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# Summaries of Physical Research in the Geosciences

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**August 1977**

U.S. Energy Research & Development Administration
Division of Basic Energy Sciences

Washington, DC 20545

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## FOREWORD

ERDA supports research in the geosciences in order to provide a sound underlay of fundamental knowledge in those areas of the earth, atmospheric and solar sciences which relate to ERDA's many missions. This research may be conducted in the major ERDA laboratories, industry, universities and other government agencies. Such support provides for payment of salaries, purchase of equipment and other materials, an allowance for overhead costs, and is formalized by a contract between ERDA and the organization performing the work.

The summaries in this document, prepared by the investigators, describe the work performed during 1976, include the scope of the work to be performed in 1977 and provide information regarding some of the research planned for 1978. The Division of Basic Energy Sciences, through its Geosciences Program, supports research in geology, petrology, geophysics, geochemistry, hydrology, solar-terrestrial relationships, aeronomy, seismology and natural resource analysis, including the various subdivisions and interdisciplinary relationships, as well as their relationship to ERDA's technological needs.

PART I

GEOSCIENCES

ON-SITE

Contractor: ARGONNE NATIONAL LABORATORY
Argonne, Illinois 60439

Contract: 09 ENG 38

Title: Geosciences Program

Person in Charge: F. A. Cafasso

Scope of Work

A. Thermochemistry of Geothermal Materials (Cafasso/Johnson)

Standard enthalpies of formation ($\Delta H_f^\circ$, 298) and enthalpy increments ($H_T^\circ - H_{298}^\circ$) for minerals of geochemical interest are being measured by fluorine bomb calorimetry and by drop calorimetry. The systems under current study are primarily sulfide-based minerals. Fluorine bomb calorimetry is unexcelled for thermochemical studies on sulfide-based materials. Enthalpies of formation have been determined by this method for $MoS_2$, AsS, $As_2S_3$, and $\alpha$-quartz. For $\alpha$-quartz the measurements resulted in an unequivocal value for the ($\Delta H_f^\circ$, 298) of this key datum in many geochemical cycles. Measurement of ($\Delta H_f^\circ$, 298) and ($H_T^\circ - H_{298}^\circ$) for $Sb_2S_3$, $FeS_2$, and $MnS_2$ are planned.

B. Physical Chemistry of Magmas (Cafasso/Blander)

This program will involve physicochemical studies of magmas essential to understanding bubble nucleation and violent gas evolution (as, e.g., contact-vapor explosions)--two related phenomena that may be important in attempts to extract heat from magmas by injection of water or with water-cooled heat exchangers.

Preliminary studies on magmas have revealed that large kinetic barriers must be overcome and large supersaturations of dissolved water or other volatiles must be attained before these substances can be evolved at a significant rate from a large magma body. Understanding the mechanisms for bubble evolution using concepts of bubble nucleation developed in this laboratory will be one of the principal objectives of this program.

When a hot substrate such as magma (or rocks derived from magma) contacts water, there is the possibility of explosive interactions called contact-vapor explosions. In addition, the cooling of gas saturated magmas can lead to the violent evolution of bubbles. Theories of these phenomena will be used to define conditions under which they might occur during heat extraction efforts. These conditions will then be investigated along with means for avoiding these dangerous and violent events.

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

Contract: EY-76-C-06-1830

Title: Development and Operation of ERDA Insolation-Aeronomy Observatory

Person in Charge: R. A. Stokes

Scope of Work

The insolation and aeronomy programs at Battelle Observatory are designed to make high-resolution studies of the solar flux (insolation) and nighttime upper atmosphere optical (auroral) emissions. The orientation of the insolation studies is directed to the development of instrumentation capable of providing multispectral data on the temporal and spatial distributions of both direct and diffuse solar radiation. The data acquired in this program will have direct applicability to specific site studies as well as forming a basis set for incorporation into studies of aerosol and cloud cover modification of insolation.

Since both the insolation studies and the auroral emissions studies share a common instrument, and to a certain extent data handling techniques, much of the development has proceeded in parallel. The aeronomy program has concentrated upon studies of optical emission patterns in the mid-latitude region. The altitude, spectral energy content and spatial and temporal distributions of the emissions are derived from the data and are used to determine the energies of the precipitating particles and bulk motion of magnetospheric plasma in the source region. The shape and motions of the emitting regions provide information on the dynamic behavior of the earth's magnetosphere and upper atmosphere during both disturbed and quiet geomagnetic conditions.

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

1. Analysis (J. J. Michalsky, E. W. Kleckner)

Work is continuing on several theoretical aspects of aerosol scattering of the solar flux. A new addition to our staff (JJM), with a strong interest in planetary atmospheres, has enabled us to pursue this area in more depth. Of fundamental interest is the problem of more precisely defining the type, quantity and size distribution of atmospheric aerosols given multispectral data on the intensity of the solar flux. Since aerosol particles possess a complex index of refraction, polarization measurements are needed in addition to the intensity in order to completely characterize the aerosol scattering properties. We intend to evaluate various existing models in order to provide a rational basis for obtaining the maximum utility from the data gathered by the experimental instruments described below.

2. Experiment (E. W. Kleckner, J. J. Michalsky)

The principal goal of the work in this area is the experimental measurement of a number of properties of the terrestrial solar radiation flux. To this end, we have developed a Mobile Automatic Scanning Photometer; it is a dual purpose instrument which makes both daytime and ighttime observations.

The instrument measures insolation in seven spectral bands from 427.8 nm to 940.0 nm. The field of view of the photometer is 2° and the basic mode of operation is that of scanning the sky in a series of almucantars. In addition, the instrument measures the direct beam of the sun at 15 minute intervals. The basic data, therefore, consists of both direct and diffuse components of insolation which can be synthesized to yield the sum total falling on a surface of arbitrary orientation. The detection mode allows a basic stability in the measurement of ±2% and the instrument module is portable and suitable for remote siting.

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

1. Analysis

The concept that the pattern and spectrum composition of the upper atmospheric optical emissions can be used to monitor the structural features and dynamic processes of the magnetosphere is extremely useful. The wealth of auroral phenomena which have optical emissions and occur in the mid-latitude region is notable. The prominent features are the Stabel Auroral Red arcs (SAR arc), the Hydrogen arcs (H arc) and the Diffuse Aurora (DIF).

2. Observations

a. Battelle Observatory

Beginning in September 1967, all-sky photometric observations of the emissions [OI] 5577A, [OI] 6300A, $N_2^+$ 4278A and Hβ 4861, and continuums 5350, 6080 and 7150A have been taken routinely on all cloudless, moonless nights from the Battelle Observatory (latitude 46.4° N, longitude 119.6° W), Richland, Washington. The observing technique consists of scanning the night sky in a series of almucantars at elevations 10°, 15°, 20°, 30° and 50°. Since the photometric field of view is approximately 5°, these scans adequately cover the entire circle of view.

b. Global Program

Because most of the detailed investigations have been done at single stations, the understanding of the emission patterns tends to be regional. The synthesis that might be provided by simultaneous global observations is lacking.

What is needed is a set of simple, reliable, identical optical instruments dispersed over the globe. Battelle has developed such an instrument called the Mobile Automatic Scanning Photometer (MASP). The same all-sky scanning technique presently used at the Battelle Observatory is implemented on the MASP.

The first chain of MASP units will be installed across the United States between geographic latitudes 40-50° N . This resultant longitude chain will provide important "global" coverage of the plasmapause which is the boundary region between the "hot plasma" of the magnetosphere under direct influence of the solar wind and the "cold plasma" of the plasmasphere which is locked to and corotates with the earth. The first MASP unit of this chain was installed on the McColly Ranch near Hinsdale, Montana (geographic latitude 48.6° N and longitude 107.1° W). The next two units will be operational in Spring 1977. Observations from the McColly installation coupled with the Battelle Observatory observations give continuous coverage for 400 km height emissions from longitudes 92° to 134° W.

3. Associations

a. ISIS-II Satellite

The ground-based observatory has the problem of scattering and extinction due to the earth's atmosphere and a relative small circle of coverage for the 100-300 km height emissions. The satellite experimenters have the problems of calibration, and albedo and temporal coverage for any given geographic region.

b. AE-D Satellite

The AE-D satellite was put in orbit during the Summer 1975. One of the experiments is a photometer and we are working with the principal experimenter (Dr. Marsha Torr) in comparing our ground-based observations with the AE-D photometric observations in methods similar to our ISIS-II collaboration.

c. International Magnetospheric Study (IMS)

Data pools are being organized and satellite and ground-based experiments are being coordinated.

d. Joint Programs

University of Washington (Dr. K. C. Clark), Central Washington State College (Dr. R. Bennett), and the LaTrobe University in Australia (Dr. K. D. Cole).

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

Contract: EY-76-C-06-1830

Title: Remote Sensing Program for Energy Related Resources Assessment

Person in Charge: J. R. Eliason

Scope of Work

The objective of this program is to conduct research in remote sensing and to develop methodology and instrumentation that will help to meet ERDA's needs for data relating to the geosciences and the environment.

A. Remote Sensing and Geophysical Data Set Correlation (H. P. Foote, G. A. Sandness)

Geological remote sensing is generally most effective when it can be combined with other kinds of geological and geophysical data. Data correlation methodologies are being developed to effectively acquire, process and utilize combinations of remote sensing and geophysical data sets. These techniques will be based on conversion of the remote sensing and geophysical data into compatible digital data sets which can be analyzed on high-speed digital computer systems and displayed on computer graphics devices.

B. Image Enhancement and Classification (H. P. Foote)

Computer and analog processing techniques are being developed for enhancing and analyzing multispectral satellite and aerial remote sensing data. These techniques include spectral analysis, image enhancement, noise filtering, pattern recognition, texture analysis and geographic transformations.

C. Broadband Active Imaging System (G. A. Sandness)

PNL has recently developed a prototype active aerial scanner which can produce multispectral imagery in three modes:

1. Passive daylight imaging using reflected sunlight.

2. Active nighttime imaging using a broadband visible light source in the scanner.

3. Active nighttime imaging of fluorescent materials using an ultraviolet light source in the scanner.

In the active modes, the imagery produced by this scanner is completely free of shadows. This means that the spectral signatures of ground materials will be uncontaminated by shadowing which is a fundamental limitation on the quality of data produced by passive imaging systems. Because of its operational flexibility, its ability to produce two-dimensional imagery, its ability to eliminate shadows and its ability to detect fluorescent materials, this scanner is potentially a powerful and significant new remote sensing tool. Testing and design studies will be initiated in FY 1978 to develop a second generation version of this remote sensing system.

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

Contract: W-7405-ENG-48

Title: Geosciences Program

Person in Charge: Paul A. Witherspoon

Scope of Work

The Geosciences Program at the Lawrence Berkeley Laboratory consists of five projects, three of which support the ERDA effort in developing geothermal energy. These three projects cover investigations in reservoir dynamics, rock fluid system properties, brine chemistry, geochemistry and mass transfer, thermodynamics of magmas, and a project devoted to the collection and dissemination of geothermal information. A fourth project on magmatic materials applies high precision neutron activation analysis to problems of final storage of radioactive wastes. The fifth project aims at measuring variations in seismic wave velocity as a function of rock stress. Work done under this project could have application in earthquake prediction.

A. Geosciences Relating to Geothermal Energy (P. A. Witherspoon)

Background. This project was started in FY 75. The purpose of the project is to apply the principles of thermodynamics, hydrodynamics and geochemistry to support investigations of geothermal systems. The investigations are a necessary part of the LBL program to develop geothermal energy from low salinity high temperature brines. However, the results of the investigations will have broader impact in geothermal energy development from other sources.

Four areas are being investigated:

1. Reservoir Dynamics
2. Rock Fluid Systems Properties
3. Thermodynamics of High Temperature Brines
4. Geochemistry and Mass Transfer in Geothermal Systems

The proposed work in these areas for FY 78 follows.

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

Two-Phase Heat and Mass Flow in Geothermal Reservoirs. Analytic techniques and a numerical model have been developed to study heat and mass transfer in a three-dimensional system including phase transition of the fluid. The study will lead to an understanding of the behavior of two-phase geothermal reservoirs under various conditions of production and injection. During FY 77, the analytic description of the two-phase flow problem was carefully reviewed and several terms usually neglected in conventional calculations were found to be significant and need to be included in the calculations.

During FY 78, these will be incorporated into the numerical model, and a comprehensive set of tests of the program will be made. The program will be used to understand the physics of the two-phase fluid and heat flow.

Double Diffusion of Heat and Salt in Porous Media. A study will be made of the double diffusion of heat and salt in porous media to gain insight into the instabilities that occur when a fluid at a certain temperature and salinity is injected into a reservoir with different temperature and salinity. The understanding of such a process will have implications in (1) the problem of disposal of used colder geothermal water into aquifers, and (2) hot or fresh water storage in aquifers.

Hot Water Storage in Underground Aquifers. Hot water storage in aquifers is a concept suggested to be an important part in large-scale total energy systems. The physical basis of the concept lies in the low heat conductivities of rocks confining the aquifer. Until recently, no sophisticated computer models were available to study the behavior of such a system. During FY 77, a preliminary study of the thermal and pressure behavior of the process was made under a particular set of storage conditions. Surprisingly high efficiency was found.

During FY 78, the process will be studies under different cyclic periods, temperatures and flow rates. Associated compaction and subsidence effects will be calculated. Chemical reactions occurring during such a process will be explored.

If time and funding permit, exploratory study in the following topics will be initiated.

a. Passive reservoir analysis may allow some properties of the underground reservoir to be determined from its responses to natural seismic or tidal effects.

b. A study will be made to incorporate convective transport in the new numerical technique as necessary. This numerical model, called FLUMP, was developed by combining the well-known Finite Element method and the Integrated Finite Difference method.

2. Properties and Behavior of Rock-Fluid Systems at High Temperatures and Pressures (W. H. Somerton)

Objectives of this project are to develop methods of and equipment for the measurement of properties and behavior of rock-fluid systems at conditions of pressure, temperature and fluid saturation which may be encountered in geothermal power development and thermal recovery methods applied in the extraction of fossil fuels. An expanded level of research in this area is planned for FY 78. Preliminary proposals have been sent to several industrial concerns seeking partial support for the construction of the new high temperature - high pressure test facility.

Most of the year will be spent in the construction, installation and testing of the new facility. However, tests will continue with the present equipment. Geothermal cores will be tested for permeability, formation resistivity factor, thermal conductivity and P and S wave velocities at temperatures to 190°C and pressures to about 500 kg/cm$^2$. Data will be used in a continuing program of developing correlations and testing theoretical models of rock-fluid system behavior.

3. Thermodynamics of High Temperature Brines (K. S. Pitzer and L. F. Silvester)

The study on the solution thermodynamics of brines covering systems both simple and complex, weak and strong, over a wide temperature and pressure range combines a theoretical and experimental program to provide essential information for the technical utilization of many geothermal resources.

The theoretical work has successfully dealt with complex mixtures at room temperature, simple systems over wide temperatures, moderately weak electrolytes involving dissociation equilibria, and moderately soluble electrolytes. Future work will continue using existing volumetric and thermodynamic data for modeling.

The experimental program includes construction and use of a flow calorimeter measuring heat capacities up to about 300°C and a kilobar on systems previously unreported plus extending existing data to higher temperatures and pressures. The experimental results will be integrated with the theoretical work to develop equations allowing prediction of properties at temperatures and compositions other than those measured.

Though the program work relates directly to electrolyte systems common to geothermal brines, the results are applicable to biological fluids, battery electrolytes in aqueous and nonaqueous solvents, waste effluents, materials corrosion from electrolyte systems, and marine chemistry.

4. Geochemistry and Mass Transfer in Geothermal Systems (J. A. Apps)

Fluid convection in a geothermal reservoir leads to the dissolution, transport and reprecipitation of rock forming materials. This phenomenon occurs naturally and causes the sealing of strata and the development of the confining beds in geothermal systems. During the exploitation of a geothermal reservoir, the mechanisms of dissolution, transport and reprecipitation will be accelerated, with potentially significant declines in reservoir production and injection capacity. The objective of this project is to determine and quantify the deleterious effects, if any, which will result from rapid withdrawal of hot water and reinjection of spent fluids in a convecting geothermal reservoir. A longer term objective will be to predict the transport and deposition behavior of major rock forming components and minor metal components in convecting geothermal systems. Emphasis will be placed on experiments to study mineral dissolution kinetics. These experiments will provide data on rate processes, transport and precipitation of rock forming components in a geothermal reservoir. Fluid flow models incorporating these processes will be developed and hypothetical cases simulating a producing geothermal reservoir will be evaluated.

B. Thermodynamic Properties of Magmas (I. S. E. Carmichael)

This is part of a continuing project to investigate the high temperature properties of silicate liquids, and their low temperature metastable equivalents, silicate glasses. Naturally occurring silicate liquids, or magmas, are ultimately responsible for a wide range of geologic phenomena, including a great part of the crust of the earth, geothermal activity and related ore deposits. However, very little is known of the physical properties of magma although its chemistry can be deduced, within limits, from its consolidation products, the igneous rocks. As natural silicate liquids vary over a considerable, but finite, range, it is necessary to express the pertinent physical properties in terms of partial molar quantities, which require experiments in temperature and composition space.

This project is presently involved with measuring the partial molar volumes and expansivities in a wide range of silicate liquids, and also with measuring the compressibilities of silicate liquids at 1 bar containing pressure using sound wave velocities.

One of the theoretical reasons for determining both the temperature and pressure dependence and the density of silicate liquids is that certain elements (e.g., Ba) have maxima on their fusion curves, or points, in P-T space above which the liquid is more dense than the solid. In silicates only sanidine has given any indication of such a maximum, for normally experiments on fusion curves are limited to pressures (and temperatures) below 40 kilobars.

This project is designed to provide data, which in conjunction with that extrapolated from fusion curves of silicate compounds, will enable the density of any silicate liquid to be predicted at high P and T. An ancilliary part of this project is the measurement of concentration variables (activities) in silicate liquids in centrifugal fields. This should allow the effects of the gravitational field on the migration of elements in large magma bodies, such as underlie the Yellowstone geothermal field, to be extracted. With the proper experimental design, it will allow the partial molar volumes determined in the density experiments to be confirmed.

C. National Geothermal Information Resource (GRID) (S. L. Phillips)

There is a need for a compilation of both evaluated and unevaluated data for the geothermal resources research and development program. In this context, GRID is screening the worldwide literature on a continuing basis, and extracts site-dependent and basic data related to geothermal exploration and utilization. The resulting compilation is maintained as computerized data bases to provide the basis for in-depth literature reviews and critical evaluations of data by GRID's technical staff. In addition, computer-produced bibliographies and data tabulations are generated from the data based for use by other information systems and data evaluators.

The National Geothermal Information Resource of the Lawrence Berkeley Laboratory is sponsored by the Division of Basic Energy Sciences to search world literature on a continuing basis, retrieve and index papers relevant to the thermodynamic and transport properties of geothermal materials, extract the numerical basic data or information content, and carry out critical evaluations leading to the publication of tables and status of data reviews. Information compiled by GRID is obtained from the literature or by exchange with other data bases and covers that which is important to geothermal physical chemistry. Consideration is given to current geothermal technology, and to that developed for other purposes which may have possible application to geothermal research, development and demonstration. The results of the compilation of basic data include critically evaluated numerical data for the physical properties of geothermal solutions at elevated temperatures and pressures, and comprehensive and in-depth bibliographies. Recommendations are made for data needs where current data is lacking or is inadequate. In FY 78, we expect to complete our evaluation of data on the viscosity of sodium chloride solutions and continue our compilation, evaluation and dissemination of other important thermodynamic and kinetic data.

D. Magmatic Materials: High Precision Neutron Activation Analysis (F. Asaro)

The application of high precision neutron activation techniques to the characterization of basalt lava flows in the Columbia River Plateau will be investigated. The flows to be studied are those considered for the final storage of radioactive wastes or else closely related to them. The purpose of the study will be to determine the extent and degree of confidence that individual flows can be identified by precise neutron activation measurements alone and in conjunction with (separately funded) major element determinations. If flows can be conclusively identified, by a single measurement, the vertical and horizontal mapping of the Plateaus flows could be done with a high level of confidence and contribute significantly to the understanding of the hydrology of the basalts. Such understanding is a prerequisite for the final waste storage. Continued funding to support this work is anticipated from other sources.

This project will also permit (with separate funding) neutron activation measurements for collaborative studies with the United States Geological Survey, concerned with dating of rhyolitic materials from chemical composition.

Neutron activation studies will also be made of lavas from the earth's mantle and their crystalline inclusions. From the partition coefficients of the trace elements in conjunction with major element data some of the temperature, pressure and compositional characteristics of the mantle should be determined.

E. In-Situ Stress Measurements: Seismic Wave Velocity (T. V. McEvilly and C.-Y. Wang)

A field technique for monitoring in-situ stress variations within the earth's crust is being evaluated along with laboratory investigations of measurable physical property changes of crustal rocks under conditions of temperature and stress appropriate to in-situ conditions. The field study utilizes a mechanical source (VIBROSEIS*) of coherent programmable seismic waves and a special recording system. Two vehicles with operators can conduct repeated measurements of travel times of seismic waves reflected from discontinuities to depths of over 20 km in the earth. Stress variations should be evident in variations of times resulting from stress-induced velocity changes. In the laboratory, changes in physical properties of rocks typical of those being sampled in the field are measured for a variety of stress fields and pore water conditions appropriate to tectonic conditions within the earth. Seismic wave velocity, electrical resistivity, and crack formation are monitored with transducers and radiography/electrostatic imaging.

*Trademark for Continental Oil Company.

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

Contract: W-7405-ENG-48

Title: Predictive Rock Mechanics

Person in Charge: Robert N. Schock

Scope of Work

The object of geoscience research at LLL funded by the Division of Basic Energy Sciences is to understand the response of geologic media to mechanical stimuli. In particular, current effort is directed to static and dynamic deformation of porous and cracked rock, explosive fracturing and permeability enhancement. Both theoretical and experimental work are in progress. Applications of this work are to ERDA programs in *in situ* coal and oil shale processing, geothermal energy recovery, gas stimulation, underground nuclear explosion containment and seismic verification of foreign nuclear explosions. Brief descriptions of the specific studies that are directly related to the Division of Basic Energy Sciences are as follows.

A. Effect of Porosity and Matrix Properties on Pore Collapse and Strength

Modeling work using spherical pores, and experimental deformation of porous tuff, sandstone and kaolinite are compared to demonstrate the range of applicability of a simple mechanical model to the loading and unloading response of porous materials. This work is essentially complete. The main conclusion is that the use of spherical elastic plastic pores can model mechanical deformation well. Other models which involve pore interactions are necessary to predict fracture induced permeability.

B. Effect of Confining Stress on Explosive Fracture

Explosive charges are detonated in blocks of gas reservoir sandstone such that the fractures are contained within the blocks. The blocks are held under confining pressure to simulate natural depths of burial. Fracture patterns, and pre- and post-shot permeability and porosity are measured to understand the effect of confinement. Results will be compared with computer predictions using existing models. Currently, rock samples have been collected in the field and test results have been obtained in a transparent polymer.

C. Effect of Simultaneous and Sequential Detonation on Explosive Fracture

Small explosive charges are detonated in blocks of a brittle polymer. The blocks are immersed in an acoustic impedence matching liquid to minimize surface effects. Charge pairs are fired, simultaneously and in varying delay sequences, and the extent and pattern of fracture is measured. To date, sample manufacture and explosive configuration have been completed and tested, and the final experiments are in progress.

D. Improved Continuum Code Modeling

A one-dimensional finite difference wave propagation code called SOC is improved with a compaction-plasticity model, a model for the effects of water in porous materials, and a model for rate effects in porous materials. These models have been tested using existing data from gas gun and high explosive shots in porous tuff and limestone. The new models have more easily measurable and fewer parameters and fit data than the old.

E. Effect of Strain Rate on Strength and Fracture

A cam-actuated, intermediate strain rate loading machine is used to load cylindrical samples of limestone, coal and sandstone at strain rates appropriate to the underground explosive process. Both load and strain data are collected. Measurements are made of the effect of rate on the stress vs. time response and the final configuration of the damaged material. Currently, the machine has been assembled and debugged. Preliminary results in the limestone indicate significant strengthening in this rate regime.

F. High Explosive Design for Rock Fracture

Small high explosive charges are designed to be used in laboratory experiments on rock fracture. These charges enable the simulation of field experiments in the laboratory without encountering sample-surface effects. The explosive design process emphasizes safety and repeatability, and both objectives have been achieved. Complete explosive characterization work is in progress.

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

Contract: W-7405-ENG-36

Title: Solid Earth Geosciences

Person in Charge: R. R. Brownlee

Scope of Work

The geoscience program at LASL was conceived to promote basic and applied science to support the experimental Hot Dry Rock (HDR) geothermal energy (GTE) project. Although GTE remains a focal point of most research projects, interests have expanded into nuclear and fossil fuels, waste management and weapons-related areas. Multidisciplinary activities encompass geology, geochemistry and geophysics. Specific research areas include: seismology; rock physics; experimental, theoretical and analytical geochemistry; thermodynamics; petrology; structural geology; sedimentology; field geology; and numerical modeling. Major experimental and analytical instruments used in the LASL geoscience research program include neutron activation, x-ray fluorescence, atomic absorption, x-ray diffraction, scanning electron microscopes, electron probe microanalyzer, and high pressure (P)-temperature (T) rock deformation equipment (including gas-, liquid-, and solid-pressure media apparatus). The LASL computer facility with an extensive library of hydrodynamic, geochemical and materials codes is also used. The LASL scientists in other research fields who have extensive experience in materials science which is applicable to geologic problems are available for consultation. Facilities, expertise and geographical location enable LASL geoscientists to respond well to ERDA missions.

A. Field, Analytical and Theoretical Petrology

1. Western United States (J. C. Eichelberger, R. Gooley, G. Heiken, J. Smyth, F. Koch, B. Crowe)

The origin and evolution of magmas and their emplacement in an eruption from the upper crust is studied by several techniques. Studies of eruption phenomenology (observed, simulated by high explosives, and modeled by computer), structure of shallow plutons and dikes (Henry Mountains, UT; Broken Top, OR), stratigraphy of volcanic units (Jemez Mountains, NM; Cascades), and xenoliths in volcanic rocks (Jemez Mountains) are yielding information concerning behavior of magma in the upper crust. Evidence of deeper processes for origin and chemical evolution of magmas is gathered by detailed electron microprobe analyses of phases in volcanic rocks. Samples under study come from Jemez Mountains, San Francisco Peaks volcanic field, Cascade Range, Andes, Lesser Antilles, and Taupo Volcanic Zone (New Zealand). The broad range of sample localities provides a basis for exploring influence of crustal and tectonic environment on magmatic processes.

Silicic volcanic complexes of the western U.S. (e.g., Jemez Mountains, San Francisco Peaks, Cascade Mountains) hold great potential for geothermal energy. Therefore, our efforts emphasize silica-rich magmas. Knowledge of location, shape, behavior and environment of such magma bodies is necessary for exploitation of these fields. Furthermore, continents are characterized by silica-rich igneous rocks. Thus, origin and evolution of these magmas is the problem of origin and evolution of continental crust.

Current field studies of pyroclastic deposits and a dissected cone in the Cascade Range lead to a picture of growth and structure of andesite volcanoes. A particularly significant finding is that sill emplacement is an important mode of cone growth.

Studies of xenoliths and shallow plutons indicate severe deformation of basement in the vicinity of magma chambers. Studies of analogous plutonic bodies suggest that most of the deformation is limited to the immediate environment (<100 m) of the pluton. In addition, xenoliths from the Jemez Mountains (Bandelier Tuff) suggest substantial changes in lithology with depth in the upper crust near the Valles Caldera.

Analysis of phase assemblages in volcanic rocks indicate a common origin of suites from all localities by melting in the mantle and lower crust and mixing of melt products. We find that amount of mixing and composition of parent magmas are controlled by tectonic and crustal environment, respectively. What can be learned about mantle and lower crustal source regions from identification of parental magma compositions are currently being explored. Heat transfer and hydrodynamic considerations are also applied to this problem.

2. <u>Rio Grande Rift</u> (J. Bridwell, J. C. Eichelberger, J. Smyth, R. Riecker)

Integrated studies of field relations, petrology, chemistry, age dating, rare earth data, deformation mechanisms and numerical models are directed toward understanding structure, tectonics and magmatic evolution of the Rio Grande Rift (RGR).

Basalt samples collected from the length of the RGR will provide approximately 100 whole rock analyses, approximately 30 rare earth analyses, and interpretations on composition of the upper mantle and magma genesis. These parameters will provide constraints on comprehensive models of major geothermal anomalies. Ultramafic xenoliths collected along the RGR are analyzed to provide P, T conditions from pyroxene geothermometry techniques. Direct estimates of stress from deformation fabrics of olivine xenocrysts provide a qualitative picture of stress in the lithosphere along the length of a major continental rift. Field mapping, structural analysis and theories of magma genesis of the north central portion of the RGR will be supported by age dates from 15 basalts collected throughout the Espanola Basin.

Gravity, heat flow and experimental deformation data provide an initial estimate of thinning of the crust and upper mantle. Bouguer gravity anomalies, geothermal anomalies and volcanic studies support approximately 16 to 60 km of thinning and convective transport of mass and heat into the crust along the rift in the last 3 to 10 m.y., resulting in the large geothermal anomaly along the rift.

3. Theoretical Modeling of Mantle Petrology (J. Smyth, T. McGetchin)

A computer program casts chemical analyses of rocks, either real or hypothetical, into a suite of "normative" minerals, similar to CIPW-norms minerals, but more appropriate to assemblages at 30 kbar. Results apply to observational petrology and planetary science.

B. Seismology (K. Olsen, D. Cash, C. Newton)

The purpose of this program is: (1) to determine regional background seismicity in order to assess possible effects of LASL programs on seismic activity (e.g., injection of water in deep wells can cause seismic activity); (2) to determine probability of earthquake damage to LASL facilities; and (3) to evaluate regional crustal and mantle structure.

Northern New Mexico crustal and mantle structure is investigated seismicly for: (1) location of major discontinuities in the crust and upper mantle to understand regional tectonics; and (2) determination of seismic velocities for accurate location of earthquake hypocenters. Focal mechanisms and relationship of seismicity to tectonics are also under study.

Measurements of the earth's gravity and magnetic fields are helpful supplements to seismic studies of crustal and mantal structure. Potential fields are measured and interpreted in geographical areas of specific interest. Two proton precession field magnetometers are in use to supplement seismic data. A LaCoste-Romberg gravimeter will be delivered in August 1977. When not in use in the field, the gravimeter will be used as a continuously recording ground-motion detector for measurement of earth tides.

We maintain a network of 15 telemetered continuously recording short-period seismic stations (three are located in the immediate vicinity of the Fenton Hill HDR project). In addition, 15 portable seismographs can be fielded to record aftershocks of larger earthquakes and earthquake swarms. A catalog of local and near-regional events is maintained continuously, and is used to update a seismicity map and summary every three months. Routine seismicity determination includes hypocentral locations and magnitudes. We are developing a microprocesser system for automatic picking and recording of seismic events. This system will be used for recording aftershocks and microearthquakes in the field as well as recording of earthquakes on the permanent seismic network.

Portable recorders are used to document seismic waves from mining explosions in northern New Mexico and explosion effects studies at White Sands Missile Range (near the southern end of the RGR). Analytical techniques include inversion of seismic refraction and reflection data, and synthesis of seismograms using generalized ray theory. Similar analysis is applied to data from teleseisms recorded on a permanent seismic network.

Research plans are developed to run detailed shallow (≤3 km) seismic reflection profiles at Nevada Test Site (NTS) using digital data processing techniques applied to a Vibroseis(T) source. In addition to data acquired for test site application, the experience will be used to assess suitability and potential usefulness of such techniques for crustal exploration in the vicinity of Los Alamos. Two permanent seismic stations will be installed at NTS to monitor seismicity and for studies associated with nuclear tests.

A low-cost, long baseline tiltmeter with a sensitivity near $10^{-12}$ radians was designed and built. After testing and adjustment, others will be built and installed in areas of suspected tectonic movement, including the RGR and the Valles Caldera.

## C. Theoretical and Experimental Geochemistry

### 1. Experimental Geochemistry (R. Vidale, R. Charles, J. Balagna, J. Potter)

Work focuses on reaction between rock and aqueous solutions at high T and P. Changes in both rock and solution are studied in closed systems (static, rocking and tipping vessels), in open systems (circulating loops with heated rock chambers and cooled heat exchange sections) and in permeability measurement systems (where solution is forced through rock at high T and P). Current experiments apply principally to chemical reaction in geothermal systems. Chemical processes in these systems cause changes in the flowing solutions, in reservoir permeability, and in reservoir size and geometry, all of which critically affect the efficiency of energy extraction.

Construction of a hydrothermal circulation system capable of 5000 psi at temperatures of 300°C is complete. This system is used to observe granite-water reactions in experiments over 8-month periods.

Reactant granite was supplied from the Fenton Hill geothermal well. Secondary overgrowths are identified and their growth documented by means of scanning electron photomosaics. These experiments are correlated with concurrent experimentation in agitated (noncirculating) vessels. These experiments provide experimental definition of reaction relations between granite and water simulating P,T conditions in LASL's geothermal reservoir.

Reaction of $Na_2CO_3$ solutions with components of granite is characterized because sodium carbonate is proposed as a leachant for the LASL geothermal well.

Granitoid rocks from cores taken from LASL's HDR geothermal well exhibit trace element signatures. For example, cobalt is present in magnetite. Monitoring these trace elements may reveal the degree of alteration of specific mineral phases in the geothermal system once all phases have been examined.

2. Synthetic Mineral Standards (C. Herrick)

Large diameter olivine discs were fabricated for equation-of-state studies. Gram quantities of fluoramphiboles are synthesized and macropreparations are underway for measurements of thermodynamic properties necessary for modeling geothermal systems.

Organic chemistry techniques are used to prepare zeolitic minerals. The catalytic potential of zeolites in synthetic fuel reformation processes and refined methods of synthesizing fluoramphiboles and iron-bearing minerals will be investigated. These minerals are used for analytical standards and for geophysical experiments.

3. Thermochemistry of Minerals (C. Holley)

Enthalpies and entropies of formation of minerals are measured for use in modeling calculations related to Synthetic Mineral Standards.

Measurements are made by using heat of solution of minerals and of their component oxide in a molten oxide solvent. These data, plus published data on heats of formation on component oxides, are used to calculate heat of formation of the minerals. A molten oxide calorimeter is under construction and thermodynamic measurements will begin upon its completion.

4. Geochemical Computer Modeling (C. Herrick)

Comparison of laboratory results of mineral alteration experiments simulating geothermal systems with computer mass-transfer experiments revealed the need for thermodynamic data on hydrated minerals such as zeolites, amphiboles and clays. The purpose of this project is to expand capabilities of an existing geochemical computer code which predicts mass transport due to chemical reactions at rock-water interfaces. Predictions are made by computing, in a step-wise fashion, a thermodynamically reasonable path to equilibrium. Mathematically, a complex equilibrium problem is solved for each step of the program variable, i.e., simultaneous solution of all mass balance and mass action equations defined by the system.

We propose further modification of the code to study open-ended systems, evaporation phenomena and time-dependent processes. Additional features such as order-disorder transitions, multicomponent solution theory, heats of reaction, revised equation-of-state for water, optimized numerical methods, and improved computer processing techniques will be included as the need arises. These modifications apply to phenomena at rock-water interfaces. In addition, we propose to model metasomatic processes, which treat reactions of fluids percolating through porous rocks. The infiltration mechanism is the method selected to formulate such processes.

The ultimate goal of this project is a series of subroutines, each describing a specific physico-chemical process. Each subroutine can be included, omitted or ordered to suit the particular geochemical process under analysis.

## D. Rock and Mineral Physics

### 1. Mechanical Properties (P. Halleck, R. Riecker, R. Bridwell, T. Shankland)

The purposes of this program are: (1) to gain an understanding of ways in which rocks and their constituent minerals fail; and (2) to provide equation-of-state and physical properties data for use in geophysical modeling of the earth's crust and interior. Specific practical applications are geothermal resource development, fossil fuel extraction, nuclear and industrial waste disposal, nuclear test containment, earth penetrating weapons technology, and earthquake prediction and mitigations. Basic research goals include an understanding of volcanic caldera collapse, tectonic strain relief mechanisms, dike emplacement phenomena, definition of deep earth stress fields, and definition of the physical state of the earth's interior.

Deformation mechanisms in silicates, specifically garnets, are studied. This experimental work within a range of T, P and strain rate conditions determines regions in which fracture, dislocation motion, kink banding and recrystallization are active. Numerical models of non-Newtonian thermal creep are used to scale experimental observations to real geophysical problems.

Stimulation studies of strain energy release from a locked friction surface have started. These experiments will use a direct-shear testing machine with a provision for applying small-shock pulses to a sliding surface between two rock samples. Numerical analysis of "stick-slip" events will apply to earthquake processes.

A program measuring elastic and thermo-mechanical properties in both rocks and minerals is underway. These measurements include compression studies of minerals using high-P x-ray, ultrasonic velocity, and attenuation measurements. Attenuation measurements will be correlated directly with simultaneously-measured electrical conductivity.

Effects of chemical composition, crystal structure and state of aggregation on sound velocities of rocks and minerals are calculated. The calculations apply to interpretation of seismic measurements (in terms of composition and thermodynamic properties of crustal and mantle rocks).

We began assembly of apparatus for simultaneous measurement of sound velocities and electrical conductivity of rocks at moderate pressures. Since both properties depend on crack density, their mutual variation can test theories of composites and allow estimations of properties (i.e., permeability from surface geophysical measurements). Results apply to problems involving fluid-filled rocks such as waste disposal or geothermal exploration.

2. <u>Transport Properties</u> (T. Shankland, U. Nitsan)

Transport properties of rocks and minerals are studied to assist in understanding emplacement of crust and upper mantle geothermal heat sources, high T thermal conductivity, and hot zone exploration in the mantle.

Current work on thermal conductivity includes measurement of optical absorption in minerals, basaltic glasses and eventually in magmas. Using absorption spectrum as a function of temperature, it is possible to calculate an effective radiative heat conductivity where the temperature is above 700°C. Theories of electrical properties of composite materials combined with experimental data from simple systems are used to evaluate bulk conductivity of rocks containing conductive fluids. Calculations provide estimates of temperature and degree of partial melting at depth from surface conductivity measurements. These calculations assist in quantitative predictions of heat flow for regional geothermal exploration. Silicates as compounds of mixed oxides afford unique examples of systematic chemical variations of electronic structure. Optical absorption and reflectivity measurements in the vacuum ultraviolet are interpreted to understand how chemical bonding in silicates is related to bonding in simpler oxides.

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

Contract: 05 ENG 26

Title: Physical Chemistry of Geothermal Solutions

Person in Charge: R. E. Mesmer

Scope of Work

In the extraction of energy from geothermal brines, temperature, pressure and compositional changes can lead to material transport and deposition and, therefore, scaling of equipment, porosity changes, plugging of boreholes and ultimately to reduced lifetime and value of the resource. To understand, model and effectively deal with such effects, a knowledge of the thermodynamics and other physical chemical parameters is required for the important components known to be present. At present such information is obtained from low temperature data and is often quite unreliable.

The objective of this program is to provide physical chemical information on processes occurring in geothermal solutions in support of the governmental and industrial efforts to harness geothermal energy from the hydrothermal sources in the western U.S. We conduct potentiometric, isopiestic, conductance, calorimetric and theoretical modeling studies on the properties of the brines and their interactions with minerals. Among the homogeneous equilibria upon which the program focuses are: the ionization of water in brines, ionization of silicic acid and polysilicate equilibria, fluorosilicate equilibria, carbonate ionization, and hydrolysis. Processes involved in silica transport are a principal focus. The thermodynamics of the major components NaCl, KCl and $CaCl_2$ and their mixtures are being determined to 250°C by the isopiestic method.

A. Ionization of Silicic Acid and Polysilicate Formation (R. H. Busey and R. E. Mesmer)

Because of the sluggishness of some of the processes occurring even in relatively dilute silicate solutions, even the simple ionization equilibria have not been previously defined to the extent that most such simple processes are now known. The experimental study of the ionization behavior of silicic acid and polysilicate formation in basic solutions has been completed by precise potentiometry using titration techniques in the hydrogen-electrode concentration cell. Polysilicate formation was studied in 1 m NaCl solutions at temperatures from 60° to 290°C and at Si(IV) concentrations 0.005 m to 0.05 m. At the lowest silica concentration only mononuclear species occur over wide temperature and pH ranges. At hydroxyl numbers from ∿ 0.7 to 1.0 small polysilicates which equilibrate rapidly occur at higher Si(IV) concentrations. These polysilicates become only minor constituents at high temperatures. The equilibrium quotient for the most significant reaction, $Si(OH)_4(aq) + OH^- = SiO(OH)_3^- + H_2O$, has been precisely determined from 0.1 m NaCl to 5 m over the range 60° to about 300°C. Values of the logarithm of the equilibrium quotient for the reaction are 3.96 and 2.20 at 50° and 300°C in 1 m NaCl, and 4.32 and 2.26 at the same two temperatures in 5 m NaCl. The reaction proceeds to a lesser extent to the right in a regular fashion as the temperature is increased. The small effect of salt concentration observed indicates little or no sodium ion-silicate ion association.

Geothermal brines contain dissolved salts whose ions could associate with Si(IV) species and influence the ionization equilibria of silicic acid. Preliminary experiments at 100°C in alkaline solution (pH ∿ 8.5) indicate a very weak association of fluoride ion with silicic adic to give an anionic species, $Q_{AS}$ ∿ 3. Preliminary experiments at 25°C indicate that $SiF_6^{2-}$ is the dominant species in acid solution (pH ∿ 3.5). Mannitol has been observed to form a week association complex with $SiO(OH)_3^-$, $Q_{AS}$ ∿ 2 at 100°C and pH ∿ 8.5.

B. Thermodynamics of Geothermal Solutions by the Isopiestic Method (H. F. Holmes, C. F. Baes, and R. E. Mesmer)

In an isopiestic experiment, supported in part by this program, measurements have been made on NaCl, KCl, $CaCl_2$ and $MgCl_2$ and three compositions of NaCl-KCl mixtures for the temperature range 110° to 200°C. NaCl is the isopiestic standard in this study and the concentration range examined was that corresponding to 1 m and saturated NaCl. The osmotic coefficients are believed to have unprecedented accuracy in this region, a few parts in a thousand. By use of existing models (and the assumption of strong electrolyte behavior) it will be possible to evaluate activity coefficients for the salts in these solutions by a Gibbs-Duhem integration.

Although the apparatus performed better than expected in this experiment, two limitations were found which had to be corrected. A temperature gradient of a few hundredths of a degree limited the dilution which could be obtained. Also, the in situ balance became inoperative above 200°C because of the thermal expansion of a Teflon part.

Modifications of the apparatus have been made to alleviate these limitations. Heaters for the air bath are now uniformly distributed on all six sides rather than being concentrated in a circle at the bottom. A further reduction in temperature gradients should result from the fact that the isopiestic vessel is now essentially contained in a cube constructed of eighth-inch copper sheet. Circulation in the air bath has been improved by using larger fans in more favorable locations. The torsion balance has been modified by substitution of insulated silver for the offending Teflon part. We will test the modifications and conduct a second series of measurements on NaCl-KCl and NaCl-$CaCl_2$ mixtures to 250°C, if possible, and at concentrations above about 0.5 m.

C. Solubility of Amorphous Silica in Salt Media (W. L. Marshall)

Preliminary measurements of the solubility of amorphous silica in concentrated aqueous solutions of sodium nitrate have been made at temperatures from 100° to 300°C. The results show that the solubility is reduced in 5.4 molar $NaNO_3$ to approximately one-half that in water at the same temperature. The information from this study will be applied to geothermal systems and to fundamental correlations at high temperatures of the thermodynamic parameters for the process.

Contractor: SANDIA LABORATORIES
Albuquerque, New Mexico 87115

Contract: 2910789

Title: Magma Energy Research

Person in Charge: H. M. Stoller

Scope of Work

Sandia Laboratories has in progress an engineering research program investigating the feasibility of extracting energy directly from buried circulating magma sources. Typically, these magma deposits have temperatures on the order of 1000°C and represent great concentrations of high quality thermal energy.

The current concept involves locating a suitable magma source, drilling into the liquid magma, and installing a heat exchanger to continually transfer the heat from the magma to a conventional power plant on the surface. Ideally, natural convection flow in the magma would circulate the liquid around the exchanger in such a way that the cooled material would settle to the bottom of the chamber. The system would be fully closed and, thus, assures no leakage of water or other working fluid. Preliminary studies have shown that the concept may be both technically and economically feasible if the magma source is within the upper five kilometers of the crust and if the heat extraction rate from the magma is at least five kilowatts (thermal) per square meter of heat exchanger surface.

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

A high priority recommendation of the Sandia/USGS Magma Workshop (SAND 75-0306) was a demonstration of the abilities of geophysical sensing systems to detect and delineate a known body of molten rock. The lava lake in Kilauea Iki crater on the island of Hawaii, still molten since the 1959 eruption, was chosen as a site for this demonstration experiment performed in FY 1976. The results are being compiled with the assistance of Professor John Hermance, Brown University, and will be published as a Sandia report in FY 1977. Additional sensing work on this site is indicated from some of last years results and will be performed in FY 1977.

The assessment of the abilities of the various sensing systems used in the Lava Lake Sensing Experiment to correctly detect and delineate the buried body of molten rock requires the drilling of a series of holes into and through the molten lense of Kilauea Iki. Two holes were drilled through 150 feet of the upper crust and into the molten rock in FY 1976. An unexpected solid layer of hot rock was encountered after penetrating only 20 inches of molten rock. An investigation into techniques for drilling hot rock immersed in molten rock was commenced (See Section B following). Additional confirmation holes through the molten lens will be drilled in late FY 1977.

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

Another high priority recommendation of the previously mentioned Magma Workshop was the determination of the strength and ductility of representative granitic rocks at conditions of 0 to 1000°C to 2 kilobars pressure. A Sandia-sponsored research study to accomplish this objective was started at the Center for Tectonophysics at Texas A&M University in FY 1975, continued through FY 1976 and is expected to be completed during FY 1977.

The results of the two lava lake confirmation holes drilled in FY 1976 (See A above) clearly showed two things: (1) that the molten lense as it presently exists in Kilauea Iki is not a simple, relatively homogeneous liquid, and (2) that the previously postulated methods for penetrating that molten lense would not work. Immediately following that drilling sequence, a program to develop and build an advanced drilling system that would reliably drill through hot (~ 1050°C), solid rock while the drill string is rotating immersed in molten (~ 1075°C) rock. This turned out to not be a trivial development problem. A number of thermal and heat transfer calculations, several studies of appropriate materials and bit fabrication methods that would be required were conducted. Results to date indicate that a workable system has been developed and it will be tested in Kilauea Iki during late FY 1977 when the planned confirmation holes are drilled.

C. Magma Characterization and Materials Compatibility (E. J. Graeber, T. M. Gerlach, P. J. Modreski and M. J. Davis)

Magmatic gases are being investigated as part of the materials compatibility and magma-properties simulation experiments. The data from high quality volcanic gas collections from Kilauea, Surtsey, Mount Etna and Erta'Ale volcanoes have been analyzed with thermodynamic computer codes. These studies indicate that most of the collection data are altered from the original gas compositions released from the magma because of reactions with metals frequently used in the collection devices. The computer codes have been used to restore the data to their original compositions and to construct a data base of select volcanic gas samples.

High temperature gas collectors have been fabricated for sampling magmatic gases in the event of a suitable volcanic eruption. Gases have been collected and analyzed from fumaroles at eruptive fissures at Kilauea Volcano. Characterization of such gases provides data on the chemical environment in which compatibility tests are being carried out.

Thermodynamic and preliminary experimental studies indicate that injection of aqueous fluids into basaltic magma would result in the generation of substantial volumes of hydrogen. If small amounts of organic material are added to the injected fluid, fuel generation is increased and includes CO and $CH_4$ in addition to $H_2$. A modest laboratory research program has been planned to evaluate engineering feasibility for this potential energy resource.

An internally heated, 4 kbar pressure system is being constructed that will be capable of maintaining large volume samples (~ 1 liter) at uniform temperature to 1600°C in a controlled atmosphere with a variety of electrical sensors present. The system will be used to study the effect of volatiles on the physical properties of molten rock and other materials, and between metals and gas or molten silicate environments.

Experiments are being conducted to examine the types and mechanisms of reactions between molten rock and metals, including pure elemental metals, binary alloys and high temperature engineering alloys. The environment of the experiments includes pressures from atmosphere to 1 kbar (in cold-seal pressure vessels); temperatures up to 1200°C; and gas atmospheres ranging from low-$f_{O_2}$ inert gas (argon) to gases "spiked" with $H_2O$, $SO_2/H_2S$, and $CO_2$.

Samples of engineering alloys are being exposed to gases in natural volcanic fumaroles to learn about materials compatibility in the environment of near-surface, moderate to low temperature, relatively oxidizing conditions that may be encountered in or around drill holes in volcanic areas.

D. Energy Extraction (H. C. Hardee, D. W. Larson, D. O. Lee and P. C. Montoya)

Several models of an open system heat exchanger were tested in the lab using paraffin as a simulant for magma. The purpose of these tests were to study techniques for forming a porous matrix adjacent to the heat exchanger tube which could be used to contain a circulating heat transfer fluid. A model test was also run in molten glass in order to study the formation of a porous matrix in a material more closely approaching the properties of magma.

A numerical code was used to determine the coupled conductive and convective effect of insertion of a cold probe into a magma chamber. Computational instabilities prevented solutions at realistic Prandtl numbers. Future developments in the code should remove these instabilities and also include the effects of temperature dependent properties, non-Newtonian fluids and arbitrary geometries. These results should lead to predictions of expected heat extraction rates.

A closed-form analytic solution was obtained of the expected magma surface heat flux from a constant temperature buried magma source. The results should be useful in predicting the degree of superheat of suspected magma chambers based on surface flux measurements.

Much of the peripheral equipment for operating the long tube heat exchanger test facility has been installed and connected. This equipment includes a steam separator, turbine, generator, condensers, circulation pump, control valving and some of the instrumentation. In preparation for operation of the facility, the LTHE computer code is being refined to give a better predictive capability.

A Lava Lake Research Experiment will be conducted in the molten rock deposit at Kilauea Iki as a logical extension of the Molten Lava/Single Tube Boiler Experiment performed in the laboratory in FY 1975 and of the 20 meter Long Tube Boiler Experiment planned for laboratory performance in FY 1977. A single tube boiler will be inserted near the center of the lava lake; connecting water supply and steam return lines will extend to a steam condensation system located just off the edge of the lake. The steam/water system will be completely contained. The condenser/heat exchanger will be air cooled.

Computational modeling of the system will be started in late FY 1977 and completed in FY 1978. The model will be experimentally verified using the 20 meter Long Tube facility. A predictive model of the operation of the Lava Lake Research Experiment will be completed before experiment start-up in FY 1979. The lava lake experiment is planned to extend over several months and to verify the ability to predict energy extraction rates from molten rock deposits about which certain parameters are known.

# PART II

## GEOSCIENCES

## OFF-SITE

| | |
|---|---|
| Contractor: | UNIVERSITY OF ALASKA<br>Geophysical Institute<br>Fairbanks, Alaska 99701 |
| Contract: | EY-76-S-06-2229 005 |
| Title: | A Study of the Magnetic Field Annihilation Process in the Magnetosphere and Some Applications (Electric Currents in the Trans-Alaska Pipeline Induced by Auroral Activity) |
| Person in Charge: | Syun-Ichi Akasofu |

Scope of Work

The magnetic field annihilation process has been believed to be one of the basic processes in cosmic electrodynamics, releasing a considerable amount of energy in a relatively short time, and has also been believed to take place in the tail region of the magnetosphere (manifested by magnetospheric substorms), in the planets (such as Mercury and Jupiter), in some comets, and in certain regions of the Galaxy. The one common feature in these regions is that the oppositely directed magnetic field regions are separated by a thin sheet-like region (often called the "neutral sheet").

Among the above regions where the annihilation process has been suspected to take place, the magnetotail is the only region where satellite-borne instruments can frequently make a detailed measurement of plasma conditions. Our analysis of satellite data indicates that the magnetic energy release during the initial phase of magnetospheric substorms arises from a sudden disruption of the electric current across the magnetotail (which constitutes a large inductive circuit), rather than from the annihilation. Our finding may have an important implication in understanding solar flares and other transient energetic processes in the sun.

We have been interested in energy-related geophysical problems in the arctic region. During the last 12 months, we helped corrosion engineers of the Alyeska Pipeline Co. in monitoring an induction current in the Trans-Alaska pipeline. We have found that electric currents of order 200 amperes are induced in the pipe during medium auroral activity. We are at present monitoring the amount of electric currents which leaks from short segments of an underground section of the pipe. We have also been interested in applying the audio-frequency ($10H_z$ - $10KH_z$) magnetotelluric method in sounding permafrost regions in Fairbanks.

Contractor: UNIVERSITY OF ALASKA
Geophysical Institute
Fairbanks, Alaska 99701

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

Title: Alaska Peninsula Telemetered Seismic Network

Person in Charge: Hans Pulpan

Scope of Work

A large aperture network of 10 short period, vertical component seismometers has been installed and is being operated on the eastern portion of the Alaska Peninsula. The network is to provide part of a long term, high resolution data base for the comprehensive study of the seismotectonics of the eastern Aleutian arc, undertaken cooperatively by Lamont-Doherty Geological Observatory and the University of Alaska.

Contractor: UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

Contract: EY-76-S-03-0034 032

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

Person in Charge: J. H. Reynolds

Scope of Work

This laboratory conducts research in rare gas mass spectrometry where the broad objective is to read the natural record which the isotopes of the rare gases comprise as trace constituents of natural gases, rocks, and meteorites. In terrestrial samples it is observed that subterraneous rare gases occur as recycled atmospheric gases, as radiogenic gases from natural radioactivity in the rocks and sediments, as much rarer radiogenic gases from extinct radioactivities, and possibly as a primordial component more ancient than the earth itself. Rocks similarly contain atmospheric gases, radiogenic gases, and sometimes primordial gas. A new program with us is to design, construct and operate apparatus which will 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. The rare gases from steam wells and other geothermal energy sources will also be examined with particular interest in assaying the proportions of recycled atmospheric gas vs. radiogenic gas. While the extensive instrumentation for the field studies on fluids is being fabricated, we are working with volcanic xenoliths and suboceanic volcanic basalts where we have already observed interesting elemental and isotopic patterns.

This group maintains a continuing interest in geochronology, particularly in problems where physicists -- as opposed to geologists -- can make contributions. Our work in establishing the $^{39}Ar$-$^{40}Ar$ method of K-Ar dating is an example of this kind of research.

Studies in natural nucleosynthesis make use of the meteorites and the clues they contain to the chronology of nucleosynthesis. Rare gases there are in part daughter products of extinct and extant radioactivities. We also study isotopic inhomogeneities, such as we observe in the carbonaceous chondrites. It is likely that they originate because of incomplete isotopic mixing of fractions with different histories of nucleosynthesis.

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

Contract: EY-76-S-03-0034 224

Title: Relationship of Rock Physics and Petrology to Geothermal Energy Technology

Person in Charge: Orson L. Anderson

Scope of Work

The research done under this contract is a continuation of our efforts dealing with the relation and correlation of rock structure and physical properties to bulk rock elastic properties. The development of acoustic techniques applicable to the problems of hot dry rock involves improving methods of interpreting acoustic data in terms of rock structure (cracks and fractures, rather than seismic layering) and improving understanding of the relations between structure networks which control various physical properties, such as permeability, and those which control acoustic wave propagation. Primarily our research is directed toward solving the rock velocity-microstructure inverse problem.

Data are obtained from velocity-pressure measurements and studies of microstructure patterns in polished sections. Suites of samples include LASL GTE core specimens and Conway granite. The velocity-pressure data are used both to predict rock microstructure and to check predicted model rock microstructure. High magnification photographs of polished sections are being analyzed in an attempt to correlate observed structural characteristics with structural classes as determined from acoustic work. SEM and TEM techniques provide information on the more detailed aspects of grain-grain bonding, microcrack deformation and closure. Computer techniques for modeling structural effects on elastic properties have been developed and incorporated into increasingly more accurate schemes for solving the velocity-pressure/rock-structure inverse problem. A correlation between the pressure dependence of bulk rock elastic moduli and permeability has been predicted based on a simple Kozeny relation. Preliminary experimental results based on two LASL core samples and Westerly granite tend to confirm this relationship.

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

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

Title: Compressibility Measurements

Person in Charge: G. C. Kennedy

Scope of Work

The pressure dependence of the Gruneisen parameter has been determined for sodium chloride, iron, lead, aluminum, indium, copper, water, mercury, methanol, ethanol, pentane, iso-pentane and ether. The measurements were carried out in a piston-cylinder apparatus up to 35 kb. Fluid cell arrangement with Bridgman's unsupported area seal was used. Temperature change in the sample associated with small adiabatic pressure changes was measured and $\gamma$ could be calculated using the thermodynamic relationship

$\gamma = \frac{K_S}{T} \left(\frac{\partial T}{\partial P}\right)_S$. The pressure dependence of $K_S$, the adiabatic bulk modulus,

is known from ultrasonics for most of the substances investigated. The results for sodium chloride are in excellent agreement with the latest theoretical calculations. For metals $\gamma$ decreases with compression. This decrease is similar for all metals investigated. For fluids $\Delta T/\Delta P$ decreases extremely fast and the $\Delta T/\Delta P$ curves converge at high pressures at about 2.5°C/kb. For water, mercury pentane and iso-pentane, $K_S$ - data are available. An increase in $\gamma$ is observed.

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

Contract: EY-76-S-02-3134

Title: A omprehensive Study of the Seismotectonics of the Aleutian Arc

Person in Charge: J. Davies, K. Jacob, L. Sykes

Scope of Work

A comprehensive seismotectonic study of the eastern Aleutian arc is undertaken to develop a coherent understanding of the present tectonic processes and the evolution of the arc in the framework of plate tectonics. The study consists of several fields of interest: (1) Detailed delineation of the Benioff zone by locally monitoring the seismicity with telemetered seismic networks near the Shumagin Islands seismic gap, the tip of the Alaskan Peninsula, and near Unalaska Island. (2) Investigation of the geothermal potential of some of the volcanoes presently by delineating the magma chamber beneath Pavlov volcano by seismic techniques. (3) Monitoring of strain accumulations from geodetic leveling data, strainmeters and mean-sea-level meters. (4) Determination of recent stresses from fault-plane solutions and volcanic dike features. (5) Integration of these geophysical results with geologic evidence into a coherent theory of tectonic processes and evolution. As a by-product the tectonic study has important implications for seismic and tsunami risks in a region with high potential for fossil and geothermal energy.

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

Contract: EY-76-S-02-4054

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

Person in Charge: C. Scholz

Scope of Work

Emphasis of this study is on the mechanical hydraulic interactions, in an attempt to understand the process of fracture closure and its influence on fracture permeability. To determine the fluid transport properties of a fracture, we investigated the effect of surface roughness, geometry and filling on fracture permeability. Permeability of these fractures was measured at various effective normal stresses at room temperature. The law of effective stress appears valid for fractures without filling but permeability of filled fractures is more sensitive to confining pressure than pore pressure. Permeability of smooth surfaces varied 5 to 0.5 darcys over a range of effective stresses from 0 to 3000 bars. Filled fractures were an order of magnitude more permeable.

Contractor: MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139

Contract: EY-76-S-02-2534

Title: Seismology of Crack Formation and Natural Geothermal Systems

Person in Charge: K. Aki

Scope of Work

An active seismic method for defining cracks in the earth will be developed by a computational study of seismic waves diffracted by cracks. The method will be applied to hydrofractures cracks and magma lens. The seismic source mechanism of volcanic tremor will be studied theoretically and observationally for finding the magma transport mechanism. An array of eight event recorders will be constructed and used for surveying micro-seismicity, velocity anomalies, attenuation, diffraction, dispersion phenomena in geothermal energy source regions.

Contractor: NAVAL WEAPONS SUPPORT CENTER
Crane, Indiana 47522

Contract: EY-76-A-02-2882 001

Title: Heat Capacities and Related Properties of Aqueous Salt Solutions

Person in Charge: J. E. Tanner

Scope of Work

The object of this work is to publish previously measured specific heat capacities of aqueous electrolyte solutions, and to correlate them with other thermochemical data from the literature.

Contractor: PRINCETON UNIVERSITY
Princeton, New Jersey 08540

Contract: EY-76-S-02-4086

Title: Origin of Fluid Inclusions in Precambrian Rocks Near Los Alamos, New Mexico

Person in Charge: L. S. Hollister, R. C. Burruss

Scope of Work

We are analyzing the density and composition of individual fluid inclusions in core samples as a function of depth in well GT-2 and in surface outcrop samples of similar rock types. These analyses allow us to constrain the thermal history, the chemistry and the possibility of circulation of the fluid phase formerly present in these rocks.

The inclusions are found predominantly in quartz and occasionally in potassium feldspar and occur as isolated inclusions, groups defining surfaces within a single mineral grain, and as healed fractures cross-cutting many grain boundaries. Inclusions on healed surfaces predominate and can be differentiated by measurement of the orientation of the surface relative to the plane of the section (i.e., the dip). Measured final melting temperatures and liquid-vapor homogenization temperatures show that the fluid inclusions on surfaces with different orientations in the same sample have distinctly different chemical compositions and densities. Measurements on samples from well GT-2 show systematic differences in density of the fluid inclusions as a function of depth in the core. Observed salinities (total dissolved electrolytes as wt.% equivalent NaCl) of fluids in all samples range from near 0 to approximately 25 wt.%. The final melting temperatures of some high salinity fluid inclusions occur at temperatures below the ice - $NaCl \cdot 2H_2O$ eutectic (-21.1°C), indicating the presence of additional dissolved electrolytes, such as $CaCl_2$ and $MgCl_2$ in these fluids. In addition, we are measuring the dips of healed surfaces containing analyzed fluid inclusions in an attempt to correlate our observations with the orientations of microcracks measured by G. Simmons at MIT in samples from the same core depth in well GT-2. These observations may allow us to sort out the history of fluid movement in these rocks.

Contractor: STANFORD UNIVERSITY
Stanford, California 94305

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

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

Person in Charge: A. Nur

Scope of Work

A. Seismic Waves in Geothermal Reservoir Conditions

In the laboratory we are measuring compressional and shear wave velocities and attenuation in porous rock with water undergoing a vapor/fluid transformation. Results in Berea Sandstone indicate strong attenuation and abnormally low velocities in the region of transition from steam to hot water. In the field we are comparing laboratory and theoretical results with reflection data in the Geysers, California area. Strong reflections from fracture zones in the field appear to be related to high fracture porosity and high permeability.

B. Study of Attenuation Mechanisms

By investigating the physics of wave energy loss in reservoir rocks, we attempt to extract more information about the state of the reservoir. In the laboratory we are measuring very carefully the effects of pore pressure, temperature, confining pressure, degree of saturation, clay content and rock type on wave attenuation. In parallel, we develop theoretical models for the physics of wave attenuation in situ. Preliminary results suggest that thermoelastic effects coupled with pore pressure are dominant in geothermal environments.

C. Destruction of Porosity and Pressure Solution

We are investigating the coupled mechanical and chemical processes which lead to the reduction of pore and fracture volume in rocks. In the laboratory we are attempting to determine the relations between temperature, stress, chemical potential, solubility and transport and changes in configuration of porosity in shallow crustal rocks. Preliminary results suggest that active tectonics are required to continuously create new fracture porosity, against the sealing effects of solution and depositon. This may explain the usefulness of microearthquake surveys as a geothermal exploration method.

Contractor: WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

Contract:

Title: Organic Chemistry of Continental Margin Sediments

Person in Charge: J. M. Hunt

Scope of Work

A research effort to evaluate the pyrolysis-gas chromatograph method for the chemical analysis of deep marine sediments. Initial testing of the method will be performed on cores taken from restricted basins such as the Persian Gulf and the Black Sea. After the testing and development of standardized methods of analysis on these samples, the focus of the research effort will shift to the continental margin sediments of the eastern United States. The research is necessary to provide information on the hydrocarbon resource potential of the voluminous continental sediments.

TOPICAL INDEX

TOPICAL INDEX (cont'd.)