Summary

The eight papers in this volume cover thoroughly the measurement of rock properties at elevated temperatures and pressures. The authors have summarized the state of the experimental art as well as presented new techniques and results. The first paper by Voegele and Brace discusses the measurement of rock permeability at elevated temperatures and pressures. Small-scale laboratory tests, block tests with controlled boundary conditions, and in situ borehole tests are reviewed. Laboratory observations indicate that permeability is temperature sensitive and that it is affected in many different ways as the temperature increases. Purely physical effects, such as thermal expansion and thermal cracking, are expected and routinely observed. The effects of fluid-rock interactions are at present more difficult to predict, but since they alter the pore geometry through solution or deposition or both, they can profoundly change the permeability coefficient of a sample. The effects of elevated stress on the permeability of rock are of two kinds. First, pore dimensions, particularly the aperture, change with changing stress state, and since permeability is an exponential function of aperture width, the permeability is affected immediately and dramatically. Second, as stress difference is increased, existing fractures are extended and new fractures are formed thus further modifying the permeability. There is some evidence that the effective stress law does not hold for permeability with either hydrostatic compression or triaxial stress. The controlled large-scale tests, while much less numerous, show that the permeability of both natural and induced joints is extremely sensitive to temperature and stress. The existing data suggest that permeability decreases with either increasing stress or temperature. In the tests conducted so far, stress by itself has not been sufficient to reduce joint permeability to that of intact rock.

Zimmerman et al in the second paper, "The Effects of Pore Pressure and Confining Pressure on Pore and Bulk Volume Compressibilities of Consolidated Sandstones," have developed, tested, and present data from a new computer-controlled testing system that allows the measurement of pore and bulk compressibilities of porous rocks at pore and confining pressures up to about 50 MPa. Pore compressibilities were measured for three sandstones: Bandera, Boise, and Berea. The data indicate that the pore compressibility of all three is a function of the effective stress. A physical explanation of this observation is given in terms of the closure of fine microcracks.

In the third paper, "An Experimental and Theoretical Approach to Rock Deformation at Elevated Temperature and Pressure," by Brodsky et al, thermally activated crack growth was studied in Westerly granite triaxial specimens as a function of strain rate and temperature. The specimens were thermally cycled to a temperature above the testing temperature to remove the effects of residual stresses, either latent or thermally induced. Using this procedure, the measurements of temperature dependent deformation should result from thermally activated crack growth during the application of the load, rather than from differences in the specimen's initial microstructure. A combined stress corrosion cracking and fracture mechanics approach was used to model the experimental results. The model predicts time dependent deformation reasonably well but is less successful at predicting temperature and confining pressure dependence.

Senseny's paper, "Determination of a Constitutive Law for Salt at Elevated Temperature and Pressure," is an example of a complete, self-contained evaluation of a particular rock type, in this case bedded salt from the Palo Duro basin in Texas. The form of a constitutive law was proposed that related strain rate, stress rate, stress, temperature, and time. A suite of experiments was designed and run, and the results of the experimental program were used to evaluate the parameters in the constitutive law. This empirically derived constitutive relationship can then be used in numerical analyses to design structures in this particular salt and to predict their performance as a function of the parameters studied. The constitutive law appears however to be valid only for the particular salt tested.

Wawersik in "Determination of Steady State Creep Rates and Activation Parameters for Rock Salt" interprets the deformation of salt from a microstructural viewpoint. The objective is to develop tests that evaluate the coefficients of a constitutive equation that would be valid for all pure sodium chloride. These are difficult measurements as it is not easy to determine in an experiment when and if steady state creep rates have been achieved. Three approaches to steady state creep measurements at low temperature and low strain rate are described. All of them rely on the occurrence of normal and inverse transients following changes in stress and temperature below 120°C. The use of these transient type tests enabled Wawersik to determine close upper and lower bounds of the true steady state creep rates with good reproducibility and little scatter for two natural rock salts. The conclusion from both the experimental and theoretical analysis is that a constitutive law based on the diffusion equation alone cannot describe the low temperature creep of rock salt. The action of multiple mechanisms, including, for example, cross-slip is indicated.

The paper by Christensen, "Measurements of Dynamic Properties of Rock at Elevated Temperatures and Pressures," is a state of the art review of the techniques and equipment used to measure elastic wave velocities as functions of confining pressure, pore pressure, and temperature. Pulse transmission methods are emphasized and the apparatus and test procedures are described. Van Buskirk et al in "Measurement of Thermal Conductivity and Thermal Expansion at Elevated Temperatures and Pressures" describe the development of laboratory equipment and procedures to measure the thermal response of basalt, shale, tuff, and sandstone to 250°C and stresses to 100 MPa. Thermal conductivity at temperature and pressure is determined by a modified "needle-probe" technique. Thermal expansion is measured with an array of linear variable differential transformers (LVDTs) sensing the linear expansion of a cylindrical sample in a pressure vessel. Pore pressure is controlled in each experiment. Some test results are given. The principle advantages of the two pieces of equipment described in this paper are their ability to collect thermal property data at elevated temperatures and pressures with good accuracy and repeatability, and their ability to monitor and control pore fluids during the tests.

The last paper, "Development of a Test Series to Determine In Situ Thermomechanical and Transport Properties," by Hardin et al describes the design and conduct of several in situ heated block tests. The paper discusses the design, preparation, field work, and analysis for heated block tests in Colorado and at the Nevada test site. These tests were performed as "research" experiments with independent control of the state of stress and temperature in blocks having a volume of about 8 m^3. In situ tests are used when it is necessary to perform experiments on features too large to carry into or to simulate in the laboratory. This particular test series demonstrated that it is possible to collect data on the apparent coupling of the effects of independently controlled stress and temperature on the deformation behavior of jointed rock, and on the conductivity of a single fracture to injected fluids.

The papers in this volume have thus come full circle from Voegele and Braces' review of the results of rock permeability tests at all scales, including in situ tests, through the papers describing the various laboratory techniques for measuring mechanical, thermo-mechanical, and transport properties of rock at elevated temperature to the Hardin et al paper at the end on the conduct of large in situ block tests to determine field values for these same properties. This is a rapidly developing area of inquiry, and the past decade's flurry of activity has been driven largely by two very applied national concerns, the production of geothermal energy and the safe underground storage of high level nuclear wastes. Both of the problems require detailed knowledge of the behavior of large masses of fractured rock at elevated temperatures and pressures in the presence of pore fluids. Careful, reproducible, laboratory physical measurements are a necessary first step and may be the only way to separate the action of the important variables. In situ masses of rock, however, often contain features that do not scale easily to laboratory size specimens. Large-scale field tests are therefore necessary to determine the importance and behavior of, for example, hydrothermally altered gouge-filled shear zones. The in situ tests are inherently less "precise" because of the difficulty of even specifying, let alone controlling, the boundary conditions. Nevertheless, safe and effective design of either geothermal energy production systems or nuclear waste storage facilities requires that we perform these tests.

This volume then contains both a review of the development of testing methods for the measurement of rock properties at elevated temperatures and pressures as well as a snapshot of the best current (1983) practice. There are a large number of active researchers in this area at Universities and National Laboratories and in private industry. Continued progress in measurement techniques and in the fundamental understanding of the physical phenomena is to be expected. Another symposium on this subject will probably be appropriate in 5 to 7 years and continued ASTM coordination and support will be most helpful.

Earl R. Hoskins

Department of Geophysics Texas A&M University, College Station, TX 77843-3114; symposium cochairman and coeditor.