which source dimensions cannot be neglected.

A computer code for numerical solution of the transport equation with chemical reactions described by nonlinear rate expressions is being developed. The nonlinearity arises from consideration of sorptive processes in which the concentration of solute sorbed on the solid phase is comparable to the sorptive capacity of the solid phase. The code is to perform sensitivity analyses of the parameters of sorption and transport in order to compare the analytical solutions for the linear case.

Studies of irreversible transport processes in steady-state open systems are being completed. These studies have focused on the characterization of the production rate of entropy by irreversible processes in such systems, and in particular on the minimum property of the production rate.

These investigations aim at describing as completely as possible those phenomena associated with chemical transport in natural systems which account directly for irreversibility. Within certain limits, the thermodynamics of irreversible processes quantitatively expresses irreversibility by evaluating the entropy changes in irreversible systems.

G. The Physics and Mathematics of Isothermal Subsurface Fluid Flow Systems (T. N. Narasimhan)

Traditionally, subsurface fluid flow equations have been expressed as differential equations. Studies over the past several years have shown that a change in perspective is perhaps needed, not only in order to make significant progress in the numerical modeling of subsurface fluid flow but also to evaluate a more general conceptual understanding of subsurface fluid flow phenomena.

The suggested new perspective is in the form of fully integral representations rather than differential equations. As part of this overall new direction, the role of the "source" term in the parabolic partial differential equation was made. New integral representations were derived which now include the explicit statement of the source term(s) as well as their dissipation over finite time intervals, simultaneous with generation. This inclusion of dissipation should help make future numerical handling of sources more efficient and accurate.

The integral perspective has inspired other new ideas. For example, an alternate expression for Darcy's law has been derived from axiomatic bases in which geometry is imbedded into the statement of Darcy's law. In this expression, the gradient of potential is dispensed with in favor of the difference in potential in conjunction with a function describing the geometry of the macroscopic channel. Preliminary application of this expression to the radial flow problem has provided some remarkable insights into the nature of diffusion process itself.

Further work based on the integral approach will be continued. New ideas and resulting improved integration procedures will be implemented in existing computer programs as expediently as possible. The goal of the research is to continue striving for mathematical models of increasingly physical realism and for a better understanding of physical phenomena themselves.

H. Aqueous Solutions Data Base for Nuclear Waste Isolation
(S. L. Phillips and A. Igbene)

The main aim of this project is to publish critically evaluated fundamental data on relevant properties of selected aqueous solutions to high temperatures. Tables of recommended values are generated from both theoretical equations and empirical interpolative equations using computer methods. These equations are developed by either LBL or other researchers.

In FY 1981, the emphasis is shifted to an evaluation of data relevant to the calculations and geochemistry for isolating nuclear waste from leaching, migration, and solvent extraction. Of immediate interest are the stability constants of those ionic species of key elements such as plutonium, uranium, and neptunium. This work has identified areas where data are lacking or are inadequate, and has recommended research to obtain the needed data.

The project also provides a single comprehensive computerized data base on basic properties of aqueous solutions germane to geothermal energy research and utilization. These properties, which range up to 350°C and 50 MPa, include enthalpy, heat capacity, viscosity, thermal conductivity, vapor pressure, solubility, and density. The solutes are mainly sodium chloride, potassium chloride, and calcium chloride. The results of this work are contained in two LBL publications: "A Technical Databook for Geothermal Energy Utilization"; and an indexed and annotated computerized bibliography, "Compilation of Geothermal Information."

I. Feasibility of Shear Wave Vibrators for Deep Crustal Studies
(S. Coen)

The elastic profiles of the earth are important for exploration of oil and minerals and for the understanding of the structure of the earth. This project concerns the determination of the elastic profiles of either a plane stratified or spherically stratified earth model from the measurements of shear and compressional surface data due to surface shear and compressional vibrators. It has been shown that the density, shear modulus, and incompressibility profiles of a layered elastic earth are uniquely determined from suitable surface data and sources. A direct (noniterative) inversion algorithm has been developed which constructs these profiles from the surface data. The extension of the theory to two-dimensional earth structure is currently under study. The integral equation solution of the forward problem is used to generate

synthetic seismograms and hopefully, from this data, the two-dimensional shear wave velocity distribution within the assumed earth model be able to be reconstructed.

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

Variations of electrical conductivity within the crust are important for determining deep structure and high temperature centers associated with crustal thinning and magmatic activity. These studies provide valuable complementary data to deep seismic studies, especially in areas where seismic waves are scattered or absorbed by relatively near-surface structure. The traditional magnetotelluric method is subject to serious interpretational problems particularly when lateral discontinuities are strong.

Controlled source (EM-60) electromagnetic sounding provides a more focused measurement of the conductivity distribution beneath the sounding site. Such a sounding is currently in progress in central Nevada over a crustal heat-flow high. The sounding is intended to confirm the existence and accurate depth of a crustal low-resistivity zone that has been inferred from magnetotelluric data. The extent and nature of this anomalous zone is critical to understanding the regional crustal structure of the Basin and Range province.

The EM-60 tests have concentrated on the use of a large moment (2-km^2) current loop, widely separated receivers (up to 30 km), and a new noise-cancellation system using remote reference magnetometer. All the sites are linked by FM telemetry to an in-field data processing computer. Using frequencies as low as 0.03 Hz, the system is able to resolve a conductive zone at depths of 15 to 20 km.

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

Title: I. Geosciences

Contract: W-7405-ENG-48

Person in Charge: A. G. Duba

Scope of Work

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

Current work at LLNL focuses on the physical and chemical properties and responses of earth materials, and, in particular, on developing computer models that aid in predicting and understanding these properties and responses. Our current effort comprises studies of aqueous geochemistry, basic rock mechanics, underground imaging, diffusion in minerals, and seismology.

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

The goal is to understand the mechanisms, thermodynamics, and kinetics of certain geochemical processes, especially those involving the isolation of radioactive wastes. To this end, measurements are made of diffusion and osmotic coefficients of certain electrolyte solutions and computer codes are developed to predict speciation, solubility, reactions, and reaction kinetics in various mineral-electrolyte solutions.

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

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

The numerical modelling effort involves development of a code using current LLNL, LANL, and SNL codes. This work will assess

the possibility that a melt, produced from heat generated by high level radioactive wastes stored in the crust, will migrate to the surface. The experimental program is closely coupled to this theoretical study. We plan to measure the thermoelastic properties, thermal conductivity, and heat capacity of rocks to 1000°C and 50 MPa.

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

The underground imaging effort aims to develop geophysical data collection methods, data processing procedures, and integrated data interpretation techniques. These efforts are directed toward providing an enhanced diagnostic capability for characterizing the subsurface environment. This involves developing improved laboratory and field instrumentation, acquiring fundamental data on the properties of materials under varied conditions, and improving the overall data interpretation process.

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

A novel technique of radiotracer diffusion, developed by LLNL, is used to study ionic diffusion in silicate minerals relevant to processes in the earth's crust and mantle. Rare, but stable, isotopes are used in diffusion experiments and afterward are selectively made radioactive. Oxygen-18 is made radioactive by ion bombardment to produce fluorine-18 (half-life = 1.8 h). Autoradiography is used to locate the tracer and measure concentrations. Measurements will be made on olivines, pyroxenes, feldspars, and perhaps some molten rocks.

E. Seismology: State of Stress in the Basin and Range Province (K. K. Nakanishi and H. J. Patton)

The objective is to characterize the regional stress field in selected areas of the Basin and Range by determining the focal mechanism, depth, and seismic moment of earthquakes in this province. The stress field will be characterized by orientation, using directions of the principal stress axes determined from the focal mechanisms, and magnitude, using the estimate of seismic moment (and field observations, when available) to calculate stress drop or apparent stress. The focal depth will be used to map the stress orientation and magnitude as a function or depth. The interpretations of the observed stress field in terms of intraplate sources of stress will be made from computer models for a three-dimensional viscoelastic medium.

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

Contract: W-7405-ENG-48

Title: II. Continental Scientific Drilling Program: Data Management

Person in Charge: A. G. Duba

Scope of Work

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

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

The information and data management project provides data bank and information services for the CSDP program, as follows: subsurface data from programmatic drilling by federal agencies and new wells drilled by industry that offer opportunity for cooperative efforts, and a computerized data bank for drill hole data acquired in CSDP projects. Information on plans and drilling activities can be disseminated to the scientific community. Researchers are encouraged to use the data base to locate opportunities for piggybacking experiments in drill holes, thus saving enormous drilling costs. The data base currently lists 1794 drill holes for which up to 25 parameters of information are stored. Drill holes may be selected and ordered on any parameter.

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

Contract: W-7405-ENG-36

Title: I. Geology and Geophysics

Person in Charge: R. E. Riecker

Scope of Work

The Los Alamos National Laboratory (LANL) basic research program in Geology and Geophysics consists of thermal regimes of the Jemez lineament and Rio Grande rift in northern New Mexico, in support of the CSDP program and geothermics; rock physics; and coal research. The thermal regimes research involves investigations of the tectonics and petrogenesis of the Paliza Canyon Formation on the flank of the Jemez Caldera; the petrology and geochemistry of the Lucero, Zuni, and Mt. Taylor volcanic fields; Sulfur Springs, a small vapor-dominated geothermal system on the flank of the Valles Caldera; seismic refraction profiling in north-central New Mexico to improve geophysical definition of the rift; the basaltic volcanism at the intersection of the Jemez and Zuni lineaments; and active hydrothermal systems in northern New Mexico. Rock physics research is performed on radiative heat transfer in minerals, glasses, and melts; mechanical properties of rock under negative effective confining pressure, micromechanics of tensile failure in rocks; creep deformation of rock under simulated nuclear waste repository conditions; and brittle-ductile transition in mafic rocks. Coal research focuses on occurrence, form, and distribution of sulfur in peats. This basic research applies directly to DOE energy technology needs in geothermics, waste isolation, fossil fuels, alternative energy resources, and conservation.

A. Thermal Regimes of the Jemez Lineament and the Northern Rio Grande Rift in Support of the CSDP

1. Tectonics and Petrogenesis of the Paliza Canyon Formation of the Keres Group, Jemez Mountains, New Mexico
(J. N. Gardner)

The Paliza Canyon Formation of the Keres Group, in the Jemez Mountains of northern New Mexico, offers unique opportunities for obtaining information regarding tectonic and magmatic evolution of the central Rio Grande rift. Occurring at the western margin of the rift, the Paliza Canyon rocks represent the revival of rift volcanism after a long mid-Miocene lull and the first of several major magmatic events that led to the presently active Valles Caldera geothermal system. Detailed geologic mapping complemented with K-Ar dates will refine stratigraphy of the formation and shed light

on the relationship of tectonics to volcanism, and the distribution and volume of volcanism through space and time. Major element whole rock and mineral chemistry, trace and rare earth element chemistry, and isotopic studies provide the basis for petrogenetic models. This study provides information and models that are directly applicable to the major objectives of the Continental Scientific Drilling Program. The research contributes to understanding the evolution of continental crust, continental rift systems, and large magmatic/geothermal systems.

2. Petrologic and Geochemical Investigation of Lucero, Zuni, and Mt. Taylor Volcanic Fields (W. S. Baldridge)

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

A major fracture zone intersecting the rift is the Jemez zone. This zone corresponds to a fundamental weakness in the lithosphere and is very important in controlling late Cenozoic alkalic and tholeiitic basaltic volcanism both within and adjacent to the Rio Grande rift. Major centers of volcanism occur at several localities along the Jemez zone, particularly where this zone intersects other major structural features. For example, the Jemez Mountains volcanic field, the most extensive volcanic field of northern New Mexico and a "known geothermal resource area," is located where the Jemez zone intersects the western margin of the rift.

The study emphasizes aspects of geology, petrology, and geochemistry of the Mt. Taylor, Zuni, and Lucero volcanic fields. Research focuses in part on the origin of magmas, their residence in the crust, and their effect on the hydrologic regime.

3. Sulfur Springs, Valles Caldera - A Detailed Investigation of a Small Vapor-Dominated Geothermal System (F. Goff)

Sulphur Springs is a small vapor-dominated geothermal system (approximately 1 km^2) on the west side of Valles Caldera, New Mexico, that possesses a variety of acid-sulfate hot springs, mud pots, and fumaroles issuing from altered volcanic rocks and colluvium. The vapor-dominated (steam) zone apparently overlies a 260°C liquid-dominated system deep within Valles Caldera.

Vapor-dominated reservoirs are specifically mentioned as target areas for research in the CSDP because they possess high energy potential and because they transport volatile elements of economic value. This investigation comprises the only known vapor-dominated system of the Rio Grande rift thermal regime. The purpose of this project is to characterize waters, gases, and altered rocks of the Sulphur Springs system, to perform detailed mapping of alteration and fracture zones within and near the system, and to study the compositions of alteration phase assemblages and fluids that are present. The aim is to model the present Sulphur Springs system and to understand its evolution through time.

4. Basaltic Volcanism at the Intersection of the Jemez and Zuni Lineaments, New Mexico (D. T. Vaniman)

A favorable site for locating a continental drilling project is at the intersection of the Rio Grande rift and the Jemez lineament. This site lies at the conjunction of four major physiographic provinces. Over the last 27 million years, a transition has occurred at this intersection from older alkaline or tholeiitic volcanism along the Zuni lineament to younger volcanism of a broader compositional range along the Jemez lineament. A detailed study of the most primitive basalts representing this timespan and this region helps to explain the deep-seated relationship between basaltic volcanism, subcontinental lineaments with crustal expression, and the mantle roots of such features.

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

Detailed geochemical and geologic characteristics of three geothermal systems of the northern Rio Grande rift at Valles Caldera, Ojo Caliente, and the Lucero volcanic field are being investigated. These systems possess many thermal/mineral waters which display widely divergent discharge temperatures, concentrations of dissolved solids, and geologic settings.

Valles Caldera contains many hot springs of varying types and is currently being explored for high temperature conventional and hot dry rock geothermal resources. The hot springs at Ojo Caliente is of moderate temperature and concentration (about 2,000 mg/l of total dissolved solids) and may offer potential for space heating and agricultural use. Its existence is not understood.

New research was initiated at Ojo Caliente and the Lucero uplift. The goals are to collect thermal and non-thermal waters for chemical and isotopic analyses; map geologic and tectonic features crucial to hydrology; integrate and model

resulting geologic, geochemical and, where appropriate, existing geophysical data; and evaluate the geothermal potential of each system.

6. Seismic Refraction Profiling in North-Central New Mexico to Improve Geophysical Definition of the Rio Grande Rift and the Jemez Volcanic Zone as Potential Targets for the CSDP (K. Olsen)

North-central New Mexico contains at least two tectonic features considered to be top potential drilling targets for the CSDP--the Rio Grande rift and the Jemez Mountain volcanic field. This research extends the present knowledge of regional crustal structure, tectonics, and thermal regimes by means of several reversed seismic refraction profiles, in order to better define the location of drilling sites to secure the largest amount of information possible. Existing geophysical data suggest the presence of mid-crustal magma bodies or partial melt zones. The objective of these profiles is to study the details and obtain improved data on the crust-mantle interface. Energy sources are optimally sited chemical explosions detonated in boreholes and a Department of Defense surface explosion at White Sands Missile Range. As part of a Los Alamos/regional university/USGS consortium, LANL deploys portable telemetering seismograph units (including triaxial instruments) that complement existing permanent seismic stations along the profiles. The resulting seismic record sections are interpreted and modeled in terms of compressional and shear wave velocity structure and attenuation, and the variations of these properties as a function of the geothermal regimes in the region.

Rock Physics

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

The study of the brittle-to-ductile transition in selected mafic rocks is achieved through deformation experiments over a very wide range of temperatures, confining pressures, stresses, and strain rates. The analysis of results is accompanied by observing the mechanisms of deformation, with particular emphasis on the effects of water.

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

The assurance of long-term nuclear waste isolation in mineral cavities in hard rock requires the 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, LANL studies the creep

deformation of basalt, granite, and tuff at simulated in situ conditions of temperature, pressure, pore pressure, and differential stress. The emphasis is on evaluating the effects of water on creep of intact, versus fractured, samples. Results of the experiments are formulated into creep equations to assist refinement of models.

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

The micromechanics of tensile fracturing is being studied. The interaction of microcracks near the tip of a much larger tensile fracture is theoretically analyzed to determine the effects of stress heterogeneity on crack growth. Experimental research is also being performed on the variation of fracture surface energies as a function of confining pressure to gain further insight into the processes occurring near a crack tip. Tensile fracturing of rock is important to numerous energy technologies. Hydraulic fracturing is necessary before heat recovery is possible in hot dry rock geothermal projects.

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

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

4. Mechanical Properties of Rock Under Negative Effective Confining Pressures (T. J. Shankland)

The elastic properties of rocks are measured when the pore fluid pressure is greater than the confining pressure. This condition is a departure in laboratory rock physics. Although unusual in nature, such an event frequently occurs when drill holes are overpressured for hydrofracture or during energy extraction from a manmade geothermal reservoir.

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

The contribution to total thermal conductivity from the radiative component in a variety of rocks and minerals, which is pertinent to geothermal and waste isolation technology, is

being determined. Radiative thermal conductivity is calculated as a function of temperature from measured optical adsorption spectra taken at temperatures up to 1500°C in a controlled atmosphere.

C. Coal Research: Occurrence, Form, and Distribution of Sulfur in Peat (R. Raymond)

Sulfur is one of the most environmentally troublesome elements in coal. In contrast, some iron sulfides have beneficial catalytic effects in processes such as coal liquefaction. LANL investigates factors that influence abundances and forms of sulfur in peats from a variety of diagenic environments, with the purpose of aiding interpretation of sulfur forms in coal. The amount of sulfur in most peats is sufficient to account for total sulfur abundances in many coals, but details of occurrence and distribution are poorly understood. This study of sulfur in peats is a three-phase program: characterizing sulfur occurrence and distribution by electron probe microanalysis; establishing the significance of particular coal precursor plant tissues germane to sulfur abundances; determining the relationships between occurrences of sulfur and various peat types.

D. CSDP Curatorial Needs (S. Goff and G. Heiken)

Cores, cuttings, and other samples produced during the CSDP are of interest to scientists in many disciplines. In order to circulate, yet protect, these samples, curators are needed. A uniform curatorial policy must be established that defines the curator's responsibilities, standard procedures for describing and handling samples, and the requirements of borrowers. Curators will be responsible for maintaining data files on samples, in cooperation with the CSDP data center and the NOAA National Geophysical and Solar-Terrestrial Data Center. The existence of these samples must be advertised through newsletters and trade publications to stimulate the use of this repository.

An investigation of state laws dealing with the preservation of rock materials concludes that 46 of the 50 states have no regulations that would prevent CSDP from removing core samples and placing them in a national repository. Two of the remaining states require that only one-quarter of the core length remain with the state; the other two states may request core but usually ask only for a representative sample.

As a result of the formation of CSDP, it has been recommended that regional repositories be established at existing facilities with a curatorial budget of about five percent of the total program. In May 1981, LANL hosted a workshop of curators from continental core research laboratories to consider problems of handling samples from the CSDP.

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. Vidale

Scope of Work

The geochemistry program includes rock-water interaction in geothermal systems, thermochemical measurements that are needed to permit the modeling of rock-water interaction, geochemical calculations, and a variety of studies of element migration and fixation in crustal rocks.

These investigations have application to the efficiency of energy extraction in geothermal systems, chemical transport, exploration for concentrations of specific elements within the earth's crust, and the modeling of chemical and energy transport systems.

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

Rock and aqueous fluids are reacted experimentally in dynamic (circulating) systems at elevated temperatures and pressures in order to determine the reactions of importance for, in particular, hot dry rock geothermal reservoirs. Rock and fluid compositions are monitored for the duration of an experiment (on the order of two to eight months) as the rock and fluid change from an initial state of complete disequilibrium to one of mosaic equilibrium. Identified experimentally grown secondary phases may then be related to the primary phases and solution in a chemographic network which predicts the important divariant mineral assemblages and univariant reactions not directly observed in the experiment. The system is modeled as a variety of infiltration metasomatism.

Chemical geothermometry has been tested in these systems indicating that the Na-K-Ca geothermometer is accurate in predicting rock reservoir maximum temperatures in the range 200°C to 310°C, once mosaic equilibrium has been established. The activities of Na, K, and Ca (in solution) are fixed by complex reactions between feldspar (+ quartz) and fluid which yields secondary mineralization. Preliminry experiments in simple feldspar plus fluid systems have been initiated to isolate the critical reactions giving this empiral geothermometer its validity.

B. Thermochemical Measurements (C. Holley)

Good thermochemical data are needed for modeling rock-water interaction in geochemical systems. A molten oxide calorimeter

for measuring heats of solution has been constructed and is being calibrated. The laboratory is uniquely equipped to determine heats of solution for materials (such as the alkali oxides) that are corrosive, hygroscopic, or otherwise difficult to handle.

C. Geochemical Calculations (C. Herrick)

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

D. Element Migration and Fixation in Rocks (R. Vidale, C. Duffy, and T. Benjamin)

The circulating fluid of a hot dry rock geothermal system might prove to be a good source for trace elements of economic value present in the hot reservoir rock. This study focuses on dissolution, transport, and reprecipitation of trace elements. Dissolution, migration, and fixation are being studied at controlled temperature and pressure in agitated gold vessel systems and in circulating systems. Source minerals in a given rock are located by neutron activation and plasma emission spectrometric analyses of separated mineral phases. Dissolution is determined by plasma emission spectrometric analysis of the solution phase and fixation is observed by scanning electron microscopy using an energy dispersive analyzer.

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

Contract: W-7405-ENG-36

Title: III. Solar-Terrestrial Physics

Person in Charge: W. D. Evans

Scope of Work

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

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

The goals of this research are to describe the structure and flow of plasma energy in the solar wind, bow shock, magnetosheath and magnetopause. Specific aims include determining long-term variations in solar wind structure near the earth, understanding basic solar wind acceleration mechanisms and their relationship to conditions in the solar atmosphere, determining the electron and ion distribution functions of the solar wind in order to understand thermal energy transport and heating processes and evolution of large scale disturbances in interplanetary space, understanding processes which determine solar wind heavy element abundances and ionization state densities, and understanding solar wind-magnetosphere coupling through fundamental studies of plasma transport in and near the earth's bow shock, magnetosheath, and magnetopause.

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

This research aims to construct models of the dynamic processes associated with the solar wind-magnetosphere interaction. The specific objectives include determining the mechanisms of entry of

magnetosheath plasma through the magnetopause and boundary layers into the magnetosphere, understanding the coupling of momentum and mass from boundary layer plasmas to the polar ionosphere and the role this coupling plays in accelerating ionospheric plasma into the outer magnetosphere, determining the mechanisms of loss of magnetospheric plasma to the magnetosheath, determining the mode of transport of plasma from the boundary layers into the tail to form the plasma sheet, establishing the role of magnetic reconnection in the plasma sheet in the substorm phenomenon, understanding the generation and evolution of "plasmoids" evidently formed in the plasma sheet in the early phase of the substorms, identifying the occurrence of the tearing-mode instability in the plasma sheet, and identifying and understanding the presumed acceleration of some plasma sheet particles to very high energies by inductive electric fields during substorms.

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

Contract: W-7405-ENG-26

Title: Geochemical Research

Person in Charge: R. E. Mesmer

Scope of Work

The geosciences program at the Oak Ridge National Laboratory (ORNL) addresses two broad areas of experimental geochemistry: physical chemistry of geothermal solutions and materials, and interactions of aqueous media with constituents of natural formations. Mineral equilibria and rock-water interactions are being studied, upwards to 500°C and 100 MPa, providing data for both equilibrium and kinetic geochemical models of chemical migration and the responses of rocks to circulating natural waters. High temperature-high pressure studies of silicate melts provide models for a better understanding of igneous processes, such as the generation of magma at depth, migration to the upper regions of the crust, crystallization, and release of energy.

A. Physical Chemistry of Geothermal Solutions and Materials

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

The aim of these studies is to further understand the physicochemical processes that operate during magma generation, migration, and consolidation. High temperature experiments at pressures ranging from 100 kPa (1 bar) to 1 GPa (10,000 bars) are conducted to obtain phase equilibria, crystal growth, and chemical partitioning data for P-T-X conditions simulating those over which magmatic processes operate in the crust of the earth. This information will be used to model the physicochemical response of silicate rocks and magmas to pressure, temperature, or composition changes. The results of these studies are relevant to locating and extracting mineral resources, developing crystalline ceramic matrix materials for industrial use (including nuclear waste isolation), extracting energy from magmas, and improving the understanding of volcanic processes and hazards.

Controlled cooling experiments with chemical models of natural igneous rock systems are conducted to investigate crystal nucleation and growth kinetics. Olivine crystallization kinetics in analogue basaltic systems are currently studied as a function of temperature and bulk composition at one atmosphere pressure. The quantitative nucleation and growth parameters obtained for olivine in this investigation

provide data to aid interpretation of the cooling histories of natural basaltic rocks. Experiments have been started in collaboration with S. E. Swanson (University of Alaska) to investigate crystallization kinetics of rhyolitic and andesitic magmas.

Studies of the high temperature behavior of model magmas will be extended to high pressure when a 1 GPa (10 kbar) hydrogen service internally heated pressure vessel is installed this year. This system will be equipped with a Shaw membrane to permit control of oxygen fugacity during experimentation. Reconnaissance experiments on element partitioning and diffusion with trace concentrations of uranium in granitic and basaltic compositions have been successfully completed. Knowledge of equilibrium relationships gained in previous studies were used to guide these experiments. This study will provide information about uranium distribution among phases and mobility in magmatic systems as a function of T, P, X, and f_{O_2}. Other economically and strategically important elements are to be systematically added to well studied silicate systems to observe their partitioning and diffusion behavior.

2. Brine Chemistry (R. E. Mesmer, M. H. Lietzke, and S. E. Drummond)

In this part of the program the speciation and equilibrium thermodynamics of geothermal brines are investigated in the range of 50°C to 350°C at modest pressures. Equilibrium processes involving the principal solutes in geothermal brines are examined including ionization, complexation, hydrolysis, association and solubility reactions. The initial emphasis has been on ionization reactions of water, silicic acid, and carbonic acid. The stability and speciation of fluorosilicates has also been examined. A comprehensive description of the acid buffering properties of brine components is being attained. Also, modeling of the thermodynamic properties of major and minor components is being attempted using data newly acquired here and in other programs.

B. Interactions of Aqueous Media with Constituents of Natural Formations

1. Solid-Aqueous Solution Interactions (F. W. Dickson and S. E. Drummond)

An experimental program is being carried out on selected reactions of natural fluids, or simplified analogues of natural fluids, with minerals and rocks. Such reactions are of prime importance in understanding crustal processes, both those in nature and those caused by man. ORNL is interested in the transport of elements by aqueous fluids; rock alteration modes, the genesis of mineral associations including ore mineral assemblages, and low-to-moderate metamorphism of rocks. The experiments are generally aimed either at measuring properties

of systems in which equilibrium between the fluids and solids has been attained, or determining the nonequilibrium kinetic pathways of reactions in systems initially far from equilibrium. Much of the earth's crust has approached equilibrium through long geological times, and equilibrium data are directly applicable in many cases. Equilibrium may not have been reached where rapid processes occur, such as at sites near intruding igneous bodies, in places disturbed by man (geothermal fields, solution mining, underground storage sites), or where low temperatures and pressures prevail.

Presently, the solubility of quartz in aqueous salt solutions is being studied over a wide range of salt concentrations at temperatures up to 300°C at the vapor pressures of the solutions. Quartz-solution reactions are particularly important to hydrothermal geochemistry because quartz is a member of many mineral assemblages and it occurs in diverse geologic environments. The investigation of quartz solubility is the first of a series of studies on pure sulfide, carbonate, silicate, oxide, and sulfate minerals.

The reactions of natural rocks with aqueous solutions up to 300°C are being studied, using multicomponent rocks (10 major components and 20 to 30 minor constituents) and simplified analogues of important natural solution types. These experiments usually achieve steady state configurations which may be far from equilibrium. The data apply directly to the low temperature (up to 350°C) regimes of the upper crust, which is that part of the earth most accessible for observations and practical uses. Out of the empirical nonequilibrium rock-solution studies come scientific and practical questions suitable for additional, more controlled experiments on simplified systems. The focus of this program is on rocks composed of minerals of high surface areas, such as sedimentary shales and volcanic tuffs, which are also useful types for underground storage or for solution mining.

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

Reactions within a single phase, particularly an aqueous phase, are studied in this program to elucidate crustal processes. Quantitative knowledge of the species in high temperature aqueous solution phases is important for deriving activity coefficients and thus describing such properties as solubilities, diffusion rates, and reactions in hydrothermal and metamorphic environments. In one approach to obtain the distribution of species in high temperature aqueous solutions, the electrical conductances of salt solutions are measured as a function of temperature, pressure, and concentration of salt. From theoretical interpretations of the results, the varying extents

of ion association may be calculated and the equilibrium speciation may be deduced.

Earlier work from Oak Ridge National Laboratory has been published on the behavior of simple salts in high temperature water solutions, for example, NaCl, NaBr, and similar salts. Present studies emphasize 2:1 electrolytes (e.g., $CaCl_2$, $MgCl_2$) that are extremely important to fully understanding high temperature natural waters but which require more complex theoretical considerations than the simple 1:1 electrolytes.

This information on aqueous chemistry is ultimately needed to describe heterogeneous systems involving gaseous and solid phases. With an adequate thermodynamic and kinetic data base it is possible, by numerical methods, to simulate hydrothermal processes that are central to problems of ore deposition, geothermal exploitation, solution mining, enhanced methods of petroleum recovery, and underground storage. Such computational techniques are being developed in this program concurrent with the experimental studies.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: I. Magma Energy Research

Person in Charge: H. C. Hardee

Scope of Work

The Magma Energy Research Project assesses the scientific feasibility of directly extracting energy from buried magma sources and is divided into five major research tasks: magma source location and definition, magma source tapping, magma characterization, magma-material compatibility, and energy extraction. Defining and characterizing magma chambers also provides information on heat sources for geothermal systems and may provide insight into the location of mineral resources.

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

The ability to locate and identify a source of molten rock in the earth's crust is critical to this project. It is imperative that the existence of a magma source, including its depth, areal extent, and general form (whether in a finite pool or in a honeycomb of crevices filled with molten material) be known with the greatest certainty before proceeding with drilling plans. Most of the recent work on this task has been performed at the Lava Lake Laboratory at Kilauea volcano, in Hawaii.

Previous geophysical measurements at the Lava Lake Laboratory suggested, but could not confirm, the presence of a low viscosity, molten rock lens. Recent drilling and thermal studies in the lava lake show that the lake is in a late stage of solidification, with no low viscosity lens, but rather a plastic, multiphase region of crystals (mainly olivine) in melt with intermittent thin (1-14 cm?) veins of very fluid molten rock. Models to predict the thermal behavior of the lava lake geothermal system and to estimate the solidification state of the multiphase lens are being developed.

Additional geophysical experiments at Kilauea Iki lava lake have begun. Several cased boreholes drilled into the lake will provide information about the current state of the molten body in the lake. A seismic experiment in which the source is located downhole and the geophones are located on the surface will provide information about the vertical velocity structure of the lake.

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

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

As drilling approaches the magma source, it is obvious that the temperatures of the rocks above the magma source are going to increase, causing the rocks to approach a plastic state. Little is known, however, about the physical properties of rocks at these elevated geostatic pressures and temperatures; thus, a basic question must be answered: Will a hole through such a hot plastic material stay open and are methods available that would keep the hole open so that the heat exchanger equipment can be inserted through it and into the magma source? To answer that question, Sandia National Laboratories has been involved in a research program with the Center for Tectonophysics at Texas A&M University to investigate the physical properties of rocks under dynamic stress conditions at pressures up to 5 kilobars and at temperatures of approximately 1000°C.

Recent Lava Lake Laboratory drilling experiments have demonstrated the ability to drill and core through 30 meters of molten basalt at temperatures greater than 1070°C, keep the holes open for several days, and insert experimental apparatus repeatedly. A Sandia-developed water jet-augmented core bit provided 100 percent core recovery.

C. Magma Characterization (J. L. Colp)

Magma is known to produce a high-temperature, highly corrosive matter. Much definitive information must be known about this environment, that is, the in situ properties and its effects on engineering materials, before heat exchanger equipment is inserted into it for long periods of time.

Samples obtained from the drilling of Kilauea Iki Lava Lake during late 1978 and early 1979 have been studied with the electron microprobe. The analyses of glass and crystalline phases provide important data on the state of the lava lake at the time of drilling. Such information is essential to understanding potential corrosion, possible heat extraction rates, and is the basis for interpreting indirect geophysical data. The lava lake exhibits a continuous transition between the solidified upper crust and the underlying magma. This transition, taking place over 4 meters, is marked by a change in composition of the residual liquid from quartz normative basaltic liquid in the chamber to rhyolitic liquid in the upper crust. This compositional change decreases the amount of residual liquid from 35 to less than 5 volume percent. The 1978-79 drilling program was successful in drilling through the magma system, as indicated by a maximum in liquid abundance at 57.5 meters. The upper crust has a thick olivine depletion zone in a depth range from 18 meters to 40 meters.

D. Magma Material Compatibility (J. L. Colp)

The ability to build a heat-transfer device that can be inserted directly into a magma source is critical to the successful utilization of magma energy. The materials for building a heat exchanger must retain their physical and structural properties sufficiently to allow the heat exchanger to perform for many years if the installation is to have an economic value.

Fifteen pure metals and 16 alloys have been evaluated in low-pressure, simulated-magma environments. Preliminary results suggest that iron, cobalt, and molybdenum--each containing chromium--will show little degradation. The chromium content of both ferritic and austenitic stainless steels is the most important factor in providing corrosion resistance. Type 310 is by far the most corrosion-resistant alloy of any commercial stainless steel.

Compatibility studies will continue and the magma simulation facility will be used for further studies at magmatic conditions.

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

The energy extraction task aims to understand energy transfer processes in molten magma and margin zones of magma systems and to find ways of extracting energy from the magma or its margins. Convective heat transfer processes in molten magma have been studied by theoretical calculations, by laboratory experiments in furnace-melted samples of molten lava or magma, and by field experiments in lava lakes and lava flows resulting from volcanic eruptions. The theoretical calculations are concerned with predicting convective rates and energy transfer rates from molten magma to bodies (calorimeters, heat exchangers) submerged in the magma. Laboratory measurements, which complement the theoretical calculations, are made by inserting calorimeters into furnace-melted samples of magma or lava. Early calculations and experiments concentrated on superliquidus temperature magmas, but recent work has concentrated on non-Newtonian convection in the subliquidus temperature range. Both theoretical calculations and laboratory measurements have shown attractive convective heat transfer rates in the subliquidus range (5 to 50 kW/m^2). Future laboratory convection measurements are planned in a high temperature, high pressure furnace corresponding to expected conditions for magma at 5 km depth in the crust. Field measurements of convection were made during the 1977 Kilauea eruption, and related thermal measurements were taken during the 1980 Mt. St. Helens eruption.

Heat transfer processes have also been studied in the permeable margin zones above magma bodies. This type of process involves the permeable convection of water and steam through fractures in the hot margin zones surrounding a magma body. This research has also comprised theoretical calculations and laboratory and field measurements. Theoretical calculations are performed for single- and

two-phase permeable convection in porous or fractured bottom-heated media. Laboratory tests are run in permeable beds to confirm the theoretical calculations. Field test data have been obtained from a number of sources including field experiments in Kilauea Iki Lava Lake, Hawaii, and Heimaey Lava Lake, Iceland. These data have aided in understanding the cooling and solidification rates of these molten bodies as well as in predicting the performance of calorimeters and heat extraction devices in these permeable margin zones. A heat extraction test was run in the permeable margin zone of Kilauea Iki in 1979.

Recent Lava Lake Laboratory energy extraction experiments have demonstrated the operation of two types of heat exchangers. In an experiment in which a closed heat exchanger was placed in the solid margin directly overlying the molten zone, a heat extraction rate of 17 kW/m^2 of heat exchanger area was measured. In an experiment in which an open heat exchanger was formed in the molten zone, heat extraction rates of 980 kW/m^2 (transient) and 93 kW/m^2 (steady) were measured.

Contractor: SANDIA NATIONAL LABORATORIES
Albuquerque, New Mexico 87185

Contract: DE-AC04-76DP00789

Title: II. Continental Scientific Drilling Program: Thermal Regimes

Person in Charge: O. E. Jones

Scope of Work

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

Sandia National Laboratories contributes to the CSDP in three areas--program coordination, joint participation in comparative site assessments, and geoscience research on hydrothermal and magma systems.

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

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

- Program development, utilizing input from the Department of Energy, the U.S. Geological Survey, and the academic community.
- Service functions provided by Lawrence Livermore National Laboratory (data base on active drilling), Los Alamos National Laboratory (assessment of core and sample repository needs), Lawrence Berkeley Laboratory (geothermal fluids data base), and Sandia National Laboratories (drilling, logging, and instrumentation technology).
- Site-specific research based on research proposals submitted to and reviewed by DOE's Office of Basic Energy Sciences and dealing with field-based geological, geophysical, and geochemical studies at potential sites of interest to the thermal regimes work of CSDP.

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

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

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

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

This research is directed toward understanding energy and mass transport within and between hydrothermal and magma systems and involves a combination of field, experimental, analytical, and modeling approaches. A factor linking these approaches is the role of volatile components in the near-surface behavior of rock-forming systems.

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

Detailed geochemical studies of crystallization in a shallow magma system (Kilauea Iki Lava Lake, formed in 1959) have begun in preparation for experimental studies on crystallization of basaltic magmas at low pressure. Samples from the 1979 and 1981 drilling programs in the "natural crucible" provided an unusual opportunity for the study of mineral and liquid evolution pursuant to crystallization, kinetics of nucleation and growth, and extent of equilibration in a natural system whose initial parameters are particularly well bounded, but over a space-time scale unattainable in the laboratory.

Electron microprobe analyses of glass and mineral phases in the 1979 and 1981 samples have been used to define the geochemical characteristics of the upper crust, transition zone to the magma, the magma zone proper, and the transition zone to the lower crust. Liquid (quenched as glass) compositions change from olivine normative basaltic through andesitic and dacitic to rhyolitic from the magma zone to the upper crust in the transition zone, defining a continuous liquid line of descent.

Geochemical studies on this unique set of samples of a quenched, in situ, magma system provide the basis for application to the evolution of the much more abundant exhumed magmatic rocks which have undergone long and convoluted cooling and solidification histories.

2. Magmatic Volatiles in Explosive Eruptions (J. C. Eichelberger and H. R. Westrich)

Thermogravimetric and mass spectrometric methods have been used to analyze silicic tephra, and obsidian (clasts, flows, and domes) to obtain information on the volatile content and degassing of shallow silicic magmas. The analysis of obsidian clasts in tephra deposits provides a new approach to the problem of volatiles in magmas. These clasts, which appear to represent samples of relatively deep and initially vapor-undersaturated magma, were quenched during ejection without loss or gain of volatiles. Volatile contents indicated for small to moderate volume (10^{-3} to 10^{-2} km^3) Plinian eruptions are 0.5 to 1.0 wt.%, with water as the dominant volatile component. Bubble growth occurs within 300 meters of the surface, in part prior to eruption; eruptions terminate when vesiculated magma is exhausted. Investigation of clasts from eruptive sequences indicate strong stratification of the parent magma body, with magma containing 0.5 to 1.0 wt.% volatiles (erupted at tephra) overlying magma containing 0.1 to 0.2 wt.% volatiles (erupted as flows or domes).

3. Energy Transport (H. C. Hardee)

This study aims to better understand energy transport processes in magma and hydrothermal systems. Research is being conducted on enhanced convective heat transfer in permeable media near the critical point. This work has included both laboratory tests and theoretical studies. Enhanced convection near the critical point has implications for geothermal energy, ore deposition, and magma emplacement in the crust.

Convection in permeable rocks above large shallow magma bodies in the crust is being investigated. Theoretical calculations are being done for single-phase and two-phase permeable convection both above and at the edges of these systems. These calculations are being correlated with field data from lava lakes and regions above suspected magma bodies in the continental crust.

Contractor: SANDIA NATIONAL LABORATORIES

Contract: DE-AC-04-76DP00789

Title: III. Modeling of Geodetic Crustal Strain Data

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

Scope of Work

The crustal deformation program is an active and ongoing research effort whose primary objective is to develop inelastic models for interpreting observed time-dependent tectonic strains in the earth. Applications resulting from this work have been made to reservoir engineering and to subsidence effects in complex inelastic geologic media due to massive mining.

This program is being used to solve the coupled elastic-gravitational or porous elastic nonisothermal field equations for the impulse response function (Green function). In this method, the solution is represented as an infinite series of Fourier-Bessel integrals, for which the coefficients for each term are then derived. Using this approach and a variety of nonisothermal source functions, deformation can be computed for faulting sources, magma sources, mine cavities, intruded masses, and injected water.

Past data interpretation has been principally based on crystal deformation measurements in Japan and southern California. Data on Japan have been interpreted using a model of shallow angle surface faulting in an elastic lithosphere overlying a Maxwell viscoelastic asthenosphere. Uplift, some strain, and tide gauge data were used to constrain models of Japan near the island of Shikoku and on the Boso peninsula, near Tokyo. Data on southern California consists of leveling over the past 80 years, triangulations over the past 30 years, geodimeter- and geodolite-derived horizontal strains, and some tide gauge records. The leveling data define the well-known southern California uplift and are presently controversial.

Water well-log records also provide information on changes in pore pressure with time in certain areas. Any improvements in the theory and computational capability greatly increased the accuracy in calculating finite source deformations in poroelastic media. These new calculations are now yielding values and bounds on material properties for the upper crust. Applying the modeling capability to deformation in Alaska is also underway, in collaboration with coworkers at the U.S. Geological Survey.

PART II

GEOSCIENCES

OFF-SITE

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

Contract: DE-AM06-76RL 02229

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

Person in Charge: S. I. Akasofu

Scope of Work

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

University of Alaska researchers are also interested in energy-related geophysical problems in the Arctic region. In particular, they are studying the electric current induced by auroral activity in power transmission lines and in oil/gas pipelines. We have successfully demonstrated that auroral activity causes surges in the protective relay system in power transmission lines. An intense surge will open the protective relay, causing a system blackout. By studying the characteristics of the surges, a protective relay system should be possible which will not be affected by auroral activity. Intense electric currents (as much as 1000 amperes at times) in an oil pipeline, induced by the aurora, may cause serious corrosion of the pipe. Various other problems associated with the induced currents are also under study.

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

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

Title: II. Alaska Peninsula Telemetered Seismic Network

Person in Charge: H. Pulpan

Scope of Work

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

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

Presently, the work focuses on

- Determining the source mechanism parameters of earthquakes from both body and surface waves.
- Inverting regional and teleseismic travel time data into a crustal and upper mantle seismic velocity structure.
- Relocating earthquakes based on results of the inversion data and the use of Joint Hypocenter Determination methods.

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

Subcontract: DE-FC07-80ID12145

Title: I. Investigation of the Thermodynamic Constraints on Water/Rock Reaction and Their Relationship to Fluid Flow Patterns in the Cerro Prieto Geothermal System in Mexico

Person in Charge: D. K. Bird

Scope of Work

Recent advances in theoretical geochemistry and heat and mass transfer models now permit calculations of the controlling thermodynamic relationships between natural aqueous solutions and minerals at various spatial locations within geothermal reservoirs. These advances of thermochemical and fluid flow analysis are to be utilized in deriving a quantitative description of the pressure, temperature, and composition controls responsible for observed compositional relationships among minerals and aqueous species in a well-explored geothermal system. This is a joint project involving W. A. Elders and A. E. Williams, from, respectively, the Institute of Geophysics and Planetary Physics, at the University of California, Riverside, and its subcontractor, the Department of Geosciences at the University of Arizona.

Intense scientific study of the Cerro Prieto geothermal field has produced an extensive data base on mineral distribution, mineral and fluid chemistry, and temperature distribution. This field, where a series of prograde metamorphic minerals have formed in response to temperatures as high as 350°C at 1.8 km depth, is the ideal candidate for this investigation.

The objective of this segment of the project is to develop thermochemical and fluid-flow models using the computational facilities and software at the University of Arizona. The results will include quantitative descriptions of the thermodynamic controls on water-rock reaction in this system and the effects of fluid flow patterns on mineral distribution.

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

Contract: DE-AC02-81ER10842

Title: II. Rock deformation in Magma-Hydrothermal Systems: The Nature of Fractures in Plutons and Their Host Rocks

Persons in Charge: D. Norton and D. K. Bird

Scope of Work

Motivation for this comprehensive field survey of fractures in exhumed fossil magma-hydrothermal systems is based on ten years experience in field and theoretical studies of magma-hydrothermal (MH) systems. During these studies the need for data on the state of stress and style of rock deformation has become apparent. The objectives of the project are:

- Improving and developing techniques for fracture mapping in fossil MH systems that will provide information relevant to understanding the transport processes.
- Mapping fracture characteristics--for example, frequency, spacing, continuity, and effective aperture--in one fossil system in detail and in several systems at a reconnaissance scale.
- Describing fracture characteristics with respect to specific locations in the pluton--for example, side margins, cupola, and interior.
- Summarizing these data in a form that benefits advanced technology groups concerned with engineering studies of active MH systems, and improving the theoretical basis for analyzing the MH systems processes.

The results of this research will help to define data requirements and mapping techniques for engineering studies related to crystalline rocks.

Contractor: UNIVERSITY OF ARIZONA
Tucson, Arizona 85721

Contract: DE-AC02-80ER10753

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

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

Scope of Work

Detecting and monitoring climatically significant changes in the solar constant has been the goal of many researchers. However, this pursuit has met with little success, primarily because of continuing difficulties in obtaining radiometer data that are reproducible at the requisite level of sensitivity over years and decades. For this reason, the development of effective indirect diagnostics of solar luminosity is being explored in various quarters.

The work at the University of Arizona is concerned with the development of an indirect diagnostic addressing luminosity changes through the study of changes of the solar shape and diameter. During the 1970's, techniques were developed at the University to measure fractional changes in the solar diameter to an accuracy of $\Delta D/D \sim 10^{-5}$ to 10^{-6} over relatively short time scales. This accuracy represents an improvement of several orders of magnitude over that achieved in the past. Current efforts aim to extend the technique to obtain this accuracy over time scales of years to decades and to study the relationship between the indirect diagnostic and the solar luminosity. Studies of the solar figure and diameter may be more sensitive and more cost-effective than direct measurement of this important climatic driving function.

A. Extending the Capabilities of the Telescope to Detect Long-Term Changes in the Solar Diameter (H. A. Hill and R. J. Bos)

1. Short-Term Solution

The solar detector developed during the 1970's is capable of detecting solar diameter changes having periods less than or equal to a few hours with an accuracy of $\Delta D/D \sim 10^{-5}$ to 10^{-6}. For the study of climatically significant changes, which have periods of years to decades at the short end of the spectrum, the stability of the telescope must be properly maintained or the lack of stability must be monitored and corrected. In addition, the basic measuring engine in the focal plane, an interferometer, must be capable of stability over this period range. The short-term solution to the first problem is to "freeze" the telescope configuration until such time as calibration procedures, which represent a long-term solution, are developed. With regard to the interferometer (a device which can only measure changes), a procedure had to be developed to

recalibrate the zero of its scale each day that it was turned on. During the present funding period, both of these solutions have been put on line. The telescope configuration has been adequately stabilized or "frozen," and the interferometer has been augmented in order to detect white light fringes to be used for its recalibration at each use.

2. Long-Term Solution

Maintaining the long-term stability of the telescope is best done by recalibrating it to the requisite accuracy at frequent intervals. A technique has been designed that has the potential to measure absolute angles in a telescope's field to accuracies of 10^{-3} to 10^{-4} arcsec. It should be noted that the development of such a technique is likely to contribute importantly to the larger field of metrology.

B. Extending the Capabilities of the Solar Detector (H. A. Hill and R. J. Bos)

The solar detector is being modified to incorporate some new developments in optical detectors. In particular, a charge-injected device (CID) camera is being developed which, when incorporated into the solar detector, will help to maintain its stability in the spirit of the long-term solution described above. During the funding period, the main effort has been to design and construct an interface between the CID camera and an on-line microprocessor with its mass storage device. This interface has been constructed and is currently being tested.

C. Observations (H. A. Hill and R. J. Bos)

With the completion of the program to "freeze" the telescope's configuration and the modification of the interferometer to detect white light fringes, the observation began. Observers have now been trained to operate the telescope and, starting in March 1981, observations have been made on a regular basis, weather permitting.

D. Analysis (H. A. Hill and R. J. Bos)

The weather during winter 1981 has permitted the acquisition of only a limited amount of data. However, these data are being analyzed to introduce the new staff to the difficult task of data reduction and to make a preliminary check on the systematic errors arising from the telescope as currently configured.

Contractor: ARIZONA STATE UNIVERSITY
Department of Chemistry
Teme, Arizona 85281

Contract: DE-AC02-80ER10765.A000

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

Persons in Charge: A. Navrotsky

Scope of Work

High temperature solution calorimetry is used to determine heats of mixing in aluminosilicate glasses and melts. Systems currently under study are $KAlSi_3O_8$-$NaAlSi_3O_8$-Si_4O_8, $CaMgSi_2O_6$-$CaAl_2SiO_6$, and CaO-Al_2O_3-SiO_2. Combined with previously obtained data on $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$CaMgSi_2O_6$ and $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-Si_4O_8, these data permit the calculation of entropies of mixing in silicate melts, the construction of models describing these entropies, and the calculation of phase equilibria. In addition, data on effective heats of fusion--parameters useful in modeling element distribution and melting phenomena--are being obtained and analyzed. The models are correlated to the structure and physical properties of silicate melts and have potential application in such diverse fields as geochemistry, magma energy generation, ceramic science, nuclear waste disposal, and reactor safety.

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

Contract: DE-AC02-79ER10401

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

Person in Charge: J. F. Hermance

Scope of Work

The focus at this laboratory is on applying geophysical and electromagnetic techniques to detecting and characterizing geological features within the earth that are related to energy resources. Present attention is directed toward understanding the dynamic processes and thermal regimes associated with centers of major volcanic activity in terms of basic scientific questions related to national priorities, such as geothermal energy, chemical transport, and the emplacement of economic ore deposits. The dynamic evolution of intraplate silicic centers in the western United States must be understood in light of the evolution of precursive basaltic activity at high levels in the crust. This is because the segregation of basaltic magma from parent mantle material at depth (30 to 100 km) and its migration to higher levels in the crust (5 to 15 km) offers an effective mechanism for transferring heat from deep mantle sources to the upper crust, which may, in turn, lead to episodes of crustal melting at shallow depth and silicic volcanism at the surface.

A. Thermal Processes Associated with Major Volcanic Centers (J. F. Hermance)

A review of geophysical investigations of the major rift zones in the world indicate that all 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 Rio Grande rift, the emplacement of basaltic magma at mid-levels in the crust may lead to extensive remelting of the crust, triggering eruptive episodes of silicic magmatism, such as those associated with the Valles Caldera. However, a reinterpretation of magnetotelluric measurements made by the research group in the Jemez Mountains (and the Valles Caldera) indicates no profound geophysical anomaly, as would be expected if a major magma body were present. We conclude therefore that silicic magma chambers, beneath resurgent calderas of this type, solidify very quickly after eruption, perhaps in the time scale of 10^4 years. Since volcanic activity in the Jemez Mountains has been active episodically well in excess of 10^6 years, a mechanism is required for reactivating magmatic conditions at depth in

the crust. We are attempting to understand possible mechanisms by which this is done through interpreting the results of geophysical field programs in the Jemez Mountains and the Long Valley/Mono Basin volcanic complex.

B. Physiochemical Processes Associated with the Genesis of Primitive Crust (J. F. Hermance)

A new interpretation of geophysical experiments on Iceland and adjacent areas suggest that crustal thickening due to underplating is a significant mechanism of crustal genesis in this region. According to this interpretation, mantle-derived melt accumulates in a thin layer (T<4 km) at the base of the crust beneath the neovolcanic zone. With time, this melt cools, solidifies, and accretes to (or underplates) the base of the crust, thus leading to crustal thickening. The crust increases in thickness from 8 to 10 km directly beneath the neovolcanic zone to an average value of 20 km for the generally older (~10 M.Y.) Iceland plateau. The much older Iceland-Faroe Ridge has a crustal thickness of 30 km. Therefore, 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. We are planning to explore the possibility that such a process may operate beneath the Basin and Range Province and the Salton Trough in the western United States. A series of geophysical field studies in Nevada and California may address this issue.

C. Magnetotelluric-Magnetic Variation Field System (J. F. Hermance)

A long-term geophysical field program has begun to investigate this system using tellurics, magnetotellurics, and geomagnetic variations over frequencies in the range of 10^3 Hz to 10^4 sec 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 US and their association with regional tectonomagmatic phenomena in the deep crust and upper mantle.

To facilitate this study, Brown University completed the development of a magnetotelluric field system which consists of a microcomputer-based (DEC; PDP 11/23) multi-component data acquisition system capable of real-time acquisition, analysis and display of magnetotelluric data in field environments. The system is mounted in a 4-wheel drive GMC van.

Contractor: UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

Contract: DE-AS03-76F00034

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

Person in Charge: J. H. Reynolds

Scope of Work

This project is concerned with research in rare gas mass spectrometry. The broad objective is to read the natural record that isotopes of the rare gases comprise as trace constituents of natural gases, rocks, and meteorites. In past years, these interests have led to the study of such diverse problems as the dating of rocks, the early chronology of the solar system as revealed by extinct radioactivities, and the elemental and isotopic composition of trapped primordial rare gases in meteorites.

In recent years the project has focused progressively more on terrestrial problems. A lengthy study is being prepared for publication on rare gases from volcanic xenoliths and megacrysts and suboceanic volcanic basalts. These samples have provided information about their genetic relationships and about the outgassing history of the mantle. Several isotopic signatures for primordial mantle gases have been identified.

Current efforts are concentrating on a new program to design, construct, and operate an apparatus to analyze the elemental and isotopic composition of rare gases from fluid sources in the field, at or near the sampling site. Long-range scientific goals are to search for additional manifestations of primordial gases and to see how they relate to convection patterns within the earth. Rare gases from steam wells and other geothermal energy sources will also be examined. Particular interest will be paid to assaying proportions of recycled atmospheric gas versus radiogenic gas. Presently, the procedures are being checked on samples of water which have been equilibrated with the rare gases in air at various temperatures. New data are being obtained on artificially prepared brines. The University's first extensive field study will soon be undertaken at the Geysers geothermal field in nearby northeastern Sonoma County, California.

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

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

Title: Relationship of Rock Physics to Geothermal Energy Technology

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

Scope of Work

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

Three classes of variables are necessary for the analysis: petrographic and mineralogical variables, crack map variables (obtained by mapping crack patterns), and descriptor variables of the elastic deformation of a sample. The output of this analysis is a set of coefficients that are cross-correlated between the variables in the three classes. A preliminary typic study for crack maps on two granites has been completed. A full study is currently being conducted on three samples of Berkeley blue granite.

Additional related studies are being carried out. The first is an experimental and theoretical study of nonlinear stress-strain relations. For this study, volumetric strain measurements were made on thick-walled cylindrical rock samples under pore pressure and triaxial loading. The second is crack modelling and inversion of elastic moduli data into crack spectra.

Contractor: UNIVERSITY OF CHICAGO
Chicago, Illinois 60637

Contract: DE AC02-80ER10763

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

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

Scope of Work

The purpose of this program is to learn about buried bodies of magma by studying crystals extruded from them during past volcanic eruptions. Inclusions of melt contained within crystals can be analyzed for H_2O and CO_2 with a vacuum gas analyzing device. The method needs to be established by first working on well documented materials, including ash-flow tuffs from Valles Caldera, New Mexico.

From measurements of H_2O and CO_2, it is hoped to establish the depths down to the tops of large bodies of silicic magma beneath volcanoes with an accuracy of 1 to 3 km. The same information bears on the expected dynamical behavior of the magma. Both the depth and dynamic behavior of bodies of magma affect their potential for geothermal energy, ore deposit formation, and eruption.

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

Contract: DE-AS02-76ER03134

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

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

Scope of Work

The objective of this project is to quantitatively define physical properties and processes of a highly active subduction zone and its associated volcano-magmatic arc using primarily seismologic information. For this purpose, a seismic network is operated that is centered on the Shumagin Islands Seismic Gap. The historic seismic record indicates that a truly great earthquake (M 8) in this eastern Aleutian arc segment is likely to occur within the next two decades. Specific tasks and the quantities to be determined in this study are:

- High-resolution, three-dimensional seismic velocity (P and S) and anelasticity (Q) structures derived using three-dimensional ray tracing and simultaneous hypocenter and inversion techniques applied to the network data. In addition, converted and reflected phases are used to refine the velocity structures beneath the seismic array.

- Orientations and magnitudes of deviatoric stresses determined within the subducting oceanic plate, near the plate interface, and in the overriding plate containing the magmatic arc. Data sources are seismic focal mechanisms and body wave forms for dynamic stress calculations in the seismogenic portions and volcanic dike patterns in the volcanic arc.

- Delineation of the shape and depth range of magma bodies in the root zone of volcanoes by seismic delay time, waveform, and attenuation analysis.

- Time histories of eruptions of a highly active volcano (Pavlof) are monitored seismically and their relation to changes in the ambient stress field (earthquakes, tides) are investigated.

- Time-dependence of seismic velocities, deviatoric stresses, and patterns of seismicity and volcanicity are monitored for any possible indication of a future great earthquake.

- Many of the scientific tasks require full-range, undistorted seismic waveforms. Therefore, technical development includes digital event recording and, eventually, digital data transmission.

A comprehensive synthesis of the collected seismologic information with results from related geodetic, geologic, and volcanic studies is attempted to develop models for subduction and magmatic arc processes. Applications of this project concern development of island arc geothermal resources; back-arc, fore-arc, and intra-arc basin formation; and the seismic and volcanic exposure of potential lease areas for hydrocarbon exploration in such basins on land and offshore.

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

Contract: DE-AC02-76ER04054

Title: II. The Time-Dependent Transmissivity of Joints

Persons in Charge: C. Scholz and T. Engelder

Scope of Work

In order to understand the effect of fracture closure on permeability, the precise effects of changing fluid pressure on the rate of flow along smooth joints in rock at effective pressures to 300 MPa are being studied. Current studies include measuring the influence on flow fracture filling or gouge along the joint surface. Results from smooth joints indicate that at low pressures (<20 MPa) permeability approximately follows the d^3 law for fluid flow between parallel plates. At much higher pressures where joint apertures (d) are less than 10 μm, permeability decreases faster with d than as d^3. The reason for this behavior is that the effective cross-sectional width (W) available for fluid flow decreases as the joint is pressed together. In effect, W is a function of pressure across the joint.

Two effects are seen in fracture filling which resemble a cataclastic gouge of angular fragments that fills the joint. For a filling of uniform particles about 25 μm in diameter, the permeability decreases faster with d than as d^3. This is attributed to the compaction of the cataclastic filling for which the effective cross-sectional width decreases with increased pressure. For a poorly sorted gouge consisting of particles varying in size from 25 μm to submicron, permeability varies less rapidly with d than as d^3. In this case, the fracture becomes clogged with the finer particles which allow the fracture to close without major changes in permeability.

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

Contract: DE-AC02-80ER10586

Title: Computerized Underground Image Reconstruction

Person in Charge: K. A. Dines

Scope of Work

The goal of this work is to develop computer processing techniques and data collection methods for reconstructing high resolution underground images applicable to a variety of energy programs. The specific goal for this phase is to develop improved measurement models and reconstruction techniques for tomographic imaging of refracting geological media based on data obtained by electromagnetic and seismic probing in the borehole and surface modes of interrogation.

This will be carried out by computer simulation of the geometrical optics model of wave propagation applicable to transmission measurements where the wave length is much smaller than the size of the refracting anomalies. This phase comprises the following tasks:

- Develop stable computer processing techniques for calculating curved ray paths in known two-dimensional refractive index fields (forward problem).
- Investigate the feasibility of implementing image reconstruction techniques for interpreting projection data of refractive media (inverse problem).
- Test the performance of ray tracing and reconstruction techniques using computer-generated test models of refractive index distributions.

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

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

Contract: EY 76-S-02-25430134

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

Person in Charge: K. Aki

Scope of Work

This research program has grown through participation in two major geothermal projects, namely, the Hot Dry Rock Geothermal Energy Development Project of the Los Alamos National Laboratory and the Magma Tap Project of Sandia National Laboratories. In order to interpret data from various seismic experiments conducted at Fenton Hill, New Mexico, and Kilauea Iki, Hawaii, the theory and methods have been developed for seismic wave generation, transmission, scattering, and attenuation in a medium containing a fluid-filled crack(s).

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

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

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

Contract: DE-AC02-78ET04972

Title: II. Microcracks and Energy

Person in Charge: G. Simmons

Scope of Work

The scanning electron microscope (SEM), petrographic microscope, differential strain analysis (DSA), and the data on various physical properties measured as a function of pressure are used to characterize microcracks in rocks that are related to various energy programs. The samples that have been examined include core from geothermal areas (Coso and Raft River) and core from several granitic bodies (Conway and Mt. Osceola granites from New Hampshire and samples from the Granite and Sherman mountains in Wyoming). A set of microcrack features has been identified that appears to be unique to geothermal rocks. Both uranium and rare earth elements have demonstrated that they migrate through microcracks in some granitic rocks and are deposited in microcracks under some physical-chemical conditions.

The objective of this project is to demonstrate the role of microcracks in various aspects of energy. Specifically, the aim is to modify fission track dating methods so they can yield absolute ages of microcracks, document further the migration of rare earth elements (REE) and uranium though microcracks, and develop methods for studying microcracks in shales.

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

Contract:

Title: Experimental Formation of Chalk from Calcareous Ooze

Persons in Charge: T. Johnson and W. Seyfried

Scope of Work

Carbonate sedimentary rocks comprise a significant fraction of the world's petroleum reservoirs. The complex process involved in carbonate diagenesis is of special interest to petroleum geologists because reservoir potential is intimately related to the porosity and permeability changes occurring during lithification. Short term laboratory simulation of diagenetic alterations taking place in natural systems over geologic time periods are especially valuable in understanding sediment transformation into rock. Such experimentation, however, can be valid only if the textural differences produced duplicate those in natural sediments. Experiments are being conducted at the University of Minnesota that attempt to form chalk from its parent material, calcareous ooze. The sediments are subjected to rigorous conditions of pressure and temperature in hydrothermal equipment to cause the diagenetic change. In order to imitate pressures provided by natural overburden, both a differential and hydrostatic pressure are applied to a sample. Sampling of the aqueous phase can also be carried out at experimental conditions. Equipment modifications are being made which will allow differential pressures of over one kilobar, while water sampling capability at hydrothermal conditions is retained.

Several important factors influence the ultimate hydraulic character of a calcareous sediment, including pore water chemistry, initial sediment composition, and sediment physical properties. Pore water chemistry is analyzed in the laboratory by atomic absorption spectroscopy; mineralogy is determined through x-ray diffraction of both the carbonate and the noncarbonate fractions. Physical properties that are measured include bulk density, porosity, and grain size. In addition, the laboratory hopes to develop the capacity to measure sample permeability at experimental conditions. Finally, microscopic textures are analyzed by a scanning electron microscope with an x-ray dispersion attachment. The textures are compared to those of Cretaceous chalks that have undergone varying amounts of diagenesis.

A laboratory system has thus far been successful in simulating sediment diagenesis that should be valuable in solving problems of interest to petroleum companies. The potential benefits include a better understanding of

- The effects of temperature and pressure on the rate of carbonate diagenesis and the consequent influences on porosity and permeability.
- The effects of sediment composition on the rate and amount of diagenesis in carbonates.
- The effectiveness of experimentally formed authigenic minerals as a barrier to oil movement.

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

Contract: DE-FG02-80ER10757

Title: I. Studies in Geophysics

Person in Charge: P. J. Hart

Scope of Work

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 are guided by the Geophysics Study Committee (GSC). Members of the committee are Charles L. Drake (chairman), Louis J. Battan (vice-chairman), John D. Bredehoeft, Allan V. Cox, Hugh Odishaw, Charles B. Officer, Raymond G. Roble, and Thomas M. Usselman.

The studies include problem-oriented studies, such as demands on geophysical knowledge related to climatic variations, fresh water resources, mineral resources, geothermal and other energy sources, geophysical predictions, and environmental maintenance; and science-oriented studies, such as geophysical data, international programs in geophysics, status of developments and opportunities in geophysics, and the 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.

Studies completed

Energy and Climate, Robert R. Revelle, panel chairman, published in 1977, 158 p.

Estuaries, Geophysics and the Environment, Charles B. Officer, panel chairman, published in 1977, 127 p.

Climate, Climatic Change, and Water Supply, James R. Wallis, panel chairman, published in 1977, 132 p.

The Upper Atmoshere and Magnetosphere, Francis S. Johnson, panel chairman, published in 1977, 169 p.

Geophysical Predictions, Helmut E. Landsberg, panel chairman, published in 1978, 215 p.

Impact of Technology on Geophysics, Homer E. Newell, panel chairman, published 1979, 136 p.

Continental Tectonics, B. Clark Burchfiel, Jack E. Oliver, and Leon T. Silver, panel cochairmen, published in 1980, 197 p.

Studies in preparation

Mineral Resources: The Practicality of Genetic Understanding, Paul B. Barton, Jr., panel chairman, to be published in 1981.

Solar Variability, Weather, and Climate, John A. Eddy, panel chairman, to be published in 1981.

Scientific Basis of Water Resource Management, Myron B. Fiering, panel chairman, to be published in 1981.

Pre-Pleistocene Climate, Wolfgang H. Berger and John C. Crowell, panel cochairmen, to be published in 1981.

Geophysical Data and Public Policy, Michael A. Chinnery, panel chairman, to be published in 1982.

Estuarine Research Perspectives, L. Eugene Cronin and Charles B. Officer, panel cochairmen, to be published in 1982.

Studies under consideration

Ground Water Contamination
Explosive Volcanism

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

- 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,
- Provide government officials with technological and scientific evaluations that can serve as a rational basis for decision making germane to policies and programs involving geophysical research.
- Provide the scientific community with a basis for rational judgments related to developing the basic science of geophysics in general and recognizing the relative importance to society of the developments within various branches of geophysics.

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

Contract: DE-FG02-80ER10670

Title: II. Continental Scientific Drilling Committee

Person in Charge: P. J. Hart

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. The report is entitled Continental Scientific Drilling Program, published by the NAS/NRC in 1979. A major program goal that is identified by this report is to aim at maximizing the scientific value of current and planned drilling activities of federal agencies and of industry, and supplementing these efforts with holes drilled solely for scientific purposes. Members of the committee are Eugene Shoemaker (chairman), Lawrence Bonham, Charles Drake, James Eidel, Howard Gould, Bob Greider, Charles Mankin, L. J. Patrick Muffler, Jack Oliver and Elburt Osborn; and Robert S. Andrews, staff.

Scientific objectives for the national Continental Scientific Drilling Program will be formulated by committee panels, three of which currently exist--the panels on thermal regimes, on basement structures and deep continental basins, and on mineral resources. Panels will address the additional subjects of earthquakes, drilling technology, and drill hole information.

A DEW (Drilling Early Warning) Newsletter has been established by the Committee to communicate with the scientific community. This DEW Newsletter will be periodically sent out using a mailing list of about 600 researchers from universities and other academic institutions, industry, government laboratories, geoscience administrators, and geoscience societies. The DEW Newsletter will provide information on the committee's activities and scientific objectives, announce important meetings and publications, and serve as a forum for interested scientists to exchange information related to drilling. The most important role of the DEW Newsletter is to announce early in the planning stage important opportunities for add-on investigations to drilling activities of government and industry and encourage collaborative efforts to the benefit of all concerned. To date, three DEW Newsletters have been printed.

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

the research proposed in this plan has been completed by the investigators and was reported at the spring annual meeting of the American Geophysical Union in Baltimore, Maryland, in May 1981.

The committee and the panel on thermal regimes have reviewed the Continental Scientific Drilling Program of the Office of Basic Energy Sciences, Department of Energy, and have prepared a report, Comments of the Continental Scientific Drilling Committee on the Department of Energy Office of Basic Energy Sciences Continental Scientific Drilling Program. In this document, the CSDC reviews the Information and Data Management Project and the Comparative Site Assessment Project of the program.

The panel on thermal regimes is preparing a report for the CSDC tentatively entitled A National Drilling Program to Study the Roots Of Hydrothermal Systems Related to Young Magmatic Intrusions. In this report, the panel recommended a 10-year plan of scientific investigation leading to better understanding of hydrothermal-magma systems, focusing on high-level silicic caldera complexes, such as Valles Caldera, New Mexico, and the Long Valley area, California. In developing this document, the panel organized a symposium, Magma-Hydrothermal Systems, for the fall annual meeting of the American Geophysical Union, in San Francisco, December 1980.

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

Contract: DE-AT02-76CH93003

Title: III. Committee on Seismology

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

Scope of Work

The Committee on Seismology meets twice a year to discuss 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.

Two reports were published during 1980:

- Earthquake Research for the Safer Siting of Critical Facilities, Panel on Earthquake Problems Related to the Siting of Critical Facilities of the Committee on Seismology, National Academy Press, June 1980.

- U.S. Earthquake Observatories: Recommendations for a New National Network, Panel on National, Regional, and Local Seismograph Networks of the Committee on Seismology, National Academy Press, December 1980.

Two new panels have been formed--seismological studies of the continental lithosphere, and data problems in seismology. Both panels are currently writing reports on their topical areas of study.

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

Contract: DE-A101-79ER10442

Title: IV. Committee on Geological and Materials Sciences

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

Scope of Work

The Committee on Geological and Materials Sciences is reviewing the scientific and technological area between these two sciences to identify and improve those conditions that impede effective interdisciplinary interactions in universities, industry, and government agencies; to examine the mechanisms through which basic interdisciplinary research needs are incorporated into the long-range planning for major geosciences projects; to examine the need for regional and/or national centers that provide special facilities; to enhance interaction between geoscientists and materials scientists through conferences attended by professionals from diverse traditional disciplines; to bring together more of the members from these two fields who have no pre-existing common interest, via lecture series that should complement workshops, symposia, etc.; and to stimulate the publication of state-of-the-art reviews with emphasis on interdisciplinary research opportunities. The study is conducted by members selected from academia, industry, and government. A report is expected during fall 1981.

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

Contract: DE-FG02-80ER10758

Title: V. U.S. Geodynamics Committee

Person in Charge: P. J. Hart

Scope of Work

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

The list of topics and respective reporters has been subject to continual review and revision, as appropriate. As of March 1981, the list was as follows:

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

The activities of the USGC and its reporters are reviewed by the committee at semiannual meetings. The committee findings have been published in progress reports for the years 1975, 1976, and 1977. All other reports for the years 1970-80 are unpublished.

The USGC has been particularly active in encouring drilling on land for scientific purposes. The USGC was instrumental in organizing the 1974 Workshop on Continental Drilling that led to the report Continental Drilling (1975). The USGC organized a second Workshop on Continental Drilling for Scientific Purposes in 1978, culminating in the 1979 report Continental Scientific Drilling Program. The report concludes importantly that, with advance planning, a greater scientific return could be yielded, based on 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 USGC has encouraged the preparation of a series of continent-ocean transects to define the nature of the transition from stable continental crust to oceanic. Guided by a USGC reporter, this program involves 15 corridors along the Atlantic and Pacific coasts of the United States. Canadian and Mexican groups have joined the effort, which will result in a North American program of transects.

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 Profiles (COCORP), Continental Scientific Drilling Program, Continent-Ocean Transects, Early Crustal Evolution, Joint Oceanographic Institutions Inc. (JOI), Gravity Anomaly Map for North America, LASE, Magnetic Anomaly Map for North America, Tectonic Map of North America, and the USGS Geological Framework Program.

The committee also emphasizes three broad areas not encompassed by any one reporter: increased emphasis on the continents, increased emphasis on processes and properties of the earth's interior, and applications of geodynamics to practical problems. The USGC is considering the desirability of organizing a workshop on the problems of the lithosphere.

The International Union of Geodesy and Geophysics and the International Union of Geological Sciences are developing an international program of geodynamics for the 1980's as a successor to the Geodynamics Project, which formally ended in December 1979. The new program is entitled Dynamics and Evolution of the Lithosphere: The Framework for Earth Resources and the Reduction of Hazards. International guidance

is provided by the Interunion Commission on the Lithosphere. The secretariat of that commission is located in the United States; basic support for the practical operations of the secretariat is provided through the USGC. The international program is developing in response to the recommendations 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.

Members of the committee are John C. Maxwell (chairman), Don L. Anderson, Hubert L. Barnes, Bruce A. Bolt, Francis R. Boyd, B. Clark Burchfiel, David B. MacKenzie, Jack E. Oliver, David W. Scholl, and Harmut A. Spetzler.

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

Contract: To be assigned

Title: VI. 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: It acts 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 it acts to promote 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 the IAGC; George W. Wetherill, of the Carnegie Institution of Washington and the immediate past president of the IAGC, now holds that position. Other U.S. members of the IAGC Council include Ernest E. Angino (University of Kansas), treasurer, and Ivan Barnes (U.S. Geological Survey, Menlo Park, California), councilor.

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

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

The committee informs members of advances in geochemistry, sponsors scientific meetings, and establishes ad hoc subcommittees or panels, as appropriate, to report on timely topics concerning geochemists both in the United States and abroad. For example, the committee interacts with the U.S. Geodynamics Project via geochemists assigned to report on specific topics of interest, reviews documents related to radioactive-waste disposal, and arranges workshops, such as that entitled "Basic

Research in Organic Geochemistry Applied to National Energy Needs," held at the University of South Florida, St. Petersburg, in December 1980. A study entitled the "Future of Geochemistry" is planned as a sequel to "Orientations in Geochemistry" (1973), by the Panel on Orientations in Geochemistry under the chairmanship of R. M. Garrels.

Under the organization's constitution, members' terms are normally 3 years, one-third of those terms expiring annually in June. The current membership of the U.S. National Committee for Geochemistry is Rosemary J. Vidale (chairwoman), V. Rama Murthy (vice-chairman), Robert A. Berner, Maria Luisa B. Crawford, Everett A. Jenne, Keith A. Kvenvolden, James J. Papike, Werner J. Raab, Arthur W. Rose, and William M. Sackett.

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

Contract:

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

Person in Charge: J. F. Dewey

Scope of Work

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

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

The Austro-Alpine nappe complex of eastern Switzerland, together with the southern Alps, represents the thinned continental crust of the southern margin of the Alpine trough whose demise led to the growth of

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

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

Contract: DE-AC02-79ER10412

Title: Thermally Induced Chemical Migration in Carbonate Rocks

Person in Charge: J. J. Papike

Scope of Work

This program studies the contact metamorphism of upper Cambrian carbonate rocks by the intrusion of a granitic stock. The carbonate rock is dominantly $CaCO_3$; the granitic rock is rich in SiO_2 and Al_2O_3, and is relatively enriched in rare-earth and other trace elements. The strong chemical contrast between granite and carbonate rock provides an ideal situation for element migration down chemical potential gradients. This investigation was undertaken to determine the magnitude of major and trace element migration over geologically significant periods of time in a deep crustal environment.

The late Jurassic Notch Peak stock, a porphyritic quartz monzonite intrudes Cambrian limestones and shaly limestones in western Utah. A total pressure of 2 KB has been estimated based on the amount of stratigraphic overburden at the time of the intrusion. The temperatures of peak metamorphism are based on a least squares fit of the experimental 2 KB calcite-dolomite data of Goldsmith and Newton (1969). The temperature estimates are $\sim 450^{o}C$ for the medium grade limestones (calcite, dolomite, quartz, talc, tremolite) and $\sim 550^{o}C$ for the highest grade rocks (calcite, dolomite, diopside, forsterite, tremolite). Fifty-two samples have been analyzed for major, minor and trace elements by X-ray Fluoroscopy (XRF) and Neutron Activation Analysis (INAA). The chemical data on all samples have been run through a factor analysis program and correlation coefficients for ten major and six trace elements have been calculated. The elements Si, Al, K, Na, Fe, Ti, Y, Rb, Th, and Ga show strong positive correlations with each other and strong negative correlations with Ca and Sr. This suggests that a large portion of the variance in chemistry may result from mixing an argillaceous and a calcium carbonate component during deposition. However, plots of element abundance ratios against sample location for a given lithologic unit show systematic trends of enrichments or depletions with proximity to the intrusion. For example, the K_2O/Rb ratio shows a systematic variation with metamorphic grade in the argillaceous samples. The ratio ranges from 2.6 to 3.7 (wt.%/ppm $\times 10^2$) in low grade samples. The higher grade samples show smaller ratios of 1.8 to 2.4. This suggests an enrichment of Rb relative to K in the higher grade samples with possible Rb addition from the stock. Continued study is necessary to discriminate between primary compositional variations and granite-to-sediment transport.

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

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

Contract: DE-AC02-80ER10762

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

Person in Charge: R. J. Martin

Scope of Work

The compressive strength of a brittle crystalline rock in constant strain rate tests is not a unique function of temperature and confining pressure, but depends strongly on the partial pressure of water within the sample. For example, the strength of granite loaded in uniaxial compression decreased 50 percent when the partial pressure of water in the text environment was increased from approximately 10^{-3} mb to 10^{3} mb. This moisture sensitivity is due to the chemical effect of water on the cracks within the rocks. The basic mechanism of deformation and failure in brittle rocks is the opening and subsequent growth of cracks, both along grain boundaries and through individual grains. In the presence of water, rocks undergo stress corrosion cracking; that is, strong Si-O bonds are hydrated to form weaker Si-OH bonds. The high tensile stress at the crack tips accelerates this corrosion reaction which in turn facilitates the propagation of the cracks at a much lower stress than would be expected for the virgin material. The overall effect of stress corrosion at crack tips is to reduce the strength of brittle materials, tested at a constant strain rate, as the moisture content is increased.

Although small variations in partial pressure of water may significantly influence rock failure in the lower crust, it is not at all clear how important this is for shallow crustal regions where the rocks are fully saturated with water. What may be important are variations in pore water pressure at high temperture. Pore water pressure in shallow crustal rocks may have a chemical effect analogous to the partial pressure of water effect on rocks tested in uniaxial compression in a gaseous environment; that is, for a fixed effective confining pressure, the effective strength of the rock decreases as the pore water pressure increases.

A laboratory has been organized to investigate the relationship between rock strength strain rate, temperature, and pore pressure. A series of constant strain rate tests on granite are underway at an effective confining pressure of 300 bars at temperatures between 100°C and 400°C. The rocks will be loaded at strain rates from 10^{-5} to 10^{-1} sec^{-1}. Each experiment consists of five loading cycles prior to fracture. Presently, distilled water is used as a pore fluid.

The result of this research program will be a description of rock strength as a function of temperature, strain rate, and pore water

pressure at an effective confining pressure of 300 bars. Such information is essential if extrapolation of fracture strength over tens of thousands of years is to be obtained. Furthermore, these results will serve as a framework for future tests on the static fatigue of the same rock over the same temperature range.

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

Contract: DE-AC0Z-81ER10921

Title: Deep Burial Diagenesis in Carbonates

Person in Charge: G. M. Friedman

Scope of Work

The purpose of this research program is to investigate deep burial diagenesis in carbonate rocks with emphasis on the evolution of rock textures, mineralogy, and porosity with depth. Specific investigative problems include the differential behavior of dolomites and limestones under deep burial, the role of fracture in porosity formation at depth, the relationship of experimentally induced rock compaction textures versus those in a geological situation, and the persistence of porosity under deep burial conditions. The latter is particularly important, since it may provide limitations on depths to which potential hydrocarbon production zones can be expected.

With the intensified search for oil extending deeper into sedimentary basins, the study of deep burial diagenesis in sedimentary rocks will become an important area of continuing research, replacing the emphasis on near surface diagenesis. This research program will provide a basis for expanding that research.

Samples for study are available from wells in the Anadarko Basin, gulf Coast Basin, and the Delaware Basin, extending to depths in excess of 30,000 feet. Sequential samples of both dolomites and limestones will be selected downhole in order to study diagenetic changes with depth. The samples chosen come from basins where there is adequate control on thermal and burial history. Experimental compaction tests will aid in extending and duplicating information gained from geological situations.

Contractor: UNIVERSITY OF SOUTH FLORIDA
Department of Marine Science
St. Petersburg, Florida 33701

Contract: DE-FG05-81ER10800.A000

Title: Basic Research in Organic Geochemistry Applied to National Energy Needs

Person in Charge: W. M. Sackett

Scope of Work

In order to determine what the organic geochemistry community can undertake as a group to help alleviate national energy problems, a workshop was held December 15-17, 1980, at the University of South Florida, St. Petersburg. The workshop was attended by geochemists from industry, academia, and governmental agencies. The objective of this workshop was to define the problems associated with the discovery and efficient utilization of carbonaceous fuels and to design strategies for solving these problems and minimizing the environmental impact of production and utilization activities. These objectives were addressed in three subgroups (exploration, exploitation, and environmental impacts) following plenary sessions in which background papers were given by invited authors. Following deliberations in the subgroups, the entire group reconvened and discussed their findings and recommendations. The subgroup deliberations, summary of recommendations, and overview will be published in late spring 1981.

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

Contract: DE-AC03-81ER10973

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

Persons in Charge: David D. Blackwell and Ian J. Duncan

Scope of Work

The objective of this project is to integrate constraints provided by fission-track annealing systematics with thermal models. Heat flow is unique among the potential fields in that it involves transient effects; i.e., it is time-dependent. The ambiguity that this introduces can be resolved, at least in part, by utilizing the time-temperature dependent annealing kinetics of fission tracks. Re-evaluation of experimental annealing data will provide activation energies and other information on the rate processes of annealing tracks. These rate laws will then be used as input into a program that calculates the relative track loss for independently specified time-temperature histories.

Preliminary results suggest that this technique provides a powerful method for evaluating the geological time scale involved in geothermal processes. For example, by using available fission-track age dates to constrain simple thermal models, it can be inferred that the area in and around the Valles Caldera of northern New Mexico is currently heating up. In contrast, the application of the simple thermal models to temperature-depth data alone, from drill holes in this area, results in very non-unique solutions: solutions involving either heating or cooling fit the temperature-depth data equally well.

Other related projects underway include fission-track dating of the mountain ranges bounding the Rio Grande Rift, in an attempt to constrain the tectonic and thermal evolution of the rift; the geothermal system at Lakeview, Oregon, and various systems throughout the Cascades; and fossil geothermal systems in south-central Colorado.

Laboratory work is being done in consultation with Dr. Charles Naeser, U.S.G.S., Denver. A complete fission-track dating facility has been established at S.M.U. and the dating technique is currently undergoing calibration runs.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

Contract: DE-AT03-76ER71045

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

Person in Charge: A. M. Nur

Scope of Work

The processes of porosity and crack healing and the effects of porosity, pore pressure, and gas on physical properties of fissured and porous rocks with fluids are fundamental to the formation and utilization of energy and mineral resources. By measuring rock properties and processes at the physical conditions which prevail in the upper and middle crust of the earth, we can better understand the applications of geophysical methods to fossil fuels and geothermal exploration in the shallow crust. The studies include the following:

- Relation between partial saturation and amplitude, and attenuation and velocity of P and S waves. This study examines the dependence of wave attenuation Q^{-1} on the degree of gas or steam saturation. Preliminary results show that a peak in Q_P^{-1} occurs at 70% water-30% steam in the pore space. The velocities V_P, V_S, and V_P/V_S show a dependence on saturation that is different than Q_P^{-1} or Q_S^{-1}. Thus, simultaneous measurement of Q_P, Q_S, V_P, V_S in situ may provide estimates for the amount of gas versus water in the rocks.

- Relation between wave attenuation, pore pressure, hydraulic permeability, and velocities in cracked rock. Wave velocities and attenuation in rocks are sensitive to the surface area density (pore surface area divided by pore volume) of the pore spaces. Hydraulic permeability in rocks is related to these same factors, but not necessarily in the same way. Thus, seismic properties of rocks are related to hydraulic permeability. Therefore, the interrelation between permeability, velocity, and attenuation is studied in rock by measuring its properties as a function of confining pressure, pore pressure, and temperature of particular interest are rocks with known crack densities and other characteristics when under the influence of pore pressure. The results may provide the means for estimating in situ pore pressure from precise seismic measurements, and estimating hydraulic permeability from these data.

- Applications to resource exploration and evaluation in the earth's crust. The distribution of pore pressure in the earth's crust and the associated hydraulic permeability are studied. By combining theoretical models and experimental results, compressional and shear velocities are calculated

as a function of depth in the crust. For example, low crustal velocity zones are explained in terms of high pore pressures. High wave attenuation is also explained by high pore pressure. Combining the results with electrical resistivity data, it appears that extensive high pore pressure regions may exist in the earth's crust. These zones could be deep geothermal targets.

Contractor: STANFORD UNIVERSITY
Stanford, Connecticut 94305

Contract: DE-AT03-76ER71045

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

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

Scope of Work

The measurements are being completed for the compressional and shear velocities and attenuation in wells in the East Mesa geothermal area in order to determine the temperature dependence of compressional and shear velocities measured within and outside the reservoir, the effects of temperature and fracture density on attenuation of compressional and shear waves, and the variation of Poisson's ratio with depth within the reservoir. A vertical P and S wave velocity and attenuation profile is obtained by lowering three component geophones down the well. This provides knowledge of rock properties in an area with known rock and reservoir conditions, thus providing vital information in converting seismic data in general into reservoir rock properties.

In particular, successful results in the field would not only establish the usefulness of attenuation measurements to infer the state of porous rock in situ but provide a powerful, yet relatively inexpensive, means for delineating geothermal reservoirs. Future applications to pressurized reservoirs and deep gas reservoirs are also envisioned.

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

Contract: DE-AS05-79-ER10361

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

Person in Charge: M. Friedman

Scope of Work

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

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

The primary goals of this research are to determine the fracture state and fracture stress under simulated conditions at depth where thermally activated processes are apt to play a major role; the boundary in pressure, temperature, strain rate, and stress (P-T-$\dot{e}$-σ) space between elastic-brittle and transient semibrittle behavior for selected isotropic and anisotropic crystalline rocks deformed in both hydrous and anhydrous environments; the corresponding transient flow laws; the physical nature of fractures, to the atomic level, in the semibrittle regime; and the nature of the comparison between the experimentally and naturally deformed rocks. Results of this work are needed to better understand the deformation of continental crust involving the crystalline basement and are essential to the design and implementation of the storage of toxic wastes in crystalline rocks and projects such as continental deep drilling.

To date, a series of creep experiments at elevated temperatures and 100 MPa confining pressure have been completed on Barre granite. The results fit logarithmic and power law functional relations equally well. Time-dependent strain under constant stress is likely to result from stress-corrosion cracking which in turn, is dependent (at least) on P_{H_2O}, T, and σ. Time to failure can be expressed by

$$t_f = t_o P_{H_2O}^{-\alpha} \exp\left(\frac{E}{RT} - k\sigma\right) \qquad (1)$$

where α, k, and R are constants. E, the activation energy calculated from our data at 25°C and 200°C, falls in the range of 3.3 to 10.3 kcal/mole, values expected on the basis of low to moderate

temperature transient creep of other crystalline rocks (Carter and Kirby, 1978).

Creep experiments on Westerly granite have been performed at higher temperatures, in the range 470°C to 767°C, constant stress differences of 6.0 to 1.2 GPa, all at a confining pressure of 1.0 GPa. Preliminary fits to the high-temperature transient and steady state creep data are

$$\varepsilon_t = 7 \times 10^{-5} \sigma^{2.2} t^{0.5} \exp(-30.5/RT.10^{-3}) \quad (2)$$

$$\dot{\varepsilon}_s = 1.4 \times 10^{-9} \sigma^{2.9} \exp(-25.3/RT.10^{-3}) \quad (3)$$

Preliminary new creep results for Quadrant and Sioux quartzites also yield an activation energy near 28 kcal/mole, 8 kcal/mole lower than the estimate by Koch et al. (1980). These close correspondences in activation energies of quartz and granite, together with microstructural evidence that quartz is the most highly deformed mineral in experimentally and naturally deformed granites, suggest that quartz deformation may control the creep rate of granitic rocks.

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

The long-term objective is to measure and understand the variation of fracture permeability of several typical crustal crystalline rocks resulting from hydrothermal reaction with through-flowing distilled water and aqueous solutions of Na_2CO_3, NaCl, and $NaCl/MgCl_2$ at temperatures to 300°C, fluid pressures to 30 MPa and effective pressures to 70 MPa. The experiments are designed to allow better understanding of the processes of dissolution and secondary mineral formation and how each of these processes affects the change of permeability during hydrothermal alteration. Our work during this contract year has concentrated on developing methods of quantitatively characterizing rough fracture surfaces; measuring at room temperature the permeability of "simulated" rock fractures (a monolayer of glass microbeads sandwiched between the faces of a steel split-cylinder) and comparing the results to predictions of theoretical models of contacting rough surfaces; and studies of the hydrothermal alteration of westerly granite in NaCl and seawater solutions and Sioux quartzite in Na_2CO_3 solutions. These experiments have focused on the changes of surface asperity characteristics arising from dissolution. The elevated-temperature permeability system was also designed and construction was started.

In the coming contract year these studies will continue with emphasis on obtaining a quantitative understanding of dissolution processes and how dissolution modifies fracture-asperity characteristics, and measuring the variation of the fracture permeability of Sioux quartzite at elevated temperatures and evaluating the

relative importance of the dissolution of load-bearing asperities (e.g., pressure solution) versus dissolution of non-load-bearing regions.

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

Energy extraction from the geothermal regime above buried magma chambers requires that rocks be drillable and boreholes be stable to depths of 10 km and at temperatures that approach those of partial melting. Accordingly, the instantaneous failure strength and ductility of room-dry and water-saturated cylindrical specimens of charcoal granodiorite and Mount Hood andesite are determined at a strain rate of 10^{-4} s^{-1}, at effective confining pressures of 0 and 50 MPa, and at temperatures to partial melting.

Data from water-saturated specimens of the granodiorite and andesite compared to room-dry counterparts indicate that the pore pressures are essentially communicated throughout each test specimen so that the pressures are effective. At effective confining pressures (P_e) of 0 and 50 MPa the granodiorite does not water-weaken; at these same effective pressures, the more porous and finer-grained andesite begins to exhibit water-weakening at about 600°C; at P_e = 0 and 870°C - 900°C, the andesite's strength averages 20 MPa whereas dry specimens at the same P and T exhibit a strength of 100 MPa; at P_e = 50 MPa and 920°C, the andesite wet strength is 45 MPa compared to 160 MPa dry. The ductility of the water-saturated specimens deformed at temperatures less than that of melting exhibit ultimate strengths at less than 3% shortening and then work-soften along faults; that is, like their dry counterparts the rocks remain brittle up to the onset of melting. Both dry and wet specimens deform primarily by microscopic fractures that coalesce into one or more macroscopic faults, and the temperature for incipient melting of the andesite is decreased ~150°C in the water-saturated state.

The extrapolations of these strength and ductility data for both wet and dry specimens indicate crystalline rocks should be drillable because they remain brittle until partial melting occurs; penetration rates should increase with temperature because there is a corresponding decrease in brittle fracture strength; boreholes in "water-filled" holes will be stable to >10 km at temperatures $<T_m$; if temperatures are kept to <700°C, even open boreholes in granodiorite are apt to be stable to 10 km; and open boreholes in the andesite are apt to be much less stable and at similar temperatures would fail at a 2 to 5 km depth. Work to date on intact specimens suggests the scientific feasibility of drilling buried magma chambers at depths to 10 km. Boreholes can be stabilized by keeping them as cool as possible and with a borehole pressure equivalent to that of a column of water at 25°C.

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, M. K. Kemp, and K. A. Kuenhold

Scope of Work

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

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

Gases associated with samples collected from deep wells in the Anadarko Basin, Oklahoma, and the False River, Louisiana, area have been analyzed for organic and inorganic components using a multicolumn gas chromatograph. In general, these gases are variable mixtures of methane, carbon dioxide, and nitrogen. Only small quantities of gas were released by crushing in the Teflon ball mill; in most cases, sensitivity for minor components, especially hydrogen, is too low. To improve analytical capability, a mass spectrometer-thermal release system is being installed. This will permit analysis of gases trapped in fluid inclusions in late stage cements and eliminate complications due to partial gas loss during sample retrieval.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTE
Woods Hole, Massachusetts 02543

Contract: EG-77-S-0204392 006

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

Person in Charge: J. M. Hunt

Scope of Work

Hydrocarbon generation from the maturation of organic matter in sedimentary rocks and its loss from these rocks by various migration mechanisms is being followed in wells drilled along the U.S. Gulf Coast and the North Slope, Alaska. The objective is to determine the types and quantities of hydrocarbons generated at different depths from rocks of varying lithologies and organic character. Carbonium ion cracking reactions at low temperatures ($< 150^{o}C$) result in distributions of hydrocarbon products that are different from free radical reactions at high temperatures. These studies define these differences.

In addition, a study of hydrocarbon distributions in the Austin chalk is being made to determine to what extent carbonates can act as both source and reservoir rock and how the composition of crude oil differ from carbonate compared to shale source rocks in the U.S. Gulf Coast.

The Alaskan wells are deeper than any others studied in the Gulf of Mexico. The objective in studying the North Slope wells is to determine the depths at which oil and gas phase out in the source rock. These wells have bottom hole vitrinite reflectance values of 3.5% R_o which is equivalent to anthracite in the coal rank. Theoretically, this should be beyond the depth at which any significant quantities of gas are generated.

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

Contract: DE-AS02-79ER10445

Title: Experimental Study of Opening Mode Crack Growth in Rock

Person in Charge: R. B. Gordon

Scope of Work

A zone of dilatation surrounds the tip of an opening-mode crack advancing through rock. Processes in the dilatation zone determine the form of the fracture surfaces and the amount of rock debris generated by the advancing crack. The objective of this research is to find the physical processes that control crack formation and to relate these data to the microstructure of the rock. Laboratory measurements of the fracture toughness are made by stable crack growth experiments on standardized double cantilever beam specimens. The standardized test procedure permits the comparison of results between different rock types. Experiments are made on both dry rock and rock saturated with water. The debris production rate is measured and the structure of the rock near the crack tip is observed under the scanning electron microscope. Experiments are being made on samples from the U.S. Bureau of Mines standard rock suite as well as on other examples of sandstone, dolerite, and granite. Where water weakening is observed, the temperature and crack speed dependence of the weakening mechanism is studied. The results are expected to prove useful in evaluating the fracture characteristics of rock formations from core and other samples and in revealing the physical processes that control fracture properties in rock.

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

ON SITE	FY1969	FY 1970	FY 1971	FY 1972	FY 1973	FY 1974	FY1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981
ANL	$ 0	$ 0	$ 50	$ 50	$ 201	$ 60	$ 86	$ 80	$ 80	$ 100	$ 140	$ 240	$ 310
BNL	–	–	–	–	95	41	0	–	–	–	–	–	–
LASL	0	0	0	0	95	291	630	806	790	810	1,004	1,420	1,800
LBL	–	–	–	–	–	295	315	816	820	660	735	995	1,075
LLL	–	–	–	–	–	–	75	135	130	250	630	910	1,060
ORNL	195	195	180	146	0	123	175	265	250	260	400	980	990
PNL	75	105	75	85	100	–	245	800	460	800	866	1,165	1,310
Sandia-A	–	–	–	–	–	–	–	–	–	–	–	–	–
On-Site Total	$ 270	$ 300	$ 305	$ 280	$ 481	$ 810	$1,886	$2,822	$2,400	$2,780	$4,079	$5,875	$6,215
OFF-SITE													
U/Alaska (Akasofu)	$ 21	$ 20	$ 21	$ 25	22	46	41	92.4	78.8	–	85.4	94.3	108.055
U/Alaska (Pulpan)	39	46	46	44	0	102	79	31.5	41.8	88.8	112.7	86.8	70
U/Alaska (Kienle)	–	–	–	–	–	–	90T	–	–	–	–	–	–
U/Arizona (Hill)	–	–	–	–	–	–	–	–	–	–	–	90.856	95.516
U/Arizona (Norton/Blvd)	–	–	–	–	–	–	–	–	–	–	–	–	85.695
Arizona State (Navrotsky)	–	–	–	–	–	–	–	–	–	–	–	34.96	61.832
Aspen Institute (Roberts)	–	–	–	–	–	–	–	–	–	–	–	–	–
Brown U. (Hermance)	–	–	–	–	–	–	–	–	–	47.6	67.2	70.5T	–
U/California (B) (Reynolds)	70	75	61	61	61	60	63	130	127	148	127	167.9	144.06
U/California (B) (Price)	0	30	37	65	–	–	–	–	–	–	–	–	–
U/California (D) (MacGregor)	–	–	–	–	–	–	–	–	–	71.2	81.4	23.84	–
U/California (LA) (Knopoff)	–	–	–	–	–	–	–	–	–	–	–	–	–
U/California (LA) (Anderson/Warren)	–	–	–	–	–	–	45	65	41	60	103.3	107	121
U/California (LA) (Boehler)	–	–	–	–	–	–	–	–	–	–	–	–	45.884
U/California (LA) (Kennedy)	62	60	60	60	60	60	60	60	60	60	72	72T	–
Carnegie-Mellon (Kohmen)	–	–	–	–	40	36T	–	–	–	–	–	–	–
U. Chicago (Anderson)	–	–	–	–	–	–	–	–	–	–	–	84.038	N.F.X
Columbia U. (Fairbridge)	–	–	–	–	–	30	75T	–	–	–	–	–	–
Columbia U. (Sykes/Jacobs)	0	70	70	96	80	137	180	200	240	266	274	311.8	317.953
Columbia U. (Scholz/Engelder)	–	–	–	–	–	–	–	65	62.1	75	100	140	150
Ft. Lewis College (Ellingson)	–	–	–	–	–	–	–	2	–	–	–	–	–
Indianapolis Center for Advanced Research (Dines)	–	–	–	–	–	–	–	–	–	–	–	60	63.924
U/Minnesota (Johnson/Seyfried)	–	–	–	–	–	–	–	–	–	–	–	–	66.175
MIT (Grodzins)	170	184	94	60	0	–	–	–	–	–	–	–	–
MIT (Aki)	44	29T	–	–	–	–	35	100	130	112.6	142	162	160.375
MIT (Simmons)	–	–	–	–	–	–	–	–	–	100	100	90	100
NAS/NRC (Petrie: Alaskan Earthquake)	–	–	–	–	–	–	–	–	–	–	–	–	–
NAS/NRC (Petrie: U.S. National Committee in Geochemistry)	–	–	–	–	–	–	–	–	–	–	–	–	16.6
NAS/NRC (Hart: Studies in Geophysics)	1	16	11	4	2	3	4	4	4	–	6	27	29
NAS/NRC (Berg: Committee on Seismology)	–	–	–	–	–	–	–	8.8	9	8.8	8.9	8.9	10.296
NAS/NRC (Berg: Geological/Materials Sciences Study)	–	–	–	–	–	–	–	–	–	–	14.17	–	9.624T
NAS/NRC (Hart: Geodynamics Committee)	–	–	–	–	–	–	–	–	–	–	15	20	29.5
NAS/NRC (Hart: CSDC)	–	–	–	–	–	–	–	–	–	–	–	60	70
Naval Weapons Support Center (Tanner)	–	–	–	–	–	–	–	5.6	–	–	–	–	–
NOAA (Donnelly)	–	–	–	–	–	–	–	–	–	5	–	–	–
U/Pennsylvania (Faul)	19	25T	–	–	–	–	–	–	–	–	–	–	–
Pennsylvania State University (Martin)	–	–	–	–	–	–	–	–	–	–	–	61.048	63.276
Princeton U. (Hollister)	–	–	–	–	–	–	–	22.9	–	–	–	–	–
Queens College (CUNY)(Schreiber)	–	–	–	–	–	–	–	–	–	–	–	–	63
Rice U. (Baker)	–	–	–	–	–	–	–	–	–	–	–	15.6	–
RPI (Friedman)	–	–	–	–	–	–	–	–	–	–	–	–	91.095
SMU (Blackwell)	–	–	–	–	–	–	–	–	–	–	–	–	54.39
U/So. Florida (Sackett)	–	–	–	–	–	–	–	–	–	–	–	–	34.034T
Stanford U. (Nur/Kovach)	–	–	–	–	–	–	–	89.6	85	103.6	146.6	140	140
SUNY, Albany (Dewey)	–	–	–	–	–	–	–	–	–	–	–	–	86.193
SUNY, Stony Brook (Schaeffer)	–	–	–	–	64	51T	–	–	–	–	–	–	–
SUNY, Stony Brook (Papike)	–	–	–	–	–	–	–	–	–	–	80.7	89.1	84.903
Texas A&M (Friedman)	–	–	–	–	–	–	–	–	–	–	82.5	208.466	202.414
U/Tulsa (Barker)	–	–	–	–	–	–	–	–	–	–	89.7	N.F.X.	74.968
USGS (Hsaa)	–	–	–	–	–	–	–	–	–	–	–	–	–
U/Wisconsin (Wang)	–	–	–	–	–	–	–	–	9.1	64	64	57.39	37.8
Woods Hole (Hunt)	–	–	–	–	–	–	–	–	–	–	–	–	–
Yale U. (Gordon)	–	–	–	–	–	–	–	–	30.6	–	102	140.66	136.661
Yeshiva U. (Cameron)	41	36	16T	–	–	–	–	–	–	–	46.14	3.6	34.525
Total Off-Site	$ 463	$ 585	$ 410	$ 375	$ 319	$ 526	$ 572	$ 842.75	$ 898.3	$1,150.4	$1,894.31	$2,807.036	$3,026,529
TOTAL GEOSCIENCES	$ 753	$ 885	$ 716	$ 656	$ 780	$1,336	$2,260	$3,664.75	$3,298.3	$3,930.4	$5,973.310	$8,082.036	$9,240,529

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