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EARTH SCIENCES

LAWRENCE BERKELEY LABORATORY / UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

New Large-Moment EM System For Deep Geosounding

A new large-moment, frequency domain electromagnetic (EM) system designed by LBL/UCB has recently been completed and operated to increase range and sensitivity in deep electrical sounding. The prototype of the present EM 60 system was tested during 1976 in Grass Valley, Nevada. Despite the relatively primitive equipment, initial sounding results obtained compared favorably with those from other electrical techniques.

The new large-moment EM 60 version has already proved useful in field tests for delineating the gross geological structure and the reservoir region in some geothermal systems. This application is based on the relationship between the bulk resistivity of the reservoir and a complex function involving temperature, type and concentration of ionic species, fracture permeability, and other effects, such as presence of a gas phase, sulfide, or clay minerals.

All techniques using a man-made source of excitation are "controlled-source" methods. Controlled-source methods for resistivity measurements use an energy source whose geometry is known and

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HYDROGEOLOGY SYMPOSIUM

A symposium entitled "Recent Trends in Hydrogeology" will honor Paul Witherspoon on his sixtieth birthday. The symposium is being organized by the Earth Sciences Division, Lawrence Berkeley Laboratory and the Department of Materials Science and Mineral Engineering, University of California. To be held on February 8-9, 1979, in the Laboratory's Building 50 Auditorium, the symposium will consist of 24 state-of-the-art papers contributed by invited speakers. The topics will cover theory of mass, energy and solute transfer in groundwater systems; laboratory and field measurements; exploration, exploitation and environmental aspects of hydrogeologic systems. A banquet will be held at the U. C. Berkeley Faculty Club, February 8, at 6 p.m.

NEW PHONE NUMBER

Please note that with the inauguration of a Centrex system, the LBL phone number has a new prefix, 486. By combining the new prefix with extension numbers previously connected by an operator, it is now possible to dial direct. Example: EARTH SCIENCES Newsletter Editor can be dialed by using (415) 486-6658; FTS remains 451-6658.

GAIN Symposium Recommendations

Recommendations have been made by geoscientists that full-scale test facilites, simulating nuclear waste repository environments, be established in various rock types. The proposal was adopted by the Geotechnical Assessment and Instrumentation Needs Symposium (GAIN). Present information and research facilities may be inadequate to assess the principal geotechnical issues associated with nuclear waste storage and disposal in crystalline argillaceous rock types. Until recently, work directed at these issues has been minimal.

More than 60 geologists, geophysicists, and engineers gathered last summer to combine their knowledge and experience in rock properties, fracture hydrology, and geochemistry in order to assess the state-of-the-art and to make recommendations for nuclear waste isolation research, tools to be developed, and methods of accomplishing the research and development. The symposium was organized by Earth Sciences Division and coordinated by Maura O'Brien.

Why Crystalline and Argillaceous Rocks?

Crystalline rocks—rocks which have formed or re-formed at elevated pressures and temperatures—are almost impermeable and have relatively high compressive strength. Many are homogeneous. Interstitial permeability is exceedingly low and what seepage occurs results from flow along fractures in the rock mass. Rock types considered for study as potential

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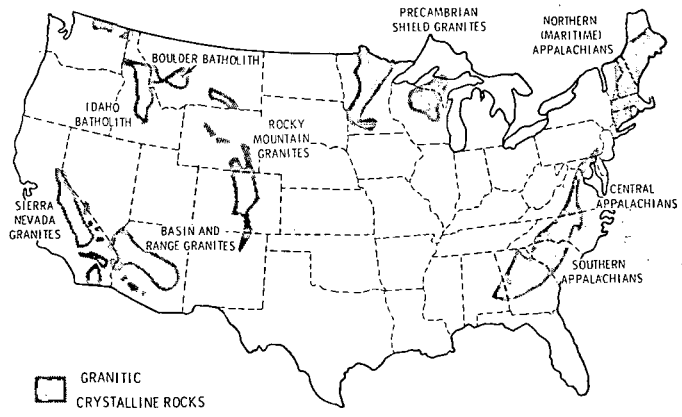

Fig. 1. — Granitic rocks in the contiguous United States.

Office of Waste Isolation/Union Carbide Corporation, Nuclear Division, *Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formation, Baseline Rock Properties - Granite*, Y/OWI/TM-36/5, Oak Ridge, TN, April 1978).

GAIN Symposium *(continued from page 1)*

waste respository sites include high-grade metamorphic rocks, granitic rocks (Figure 1), and basalts, which are widely distributed in the U.S.

Argillaceous rocks—fine-grained sedimentary rocks with a high proportion of clay minerals—may also have low permeability. They have the added advantage, however, of having high ion exchange capacity which increases adsoprtion of radionuclides and thus retards nuclide migration. Many have high plasticity which assists in "healing" of fractures. Rocks in this group, such as argillite, shale, claystone, and slate, are also widely distributed in the U.S. (Figure 2).

Waste isolation in crystalline and argillaceous rocks depends on knowing such characteristics as the movement of water through fractures in these almost impermeable rocks, geochemistry of rock-groundwater interactions, and ultimately, the interaction of nuclear wastes with groundwater, engineered barriers, and the surrounding rock mass.

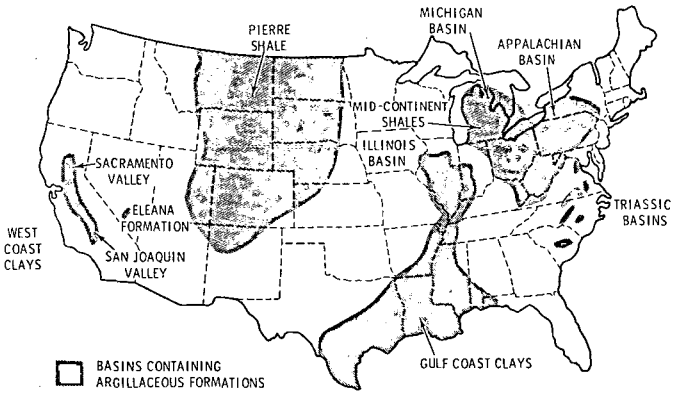

Fig. 2 — Shale formations in the contiguous United States.

Office of Waste Isolation/Union Carbide Corporation, Nuclear Division, *Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formation, Baseline Rock Properties - Shale*, Y/OWI/TM-36/6. Oak Ridge, TN, April 1978).

GAIN Recommendations

The Symposium report, LBL-7097 Draft, summarizes the discussions of the technical sessions and the resulting recommendations. As a first priority, the Symposium participants urged that full-scale test facilities, which would serve as fundamental research sites, should be established immediately in at least two rock types. Full-scale heating experiments in a number of rock types are also recommended, in addition to the few currently under study. These facilites and experiments would be used for fundamental data-gathering, testing of theories and of instrumentation, and model construction and validation. Experiments on a scale representative of future repository design would allow the examination of such rock properties as thermally-induced deformation, permeability changes, sonic velocity changes, thermal cracking, electrical conductivity changes, thermal expansion of jointed rock masses, and time-dependent properties of rock.

Other recommendations:

- A significant research effort should be mounted to improve determination of fracture permeability in rock masses, especially directional permeability, the hydraulic continuity of fractures within a rock mass, and the effect of different stresses—thermal, tectonic, lithostatic, and shear—on apertures and permeability.

- Theoretical and experimental work should be encouraged to directly measure in situ the volume, size distribution, and interconnections of fractures in rock.

- Research should be conducted on developing borehole stress measurement techniques because the in situ state of stress effects deformation, seismic activity, and permeability changes along existing and new fractures.

- Investigation should be made of the chemistry of groundwater and rock at potential respository sites. Such investigations would help in the choice of the waste form, assist in synthesizing the most effective plugging and backfill materials, and in determining the ultimate fate of waste materials if they should ever contact the groundwater/rock system.

- Continued extensive work is needed on the sorption of waste products by rock surfaces, information is needed on the behavior of actinide compounds in aqueous solutions, and work is needed on potential mechanisms such as colloid formation and organic complexing

that might change the effectiveness of the rock barrier to inhibit radionuclide migration.

- Development is needed of specialized instruments such as
  1. a suite of slime-hole logging tools for detecting fractures and evaluating their apertures, frequencies, and orientations
  2. downhole tools for stress determinations at depths of 500 meters or more and having stability for a decade or longer
  3. stable and long-lived downhole electrochemical sensors
  4. a device for better measuring aluminum dissolved in ground water.

The Symposium proceedings also give state-of-the-art reviews, additional research recommendations and justification for them.

Large-Moment EM System (continued from page 1)

whose frequency and intensity can be controlled. These methods involve either current passed directly into the ground or currents inductively generated by means of an oscillating magnetic field.

Large Dipole Moment

For most geothermal exploration, deep electrical soundings are necessary because targets lie at considerable depth and powerful systems capable of operation at low frequencies are required. For effective EM depth sounding it is necessary to have a large dipole moment where dipole moment determines the strength of the exitation magnetic field.

The new EM-60 system was designed and fabricated at LBL in 1977. It is powered by a 60 kW generator and was completed and tested in 1978. The system is designed around a horizontal coil transmitter of small diameter (30 m). The magnetic moment is directly proportional to the coil area, the number of turns in the coil, and the amount of current passing through the wire windings on the coil. Despite the small number of turns on the coil, usually only four, large moment is obtained by using a large current.

Advantages

With this design, the EM-60 system is able to overcome a number of problems inherent in other controlled-source EM systems. Advantages of the EM-60 system are:

- Because no ground contact is needed, the system is well suited to areas where contact resistances are high, such as sand or talus covered areas.
- A magnetic field detector can be used, eliminating the need for long wires.

Rear of transmitter truck, with electronics box (top) and instrument crate (bottom) swung out for operations. A 4/0 transmission cable is being connected to the mobile unit. CBB 781-953

- The transmitter can be placed at any convenient location, and the surrounding area surveyed by moving the receiver only. This is especially helpful in rugged terrain where access is limited.
- Vertical resistivity soundings are made by varying frequency, not transmitter-receiver separation, which avoids interpretational difficulties caused by lateral inhomogeneities.
- By generating an EM field over a broad range of frequencies (10^3 Hz to as low as

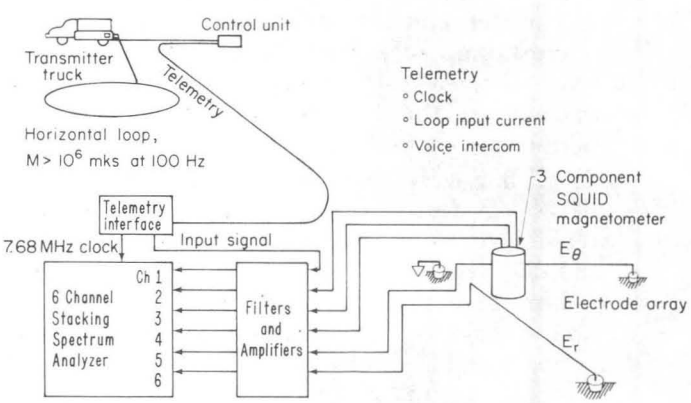

Diagram of a low frequency electromagnetic prospecting system. XBL 786-2575

10^{-3} Hz) the system provides good resolution of the near-surface and better depth penetration than conventional resisitivity methods in conductive environments.

The system consists of two sections: a *transmitter section* comprised of the power source, control electronics, timing circuits, and a transistorized switch capable of handling large currents, and a *receiver section* consisting of a combination of magnetic and electric field detectors, signal conditioning amplifiers and filters, and a multichannel, programmable receiver (spectrum analyzer).

Figure 1 is a photo of the truck with the EM-60 components swung out for operations. Figure 2 shows a diagram of the components of the system.

Field tests were conducted with the system in Grass Valley, Nevada, and Mt. Hood, Oregon. Data from these tests are being analyzed.

Detailed descriptions of the EM-60 system are being published in LBL-7088: Description, Field Test, and Data Analysis of a Controlled-Source EM System (EM-60), by H. F. Morrison, N. E. Goldstein, H. Hoversten, G. Oppliger, and C. Riveros.

VERY DEEP HOLE

Investigation of the potential of very deep holes for disposal of high-level nuclear waste has been made by Earth-Sciences with the support of TerraTek, Salt Lake City, in response to a request by Battelle Northwest Laboratory, Richland, Washington. At very great depth, the rock surrounding waste containers would be utilized to delay the release and reentry of radionuclides to the earth's surface and biosphere.

Four major areas of uncertainty were found to exist.

1. How deep is deep enough? Hydrologic conditions, rock strength, and rock/waste interactions at great depth are not well known. For example, very deep holes might be drilled into strong, relatively unfractured rock of low water content and permeability, such as a crystalline rock like granite, when comparatively shallow holes in salt domes might suffice because of the low water content and low permeability of salt.
2. Can a very deep hole (6 m wide and 10 to 20 km deep) be excavated? At present it is possible to drill a narrow deep hole to 10 km (33,000 feet) or to sink a wide shaft to about 4 km (15,000 feet). How and if a very deep hole should be cased would depend on rock strength and confining pressures.
3. Is it possible to adequately seal a very deep hole? Drill holes at great depth in oil fields are routinely sealed to prevent gas leakage but this sealing may not be adequate for the isolation of radioactive wastes.
4. Will heat generated by the waste cause the rock to melt or cause large stresses to develop? This is a limiting factor on the amount of waste that could be emplaced.

Until answers are forthcoming in these four areas of uncertainty, the very deep hole concept cannot be adequately evaluated as an alternative for nuclear waste disposal.

The report submitted to BNL is LBL-7089 Draft. The Very Deep Hole Concept: An Alternative for Commercially Generated Nuclear Wastes—Generic Environmental Impact Statement, August 1978, for incorporation in DOE 1559 Draft: Environmental Impact Statement, Management of Commercially Generated Radioactive Waste, 1978.

Earth Sciences Division members primarily involved with production of this report were Maura O'Brien, Terry Simkin, and Harold Wollenberg.

Alteration of Pasco Basin Basalts

Basalts are formed from very fluid magmas which produce lava flows large in areal extent and volume. The two greatest mountains (in volume) on earth—the volcanoes Mauna Loa and Mauna Kea—have been built of successive basaltic flows. Of special interest are the Columbia River Basalts (which did not emanate from volcanoes, but from fracture zones). These are one of the largest accumulations of basalt in the world and are a potential rock unit for a nuclear waste repository.

Studies of the chemical and mineralogical evolution of the basalt-water geochemical system of the Pasco Basin in Washington state are being conducted by several members of the Geoscience Group: Larry Benson, Chalon Carnahan, Don Corrigan, Connie Frisch, Catherine Mouton, Lisa Shomura and Bob Stolzman. The mineralogy and composition of secondary phases which replace primary minerals and coat fluid pathways (vesicle and fracture surfaces) are being determined by scanning electron microscopy, transmission electron microscopy, petrographic analysis, electron microprobe analysis, standard wet chemical analysis, and X-ray diffraction techniques. The fractures and interconnected vesicles are the pathways radionuclides would take if transported by groundwater away from a waste repository, and the sorptive properties of the coating minerals strongly affect the rate of radionuclide transport in the hydrologic system.

Geologic Setting

The Columbia River Basalts were erupted during the Miocene epoch, 14-17 million years ago. The flows eventually covered over two million km^2

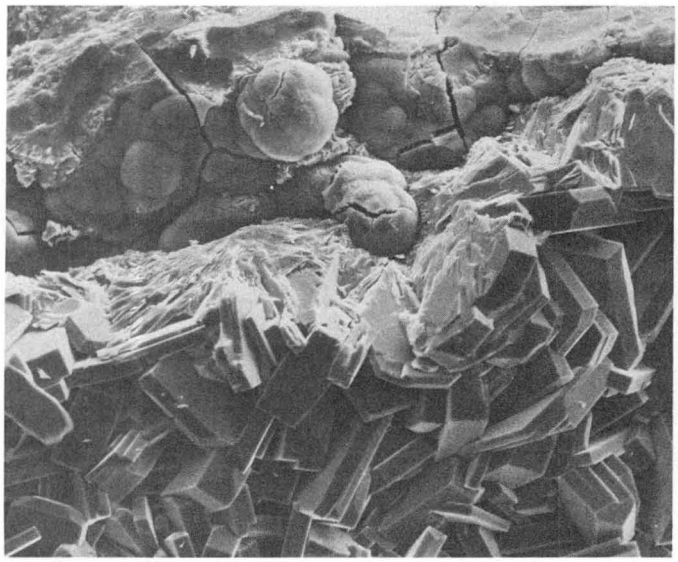

Fig. 1. Vesicle filled with layer of nontronite (smooth rounded material in upper portion of photo). Nontronite is coated with tabular crystals of the zeolite clinoptilolite. Tabular crystals are 25μm wide. (DC2 2206 52A 2004)

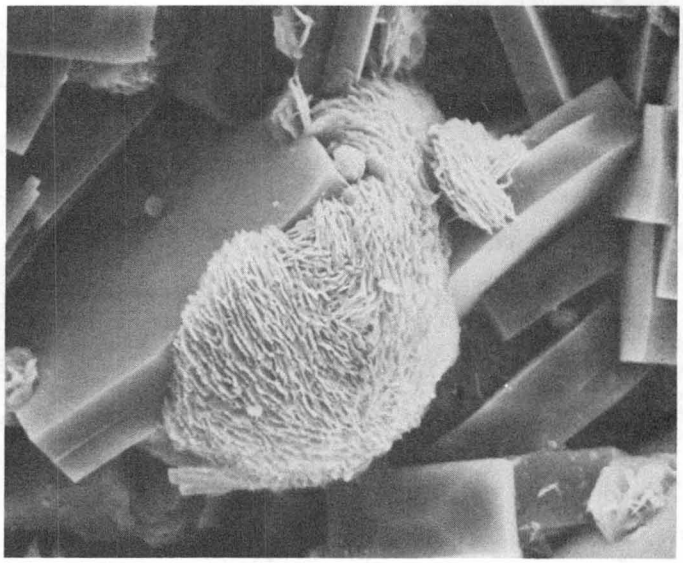

Fig. 2. The interior surface of a vesicle, showing tabular crystals of clinoptilolite intergrown with spheroids of silica. Tabular crystals are 25μm wide. (DC2 2206 51 2KX)

of the states of Oregon, Washington, and Idaho. The Pasco Basin is situated in southeastern Washington in the northern portion of the Columbia Plateau and is a long-standing structural and topographic low. Basalts in the Pasco Basin accumulated to a total thickness in excess of 1500 m and were overlain by later sedimentary deposits. During the extrusion of basalts, entrained gas escaped from the basalt surfaces leaving small cavities (vesicles) in the solidified melt. Stress also accompanied cooling, resulting in fractures in the basalt. Later, fractures were also caused by tectonic movement in the earth's crust. Meteoric waters entering the basalts have moved through fractures and vesicles in the basalt, dissolving primary minerals and glass and precipitating secondary minerals.

The core samples studied were taken from the Grande Ronde Basalt, one of a number of Columbia River Basalt flows which occur in the Pasco Basin. The Umtanum Unit located in the lower portion of the Grande Ronde has been considered by workers on the Hanford Reservation to be a flow unit possibly suitable for the containment of high-level radioactive wastes.

Results

Two 1000 m drill cores have been studied. All surfaces have been found to be coated with secondary minerals. Fractures are most often lined with an iron- and magnesium-rich expandable clay (nontronite). Vesicles are coated with a complex assemblage of mineral phases. Usually one or more layers of the iron- and magnesium-rich clay are followed by silica (cristobalite, quartz, or tridymite). The silica is followed by or intergrown with a sodium- and potassium-rich zeolite (clinoptilolite). The last mineral to have formed is most often an expandable clay, but other zeolites (erionite, chabazite) and even apatite (a calcium-fluoro-phosphate mineral) sometimes occur. This mineral sequence is best illustrated by the results of scanning electron microscopy. (Figures 1-3).

Compositional and mineralogical data will be incorporated in a mass transfer model which will be used to calculate the order of secondary mineral formation and the composition of groundwater in equilibrium with the mineral assemblage. Once a

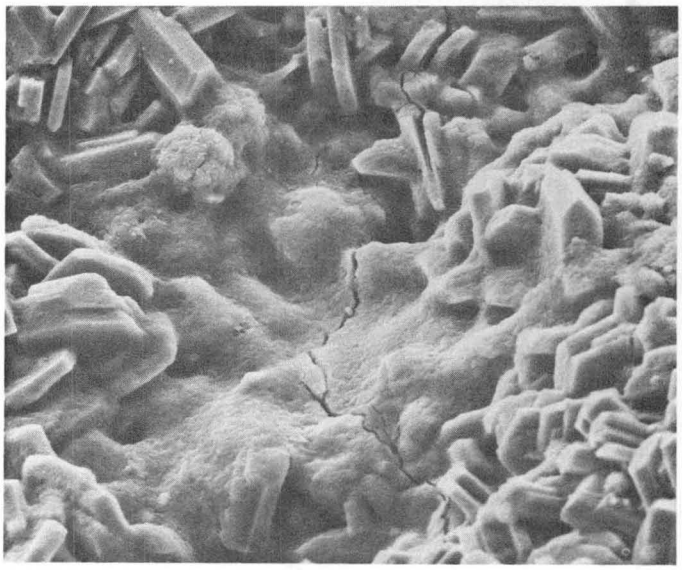

Fig. 3. The interior surface of a vesicle showing spheroidal silica and tabular clinoptilolite coated with a fine-grained mat of nontronite. (DC2 2632 53P 2KX)

successful simulation of the natural geochemical system has been achieved, the effects of the introduction of radioactive waste materials on that system will be studied.

Initial Corcordances with Predicted Stripa Granite Heating Rates

Rock temperatures resulting from application of the 5 kW full-scale heater output at the Stripa mine in Sweden ran close to predicted levels in the first 65 days of operation. Similar concordance was observed in the time-scaled experiment after 90 days operation.

A total of three heating experiments, two full-scale and one time-scale, were started in the summer of 1978 in the granite rock mass at the Stripa mine. The full-scale heating experiments will assess the local effects of thermal loading. These data are needed for the design of an underground nuclear waste repository. The time-scale heating experiments will generate field data on the interaction between heaters and the effect of heating the rock mass during a 2-year period, corresponding to twenty years of full-scale operation.

Full-Scale Experiments

The two full-scale tests use electrical heaters with a 20 kW maximum power output. The heaters are contained in simulated high level radioactive waste canisters measuring 0.3 m in diameter and having a heated length of 2.5 m. The canisters were placed in vertical boreholes 0.4 m in diameter and 5.5 m deep. The boreholes in the floor of the full-scale drift are separated by a distance of 22 m.

The full-scale heater nearest the entrance of the drift is operating at 5 kW power output. This power output is equivalent to that from a canister of reprocessed high-level waste only 3½ years after removal of the fuel from the nuclear reactor. This is likely to be the highest power output of any canister of reprocessed waste that may be buried.

The full-scale heater at the end of the drift is operating at a power output of 3.6 kW, which corresponds to the heating resulting from a canister of reprocessed high level waste 5 years after removal of the fuel from a nuclear reactor.

Time-Scale Experiments

The time-scale experiment utilizes 8 heaters 0.8 m in length placed in vertical boreholes on centers 3 m × 7 m, drilled to a depth of about 11 m below the floor of the time scale drift.

At the beginning of the heating period, the power output of each heater was 1.1 kW, equivalent to 3.6 kW of the full-scale heater. In time, this power output will be reduced to about 0.4 kW, simulating the reduction in thermal output over a period of 20 years of the heat generated by radioactive decay from canisters of high level waste.

To assess the in situ response of the rock mass to heating, measurements are being made as a function of time of temperature fields (with thermocouples), displacements (with extensometers), and stress (with USBM and Irad gauges).

When heat flow is primarily by conduction, the development of the temperature field depends on the amount of heat passing through a given area of the rock, and the power output and geometry of the heat source.

In material that expands linearly with heating, heat induced displacements are a function of the temperature field, the boundary conditions and a factor, D, given by

$$D = \frac{1+\nu}{1-\nu}\,\alpha,$$

where ν = Poisson's ratio, and
α = coefficient of linear thermal expansion.

Heat induced stresses are a function of the temperature field, the boundary conditions and a thermomechanical factor, S, given by the equation

$$S = \frac{\alpha E}{1-\nu}$$

where E = Young's modulus of elasticity. The other terms were defined above.

Predictions were made of the temperature fields, displacements and stresses as a function of time for each experiment using the linear theory of thermo-elasticity and laboratory values for the thermal and elastic coefficients of the granite at Stripa. The laboratory values used are:

Thermal Conductivity	= 3.2 (W/m°C)
Specific Heat	= 837 (J/kg°C)
Density	= 2600 kg/m^3
Thermal diffusivity	= 1.47×10^{-6} (m^2/s)
Coefficient of linear thermal expansion	= 11.1×10^{-6} (/°C)
Poisson's ratio	= 0.23
Young's modulus	= 51.3 (GPa)

In Figure 1 are plotted the predicted isotherms in a horizontal plane through the center of the 5 kW full-scale heater 65 days after heating began. Measured values of temperatures in this plane at various radii and in different directions at that time are also plotted. Measured temperatures are slightly lower than predicted but there is no gross evidence of differential heating along the three axes, nor of heat transfer other than by conduction.

In Figure 2 are plotted predicted isotherms in a horizontal plane through the middle of the time-scale heaters, together with measured temperatures

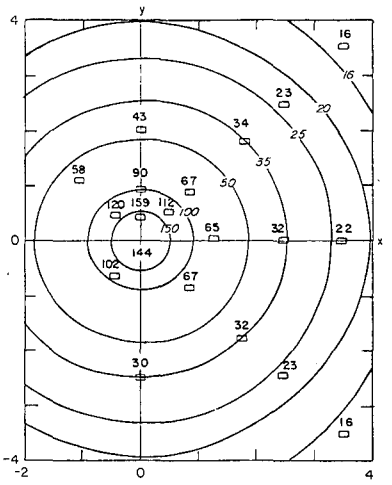

Fig. 1 — Predicted isotherms and measured temperatures in a horizontal plane through the middle of the 5 kW full-scale heater, 65 days after heating had started. (Axes scales are in meters.) XBL 7810-5908

90 days after heater turn-on. Again, there is close agreement between measured and predicted values.

The temperature measurements suggest that heat flow in the rock mass is predominantly by conduction and that theoretical calculations using laboratory values of thermal coefficients can be used to predict rock temperatures reasonably well.

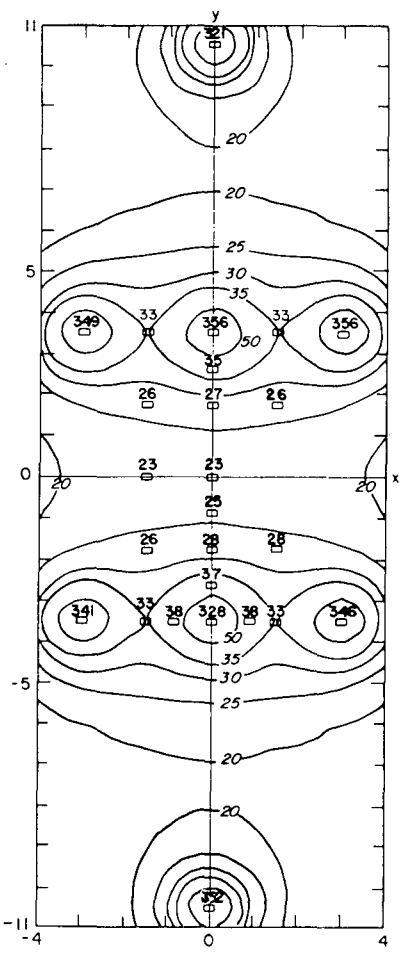

Fig. 2 — Predicted isotherms and measured temperatures in a horizontal plane through the middle of the time-scale experiment, 90 days after heating had started. (Axes scales are in meters.) XBL 7810-5911

Displacement Discrepancies

To date, displacement measurements have yielded puzzling results. Measured values of displacement are all from ½ to ¼ of predicted values, even as both change with time.

Several sources of discrepancy have been considered. Predicted and measured values of displacement have been checked for any consistent error which might explain the disparity; the measured values appear to be accurate. The values of Poisson's ratio and the coefficient of thermal expansion for the rock mass in situ could differ from those used in the calculations by an amount sufficient to account for the observed disparity, but this seems most unlikely. Thermal expansion of the rock mass into open joints would explain the disparity. Initial displacements may be very small, as the thermal expansion of the rock is taken up by spaces between joint surfaces. The discrepancy between measured and predicted values may be expected to vary with the direction of the displacement because of the anisotropy of jointing. Displacement may tend to be discontinuous because of stick-slip caused by friction across joints. More experience with the heating experiments should provide answers.

PUBLICATION UPDATE

(Through November 20, 1978)

Copies of LBL and UCID Reports may be obtained from Joyce Graves, Earth Sciences Reference Room, Building 90.

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LBL-7074 Swan, G. The Mechanical Properties of Stripa Granite. 25 pp. August 1978.

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UCID-8029 Rapier, P. M. Proposed Design for Direct Contact iC_4H_{10} Boiler, 17 pp. June 1978.

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