ROCK-MECHANICS RESEARCH REQUIREMENTS for Resource Recovery, Construction, and Earthquake-Hazard Reduction

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16. Abstracts
This report is the culmination of a series of studies initiated in 1976 to examine rock-mechanics problems bearing on current, major national needs. The objective of the report is to provide advice and recommendations concerning the needs, requirements, and priorities for rock-mechanics research that is vital to resource development and recovery (mineral and energy), construction (civil works and defense), and earthquake-hazard reduction. In 1978, a Panel and 7 technical Subpanels were organized to consider (1) porosity, permeability, and fluid flow *in situ*, (2) determination of *in situ* stress, (3) mapping of natural and artificial fractures, (4) rock fragmentation—drilling and excavation, (5) scaling test data to field applications, (6) thermophysical, thermomechanical, and thermochemical properties, and (7) numerical modeling. The comprehensive discussion of each topic includes the state of the art, state of need, detailed recommendations for research, and references. The report includes additional chapters presenting an executive summary and a technical summary and conclusions. An index to authors cited and a subject index are also included.

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U.S. National Committee for Rock Mechanics
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

This report, *Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction*, is the culmination of a series of studies initiated in 1976 by the U.S. National Committee for Rock Mechanics (USNC/RM). These studies were undertaken by the USNC/RM in accordance with its constitution, which specifies the functions of the Committee, including the following:

- To initiate and encourage programs and actions directed toward advancing the science and technology of rock mechanics and their effective application;
- To collect and disseminate technical information related to rock mechanics, including current research, interdisciplinary developments, and innovative programs.

BACKGROUND

During calendar years 1976 and 1977, three *ad hoc* Panels of the Committee examined rock-mechanics problems bearing on current, major national needs. These were the Panel on Rock-Mechanics Problems That Limit Energy-Resource Recovery and Development, the Panel on Rock-Mechanics Problems Related to Underground Construction and Tunneling, and the Panel on Rock-Mechanics Problems Related to Seismology and Earthquake Engineering. The work of each Panel was considerably more detailed than its title indicates. For example, the first Panel was composed of Subpanels on exploration for and production of geothermal energy, mining and *in situ* recovery, nuclear-waste disposal, oil and gas recovery, underground storage of fluids (oil, gas, water, compressed air), and under-ocean tunneling for petroleum recovery.

At its annual meeting in June 1977, the USNC/RM discussed the reports* of the three Panels and concluded that the following research in rock mechanics is critical:

- Determine and predict porosity, permeability, and fluid flow *in situ*;
- Develop better methods for determining shallow and deep *in situ* stresses;
- Improve the ability to map fracture patterns, particularly major fractures and faults, at depth;
- Improve the understanding of rock-fragmentation processes for increasing the effectiveness of drilling and excavation systems;
- Increase understanding of the relation of laboratory-measured quantities to *in situ* conditions;
- Provide thermophysical, thermomechanical, and thermochemical properties of rock, including fractured rock.

Although not technological research *per se*, the USNC/RM also identified the need for advances in numerical modeling. Mathematical models are valuable for their ability to simulate complicated engineering situations at a small fraction of the cost of full-scale tests. They are the only means for predicting effects of very long duration, say thousands of years. However, computer simulations should be capable of validation; although millions of dollars are spent on such simulations, their adequacy to handle realistic boundary conditions and constitutive equations of state has been open to serious question.

None of these research needs is restricted to a single resource or construction problem, and each of the three *ad hoc* Panels clearly identified more than one research need. For example, ineffectiveness in mapping fractures and in predicting porosity and permeability of rock masses *in situ*, or as modified by processes such as hydraulic fracturing,

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*U.S. National Committee for Rock Mechanics (1978). *Limitations of Rock Mechanics in Energy-Resource Recovery and Development*, National Academy of Sciences, Washington, D.C., 67 pp.

U.S. National Committee for Rock Mechanics (1978). "Rock-Mechanics Problems Related to Underground Construction," in *Report for 1977—U.S. National Committee for Rock Mechanics*, National Academy of Sciences, Washington, D.C., pp. 7-14.

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has adverse effects on many energy-resource recovery and storage activities. These problems seriously affect programs for maximizing production of oil and gas from known reserves, for developing geothermal-energy resources, and for storing energy-producing products in aquifers. Problems in determining *in situ* stresses, in developing cost-effective rock-fragmentation systems, and in understanding the thermophysical and thermomechanical behavior of rock all have serious consequences in the mining of coal and in the storing of energy-producing products in underground cavities. These problems, as well as those of determining porosity and permeability, must be confronted in the high-priority, national program for long-term storage of waste from nuclear power plants.

Other national programs adversely affected by the same rock-mechanics problems that limit energy recovery are those involving extensive underground construction. These include waste-water collection and treatment facilities, such as the multibillion dollar Tunnel and Reservoir Plan (TARP) being constructed by the Metropolitan Sanitary District of Greater Chicago, and major underground transportation systems, such as those under way in Washington, D.C.; Atlanta, Georgia; Baltimore, Maryland; Boston, Massachusetts; and New York City, New York. In addition there are several high-priority, national-defense programs for which these problems are significant.

The rock-mechanics problems affecting both the energy and underground-construction programs are also of concern in the current national programs in seismology and earthquake engineering; in particular they are important in both earthquake-hazard mitigation and earthquake prediction. These problems include determining *in situ* stress conditions and fracture and fault-zone properties and understanding the relation of laboratory-measured quantities to field conditions.

METHODOLOGY

In 1978, a Panel was organized to study past and current research in rock mechanics and to identify opportunities for further research in the seven areas determined to be critical from the *ad hoc* Panel reports. The study was focused on those needs affecting energy- and mineral-resource development, construction (both civil works and defense), and earthquake-hazard reduction.

Subpanels were formed to consider each of the areas previously identified; they were composed of volunteer members having specialized experience in the designated technical subject. Each Subpanel was assisted by one consultant (typically) whose assignment, full-time for a period of one to two months, was to survey the state of the art in the subject area and to write a draft report for the Subpanel's consideration. The work of the Subpanels was coordinated by a Steering Group and Study Director working closely with the Secretariat of the USNC/RM.

The activities of the 45 Panel members span a wide range of interests in rock mechanics—19 are from academic institutions, 13 are from industry, and 13 are from national laboratories and government agencies.

The members from academia represent 12 universities and the fields of civil engineering, geology, tectonophysics, petroleum engineering, geophysics, mechanical engineering, mining engineering, and material science. The members from industry also represent a diverse group of interests: employers include oil companies, independent laboratories, engineering and consulting firms, and a large chemical manufacturer. The members from national laboratories and government agencies include employees of the U.S. Geological Survey, the Bureau of Mines, the Corps of Engineers, Lawrence Livermore National Laboratory, Los Alamos Scientific Laboratory, and Sandia Laboratories.

Of the eight consultants, seven are university professors and one is a government employee who served without compensation. The professors represent six institutions, only two of which are the academic homes of Panel members.

With general guidance from and periodic review by the Steering Group, the Subpanels organized and conducted their individual technical studies in the manner they felt to be most suitable. However, recognizing a need for communication and coordination among the Subpanels, the Steering Group encouraged the Subpanel members to attend each others' meetings, as appropriate, and to establish and maintain liaison. Several meetings of Subpanel Chairmen were held during the course of the study, as were meetings with representatives of government agencies. In addition, throughout the study the Subpanels actively solicited the views and needs of potential users—scientists, engineers, and administrators in government, industry, and universities.

Following completion of initial draft reports, a workshop was held in February 1980. Of the 41 people who attended, 17 participated as representatives of federal agencies and other interested organizations. The remaining participants included the Steering Group, Subpanel Chairmen and consultants (or their representatives), and officers of the USNC/RM. The workshop provided an opportunity for critical discussion and review of the draft reports of the Subpanels. The drafts were revised as a result of suggestions made at the workshop and subsequently distributed for review and comments by the membership of the USNC/RM. The full Committee discussed the report at its May 1980 annual meeting, and the draft then was revised accordingly. The Committee and the Panel reviewed and approved the final draft of the report.

It should be emphasized that the study leading to this report was a sequel to a series of earlier studies and that the research areas selected for discussion herein were derived from conclusions developed in those studies on energy-resource recovery, underground construction, and earthquake-hazard mitigation. Therefore, the exclusion of other research needs in rock mechanics is not necessarily an indication that they are less important than the research needs presented in this report.

Acknowledgments

The members of the Panel on Rock-Mechanics Research Requirements acknowledge with gratitude the contributions of many more individuals than can conveniently be listed here. Many colleagues gave helpful advice and suggested improvements in the report; the writings of others were consulted in reviewing the state of the art, and their names appear in the references cited. The Panel particularly wishes to thank those participants in the workshop who were not part of the study team but who took the time to review the draft report and offer constructive criticism. Their names are listed in Appendix A.

The study was supported by three government agencies—the U.S. Geological Survey (USGS), the U.S. Department of Energy (DOE), and the National Science Foundation (NSF). Without neglecting in any way the many persons in these agencies who aided the Panel, several individuals merit special acknowledgment for their particular support and encouragement: J. Linn Hoover, Bruce Henshaw, and Rachel M. Barker of the USGS; Donald L. Vieth, Alex B. Crawley, and Harold E. Thomas of the DOE; and S.C. Liu and William W. Hakala of the NSF.

The eight consultants who participated in the study have earned the Panel members' appreciation for their research, preparation of preliminary drafts, and assistance in preparation of the final report. The Secretariat staff also supported the Panel's effort with diligence and abundant understanding throughout the study.

The Panel expresses its sincere appreciation to all the participants and the sponsors for their interest in and support of the study.

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Executive Summary

Rock mechanics is the theoretical and applied science of the mechanical behavior of rock and rock masses; it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment.* The purpose of this study is to review the current state of knowledge and practice and to identify deficient areas in which research is required to advance understanding of the science of rock mechanics, so as to enable successful resolution of the vital issues of energy and resource recovery, construction, and the mitigation of earthquake hazards.

At present, the state of knowledge in rock mechanics varies widely. A few principles are understood completely, but much of the understanding is phenomenological or qualitative, and theories frequently are based on insufficient data. Important disparities between experiment, theory, and field experience are recognized but not fully understood.

The United States is committed, and will become increasingly so, to major projects involving rock masses at the earth's surface or in the subsurface. Examples of such projects include conventional and novel methods for the production of fossil fuels and chemical feedstock, the disposal of radioactive wastes in deep geologic repositories, underground excavations for the storage of strategic reserves of oil, the construction of

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*As defined by the Committee on Rock Mechanics (1966), modified by adding the term "rock masses." Rock mass refers to rock as it occurs *in situ*, including its structural discontinuities (International Society for Rock Mechanics, 1975).

dams, the mitigation of hazards from earthquakes, and defense projects. The economic and safe execution of these projects is vital to the national welfare and security. To a significant extent, the success of each project depends on an adequate understanding of the behavior of the rock masses that it will affect.

In general, present knowledge of the behavior of rock masses is not of the quality or certainty normally required for good engineering practice. The difficulty of resolving rock-mechanics problems deserves emphasis. Rock masses are heterogeneous in composition, fabric, and water content. "Because of the multiplicity of the processes involved and the long geological times in which many of the deposits have been altered physically and chemically, these materials are incredibly complex..." (Peck, 1980).

In its three previous studies, the U.S. National Committee for Rock Mechanics (1978) considered the extent to which the current understanding of the behavior of rock masses severely limits the ability to complete projects of national interest in a proven safe, economical, and environmentally acceptable manner. These studies identified inadequacies in the following areas:

- The measurement and prediction of porosity, permeability, and fluid-flow properties *in situ*;
- The determination of *in situ* stresses near the surface and at depth;
- The delineation of fracture patterns at depth, and particularly beyond the exposed surfaces of boreholes and tunnels;
- Understanding of the processes of rock fragmentation;
- Understanding of relations between the values of properties measured in laboratory experiments and those of the corresponding properties of rock masses *in situ*;
- Knowledge of the thermophysical, thermomechanical, and thermochemical properties of rock, both in the laboratory and *in situ*;
- The proper use of numerical models to simulate the behavior of rock masses *in situ*.

In this study, seven Subpanels of experts assessed the current state of knowledge in each of these areas and recommended the research that should be undertaken to reduce or eliminate deficiencies. Each Subpanel formulated its recommendations in response to the following questions:

- Why is an understanding of the behavior of the rock mass relevant?
- To what extent is the current state of knowledge sufficient to resolve practical problems?
- What research is needed most critically to ensure the success of national goals?
- What research, or other activities in rock mechanics, is necessary to bridge the gaps in our understanding that currently impede the achievement of these goals?
- What specific research in each area is most necessary?

From the search by the Subpanels for answers to these questions, the following major research areas were identified:

- The development of *in situ* techniques for the measurement of the hydraulic properties of discontinuities, especially in rocks of very low permeability and porosity and at high pressures and temperatures;
- The development of improved methods for determining *in situ* stresses, particularly on a regional scale and at high pressures and temperatures;
- The development of methods for detecting discontinuities remotely, for analyzing them in three dimensions, and for determining their effects on the hydraulic and mechanical properties of rock masses;
- Studies of rock fracture, particularly fracture propagation resulting from explosives, mechanical forces, and fluid pressures;
- The resolution of the disparities that appear to exist between the results of laboratory and field tests, of the effects of scale on rock properties, and of methods for the *in situ* measurement of the properties of rock masses;
- Research into the dynamic properties of rock and their significance in the interpretation of seismic data relating to earthquakes;
- Improved understanding, through laboratory and field studies, of the thermochemical, thermomechanical, and thermophysical properties of rocks;
- The development of numerical models to handle realistic problems including three dimensions, large strains, fracture propagation, instability, and the effects of discontinuities, as well as the coupling of simultaneous effects of thermomechanical, fluid-flow, and thermochemical processes.

Although the Subpanels endeavored to assess costs, time, manpower, and appropriate funding agencies, these matters were generally beyond their scope because their specific recommendations are essentially technical rather than administrative. Nevertheless, certain common themes emerged from the several sets of recommendations, and the Steering Group has discussed these with the U.S. National Committee. As a result, the Steering Group offers the following observations:

- The current lack of understanding of rock-mechanics principles constitutes a serious impediment to the nation's ability to execute projects vital to its welfare, security, and defense.
- Expenditures for rock-mechanics activities within the United States in 1978 have been estimated as $80 million to $100 million from the federal government and $25 million to $50 million from private industry; these figures exclude costs of drilling, excavation, and construction and other expenditures such as hardware, legal services, and environmental measures. Only about 5 percent of these monies was spent on fundamental research, and this expenditure has not proved to be sufficient to advance the science to the point of routine application in engineering practice (Green, 1979).

- There are pressing needs for large-scale laboratory tests and for more field testing to advance the science of rock mechanics in all areas treated by the Subpanels.
- Increased funding for rock-mechanics research is necessary from both industry and government, but it must be recognized that major support will have to come from the federal government.
- Many major engineering projects involving rock masses are under way, and a small increment in funding could readily enable field tests to be piggybacked on these projects, obviating the need for many otherwise prohibitively costly experiemnts.
- Funding for fundamental research in rock mechanics should be doubled from about 5 percent at present to about 10 percent of the total that is budgeted nationally for rock-mechanics activities. Although this would increase the funding for fundamental research in rock mechanics substantially, additional funding to the extent of about an order of magnitude, in constant 1980 dollars, is needed progressively over the next 5 years.

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2

Technical Summary and Conclusions

INTRODUCTION

The objective of the work described in this report is to provide advice and recommendations to the federal government, industry, and academia concerning the needs, requirements, and priorities for rock-mechanics research. The approach adopted to achieve this objective was to identify areas in rock-mechanics research vital to the success of national projects concerned with resource recovery, construction, and earthquake-hazard mitigation. The topics addressed by the seven Subpanels of experts were derived from conclusions reached as a result of three earlier studies by *ad hoc* Panels of the U.S. National Committee (1978). The recommendations of the Subpanels are almost entirely technical, with emphasis on the knowledge needed for successful engineering applications. It was not feasible to cover all aspects of rock mechanics, for example, structural geology.

The evolution of rock mechanics in the United States can be read by comparing the findings of a previous National Academy of Sciences report on rock-mechanics research (Committee on Rock Mechanics, 1966) with those of this report. The earlier report cited the case for more widespread application of rock mechanics together with a supportive research effort. Later, as the many shortcomings of the subject were recognized fully, the inadequacy of present understanding as a basis for engineering design became apparent. This report identifies the current shortcomings and the need for a more adequate fundamental understanding of rock mechanics to ensure the success of national projects. Interestingly, both reports stress the need for more field and laboratory measurements than have been accomplished thus far.

A review of the support for rock-mechanics research shows that industry contributes relatively little. Furthermore, because of its special requirements and priorities, industry is unlikely to increase its support significantly in the future. However, this Panel's recommendations provide industry with guidance on needed research efforts.

In considering federal government support for rock-mechanics research, it is prudent to note that rock mechanics itself is not generally an end product. For example, the production of oil or gas and the isolation of nuclear wastes are the end products. Furthermore, experts well versed in the projects should be aware of the significance of rock mechanics in resolving the problems. Because rock mechanics is a step in the process and not the end product, these recommendations were formulated after two Panel reviews had been conducted. The first, involving representatives of federal agencies, was less technical and aimed at an overview of national problems; the second, reported here, is highly technical and defines specific rock-mechanics research tasks. These tasks are presented primarily as goals, and, as with much fundamental research, new findings will modify these goals.

The findings of each Subpanel are summarized in the following section. Afterwards, the Steering Group synthesizes the major recommendations and provides additional commentary.

FINDINGS OF THE SUBPANELS

Porosity, Permeability, and Fluid Flow *in Situ* (Chapter 3)

Considerable progress has been made in developing techniques for measuring porosity, permeability, and fluid-flow properties *in situ* for nonfractured, porous rock. To a lesser extent this is true also for fractured, porous rock. Only recently, however, has it become necessary to measure these properties in nonporous rocks with extremely low permeability (<1 nm^2). It is clear that *in situ* techniques for measuring permeability and other fluid-flow properties have lagged behind those for measuring porosity. The variation of porosity, permeability, and other fluid-flow properties with changes in applied stress and temperature are not clearly understood, especially for low-porosity rock masses with extremely low permeability. In particular, the development of geothermal and other resources is hindered by a lack of geophysical borehole sondes capable of withstanding high temperatures and pressures. General agreement still has to be reached on tests for the measurement *in situ* of properties such as dispersivity and the distribution coefficient.

The Subpanel's recommendations, along with brief supporting comments, are as follows:

- *Develop methods to determine the orientation and continuity of fractures away from a borehole or other free surface.* Measurements of permeabilities and fluid-flow properties made *in situ* from a borehole apply only to a limited volume of rock surrounding the borehole. Because the presence of fractures often controls the permeability, it is important to know the fracture orientation and continuity away from the borehole (Chapter 5). The ability to determine fracture orientation and continuity away from a borehole may be of considerable aid in enhancing the use of hydraulic fracturing for oil and gas recovery and in developing geothermal resources. It will also be of significant value in predicting the movement of fluids in rocks of low permeability surrounding underground repositories for the disposal of hazardous wastes and storage caverns for hydrocarbons and other fluids.

- *Obtain field case-history data on well tests in porous, fractured and in nonporous, extremely low-permeability rocks, and conduct or establish field tests in similar rock masses, to gain a better understanding of permeability and other fluid-flow properties.* Few case histories have been reported for well tests in porous, fractured rock and in rocks of low porosity. Case histories and the establishment of field tests (Chapter 7) are required to develop techniques for determining permeability and other fluid-flow properties and for validating interpretative models (Chapter 9). Field tests are needed to provide the data essential to understanding fluid-flow properties in such rocks. Work at new field-test sites can be piggybacked, as needed, with stress-measuring and fracture-mapping programs.

- *Develop a more thorough understanding of the effects of changes in stress and temperature on pore compressibility in porous, sedimentary rock.* There are uncertainties in interpreting transient well tests in such rocks. A thorough understanding of the stress and temperature dependence of pore compressibility is of importance in making decisions about the economies of enhanced recovery in the oil industry and in deciding the water-producing potential of aquifers.

- *Develop proper methods for determining* in situ *the dispersivity and distribution coefficient for fluid flow and for relating laboratory measurements of these quantities to those measured in the field.* There is yet no general agreement on how these quantities should be measured *in situ* and how such measurements should be related to those made in laboratories. The resolution of this issue is important for the underground storage of nuclear waste and other hazardous fluids and in certain enhanced-recovery techniques, such as polymer flooding in the oil industry.

- *Develop methods to distinguish between granular and fracture porosity in porous, fractured rock masses.* Permeabilities and other fluid-flow characteristics differ markedly between rocks with granular porosity and those with fracture porosity. The ability to identify the two types of porosity is necessary to predict fluid flow in rock masses.

- *Design geophysical borehole instruments to measure permeability and porosity in environments of high pressures and temperatures.* It is necessary to develop borehole logging techniques to permit successful measurement *in situ* of permeability; such techniques lag far behind those for measuring porosity *in situ*. Based on experiences in drilling boreholes in connection with enhanced oil-recovery projects, geothermal-energy development, and coal gasification, instruments for use at high pressures and temperatures are required.

Determination of in Situ Stress (Chapter 4)

An understanding of the mechanical response of rocks to surface and subsurface engineering activities and to tectonic adjustments is necessary for predicting deformation or potential instability (failure) in the rock. The response of the rock mass during excavation and construction depends in large part on the *in situ* stress field, the knowledge of which is important in assessing new engineering projects such as extraction of geothermal power, *in situ* coal gasification, and storage of high-level radioactive waste. Finally, tectonic activity giving rise to earthquakes is controlled by a regional stress field, which is incompletely known at best.

Substantial advances in the measurement of *in situ* stresses have occurred in the past 20 years. However, the present technology is not adequate to match the needs of good engineering practices, particularly those requiring knowledge of stresses in deep or remote locations, in inelastic rocks, or in hot or corrosive environments.

A major problem faced by researchers in stress measurements is the lack of adequate data sets, particularly in complicated geologic settings. More data would be available if the values of stresses could be determined more readily than at present. This could be achieved by making installation methods in the field and instrument performance more reliable and by reducing the drilling costs per measurement.

The recommendations, including supporting comments, are as follows:

- *Improve data-reduction methods to take account of discontinuities, time-dependent strain, and hysteresis in cyclic loading.* The inference of a stress level from strain-relief or hydrofracturing measurements requires an accurate method for converting these measured quantities to stress. In strain-relief methods, this step is straightforward only in rocks that respond reproducibly and elastically. Despite its widespread use, hydrofracturing is not a fully understood physical process; thus the data reduction for this procedure remains uncertain.
- *Improve understanding of coherence among measurements in space and time.* The lack of consistency among stress measurements in a small area, at varying depths, at different times, or with different instruments, makes all such measurements suspect. The degree of coherence among measurements may be a function of local lithology, the presence of discontinuities or naturally stress-relieved areas, or the ability of particular techniques to yield accurate values dependent on the local conditions. If these factors were understood better, measured values of stress could be used more effectively.
- *Refine methods of monitoring stress changes with time.* Present methods show great promise, but new engineering problems will require sensitive, highly stable instruments capable of recording changes over periods of tens of years. Nonmechanical methods may be needed.
- *Develop the technology to permit determination of stress at high temperatures and in hostile environments.* The measurement of stresses at high temperatures clearly is needed in geothermal-energy recovery and nuclear-waste isolation.

- *Refine or develop alternatives to* in situ *stress measurements to detect instability or predict imminent failure.* Many rock-mechanics applications of *in situ* stress measurements could benefit from alternative methods of predicting rock-mass behavior. For example, research into acoustic emission shows some success in predicting rock failures. Convergence and other strain-monitoring techniques can be used directly to monitor rock movements and deformations and for some problems can eliminate entirely the need for stress data.
- *Improve characterization of the* in situ *mechanical properties of the rock mass.* A fundamental requirement of the data-reduction process is accurate characterization of the *in situ* properties of the rock mass itself (Chapter 7). Elastic and inelastic properties, the effects of discontinuities and heterogeneities, and the changes in these properties with drilling, stress relieving, or pressurizing are all important considerations. However, at present these effects can be measured only crudely and are understood but poorly.
- *Improve measurement of pore pressure at depth and methods of evaluating its role in the total stress measurement.* Pore-pressure measurements are extremely difficult to make at depth, especially in rocks with very low permeability (Chapter 3). Measurements in such rocks are sensitive to the particular method used, and mere drilling of the access hole may affect pore pressures in the adjacent rocks. Effective stresses may determine mechanical behavior and stability, but there is a serious deficiency in current knowledge.
- *Use long-baseline methods of mapping regional stress patterns.* Present methods of mapping stress fields depend on local measurements, which are then extrapolated to map regional patterns. The validity of this extrapolation is questionable, particularly if coherence among closely clustered measurements is poor. Some regional stress patterns might be obtained better from regional rather than "point" strain measurements. Alternative methods of obtaining regional stress fields from geodetic-type measurements should be explored.
- *Develop reliable geophysical methods for obtaining information about the state of stress in remote volumes of rock.* Many geophysical measurements contain information about the state of stress. A proper understanding of these phenomena might permit nondestructive, remote measurements of stress, particularly at great depths and throughout large volumes of rock. Because the effect of stress on most geophysical measurements is of second order, much research will be needed to tell whether reliable methods can be developed at all. However, the rewards of success would be well worth the effort; geophysical methods most likely will be the only tools for evaluating stress conditions at great depths, or at sites where drilling is limited or precluded by economic or possibly design requirements, or where the installation of measuring devices can be expected to alter the ambient stress field. Even near-surface engineering and construction projects would benefit substantially from an improved ability to make stress measurements more than 50 m from an open working surface.

Mapping of Natural and Artificial Fractures (Chapter 5)

The mechanical and hydrological behavior of large masses of rock is governed principally by natural fractures. Examples of projects in which fractures are important are emplacement of nuclear-waste repositories, which should be in rock masses with extremely low hydraulic conductivity; construction of transportation tunnels and power-plant caverns and the operation of mines, which are safest in rock masses least disturbed by fractures; and economic recovery of geothermal energy, which depends on the interconnection of fractures between adjacent wells.

Fractures should be mapped in three dimensions. Surface mapping provides only shallow three-dimensional data on the fractures in a rock mass, and borehole contact methods detect only the fractures that intersect the borehole. Therefore, a representation of the fractures in the entire volume of the rock mass is constructed by extrapolating and interpolating from surface and borehole data and/or employing geophysical methods. Interpolation, extrapolation, and remote sensing are often neither accurate nor precise and require considerable improvement for predicting patterns of fractures or single fractures in a large rock mass.

Several recommendations, and supporting comments, are as follows:

- *Develop methods for the reliable detection of fractures at depth.* The greatest need lies in developing methods to detect and describe fractures in the large volumes of rock beneath outcrops and between boreholes or other underground openings. Geophysical methods for fracture detection between boreholes, derived largely from the oil industry, tell us at best only how densely the rock is fractured. Future work requries the ability to detect single fractures; this will entail development of new, high-frequency wave-propagation techniques, coupled with computer modeling.
- *Develop exploration-planning and interpretation procedures based on analytical models of fracture patterns.* Increased use of analytical models representing the stochastic nature of fracture patterns must be brought about by improvements in existing models, development of new models, and further application of modeling techniques. They will lay the groundwork for developing rational approaches to exploration planning and to interpretation of exploration results. Interpolation and extrapolation of results can then be put on a firm analytical basis to include the assessment of the remaining uncertainties.
- *Develop efficient procedures for the acquisition, processing, and display of three-dimensional fracture data.* This will involve processing large amounts of data and will require improved or new methods of aquisition, processing, storage, and modeling. Advantage should be taken of advancements in interactive computer graphics and color displays.
- *Develop reliable methods to determine the hydraulic conductivity of fractures.* Some ideas of the persistence and interconnection of fractures can be gained by using electrical-conductivity methods. However, the results are not satisfactory, and alternative methods of determining the hydraulic conductivity of fractures in rock masses are needed urgently.

• *Develop ground-truth sites and conduct associated experiments; evaluate fracture-mapping techniques in controlled laboratory-scale experiments.* New methods for mapping fractures will have to be validated in the field. A variety of geologic structures and materials should be used in this work. Physical modeling and verification (Chapter 7) and numerical modeling (Chapter 9) would be essential components of such investigations.

Rock Fragmentation—Drilling and Excavation (Chapter 6)

The depletion of easily accessible natural resources and continuing demands for energy and minerals, as well as the need for alternative sources of energy and minerals, require innovative or more efficient methods of recovery and the development of new technologies. Current support from industry is limited to those activities that promise immediate success and early return on investment. High-risk ventures receive little support, even though they may hold great promise for the future. Although fracture mechanics in other branches of science and engineering has received generous support, research into fracture-propagation problems associated with rock fragmentation has not.

The recommended research, and supporting comments, are as follows:

• *Improve prediction and control of fracturing in drilling and excavation.* The study of fracture initiation must be extended to include fracture propagation and rock fragmentation, the morphology of fractures, and the relevant activation processes. Proper constitutive equations for rock fracture are required for numerical modeling of processes and for controlled fracture propagation in presplitting and well stiumlation, and fracturing in caving and subsidence.

• *Refine controlled blasting techniques.* Included here are such diverse problems as the limitation of damage to residual rock structures, the preparation of high-permeability rubble beds for *in situ* processing, and quantitative analysis of the effects of discontinuities in rock fragmentation.

• *Improve understanding of explosive/rock interactions.* The relative importance of the effects of dynamic loading by stress waves, fracture propagation, and gas pressures on rock fragmentation is known empirically but not understood fundamentally. Improvements and new applications require a firm, scientific understanding of these factors.

• *Improve understanding of tool/rock interactions.* Drilling at depths at which stresses and temperatures cause the rock to become ductile presents serious difficulties. On the other hand, the effectiveness of drilling or excavation in hard rock is limited by tool wear. Tool/rock interactions require greater understanding for efficient work in rock of all types and under hostile conditions.

• *Improve understanding of high-pressure fluid/rock interactions.* Of all the exotic or novel methods of rock excavation, high-pressure fluid jets offer the most promise, either alone or in combination with mechanical fragmentation. The processes of rock excavation by fluid jets are not sufficiently understood to support optimal design.

Scaling Test Data to Field Applications (Chapter 7)

Determination of the properties of rock masses by field tests is time consuming and costly; often there is wide scatter in test results. Laboratory tests are used frequently because of their low cost and low scatter. However, the removal of the samples from the natural environment for laboratory testing disturbs them and may significantly alter their mechanical behavior. In addition, the nature of discontinuities under *in situ* conditions may be quite different from that in laboratory samples. Further research is needed because there are no well-understood procedures by which laboratory data can be used to predict reliably the behavior of rock masses *in situ*. Until laboratory and field behavior of rock is better understood, prediction of the performance and safety of projects in rock masses by numerical modeling will not be reliable (Chapter 9).

In situ rock-mass characteristics that are of particular importance include the modulus of deformation or elasticity; compressive, shear, and tensile strengths; frictional properties; bearing capacity; postfailure modulus; precursive seismic phenomena; hydraulic conductivity and storage; thermomechanical properties; and anelastic behavior.

The study of earthquakes can be divided into three major research areas: the earthquake source, the transmission path, and site dynamics. At the earthquake source, factors of importance include the *in situ* state of stress, fluid pressure, and the physical mechanism of faulting. The transmission path determines the character of the seismic energy at a specific site. Site dynamics are important because damage may result from the local ground response; landslides, rockfalls, and other types of failure may be induced.

The many current underground projects for nuclear-waste disposal, compressed-air storage, power-plant location, and other purposes provide a valuable opportunity for large-scale field tests in rock mechanics.

Recommendations, with brief supporting comments, are as follows:

- *Perform large-scale tests and monitor prototype structures.* Such tests would enable determination of the physical properties and behavior of large volumes of jointed rock under various conditions of stress, moisture, and time. The values obtained could then be compared with those expected from laboratory tests using predictive numerical models. Only in this way can current shortcomings be identified and numerical models be validated.
- *Conduct both theoretical and field tests to determine the practicability of engineering geophysical methods for assessing* in situ *properties of the rock mass.* For example, the "petite sismique" method is particularly promising for *in situ* studies of deformability. The utility of such methods should be determined by both theoretical and field studies.
- *Develop methods for scaling rock-mass deformability, frictional properties, and permeability.* Laboratory experiments constitute the only

practical means of obtaining, at acceptable costs and within a reasonable period of time, many of the data needed to understand the behavior of rock. However, major disparities are known to exist between the behavior and properties of rock masses and those of the same rock in small-scale laboratory experiments. These disparities must be understood and resolved. Such a resolution can be derived only from a better understanding of the chemical and physical processes that give rise to the phenomena observed.

- *Conduct theoretical and field studies to develop methods to learn more about earthquake-source parameters from teleseismic signals.* Factors of importance are the *in situ* state of stress, fluid pressure, and the physical mechanism of faulting. Additional considerations include premonitory slip, redistribution of strain after faulting, and influence of fault geometry on the radiation pattern.
- *Develop laboratory techniques to measure dynamic rock-mass properties and earthquake-source parameters.* Tests should be carried out on discontinuities, within large rock specimens subjected to defined and controlled conditions of stress, fluid pressure, and temperature, and at strain rates appropriate to the processes of seismogenic faulting.
- *Develop laboratory and* in situ *procedures for determining the thermomechanical properties of rock.* Such properties are important in nuclear-waste disposal and in the development of geothermal-energy sources (Chapter 8).
- *Develop numerical techniques for estimating rock-mass response to static and dynamic loads, within a probabilistic framework.* The probabilistic approach is necessary because the data sampled represent a small fraction of the parent population of rock-mass properties (Chapter 9).
- *Conduct physical modeling, using techniques such as centrifuge and shaking table to study rock dynamics.* Uncertainties remain in verifying the relation between centrifuge tests and actual field situations and in applying realistic dynamic loads. Shaking tables can be used for evaluating models of rock slopes and rock/reinforcement interaction. Effects of fatigue on mechanical properties of joints and faults require study.
- *Develop methods for assessing the* in situ *strength of rock masses.* Data on the compressive strengths of rock masses would be useful in the design of mine pillars; data on shear strength would be helpful in the design of rock slopes, foundations, and dam abutments.
- *Develop techniques for assessing postfailure characteristics of rock masses.* In many situations, particularly mining, safety depends on the stability of failed rock rather than on strength. This concept was recognized experimentally only during the past decade and needs further research to be understood and used properly.
- *Develop techniques to assess rock-mass/reinforcement and rock-mass/structure interactions.* Methods applicable to jointed rock, especially when subjected to strong dynamic loads, have yet to be developed.

Thermophysical, Thermochemical, and Thermomechanical Properties (Chapter 8)

The need to deal with the effects of high temperatures is relatively new to engineering rock mechanics. In geothermal-energy exploration and production, questions arise about thermal effects on mechanical processes in reservoir rocks, especially thermal fracturing and hydrofracturing. *In situ* recovery of energy from coal, oil shale, and tar sands requires evaluation of high-temperature effects on compositionally complex sedimentary rocks, especially with respect to porosity and permeability. Tertiary recovery of conventionally reservoired oil may utilize hot water or steam, and the affected rock properties need study to optimize project design. Radiogenic heating of rock masses by the deep, geologic disposal of high-level nuclear waste may result in thermal stresses and cracking of the rock. Creep is expected to occur at moderate temperatures in rock salt if this rock is used as a host in a nuclear-waste repository. In underground storage of fuel oil, gas, water, or compressed air, thermal cycling and shock to the rocks during emplacement and removal of the products may create unwanted cracks and leakage paths. The thermochemical and thermomechanical properties of rock are also important to waste-fluid injection and to the processes of seismogenic faulting.

The lines of research that seem to be most promising are the following:

- *Investigate thermophysical properties.* The effects of temperature depend on the intensive parameters of state (the absolute pressure, temperature, and chemical potential), on the sources of heat, and on the thermal properties of the rocks. Properties such as compressibility and thermal expansion are temperature dependent. Thermophysical properties include the important intrinsic ones of thermal conductivity, diffusivity, and expansion and others such as the effects of temperature on the elastic moduli, porosity, and permeability. In particular, research is needed into the fundamental chemical and physical processes that result in the measurements and observations made in laboratory experiments, so that these measurements can be used correctly in the design of field projects.
- *Investigate thermomechanical properties.* Little is known as yet about the thermomechanical properties of discontinuous rock masses and the effects of artificial thermal cracking on these properties, particularly strength and permeability. For example, effects as important as those of discontinuities on the elastic moduli and on the hydraulic conductivity of rock do not have a common, self-consistent explanation. Especially wanting are creep data on all rocks, except salt, under shallow crustal conditions. Time-dependent deformations involve thermally activated processes such as stress-corrosion cracking and diffusion, which deserve much more study.
- *Investigate thermochemical properties.* The interactions of heat and the physical and chemical properties of rock and their fluids are complex; they are predictable only under equilibrium conditions using thermodynamic functions of state for known mineral and fluid phases of

known compositions. Chemical reactions and mass, momentum, and energy transport are thermally activated, and such kinetic processes need more study. Of special interest is the thermochemistry of hydrous clay minerals and zeolites and their amorphous precursors, the solubilities of mineral phases subject to pressure, and the accompanying reductions of permeability and porosity. The thermodynamic data for rock-forming minerals need careful evaluation, as do those for geologically important solutions. Further theoretical work is needed on the nature of the rock/fluid interface and how it changes with pressure, temperature, and time.

Numerical Modeling (Chapter 9)

All rock-mechanics investigations involve the formulation and application of some conceptual model. Normally, the model comprises a description of the system, its initial state, and some characterization of the behavior and properties of the rock. In some instances, such a conceptual model suffices. More often, the investigation proceeds by the use of analytical, physical, or numerical models that attempt to reproduce the behavior and response of the prototype. Success depends on the adequacy of the conceptual model, especially the understanding of the chemical and physical processes that will occur in the rock, as well as on the capabilities of the modeling techniques.

Numerical methods are required to study most practical problems involving rock masses, because boundary conditions are not geometrically simple, the rock mass is discontinuous, and constitutive relations are nonlinear. Whenever possible, numerical models are calibrated against corresponding analytical solutions for problems with simple boundary conditions. Powerful numerical methods have largely superseded even scientifically scaled analog models for solving complex problems. However, such analogs may yet provide the insight needed to formulate numerical models properly when applied to simple problems.

Rock-mechanics activities were subdivided into areas of investigation sufficiently narrow to make statements about modeling needs in each area. Comparisons with the capabilities of currently available numerical models revealed several areas with practical deficiencies. Specifically, when the following conditions are encountered, the current models are either inadequate or involve prohibitive computer costs:

- The problem has a complex, three-dimensional geometry.
- Large displacements and strains occur.
- The behavior includes fracture initiation, fracture propagation, and material damage.
- The material behaves in an unstable manner after yield or failure.
- The rock mass is strongly discontinuous.
- Several simultaneous processes—thermal, mechanical, and hydrological—are interactive so that computer codes must be coupled.

Overcoming deficiencies will require further development of existing models, basic research on new numerical methods, and a better understanding of many of the fundamental chemical and physical processes involved in the behavior of rock.

The most promising lines of research are regarded to be as follows:

- *Improve strategies.* What approach to a given problem is likely to yield adequate results without excessive cost? Which numerical techniques are best suited to particular classes of problems? How may predictive models be verified?
- *Improve computer codes.* Codes must be extended to handle three-dimensional problems, large strains, yield criteria for fracture and time-dependent deformations, geometric and physical instabilities, and discontinuities.
- *Improve numerical models.* Explicit finite-element and finite-difference techniques must be extended to handle complex, nonlinear behavior. Boundary-element methods may be economical alternatives to differential methods. Better interfacing of methods is needed to achieve appropriate levels of detail in different parts of a model, and hence to reduce computer time. Automatic remeshing also will be helpful.
- *Develop coupled models.* Many rock-mechanics applications of immediate concern, such as geothermal-energy recovery and the disposal of high-level nuclear waste in geologic repositories, must account for the heating and cooling of the rock mass as well as the flow of groundwater through it. Adequate predictive modeling of such systems requires the coupling of thermal, mechanical, and hydrological models.
- *Use numerical modeling jointly with field and laboratory work.* Finally, the development of models cannot advance independently of laboratory data on physical properties, field verification, and intended applications. For specific classes of problems, the validity of models may be established by comparison between field observations and predictions made by numerical analyses. *Post-facto* testing should lead to progressive refinement of constitutive models of rock behavior as well as provide evidence that the models are consistent with their governing equations. The adequacy and uniqueness of numerical solutions depend ultimately on a proper understanding of the principles of rock mechanics on which the model is based; there is no substitute for the necessary understanding of rock properties and *in situ* conditions. Research should be organized to ensure the needed cooperation of the rock-mechanics team—the laboratory investigator, the modeler, and the engineer and geologist in the field.

CONCLUDING COMMENTARY

Study of the recommendations of the seven Subpanels reveals some overlap, as is to be expected. Multiply cited recommendations include performance of more large-scale or field tests; improvement in methods of characterizing rock masses; development of borehole-logging methods, with extension of measurements to high temperatures and pressures and to corrosive environments; development of methods for determining the orientation and continuity of fractures away from a borehole or other free surface; and improvement in modeling the behavior of discontinuities. The *in situ* measurement of low permeabilities and stresses, the determination of thermomechanical properties, and the application of numerical modeling are widely emphasized.

More emphasis has been placed on field than on laboratory studies, despite the greater difficulty and cost of field tests. It is recognized clearly that the productive use of rock mechanics to resolve problems in engineering requires consideration of the properties of the rock mass, its structural discontinuities, and the *in situ* environment. Laboratory testing of a 50 mm × 150 mm specimen, for example, yields information of little use concerning the effects of a set of fractures with 1-m spacing. However, laboratory tests must be developed to help resolve such problems because field testing can become prohibitively costly and time consuming.

Many problems can be traced to the difficulty of quantifying the geological constraints arising in rock mechanics; this is reflected in some recommendations made by several of the Subpanels. A thorough understanding of the structural geology of an area is needed to deal realistically with questions of anisotropy and heterogeneity. Clearly a geological analysis is required to understand how structural discontinuities—fractures, partings along bedding, and cleavage—are distributed through the rock mass.

It is relevant to note that the most important distinction between rock mechanics and soil mechanics stems from the key role that discontinuities play in the behavior of rock masses. This distinction alone accounts for much of the difference in substance and practice between these two fields.

Clearly there are serious deficiencies in some types of laboratory-testing facilities. Capabilities are needed, for example, for testing large specimens (>1 m), testing at high pressure and temperature in corrosive environments, performing adequate numbers of creep tests, and conducting dynamic shear tests on natural discontinuities in rock. Some of the needed facilities would bridge part of the gap between current laboratory practices and large-scale, *in situ* tests, primarily by providing the means toward better understanding of the phenomena involved.

Implementation of the technical recommendations presented by the Subpanels would contribute significantly to the success of national projects concerned with energy and resource recovery, construction, and earthquake-hazard mitigation. However, progress in rock mechanics—and consequently progress in resolving the technical problems treated in this report—is impeded by manpower problems. Available personnel are not being used to full capacity. With a significant investment in new capital equipment for rock-mechanics research and a considerable increase in the level of operating funds, more complete utilization of manpower would be achieved and a good deal of the recommended research could be undertaken promptly and productively. Realistically, however, all the technical recommendations cannot be implemented fully by the small pool of trained people currently available, even with the anticipated input of newcomers to the field. A practical approach to increasing the supply of qualified people requires the use of such time-proved devices as graduate fellowships, summer internships, postdoctoral fellowships, and well-planned apprenticeships in industry and government.

This report's technical recommendations can be applied to a broad range of particular programmatic needs. Accordingly, it may be helpful to program managers and planners, as well as research engineers and scientists, to relate these recommendations to what is apparently the only formal, mission-oriented plan for rock-mechanics research ever designed for a major national program—*NWTS Rock-Mechanics R&D Technical Plan for Mined Geologic Disposal of Radioactive Waste* (Rock Mechanics Subgroup, Working Group on the Earth Sciences Technical Plan, 1980). That plan assesses the state of the art, identifies deficiencies in knowledge and ways to correct them, and recommends an orderly, sharply focused research program with the careful estimates of milestones and costs that are possible for a specific mission. The plan's four steps follow, accompanied by correlations with the chapters in this report, amplifying and broadening the applications of each step.

1. *Rock-mass characterization* for defining the state of the material, the undisturbed state of stress (Chapter 4), and the geothermal heat flux (Chapter 8). Measurements are made in the laboratory and/or the field (Chapter 7) and include the following: lithologic properties—composition, fabric, and porosity (Chapter 3); thermal properties—conductivity, heat capacity, and thermal expansion (Chapter 8); mechanical properties—elastic or deformation moduli, fracture strength, and rheological behavior (Chapter 8); hydrological properties, especially permeability (Chapter 3); and chemical properties relating to waste/rock interactions and radionuclide retardation (Chapter 8).

   Because macrofractures (joints and faults) largely govern the flow of groundwater through and the failure of crystalline rock, research on adequate delineation of fracture systems rates the highest priority (Chapter 5).

2. *Predictive mathematical modeling* for mine design and consequent analysis with complex boundary conditions, nonlinear constitutive relations, large deformations to failure, rock-mass discontinuities, and coupling between thermal, mechanical, and hydrological computer codes (Chapter 9).

3. *In situ testing* for model verification at least in the short term and near field (Chapters 3 and 7), including monitoring of changes in stresses and displacements (Chapter 4).

4. *Engineering design* of safe, high-level nuclear-waste repository systems, probably sited in fractured, water-saturated rock masses at high pressure and temperature. As is true of all projects that involve extensive excavation, significant cost savings can be achieved by improving the technology of rock fragmentation (Chapter 6).

Each of the Subpanels' chapters presents facts based on much practical experience, identifies deficiencies of knowledge, and reasons out the recommendations for research needed to correct these deficiencies. These accomplishments will improve our ability to design safe, cost-effective structures in or on rock masses that are inherently heterogeneous and discontinuous.

The research goals of this report may give rise to problems in the funding provided by the mission agencies, such as the U.S. Geological Survey or the Department of Energy Division of Nuclear Waste Isolation. Agencies such as the National Science Foundation clearly have more flexibility to support a given research effort. Nevertheless, the obvious advantage of piggybacking the project of one agency on the project of another should not be overlooked.

It is important that coordination in budgeting and planning be developed and maintained among all agencies that may support the recommended research programs. Some agencies that concentrate their efforts chiefly on the purchase of hardware and services directly and indirectly related to agency missions may encounter philosophical difficulties in supporting the research programs recommended in this study. The contracting for basic research, sometimes done jointly by universities, private researchers, national laboratories, and industry, will require special consideration.

Several members of the parent Committee (USNC/RM) have attempted to estimate the current level of funding for each of the seven tasks treated in this report and to recommend levels over the next 5 years that are regarded as realistic for achievement of the research required (Table 2.1). Because many agencies are supporting a wide variety of rock-mechanics projects, and because the research components within them are difficult to identify, these cost estimates are rough and open to argument among technical experts. Their purpose is to emphasize that an order-of-magnitude increase in funding would be needed to solve the critical problems within the next few years. They are also intended as a guide to general comparability of effort year by year and among tasks.

TABLE 2.1 Estimated Federal Funding to Implement the Recommended Research

	Yearly Total Program (Millions of Dollars per Federal Government Fiscal Year)					
Rock-Mechanics Research Task	Year 1 (current est. actual)	Year 2	Year 3	Year 4	Year 5	Year 6
1. Measurement of porosity, permeability, and fluid flow *in situ*	≃1.0	2.0	5.0	8.9	8.9	5.3
2. Determination of *in situ* stress	≃0.5	2.0	5.0	8.6	8.6	7.5
3. Mapping of natural and artificial fractures	≃0.5	1.5	4.5	8.7	8.7	6.0
4. Rock fragmentation–drilling and excavation	≃0.5	1.9	6.4	9.1	9.1	7.1
5. Scaling test data to field applications	≃0.3	1.0	3.0	7.8	7.8	5.2
6. Determination of thermophysical, thermomechanical, and thermochemical properties	≃1.0	2.0	4.0	7.5	7.5	5.1
7. Numerical modeling	≃0.7	1.0	2.0	4.7	4.7	3.5
TOTAL	≃4.5	11.4	29.9	55.3	55.3	39.7

The Steering Group recommends that at the end of fiscal year 1983 the USNC/RM arrange for a review of these recommendations and their impact on research funding. At that time, progress should be assessed and goals reconsidered, if necessary.

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3

Porosity, Permeability, and Fluid Flow *in Situ*

INTRODUCTION

In developing this chapter on the measurement of porosity, permeability, and fluid-flow properties *in situ*, the Subpanel decided to consider certain parameters, in addition to porosity and permeability, that are associated with fluid flow in porous media. These include, under transport processes in both porous and fractured media, the parameters of distribution coefficient and dispersivity. The distribution coefficient represents the partitioning of states between the solid and fluid phases during mass transport in a porous medium; it is defined as the ratio of mass of solute in the solid phase per unit mass of solid phase to the concentration of solute in solution. The dispersivity represents the tendency of a solute to spread out during transport in a porous medium because of molecular diffusion and hydraulic dispersion; it is a characteristic property of a particular porous medium. It is clear that consideration must also be given to the influences of state of stress and temperature on the deformation of porous and fractured media and on single and multiphase flow properties of fluids.

Rock-Mechanics Applications

In situ measurements of porosity, permeability, and fluid-flow properties are essential in almost all fields in which rock mechanics plays a role. Important examples are the recovery of oil and gas, geothermal energy, conventional mining and *in situ* recovery of minerals, underground coal gasification, civil-engineering applications, nuclear-waste isolation, underground storage of fluids, and earthquake prediction and engineering.

In oil and gas recovery, where *in situ* measurements of porosity, permeability, and fluid-flow properties have received the most attention in the past, the volumes of hydrocarbons in place and the ease with which they are produced are determined by these reservoir properties. The enhanced recovery of oil depends particularly on the fluid-flow and mass-transport properties of the reservoir rock; in the case of thermal recovery processes, these properties will need to be known at high temperatures. The stimulation of producing wells by hydraulic fracturing requires a knowledge of fluid-flow characteristics in propagating fractures. The early characterization of systems of fracture porosity adjacent to producing wells is often necessary to determine the economics of a particular reservoir, as is an understanding of the pore and fracture compressibility of the fluid-rock system. Finally, the measurement of these properties *in situ* requires rugged instruments of high precision, capable of withstanding high temperatures and pressures.

The problems associated with developing and producing nonfractured, porous, geothermal systems are similar to those mentioned above for the recovery of oil and gas from essentially similar formations. The development of wet- and dry-steam geothermal fields in nonporous, fractured formations requires knowledge of the fluid-flow characteristics in such fractures. In all instances, development of models requires knowledge of the influence of high temperatures and pressures on the fluid-flow properties. As noted above for oil and gas recovery, the *in situ* measurement of porosity, permeability, and fluid flow requires rugged instruments capable of operating in a hostile environment.

Conventional mining requires a knowledge of the permeability of the resource and country rock masses to predict the occurrence and severity of possible gas or water influxes to the workings. The *in situ* leaching of minerals also requires knowledge of the rock-mass permeability. In the case of massive, "tight" formations, such as oil shale, large volumes of the deposit will first have to be reduced to rubble; both the porosity and permeability must be measured *in situ* in order to design the recovery process.

In controlling underground coal gasification, prior knowledge of the variation of permeability within the coal deposit to be gasified is important. Underground gasification also requires a knowledge of the coal permeability, particularly as a function of high temperature and *in situ* stress conditions, during the process.

In civil-engineering applications, understanding of the water-flow regime within and around the foundations of large structures, such as dams and power stations, is important in predicting their stability and minimizing reservoir-water loss. Successful grouting for improved stability and seepage control requires a knowledge of the *in situ* porosity and permeability of the rock mass.

The most important problem facing nuclear-waste isolation is long-term prediction of the movement of fluids in low-permeability rock surrounding the repositories, particularly with respect to possible contamination of groundwater. In view of the long time-constant involved, it is important to be confident in the ability to scale comparatively short-term, fluid-flow experiments to those spanning very long times. It is clear that techniques must be developed for the long-term monitoring of fluid-flow properties around a repository. The characterization of potential sites for repositories requires knowledge of the presence of porous, fractured zones of higher permeability in an otherwise "tight" rock mass; techniques must be developed for this purpose.

Many of the problems associated with the underground storage of fluids, both liquids and gases, are common to those described above for nuclear-waste disposal. Containment of fluids in hard-rock environments will require knowledge of the groundwater regime and an assessment of different grouting techniques for sealing permeable zones in the rock mass. Also, techniques will be required to monitor the fluid-flow properties adjacent to the storage caverns.

An important aspect of earthquake prediction is an understanding of the variations of fault-zone parameters, in particular the variation of porosity, pore pressure, and permeability during dilation. Soil liquefaction during earthquakes and its effect on the stability of structures and surface layers also fall into this category. In the field of earthquake engineering, these aspects are important in estimating earthquake hazards and in predicting reservoir-induced earthquakes.

When studying the parameters describing fluid flow in porous, fractured media, the influences of fracture pattern and continuity and of changes in stress and temperature are of considerable importance. At the same time, interpretation of *in situ* measurements of these parameters usually will require numerical modeling and, often, the scaling of laboratory-test results to field conditions. It is clear then that the findings noted in the other chapters of this study will have important implications for measurements *in situ* of porosity, permeability, and fluid flow.

STATE-OF-THE-ART SUMMARY

In studying statistical parameters describing a porous medium, such as porosity and permeability, it is necessary to consider the representative elementary volume (REV)—the minimum volume of material that will provide a reliable estimate of mean—in order to establish the variance of the parameter in question. This point is particularly important in interpreting geophysical borehole logs or other *in situ* measurements made over comparatively small volumes of porous and fractured media.

The precision required for *in situ* measurements of the various fluid-flow and rock parameters is an important, general consideration because of the exponential increase in the cost of obtaining data to successively larger numbers of significant figures. Measurements are either site-specific, mission-specific, or model-specific; the specific requirement must be taken into account when establishing the precision necessary to obtain the data.

In planning any test program, consideration should always be given to the influence of known geologic processes, such as tectonism, deposition, and erosion, on the parameters to be measured *in situ*. Then an estimate often can be made of the anticipated results and a guide provided as to the spacing, location, and number of measurements required.

Porosity Measurements in Situ

In this review of the state of the art in the measurement of porosity *in situ*, the different types of porosity have been identified following Bear (1972). Primary porosity is that caused by the original processes forming the soil or rock; secondary porosity is that resulting from such processes as secondary solution or structurally controlled fracturing. The total void space comprising the primary and secondary porosity is referred to as the absolute or total porosity. From the standpoint of fluid flow, however, only the interconnected pores are of interest. The porosity associated with all of these is referred to as the effective porosity.

The interconnected pore space may consist of well-rounded pores (with aspect ratios in the range 1 to 10^{-2}) or cracks (with aspect ratios $<10^{-2}$). Although crack porosity often comprises only a small fraction of the interconnected pore volume, it may affect significantly certain fluid-flow properties of the medium, particularly if the cracks are pervasive. It is important to ascertain that the volume of material investigated by the *in situ* porosity-measuring technique is a REV.

The measurement of *in situ* porosity as developed by the oil industry and associated service companies relies principally on data obtained with wireline instruments. The instrument is lowered into a borehole and provides a continuous record or log of one or more specific parameters influenced by the surrounding material as it traverses the borehole (Pirson, 1963; Schlumberger, 1972, 1974). To a considerably lesser degree, surface geophysical methods, particularly seismic reflection, may be employed in the prediction of porosity in regions where exploration has reached a mature stage (Maureau and Van Wijhe, 1979).

The zone of investigation for the different borehole logs varies from several centimeters to several meters. As this zone may represent only a small fraction of the volume of material between boreholes, it is fair to question the validity of extrapolating the value of porosity estimated from the borehole-log parameters to the whole reservoir.

All geophysical borehole logs are affected to some degree by borehole conditions such as properties of the fluid contained in the borehole, invasion of the surrounding formation by the borehole fluid, heterogeneity of the surrounding formations, and changes in borehole size. Experience has shown that log-derived parameters should be correlated with the porosity measured on core samples that have been recovered from the same formation interval and subjected to the same conditions of stress and temperature as those prevailing in the formation. This is particularly important when a new field is under development, in order to establish valid correlations between the measured parameters and the derived porosity.

The principal geophysical borehole logs used to determine *in situ* porosity are, as described by Schlumberger (1972; 1974), (a) the microresistivity log, (b) the acoustic or sonic log, (c) the gamma-gamma density log, (d) the compensated neutron log, and, as described by Snyder (1976), (e) the borehole gravimeter. For each borehole log the porosity is calculated from a measured parameter, which itself is influenced by changes in porosity. In the case of the microresistivity log, the parameter measured is the resistivity of the mud-filtrate flushed zone immediately adjacent to the borehole in a porous, permeable formation. An empirical relationship is then employed to calculate the interconnected porosity. In the case of the sonic log, the measured parameter is the time that a pulse of acoustic energy takes to traverse a given path in the formation adjacent to the borehole. Again there are empirical relationships available to calculate the interconnected porosity. These relationships are sensitive to the presence of shale and gas in the pore space and also must be corrected for the degree of compaction of the formation. The gamma-gamma density log provides a direct measure of the bulk density of the formation adjacent to the borehole; if the nature of the matrix material and pore fluids is known, the total porosity is calculated directly. The compensated neutron log responds directly to the amount of hydrogen present in the formation; the interconnected porosity is then calculated directly, if the nature of the pore fluids is known. The total porosity may be calculated from the response of the borehole gravimeter, if the nature of the matrix material and pore fluids is known. The range of investigation of this device is discussed by Hearst (1977).

Since the introduction of the borehole logs referred to above, much of the oil-industry effort has been devoted to interpreting lithology and porosity adjacent to the borehole from cross-plots of the apparent porosities calculated from the logs, particularly the acoustic or sonic, gamma-gamma density, and compensated neutron logs (Schlumberger, 1974). For example, a transition from oil to gas saturation in a given porous formation is reflected by changes in the apparent porosity of opposite sign calculated from the gamma-gamma density and neutron logs. At the same time, the industry has refined the empirical correlations between measured parameters and porosity calculated from them.

Two geophysical borehole logs under development by the oil industry and associated service companies demand mention. The first of these is the nuclear magnetic resonance (NMR) log, developed originally to provide a direct measure of permeability adjacent to the borehole (Brown and Gamson, 1960; Seevers, 1966). The fact that the NMR log provides a measure of the free-fluid index (or pore fluid free to move) in porous rocks (Timur, 1969) makes it attractive for determining interconnected porosity, because it responds directly to the parameter of most interest in fluid-flow studies. The second logging device is the electromagnetic propagation (or dielectric) log described by Calvert *et al.* (1977). This device provides a measure of water content of the formation; where the formation is fully water saturated, the interconnected porosity can be calculated directly.

A key review of the use of borehole logging in hydrology is provided by Keys and MacCary (1971), who cover use of the fundamental porosity logs developed originally for use in the oil industry. A more recent and comprehensive key review on advances in borehole geophysics for hydrology is by Nelson (in press). In this review, which refers the reader to Keys and MacCary (1971) for coverage of the routinely applied porosity logs, Nelson discusses the use of new devices that might be employed for the *in situ* measurement of porosities, including the dielectric log (described by Calvert *et al.*, 1977) and the induced-polarization or complex-resistivity method. Nelson notes that a potential application of the dielectric log is the detection of fractures in rocks of low porosity because the vertical resolution of the device is excellent.

In addition to discussing the measurement of rock properties immediately adjacent to the borehole, Nelson (in press) addresses the question of measurements between boreholes separated by several meters to 100 m. For this application he identifies the use primarily of acoustic and electromagnetic methods, indicating that a high redundancy of spatial data points is necessary to sample the rock mass adequately. He notes that accurate surveys of the borehole positions and directions are required for interpreting the data. Both of these cross-hole methods provide information on zones of intense fracturing in an otherwise homogeneous rock mass. However, it is clear that the acoustic cross-hole technique is more sensitive to changes in porosity because it offers the possibility of sampling four parameters: compressional and shear-wave velocity, and compressional and shear-wave attenuation.

A discussion of the use of geophysical borehole logs in igneous and metamorphic rocks is provided by Keys (1979). He indicates how orientation of fractures can be obtained from the borehole televiewer log and suggests how the degree of fracturing may be obtained from the amplitude of acoustic tube waves. Zones of hydrothermal alteration, and therefore of past fluid migration, are indicated by the neutron log.

In situ porosity not only may be measured by using geophysical borehole logs, but also it may be backanalyzed from the storage coefficient calculated from transient well tests, providing the matrix and pore-fluid compressibilities and aquifer thickness are known. This may have an application in the interpretation of between-hole pulse transient tests in low-porosity crystalline rocks. An interesting application of the extremely sensitive pressure gauges developed for transient well testing is suggested by Ramey (1977) for obtaining formation porosity. He notes that these gauges are sufficiently sensitive to measure earth-tide effects and that these effects could be used to estimate the porosity of subsurface formations.

In previous paragraphs, reference has been made to the determination of porosity *in situ* by employing the transmission characteristics of acoustic waves, e.g., placing borehole sonic logs within boreholes and using the acoustic cross-hole technique between boreholes. A key reference with an extensive bibliography of applications of borehole sonic logs is by Timur (1978). Several laboratory petrophysical studies of the influences of fissures and pore fluid on the elastic properties, velocities, and attenuation of acoustic waves in fissured media are reported by research groups at the Massachusetts Institute of Technology (Kuster and Toksöz, 1974; Toksöz *et al.*, 1976), at Harvard University (O'Connell and Budiansky, 1974), and at Stanford University (Mavko and Nur, 1978, 1979). In a recent paper, Cheng and Toksöz (1979) suggest methods for inversion of acoustic velocities to provide a spectrum of pore-aspect ratios in a fissured material. It should be noted, however, that the scheme is model dependent. The application of continued research of this type to field conditions should provide correlations between acoustic parameters and *in situ* porosity and permeability in fissured materials.

Under certain conditions, the state of stress and temperature have important consequences for the magnitude of *in situ* porosity. The compressibility of fluid-bearing porous media is of considerable importance in the interpretation of transient well tests. Earlougher (1977), in his key study of advances in well-test analysis, concludes that in view of a considerable scatter in reported measurements, the formation compressibility should be measured on samples obtained from the reservoir under study. He notes that correlations of formation compressibility with porosity can be expected to give only order-of-magnitude estimates. As an example of the effects of stress and temperature, Sprunt and Nur (1977) report laboratory experiments resulting in the destruction of porosity through pressure solution. It appears that considerably more research must be devoted to analyzing the influences on porosity of state of stress and temperature representative of *in situ* conditions. The problems referred to above will become much more severe as conditions such as those occurring in geothermal-well development are met. Clearly the sections of this report that are devoted to *in situ* stress measurement (Chapter 4) and determination of thermophysical, thermomechanical, and thermochemical properties (Chapter 8) will have an important bearing on these problems.

Wolff (in press) has compiled a considerable data base on measurements of the physical properties of soils and rocks of interest in fluid-flow studies, including porosity, permeability distribution coefficient, and dispersivity.

Permeability Measurements *in Situ*

In considering the hydraulic properties of rocks, it must be recognized that rock masses generally consist of two subdomains, the intact rock and the discontinuities. Sometimes the influence of discontinuities present in the rock mass is not significant, and the interconnected pore space in the intact rock provides the permeability; more often, however, the fluid path provided by the discontinuities is significant. In some cases, the discontinuity or fracture permeability is dominant and fluid flow through the interconnected pore network is negligible. The recommendations noted in Chapter 5, which is devoted to fracture mapping, will be of considerable importance in determining the fracture permeability.

It is clear that when fracture permeability predominates, the state of stress in the rock mass will be important. Whereas well-rounded pores are relatively uninfluenced by the applications of large stresses, cracks or fissures with small-aspect ratios will be closed completely by stresses applied normal to their long axes. The application or removal of even small stresses normal to the long axes of low-aspect-ratio fissures will deform then appreciably and alter their aperture. Certainly when there is a preferred orientation of fissures, the directions of the principal axes of stress will be important.

At this point it might well be noted that, as is the case with porosity, the permeability calculated from *in situ* measurements is a derived value and depends on some conceptual model of the system or on the validity of a constitutive relationship. Thus, the value of porosity or permeability obtained is only as valid as the interpretive relationship itself, as errors in measurement of the basic parameter are generally small by comparison. This is a point considered in Chapter 9, which deals with numerical modeling.

The measurement of *in situ* permeability by geophysical borehole-logging techniques is not so well developed as it is for *in situ* porosity measurements, because the relationships between the parameters measured by the logging techniques and permeability are not so well established as for porosity. At best, borehole logging currently provides a qualitative estimate of *in situ* permeability and will normally identify only permeable zones adjacent to the borehole. Ershagi *et al.* (1978) point out that attempts to employ borehole logs to estimate permeability fall into one of four categories: (1) methods based on general correlations between permeability, porosity, and specific surface area; (2) methods based on acoustic-wave propagation characteristics; (3) methods based on the free-fluid index [which, in turn, depends on the correlations between permeability, porosity, and specific surface area referred to in (1)]; and (4) methods based on the decay of thermal neutrons in the formation.

Engelke and Hilchie (1971) state that the NMR log [method (3), above] is probably the only wireline device aimed directly at the detection of permeability. Seevers (1966) relates specific permeability to NMR properties and proposes a technique for determining permeability in sandstones. Timur (1968; 1969) extends the method, develops correlations, and relates the results to measurements on core samples. Although encouraging, Timur's results indicate that correlations tend to be better in some areas than in others where they were rather poor. Research continues in this field, and it appears that a borehole-logging service company will soon be providing the NMR log on a limited basis (W.E. Kenyon, Schlumberger-Doll Research Center, personal communication, 1979).

Ershaghi *et al.* (1978) propose a method for determining *in situ* permeability in liquid-dominated, geothermal reservoirs using the induction and focused resistivity devices. Other recent approaches involve acoustic-wave propagation and other properties (Coates and Dumanoir, 1974; Barlai, 1976; Staal and Robinson, 1977; Lebreton *et al.*, 1978). None of them, however, is applicable in a general sense to all conditions. A borehole-logging technique that appears to show promise for determining *in situ* permeability indirectly is described by Plona and Tsand (1978). These workers are using ultrasonic pulses to determine the average microscopic dimensions of granular media by an acoustic backscattering technique. The results of further research appear even more promising (W.E. Kenyon, Schlumberger-Doll Research Center, personal communication, 1979). Used in conjunction with a borehole porosity log, this technique should also provide a measure of the *in situ* permeability. Another device capable of providing an accurate measure of formation pressure is the wireline formation tester (Smolen and Litsey, 1979). Experience has shown that this tool often can be employed to provide an estimate of the permeability of the formation adjacent to the borehole.

The permeability adjacent to and between boreholes is normally obtained from well-test analysis. Well testing consists of correlating well flows with changes in pressure or water level and then calculating the ability of the reservoir to store and transmit fluids. Although based on the same fundamental theory, well testing has developed along parallel but independent lines in hydrology and petroleum-reservoir engineering. Because hydrologists are generally concerned with shallow systems, they usually have been more interested in the interference type of well testing among wells. Reservoir engineers, on the other hand, traditionally have been faced with the problem of exploiting reservoirs penetrated by deep, expensive wells. As a consequence, most of their energies have been devoted to pressure drawdown or buildup tests in a single production well.

From the point of view of hydrologists, key references on well-test analysis are contained in Glover (1974), Witherspoon *et al.* (1971), and Weeks (1977), for example. Theoretical considerations are discussed in depth by Bear (1972). In an attempt to bring the two groups closer together, the U.S. Department of Energy, through the Lawrence Berkeley Laboratory (LBL) of the University of California, has recently sponsored two symposia on well testing, with particular reference to geothermal systems. The proceedings of these symposia (Schwartz, 1977; 1978) provide important references.

In the modeling of heterogeneous aquifer performance, the values of parameters including permeability are required at each point in the aquifer. The inverse problem involves deducing these values from measurements of well-flow rates and heads made at a limited number of positions in the aquifer. The solution to the inverse problem is not, in general, unique. Emsellem and de Marsily (1971) discuss the inverse problem in detail. Tang and Pinder (1979) report a direct solution of the inverse problem in groundwater flow. Further discussions of numerical modeling are contained in Chapter 9.

Key references in well testing from the point of view of petroleum-reservoir engineers are the two Society of Petroleum Engineers (SPE) monographs prepared by Matthews and Russell (1967) and Earlougher (1977) Earlougher notes that when the Matthews and Russell monograph was being prepared in the mid-1960's, the application of reservoir simulation to well-test problems in the oil industry was in its infancy. He notes that since publication of their monograph, more than 150 additional, well-test analysis technical papers have been published. Perhaps the most important point to emerge from Earlougher's work (contained in his Appendix D) is that there is a definite need for values of compressibility of rock pore-volume (formation compressibility), a parameter basic to the interpretation of transient well tests.

The problem of formation damage or impairment of permeability is one that receives much attention in the petroleum literature. There are many reasons why the drilling, completing, or the working-over of a well can adversely affect permeability, such as reactions between the fluids used and the rock, incompatibility between the fluids used and the fluids *in situ*, and plugging by authigenic or extraneous solid particles. In any of these cases, the productivity or injectivity of the well is impaired.

Study of the references noted in previous paragraphs leads to the conclusion that major areas of concern lie in estimating the permeability of porous, fractured media and of relatively impermeable, fractured media. The importance of fluid flow in porous, fractured sedimentary rocks has long been important in groundwater and oil-field exploitation; in groundwater studies, the flow in metamorphic and igneous rock masses is of growing importance. These problems are discussed, for example, by Gringarten *et al.* (1975) and Narasimhan and Palen (1979) for fractured wells and Streltsova-Adams (1978) for naturally fractured reservoirs; there are other excellent references in the LBL symposia volumes (Schwartz, 1977; 1978). After first discussing the history of the dual-porosity model for porous, fractured media, extending back to the work reported by Barenblatt *et al.* (1960), Streltsova-Adams (1978) stresses that the problem of determining the fractured-reservoir parameters is not unique: the reservoir behavior may be interpreted uniquely only if the matrix and fracture properties are known independently. She suggests that the use of multiwell interference tests, in conjunction with pressure drawdown and buildup tests and measurements made on core samples, might eliminate step by step the uncertainties in interpreting well tests in fractured formations. It is clear that the findings noted in Chapter 5, which discusses fracture mapping, are of the utmost concern in dealing with the problems discussed above.

The permeability of relatively impermeable fractured media is important in the case of waste storage underground. In radionuclide transport, for example, species velocity is proportional to permeability and inversely proportional to porosity. Because fracture permeability is likely to be significant and fracture porosity rather small, the accurate measurement of these parameters becomes of paramount importance. If they are measured only at a limited number of points in the formation, it is fair to question the validity of assuming that the measured values truly reflect the properties of the formation as a whole. Some of the problems encountered in these media are outlined in the proceedings of a symposium on needs for nuclear-waste isolation in crystalline and argillaceous rocks (Lawrence Berkeley Laboratory, 1979).

In a paper that discusses the relation between the mechanical and hydraulic properties of fractured rock masses and induced seismicity, Witherspoon and Gale (1977) claim that the interactions of mechanical hydraulic effects must be considered because, besides providing the main fluid-flow paths, the fractures are relatively easily deformed. They conclude that the discrete model provides more hope than the continuum model in numerically modeling the hydraulic behavior of porous, fractured media, even though the discrete model requires details of the fracture geometry and material properties of both the fractures and the porous rock matrix. These authors consider that improvements in borehole techniques can make it possible to obtain the necessary data, at least at shallow depths.

The significance of permeability anisotropy in fractured rock masses is also discussed.

Important references to the flow of fluids in fissured media are contained in the proceedings of a symposium on percolation through fissured rock (Wittke, 1972). Some of the points raised by Witherspoon and Gale (1977), above, also are addressed in the proceedings. In particular, Louis and Pernot (1972) discuss an *in situ*, experimental technique for determining the three-dimensional permeability tensor in fractured gneiss and amphibolites in the foundation for a large dam.

From the preceding paragraphs, it is evident that borehole-logging techniques capable of providing the orientation of individual fractures intersecting the borehole and a measure of the aperture (noting, however, that the latter is influenced in the vicinity of the borehole by stress concentrations and by washout of the infilling material) would prove to be particularly valuable. Key references in this field are related to the dipmeter log (Babcock, 1978), the borehole televiewer or seisviewer (Zemanek *et al.*, 1970; Keys *et al.*, 1979), and the borehole impression packer (Barr and Hocking, 1976). These techniques should be borne in mind. Logan and Teufel (1978) have studied methods for predicting the directions of fracturing away from the neighborhood of a borehole. Once again, Chapter 5 will have considerable bearing on the problems discussed above.

Fairhurst and Roegiers (1972) suggest a procedure that uses the technique of hydraulic fracturing for estimating fractured rock-mass permeability, particularly in the case where the fractures are widely spaced. It employs a special probe, based on the standard hydraulic-fracturing procedure but designed specifically to measure *in situ* stresses in the rock mass. Other research, based on an analysis of the early history of hydraulic-fracturing data itself, is being conducted (T.N. Narasimhan, Lawrence Berkeley Laboratory, personal communication, 1979) to determine the pressure-deformation characteristics of the rock once the fracture has been initiated, to relate the mean fracture aperture to fluid flow, and to determine the extent of the resulting fluid-filled cavity.

A borehole technique that involves the injection of air to packed-off sections of the borehole in order to determine the permeability of the rock mass is described by Barron (1978). This technique shows promise in mining and tunneling at elevations above the water table. One of the problems encountered with low-permeability rocks involves the long time constant associated with transient well-test pressure measurements. A means of reducing the time constant under these conditions is to measure smaller pressure differences. A number of extremely sensitive pressure sensors have been developed for accurately measuring small pressure changes. Some of the characteristics of these sensors are described by Earlougher (1977). Development of sensitive pressure sensors for high temperatures (275°C) are described by Eernisse *et al.* (1978) and Veneruso and Coquat (1979).

The hydrology group of the Water Resources Division of the U.S. Geological Survey is investigating new methods for determining the relative permeability of unsaturated porous media and plans to extend laboratory measuring techniques to the field (J. Rubin, U.S. Geological Survey, personal communication, 1979). This group is also developing methods for determining very small rates of flow with regard to recharge of desert aquifers.

A promising method for measuring the *in situ* permeability of tight rock masses is described by Lawrence Berkeley Laboratory (1979). It involves measuring the amount of moisture evaporating from the walls of a sealed-off section of a mine drift and the head of water at different distances into the rock mass adjacent to the drift.

Fluid-Flow Measurements *in Situ*

Borehole-logging methods for *in situ* fluid-flow measurements are discussed by Nelson (in press). These include the radial differential temperature (RDT) log (Cooke, 1979) and the borehole-spinner (Dowdell and Wendt, 1974) and radioactive-tracer (Apps *et al.*, 1979) methods. An example of the latter method, in which the water flowing behind the casing is irradiated with neutrons, is described by Arnold and Paap (1979). This nuclear-activation technique does not require perforations in the casing. Borehole noise as an indicator of fluid flow is discussed by Robinson (1976) and Britt (1976). The detection of water leakage from a dam, using streaming potentials, is described by Haines (1978). Nelson (in press) discusses the use of the borehole gamma-ray spectrometer to study migration of radioactive species in the vicinity of a borehole.

A key reference in fluid-flow measurements *in situ* is Freeze and Cherry (1979), who cite reviews of direct tracer techniques in groundwater investigations by Knutson (1968), Brown *et al.* (1972), and Gaspar and Onescu (1972). Freeze and Cherry discuss the disadvantages of this method, particularly when the porous material is heterogeneous. It appears from the work by Thompson *et al.* (1974) that the chlorofluorocarbon $CFCl_3$ may be one of the best artificial tracers because it is nonreactive with geologic materials and can be used in extremely small, unhazardous concentrations. The borehole-dilution or point-dilution tracer technique, which avoids the disadvantages of the direct technique, is described in detail by Halevy *et al.* (1967) and Drost *et al.* (1968). Grisek *et al.* (1977) describe a borehole-dilution system employing a readily available tracer. In a report of recent field studies of dispersion in a shallow sandy aquifer, Pickens *et al.* (1977) conclude that the borehole-dilution technique provides an efficient and reliable means for identifying high-transport zones within aquifers. Freeze and Cherry (1979) suggest the even simpler approach of using salt as the tracer, with downhole measurement of electrical conductance as the salt is flushed from the well.

In a discussion of transport in porous and fractured media, Freeze and Cherry (1979) point out that the magnitudes of dispersivities measured in the field are considerably greater than those measured in laboratory samples. This difference is generally attributed to the effects of heterogeneities larger in scale than those possible in the laboratory sample. Although it is accepted that dispersivity measurements should be made in the field, so few actually have been reported that agreement apparently has not been reached on standard types of field tests or analysis. Freeze and Cherry (1979) provide several references to field measurements of dispersivity; in particular the work of Castillo *et al.* (1972) is interesting because it indicates the complex behavior exhibited by *in situ* fractured-rock dispersivity compared with that expected for granular materials.

In the study of absorption of solids suspended in liquids onto the solid material making up the porous medium, as in the case of transfer by any other chemical process, the distribution coefficient and retardation factor play important roles. References to the migration of radionuclides in porous media are provided by Baetslé (1967; 1969) and Ames and Rai (1978). A method involving the use of two tracers for determining the distribution coefficient is described by Lawrence Berkeley Laboratory (1979, p. 130).

A number of useful references and field data for distribution coefficients and dispersivity values are reported by Wolff (in press). He also concludes that there is a need for more data from field experiments.

STATE-OF-NEED SUMMARY

A survey of the literature indicates that considerable progress has been made in developing techniques for measuring porosity, permeability, and fluid-flow properties *in situ* for nonfractured, porous rocks and, to a lesser extent, for fractured, porous rocks. However, it appears that a start has been made only recently in developing techniques for measuring permeability and fluid-flow properties in nonporous, tight rocks. It is evident also that techniques for measuring permeability *in situ* lag behind those for measuring porosity and therefore still need considerable development and refinement. Agreement is required on standard tests for the measurement *in situ* of some fluid-flow properties, such as dispersivity. Progress is hindered by a lack of geophysical borehole sondes capable of withstanding the high temperatures and pressures associated with the development of geothermal and other resources.

Porosity Measurements *in Situ*

A major requirement in the measurement of porosity *in situ* is the capability to distinguish between porosity contained in well-rounded pores and that contained in cracks or fissures. Studies of radionuclide transport in porous media require a wide range of pore sizes in order to establish the specific surface area. In borehole geophysics, this may well be achieved by development of the nuclear magnetic resonance (NMR) log, the dielectric log, and the embryonic ultrasonic backscattering technique. Considerably more information obviously can be obtained by computer analysis of data from acoustic logs, particularly in view of the prospects of inverting velocity data to provide a wide range of pore aspect ratios.

In those cases when cross-hole geophysics can be employed, acoustic methods may well prove able to differentiate between well-rounded and fracture porosity, for the reasons given above. It appears that electromagnetic (EM) techniques may provide useful information on bulk porosity in cross-hole tomographic applications. The response of sensitive pressure gauges to earth tides should be pursued as a method to determine *in situ* porosity.

There is a need for developing borehole-logging devices that can provide information on the aperture and inclination of fractures intersecting the borehole. When used in conjunction with the techniques referred to in the preceding paragraphs, they should provide a much better idea of fracture porosity *vis-à-vis* well-rounded porosity. Techniques for determining fracture orientation away from a borehole and the areal continuity of discontinuities also require development.

Some geophysical borehole logs are sensitive to changes in porosity. However, the sensitivity varies in different ways, depending on changes in type and degree of fluid saturation and on type of rock matrix material. If run together, these porosity logs will provide more information than the sum of information if they were run separately.

There is a basic need for more careful laboratory measurements of pore volume compressibility of reservoir rocks at conditions of temperature and stress representative of those existing in the reservoir. Particular note should be made of any temperature and stress hysteresis observed.

In the development of geothermal and other resources where the environment is hostile, there is a need for geophysical borehole logging sondes capable of withstanding high temperatures and pressures.

Permeability Measurements *in Situ*

It appears that much more development work is required on geophysical borehole-logging techniques for measuring permeability *in situ*. Tangible results have already been achieved in research programs with the NMR and dielectric logs and with the ultrasonic backscattering technique.

There is a definite need for the collection of field case-history data on transient well tests in porous, fractured formations. A thorough assessment should then be made of the data in order to judge the merits of different interpretive models, because it appears that capabilities for modeling exceed those for data collection.

In fractured media, fluid-flow properties are governed by the fractures. If they are closely spaced, permeability can probably be determined from the borehole logs; however, if they are widely spaced this is probably not possible. In either case, fracture spacing and orientation should be determined before testing for permeability. In this way, a representative elementary volume (REV) can be established first and a decision made as to whether it is sufficiently small to be encompassed by the radius of investigation of the borehole log. The proposal, noted in the earlier discussion of hydraulic fracturing, to use a probe for recording impressions of the borehole wall before and after well testing appears to have merit. However, a need also exists for techniques to determine fracture orientation and continuity away from a borehole.

Techniques for determining the permeability anisotropy of heterogeneous rock masses need to be developed. Cross-hole geophysical methods, such as acoustic-wave propagation, might be employed to determine the principal axes, and tracer-injection tests might be used to obtain the permeability tensor for a volume sufficiently large to be a REV. When access to the fractured rock mass is fairly easy, as in the case of near-surface developments, it appears feasible to obtain sufficient data from individual fractures or systems of fractures to establish a permeability tensor. In this instance, a measuring technique using a triple probe of the type described by Louis and Pernot (1972) might be refined further.

A problem that still has not been addressed satisfactorily for fractured media is that of the deformation characteristics of fractures and fissures, especially the hysteresis involved in loading and unloading. There appear to be two avenues open for the research required in this field: large-scale laboratory tests under closely controlled conditions and field tests of the type being performed by Narasimhan at Lawrence Berkeley Laboratory, using hydraulic-fracturing techniques.

There is a need for more data on the influence of temperature, in addition to stress, on the porosity and multiphase permeability of liquid-saturated rocks. Some laboratory data related to this problem have been noted above in the paragraph on pore-volume compressibility.

Techniques need to be improved for determining the permeability, especially the directional permeability, of low-permeability rock masses. The continuity of fractures is particularly important in this case, as is the effect of the application of stress on the fractures. There is also a need to reconcile the results of tests at the laboratory scale with those obtained in the field. Another need is the development of techniques for determining the relative permeability for multiphase fluid flow in porous, fractured media *in situ*.

Fluid-Flow Measurements *in Situ*

In view of the paucity of case histories reported in the field of fluid flow and transport in porous, fractured media, there is a definite need for more research in all aspects of this subject. Agreement must be reached on standard types of field tests for, and analysis of, dispersivity data in porous and fractured rocks. The scale effect observed between laboratory and field measurements of dispersivity requires investigation.

Difficulties associated with effecting reproducible measurements of distribution coefficient in the laboratory and in the field, and in reconciling the two measurements, must be resolved. The two-tracer method for determining the distribution coefficient in the field warrants further development.

RECOMMENDATIONS

Current needs in the measurement of porosity, permeability, and fluid-flow properties *in situ* are as follows:

- *Develop methods to determine the orientation and continuity of fractures away from a borehole or free surface.*
- *Obtain field case-history data on well tests in porous, fractured and in nonporous, tight rocks in order to gain a better understanding of permeability and other fluid-flow parameters; establish new or develop existing field-test sites in fractured and tight rock for this purpose, piggybacked with stress-measuring and fracture-mapping programs as necessary.*
- *Develop a more thorough understanding of the effects of changes in stress and temperature on pore compressibility in porous, sedimentary rocks; establish facilities for this purpose.*
- *Standardize methods for determining the fluid-flow parameters of dispersivity and distribution coefficient* in situ; *establish facilities for relating measurement of these parameters and permeability in the laboratory to measurements in the field.*
- *Develop methods to distinguish between granular and fracture porosity in porous, fractured rock masses.*
- *Refine the design of instruments for geophysical borehole measurements of porosity and permeability in environments involving high pressures and temperatures.*
- *Research and develop geophysical borehole-logging techniques to permit the successful measurement of permeability* in situ.

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4

Determination of *in Situ* Stress

INTRODUCTION

In situ stress in rocks arises both from actively applied forces and from stored rèsidual-strain energy. The *in situ* state of stress is measured for two principal reasons: to predict rock response to changed loading conditions caused by construction or excavation and to further understand tectonic processes, including earthquakes (Table 4.1). Included in construction and excavation are both traditional activities and new engineering procedures such as *in situ* extraction of geothermal power, *in situ* coal gasification, and storage of high-level radioactive waste—procedures that make use of the *in situ* stress field to guide the formation of fractures or their sealing as part of the design.

Unfortunately, the stress field cannot be measured directly. Instead, it is determined indirectly from the measurement of rock response to a perturbation of the stress field. That response is usually a strain or deformation measured over a small volume of rock or fluid pressure measured over a somewhat larger, but still small, volume. If the properties of the rock are well known, the stress state can be obtained from inversion of the measured quantity. When the rock properties are reasonably continuous, elastic, homogeneous, and reversible, the inversion is straightforward and successful measurements of stresses are not difficult. However, if the rock behavior cannot be characterized easily, the inversion can be correspondingly inaccurate. If the rock behavior is variable in space, then, depending on the study's needs, stress measurements may have to be treated individually or it may be acceptable to average them to obtain the stress state in what is presumed to be a representative

TABLE 4.1 The State of Stress in Crustal Rocks: Fields of Application

Design of Excavations (e.g., mines, tunnels, power plants, storage facilities)
Short- and long-term stability
Safety
Cost reduction
Subsurface Hydrodynamics (e.g., conventional oil-field work, tight gas-sand exploitation, shale and coal gasification, geothermal-energy extraction, nuclear-waste disposal)
Orientation of hydraulic fractures
Dominant permeability directions
Subsidence
Containment
Induced Displacements (e.g., nuclear tests, explosive impacts, excavations)
Containment
Vulnerability of structures
Earthquakes (seismic and aseismic regions)
Occurrence
Mechanics
Prediction
Induced or triggered seismicity
Global Dynamics
Tectonic processes
Flow processes
Plate tectonics

volume of rock. However, the methodology for averaging is not well developed. Furthermore, at large distances from a working surface or in highly fractured rocks, the measurements themselves are not easily made. The challenge is to extend the ability to make accurate stress determinations to more complex field settings and at reasonable cost. Present technology is not adequate to match the needs of engineering designs requiring knowledge of stresses in deep or remote locations, in ductile or inelastic rocks, or in hot or corrosive environments. Neither do generally accepted procedures exist for integrating measurements of *in situ* stress, made over small volumes of rock at widely separated locations, into a tectonic-stress framework for fault-motion prediction.

BACKGROUND

The state of stress is typically specified at a point by principal stresses, a unique set of three orthogonal normal stresses and their orientations, for which all shear stresses vanish. Six independent quantities are thus required to define the stress state at any point, and any or all of these values can vary from point to point. Therefore, defining the stress field through a finite volume of rock can be a difficult problem. Interpreting the stress field in a volume from a few stress measurements involves some simplifying assumptions. The most critical assumptions are discussed in this chapter, and some of them are central to future research efforts.

A further step in the interpretation is the "cause" of the stress. Calculated *in situ* stresses represent the sum of various components elucidated below, and it is often necessary to remove unwanted components from the desired cause. Although the terminology for describing measured and inferred components of rock stress is unsettled, the concept of multiple sources is important. The following annotated working definitions are presented to highlight some of the difficulties involved in this interpretive step:

Gravitational stress—the portion of the total stress field produced by the weight of the overlying rock or soil material. The vertical component of the gravitational stress is simply ρgh, where ρ is the average density of the overlying material. The horizontal components resulting from lateral confinement are a fraction of the vertical and are dependent on Poisson's ratio for the rock.

Tectonic stress—the portion of the total stress field resulting from tectonic movements in the earth's lithosphere. Because the earth's surface is a free surface, tectonic stresses are sometimes assumed to be essentially horizontal and not to contribute to the vertical-stress component. This is strictly true only at the earth's surface, although, in general, vertical stress does correlate closely with the expected contribution of the gravitational stress (McGarr and Gay, 1978; Brown and Hoek, 1978).

Thermal stress—the portion of the total stress due to the elastic expansion or contraction of a confined rock mass from heating or cooling. Thermal stress can arise from diurnal or seasonal temperature changes, from deep-seated natural sources such as magmatic intrusions, or from human activities such as nuclear-waste disposal. A thermal stress is actually a *change* of stress relative to the ambient stress of the rock at a reference temperature.

Hydrodynamic stress—the portion of the total stress field caused by fluid movements within the rock mass. This stress is often negligible, and even more often neglected, in *in situ* stress interpretation.

Residual stress—"stress remaining in a solid under zero external stress after some process that causes the dimensions of the various parts of the solid to be incompatible under zero stress, e.g., (i) deformation under the action of external stress when some parts of the body suffer permanent strain, (ii) heating or cooling of a body in which the thermal expansion coefficient is not uniform throughout the body" (International Society for Rock Mechanics, 1975).

Residual stress is generally understood to be stress stored in the rock even after confinement is removed. Residual-stress magnitudes may be as large as 100 MPa, and the stresses may persist in rocks for periods as long as 3 billion years (Gay, 1975). They tend to be relatively more important to the measured stress field at shallower sites (Gay, 1972; Haimson and Voight, 1977). Engineering problems involving residual stress were recognized long ago, and examples cited commonly included time-dependent relaxation (Muller, 1964; Coates, 1964). Purely elastic residual stresses also exist and can be observed as episodes of instantaneous strain release, as strain-gauged rocks are overcored concentrically with progressively smaller core bits (Swolfs *et al.*, 1974; Nichols, (1975). It is clear that in an engineering sense residual stress may or may not be equivalent to the measured values from *in situ* tests. Furthermore, the *in situ* measurements indicate extremely complex behavior on a small scale, and attempting to scale local behavior to predictable effects on larger excavations or openings presents almost insurmountable problems. Finally, the tectonic interpretation of residual stresses appears to be straightforward only in a minority of rocks (Friedman, 1972).

Paleostress—a stress condition that existed prior to the present time at the point of measurement. A paleostress state commonly is inferred from permanent strain features. It may also bear a general relation to the present residual-stress state, but residual-stress measurements are not likely to be a direct measure of the true magnitude or orientation of that paleostress.

The stress field calculated at a point is assumed to be a reasonable approximation of the total field at that point in space and time; this assumption is borne out by both laboratory and field measurements under controlled stress conditions. Separation of the total field into its component parts is a simple step to accomplish mathematically, but in practice it is often impossible because few of the components can be measured independently or apart from the others. The terms defined above are interpretations of the origin of portions of the measured field, and this interpretive division is an important part of the successful analysis of the *in situ* stress field.

The art of stress measurement and its associated technology evolved primarily through the efforts of mining engineers attempting to improve design, stability, and safety criteria for surface and underground man-made structures (Hast, 1958). The development of the required tools and methods was dictated by the task at hand—the determination of the absolute field stresses in the near vicinity of the excavation.

As mines were extended to greater depth in highly stressed areas, such as the Coeur d'Alene mining district in the United States and the South African gold fields, simple analyses based on lithostatic-stress conditions at depth were inadequate to explain the behavior of tunnels and mine workings and incorrectly estimated their stability. Existing designs had to be revised. By determining the stress state independently, the overly simplified assumption of a gravitational-stress state could be eliminated and the mathematical model of the opening could be improved.

The only viable technique for determining the absolute stress at great distances from the surface grew out of the oil- and gas-field practice of forcefully inducing fractures into target subsurface formations to enhance recovery of the economic commodity. Demand for greater knowledge of the state of stress at crustal depths has increased dramatically in recent years as deeper excavations and engineering processes have been contemplated and as the geophysical community has become aware of the utility of the knowledge in resolving such questions as the mechanics of crustal faulting and the driving mechanisms of plate tectonics.

Modern engineering needs are placing even greater emphasis on ambient stress levels. An example of the present scale of the problem is the successful stimulation of a deep geothermal field (Aamodt, 1977). In the Hot Dry Rock Experiment of the Los Alamos Scientific Laboratory (Blair *et* *al.*, 1976), fracture orientation is important in the location and spacing of additional wells for completing the subsurface path of fluids. The orientation of the fracture in turn is controlled by rock anisotropy and the ambient stress field. Another example is the prediction of stresses in a high-level radioactive-waste disposal site. The problem is complicated by stress fields changing with time as the result of heating of the host rock by the decaying waste. Yet, the site should effectively isolate the waste during both the initial heating phase and the subsequent cooling of the rock. The effect of the stress change should be predicted by accurate mathematical models to assure that the stress changes will not breach the security of the site. Finally, underground fuel-storage vaults are subjected to pressure changes that flex the walls of the vault. The degree of "working" of the walls from pressure changes is sensitive to the ambient stress state in the surrounding rocks. If the stress state is known, the optimum orientation and shape of the vault can be determined to minimize the hazard of vault failure.

On a scale useful for elucidating tectonic processes, the stress field is as yet only poorly known, mostly from earthquake fault-plane solutions. However, several recent papers attempt to synthesize regional- or global stress patterns from earthquake data together with the *in situ* stress measurements (Sbar and Sykes, 1973; McGarr and Gay, 1978; Zoback and Zoback, 1980). The measurement of *in situ* stress levels and stress changes is recognized as important both for understanding the mechanism of earthquake generation (Zoback and Roller, 1979) and for predicting impending earthquakes (Sbar *et al.*, 1979; Swolfs and Brechtel, 1977; Clark, 1981).

The technology of *in situ* measurements has been a common theme in international conferences and symposia among both engineers and geophysicists. An early, but quite comprehensive, summary of thinking for both groups is in the proceedings of the International Conference on State of Stress in the Earth's Crust, held in 1963 in Santa Monica, California (Judd, 1964). The summary reviews both the types of instruments being developed (esp. Merrill *et al.*, 1964; Jaeger and Cook, 1964) and the importance of ground stresses to surface and subsurface stability problems (esp. Muller, 1964; Bergman, 1964; Coates, 1964). Later summaries of instrumentation by Leeman (1964), Obert (1966), Fairhurst (1968), Jaeger and Cook (1969), and Hall and Hoskins (1972) chronicle the considerable improvements in measuring techniques, particularly strain-relief techniques, resulting from wider recognition of the significance of the ambient stress field. A few key comparisons among different types of instruments were conducted (e.g., de la Cruz and Raleigh, 1972; Gay, 1975; Gysel, 1975), but considerable differences of opinion were voiced by numerous workers. It became clear that experience with the use of specific techniques is an important factor in the quality of the results obtained (Grob *et al.*, 1975).

During the same period, the methods of interpreting hydraulic-fracturing data developed beyond the original theoretical work of Hubbert and Willis (1957) and Kehle (1964). Laboratory results (Haimson and Fairhurst, 1970; Zoback *et al.*, 1977) are consistent with theory, and field data (Haimson, 1973; Haimson *et al.*, 1974) appear to be consistent with other measurements.

Proceedings of the Fifth International Symposium on Recent Crustal Movements (Pavoni and Green, 1975), held in Zurich in 1974, emphasized regional patterns of stress distribution (esp. Greiner, 1975; Gay, 1975). However, most information still was obtained from seismic and geodetic data rather than from *in situ* stress measurements.

The International Symposium on Investigation of Stress in Rock, held in Sydney in 1976, considered advances in applications of stress measurements to practical engineering problems, particularly in underground openings (Bridges, 1976; Schaller *et al.*, 1976; Myrvang, 1976; Ishijima, 1976). To a lesser degree, instrumental problems were also reviewed (Enever and Khorshid, 1976; Worotnicki and Walton, 1976; Haimson, 1976).

Proceedings of the International Symposium on Field Measurements in Rock Mechanics (Kovari, 1977), held in Zurich, updated the instrument technology (esp. Blackwood, 1977; Bonnechère and Cornet, 1977; Pahl, 1977; Filcek and Cyrul, 1977; Haimson, 1977; Pariseau and Eitani, 1977; Sellers, 1977). Also documented were numerous applications to engineering problems, particularly in underground openings, slopes, and foundations.

The importance of *in situ* stress measurements to understanding tectonic processes recently has become clear as a result of several review articles. McGarr and Gay (1978) summarize measurements from different parts of the world and discuss the state of stress as a function of depth. Brown and Hoek (1978) also analyze the relationship between vertical stress levels and depth. Zoback and Zoback (1980) review *in situ* stress determinations in the United States and distinguish "provinces" in which the horizontal stress field appears to be relatively continuous.

The International Society for Rock Mechanics is in the process of preparing a number of "Suggested Methods" publications for measuring *in situ* stress in rocks, an indication of the growing view that no additional fundamental improvements in measurement instrumentation are needed to justify their effective use in the field. The efforts to develop new instruments and techniques appear to be on the decline. This is a sign of increasing maturity in the field, as the major effort shifts to more-widespread use of existing methods to solve the fundamental rock-mechanics problems ahead.

STATUS OF MEASUREMENT TECHNOLOGY

Values of the ambient stress state are determined from measurements in two fundamentally different modes, active and passive (Hult *et al.*, 1966). In the active mode, the stress component is determined by eliminating stress-induced deformations with a counterbalancing force (e.g., fluid under pressure). In the passive mode, the stress components are inferred from measured displacements (strains) and are calculated using known elastic moduli.

The measure of the instantaneous shut-in pressure (ISIP) during a hydraulic-fracturing test is, in a limited sense, an example of the active technique. Fluid pressure is applied until the compressive-stress concentration at the hole is counterbalanced, then exceeded. In principle, no knowledge of rock properties is needed when using an active technique. The passive technique requires that a portion of the host rock containing the instrument be removed from its surroundings by, for example, overcoring. The extent to which rock properties are needed with the passive technique depends on the rigidity of the instrument relative to that of the host rock. Stiff, passive instruments are relatively insensitive to elastic moduli because they essentially prohibit the deformation of the rock. Their rigidity exceeds the rock rigidity by a factor of 3 to 5. Soft instruments permit the strain in the rock to be complete; hence, the stresses are directly proportional to the rock's elastic modulus.

Passive techniques are used far more frequently than active ones. They perform best in rocks, whose initial response upon relief is elastic. Principal stress orientations are determined by obtaining measurements in three or more noncoplanar but known directions. With some passive techniques, this may require the drilling of additional nonparallel holes; however, with more-sophisticated equipment, all the information can be obtained in a single hole. The hydraulic-fracturing technique reliably will give only the magnitude of the minimum principal stress. Separate equipment is required to produce an impression or picture of the induced fracture in the wall of the open hole, which is used to obtain information about principal stress orientations. Fracture tests in cased holes require remote-sensing equipment to detect the extension direction.

The measurement of relative stress changes can be accomplished using both active and passive techniques. Passive techniques that use adhesives for coupling in the hole are less likely to yield stable data over long periods than those that use spring-loaded or wedged devices, owing to time-dependent creep of the bonding material. Because measurements of relative stress change are of long-term duration in all cases, time-dependent deformation of the instruments and the rock must be considered.

Instrumentation

The main features, performance ratings, and fields of application of commonly used instruments or procedures are summarized in Table 4.2. With few exceptions, it does not include instruments or techniques that have a limited data base or are being developed. Instruments that are now being modified or redesigned for operation at, for example, elevated temperatures are identified by principal agency or laboratory. The following discussion of field performance of each instrument includes performance in rocks that are elastic, ductile, fractured, wet, and disking. The latter adjective refers to rock that disks or chips in a pilot drill core, usually indicative of high differential stress—i.e., in excess of one half the unconfined strength of the host rock.

HYDRAULIC FRACTURING

The hydraulic-fracturing technique consists of pressurizing a portion of a borehole until a tensile fracture is induced in the wellbore. As shown

TABLE 4.2 Techniques for Absolute and Relative Stress Measurements

Techniques	Type	Measured Quantity	No. of Individual Measurements at a Point in Single Hole	No. of Holes for Complete Stress Determination	No. and Type of Readout Equipment Per Hole	Coupling in Hole	Maximum Depth from Working Surface (m)	Additional Rock-Property Determinations Required	Auxiliary Equipment Required	Elevated Temperatures	High Fluid Pressures	Fields of Current Applications
Hydraulic fracturing	Active	Pressure	1 to induced fracture	1, assuming $\sigma_v = \sigma_{min}$	1 downhole pressure gauge	Packers	5000+	None for $S_{H\ min}$; density; tensile strength or K_{IC}; poro-elastic parameter	Impression packer; televiewer	[a] Redesign of packers proposed	Good	Oil and gas; Geothermal; Nuclear testing; Excavation; Research; Containment; Earthquake
Flat jack	Active	Pressure	1 to slender slot	3 slender slots (biaxial only)	1 pressure-gauge transducer	Cemented	Surface to 300	None	Displacement gauge	[a] P/T effect unknown	N.A.	Mining; Research; Earthquake
					1 manometer				None			
					1 differential pressure transducer	Wedged						
Borehole deformation gauge, USBM	Passive, soft	Displacement of cantilevers	3 in plane to hole axis	3	3 strain indicators	Spring-loaded	50+	Elastic modulus; Poisson's ratio	Biaxial cell	[a] Redesigned by Rogers White, Grand Junction, Colorado	N.A.	Mining; Underground; Waste disposal; Storage; Nuclear testing; Research; Earthquake
Doorstopper, CSIR (South Africa)	Passive, soft	Strain	3 or 4 in plane to hole axis	3	1 strain indicator	Glued	10+	Elastic modulus; Poisson's ratio; stress concentration factors	Biaxial cell	[a]	N.A.	Mining
Triaxial strain cell, CSIR (South Africa)	Passive, soft	Strain	9 or 12	1	1 strain indicator	Glued	50	Elastic modulus; Poisson's ratio	Hoek-Franklin triaxial cell	[a]	N.A.	Mining; Underground; Waste disposal; Research; Earthquake; Rock burst
Biaxial photoelastic gauge	Passive, soft	Strain	Principal strain directly; plane perpendicular to hole axis	3	1 optical viewer	Glued	10+	Elastic modulus; stress concentration factors	Biaxial cell	[a]	N.A.	Mining

[a] No results likely.

by Hubbert and Willis (1957), the fracture should form (in an impermeable rock with pore pressure, P_o, and $S_{H\ min} \leq S_V$) when the borehole pressure reaches the breakdown pressure, P_b, given by

$$P_b = T + 3S_{H\ min} - S_{H\ max} - P_o, \tag{1}$$

where $S_{H\ max}$ and $S_{H\ min}$ are the greatest and least principal horizontal stresses (compression is positive), P_o is pore pressure, and T is the tensile strength of the rock. The fracture should form at the azimuth of $S_{H\ max}$. After the fracture has been extended, the pumping is stopped, the well is sealed off, and the shut-in pressure is measured. This pressure is assumed equal to the least principal compressive stress because the fracture should propagate in a plane perpendicular to the direction of this stress. Assuming that one of the principal stresses is due only to the vertical pressure of the overburden, S_V, the fracture both initiates and propagates in a vertical plane, and $S_{H\ min}$ is taken to be equal to the shut-in pressure. Estimates of the least principal stress that are based on the use of shut-in pressure are consistently reliable and often show regional conformity (Bredehoeft *et al.*, 1976). P_o can be either measured or estimated, T can be determined from laboratory tests on recovered core, and Eq. (1) theoretically can be used to yield $S_{H\ max}$.

Because recovery of core for determination of tensile strength can be expensive, and T is a fairly unreliable parameter, an alternative to Eq. (1) for computing $S_{H\ max}$ has been used by several investigators. By repeatedly pressurizing the well after fracture formation, the pressure at which the fracture opens abruptly (with zero strength) can be determined. $S_{H\ max}$ can then be determined with $T = 0$ substituted into Eq. (1). Zoback and Roller (1979) show that very repeatable results can be obtained with this method.

An alternative and physically more-rigorous theory for use in impermeable, fractured, or jointed rock comes from fracture mechanics (Abou-Sayed *et al.*, 1978):

$$P_b = \frac{0.75K_{IC}}{\pi\sqrt{L}} - 0.5S_{H\ max} - 0.5P_o,$$

where K_{IC} is a critical-stress-intensity factor, L is the natural fracture or joint length, and the other terms are as defined above. In this theory also, $S_{H\ min}$ is taken to be equal to the shut-in pressure. Although the fracture-mechanics approach is more exact in fractured and jointed rock, and although most rock is flawed to some extent, the difficulty of estimating K_{IC} and L has precluded its widespread application.

Both linear-elastic and fracture-mechanics formulations can be adapted for use in permeable rock, but, here again, additional information about the rock-mass properties is required. This information, a poroelastic parameter, is not usually available.

FLAT JACKS

Flat jacks are simple devices that, in principle, can be used to measure stress and the static value of Young's modulus near free rock surfaces. These devices, made by welding together two metal sheets and incorporating a tube for oil or water to enter between them under pressure, are usually inserted or cemented in long, narrow slots cut into rock surfaces using the drill-and-broach method. The slotting relieves the normal stress parallel to the working surface and causes a measurable amount of closure across the slot and extension in the host rock adjacent to the slot. Subsequent pumping of the flat jack expands the slot until a pressure is reached at which the initial closure is canceled. This pressure is equal approximately to the original stress that existed across the slot before it was cut. This technique is one of the examples of the active method of stress measurement (Jaeger and Cook, 1969).

The technique has been adapted for measurements in boreholes by Potts (1959), May (1960), and Panek (1961), among others. These adaptations measure changes in stress induced by excavations and other man-made disturbances. The flat-jack-slot technique also has been modified to monitor remotely the stress changes associated with earthquakes and rock bursts (Swolfs and Brechtel, 1977).

The major limitations of this active or direct method of stress measurement are the necessity to remain near a free working surface, time-dependent effects associated with the slot cutting, and the fact that each device measures only one stress component. The borehole (passive) devices suffer from a largely unknown relationship between the measured change in pressure and stress change, usually assumed to be equal. The effects of changes in temperature and thermal stress on stress-change data are difficult to assess, but, in principle, compensating mechanisms to minimize their influence can be devised at some cost.

BOREHOLE DEFORMATION GAUGE

The U.S. Bureau of Mines (USBM) borehole deformation gauge has been used successfully in rocks with a wide range of physical properties. The gauge construction and details of the overcoring process have been well documented (Hooker and Bickel, 1974). The overcoring process consists of drilling a pilot borehole, positioning the deformation gauge in the pilot borehole, and drilling a concentric borehole over the gauge. The gauge measures three diametral deformations (in the same plane) during overcoring (Hooker *et al.*, 1974).

The thick-walled cylinders that are obtained after overcoring can be tested in a biaxial pressure cell (Becker, 1968) to determine the elastic constants and their anisotropy in the rock. The core can also be tested in a triaxial pressure cell at stress levels comparable with *in situ* levels (Obert, 1964). The unloading secant elastic properties obtained from the triaxial test are used in the subsequent calculations because these properties compensate for nonlinearities in the stress-strain curve of the rock (Aggson, 1977). The deformation measurements and the anisotropic elastic properties are then combined to calculate the stress distribution in the plane normal to the borehole (Merrill and Peterson, 1961; Hooker and Johnson, 1969). If borehole deformation measurements are obtained in three nonparallel boreholes, the complete three-dimensional state of stress can be calculated (Panek, 1966).

The USBM borehole deformation gauge has been evaluated under both field (de la Cruz and Raleigh, 1972; Ageton, 1967; Merrill *et al.*, 1964; Van Heerden and Grant, 1967) and laboratory (Merrill and Peterson, 1961; Austin, 1970) conditions. The laboratory tests consisted of overcoring the deformation gauge in large, concrete samples under known load. Calculated stresses were within 15 percent of the applied load. The concrete used in these experiments contained 1.5-in. (3.8-cm) coarse aggregate. Thus, errors of 15 percent were not unreasonable because the elastic properties were highly variable. Similar experiments in fine-grained granite produced errors of less than 5 percent.

The deformation gauge has been used successfully in boreholes up to 150 ft (46 m) deep. The use of this gauge and overcoring method is limited to rock in which a minimum of 8 in. (20 cm) of continuous core can be recovered (Hooker *et al.*, 1974). The USBM deformation gauge has been used successfully in holes drilled vertically up, vertically down, and at numerous other inclinations. The presence of water in the hole has no effect on the measurement.

DOORSTOPPER

The Council for Scientific and Industrial Research, South Africa (CSIR) doorstopper may be used successfully in both hard and soft rocks that respond in an elastic manner on relaxation. In special cases, the doorstopper also gives data on the time-dependent relaxation of rocks. The quality of these data is highly dependent on the properties of the adhesive used to bond the doorstopper to the rock.

Most doorstoppers are designed to fit into an *NX* (7.6-cm) or smaller borehole. The sample to which the doorstopper is bonded is then less than 7 cm in diameter. This relatively small sample size permits use of the doorstopper in a more intensely fractured rock than is possible with other passive techniques. However, the interpretation of stress data within highly fractured rock is still a subject of considerable debate.

The doorstopper may be bonded to rock in holes filled with water, provided the proper epoxy is used. The main limitation in a hole filled with water is that debris from drilling is difficult to clear, and in many cases the doorstopper is bonded to surfaces that cannot be checked for cleanliness. Even in dry holes drilled downward, the depth to which holes can be cleaned is limited to less than 10 m. Doorstoppers have been used most successfully in holes drilled upward; in this case, debris is easily cleaned from holes 10 m or more in depth.

In rocks that disk or are ductile, doorstoppers are difficult if not impossible to use. The CSIR doorstopper or other similar instruments are described by Leeman (1969), Greiner and Illies (1977), Gay (1977), and Sbar *et al.* (1979).

TRIAXIAL STRAIN CELL

The original CSIR triaxial strain cell (Leeman and Hayes, 1966; Leeman, 1969) was designed to obtain six independent strain measurements by overcoring in a single borehole. The device contained three 3-gauge strain rosettes that were bonded to the wall of the pilot borehole at known orientations and positions ($\theta = \pi/2$; $\theta = 7\pi/4$). After overcoring with an oversized bit, the complete stress tensor was calculated from the six independent strain changes, using the known elastic constants of the rock.

Further developments and modifications of the triaxial strain cell are reported by Grob *et al.* (1975) and Van Heerden (1976). The former uses pneumatic pistons to set and bond three 3-gauge rosettes to the borehole wall; the latter employs three 4-gauge strain rosettes to improve the precision of the measurement. A recent report by Herget *et al.* (1977) contains a complete description of a 12-gauge device (Van Heerden, 1976) that is commercially available.

PHOTOELASTIC SENSORS

There are two basic types of photoelastic sensors, plastic and glass. The plastic strain gauge (Hawkes and Moxon, 1965; Preston, 1966) is used in much the same way as the doorstopper (Leeman, 1969) and the direct strain-gauge technique (Swolfs *et al.*, 1974). These devices are bonded to flattened surfaces or ends of pilot boreholes and subsequently overcored. The plastic strain gauges have the advantage that poor bonding conditions are immediately detectable, which is not the case with electrical strain gauges. The applications of photoelastic coatings in rock-strain measurements are described by Pincus (1966). A more-recent development is the cast-in-place epoxy method of Riley *et al.* (1977) in shallow boreholes.

The photoelastic stressmeter (glass plug) is a rigid-inclusion borehole device that makes use of the birefringent properties of prestressed glass (Roberts *et al.*, 1964, 1965; Roberts and Hawkes, 1979). The use, applications, and limitations of the device in measuring relative stress are described by Hall and Hoskins (1972) and Roberts (1977). The major advantages of the glass plug are its low cost and efficienty in the field.

Data Reduction

For economic and other pragmatic reasons, data-reduction methods for each instrument are designed to be straightforward and simple to use. Time-consuming and tedious routines are rarely used, except in research applications. Plane-stress or plane-strain conditions are generally assumed, as is collinearity of one of the principal stresses with the wellbore or borehole or normal to the slot in which the stress measurement is made. All passive techniques, but especially the soft types, require some knowledge of the elastic moduli of the host rock. This information is usually obtained by pressure cycling the overcore and instrument in a radial, biaxial cell or by subjecting rock samples to known applied loads in testing machines. Some data-reduction techniques incorporate effects due to anisotropy or nonlinearity in rock behavior.

For many traditional engineering and mining applications, the data-reduction methods are considered adequate. Unfortunately, the magnitude of the error introduced by the various assumptions and idealizations is difficult to assess *a priori*. For example, Benson *et al.* (1970) report a factor-of-2 difference in the moduli computed from plane-stress, thick-walled cylinder measurements (a biaxial technique) and those derived from uniaxial tests of the same material. Even the best-designed laboratory tests can only approximate the *in situ* loading conditions on the rock; thus, if major differences exist between the elastic constants determined by various means, the absolute values of the calculated *in situ* stresses must be regarded as estimates only.

Rock heterogeneity is another source of uncertainty. *In situ* stresses are determined by measuring some property of the rock mass over a small area, a few square centimeters to a few hundred square meters. It is not clear how these should be averaged in heterogeneous rocks to create a representative value for the bulk volume. With many methods, measurements made at separate points in the rock mass must be combined to calculate the principal stresses. Thus, each of these principal stresses is itself an "average" of the stress state in the rock, even before combination with other principal stress values.

Jointing and fracturing are the most widely discussed sources of rock heterogeneity, but rock-property variations due to depositional or intrusive contacts are equally common in the field. Rock heterogeneity can easily account for a 20 percent difference in stress magnitudes measured at adjacent sites (Hobbs and Clarke, 1966).

System Geometry

Boundary conditions assumed in data reduction include circular holes, rigid planar boundaries, and uniform far-field stresses. These conditions may not hold for the rock under study. The assumption of the infinite or semi-infinite extent of the rock medium reduces the accuracy of the interpretation in the vicinity of a free surface, either natural (topographic) or man-made (slope or subterranean excavation face). Much discussion has been devoted to the difficulty of interpreting surface measurements owing to the presence of near-surface bedding, shallow fracturing, and weathered zones. However, in the subsurface, relief by fracturing or flow in the area of high stress concentrations around the working face and the damage zone created by blasting can cause just as much difficulty in interpreting the virgin stress state from measurements in mines or other excavations. In general, stresses in these zones are lower than those predicted by elastic analyses.

Geophysical and Geological Observations as Stress Indicators

Attempts to measure stresses by relieving strains or producing hydraulic fractures can be augmented by careful geophysical and geological observations. Several methods have been used, including earthquake fault-plane solutions, fracture mapping in surface and subsurface rocks, and observations of geologic structures and microstructures.

Earthquake fault-plane solutions—the determination of quadrants of compressional and "tensional" first motions of P waves—can be related closely to the orientations of maximum and minimum principal stress directions at the earthquake focus, and thus can be used to estimate stress conditions at depth (Scheidegger, 1964; Sbar and Sykes, 1973). The magnitude of the stress difference is a function of the model of the earthquake source, but strong seismic constraints (Brune, 1970; 1971) and other geophysical evidence (Lachenbruch and Sass, 1980) seem to indicate that shear-stress drops during earthquakes are probably limited to 10 MPa or less. The ambient shear-stress levels cannot be determined directly. The passive seismic methods of determining deep crustal stress levels are dependent on a natural earthquake source and are not discussed further in this chapter.

Careful mapping and analysis of fracture patterns is a useful method of determining a considerable amount of stress-related information. In many cases, the ambiguous age of the fractures does not permit the separation of present stress conditions from paleostresses. But Price (1974) describes the process of fracture formation in otherwise undeformed sediments and argues that careful analysis and sound deduction are likely to yield at least the present stress orientations (see Raleigh *et al.*, 1972). At the other extreme, the presence of active fault systems can be used to deduce principal stress directions (Anderson, 1951) that match other measurement methods in some locations (Zoback and Zoback, 1980). Commonly, the most difficult geological question is the age of the structure. It is not always possible to distinguish among structures formed in the past in a paleostress regime, those being formed from the relief of residual stress (e.g., by erosional unloading), and those being formed by an applied stress due to continuing tectonic activity.

Microstructures can also be used to great advantage in determining the stress history of the rock (Carter and Raleigh, 1969). The microstructures in minerals tend to be a permanent record of all deformation since the mineral crystallized or recrystallized; hence, the analysis may not be able to distinguish active stress from paleostress. Some minerals, particularly quartz, can record residual stress as an elastic lattice distortion detectable by x-ray methods (Friedman, 1972), so the presence of residual stress can be established.

None of the more indirect methods of inferring stresses can give as complete a description of the stress state of the rock as the strain-relief or hydraulic-fracturing methods. Even so, they should not be overlooked for their ability to provide independent corroboration of the measured stress state of the rock.

STATE OF NEED AND RECOMMENDATIONS FOR RESEARCH

Current and continuing needs in the measurement of stress *in situ* include the following:

- *Improve characterization of* in situ *rock-mass properties.*
- *Improve data-reduction and instrument-calibration procedures, including time stability for stress-change measurements.*
- *Improve spatial and temporal averaging techniques for* in situ *stress measurements, including methodologies for integrating point-stress measurements into a unified picture of stress on a larger scale and understanding of space-time coherence of stress variations.*
- *Make more widespread the use of* in situ *stress measurements and the availability of results.*
- *Improve pore-pressure measurement techniques.*
- *Develop reliable methods for obtaining information about the state of stress in remote volumes of rock and in hostile environments.*
- *Develop alternatives to* in situ *stress measurement for special applications.*

Although not a specific research need, reduced cost or improved cost-effectiveness would increase usage in engineering, geological, and geophysical applications.

Research activities addressing these needs are discussed in the paragraphs that follow; recommendations are considered in three categories, based on the projected length of time and ultimate cost to achieve research goals. The categories are immediate (lower cost, 0-5 years), intermediate (higher overall cost, 5-10 years), and long-range (technological breakthrough required, probably greater than 10 years). This categorization does not reflect the relative magnitude of particular needs. One, improved characterization of rock-mass properties, is fundamental to the achievement of all the rest; but, in general, advances in one area of need are linked to advances in several others. Thus, it is not suggested or even possible that one research activity should be pursued to the exclusion of others.

Immediate

- *Improve data reduction and instrument calibration.*

The existing instruments have been calibrated relatively thoroughly, and data-reduction techniques appear to be reasonably accurate, though not very elaborate. Nevertheless, some problems remain; for example, the access holes required by all current techniques produce their own stress concentrations. These become complicated at the end of the hole where doorstopper gauges are attached. Newly developed strain-measuring instruments need further calibration, especially as the instruments are adapted to high temperatures. Ground-surface thermal-stress effects are observable as deep as 3 m but are seldom removed by data-reduction techniques.

The data-reduction and calibration area will probably require a continued research effort as the techniques are adapted to new thermal and depth regimes.

- *Improve understanding of coherence between measurements in space and time.*

A lack of consistency in results with different types of instruments at the same site, with the same instrument at nearby sites, or with the same instrument at the same site but at different times, is a source of legitimate concern. Instrumental problems must be separated from actual, local variations of stress level in the rock itself. For detailed engineering design purposes, the establishment of a variable-stress level in the rock can be used advantageously when supports or excavation geometry are considered. For tectonic analysis purposes, integration of the stress field into an "average" field generally is desirable, and it is important to be able to explain or eliminate the anomalous data in favor of the most representative data. Therefore, it is valuable to understand the causes of the variations and, if possible, to use the information to improve the characterization of the stress field.

The accuracy of the current measurement technology is too poor to detect the magnitude of absolute stress changes that can be expected from tectonic forces during short periods of time (e.g., years). Relative stress changes can be detected by existing instruments, but they must be installed, maintained, and monitored to provide time-dependent changes. Improved absolute stress measurement coherence could permit detection of true changes in stress from a sequence of absolute measurements. However, because the same point cannot be measured a second time, the coherence between immediately adjacent holes must also be established to validate the results.

- *Refine methods of monitoring stress changes with time.*

Instruments capable of monitoring small changes in stress with time are being developed. Current instruments are either wedged or grouted into place and are useful only for measuring changes, not absolute stress values. These techniques probably do not yet employ the ultimate in instrument design. The stress changes being observed are consistent with tectonic conditions, but the details of the changes are suspect because nearby measurements do not track consistently and instrument drift is poorly known. Few independent measuring techniques are available to verify the stress-change measurements, and more research and applications are needed to establish the techniques as valid.

- *Improve cost effectiveness.*

The present costs of making a successful *in situ* measurement are high—on the order of hundreds to thousands of 1980 dollars per measurement. Numerous successful measurements are needed to verify local stress levels, and, as a result, each useful set of measurements is a substantial project.

There are at least three ways of improving cost effectiveness: reduce the cost of making each measurement, reduce the number of unsuccessful measurements, or reduce the number of successful measurements necessary to establish a local stress state with confidence. The number of unsuccessful measurements in a field program can run as high as 80 percent of the total attempted. Therefore, considerable time and cost savings could be obtained by developing methods to pretest the site for feasibility of measurement. Other high-cost items include drilling, the need for highly skilled field technicians, and installation and measurement electronics—all areas in which equipment development might reduce overall costs.

- *Make more widespread the use and availability of* in situ *stress data.*

An underlying problem with *in situ* stress measurements to date has been the relative paucity of publicly available data. A large number of measurements is required, particularly for regional interpretations, but each measurement is expensive and time-consuming, and the data base is expanding only slowly. To some extent, this problem will be solved with time, but the tools exist now to make relatively good measurements. Therefore, a very valid research objective is simply to obtain enough field data at the present state of the art to permit more detailed analysis of the problems we do face.

Intermediate

- *Improve characterization of* in situ *mechanical properties of the rock mass.*

Stress fields obtained from *in situ* measurements using soft, underground devices depend on accurate values of elastic moduli, particularly in the low-stress range in which stress relief is occurring during the measurements. The presence of fractures, anisotropy, local heterogeneity, or anelastic or irreversible stress-relief behavior would have a substantial effect on the stress value finally obtained. This concern is reflected in attempts to obtain rock-mass behavior characteristics *in situ* rather than by restressing cores in the laboratory at a later time. However, *in situ* properties are difficult to measure, and improvements in the techniques for making the measurements, particularly at locations far from a free surface, would be of major benefit in increasing the quality of stress values obtained nearby.

- *Improve methods of integrating point-stress measurements.*

Stress measurements being made today suffer from the shortcomings of most point measurements. The data are extremely location-sensitive and may bear little relation to the actual integrated value of stress over some meaningful volume. Although long-baseline strain nets covering several kilometers are now common at the ground surface in tectonically active areas, stress measurements commonly are made on baselines a few millimeters long. At that scale, many rocks are highly heterogeneous in terms of both mineralogical composition and fracture spacing. New methods of making more-integrated measurements could reduce both the scatter of the data and the number of independent measurements necessary to obtain a satisfactory "average" stress value.

- *Improve measurement of pore pressure at depth.*

In areas where pore pressures are important, the tectonic (or active) stress being sought is, in fact, the total stress value minus the pore pressure, i.e., the effective stress. Pore-pressure measurements are extremely difficult to make at depth, especially in fine-grained rocks where permeability is low and the pores might not be interconnected. Pore-pressure measurements in fine-grained rocks are particularly sensitive to normal sampling, and the mere drilling of the access hole will have considerable effect on pore pressures in the wall rocks adjacent to the hole. How large this effect is and how seriously if affects future stress measurements are not known. However, it is clear that the presence of high pore pressure can drastically change the predicted fracture stress of the rock based on the total ambient stress measurement alone. Furthermore, high pore pressures have an unknown effect on most of the types of measuring devices now being used. Research could be directed profitably both to the pore-pressure measurements themselves and to improved methods of discounting their roles in the total stress measurement.

- *Extend measurement technology to high temperatures and pressures and to hostile environments.*

Existing measuring techniques are being adapted to make important measurements of stress levels at greater depths from the ground surface and in thermally active environments. Three major problems confront this work. First, only hydrofracture measurements are capable of being made at present beyond about 50 m from a free surface from which drilling can be done. Second, the harsh environments require a generation of new, highly stable, measuring instruments. Third, stress values are both temperature and pressure sensitive; thus, the differentiation of tectonic stress from thermal or gravitational stresses, especially in geologically heterogeneous terrain, will require more-complicated data analysis. This work is likely to be verified only after numerous measurements with different techniques can achieve similar results.

- *Refine or develop alternatives to* in situ *stress measurements.*

Many rock-mechanics applications for which *in situ* stress measurements currently are being used might benefit more from other methods of predicting rock-mass behavior. *In situ* stress measurements are less effective for detecting imminent rock failure than are several monitoring methods that make use of the change in rock behavior near the failure point. A good example is the monitoring of acoustic emissions prior to major failures in overstressed rock. Patterns of acoustic emissions appear to be capable of indicating both the location and the time of failure. Likewise, characteristic strain-rate or convergence-rate changes in openings can signal the onset of unstable rock behavior.

Because progressive-strain and acoustic-emission measurements are easier to make than absolute stress measurements, research into the applicability of these stress-related effects is desirable. If a specific type of rock behavior can be characterized adequately by a more indirect or empirical approach, then the difficult inversion from a measured strain value to stress and reinversion from stress to rock response could be eliminated and the behavior predicted more directly.

Long-Range

- *Develop reliable geophysical methods for obtaining information about the state of stress in remote volumes of rock.*

The Subpanel recognizes a specific need for developing methods of making measurements of stress values in remote volumes of rock, i.e., either not easily accessible from the ground surface by drilling or purposely intended to remain intact for specific future uses. Measurements of stress under these conditions are likely to depend on the secondary stress effects on a more easily measurable property (e.g., seismic velocity or attenuation, heat flux, magnetic or gravitational field) than on direct stress relief. Such secondary measurements are likely to be greatly affected by other rock properties at the site. It is believed that if alternate remote measuring techniques can be developed at all, a major geophysical-research effort will be required and a ten-year time scale for the research and development phase is not unrealistic. While the goal is probably achievable, a specific research program is needed to remove this particular limitation in our abilities to make stress measurements in rocks.

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5

Mapping of Natural and Artificial Fractures

INTRODUCTION

The mapping of fractures is a three-dimensional problem. Careful geologic mapping of fracture systems that intersect the ground surface can provide a three-dimensional but shallow picture of the fractured rock mass. The accuracy and precision of the interpretation decrease with depth. Borehole-contact methods for fracture detection (e.g., the impression packer technique) indicate the fracture pattern immediately adjacent to the borehole. In theory, by drilling enough holes in a rock mass and by extrapolating from surface outcrops, it should be possible to construct a three-dimensional representation of the fracture network. However, drilling many boreholes is not usually an economical method for the dense sampling of subsurface-rock properties. Hence, in order to project fractures downward from the ground surface and outward from judiciously placed boreholes, it is necessary to employ extrapolation in conjunction with remote detection methods.

Fractures range in scale from gross tectonic features, the extent of which are measured in kilometers, down to microfractures measured in fractions of millimeters. Consequently, the methods and the instruments required to map fractures vary over a wide range in terms of sensitivity, resolution, and accuracy. The techniques necessary for remote characterization of single fractures or fracture sets cannot be transferred directly from geophysical methods used in oil exploration. Single discontinuities are smaller in terms of physical dimensions and material contrast within the host rock and, hence, are more elusive exploration targets than are structural stratigraphic traps.

The discussion in this chapter is organized around the distinction between methods that are used to characterize the fracture pattern at the ground surface or borehole wall and those techniques for mapping fractures in the interior of the rock mass. This distinction serves to emphasize the large contrast in detail that results from mapping in these two situations.

Ideally, there are several levels of detail at which fracture patterns can be described from geologic mapping. These include the following:

- The relative abundance of fracture sets (fracture density) among rock types (considering texture, bedding thickness, and fracture location within the geologic framework of the rock mass);
- Spatial and material characteristics of individual discontinuities viewed within the context of local and regional structures (orientation, aperture, and filling material);

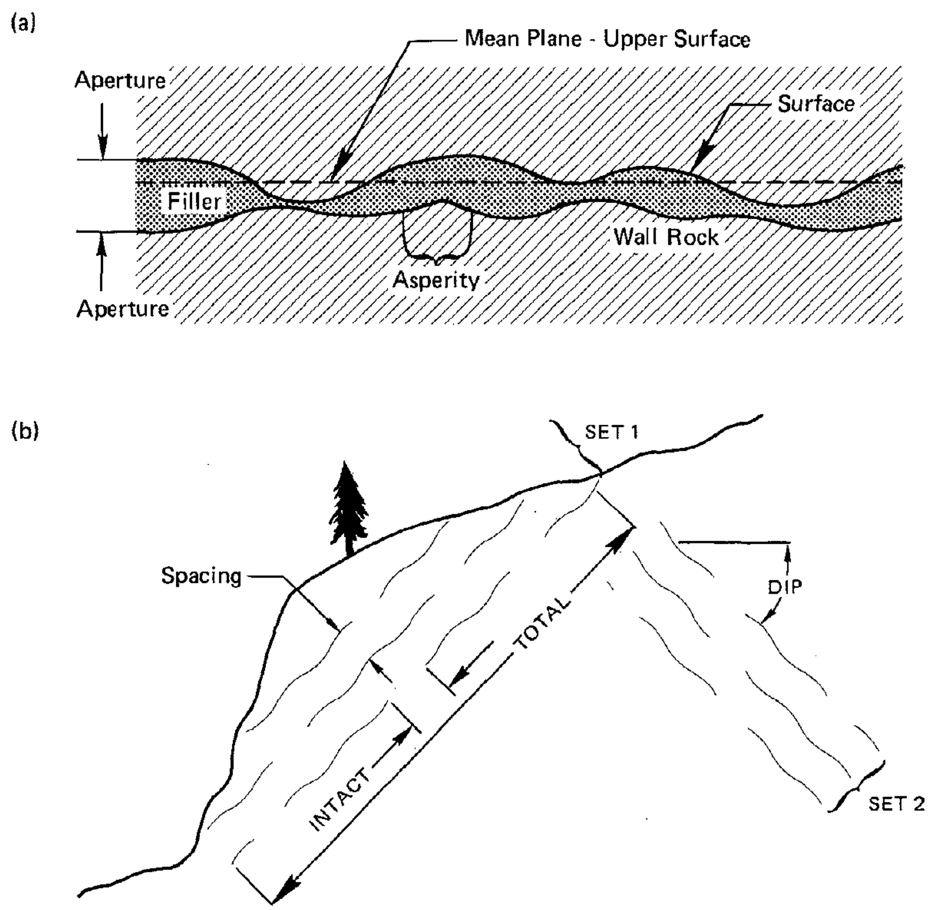

FIGURE 5.1 (a) Individual open discontinuity. (b) Discontinuities in the rock mass.

- The description of displacements along fractures;
- Fracture-surface roughness;
- The relative fracture permeability (as a function of fracture type, relative fracture thickness, fracture filling, and gouge development);
- Absolute fracture spacings;
- Persistence and linkage of fractures;
- Absolute fracture permeability.

Figures 5.1(a) and 5.1(b) illustrate some of the features that are important in fracture description. The term "absolute," as used above, connotes a description resulting from a specific measurement, observation, or prediction.

All parameters that constitute a complete fracture description, as listed above, cannot be measured by methods currently used for remotely mapping fracture systems. At present, remote methods can, at best, only attempt to characterize fracture patterns in terms of the first three levels of detail described and normally do not provide detail beyond the first level.

The Importance of Fracture-Pattern Mapping

A number of important rock properties are affected by the presence of fractures in the rock mass. Among these properties are permeability, porosity, deformability, and rock-mass strength. In turn, a knowledge of these particular rock parameters is essential to the success of geotechnical activities as diverse as nuclear-waste isolation, earthquake prediction, geothermal energy production, and tunneling. Information concerning fracture patterns is, therefore, at least indirectly important in the solution of the engineering problem.

Porosity and permeability control the dynamics of fluid transport and storage in rock. In general, both the porosity and permeability of a rock unit are enhanced by the presence of fractures. Detection and characterization of the fracture pattern in a rock mass facilitate the determination of fracture porosity and permeability, which must be considered in conjunction with water-resource development, underground storage (including water storage), underground nuclear-waste isolation, geothermal energy production, gas- and oil-reservoir stimulation, and fluid transport associated with the *in situ* production of oil shale and *in situ* mineral leaching. A more-complete discussion of matterns concerning porosity and permeability is found in Chapter 3. Fracture porosity is sensitively adjusted to the state of stress in the rock and therefore can be used as a tool for inferring *in situ* stress (see Chapter 4).

Fractures govern the initial deformability of the rock, with the character of filling material, fracture roughness and waviness, and fracture spacing being influential factors. Rock deformability is an important consideration in the design of underground and surface structures in rock as well as in the determination of thermal stress around heat-sensitive storage projects.

Rock-mass strength is influenced by fracture surface properties, fracture orientation, fracture filling-material character, fracture spacings, persistence, and internal fluid-pressure distributions. Therefore, the mapping and description of fracture systems are relevant to the assessment of the stability of tunnels, mines, wells, shafts, and other underground chambers; the construction of foundations; fragmentation for excavation; prediction of subsidence; and the *in situ* processing of mineral commodities.

Earthquake prediction and focal-mechanism studies are predicated on fracture-pattern (fault) models. Hence, the mapping of these relatively large fractures and description of their properties are essential to the study of earthquakes.

This chapter focuses on the methods used to obtain the elemental geometric data from which the above fracture-related physical properties are derived.

STATE OF THE ART

Methods of Mapping Fractures

In the detection and mapping of fracture patterns, a vast assortment of geological and geophysical techniques must be employed owing to great variations in (a) the dimensions and shapes, i.e., curvature and/or roughness, of fractures; (b) the displacements associated with fractures, i.e., faulting; (c) the lithologies in which fractures are found; (d) the proximity of fractures to the line of survey, either along the surface or in the borehole; (e) the three-dimensional spatial orientation of fracture planes; (f) the spacing of fractures in a given medium; (g) the time dependence of fracture characteristics; and (h) the contrast of physical properties between the fracture-filling material and the surrounding medium. Table 5.1 contains a list of fracture-mapping methods classified according to type of survey, i.e., surface, airborne, or borehole.

Some fracture-mapping methods require intersection of the fracture with the ground surface, a tunnel, or the wall of a borehole. Other methods have a remote detection capability, either downward from the ground surface, outward from a tunnel wall, or outward from the borehole. Because the drilling of deep, densely spaced boreholes is expensive and often otherwise infeasible, and because adequate fracture-pattern mapping requires three-dimensional data, the distinction between surface and remote capabilities is important.

SURFACE FRACTURE PATTERNS

A surface fracture system is mapped optimally by conventional geologic methods. Surface geologic mapping can facilitate the detection of fractures that range in scale from large faults to small joint sets and cracks.

TABLE 5.1 Methods of Mapping Fracture Patterns

Types of Survey	Methods: Surface Fracture Patterns	Methods: Remote Fracture Patterns
Surface	Geologic mapping	Gravity[a] Magnetic[a] Electrical (resistivity and surface potential) Electromagnetic (including ground-penetrating radar) Seismic reflection and refraction Passive microseismic and acoustic emission Surface-tilt measurement
Airborne	Photogeology and photogrammetry Satellite imagery[b]	Magnetic Electromagnetic Side-scan radar
Borehole	Borehole photography Acoustic televiewer Oriented core analysis Impression packer Full-wave-form acoustic (character) log Density (gamma-gamma) log Caliper log	Electromagnetic and acoustic reflection[a] (radar and sonar) and through-transmission Vertical seismic profiling Electrical resistivity Borehole gravimeter

[a]Employed in both land and marine surveys.
[b]Classified here for convenience.

By study at the outcrop, a two dimensional (or limited three-dimensional) description of fracture orientation, dimensions, curvature, and spacing may be obtained and the fracture-filling material (e.g., mineralization, gouge) and roughness may be determined (see Figure 5.1).

Photogeologic and photogrammetric techniques also involve visual identification and measurement of surface or outcropping fractures, but frequently the greater distance between the observer (camera) and the ground surface results in reduced resolution. Whereas the minimum fracture dimension that is detectable by geologic study at the outcrop is measured in millimeters, that which can be observed using photogeology is often greater. However, an overview of often intermittent, surface lineament patterns is easier to obtain from aerial photographs than from mapping along a surface traverse. Satellite-imagery techniques, while nonvisual in principle, are essentially an extension of photogrammetric methods. Computer-enhanced photomosaics, composed from multispectral Landsat data, permit resolution of features with dimensions of 80 m or greater (Offield *et al.*, 1977). Here, as is the case with all remote-sensing techniques, ground truth needs to be established by hands-on measurements of the fractures.

Subsurface fractures are best detected when they intersect a borehole surface, because most borehole tools used for fracture mapping are effective only for describing fracture patterns at the borehole wall. The caliper-logging tool is a gross detection device of this kind. Borehole photography, the borehole impression packer, and the acoustic televiewer give more detailed data concerning fractures along the wellbore

(Telford *et al.*, 1976; Keys and Sullivan, 1979; Keys *et al.*, 1979; Goodman, 1979).

REMOTE FRACTURE PATTERNS

There are several geophysical-exploration methods that have been used for years in the detection and mapping of zones of intense fracturing: gravity, magnetics, seismic reflection, and seismic refraction. The physical principles underlying the applications of these methods are well known and are not discussed here (Telford *et al.*, 1976). However, in considering the state of the art of fracture mapping, some recent refinements of these traditional methods and some relatively new techniques are surveyed.

Recent trends in the application of the reflection-seismic method, which enhance its suitability for fracture-zone mapping, include the use of higher frequencies, the acquisition of data in three dimensions, and the redundant acquisition of compressional- and shear-wave data. All of these trends contribute to an increased resolving capability of the seismic-imaging process (McEvilly and Nelson, 1979; Waters *et al.*, 1978; Edwards and Mitchell, 1978). Recent research and development of the vertical seismic profiling (VSP) method should result in increased understanding of the transmission and attenuation characteristics of various media, including fractured lithologies (Wuenschel, 1976).

The most noteworthy refinement of the gravity-prospecting method, in recent years, is its use in borehole surveys. By analogy with placing geophone spreads downhole, borehole gravimetry surveys contribute a new perspective from which to "view" subsurface anomalies (Fajklewicz, 1976; Hearst and McKague, 1976). However, this refinement allows the detection only of near-borehole zones of anomalously low density, which may be associated with fracturing.

The transfer of radar, sonar, and tomographic technologies into the field of geotechnical investigation has greatly improved the resolving capabilities of wave imaging of the subsurface. The geotomographic method, which employs borehole-to-borehole wave transmission to probe the intervening rock mass, has been applied to a number of detailed, subsurface mapping problems, including detection of fracture zones (Dines and Lytle, 1979; Laine *et al.*, 1978, 1979; Lytle, 1979; Lytle *et al.*, 1978, 1979). Radar and sonar techniques have been used to investigate a variety of rock types in conjunction with mining, tunneling, and site-characterization activities (Holser *et al.*, 1972; Suhler and Owen, 1978; Cook, 1975, 1977; Dolphin *et al.*, 1978; Stewart and Unterberger, 1976; Coons *et al.*, 1979; Gupta *et al.*, 1972). The use of high-frequency wave propagation in through-transmission and reflection studies has resulted in the delineation of fracture zones at distances on the order of a few tens of meters. Increased resolution is obtained at the expense of reduced penetration, because of high-frequency attenuation effects of earth materials (Dowding, 1979; McEvilly and Nelson, 1979; Farr, 1979; Keller, 1979). The resolution-versus-penetration trade-off, which is an unavoidable limitation associated with remote detection methods, is discussed at length later in this chapter.

A special case of remote fracture-pattern mapping involves the monitoring of hydraulic-fracturing operations, which are used to increase the general permeability of a rock mass. In this context, a time-dependent fracture system can be probed before, during, and after its artificially stimulated extension. Monitoring is accomplished with high-frequency, acoustic through-transmission methods, passive acoustic-emission recording, and high-gain surface-tilt measurements (Wood and Holzhausen, 1979; Wood *et al.*, 1980; Power *et al.*, 1976). The success of hydraulic-fracturing operations also can be evaluated by taking surface electrical-potential measurements before and after fracturing (Bartel *et al.*, 1976). The geothermal environment also contains fracture systems that may be artificially extended for the purpose of hydraulic continuity and fractures whose properties are time-variant because of fluid-transport phenomena. Monitoring techniques used with hydraulic-fracturing operations are also applicable in the geothermal situation.

It is important to recognize that the methods described above for detection and mapping of remote fracture zones are generally incapable of delineating single, discrete fractures. Unlike surface-mapping techniques, many of which can detail both individual and sets of discontinuities, remote detection methods reveal anomalies associated with aggregate effects of a *zone* of fractures (e.g., low density or the attenuation of wave energy).

Comparison and Classification of Methods

GEOLOGICAL VERSUS GEOPHYSICAL METHODS

For the sake of emphasizing the relative strengths and weaknesses of fracture-mapping methods, it is useful to consider alternative schemes for classification of methods besides the general one utilized in Table 5.1. An obvious distinction can be made between geologic and geophysical methods. On the one hand, surface mapping using geologic methods entails direct observation of (at least one surface of) the rock mass. On the other hand, most geophysical techniques are indirect in nature, yielding a description of the rock mass that results from the interpretation of physical measurements. Similarly, images of the subsurface obtained by geophysical methods are not pictures in the same sense as the surface images acquired using photogeology.

Geologic and geophysical methods are interdependent. Although geologic mapping provides a far more complete and precise fracture description along the line of survey than is possible by geophysical means, accurate projection or extrapolation of surface geology into the subsurface may involve geophysical probing of the interior. Conversely, the interpretation of geophysical measurements of the subsurface is guided by knowledge of the surface geology.

Both geologic and geophysical methods entail extrapolation. Data acquisition by either means is a sampling process that can be evaluated statistically. Fracture-pattern mapping in three dimensions involves uncertainty, which derives from interpolating between sample points and extrapolating features into sparsely sampled or unsampled regions. Because the media being sampled generally are not homogeneous, the uncertainty associated with fracture mapping may be mitigated by probabilistic techniques.

CLASSIFICATION OF GEOPHYSICAL METHODS

The geophysical methods listed in Table 5.1 are frequently contrasted according to whether they are (1) wave-propagation or potential-field methods versus (2) active or passive techniques.

Potential-Field versus Wave-Propagation Methods

With respect to the geophysical methods in Table 5.1, a useful distinction often is made between the potential-field methods—gravity, magnetic, electrical, and electromagnetic—and the wave-propagation methods—seismic, electromagnetic, and acoustic reflection (including sonar and radar); electromagnetic and seismic through-transmission; and acoustic emission. The potential-field and wave-propagation methods both depend on the presence of physical contrasts (heterogeneities and anisotropies) in the medium being investigated. However, wave-propagation methods are generally able to resolve smaller-sized contrasts than potential-field methods. Whereas the potential-field methods measure gross material properties (e.g., density, porosity), wave-propagation methods can be employed for the remote imaging of geometrical shapes.

Active versus Passive Methods

Geophysical methods of fracture detection may also be characterized as active or passive, i.e., according to whether they utilize an artificial or natural source (Sheriff, 1973). On the one hand, the reflection and refraction methods of seismic exploration probe the subsurface with waves generated by a controlled source. On the other hand, passive monitorings of acoustic emissions and of microseismic activity are successful approaches to characterizing geothermal prospects, massive hydraulic-fracturing efforts, and earthquake focal regions. In addition to passive monitoring of seismic and acoustic emissions, the gravity and magnetic methods as well as some electromagnetic methods (e.g., magnetotellurics) generally are classified as passive. Other geophysical methods in Table 5.1 belong in the active category.

Site-Specific and Objective-Dependent Aspects of Mapping

No single fracture-mapping technique is generally applicable. Specific sites vary in terms of their dimensions, the lithologies present, the degree of fracturing in these lithologies, the presence or absence of boreholes, and the defined objective for exploring the site. For example, a partial list of predominant geologic environments relevant to nuclear-waste-containment siting includes salt domes, bedded salt, basalt, granite, shale, sea bottom, welded tuff, argillite, and combinations thereof (Romig, 1979). A mapping method that succeeds at one site may be impossible to apply at another site because of the absence of necessary physical contrasts, e.g., velocity, conductivity, stratigraphic patterns.

It was pointed out above that some geotechnical objectives present unique challenges or settings for the mapping process. For tunneling and mining operations, the locations of shear zones are important. In both tunneling and construction activities, grout-front mapping is significant. The issue of fracture persistence and the definition of fracture end points are important in the context of nuclear-power-plant siting and nuclear-waste isolation, as is the age of last movement on the structural feature. Fault mapping in connection with earthquake-prediction studies may require extremely deep boreholes or an attempt to obtain both high resolutions *and* deep penetration with a single remote-mapping technique.

Owing to site-specific and objective-dependent aspects of fracture-pattern mapping, no single, present method can be employed generally to any satisfactory degree of precision. A beneficial (and necessary) synergistic effect results from the combination of several methods for one mapping problem. The quality of fracture description ultimately obtained in a given situation will be controlled by the inherent limitations of the methods employed.

Modeling

With respect to the fracture-mapping process, the subject of modeling can be considered in three different contexts, all of which are important. First, the entire process of mapping fractures can be viewed as a kind of modeling, in which the true, complex, three-dimensional distribution of physical properties is represented by a simpler distribution obtained by a combination of data interpretation and an interpolation procedure between data points. Second, numerical modeling has become an integral part of geophysical methods both in terms of data reduction, processing, and inversion (interpretation) and in terms of computer simulation of the geophysical data-acquisition process. Finally, laboratory-scale modeling, which is the subject of Chapter 7, provides a unique setting for investigating the fracture-mapping problem.

MAPPING AS A MODELING PROCESS

The process of mapping a subsurface fracture pattern begins with making observations or measurements at various points on the surface and within the rock medium (perhaps including points along boreholes). The three-dimensional array locations at which measurements have been made can be viewed as a distribution of sample points between which there are finite spatial intervals. If the maximum sample spacing in the mapping problem were to be reduced to an infinitesimal dimension, the sampling process would change from discrete to continuous and the fracture pattern could be characterized completely and accurately. To the extent that the actual mapping method utilizes a finite sample spacing and the process is discrete rather than continuous, there is statistical error in the interpreted data. The data are inverted to a simplified picture (model) of the fractured medium, based on some assumed pattern that influences interpolation between sample points.

By increasing the amount of detail observed with respect to the fracture characteristics at each sample point—i.e., by measuring more parameters at each point—the accuracy of the interpretation (model) can be increased. However, statistical uncertainty cannot be eliminated from the model because the density of measurements will be limited by practicality. Extrapolation of fracture data from a sampled to an unsampled region of the rock mass introduces further uncertainty into the model (map) obtained. If the medium were in fact homogeneous, the extrapolation procedure could be based on statistical results obtained in the sampled region. In reality—in the absence of such homogeneity—the extrapolation is guided by subjective probability.

Statistical methods are useful in the design of a field sampling procedure and in the assessment of the data obtained (Baecher *et al.*, 1977). The statistical evaluation of empirical data can lead to a better understanding of frequently recurring fracture patterns. For example, empirical evidence shows that joint trace lengths seem to be log normally distributed and joint spacing exponentially distributed. These distributions appear valid for greatly differing local geologic regimes (Baecher *et al.*, 1977). There are also predictable fracture patterns associated with known geologic structures (Friedman, 1975).

MODELING IN CONJUNCTION WITH GEOPHYSICAL METHODS

Geophysical methods employ data-acquisition and interpretation schemes that can be viewed in the context of statistical modeling as described above. However, within the applied geophysics community, the use of computer simulation of the geophysical method (forward modeling) and reliance on computer-assisted data inversion (inverse modeling) are essential activities whose statistical foundations are often de-emphasized.

High-speed digital computers with large data-storage capacities have made forward modeling a viable alternative to field experiments for learning about fracture mapping. Using a mathematical description of the physical process of detection, various site models can be used for calculating a synthetic response (data set). A proposed survey using a particular detection method can be modeled in the computer to predict the probable survey effectiveness for a given geologic setting. Forward modeling can be used to find the synthetic response to an inferred fracture-pattern model for comparison with field data, in order to enhance the interpretation process (Romig, 1979; Kelly *et al.*, 1976). Extension of the theory concerning fracture mapping by various techniques can be supported by forward-modeling studies. Fundamental research concerning the correlation of geophysical signals with critical geotechnical parameters can be conducted by means of computer simulation. Computer modeling escapes the site-specific limitations associated with actual field experiments. However, it presents its own suite of limiting factors, e.g., use of simplifying assumptions in mathematical approximations and introduction of artificial edge effects.

Computer data processing has become a routine part of geophysical investigations. Interaction with the computer throughout the interpretation process results in great flexibility with data manipulation and analysis. The inverse-modeling procedure is an integral part of the interpretation process. The geophysical inverse problem is underconstrained, and, therefore, an element of ambiguity resides in the final interpretation (Romig, 1979; Taner *et al.*, 1970).

The degree of uncertainty associated with geophysical-data interpretation can be reduced through simultaneous inversion of complementary data sets. For instance, gravity and seismic interpretation might be used as general checks on one another. The seismic data reduction and interpretation processes often depend on the use of correlative well-logging data.

Various signal-enhancement procedures may be employed in the computer to improve data quality through leverage on the signal-to-noise ratio; such techniques are standard in seismic data processing. Data can also be enhanced in terms of its display. The use of three-dimensional and color-plotting capabilities leads to better perception of anomalies (e.g., fracture patterns) in the data by the interpreter (Taner and Sheriff, 1977).

LABORATORY MODELING

The laboratory models that simulate fracture mapping in the field are particularly useful because the medium being probed is well specified. The effects of artificial inclusions and known fracture patterns are perhaps more easily diagnosed in the laboratory-scale model data (Goodman, 1979; Waters *et al.*, 1978). On the negative side, greater efforts may be required for proper scaling and realistic simulation than the demands associated with actual field surveys. When modeling wave-propagation techniques, the laboratory-model scale data may be unnecessarily complicated by mode conversions and boundary reflections, which would be absent from the actual field data.

Resolution

There is a notable discrepancy between the level of detail that can be used ideally in fracture description and the degree to which fractures can be characterized by remote-detection methods. Even the so-called high-resolution wave-propagation techniques detect zones of fracture rather than delineate discrete fractures within a zone.

TABLE 5.2 Resolution and Attenuation Data for Wave-Propagation Methods: Elastic and Electromagnetic Waves[a]

		Distance for 50-dB Decrease in Power		Smallest Size Object Reflecting Waves	
Wave Type	Frequency	Saturated Clay (m)	Rock (m)	Saturated Clay (m)	Rock[b] (m)
Electromagnetic	700 MHz	1.3	8.2	0.013	0.05
	400 MHz	1.6	16.4	0.013	0.08
Elastic	10 kHz	–	13	0.076	0.106
(acoustic or	1 kHz	6.5	130	0.76	1.06
seismic)	100 Hz	65	1300	7.60	10.60

[a]Data from Gates and Armistead (1974); table adapted from Dowding (1979).
[b]Dimension calculated using $\lambda/2$ (λ represents wavelength); dependent on wave velocity in rock.

TABLE 5.3 Resolution and Attenuation Data for Wave-Propagation Methods: Elastic Shear and Compressional Waves[a]

	Frequency Range		
Source (Application)	P (Compressional Waves)	S (Shear Waves)	Distance Range
Explosion–refraction (downhole, cross-hole)	20-300 Hz	10-? Hz	<300 m
Hammer–refraction (downhole, P and S waves)	50-150 Hz	30-80 Hz	<100 m
Mechanical shear (cross-hole)	500-1500 Hz	50-1200 Hz	<20 m
Piezoelectric (cross-hole)	20-60 kHz	5-30 Hz	<15 m
Piezoelectric–surface (crack and flaw detection)	50-100 kHz	20-40 kHz	<2 m
Borehole sparker (cross-hole)	1-10 kHz	0.5-2 kHz	<50 m

[a]Table adapted from McEvilly and Nelson (1979).

Certain rules of thumb for estimating the resolving capabilities of geophysical surveys have been advanced. For example, current, geophysical, potential-field technology permits mapping of anomalies having dimensions on the order of 10 percent of their depth, in most cases. Given special circumstances, such as unusually careful surveys conducted at particular sites, resolution of anomalies may be possible down to dimensions on the order of 1 percent of anomaly depth (Romig, 1979).

The resolution characteristics of various potential-field methods are known empirically, whereas resolution capabilities of wave-propagation methods have been well documented and conveniently tabulated. Tables 5.2 and 5.3 present resolution data for wave-propagation techniques. The tabulated data reflect the well-known correlation between high-frequencies, necessary for high resolution, and the inevitable high attenuation (reduced penetration) (Dowding, 1979; McEvilly and Nelson, 1979; Farr, 1979; Keller, 1979; Gates and Armistead, 1974). The resolution issue is considerably more complex than is indicated by the data in Tables 5.2 and 5.3. Depending on the spatial orientation of a fracture plane relative to incident waves, the wavelength dimension must be compared with fracture-plane dimensions (in the case of fracture-plane reflections) or fracture width (scattering or diffraction of the waves). The inference of the mechanisms behind the backscattering of waves from fracture zones is a critical interpretational challenge in the further development of electromagnetic, acoustic, and seismic-reflection techniques.

Earlier efforts to classify fracture-mapping methods, in order to contrast their relative effectiveness, involved the discussion of active versus passive and potential-field versus wave-propagation methods. Considering these classifications along with the high-resolution/low penetration compromise leads to an attempt to place the various methods described on a single-resolution continuum. An approximation to this kind of continuum is presented in Table 5.4. Obvious deficiencies are noted in the table: some of the methods do not fit the categories of potential field or wave propagation; the resolution scale does not overlie directly the detector-to-fracture distance scale; and the distance scale was used in place of penetration to accommodate airborne methods. Nonetheless, Table 5.4 does provide an opportunity to compare the effectiveness of the various methods.

TABLE 5.4 Range (Penetration)–Resolution Continuum

High ◄——— Scale of Resolution ———► Low

Short ◄——— Distance between Detector and Fracture ———► Long

Surface geologic mapping

- Borehole acoustic televiewer
- Borehole photography
- Impression packer
- Core analysis

  - EM and acoustic reflection and through-transmission
  - Acoustic full-wave-form log

    - Photogeology
    - High-resolution seismic reflection
    - Side-scan sonar and radar
    - Density log
    - Vertical seismic profiling

      - Seismic reflection and refraction
      - Satellite imagery
      - Borehole electrical resistivity
      - Borehole gravimetry

        - Gravity
        - Magnetic
        - Electrical resistivity

          - Electrical surface potential
          - Passive microseismic and acoustic emission
          - Tilt measurement

            - Airborne magnetic
            - Airborne electromagnetic

Wave methods ◄———► Potential methods

Active ◄———► Passive

RESEARCH AND DEVELOPMENT RECOMMENDATIONS

The recommendations presented below should be considered in light of several major points:

- There is a variety of reasons for wanting to map fracture patterns.
- In some cases, it is important to locate and characterize discrete fractures (faults).
- In other situations, the way in which the fracture pattern influences the bulk physical properties of the rock mass is perhaps more significant than the pattern itself.
- It is currently possible to obtain far greater detail for fractures that intersect the ground surface or a borehole than for fractures that are interior to the rock mass (remote).

The emphasis in the list of recommendations is directed toward the need for major improvement in methods used for mapping remote fractures and for extrapolating surface or borehole fracture data into the rock-mass interior. At the same time, however, it is recognized that while borehole contact methods currently are in many respects superior to remote detection techniques, they still need to be improved.

The recommended research items are discussed in order of priority. The assignment of priorities was based to some extent on comparing items in terms of their estimated importance, likelihood for success, and cost. Even so, the assignment of priorities also had to be somewhat arbitrary because not all methods apply to all applications, and different applications of fracture mapping serve different needs. Any particular research item ultimately will be viewed as high priority by the agency whose needs are addressed by the research.

- *Develop analytical models for fracture patterns.*

Analytical models that represent the stochastic nature of fracture patterns need to be developed and calibrated beyond the present state of the art. Such models should not only represent fracture characteristics such as length, spacing, and attitude but also the spatial correlation of these characteristics. Extensive collection of data (existing and new) is required to develop and calibrate the models.

- *Develop exploration-planning and interpretation procedures.*

Rational approaches to exploration planning and analytical or numerical methods to interpret results from fracture exploration are of great significance. Exploration planning and interpretation, which are closely related, must be based on analytical fracture-pattern models, on search and sampling theory, and on models representing the physical characteristics of the various fracture exploration methods. The development of such rational approaches will allow improvement in traditional methods of geophysical (forward and inverse) interpretation and in extrapolation and interpolation of direct-contact data.

• *Develop high-frequency electromagnetic, acoustic, and seismic-imaging techniques (including borehole radar, sonar, and geotomography) for the detection and description of single fractures.*

The following facets of these techniques need improvement: theory, signal processing and enhancement, field procedures (specifically directional control of signal), and integrated systems. Research in this area should result in improved high-resolution remote mapping of discrete discontinuities. These methods would be employed in numerous applications, such as studies of rock-mass strength and stability in mining and tunneling.

• *Improve direct-contact and visual methods.*

Although most widely used, direct-contact and visual methods (both on the surface and in the borehole) need additional improvement. Combinations with shallow penetration geophysical methods need to be examined. Borehole techniques such as the televiewer, impression packer, full waveform, and density logging have the disadvantages that they cannot be employed in hostile environments or at great depths. This needs to be remedied, particularly since these techniques are often the only ones capable of determining the fracture parameters of aperture and filling material. All direct-contact and visual procedures require substantial development in data-processing and management techniques.

• *Develop ground-truth sites and conduct associated experiments in a variety of geologic provinces.*

An advisory panel would be needed to steer this effort. Both excavation and drilling should be employed in the verification process. The geologic environments should include some simple and verifiable rock conditions. Specific experiments need to be designed for the evaluation, correlation, and standardization of various fracture-mapping techniques. Mapping techniques are needed that are observer independent. Data libraries associated with individual sites should be organized to permit extensive study of the correlations between geological conditions and geophysical data.

• *Conduct research concerning the correlation of geophysical signal responses with geotechnical parameters of interest.*

This item is necessary to facilitate the application of methods noted in the first recommendation. The study should focus on the effects that variations in, for example, fracture density, orientation, and size have on wave amplitude, frequency, phase, and velocity.

• *Investigate optimum procedures for three-dimensional acquisition, processing, and display of fracture-mapping data.*

By taking advantage of technological advancements related to interactive computer graphics and color plotting, data-management aspects of fracture mapping can be improved.

- *Develop vertical seismic profiling (VSP) for fracture-mapping applications.*

The geometry associated with VSP data acquisition allows differentiation of rock properties at discrete depths. The VSP technique is a promising remote-detection method that could be applied in such areas as water-resource studies, hydrocarbon-reservoir evaluation, and site characterization for nuclear-waste isolation.

- *Develop methods to integrate fracture-mapping data (acquired by various methods) ranging in scale from kilometers to millimeters.*

Analysis and comparison of effects observed on such drastically different scales is difficult in the absence of appropriate statistical criteria to guide such a comparison. The statistical integration of variously scaled data sets is a topic of importance to fracture-pattern mapping; it is considered at greater length in Chapter 7.

- *Conduct trace-fluid studies to determine the persistence and linkage of fractures.*

This is necessary for calculating rock-mass fluid flow. Attempts have been made to study the persistence of fractures using the injection of trace fluids into a fracture system. The movement of conductive trace fluids along fracture surfaces can be monitored by means of the electrical resistivity anisotropy effects that they cause. In conjunction with hydraulic-fracturing activities, the electrical (surface) potential gradients resulting from fluid injection have been measured. Further research along these lines is needed for improvement of methods to determine the persistence of fractures. The significance of this particular research relates to the discussion of porosity, permeability, and fluid flow *in situ* contained in Chapter 3.

- *Improve field techniques for passive microseismic and acoustic-emission methods; conduct related studies concerning signal discrimination and enhancement; and correlate these data with those obtained from other methods.*

Passive microseismic and acoustic-emission methods are specifically useful for monitoring geothermal activities and the stimulation of hydrocarbon reservoirs.

- *Evaluate fracture-mapping techniques under controlled circumstances, using laboratory-scale experiments.*

For example, high-frequency wave-imaging techniques can be tested utilizing media with fractures of known orientation and filling material. Particular attention must be given to the problems of boundary reflections and appropriate scaling of parameters, as addressed in Chapter 7 of this report.

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6

Rock Fragmentation — Drilling and Excavation

INTRODUCTION

The Subpanel divided its study into three distinct elements, which, because of their time phasing and sequential interdependence, could be considered as separate phases of the study. They are (1) the quantitative identification of mining, drilling, and energy-exploitation methods now facing formidable obstacles related to the state of the art of rock fragmentation or cutting; (2) the detailed description of physical processes influencing or controlling the barriers to energy- and mineral-resource recovery methods; and (3) recommendations for specific experimental and analytical studies required to understand, predict, and control the physical processes of energy- and mineral-resource recovery and to integrate this knowledge into the reduction or elimination of impediments to technology development.

The topics considered generally fall into one of two functional areas or groups: the first group includes energy- and mineral-resource recovery methods dependent on rock fragmentation; the second group includes supporting science and engineering technologies related to specific physical processes. The relationship between these two groups is illustrated in Table 6.1. The dependence of a recovery method on a support technology is indicated as (a) critical, (b) important, or (c) unimportant. Each of the support technology areas is discussed in turn in this chapter, and the reader interested in a specific application area may refer to Table 6.1 for the importance assigned.

A topic that is not truly technology related but is between recovery and support technologies is commercial implementation. This can also be

TABLE 6.1 Importance of Supporting Technologies to the Energy- and Mineral-Resource Recovery Methods Involving Rock Fragmentation or Drilling

	Recovery Methods													
	In Situ Processing				Mining and Excavation					Well Extraction			Waste Disposal	
Supporting Technologies	Oil Shale	Tar Sands	Coal Gasification	Mineral Leaching	Coal Mining	Oil Shale	Mineral Mining	Quarry Mining	Tunneling and Development	Oil	Gas	Geothermal	Nuclear	Toxic Chemicals
Rock fracture	C	U	C	I	I	C	I	I	I	C	C	C	C	U
Rock fragmentation	C	U	I	I	U	I	C	I	I	U	U	U	U	U
Explosive characterization	C	U	I	I	U	I	I	I	I	I	I	C	U	U
Explosive/rock interaction	C	I	C	C	I	I	I	I	I	I	I	I	I	I
Tool/rock interaction	I	I	I	U	C	I	C	I	C	I	I	C	U	U
Fluid/rock interaction	I	U	I	I	C	I	C	U	C	U	U	U	U	U
Tool and machine design	I	U	I	U	C	I	C	U	C	I	I	C	U	U
Special materials	U	U	U	U	U	U	C	U	C	U	U	C	U	U
Rubble characterization	C	I	C	C	U	U	U	U	U	U	U	U	U	U
Fracture evaluation	C	C	C	C	I	I	I	U	I	C	C	C	C	C
Geologic control	I	I	C	I	I	U	I	I	C	I	I	I	C	C
Ground control and subsidence	I	I	C	U	C	I	I	U	I	I	U	I	C	C
Health and safety controls	C	I	I	I	C	C	I	I	I	I	I	I	C	C
Chemical and thermal pollution	I	I	C	I	C	C	I	I	I	U	U	I	C	C
Energy requirements	U	U	U	U	C	C	C	U	C	U	U	I	U	U
Commercial implementation	I	I	I	I	C	I	C	U	C	I	I	I	U	U
Material transport	I	U	U	U	C	C	I	U	C	U	U	I	U	U

Key: C, critical; I, important; U, unimportant.

referred to as technology transfer or research commercialization. Commercial implementation is critically important to the direction of research efforts in the technology support areas, and therefore it should be included as part of the research requirements.

ENERGY- AND MINERAL-RESOURCE RECOVERY METHODS

The review and evaluation of energy- and mineral-resource recovery methods dependent on fragmentation or drilling were approached from two directions. The first was the recovery methods or technology applications that are relevant to commercial operations; the second was the supporting technologies (specific physical processes and constraints) that might apply to several recovery methods. While an extended discussion of rock fragmentation and drilling requirements is effective from the direction of the supporting technologies, the applications and methods need to be identified and some of their critical constraints to efficient commercialization need to be analyzed. The recovery methods or technology applications considered were classified into four categories: *in situ* processing, mining and excavation, well extraction, and waste disposal. Although the latter is not a recovery method *per se,* waste disposal is a critical part of many energy- and mineral-resource recovery operations and does contain rock-mechanics processes critically dependent on fragmentation or drilling. This listing is similar to one developed in another study by the U.S. National Committee for Rock Mechanics (1978).

In Situ Processing

Oil-shale retorting, recovery of petroleum products from tar sands, coal gasification, and mineral leaching are segments of the *in situ* processing category. Of these, oil-shale retorting and coal gasification have the greatest dependence on the various supporting technologies. A quantitative assessment of the research requirements and state of knowledge for the supporting technologies is given in Table 6.2. The letter key for the level of need for research is comparable with the designations in Table 6.1. The state of knowledge is graded numerically according to the research required. A 3 indicates that current knowledge is good and that further research efforts could be applied directly to the solution of specific problems. A poor state of knowledge, or a 1, indicates that long-range, basic, and developmental research is required to provide the tools needed for more applied problems. The most crucial research areas are those designated C1, which indicates a critical need and currently poor knowledge.

In situ oil-shale retorting is most dependent on those technologies used in retort preparation. Mining geometries and explosive loading and detonation schemes that will yield efficiently burnable retorts on a consistent basis must be developed in order to make viable the prospects for synthetic fuels from our vast oil-shale resources.

TABLE 6.2 Research Needs and State of Knowledge for the Supporting Technologies Related to Recovery Methods Involving Rock Fragmentation or Drilling[a]

	In Situ Processing				Mining and Excavation					Well Extraction			Waste Disposal	
	Oil Shale	Tar Sands	Coal Gasification	Mineral Leaching	Coal Mining	Oil Shale	Mineral Mining	Quarry Mining	Tunneling and Development	Oil	Gas	Geothermal	Nuclear	Toxic Chemicals
Fracture and Fragmentation														
Rock fracture	C 2	U 2	C 1	I 1	I 2	C 2	I 2	I 2	I 2	C 2	C 1	C 1	C 1	I 2
Rock fragmentation	C 1	U 2	I 2	I 1	U 2	I 1	C 2	I 3	I 2	U 2	U 2	U 2	U 2	U 2
Explosive characterization	C 3	U 3	I 3	I 3	U 3	I 3	I 3	I 3	I 3	I 2	I 1	C 1	U 2	U 2
Explosive/rock interaction	C 1	I 1	C 1	C 1	I 2	I 1	I 1	I 2	I 2	I 1	I 1	I 1	I 2	I 2
Drilling and Cutting														
Tool/rock interaction	I 2	I 2	I 2	U 2	C 2	I 1	C 1	I 2	C 2	I 2	I 2	C 1	U 2	U 2
Fluid/rock interaction	I 2	U 2	I 2	I 2	C 1	I 1	C 1	U 1	C 1	U 2	U 2	U 2	U 2	U 2
Tool and machine design	I 2	U 3	I 3	U 2	C 1	I 1	C 1	U 2	C 1	I 2	I 2	C 1	U 2	U 2
Special materials	U 3	U 3	U 3	U 2	U 2	U 2	C 1	U 2	C 1	U 2	U 2	C 1	U 2	U 2
Diagnostics and Instrumentation														
Rubble characterization	C 1	I 1	C 1	C 1	U 2	U 2	U 2	U 2	U 2	U 2	U 2	U 2	U 2	U 2
Fracture evaluation	C 2	C 1	C 1	C 1	I 2	I 1	I 2	U 2	I 1	C 1	C 1	C 1	C 1	C 1
Geologic control	I 1	I 2	C 1	I 1	I 2	U 2	I 1	I 2	C 1	I 1	I 1	I 1	C 1	C 1
Environmental Concerns														
Ground control and subsidence	I 1	I 2	C 1	U 1	C 2	I 2	I 2	U 2	I 2	I 2	U 2	I 1	C 2	C 2
Health and safety controls	C 3	I 3	I 3	I 3	C 2	C 2	I 3	I 3	I 2	I 2	I 2	I 2	C 2	C 2
Chemical and thermal pollution	I 1	I 1	C 1	I 1	C 2	C 2	I 2	I 3	I 2	U 2	U 2	I 1	C 1	C 1
Special Problems														
Energy requirements	U 3	U 2	U 2	U 2	C 2	C 2	C 1	U 2	C 1	U 2	U 2	I 1	U 2	U 2
Commercial implementation	I 2	I 2	I 2	I 2	C 1	I 1	C 1	U 2	C 1	I 2	I 2	I 1	U 2	U 2
Material transport	I 2	U 2	U 2	U 2	C 2	C 2	I 2	U 3	C 2	U 2	U 2	I 2	b	b

[a]Key: Need for research; C, critical; I, important; U, unimportant. State of knowledge; 3, good; 2, marginal; 1, poor.
[b]Critical material-transport problems in waste handling do exist but are not related to rock fragmentation or drilling.

While coal gasification is less critically dependent than oil-shale retorting on technical capabilities, it is more dependent on environmental constraints such as subsidence. Realization of large-scale coal gasification operations depends critically on the development of means to monitor and control the generation and burning of rubble and consequent subsidence.

In the processing of tar sands with adequate natural permeability, there is only one critical constraint to commercialization, namely the evaluation and control of artificially induced fractures required to provide well-bore formation communication. The processing of low-permeability tar sands, however, requires all the technologies needed for *in situ* oil-shale retorting and is critically dependent on them.

The *in situ* leaching of minerals, primarily uranium and copper, depends on the formation of adequately rubblized leach beds. However, it does not have a severe dependence on most of the supporting technologies.

Mining and Excavation

Coal mining, oil-shale mining for surface retorting, mineral mining, quarry (open-pit) mining, and tunneling operations are considered in the mining and excavation category. While the majority of the critical problems in *in situ* processing are related to bed-preparation technologies, the mining and excavation methods are constrained critically by the rock cutting, machine design, environmental, and institutional categories. It should be emphasized (Table 6.1) that the three recovery methods with critical problems in commercial implementation are in the mining and excavation category—coal mining, mineral mining, and tunneling and development. This crucial dependence arises because field operations are carried out by numerous and often small-scale operations using traditional and empirically developed methods, and communications between them and the research community are minimal.

Well Extraction

Three recovery methods—oil, gas, and geothermal energy—are included in the well-extraction category. Solution mining through well bores could be included appropriately, but the research requirements for solution mining are analogous to those for mineral leaching in the *in situ* processing category. Oil and gas recovery from reservoir rocks can be significantly different and have been considered separately because of the increasing interest in the tertiary recovery of oil and the production of gas from unconventional sources (e.g., methane from coal, eastern gas shales, tight western gas sands, and geopressured aquifers).

Two support technologies are considered as critical for oil and gas recovery (Table 6.2): rock fracture and fracture evaluation (Chapter 5). Both technologies relate directly to stimulation treatments and are important in improving recovery in tight reservoirs, such as low-permeability shales and western gas sands. The stimulation of geothermal wells involves special explosive formulations, and characterization of these explosives is critically important. In addition, the adverse environment of geothermal drilling requires special consideration of tools and materials for improved drilling techniques.

Waste Disposal

Two categories of waste disposal, nuclear and chemical, have significant fragmentation or drilling problems. Both of these involve subsurface disposal in mine-type openings or well-bore injection into deep, geologic formations. Material-waste disposal, with few exceptions, involves large surface emplacements such as tailings, dams, and ponds; although many critical geotechnical problems exist in surface disposal, they are not affected by drilling and fragmentation.

The three critical areas with currently poor capabilities (C1) for each type of waste are all related to containment. Evaluation of both natural and induced fractures must be closely combined with geologic controls to ensure containment of the waste material.

SUPPORTING TECHNOLOGIES

Rock Fracture and Fragmentation

While a detailed knowledge of several areas of rock-mechanics engineering and science is important to the solution of many vital problems facing the nation in energy- and mineral-resource recovery, effective rock fragmentation has been an essential operation since the inception of the Industrial Revolution. Originally, the problems concerned the technical development of drills, explosives, and blasting methods, largely for the production of iron ore. Today, the problems faced by the United States include a wide variety of technical, ecological, economic, and political processes, all of which are closely interrelated. New technological developments in rock fragmentation are needed to overcome current and future problems for development and production from domestic natural mineral and energy resources. Four categories of supporting technology are involved in the general area of rock fracture and fragmentation (Table 6.2): rock fracture, rock fragmentation, explosive characterization, and explosive/rock interaction.

In the decade since issuance of the report *Rapid Excavation: Significance, Needs, Opportunities* (Committee on Rapid Excavation, 1968), a significant amount of funding and research has been devoted to rock fragmentation methods and mechanics; marked improvements have been made in some areas (Olson, 1974). These improvements have been largely in special areas of equipment and in a more complete understanding of how the rock breaks (Carroll and Sikarski, 1977). However, the current problems related to the mechanics of rock fragmentation are increasing faster in number and character than solutions are being obtained.

In the basic area of rock fragmentation, a more complete understanding of the fracture process under dynamic conditions is needed. This includes examination of fracture initiation, crack propagation, factors influencing direction of crack growth, gas penetration into cracks, effects of transient stresses, loading rates, explosive/rock interaction, and effects of geologic factors such as bedding, joints, and mineralogy.

There is a vital need for improvement in our understanding of the principles of blasting, although in most cases the fundamentals are known. The outstanding progress in recent years has come from research attempts to understand the relationship between charges and the effects of their timing, as well as the effects of the various explosive properties on rock breakage (Winzer *et al.*, 1979). Precision blasting, employing delayed detonators with better than millisecond accuracy, promises to improve conventional fragmentation and is critical in limited-void-volume *in situ* fragmentation, such as for oil-shale retort development.

Rock fragmentation for *in situ* processing, whether for chemical leaching or for retorting, is an important challenge. While the operating constraints are sometimes severe, the desired result usually is production of relatively uniform, small fragments. The need to blast underground to provide a large *in situ* permeability is an art that is new to the American mining industry.

As in other areas of rock mechanics, computer modeling of the blasting processes can provide insights into the influence of explosive properties and their relationship to rock properties. Technology in this area has advanced in recent years, and under ideal conditions the explosive-fracture analysis has been of considerable value. The greatest need for further research in numerical modeling is the development and validation of constitutive equations for rock failure (Chapter 9).

An area needing in-depth rock-mechanics studies is the effect of rock discontinuities (e.g., joints, bedding, small faults) on blasting results. This problem lends itself to straightforward modeling, but results from physical experiments are affected greatly by uncertainties stemming from the natural occurrences of the materials involved. Numerical modeling research is required to improve the constitutive models describing joint and bedding behavior. Because joints contribute significantly to the scaling effects observed in rocks, efforts here are also relevant to the needs discussed in Chapter 7.

Recent research deals with solutions to the problems of automated drilling and blasting in tunnels and stopes to reduce the cost of cyclic operations (Peterson *et al.*, 1979; Wetherell *et al.*, 1976; Clark *et al.*, 1979). Viable machine, energy, and rock-mechanics relationships must be established to provide for their efficient use in a practical method. Research support must be forthcoming for rock-mechanics and machine studies if barriers that exist in machine design and explosive handling are to be overcome. Improvements in fragmentation control of broken rock requiring transport are needed for cost trade-offs and saving of mined material in transport, such as coal.

Research in fracture control, specifically studies of stress waves and fractures developed by contained explosives in photoelastic materials (Dally, 1971; Dally and Fourney, 1977; Barker *et al.*, 1979) shows how stress waves interact with each other and with free faces, notches, and similar items. Much more can be learned about explosive-energy transfer and usage in blasting through additional basic and applied research.

Only a relatively small portion of the explosives used in the United States is applied to underground blasting, but the minerals produced and the excavations made are critical to our economy and security. Most mineral products (except coal) cannot be mined by any means other than blasting; currently, the only means of preparing underground deposits of minerals or fuels for *in situ* leaching or retorting is to use blasting agents or explosives. An increased near-term effort and funding for research and development in the use of explosive energy for underground blasting should be given high priority.

Drilling and Cutting

Four technologies support the area of drilling and cutting (Table 6.2). They are tool/rock interaction, fluid/rock interaction, tool or machine design, and special materials.

The drilling of rock is accomplished by means of percussive, rotary-percussive, and rotary-type drills; the latter includes diamond drills, dragbit drills, and rotary-cutter drills for larger holes (McGahan and Adams, 1975). Percussive and rotary-percussive drilling research has established penetration rates, some basic, specific energy requirements for rocks, and correlations with a coefficient of rock strength (Clark, 1979; Tandanand and Unger, 1975). Major current problems are concerned largely with the definition of rock properties that determine its cutability, fragmentation, and fracturing in relation to the energy output and capabilities of available machines. More-effective drills will be designed and built when additional basic theory and data become available. Data are required about the relationship of pulse magnitude and duration and rock properties (Clark *et al.*, 1979). Down-the-hole drilling in hot rock for geothermal recovery merits special consideration (Varnado, 1979).

Of the mechanical methods of penetrating rock for exploration and rock-mass evaluation, the diamond (core) drill is the most feasible. This method has been the subject of considerable laboratory research (Paone and Bruce, 1963; Paone *et al.*, 1966).

Some attention has been given to nonmechanical rock-fragmentation processes for drilling, such as flame drilling, water-jet drilling, fusion and vaporization, and chemical drilling. The jet-piercing process has some special applications, and water-jet drilling appears to hold some promise. However, mechanical rock fragmentation will continue to be the dominant method of drilling for the foreseeable future.

Three potential systems for increasing penetration rates in geothermal wells were proposed during a recent workshop on advanced geothermal drilling and completion systems (Varnado, 1979). They are water-jet drilling, high-speed downhole motors (which will require the development of high-speed bits), and percussion drilling of brittle rocks.

Many offshore oil or gas wells are drilled from a single platform. Consequently, these wells must be directionally drilled, which raises the problems of hole-direction control and better directional tools. Improved knowledge of how bits interact with dipping beds, and how the rock and tool interact to produce hole deviations, is needed to advance directional-drilling technology. Also, hole stability for inclined holes is a problem deserving specific research considerations.

To date, much of the theoretical work relating to tool/rock interaction has been done for rather idealized conditions. In most cases, the rock has been assumed to be isotropic and homogeneous and either ideally elastic or perfectly plastic. In order to provide better theoretical descriptions of the rock, work needs to include the effects of anisotropy and inhomogeneity, fluid effects in porous rock, and loading-rate effects. Strain-hardening and consolidation or compaction effects in porous rock must also be considered. For elastic brittle rocks, the theory of tool/rock interaction requires a description of fracture growth and chip formation, and this problem is not yet well understood. Research is needed to determine how fractures change the stress field as the fragmentation process proceeds and to relate crack growth to stability of fractures. The problem of indexing also needs more attention; this involves the interaction of the tool with previously formed craters or cuts and is important for optimization of rock-fragmentation processes in drilling. Design problems include determination of the best tool shape and the optimum direction of attack to accomplish specific design goals. More-refined experiments are needed to understand tool/rock interaction and to substantiate analysis of the onset, growth, and stability of fractures during chip formation.

Energy requirements increase rapidly with processes that produce small particles. The goals of lower costs and higher drilling rates provide incentives for advancing technology by improving the understanding of the tool/rock interaction processes. Research and experiments in tool/rock interaction are needed to postulate and prove the theories and principles governing rock fragmentation during drilling. The designers of tools need more basic data relating to rock properties, tool geometries, and methods of rock attack. Research must produce the physical and engineering data related to these processes for use by the tool designer.

In many drilling applications of rock fragmentation, the limiting factor in improving drilling efficiencies does not involve the mechanical fragmentation process itself but rather the hole-cleaning process. During the drilling of deep oil, gas, or geothermal wells, high bottom-hole fluid pressures can interact with porous formations and with non-porous shales to induce rock ductility. This ductility inhibits rock-fragmentation processes that involve crushing or brittle fracture. Rocks in the ductile state must be attacked by methods that utilize cutting in a manner somewhat similar to the machining of ductile metals. Recently developed stratapak drill bits have a potential for improved shale drilling when optimizations of cutter design and hydraulics have been achieved. Differential pressures between the borehole fluid and formation pore fluid also make removal of cuttings difficult.

The major advances in tunnel boring during the past decade have been derived from increased penetration rate and increased machine availability.

Major progress has resulted from better cutter and bearing performance, improved machine design, and better understanding of the effects of rock structure and properties on the boreability of rock. For incompetent rock, the improvement of methods of rock support immediately behind a tunnel boring machine (TBM) has contributed to increased machine availability and consequently to better advance rates. Mixed-face conditions offer special problems and research challenges for both machine design and ground support.

A reasonable projection of foreseeable technological advances indicates that advances have leveled off, or will do so in the very near future. This leads to the conclusion that there will be no significant lowering of costs (relative to 1979 dollars) or increase in advance rates in the near future. One exception could be the successful application of high-pressure water jets to assist in cutting, particularly soft rocks. The application of water jets to tunnel boring is still in the experimental or developmental stage and has not yet been established as a practical operation in the United States.

In order to cut material with a water jet, it is necessary that a threshold pressure be developed. Above this pressure the water jet will cut the material most effectively; below it, cutting is not significant. Laboratory research has shown that threshold pressure is controlled to an extent by the volume flow rate. It has been demonstrated that the same extraction rates for cutting granite can be achieved at high flow rates with fluid pressures of only 103 to 138 MPa as can be achieved at lower flow rates but at operating pressures of 414 MPa. Subsequent to these experiments, the granite industry has moved toward applying high-pressure water jets for cutting rock as opposed to the conventional flame-jet burning system.

Major applications of water-jet cutting, primarily in coal mining, have been made in foreign countries; for example, large jets are currently used for mining coal in bulk in Canada. However, there has been only limited application in the United States, although high-pressure water jets have a great potential for use in slotting, hole drilling, coal mining, and as an assist in tunnel boring. They are more quiet in operation than other processes that accomplish similar tasks, they are safe to use, and, in the case of coal mining, they minimize explosion-causing coal dust.

Most of the research in water-jet applications for drilling has been carried out in the laboratory, with limited field research. Very little fundamental work has been done on the principles involved in high-pressure water-jet technology, although it can be shown that substantial increases in performance can be achieved for systems that are optimized. Where theoretical and basic studies have been conducted, potential improvements for such an optimized system have been illustrated by field studies of prototype, longwall, water-jet mining machines.

Field programs are needed to demonstrate further the essential benefits that can be achieved from the application of high-pressure water jets in mining. Also, there is an increased need for programs to provide funding for basic research in the promising area of water-jet cutting systems. In many instances, these systems have great advantages over conventional systems, not only because of their potential for productivity but also because they can be constructed to be much smaller, quieter, and safer.

Diagnostics and Instrumentation

Three support technologies are grouped under this heading. Two of them, fracture evaluation and rubble characterization, relate to the effects of processes used to modify rock properties. The third, geologic control, concerns the definition, principally by detailed mapping, of the geologic setting in which various rock fragmentation or drilling operations are carried out. The instrumentation technologies are important to all of the *in situ* processing methods (Table 6.2). Rubble characterization and geologic control are especially important to the control of subsidence in *in situ* coal gasification.

For the various mining and excavation methods, geologic control, and in particular mapping, is especially critical to tunneling operations. Poor geologic mapping has contributed significantly to the costs and delays of major tunneling projects. A broad range of geophysical, remote-sensing, and advance-probe techniques need to be explored and developed for improving the understanding and prediction of the geologic environment into which tunnels will be driven.

Fracture evaluation (Chapter 5) is especially important to well-extraction methods. It is critical to the further development of secondary and tertiary recovery methods in oil reservoirs because the orientation, extent, and conductivity of induced and natural fractures can dominate the efficiency of any secondary or tertiary recovery operation. Better methods for determining the geometry, orientation, and conductivity of artificially induced fractures would be extremely valuable in the primary recovery of gas, oil, and geothermal fluids.

Fracture evaluation and geologic control are crucial components of the waste-disposal methods analyzed in this study. A detailed and quantitative description of both natural and induced fractures is required for the proper evaluation of all nuclear-waste disposal approaches. Chapter 5 presents a more detailed consideration of the problems of fracture evaluation for both well extraction and waste isolation.

Environmental Concerns

Three support technologies for energy- and mineral-resource recovery methods involving rock fragmentation and drilling are related to the environment. Two of these, ground control (including subsidence) and chemical or thermal pollution, are concerned with the environment as observed by the bystander and society as a whole. The third, health and safety controls, concerns the environment of the engineers, miners, and other personnel involved in the recovery operations. Naturally, there is some overlap between these areas and a great deal of overlap between ground control and safety. With the exception of ground control, environmental concerns do not concern rock mechanics *per se*. It is important, however, that researchers in rock mechanics areas be cognizant of and responsive to applicable environmental constraints.

Rock fragmentation and drilling for tunneling, mining, and excavation produce a variety of environmental hazards. These result both directly (e.g., dust from a cutting machine) and indirectly (e.g., chance of accidental explosion of methane by a coal-mining machine) from the processes of fragmentation and drilling.

Health and safety problems are those that directly affect the miners or other workers engaged in the fragmentation or drilling effort. The most serious hazards are the dust and fumes that they breathe, the possibility of disabling accidents, and noise. Many of these can be controlled by following proper procedures, whereas others are difficult. In some cases (e.g., noise and radioactivity) universally accepted safe-dose limits have not been established. Although many old problems (e.g., dust and machine-cutting parameters, collectors, and sprays) are yielding to long-term research, new processes are creating additional health and safety hazards, such as fumes resulting from coal gasification and fires and explosions associated with *in situ* oil-shale recovery.

Ground control and chemical- or thermal-pollution problems differ from those of health and safety in that they affect bystanders and neighbors. Noise and vibration can be serious, but the most widespread effects result from air and water pollution. Air pollution can probably be controlled, provided that the price can be paid. Water pollution is more serious in that it is harder to control (e.g., *in situ* leach solutions), harder to prevent (e.g., acid rain from coal combustion), and harder to reverse. The entire radioactive-waste disposal problem, control of radioactive mine tailings, dust and groundwater pollution, and radioactive phosphates must be seriously examined as there is no consensus of finding solutions that will be effective.

The principal health and safety and environmental concerns associated with the various recovery methods are identified in Table 6.3. It is important that the potential hazards associated with technology development be identified and that the impact of such hazards on the recovery methods be evaluated. Potential health and safety and environmental hazards could dictate that the development of certain technologies not be undertaken or that special planning and precautions be taken to control the hazards.

Special Problems

Three topics have been included in this general support technology category. Only one of these, material transport, is a technology *per se*. The other two, energy requirements and commercial implementation, are related to a philosophy of establishing research directions and the interaction between research and development efforts and final application.

Until quite recently, rock has been excavated using a rather narrow range of techniques. Except for special cases, drill-and-blast methods have been used that have changed little in principle since the introduction of black powder. Recently, nonexplosive machine-excavation means

TABLE 6.3 Technologies for Rock Fragmentation and Resulting Hazards

Technology Applications	Health and Safety	Environment
In Situ Processing		
Oil shale	Fumes and gases[a] Fires and explosions Dust	Groundwater[a] Ground control (modified *in situ*)
Tar sands	Fumes and gases[a] Fires and explosions	Groundwater
Coal gasification	Fumes and gases Fires and explosions	Groundwater Fumes
Mineral leaching	Fumes	Groundwater
Mining and Excavation		
Coal	Ground control[a] Fumes and gases (underground)[a] Dust and noise Fires and explosions Mobile equipment	Surface water and groundwater Ground control (subsidence) Noise and vibration (blasting) Explosives (surface: flyrock and fumes)
Oil shale	Fumes and gases (underground)[a] Fires and explosions Noise Mobile equipment	Surface water and groundwater Dust and noise Explosives (surface: flyrock and fumes)
Mineral mining	Ground control[a] Gases (radon from uranium)[a] Dust (asbestos) and noise[a] Mobile equipment Fires and explosions	Dust and fumes Radioactivity (phosphate and uranium mining) Noise Surface water and groundwater (tailings and smelting)
Quarry mining	Dust and noise Mobile equipment	Dust and fumes Noise and vibration Explosives (flyrock and fumes)
Tunneling and development	Dust and noise Ground control Mobile equipment	Noise and vibration (blasting)
Well Extraction		
Oil	Mobile equipment Fumes and gases Fires and explosions	Fumes
Gas	Mobile equipment Fumes and gases Fires and explosions	Fumes
Geothermal	Fumes and gases	Fumes Ground control
Waste Disposal		
Nuclear		Surface water and groundwater[a] Dust Ground control (long-term stability)
Toxic		Fumes[a] Surface water and groundwater Ground control (vibration from pumped storage)

[a]Most serious.

have been developed, at first by extreme, and perhaps not optimum, extrapolation of small-hole drilling technology. For a brief time, various exotic techniques promised to revolutionize the technology.

As experimentation accelerated in a variety of excavation means, the energy consumed to accomplish the task was recognized as an important and convenient basis for comparison of techniques. It was readily apparent that conventional excavation means employing percussive, drag, and roller cutters were reasonably comparable in terms of specific energy (or energy per unit volume excavated), whereas the specific energy requirements of various novel means were typically an order of magnitude or more higher. In fact, large power requirements have discouraged most further experimentation with novel concepts, in terms of the cost and complexity of the necessary equipment if not in direct energy cost *per se*. For this reason, the following discussion relates primarily to more-conventional mechanical excavation techniques, in which it is believed that substantial improvements can be made.

With respect to energy considerations in the design and development of mechanical excavation devices, it is doubtful that energy consumption *per se* is of primary concern as long as one treats relatively conventional mechanical fragmentation devices. However, energy consumption *is* of concern because initial machine costs, size, complexity, ventilation problems, wear rate, cutter cost, and maintenance cost rise with increasing power consumption. Thus, to explore means to reduce specific energy is to look for ways to decrease many significant design and performance problems.

In the future, the type of power and energy required for excavation will become a more-critical factor. For example, a tunnel-boring operation in either a populated or an isolated area requires electrical power in amounts considerably above the local normal load. Problems with operating fuel-powered equipment are becoming more severe, not only from the standpoint of cost but also of the availability of fuel.

The bulk of the energy now used in blasting is furnished by explosives based on ammonium nitrate. This and other ingredients are becoming more costly, and the availability of basic manufacturing materials for explosives will be a crucial factor in the future.

The foregoing emphasis on improving conventional techniques is not intended to indicate that exotic methods should be abandoned. If we were to concentrate our research only on familiar methods, our long-term progress would be very slow indeed. However, it should be noted that basic research is long term in nature, and it does not promise to revolutionize the industry promptly. Therein lies an important recommendation—that research on advanced rock-excavation methods be supported by sufficient *long-term* commitments that are commensurate with the time span of worthwhile progress.

The purpose of the various research and development efforts considered in the foregoing is reduction to commercial practice, so that the fruits of the efforts will benefit society. As has been stated, commercial implementation, although not a technical issue, is critically important to the sense and direction of the necessary research efforts, and, therefore, it should be considered carefully in research planning.

Indeed, concern for ultimate commercial implementation should motivate some basic improvements in long-range research planning.

Solution of underground problems is particularly difficult in both research and implementation efforts. In the former, no reliable means for simplifying or scaling experimentation are available. In the latter, only full-scale applications are meaningful, and these are so costly that applications of research and development are limited to evolutionary changes that are themselves limited by the risk permitted in commercial ventures. Furthermore, in underground applications human risk, as well as economic risk, must be considered if workers are present; if workers are not present, there is the added difficulty of monitoring experimental progress. In any case, the risk of destroying a valuable resource exists. For these and related reasons, technical progress in underground operations has not been rapid.

RECOMMENDATIONS

The review of energy- and mineral-resource recovery methods and their supporting technologies presented in this chapter has identified numerous areas for increased and concentrated research efforts. Recommendations for both specific and generic research were made in terms of the needs of the recovery methods and the state of the art in the supporting technologies.

The following recommendations are formulated specifically for the research efforts considered to be especially critical to the development of rock-fragmentation and drilling capabilities. Because these recommendations are quite specific, there may be errors of omission that should not be construed to imply the lack of a critical need for any research effort not itemized here. These recommendations also are restricted to areas and support technologies that directly involve rock mechanics. Efforts in related supporting technologies, such as instrumentation development, environmental control, or material handling, are not elucidated explicitly, although efforts in these areas must be pursued in order to complement the direct rock-mechanics research efforts.

Rock Fracturing

Research efforts should be increased and focused toward a better understanding, prediction, and control of

- *Fracture propagation in naturally fractured rock;*
- *Morphology of fractures in naturally fractured rock;*
- *Very-low-rate fracturing during thermomechanical loading;*
- *Microfracturing by differential thermal expansion in granular rock;*
- *Thermochemical effects in fracturing;*

- *Controlled, dynamic fracture propagation for presplitting;*
- *Dynamic fracture propagation in well-stimulation operations;*
- *Fracturing processes in caving and subsidence.*

In addition, the development of constitutive equations for rock fracturing, suitable for inclusion in various numerical models, is required.

Rock Fragmentation

Specific research efforts should be addressed to

- *Stress-wave interactions in blasting operations;*
- *Controlled-blasting techniques for limiting damage to residual rock structures;*
- *Controlled-blasting techniques for preparation of high-permeability rubble beds for* in situ *processing;*
- *Quantitative description and understanding of the role that discontinuities play in rock fragmentation;*
- *The development of constitutive equations for use in numerical-modeling efforts.*

Explosive/Rock Interaction

Specific research efforts should be devoted to

- *Understanding and quantifying the role of high-explosive, gas pressurization of fractures in rock fragmentation;*
- *Understanding the yielding and crushing of rock by stress-wave loading in blasting operations;*
- *Quantifying the role of tailored explosive formulations in improved fragmentation and in improved explosive stimulation of wells.*

Tool/Rock Interaction

Specific research efforts should be focused toward an improved understanding of

- *Ductile flow of rock at high temperature, pressure, and pore pressure;*
- *Physics of chip formation in rock displaying ductile behavior;*
- *Ways in which rock cutting might be modified or improved by the utilization of tools of special geometries and materials;*
- *Techniques to minimize frictional effects in drag-bit cutting;*
- *Mechanisms of rock failure and chip formation under dynamic (percussive) bit loading.*

Fluid/Rock Interaction

Research efforts should be directed toward a better understanding of

- *Erosion of rock under the effects of steady fluid-jet impact;*
- *Rock fracture under continuous or steady fluid-jet loading;*
- *Crushing and fracturing of rock under the effects of impulse-jet loading;*
- *Rock conditioning by water-jet action in roller-bit cutting;*
- *Rock conditioning and modification of frictional behavior by water-jet action in drag-bit cutting.*

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7

Scaling Test Data to Field Applications

INTRODUCTION

In the field of rock mechanics, laboratory-measured quantities obtained from tests conducted on small rock specimens generally do not yield data that are directly applicable to the *in situ* rock mass from which the specimens were taken. Removal of samples from their environment inevitably disturbs them, altering their mechanical behavior. Furthermore, a small rock specimen is usually a continuous material, or approaches such a state, whereas rock masses are discontinuous owing to the presence of such geological features as joints, bedding surfaces, and faults. The smaller the specimen, the fewer the discontinuities present; hence, a smaller specimen tested in the laboratory may be expected to have different characteristics (higher strength and modulus) than a large specimen *in situ* (Judd, 1965).

In order to obtain realistic data reflecting rock-mass conditions, *in situ* tests on large specimens may be preferable to laboratory tests that provide rock-material characteristics. *In situ* tests also are advantageous because the large rock specimens are tested under the same environmental conditions as those prevailing in the rock mass. However, *in situ* tests are expensive, time consuming, and in general less well constrained; hence, they are not so attractive in engineering practice as small-scale tests conducted under controlled laboratory conditions. Furthermore, there are some controversial questions pertinent to *in situ* tests. One can argue, for example, that interpretation of measured *in situ* data is at best an estimation and open to criticism and thus does not justify the high expenditure. It is clear, therefore, that if laboratory-test results could be scaled reliably to field conditions, then small-scale, easily controllable tests would provide a convenient means for the determination of rock characteristics necessary for the design and construction of engineering projects in rock.

The study of scaling laboratory-test results to field problems entailed interaction with almost all of the other Subpanels because the subject of this chapter is not sharply demarcated from their interests. As a result, some overlap has been necessary. It has been indicated that reliable field measurements are essential if meaningful correlations between laboratory and field data are to be established. This involves detailed and careful mapping of the test site, especially the planes of weakness, as discussed in Chapter 5. It is also important that the stress field in the area be understood, as indicated in Chapter 4, to enable interpretation of the data obtained. The groundwater conditions involving the parameters dealt with in Chapter 3, and the thermomechanical properties covered in Chapter 8, need to be known for most applications. Numerical modeling, the subject of Chapter 9, is required to simulate the field conditions so that laboratory data can be utilized in a rational manner. Improved fragmentation techniques, the major emphasis of Chapter 6, are essential for the economic construction of any large-scale facility in rock, the justification for existence of the entire scaling or interpretation exercise.

In reviewing the relation of laboratory-measured quantities to *in situ* conditions, it was necessary first to establish which *in situ* conditions—i.e., rock-mass characteristics, phenomena, or events—are most important in engineering applications. The subsequent steps were to consider which *in situ* tests may be used to characterize the field conditions and then to determine whether any links are available for extrapolating laboratory-test data to *in situ* conditions.

IN SITU CONDITIONS IMPORTANT IN ROCK-MECHANICS APPLICATIONS

For the purpose of this chapter, *in situ* conditions are defined as the *in situ* state of stress, water flow and pressure, and temperature, as well as characteristics of a rock mass such as strength, deformability, and frictional properties. Other characteristics such as chemical and mineralogical composition, electromagnetic properties, and radioactivity are omitted because their influence on structural stability is minor. Such events or phenomena as earthquakes, rock bursts, and seismicity are also included as *in situ* conditions, the understanding of which might be increased through relevant laboratory studies.

Rock-mass characteristics of particular significance in static rock mechanics are as follows:

- Modulus of deformation or elasticity, essential for the design of tunnels, chambers, mines, and dam foundations;
- Compressive strength, important for the design of mine pillars;

- Shear strength, important in rock slopes, foundations, and dam abutments;
- Tensile strength, important in mine roofs;
- Frictional properties (cohesion and friction angle), important in fractured rock masses, yield zones, residual strength, and rock-bolt design;
- Bearing capacity, important for mine floors and foundations;
- Postfailure modulus, important in longwall mining and pillar design;
- Seismic event precursors, important in rock-burst studies and potential roof falls;
- Fluid-flow transmissibility and storage, important in petroleum and geothermal engineering and in dam foundations;
- Thermomechanical response, important in nuclear-waste disposal;
- Anelastic behavior (e.g., creep and dynamic phenomena), important in radioactive-waste disposal, nuclear blasts, and earthquakes.

Within the strong-motion, rock-dynamics framework, the scaling of laboratory-test results to field design is interpreted broadly to include mathematical modeling and testing, in addition to physical modeling and testing. Links found to exist for correlating laboratory models to actual full-scale field situations should be viewed within a probabilistic framework because knowledge about true field conditions (e.g., discontinuity geometry, rock-mass stresses) is always imprecise. The fact that all laboratory and *in situ* measurements yield scatter or dispersion about some mean value indicates that the dispersion, in addition to the mean value, should be incorporated into rock engineering, as well as an appreciation of the number of tests that make up the data set.

Strong-motion rock dynamics encompasses a broad range of research endeavors. This review has been divided into three basic research areas:

Earthquake source—Conditions at an earthquake source are important to ascertain in order to improve earthquake prediction and to characterize more accurately the amplitude, duration, and spectral content of earthquake-design motions.

Transmission path—Rock conditions between an earthquake source and a site have a strong influence on site dynamics.

Site dynamics—Ultimately, the success or failure of a particular project depends on the ability to characterize the site, in terms of geometry and physical properties, and to calculate the site response to input seismic motion.

Earthquake Source

Few attempts have been made to conduct comprehensive *in situ* tests in the vicinity of an earthquake source, even though many mathematical models have been developed that need such data as input. Of particular importance in characterizing an earthquake-source function are the following:

In situ *state of stress*—Important aspects of the *in situ* state of stress include the distribution and anisotropic characteristics of the stresses, together with the redistribution and changes in isotropy as a result of fault displacement.

Fluid pressure—Numerical models and field tests indicate that addition and withdrawal of fluid profoundly affect the effective stresses and that these changes can trigger earthquakes. Numerical studies (Witherspoon and Gale, 1976) indicate that the effect of increasing fluid pressures by pumping or reservoir filling is greater over larger volumes of rock than the effect of withdrawing fluid. Few *in situ* measurements are available to verify this.

Physical mechanism of faulting—Important aspects of the physical mechanisms of faulting, which are still poorly understood, include causes of nucleation of fault slip; partition of energy at a source; effects on seismic motion of fault geometry, such as fault-length area, volume, thickness, depth, and curvature; propagation rupture along a fault; precursors; field prediction of stable sliding and stick-slip sliding; and impact of the above parameters on earthquake magnitude, moment, maximum particle acceleration, strong-motion duration, and frequency content of seismic motion.

Transmission Path

The transmission path (the rock volume between an earthquake source and a specific site) determines the character of the seismic energy at a specific site. The transmission path forms a transfer function that operates on the earthquake-source function to determine the partition of energy into surface waves and body waves, attenuation, and frequency filtering. Because the transmission-path transfer function varies with sources and sites and can never be determined uniquely, its properties should be considered within a probabilistic framework. To date, transmission-path transfer functions have been approached empirically, or analytically assuming homogeneity and isotropy. More attention needs to be given to near-surface attenuation and gross geometric effects on seismic propagation to derive realistic bedrock seismic motion on which a probabilistic overlay can be applied.

Site Dynamics

In situ conditions for site evaluation vary, depending on whether the site is on the surface or within a rock mass. The ability to characterize the site is an important factor in the success or failure of surface and subsurface facilities.

Failures associated with surface facilities are due to landslides or rock falls. There is no indication in the literature of earthquake stresses combined with *in situ* stresses exceeding rock strength at the earth's surface (Glass, 1974; Dowding and Rozen, 1977). Consequently, important *in situ* conditions for surface sites are associated with properties of rock-mass discontinuities such as joints, seams, and faults. Static and dynamic shear strength and frictional characteristics are especially important, as well as the impact of gouge, varying normal loads, and rock reinforcement techniques on the dynamic strength and friction of rock discontinuities. Better mathematical techniques that properly incorporate these *in situ* properties are also needed to model rock slopes.

Most failures of subsurface facilities as a result of strong seismic ground motion have been associated with failures of rock blocks or wedges into an underground opening. Though failure due to high stresses or resonance is theoretically possible, no instance documenting such failures has been found. Important *in situ* conditions for subsurface sites parallel those for surface sites and include strength and frictional properties of rock-mass discontinuities under time-varying loads. In addition, the state of *in situ* stresses, the geometry of underground openings with respect to possible earthquake sources, and the interaction between the rock mass and the reinforcement or lining should also be ascertained.

IN SITU TESTS FOR ASSESSING ROCK-MASS CONDITIONS

Static Tests

Many types of *in situ* tests are available for determining rock-mass characteristics. For deformability data, the following tests are available: plate-bearing tests (Misterek *et al.*, 1974; Dodds, 1974), flat-jack tests (Rocha and da Silva, 1970; Pratt *et al.*, 1974b), radial-press test (Misterek, 1970), pressure-chamber test (Schneider, 1967), borehole jacks (Goodman *et al.*, 1972; Hustrulid, 1976; Heuze and Salem, 1977), dilatometers (Rocha, 1974; Hustrulid, 1979), tunnel relaxation (Deklotz and Boisen, 1970), and petite sismique* (Bieniawski, 1980). Also, compressive tests (Bieniawski and Van Heerden, 1975) and shear tests (Franklin, 1979) can be used. All of these tests are static *in situ* tests, in addition to which certain geophysical tests are available for estimating the dynamic properties of rock masses, e.g., seismic modulus (Goodman, 1979).

No *in situ* tests are used specifically for determination of the tensile strength. Bearing capacity is determined by plate-bearing tests (Rhodes *et al.*, 1978). Postfailure modulus so far has been determined *in situ* only for coal, utilizing large-scale compression tests (Bieniawski and Van Heerden, 1975). Seismic-event precursors are detected by microseismic techniques featuring P-wave velocity measurements (Brady, 1977).

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*The petite sismique technique, developed in France (Schneider, 1967), involves the measurement of the frequency of shear waves generated over a small distance during a seismic refraction survey. The most useful feature of this method is a correlation between the shear-wave frequency and the *in situ* static modulus of deformation (Hoek and Londe, 1974; Bieniawski, 1979).

Pressure buildup (drawdown) tests and interference (pressure pulsing) tests are used to measure permeability, reservoir continuity, and storage (Johnson *et al.*, 1966).

In the field of strong-motion rock dynamics, *in situ* conditions can refer to conditions within a rock volume of several hundred cubic kilometers for an earthquake source or transmission path or to conditions within a volume of less than 1 km^3 for specific sites. This two or three order-of-magnitude variation in scale contributes unique problems to attempts to conduct meaningful *in situ* tests or to link or extrapolate laboratory and mathematical models to field situations.

Tests for Earthquake Sources and Transmission Paths

Important *in situ* conditions related to earthquake sources and transmission paths include the state of stress, the state of fluid pressure, and the physical mechanisms of faulting, seismic-wave attenuation, and energy partition. Because these conditions exist within a large volume of rock, extensive application of discrete physical tests, such as borehole stress measurements, should be restricted to optimum locations to verify other techniques.

Borehole techniques that have been used successfully to measure stresses include overcoring for shallow measurements of less than 50 m (Engelder *et al.*, 1978; Tullis, 1977) and hydraulic fracturing for deeper measurements (Pollard, 1978; Zoback and Pollard, 1978; Kim and Gray, 1978; Haimson, 1978). Geophysical techniques that have been applied successfully to measure rock-mass stress distribution include anisotropic wave-propagation velocity (birefringence or acoustic double refraction) measurements of shear waves (Todd *et al.*, 1973). *In situ* measurement of the state of fluid pressure can be accomplished using borehole-pressure tests, pressure-pulsing tests, seismic-wave velocity and attenuation measurements, and electromagnetic measurements.

Tests to Determine Important Rock-Mass Conditions at Specific Sites

Tests to determine the strength and frictional properties of rock-mass discontinuities under dynamic loads are seldom applied in the field. Godfrey (1974) studies the dynamic properties of *in situ*, jointed, granitic rock through the use of underground explosions. These tests indicate that damage to rock does not occur at radii where the peak stress does not exceed 700 MPa, even though elastic behavior does not prevail until the peak stress falls below 10 MPa, slightly above the overburden stress. Between these two limits, a zone of inelasticity was found to exist. Godfrey postulates that response within this zone of inelasticity is dominated by relative motion across joints, with a consequent energy dissipation by frictional losses and plastic deformation at joint intersections.

The Air Force Weapons Laboratory has conducted a number of studies to determine the effects of nuclear detonations on ground behavior (e.g., HEST, DIHEST, HANDEC, and ROCKTEST series). Alteration of *in situ* static tests, such as plate-bearing tests, to include cyclic loads could be employed for such a determination, though laboratory tests appear to provide more promise.

The Department of Defense has long been interested in rock-mass response to dynamic and static loads. The determination of strength moduli and elastic properties of a wide variety of earth materials is required for the development of constitutive models to predict the accelerations, velocities, and displacements associated with nuclear and conventional explosions. The material response is also used in experimental design, instrument requirements, and site selection for containment. Because of the complexity of the resulting ground motions, knowledge is required of material properties under a variety of load states and strain rates and to pressures of up to several hundred megapascals. Also important is knowledge of the *in situ* conditions such as stresses and saturation condition. The earth media of interest range from strong granites to weak deformable shales. All the above requirements translate into a continuing research and development program of laboratory and *in situ* testing.

In situ tests to determine dynamic moduli are well established and include both downhole and cross-hole compressional- and shear-wave determination. Geophysical techniques that show a great deal of promise for evaluating local rock-mass structure include compressional- and shear-wave attenuation and velocity measurements, wavefront reconstruction techniques (Glass and Higgs, 1979), and geophysical tomography techniques (Lager and Lytle, 1977).

Advantages of Tests

The above *in situ* tests have the advantage of involving large volumes of rock; thus, the results obtained can be more representative of rock-mass conditions than the results of laboratory tests, both from the point of view of the test volume and the environmental conditions (temperature, humidity). For example, Heuze (1980) compares test volumes for various deformability and strength tests as follows:

NX sample for laboratory tests	245×10^{-6} m^3
100-mm cube laboratory specimen	1×10^{-3} m^3
NX borehole jack *in situ*	140×10^{-3} m^3
300-mm-diameter plate-bearing test	950×10^{-3} m^3
0.9-m-diameter plate bearing	26 m^3
Pressure tunnel, 1.5-m diameter, 6 m long	82 m^3

As a result of the large volumes involved, *in situ* tests on large samples may show less scatter of the results than do laboratory tests on small samples (Pratt *et al.*, 1972). Geophysical techniques, depending on the application and types of energy sources, can be used to sample rock volumes covering several orders of magnitude in scale.

Limitations of Tests

In situ tests have limitations. Considering deformability data, even the most commonly used plate-bearing test (with standarized test procedures) may provide widely differing results (Rocha and da Silva, 1970; Dodds and Schroeder, 1974). The large flat-jack test of the Rocha (1974) type suffers from theoretical uncertainties (Deklotz and Boisen, 1970; Vogler *et al.*, 1977), while the analytical solution for the results of the popular small flat-jack test is limited to square-shape jacks, and openings of this shape are difficult to produce reliably in the field. Borehole jacks and dilatometers generally produce modulus values two to three times lower than *in situ* values determined by the plate-bearing test (de la Cruz, 1978). Corrections are required involving either the contact angle between the loading platen and the borehole surface (Hustrulid, 1976) or the stiffness ratio of the platen material to that of the rock (Heuze and Salem, 1977). Depending on which correction is chosen, the difference in the results can be significant. The Colorado School of Mines (CSM) cell (Hustrulid, 1979) would benefit from direct comparisions with *in situ* tests on a few projects. Finally, the petite sismique method, although appearing to hold great promise, has seldom been used to date and still requires a thorough assessment (Bieniawski, 1979).

Geophysical techniques, although versatile and relatively inexpensive, seldom measure important rock-mass conditions directly. Rock-mass characteristics such as moduli, *in situ* stress, and field fracture distribution must be inferred from their effects on the propagation velocity or attenuation of waves. Because a number of factors influence propagation velocity and attenuation, uniqueness becomes a problem, and geophysical techniques often are applied more accurately to measure the spatial or temporal change in rock-mass characteristics rather than as a direct measure. For example, a great deal of attention has been focused on correlations between wave attenuation and rock type, fluid content, and state of rock-mass fracture. Studies (Mavko and Nur, 1979) indicate that seismic-type attenuation is strongly influenced by a number of factors, including intergranular friction, pore and fracture fluid content, and details of pore and fracture geometry. Rock masses having flatter pores containing fluid tend to be associated with higher attenuation than rock masses having low pore-aspect ratios (ratio of pore length to width). In addition, the degree of saturation of pores or fractures having high aspect ratios, rather than the degree of saturation of the overall rock mass, appears to control seismic attenuation. The discrete nature of borehole measurements and the indirect nature of geophysical measurements make links between the two difficult to establish, and a significant effort in this area is justified.

Precision of Tests

Unfortunately, few projects to date have featured a sufficient number of different tests to allow a meaningful comparison of *in situ* test data. Table 7.1 compares field and laboratory moduli; it can be seen that very

TABLE 7.1 Field and Laboratory Moduli from Major Projects (after Bieniawski, 1978, and Heuze, 1980)

Project (Date)	Type of Rock	Type of Field Test	No. of Tests	E_F (GPa)[a]	E_L (GPa)[a]	E_F/E_L
Oroville Dam (1961)	Amphibolite (massive)	Plate bearing	5	10.4	89.0	0.11
		Tunnel relaxation	22	17.9		0.20
		Flat jacks	30	51.8		0.58
Tumut 2 (1962)	Gneiss/granite	Plate bearing	6	6.9	59.1	0.12
		Tunnel relaxation	3	11.0		0.19
		Flat jacks	6	57.5		0.97
		Pressure chamber	2	17.7		0.30
Poatina (1965)	Mudstone	Flat jacks	Not known	20.6	34.5	0.60
Dworshak Dam (1966)	Granite/gneiss (massive)	Plate bearing	24	23.5	51.7	0.45
		Goodman jack	14	23.6		0.45
Tehachapi Tunnel (1967)	Diorite gneiss (fractured)	Plate bearing	4	4.8	77.9	0.06
		Goodman jack	4	5.8		0.07
Crestmore Mine (1966 to 1974)	Marble (blocky)	Plate bearing	2	15.0	47.5	0.31
		Flat jacks	12	12.4		0.26
		Goodman jack	30	14.0		0.30
Gordon Scheme (1971)	Quartzite	Plate bearing	8	19.0	67.0	0.28
		Dilatometer	2	25.0		0.37
		Tunnel relaxation	10	25.0		0.37
		Flat jacks	16	58.0		0.87
Churchill Falls (1972)	Gneiss (massive)	Plate bearing	10	41.5	55.0	0.75
Waldeck II (1973)	Greywacke	Plate bearing	Not known	5.0	20.0	0.25
		Tunnel relaxation		15.0		0.75
Mica Project (1974)	Quartzite gneiss	Plate bearing	12	27.6	27.0	1.04
		Flat jacks	19	28.8		1.07
		Goodman jack	132	16.6		0.61
LG-2 Project (1976)	Granite (massive)	Plate bearing	Not known	50.0	80.0	0.62
Elandsberg (1977)	Greywacke	Plate bearing	33	39.6	73.4	0.54
		Small flat jacks	37	45.5		0.62
		Large flat jacks	3	42.2		0.57
		Goodman jack	39	28.4		0.39
		Tunnel relaxation	23	42.5		0.58
		Petite sismique	43	26.0		0.35
		RQD prediction	34	35.5		0.48
		RMR prediction	45	41.3		0.56
York Canyon Mine (1977)	Coal	Smaller bearing plate (15 cm × 15 cm)	9	0.31	9.4	0.033
		Larger bearing plate (36 cm × 36 cm)	4	0.16		0.017
	Shaly sandstone	Smaller bearing plate (15 cm × 15 cm)	5	0.65	43.4	0.015
Stripa Mine (1979)	Granite	CSM cell	385	36.8	51.3	0.72
Climax/NTS (1980)	Quartz monzonite	Goodman jack	Not known	25.0	70.0	0.36
		de la Cruz jack	Not known	66.0		0.94
		Tunnel relaxation	Not known	27.0		0.38
		Petite sismique	Not known	50.0		0.71

[a] E_F, field modulus; E_L, laboratory modulus at 50 percent strength.

different *in situ* results may be obtained depending on the test method. Under the circumstances, it is not helpful to discuss the precision of the *in situ* methods. For example, an examination of Table 7.1 reveals that even in an extensive *in situ* test program in fairly uniform and good quality rock-mass conditions, deformability data may feature a standard deviation of 25 percent, or as much as 10 GPa for an average *in situ* modulus of 40 GPa. Note that the tests involving full-scale prototype behavior (tunnel relaxation) give different results by comparison with other *in situ* tests. The choice of the design value for the *in situ* modulus of deformation thus becomes a matter of engineering judgment. This means that it is difficult to rely on any one *in situ* method alone; two or more methods should be used to cross-check the results. Clearly then, if *in situ* test results are method dependent and lead to large scatters in data, the potential of any relevant laboratory test assumes particular importance. It should be noted, nevertheless, that some laboratory tests may also be method dependent.

All test results tend to display a dispersion about some mean value and fit a variety of statistical distributions. Rock-mass properties, for example, are generally estimated from field sampling and boring logs. Geometric data consist of fracture strikes and dips, together with some measure of size. Mechanical data may consist of correlations with index properties or *in situ* test results. There are two sources of variation in these data, spatial and statistical (Baecher and Einstein, 1979). Properties change from place to place, and the properties of any single fracture or element of rock can be known only up to the spatial distribution. In addition, because sample sizes are finite, statistical uncertainty always exists in estimates of the frequency distribution.

The wide disparity between the sample population and the actual target population containing rock-mass properties will make a deterministic functional relationship all but impossible to define uniquely. For this reason, probabilistic techniques that incorporate the spatial and statistical uncertainties that inevitably enter into rock design, such as stochastic models in which rock properties are assumed to be spatially variable and uncertain (Baecher and Einstein, 1979), should be developed and utilized more fully.

Costs and Durations of Tests

Although detailed information concerning the costs of *in situ* tests, as well as equipment development and test durations, are seldom given in the literature, some information is available. The overall cost of an *in situ* testing program is typically a small percentage of the excavation costs.

In the case of an underground hydroelectric power chamber with an estimated excavation cost of about $100 million, a reasonable *in situ* test program could be expected to range from 0.5 to 1 percent, or $500,000 to $1 million (equipment, labor, drilling, and test adits). A test series could take up to six months to complete.

Most-Promising Tests

From the point of view of strength and deformability characteristics of rock masses, the most commonly employed *in situ* test method is the plate-bearing (uniaxial jacking) test. This method is expensive and time consuming, however, and is not free from uncertainties in data interpretation (Dodds, 1974).

Recent research (Hustrulid, 1979; Bieniawski, 1979; Heuze, 1980) suggests that two *in situ* methods are most promising for deformability measurements; borehole-jacking tests (Goodman jack, CSM cell) and the petite sismique. In petroleum engineering, the interference test (Johnson *et al.*, 1966) characterizing fluid-flow parameters is most promising. For *in situ* strength determinations, as well as for other characteristics important for describing the *in situ* conditions of rock masses, reliable and economical *in situ* tests still need to be developed. In this respect, geophysical tests could make significant contributions (Farr, 1979; Lytle, 1979), if made more relevant for engineering-design applications. In view both of this deficiency and of the uncertainties inherent in *in situ* tests, as well as their high costs, it is clear that more attention must be paid to scaling laboratory-measured quantities for *in situ* conditions.

DYNAMIC ANALYSIS TECHNIQUES

Earthquake Source and Transmission Path

Numerous mathematical models have been developed to represent slip on faults having simple geometries. These models appear to represent the gross characteristics of earthquake-motion and energy-radiation patterns fairly well. Little information is available in the literature on the effects of variations in fault geometry on seismic amplitudes, frequency characteristics, and radiation patterns.

The causes of reservoir-induced earthquakes are also poorly understood. Limited work has been conducted using numerical techniques to evaluate the coupled stress/fluid-flow problem within a fractured medium (Witherspoon and Gale, 1976). This work indicates that areas over which fluid pressures are increased during fluid injection can be considerably larger than the areas over which pressures are decreased by fluid withdrawal. No attempt is made to correlate fluid-pressure distribution to the size of possible earthquakes; however, results indicate that strike-slip faults may be more susceptible to reservoir-induced failure than other types of faults when the triggering mechanism is pore-pressure variation instead of loading. A great deal of additional effort is warranted in this area of research.

Site Dynamics

Even though economic and life risks associated with failure of rock slopes or cavity structures are increasing, the seismic behavior of rock sites remains poorly understood. Simple extensions to rock dynamics of techniques developed for structural dynamics appear inappropriate.

SURFACE SITES

For the most part, dynamic analyses conducted to evaluate rock slopes are pseudostatic techniques; but pseudostatic techniques bear no physical relationship to actual field conditions, so there is little justification for their use. Stimpson (1978) examines the static stability of rock slopes with discontinuous sets. His study points out that vibrations tend to extend the joints to form continuous joint sets, implying that a continuous joint set should be assumed when analyzing a jointed rock slope for dynamic stability. No suggestion is made regarding possible analytical techniques. Two techniques developed specifically to evaluate the dynamic response of rock blocks have proven helpful: a graphical technique by Hendron *et al.* (1971) is applicable to rock slopes, even though it was developed for blocks on horizontal planes; Newmark's (1965) technique analyzes a rock block on an inclined plane, using the maximum particle velocity of the earthquake motion. Model studies of rock blocks using a shaking table (Wilson, 1979) indicate that the above techniques tend to bracket the range of block motions for low frequencies (less than 5 Hz) but are in error for frequencies greater than 5 Hz. This may indicate that earthquake accelerations are more important for rock-slope design than are velocities. Neither of these techniques is capable of accounting for pore pressures under dynamic excitation. Clearly, more work is needed to develop techniques for analyzing rock slopes under dynamic loads. Both detailed analysis techniques, such as finite-element, and simple techniques should be developed—detailed techniques to evaluate a few complex slopes, such as in dam design, and simple techniques to evaluate numerous slopes, such as in open-pit mine design. These models should incorporate an entire earthquake time history or response spectrum as the forcing function.

In addition to analyses of simple rock blocks (plane failure), it is important to extrapolate analysis techniques to include more-complex wedge failure, toppling failure, nonplanar surfaces, and step-path failure (Call and Nicholas, 1978).

Little information related to rock/structure interaction is available in the literature. In many cases, numerical methods developed for soil/structure interaction problems can be utilized for rock/structure interaction (Borm, 1977). However, the potential differences in constitutive behavior of jointed rock subjected to strong dynamic loads, as opposed to soil, require a more detailed look at the rock/structure interaction and possibly development of new analysis techniques.

Another area where a major lack of information exists is the general area of rock-support behavior under dynamic loads. The rock-support system includes the rock mass and the support system, such as rock bolts, grouts, retaining walls, and anchors.

SUBSURFACE SITES

Most failures of subsurface facilities as a result of strong seismic ground motion have been associated with failures of rock blocks or wedges into an underground opening. Analysis of this type of failure can be approached in the same way as rock-slope stability, mentioned in the preceding section, and the same research needs are shared.

Failure of subsurface facilities due to high stresses or resonance is theoretically possible, though not documented in the literature. Numerical studies (Glass, 1974) show that the hoop-stress concentration around an opening due to an impinging seismic wave exceeds the hoop-stress concentration calculated by a pseudostatic analysis by as much as 20 percent. Thus, in areas of high stress, appropriate dynamic analyses should be applied to evaluate subsurface stability. Numerous measurements have been attempted in an effort to evaluate the possibility of resonance of subsurface cavities and pillars (Russell, 1970). Experimental results (Cook and Valkenburg, 1954) indicate that waves having wavelengths greater than approximately one half the radius of curvature of a cavity cannot produce resonance. The possibility of resonance caused by waves traveling down a conduit or tunnel should be evaluated in more detail. The important consideration in evaluating stress concentrations and resonance for subsurface facilities is to treat the problem as a wave-propagation problem. Assumptions common to many structural-engineering techniques, such as modal analysis (where one assumes that multiple reflections have taken place, forming a standing wave), are not appropriate for analysis of subsurface rock structures.

As with surface sites, the dynamic interaction between rock masses and subsurface support and reinforcement needs definition. A significant amount of analytical work has been conducted to study the response of circular lining (Glass, 1974), but a significant amount of research is still lacking on other geometries and reinforcement types.

SCALING OF LABORATORY TEST DATA TO IN SITU VALUES

There are a number of "links" or correlations that can be used for extrapolating laboratory-measured quantities to *in situ* conditions. For example, use has been made of the correlation between the RQD (rock quality designation) index and the modulus reduction ratio E_M/E_L—the ratio between *in situ* modulus of deformation, E_M, and the laboratory modulus, E_L, determined from small rock-material samples. A recent study (Heuze, 1980) of the scale effects of the determination of rock-mass strength and deformability shows that the moduli values measured in the laboratory are, on the average, 2.5 times higher than the values determined *in situ*.

In particular, most of the *in situ* modulus results seem to be between 0.2 and 0.6 of laboratory values. It must be noted, however, that these values are dependent on the rock quality, as depicted in Figure 7.1.

Herget and Unrug (1974) and Kendorski (1975) study scaling of laboratory test results to field problems involving mining structures such as pillars and drifts. Kendorski (1980) investigates rock-mass strength assessment for tunnel design.

It should be noted that numerical or physical modeling is an important approach for scaling measured quantities to *in situ* conditions. In fact, with the development of sophisticated computer techniques, numerical modeling is extensively used for this purpose. The subject of the correlation of scaled experiments with large-scale rock/structure configurations is addressed in Chapter 9.

Physical models based on the principles of dimensional analysis and similitude have been used to study mine openings (Bucky and Fentress,

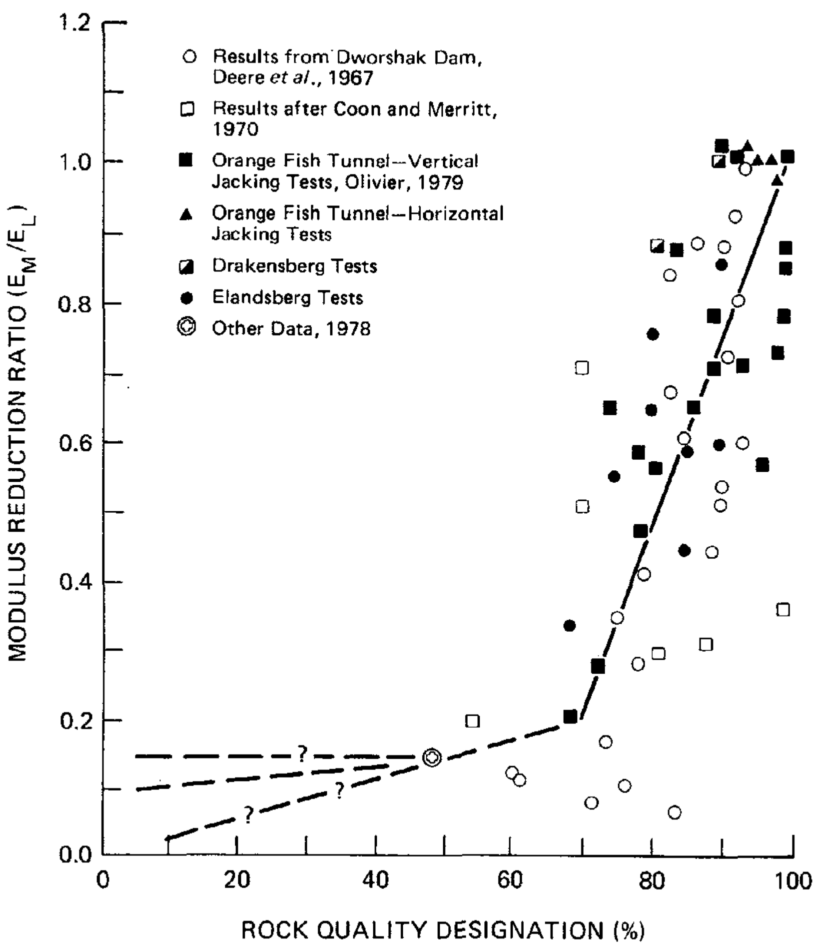

FIGURE 7.1 Correlation between RQD and modulus ratio E_M/E_L (Bieniawski, 1978a).

1934), roof bolts (Panek, 1956), pillar size (Panek, 1979), spiling in tunnels (Korbin and Brekke, 1979), jointed rock masses (Rosenblad, 1970; Einstein and Hirschfeld, 1978), slopes (Barton and Choubey, 1977), dams (Fumagalli, 1968), and other structures. It is difficult to model the fractures in the rock mass, although this has been attempted (Stimpson, 1979); therefore, Singh (1980) resorts instead to modeling the rock-mass strength. Centrifuges have been used for studying roof bolts (Panek, 1962) and mine subsidence (Sutherland *et al.*, 1979).

For a number of reasons, links (or scaling laws) to extrapolate laboratory tests to actual field situations are almost totally lacking in strong-motion rock dynamics. Links relating earthquake-source parameters obtained in the laboratory to *in situ* values are difficult to obtain because of the extremely large extrapolation needed (from several cubic centimeters to tens of cubic kilometers). This situation is improving with the advent of larger-scale laboratory testing, and for the first time it appears that links may be possible; however, *in situ* parameters with which to link are lacking. Larger-scale laboratory tests, together with *in situ* tests with emphasis on geophysical techniques, should be a high priority for future research.

With respect to site dynamics, the result of the virtual nonexistence of dynamic laboratory and *in situ* tests is that there is essentially nothing to link. Even if test results and links were available, there are few realistic analysis techniques available in which to use them. This situation should receive a high priority in future research.

Deformability Data

Attempts at scaling laboratory-measured quantities to *in situ* values are not new. Deere *et al.* (1967) suggest the use of quality indices to estimate rock-mass deformability—either the RQD index or the seismic velocity index. The seismic velocity index is defined as the square of the ratio of the field seismic-wave velocity to the sonic velocity in a laboratory specimen, $(V_F/V_L)^2$. The ratio is squared to make the velocity index equivalent to the ratio of the dynamic moduli. Coon and Merritt (1970) show that the RQD index correlates with the modulus reduction ratio, E_M/E_L, with a correlation coefficient of 0.544, but the velocity index shows a poorer correlation (coefficient 0.368). However, the RQD data for the correlation with the E_M/E_L ratio were mainly from good-quality rock and predominantly from one project, the Dworshak Dam, although a few results were included from three other projects. These results were updated recently by Bieniawski (1978a) and are shown in Figure 7.1.

Kulhawy (1978) proposes a modified RQD model, enabling the reduction of rock-material properties caused by the presence of discontinuities, and shows a better correlation of the RQD index with the modulus reduction ratio as a function of discontinuity properties (stiffness). Dershowitz *et al.* (1979) discuss currently used empirical correlations and analytical models and show that the RQD index may be sufficient (in the statistical sense) to describe rock-mass deformability, particularly for

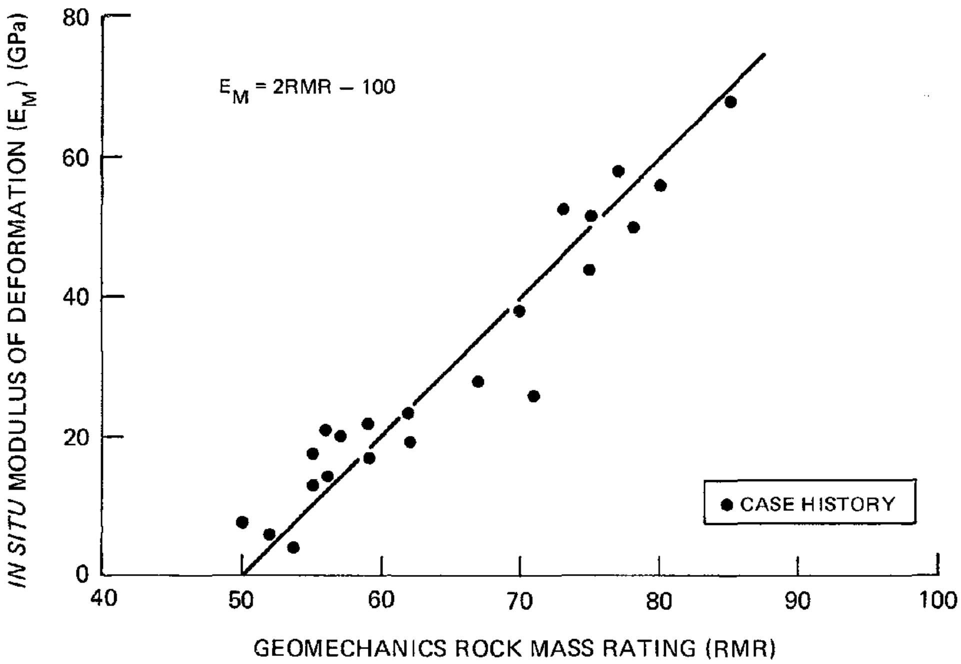

FIGURE 7.2 Correlation between the *in situ* modulus of deformation and the Geomechanics Classification rock-mass rating (RMR).

lower-quality rock masses. In this respect, use was made of the findings by Priest and Hudson (1976), who propose a relationship between RQD and the spacing as well as the orientation of discontinuities.

For better-quality rock masses, Bieniawski (1978a) obtains a good correlation (coefficient 0.9612) directly between the *in situ* modulus (not the modulus ratio) and the rock-mass rating (RMR). This is shown in Figure 7.2. The RMR approach has the advantage that the scatter inherent in laboratory values, which affects the modulus reduction ratio, is avoided because no laboratory data are used in this case.

Correlations between RQD and RMR and the *in situ* modulus are very promising. However, more research is required in this direction because not enough case studies have been made to confirm the correlations.

Strength Data

The subject of strength reduction from the data determined in the laboratory to *in situ* values has received considerable attention in the past, particularly as related to mine pillars. However, only two approaches seem to be promising, namely those of Protodyakonov (1964) and of Hoek and Brown (1980).

Protodyakonov proposes a method whereby the strength of the rock mass can be estimated from the following equation:

$$\frac{\sigma_d}{\sigma_M} = \frac{d/b + m}{d/b + 1},$$

where σ_d is the strength of a cubical specimen with side length d, σ_M is the *in situ* strength of the rock mass, b is the distance between discontinuities in the rock mass, and m is the strength reduction factor. The curves representing this relationship are given in Figure 7.3. From the experimental data on a number of rock types, it is evident that the value of m depends both on the type of rock material and on the stress state to which the specimen is subjected, namely:

Rock Strength	Compression	Tension
>75 MPa	$2 < m < 5$	$5 < m < 15$
<75 MPa	$5 < m < 10$	$15 < m < 30$

The strength reduction in weaker (more fissured) rock is more pronounced than in stronger rock containing only minor cracks. The effect is greater in tension, when cracks open and give rise to large strength reductions, than in compression, when cracks close and thus the disturbances are reduced (Müller, 1974).

There is much experimental evidence supporting the phenomenon of strength reduction with increasing specimen size, as depicted in Figure 7.4. It will be noted that from a certain specimen size onward, the *in situ* strength remains constant, irrespective of size. Consequently, attempts to extrapolate the laboratory specimen data to *in situ* values may not prove reliable because the best fit must be truncated when the constant *in situ* strength is reached.

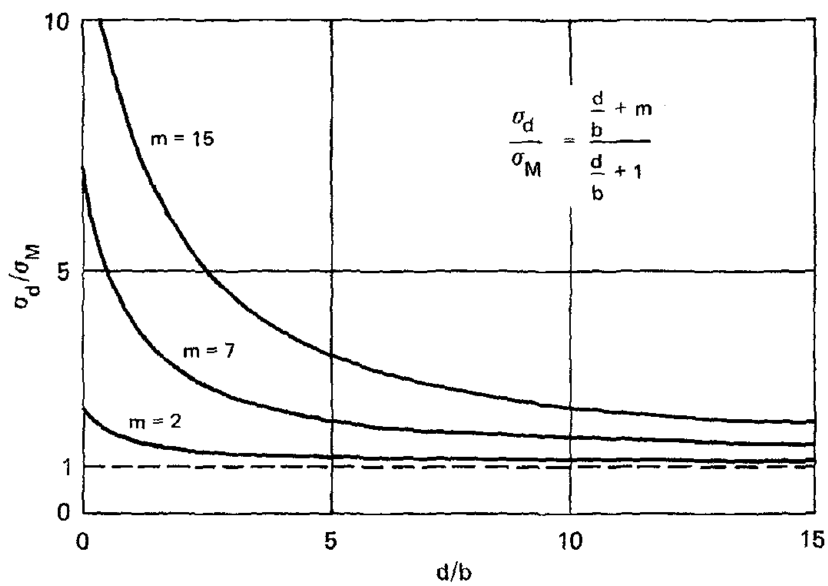

FIGURE 7.3 Graphical representation of the Protodyakonov formula.

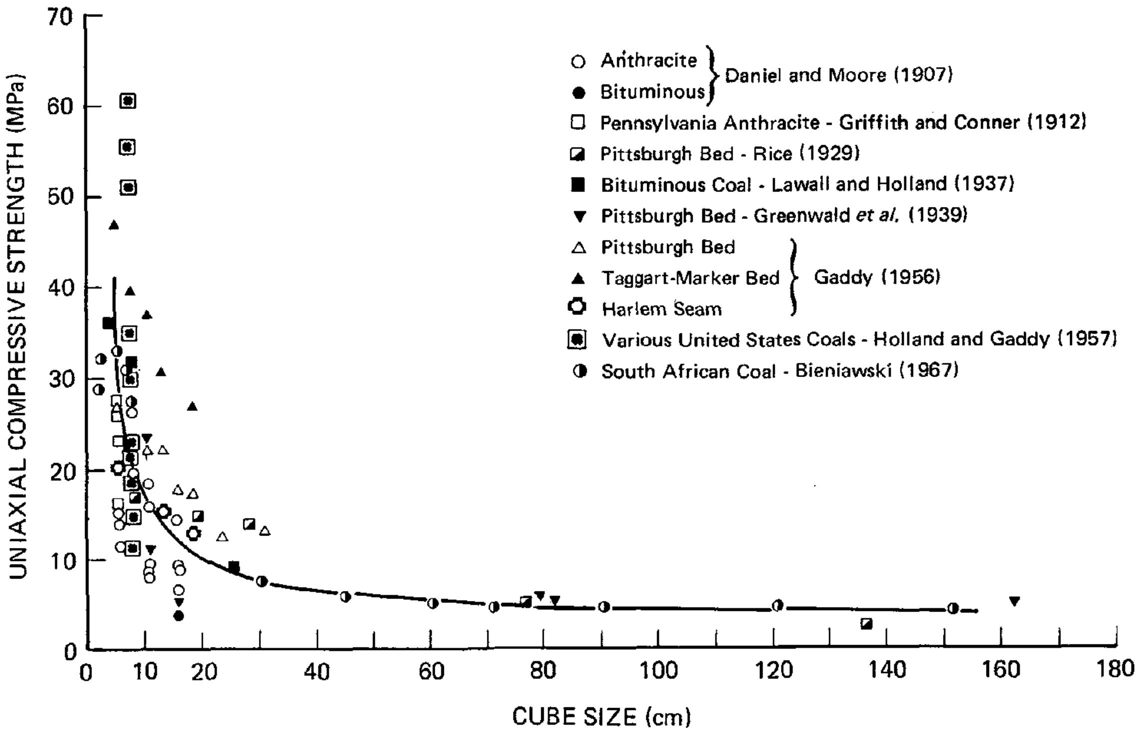

FIGURE 7.4 Effect of size on compressive strength of coal (after Singh, in press).

Bearing-capacity strength tests (plate-loading tests carried to bearing-capacity failure) are discussed by Heuze (1980). No clear trends have emerged, however, because of diversity of the test data.

Hoek and Brown (1980) propose a criterion for the strength of rock masses. In view of the scarcity of reliable information on the strength of rock masses, they consider it unlikely that comprehensive quantitative analysis of rock-mass strength would ever be possible and propose a method for the prediction of rock-mass strength based on rock-mass classification. This criterion of failure is as follows:

$$\frac{\sigma_1}{\sigma_c} = \frac{\sigma_3}{\sigma_c} + \sqrt{m\frac{\sigma_3}{\sigma_c} + S},$$

where σ_1 is the major principal stress at failure, σ_3 is the applied minor principal stress, σ_c is the uniaxial compressive strength, and m and S are constants that depend on the properties of the rock and the extent to which it has been fractured by being subjected to σ_1 and σ_3.

In Figure 7.5 (after Hoek and Brown, 1980), a plot is given of the ratio m/m_i and of the value of S versus the rock-mass ratings from the Geomechanics Classification and the Q-System for andesite. In this procedure, m_i for intact rock is determined from a fit of the above equation to triaxial-test data from laboratory specimens, taking $S = 1$ for intact rock.

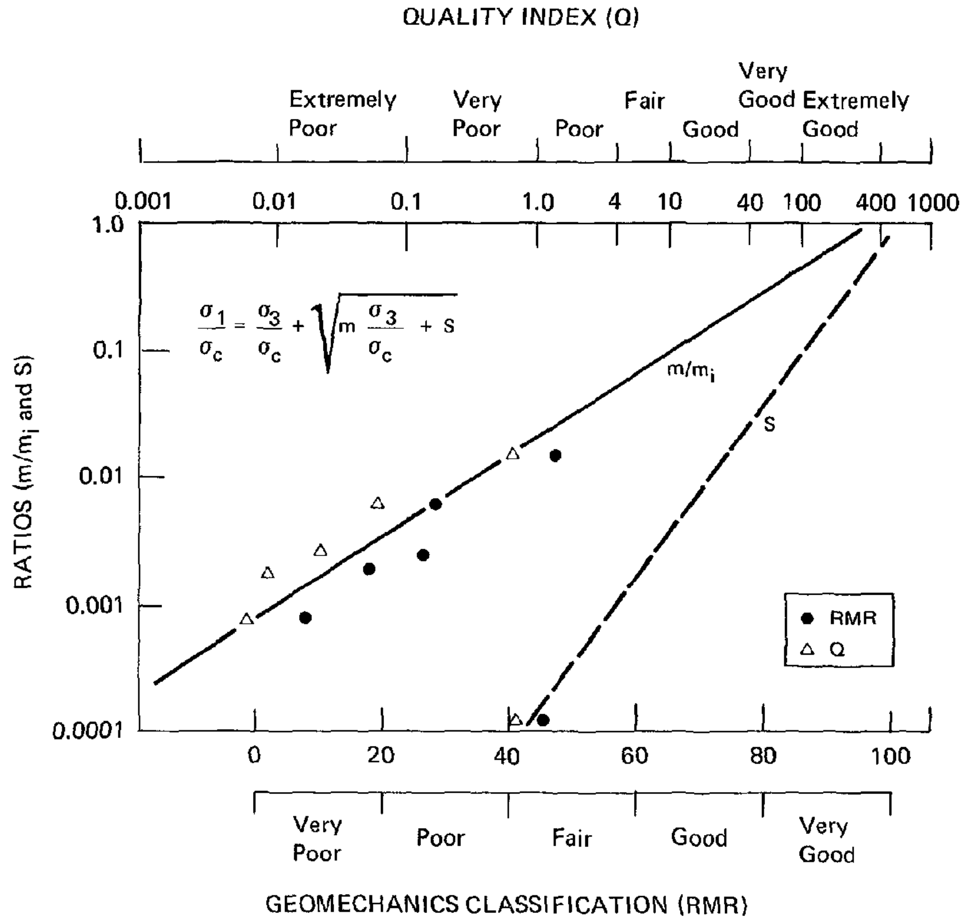

FIGURE 7.5 Criterion for *in situ* strength of rock (after Hoek and Brown, 1980).

It is clear from the above discussion of the Protodyakonov and the Hoek and Brown approaches that much research is required on the aspect of scaling the laboratory-determined rock strength to *in situ* values. A more-promising approach in this respect is that proposed by Hoek and Brown.

Frictional Properties

Rock friction is a very complex phenomenon, and much more laboratory research is required to understand the microscopic processes occurring in friction before the macroscopic processes can be deduced. Hence, the stage has not been reached as yet that laboratory-measured frictional properties can be scaled to *in situ* values. Nevertheless, promising research in this respect should be noted, namely that by Pratt *et al.* (1974a; 1974b) and Barton and Choubey (1977).

Precursor Time for Seismic Events

Recent research by Brady (1977) shows that short failure precursors on the small (laboratory) scale and large (mine or earthquake) scale may satisfy a scale-invariant process. This means that the physical process that leads to and culminates in fractures may be identical for all failures, regardless of size; scale invariance does not imply simple scaling laws.

Figure 7.6 illustrates precursor times as a function of effective lengths for selected failures, including several mine rock bursts and earthquakes. In this context, it is accepted that there is a decrease in seismicity prior to failure, and the term "precursor time" means the time interval from the moment failure becomes inevitable to the actual

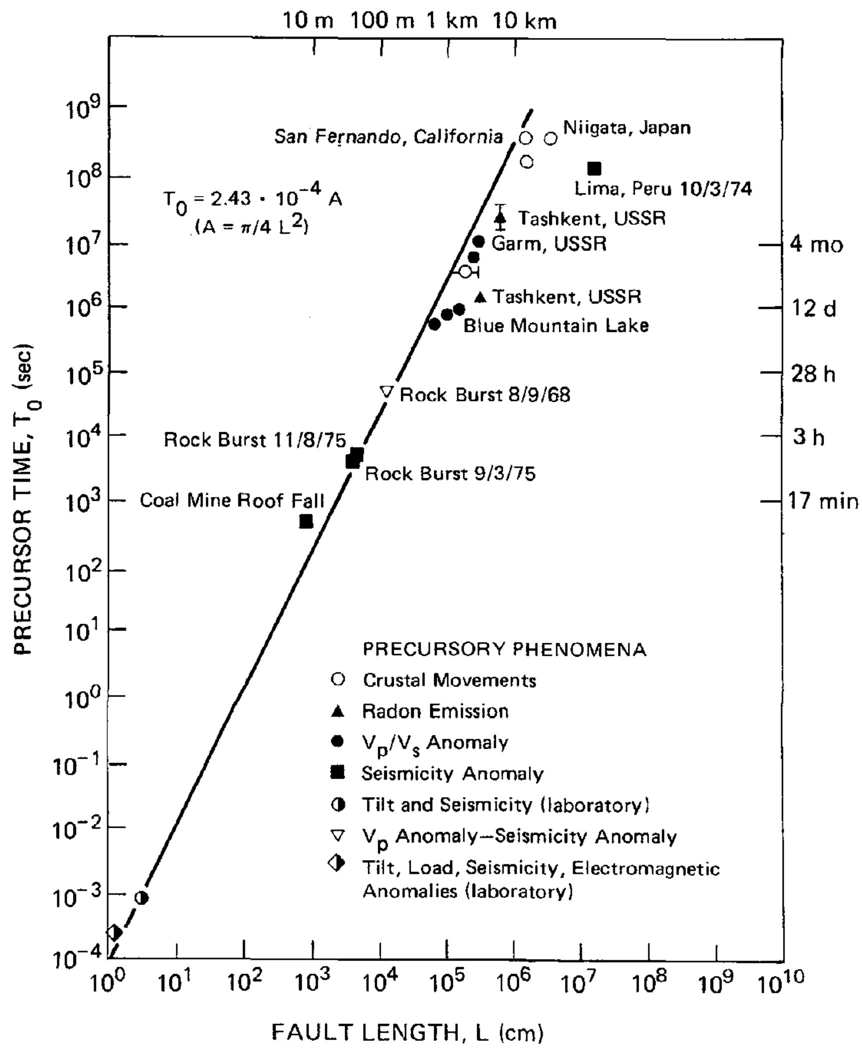

FIGURE 7.6 Precursor time of seismic events versus fault length (after Brady, 1977) for laboratory and *in situ* failures.

failure. Prior to the precursor time (also known as "preparation time"), fracture still may be prevented by merely unloading the system; once the precursor time has begun, catastrophic failure inevitably ensues. It is possible that laboratory studies may provide valuable insight into the failure preparation process but only when studied during a short time interval, a few microseconds prior to failure. More research is needed, however, on this subject.

Nevertheless, there are many earthquakes on record for which there are no precursors, and there are many large earthquakes for which the fault lengths varied enormously. That problem has generated the idea of a seismic moment (Wyss, 1979). Research should relate geological setting, local tectonism, fault mechanics, stress drop, and laboratory modeling to predict the variability in precursory events.

An alternative approach in the study of rock bursts is that involving the critical energy-release rate during mining (Cook, 1965). A proposed laboratory test method, the split-platen technique (Hustrulid and Ramos, 1978), warrants further development in conjunction with this approach.

Scaling Links

To summarize, the links that have been identified for scaling laboratory results to *in situ* values are as follows:

- RQD for estimating the modulus reduction ratio, E_M/E_L.
- Velocity index, V_F/V_L, for the modulus reduction ratio, E_M/E_L.
- Rock-mass classification rating, RMR, for *in situ* modulus, E_M.
- Protodyakonov's formula for *in situ* strengths (compressive and tensile).
- Hoek's and Brown's *in situ* strength criterion.
- Precursor time versus fault-length concept.

LABORATORY TEST METHODS AND FACTORS OF INFLUENCE

Laboratory testing methods are generally well established, and standard testing techniques have been recommended by both the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM). From the point of view of scaling laboratory-measured quantities to *in situ* values, the relevant laboratory testing techniques are well documented. In fact, the latest ISRM review (Franklin, 1979) indicates that no less than 21 laboratory test methods have been described and 28 field test methods have been documented. More techniques are in various stages of preparation. A complete list of the available laboratory and *in situ* methods is given in Table 7.2. For the purposes of this chapter it is concluded that laboratory testing methods are well established.

TABLE 7.2 Test Categories Published (or Scheduled to be Published) by the ISRM as "Suggested Methods" (Franklin, 1979)

Field Index Tests for Characterization

Discontinuity orientation
Discontinuity spacing
Discontinuity persistence
Discontinuity roughness
Discontinuity wall strength
Discontinuity aperture
Discontinuity filling
Discontinuity seepage
Discontinuity number of sets
Discontinuity block size
Discontinuity drill core recovery/RQD
Geophysical logging of boreholes
Seismic refraction (2 methods)
Acoustic logging
Seismic measurements between boreholes
Sonic log
Caliper log
Temperature log
SP log
Resistivity logs (2 methods)
Focused current logs
Induction log
Gamma ray log
Neutron log
Gamma-gamma log

Field "Quality Control Tests"

Rockbolt anchor strength
Rockbolt tension (torque wrench)
Rockbolt tension (load cells)
Cable anchor tests
Shotcrete - visual assessment
Shotcrete - pull tests
Shotcrete - box mould tests
Shotcrete - core tests
Gas level measurements

Laboratory Index Tests for Characterization

Water content
Porosity/density (4 methods)
Void index (quick absorption)
Swelling pressure
Swelling strain (2 methods)
Slake-durability
Uniaxial compressive strength
Uniaxial deformability (E, ν)
Point load strength index
Resistance to abrasion (Los Angeles test)
Hardness (Schmidt rebound)
Hardness (Shore scleroscope)
Sound velocity
Petrographic description

Field "Design Tests"

Deformability using a plate test
Deformability plate test down a borehole
Deformability radial jacking test
Deformability flexible borehole jack
Deformability rigid borehole jack
Deformability flat jack
Deformability *in situ* uniaxial/triaxial test
Shear strength-direct shear
Shear strength-torsional shear
Piezometric head (3 methods)
Permeability/transmissivity (5 methods)
Flow velocity logs
Flow velocity - tracer dilution
Flow paths using tracers (4 methods)
Stress determination - flat jack
Stress determination - surface coring
Stress determination - "doorstopper"
Stress determination - strain-gauge cell
Stress determination - USBM-type gauge
Stress determination - hydraulic fracturing

Field Monitoring

Movements - probe inclinometer
Movements - fixed-in-place inclinometer
Movements - tiltmeter
Movements - borehole extensometers
Movements - convergence meter
Movements - joints and faults
Movements - survey triangulation
Movements - survey leveling
Movements - survey offset
Movements - survey EDM
Vibration and blast monitoring
Pressure - hydraulic cells
Rock stress variations
Pendulum and inverted pendulum
Strains in linings and steel ribs

Laboratory "Design Tests"

Triaxial strength
Direct tensile strength
Indirect (Brazil) tensile strength
Direct shear test (+ field method)
Permeability
Time-dependent and plastic properties

TABLE 7.3 Factors Governing the Behavior of Rock

Rock Characteristics
Material
Lithology and stratigraphy (rock type, occurrence, grain size, color, minerals)
Anisotropy
Porosity
Cracks and weaknesses
Specimen geometry (shape, size)
Physical and mechanical properties (density, strengths, moduli, failure mode)
Chemical properties
Mass
Structure (stratification, lamination, dip and strike, size, shape)
Discontinuities (type, orientation, spatial configuration, condition)
Porosity
Permeability
Physical and mechanical properties (strengths, moduli, friction angle)
Creep
External Parameters
Environment
Pressure
Temperature
Hydrologic (moisture content, groundwater flow, pore pressure)
Chemical
Stress-Strain State
In situ stresses (magnitude, direction, distribution)
External loads (type, magnitude, direction, distribution and configuration, nature, rate)
Nonmechanical stresses (thermal, electrical, magnetic)

Many factors influence the behavior of rock (Table 7.3) and must be taken into account when interpreting the laboratory test data. The following factors are particularly important: lithology, porosity, fabric, anisotropy, confining pressure, time-dependent deformation (creep), rate of loading, moisture content, and pore water pressure.

It should be noted that a discussion of the above factors is beyond the scope of this chapter. The purpose here is not to identify research requirements for laboratory studies in general but to consider research needs to determine the laboratory-measured quantities that make it possible to estimate the *in situ* values.

Source and Transmission Path

Numerous studies have been undertaken to investigate the mechanics of creep and fault slip (Teufel and Logan, 1978; Scholz, 1968; Kranz and Scholz, 1977; Solberg *et al.*, 1978). These studies indicate that premonitory stable creep always precedes unstable slip events. The amount of premonitory slip is proportional to the rate of application of load (Teufel and Logan, 1978). A problem with these tests has been related to scaling the slip phenomena in laboratory specimens having fault dimensions of a few centimeters to naturally occurring faults having dimensions on the order of tens of kilometers. In an attempt to provide new information, larger-scale biaxial tests have recently been conducted on granite specimens measuring 1500 mm × 1500 mm × 400 mm (Dieterich *et al.*, 1978). These laboratory experiments show that stable slip precedes unstable slip events and is controlled by inhomogeneity of shear stresses relative to frictional strength of the failure surface. The large-scale tests showed, for the first time, that preseismic displacements are proportional to the length of the sliding surface. In addition, and unlike experiments on small samples in which the entire failure surface moves during unstable slip events, some of the unstable slip events were confined to the central portion of the sliding surface. This latter finding suggests that experiments using larger sliding surfaces are required to produce confined unstable slip under low normal stress representative of actual faults. Further experiments should include fluid-pressure effects and more-complex geometries.

Site Dynamics

Laboratory tests to determine dynamic properties of rock are scarce. A large portion of the study conducted on dynamic rock properties has centered on the determination of the cyclic dynamic strength, related to fatigue. On the basis of tests conducted on white Tennessee marble, Haimson and Kim (1971) conclude that where the maximum load is in the range of 75-100 percent of the compressive strength of the rock, dynamic (cyclic) loading results in a lower rock strength due to fatigue. These researchers suggest that this lower fatigue-related strength should be used in all rock design work. Haimson (1974) supports this conclusion with subsequent research that indicates, through the use of triaxial testing, that fatigue-related strength of rock is 60-80 percent of the static strength; this work also notes that fatigue strength increases with increased confining pressure.

In related research, Montoto (1974) explains cyclic fatigue in terms of petrographic considerations. From results of uniaxial tests conducted on Barre granite, intracrystalline slips and deformations are observed throughout the specimen if cyclic stresses are applied below the static strength. As the cyclic loading progresses, the deformations are seen to concentrate in some areas of the rock, which results in the development of intracrystalline cracks. Successive load cycles extend the cracks, which eventually interconnect to cause sudden failure.

With this study in mind, there is a disagreement whether time has a significant influence on rock strength. In the study above, the number of load cycles and magnitude of load are significant and time is not. Along the same line, Wawersik (1974) finds, through tests that considered static strength only, that rock strength changes minimally with time. In contrast, John (1974) and Houpert (1974) find that long-term, *in situ* static strength is less than that determined by triaxial loading in the laboratory. Therefore, there is a considerable lack of understanding of the role that time plays in rock strength. In Montoto's (1974) work, for example, varying the time of application of the load cycles might influence the fatigue strength. Dynamic tests have been conducted for a number of years on the dynamic properties (moduli and damping characteristics) of soils, but similar tests on rock are lacking, mostly owing to a lack of large, dynamic, direct-shear machines. Important parameters that can be measured in the laboratory are dynamic joint and fault properties such as dynamic shear strength as a function of time and frequency, contribution of fatigue, effect of gouge or filling material, and the role played by fluids during dynamic excitation.

Dynamic shear tests should be conducted on rock discontinuities with machines that are capable of applying earthquake loads both as a varying normal and shear load. A suitable test machine would cost approximately $2 million; to the Subpanel's knowledge, such a machine does not exist. Scaling laboratory static tests to field dynamic situations is inappropriate.

Centrifuge tests show a great deal of promise if dynamic loading conditions can be successfully applied and pore pressures can be incorporated. These tests can be scaled adequately to field situations by increasing the speed of the centrifuge. Centrifuge testing in the United States has been hampered by the lack of a suitably sized centrifuge. However, with the adaptation for geotechnical experiments of the 2000 *g*-ton centrifuge (the capacity of a centrifuge is expressed in *g* tons, the product of the maximum *g* force available and the weight of the specimen) at Ames Research Center in Palo Alto, California, the prospects are encouraging. In centrifuge experiments, all model dimensions decrease directly with an increase in the *g* force. Problems still remain in verifying the relationship between centrifuge tests and actual field situations and in applying realistic dynamic loads. These problems should be evaluated in future research. In addition to the above techniques, other physical modeling should be pursued concurrently. For example, use should be made of existing earthquake shaking tables for evaluating models of rock slopes and rock/reinforcement interaction.

RESEARCH NEEDS

The foregoing review of past and current research reveals that in order to recommend investigations of scaling laboratory data to *in situ* values, certain gaps in the knowledge of the *in situ* tests must be considered first. In other words, unless reliable characterization of *in situ* conditions is first achieved, it will be unrealistic to attempt scaling of laboratory data to unknown field values.

It seems imperative, therefore, that some *in situ* testing of rock masses should be pursued to clarify uncertainties in field data interpretation as affected by the test method and specimen or site conditions. Although it is recognized that *in situ* testing is generally expensive and time consuming, this is not true of all field tests. For example, as suggested earlier, borehole-jacking tests and the petite sismique technique are promising methods for rock-mass deformability assessment, and, at the same time, they are both economical and convenient to use.

In situ characterization of rock masses requires information not only on strength and deformability but also on many other parameters, depending on the particular engineering application. Thus, it is clear that large-scale *in situ* tests are required to provide a field data base that would enable determination of physical properties of large volumes of jointed and fractured rock at various stress, moisture, and time-factor conditions. The relationships between the *in situ* and laboratory values for a number of parameters could be studied and comparisons made between laboratory and field properties. The experiments could also be correlated with numerical modeling.

It is believed that such a testing program would be achieved best by incorporating it with existing programs, such as the construction of underground chambers for nuclear-waste disposal, compressed-air storage, and power-plant location. Such a field experiment would require not only careful planning of the envisaged tests but also might necessitate development of specialized, new field instrumentation. For instance, in some test areas current instrumentation is insufficient, namely, for long-term monitoring of creep effects *in situ*.

The following research needs—i.e., research required but not in progress—have been identified.

In Situ Testing

- *Clarify the principles and the potential of engineering geophysical methods (e.g., petite sismique technique).*
- *Clarify data-interpretation procedures for borehole jacks (Goodman jack, CSM cell).*
- *Develop an economical technique to determine* in situ *strength of rock masses.*
- *Develop more-meaningful geophysical techniques for engineering applications (e.g., use of shear-wave measurements and geophysical logging).*
- *Develop a large-scale* in situ *test program for field data base purposes.*
- *Develop new instrumentation for long-term monitoring of creep effects* in situ.
- *Develop* in situ *and laboratory methods for determining thermomechanical properties (Chapter 8).*
- *Investigate (with emphasis on the use of geophysical techniques) earthquake-source parameters including (a) influence of stress inhomogeneity and anisotropy on fault dislocation propagation, (b) relationship between the amount of premonitory slip and the geometry of the eventual unstable-slip surface, (c) redistribution of stress after fault dislocation and the impact that redistributed stresses have on geologic structures, (d) influence on faulting of changes in fluid pressure, (e) partition of energy at a dislocation surface, and (f) influence of fault geometry on radiation pattern and amplitude and frequency of ground motion.*
- *Develop tests to determine the dynamic response of rock masses both on the surface and underground.*

- *Develop tests to evaluate rock-mass/reinforcement response to earthquake loads.*
- *Develop tests to evaluate rock-mass/structure interaction under earthquake loads.*

Laboratory Testing

- *Develop more-reliable techniques for studies of frictional properties.*
- *Develop more-reliable techniques for accurate precursor measurements.*
- *Improve techniques for studies of low permeabilities (nanodarcy range).*
- *Improve the split-platen technique (Hustrulid and Ramos, 1978) for postfailure modulus studies.*
- *Perform larger-scale laboratory tests to evaluate earthquake-source parameters.*
- *Increase the effort to improve large-scale centrifuge testing capability to use earthquake loads and fluid pressures; evaluate the ability of centrifuge techniques to provide intermediate-scale constitutive relationships for fractured media under earthquake loads.*
- *Develop large-scale, dynamic, direct-shear testing machines capable of time-varying (earthquake) normal and shear loads in order to evaluate the effects on fault and joint properties of (a) fatigue, (b) frequency, and (c) fluid.*
- *Develop tests to study rock-mass/reinforcement interaction.*

Analytical Techniques

- *Develop realistic dynamic-analysis techniques to evaluate both surface and subsurface rock-site response so that links developed by laboratory and* in situ *testing can be used effectively.*
- *Develop probabilistic techniques, such as stochastic modeling, for efficient use in rock engineering projects.*
- *Develop numerical-modeling techniques for data scaling and interpretation.*

Links for Scaling Laboratory Data to in Situ Values

- *Assess methods for determining* in situ *compressive and tensile strengths.*
- *Assess methods for measuring* in situ *deformability (RMR and RQD).*
- *Develop links for time-dependency (creep) assessment.*
- *Develop links for frictional-properties assessment.*
- *Develop links for postfailure modulus assessment.*
- *Develop techniques for scaling dispersivity and distribution coefficients (Chapter 3).*

RECOMMENDATIONS FOR RESEARCH: PRIORITIES AND PROGRAM

Research Priorities

The recommendations for research activities that should be accorded high priority to meet immediate needs are as follows:

- *Perform large-scale tests and monitor prototype structures.*
- *Conduct both theoretical analyses and field tests to determine the resolution and practicability of engineering geophysical methods (e.g., petite sismique) for* in situ *mass deformability assessment.*
- *Develop methods for scaling rock-mass deformability, frictional properties, and permeability.*
- *Conduct theoretical and field studies to compare and develop useful links between parameters measured using proximal and remote methods in order to determine earthquake-source parameters (e.g.,* in situ *stress, influence of fluid pressure).*
- *Develop laboratory equipment and techniques to measure dynamic rock-mass properties and earthquake-source parameters.*
- *Develop laboratory and* in situ *procedures for determining the thermomechanical properties of rock.*
- *Develop numerical techniques for estimating rock-mass response to static and dynamic loads, within a probabilistic framework.*
- *Conduct physical modeling using such techniques as the centrifuge and shaking table to study rock dynamics.*
- *Develop methods for assessing the* in situ *strength of a rock mass.*
- *Develop techniques for assessing the postfailure characteristics of rock masses.*
- *Develop techniques (laboratory, numerical, and/or physical) to assess rock-mass/reinforcement and rock-mass/structure interaction under dynamic loads.*

Research Program Plan

In order to assess the value of the correlation between laboratory-measured quantities and *in situ* values, large-scale *in situ* experiments should be considered to provide a sufficient field data base. It must be emphasized that when attempting correlations between the laboratory and *in situ* data, geological mapping of rock-mass conditions is essential for meaningful interpretation of the test results. (A discussion of the requirements in this area is found in Chapter 5.)

The following guidelines have emerged from the research and case-history studies for a systematic and integrated approach to laboratory and field investigations (Deere *et al.*, 1967; Cook, 1977; Bieniawski, 1978b). First, a detailed engineering geological assessment of the rock-mass conditions is required, which should be expressed in quantitative terms by an engineering classification of the rock masses encountered. Second, at least two different types of *in situ* tests should be selected, and a sufficient number of these tests should be conducted to determine *in situ* rock-mass characteristics of the field zone. For deformability measurements, the plate-bearing test, borehole jacking, and petite sismique techniques are recommended. Third, the stress field should be established in the area concerned by means of either an overcoring technique or flat jacks. (Improvements desired in this area are discussed in Chapter 4.) Fourth, seismic-velocity surveys should be conducted to determine the continuity of the rock mass throughout the area of the experiment. (Fifth, diamond drilling of good quality core of *NX* size should be undertaken at the *in situ* test sites so that samples can be selected for laboratory tests to determine the characteristic properties for intact rock specimens. The core and the boreholes should be logged and the RQD established.

Because a large-scale, *in situ* testing experiment would be extensive in scope, it should be a joint research venture involving universities, industrial research organizations, and federal laboratories. For other research priorities, aspects necessitating basic research and laboratory measurements would be best suited to study at universities. Applied research, development of instrumentation, and field measurements could be done more appropriately by industrial and federal research organizations.

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8

Thermophysical, Thermomechanical, and Thermochemical Properties

INTRODUCTION

The rising cost of energy from petroleum products necessitates the development of alternative energy sources, and each development involves perturbation of a natural system, which must be analyzed and predicted. Various models are used to predict the effects of development, but there is an extreme paucity of quantitative information in the field of rock mechanics that is essential for this purpose, especially information on the thermal behavior of the natural systems as intensive parameters are varied.

The thermal effects on rocks that limit energy-resource recovery and development can be described briefly; each area needs new research studies. In geothermal-energy exploration and production, questions arise concerning temperature effects on mechanical properties of reservoir rocks, especially thermal fracturing in nature and by hydrofracturing. *In situ* energy recovery from coal, oil shale, and tar sands requires evaluations of high-temperature effects on sedimentary rock, including heat conduction and permeability. Tertiary recovery of conventionally reservoired oil may utilize hot water or steam, and the affected rock properties need study to optimize project design. Self-heating of radioactive waste can create thermal stresses and cracks in surrounding rock. Such cracks can serve as possible channels for groundwater and must be monitored; creep may occur at moderate temperatures in rock salt used as a repository. In underground storage of fuel oil, gas, water, or compressed air, thermal shock to the chamber-wall rocks during emplacement and removal can create unwanted cracks and leakage paths. In addition to energy-related needs, the thermochemical and thermomechanical properties of rock are important for waste-fluid injection in the earth and for other industrial pollution problems. Finally, the frictional behavior of rocks observed in the laboratory is temperature dependent; hence, the mechanism of seismogenic faulting may be temperature dependent.

Effects of temperature on rock in the earth's crust depend on the following: the intensive parameters of state, such as the absolute pressure, temperature, and chemical potential; the sources of heat, whether internal heat flowing out of the earth, the sun's heat, or a man-made source; and the properties of the rocks. Properties such as compressibility, thermal expansion, fracture strength, and chemical potential are all temperature dependent. This chapter considers the temperature effect on certain but not all physical properties; those omitted include electrical, magnetic, density (gravitational), and optical properties. Thermophysical properties described are the intrinsic type: conductivity, diffusivity, thermal inertia, radiative transfer, and expansion, as well as related properties, including heat transfer between rock and water, elastic moduli, porosity, and permeability. The intrinsic specific heat, other thermodynamic properties, and some phase equilibria are considered under thermochemical properties. Thermomechanical properties, including thermal cracking, stress-corrosion cracking, effects of water, creep, and plastic flow, are considered separately.

The effects of heat on the physical and chemical properties of rocks and fluids can be complex and are predictable only under equilibrium conditions using thermodynamic functions of state for known mineral and fluid phases of known compositions. Chemical reactions and diffusional mass, momentum, and energy transport are thermally activated, and such kinetic processes are discussed briefly. For almost all of these properties, measurements are made in the laboratory and results must be extrapolated to the earth for application in the field; the problems involved in scaling data are examined in detail in Chapter 7.

This discussion of thermal properties considers only behavior at temperatures to 400°C and pressures to 500 MPa, corresponding to conditions in the upper 10 km of the earth's crust. The actual state of stress in the crust and the pore pressure are not well known, but the temperature distribution in the upper crust is better understood. A review of the thermal regime of the earth's crust will serve as a frame of reference for applying discussions of the thermal properties of rocks and minerals to problem areas in rock mechanics.

THERMAL REGIME OF THE EARTH'S CRUST

Regions where transport of heat is by conduction will be considered first, then we consider regions where transport of heat is by advective movement of groundwater or intrusion of magma. Surface heat flow, q, can be related to the heat flow from the mantle and lowermost crust, q^*,

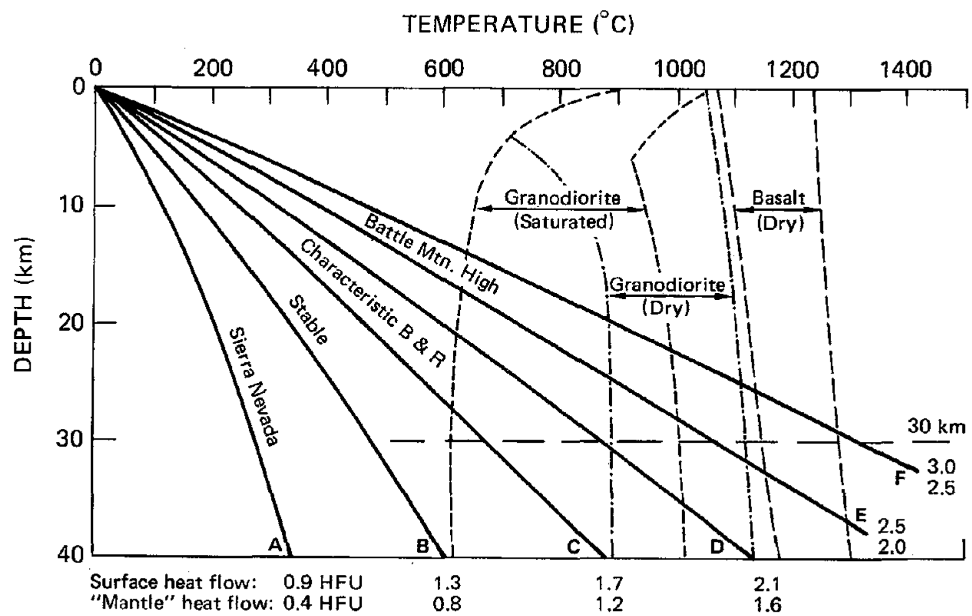

FIGURE 8.1 Generalized conductive temperature profiles for the crust (Lachenbruch and Sass, 1978): (A) the Sierra Nevada crust; (B) a stable reference crust, approximate eastern United States; (C to D) the characteristic Basin and Range crust; and (E) lower limiting and (F) typical conditions of the Battle Mountain High. Dashed lines are melting curves; all solid curves are drawn for a surface heat production, A_0, of 5 heat generating units and thermal conductivity, K, of 2.5 W/mK. Corresponding surface heat flow and reduced or "mantle" heat flow are shown at the bottom of each curve.

and to the radioactive heat generation in the crust, A, by a linear relationship

$$q = q^* + DA,$$

where D is an empirically determined parameter that is about 9.0 (±0.2) km. Summaries of the discovery and development of this idea are given by Birch *et al.* (1968), Roy *et al.* (1972), Blackwell (1971), Lachenbruch (1968), and Lachenbruch and Sass (1978).

Temperature profiles of the steady-state temperature variation with depth may be derived by assuming various values of the thermal properties. Lachenbruch and Sass (1978, Figure 22) calculate sample profiles with melting curves of dry and water-saturated granodiorite and basalt, as shown in Figure 8.1. Given this perspective, it is easy to see that abnormally high gradients cannot be extrapolated to great depth without melting. It has been noted (Blackwell, 1971; Roy *et al.*, 1972) that melting constitutes a thermal buffer, probably near the base of the crust. The fact that rocks at these depths cannot be wholly molten over wide regions has long been known from the velocity of seismic waves traversing them. From this we have an upper limit of what the temperature might be deep within a conductive crust.

Volcanoes, geysers, and hot springs are spectacular reminders that heat transport from the interior of the earth is not by conduction alone. More subtle reminders include the fact that q versus A plots for certain regions exhibit a wide scatter that cannot be explained by uncertainties of measurement. Some advective component is required. The Basin and Range province is one such region (Blackwell, 1978; Lachenbruch and Sass, 1978).

It is difficult to draw a line between conductive and advective regions. Some transport of heat by movement of groundwater could be expected in any region, provided that sufficient permeability and hydraulic gradient exist. Whether this effect is obvious or subtle, the extrapolation of temperatures to great depth is risky. The uncertainties in

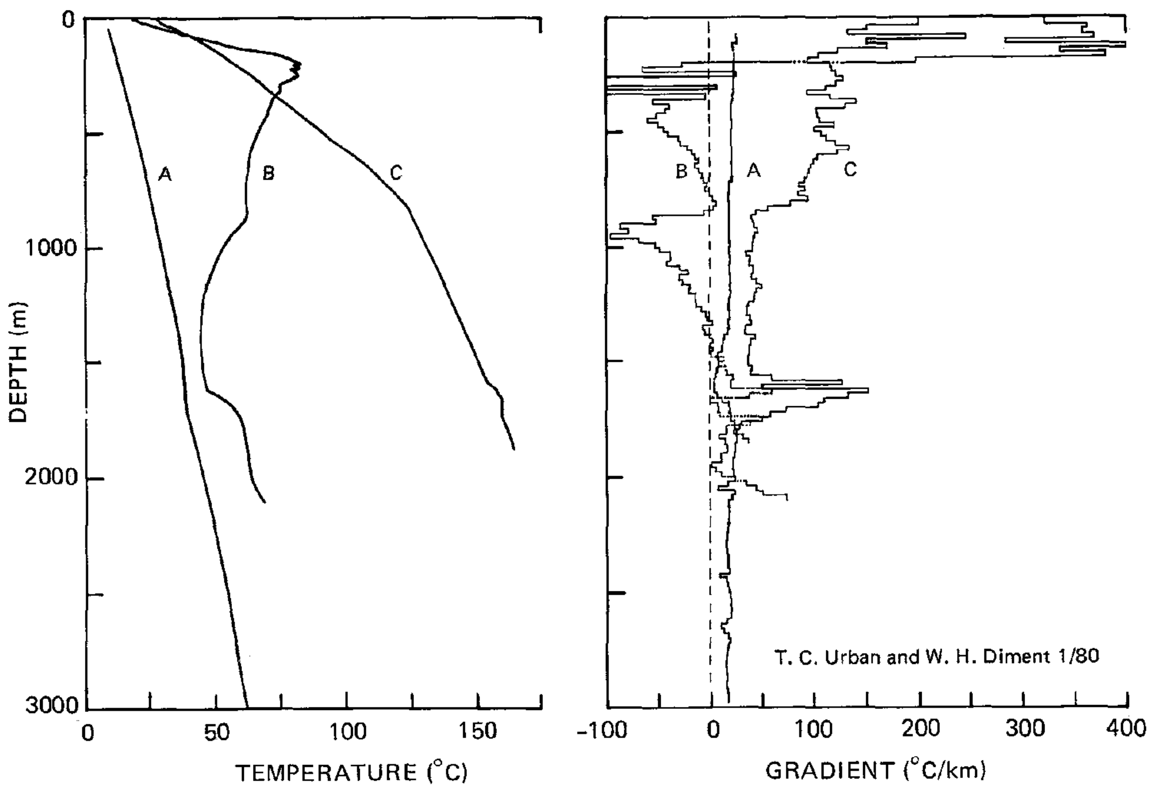

FIGURE 8.2 Temperatures and temperature gradients in three deep drill holes near thermal equilibrium with surrounding rock (T.C. Urban and W.H. Diment, U.S. Geological Survey, 1980). The profiles illustrate a wide range of conditions discussed in this chapter.

predicting the variation of temperature with depth is shown by three examples in Figure 8.2 (T.C. Urban and W.H. Diment, U.S. Geological Survey, written communication, 1980).

Temperature profile A from Pinedale, Wyoming (Sass and Munroe, 1974; Sass *et al.*, 1971b), illustrates what might be expected in crystalline rocks in a conductive region of low heat flow. The gradients are low and rather uniform.

Profile B in the Long Valley Caldera, Mono County, California (Smith and Rex, 1977; Diment, 1980), shows extremely high gradients near the surface, a dramatic decrease below 300 m, negative values to 1300 m, and positive values below 1300 m. Evidently, hot water rises along distant fractures and spreads out laterally through permeable formations, thus giving rise to high near-surface gradients.

Profile C from the East Mesa geothermal anomaly, Imperial County, California (Urban *et al.*, 1978), shows very high gradients near the surface, decreasing sharply at 800 m and remaining constant to 1900 m. The region above 800 m may be impermeable and may act as a conductive cap to a convective thermal regime below, or the cap may simple impede the upward flow of hot water along nearby faults to cause lateral dispersal of the buoyant water beneath the cap. Conductive heating of the region below could cause its observed thermal profile (Urban *et al.*, 1978).

THERMOPHYSICAL PROPERTIES

The intrinsic thermal properties—i.e., conductivity, diffusivity, thermal inertia, radiative transfer, and expansion of rocks, minerals, and fluids in the upper crust—are important for both practical and research problems and have been studied sufficiently that reliable estimates of their values can be made easily. These properties, plus fluid heat transfer, elasticity, porosity, and permeability are considered here. Mechanical properties and the effects of fluids are considered in the thermomechanical and thermochemical sections that follow, as well as in Chapter 9 with regard to numerical modeling.

The thermal conductivity of rocks has been studied more thoroughly than thermal diffusivity and inertia of rocks and minerals, reasonably accurate values of which can be calculated from conductivity, specific heat, and density of the mineral components. The effects on these properties of porosity, temperature, pressure, anisotropy, and pore contents of air and water need to be considered also. Fluid heat transfer in the earth, primarily between water and rock, has received little attention.

Direct measurements in the laboratory of the thermal properties of rock samples are usually more satisfactory than estimated values, but values for friable, porous rocks and even dense but inaccessible rocks often must be estimated. Of course, it is necessary to extrapolate laboratory measurements to rocks in place, with their large-scale inhomogeneities of bedding, fracturing, and other variations in composition and structure.

Thermal Conductivity

The most complete, published compilations of thermal conductivities of rocks are the tables of Clark (1966, Section 21) and of minerals, the tables of Horai (1971). The theory of conduction of heat is described for geologic purposes by Ingersoll *et al.* (1954), and the classic treatise is by Carslaw and Jaeger (1959). Compilers of the thermal conductivity, *K*, of rocks and minerals from published laboratory data tacitly assume for the various investigations that samples of each rock type are uniform and experimental measurements are accurate, producing comparable grain-to-grain thermal conduction around pores and through pore fluids. Techniques of laboratory measurement of *K* are described by Birch (1950), Beck (1965), and Sass *et al.* (1971a); *in situ* methods of measurement are reviewed by Beck (1965). Units of *K* are equivalent as follows:

$$1 \text{ W mK}^{-1} = 2.390 \times 10^{-3} \text{ cal cm}^{-1} \text{ sec}^{-1} \, ^\circ\text{C}^{-1} = 0.5797 \text{ Btu ft}^{-1} \text{ h}^{-1} \, ^\circ\text{F}^{-1}.$$

The effect of porosity, ϕ, on *K* in rocks is best considered by using its complement, namely solidity, γ, which is the ratio of volume of solid to bulk volume; thus, $\gamma = 1 - \phi$. Robertson and Peck (1974) and Robertson (1979) find that *K* varies linearly as γ^2, shown in Figure 8.3 for water-saturated basalt at room pressure and temperature. Thermal conduction in a rock is apparently controlled by solid grain-to-grain paths; this relation is analogous to Archie's law, in which electrical conductivity varies as ϕ^2 when most of the pores are isolated (Shankland, 1975). The same linear variation of *K* with γ^2 is found also to hold for saturated sandstone, limestone, dolomite, shale, and soils (Robertson, 1979). Similar linear variation is found for rocks with air in the pores, but lines are displaced to about 30 percent lower *K* values.

Values for *K* of a basalt at room pressure and temperature can be calculated from its mineral composition, as explained by Robertson and Peck (1974); the *K* of granites is explained by Sibbitt *et al.* (1979). Estimates of *K* of most rocks are possible if their approximate content of quartz or olivine is known; clay and mica minerals lower the *K* of rocks, and their content can be allowed for (Robertson, 1979).

TEMPERATURE (T) EFFECT ON K

The *K* of most rocks decreases with increase in *T*, about -30 percent from 0 to 100°C for rocks rich in quartz, calcite, and olivine. The *K* of basalt and rock glass increases slightly with *T*. The decrease in *K* for a *T* change from 0 to 400°C is from 4 to 2.4 W/mK for highly conducting granite and from 2 to 1.7 W/mK for poorly conducting granite (Birch and Clark, 1940). Ultramafic rocks have a similar decreasing curvature of *K* with *T*, and carbonate, mafic, and halide minerals show a similar decrease in *K* with *T*. Feldspar minerals have roughly constant values of *K* with *T*. Mechanisms of conduction in single-crystal minerals include lattice vibrations (phonons) and radiative transfer; resistance occurs because of scattering. Reviews are given in Klemens (1958), Goldsmid (1965), and Parrott and Stuckes (1975). A comprehensive listing of *K* for minerals is found in Horai (1971).

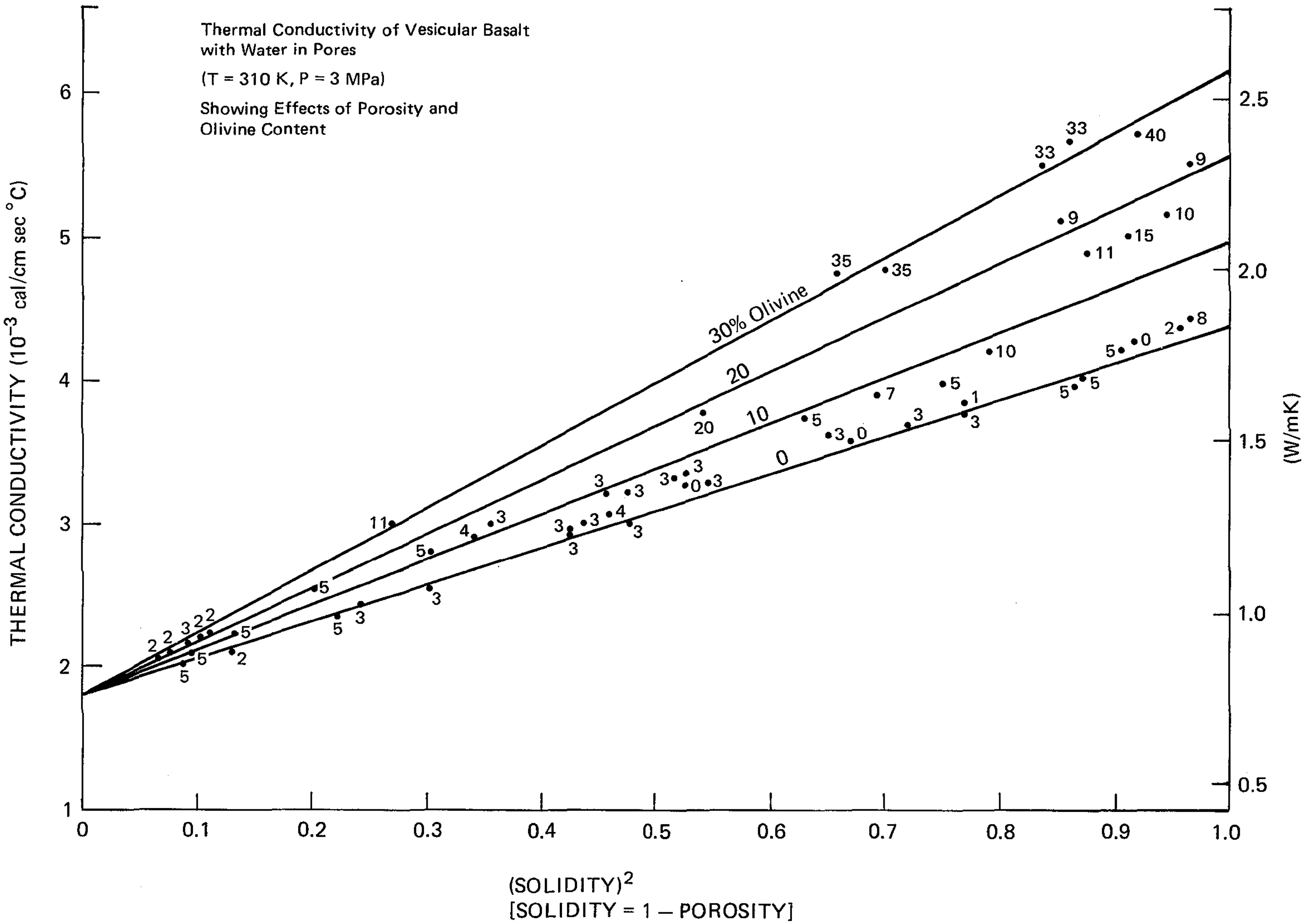

FIGURE 8.3 Variation of thermal conductivity of basalt with solidity (Robertson, 1979).

PRESSURE (P) EFFECT ON K

The effect of P on K is much less important than that of T and can be given by the coefficient, $a = (1/K_0)\ (\Delta K/\Delta P)$, in units of 10^{-9} Pa^{-1} = GPa^{-1}. For rocks and minerals with low porosity, <10 percent, values of a are linear with P, for $0 < P < 5$ GPa and a ranges from +0.5 to +5 percent/GPa. In porous rocks, a is much higher at low P; for example, in Berea sandstone, $\phi = 20$ percent, $a = 3000$ percent/GPa for $10^{-4} < P < 0.01$ GPa, and $a = 600$ percent/GPa for $0.01 < P < 0.03$ GPa. The effect of adding water to the pores is large; a decreases by a factor of 6 for many porous rocks from a dry to water-saturated condition.

ANISOTROPY OF K

In dense, igneous rocks and in gneisses, the ratio, r, of K parallel to K perpendicular to the foliation ranges from 1.05 to 1.5; $r = 3$ for schists and $r = 1.0$ to 1.5 for shales and soils. Large values of r are due to the mica and clay content; $r = 6$ for mica minerals.

Heat Transfer between Water and Rock

Studies of this heat-transfer parameter are needed urgently for practical problems. Hot-water and steam drives for secondary recovery of oil have been studied and some empirical data obtained on heat transfer to the rock, but those results are few. Measurements of the heat-transfer coefficient in rock/water systems in the laboratory are meager (Ramey *et al.*, 1976). Transfer of heat from hot rock to deeply circulating water occurs in one theoretical model by perfect mixing in a cell for which the amounts of mass and energy within and crossing the cell boundaries are known; thus, transfer coefficients can be eliminated for large-scale geothermal problems (Mercer and Faust, 1979; see also Chapter 9 in this report).

Radiative Heat Transport

Radiative heat transfer takes place by diffusion of photons down a thermal gradient in a process of absorption or scattering and re-emission. This transport mechanism operates in parallel with the usual phonon diffusion, i.e., lattice conductivity, that dominates at low to moderate temperatures. Radiative conductivity is a relatively high-temperature phenomenon that becomes effective above 500°C; it is found in the upper crust only near magmatic regions. Theoretically, radiative heat transfer can be calculated adequately if the absorption spectrum is known as a function of temperature and if the scattering mechanism is established. The calculated radiative conductivity for samples of obsidian changes from 0.1 to 0.5 W/mK, from 500 to 1000°C (Stein *et al.*, in press); this is 10 to 40 percent of lattice conductivity, therefore it is important.

Commercial glasses lack the scattering of obsidian, and effective radiative conductivity can be an order of magnitude larger (Gardon, 1961; Schatz and Simmons, 1972).

Temperature Effect on Elastic Moduli

The effects of temperature on the elastic moduli of single crystals have been studied for only a few minerals (e.g., halite and quartz). Increase in temperature reduces stiffness coefficients, e.g., in alpha-quartz as the alpha-beta transition temperature is approached. The effect of temperature on the elastic moduli of rocks has been measured for the dynamic moduli, mostly at low confining pressures. In rocks susceptible to thermal cracking, the observed decreases in moduli with increasing temperature are due largely to the increased microcrack density and not to a reduction of the intrinsic moduli of the minerals. The work of Kern (1978) at high confining pressure indicates that the dynamic moduli are only weak functions of temperature, provided that thermal cracking does not occur.

Thermal Expansion

For minerals, numerous measurements have been made of thermal expansion under atmospheric pressure (Skinner, 1966). The coefficients of thermal expansion increase moderately with increasing temperature for most minerals; exceptions are minerals at phase transformations, as in quartz between 450 and 573°C. For rocks, however, many measurements of the thermal expansion are unreliable because of thermal cracking and accompanying irreversible strain (Richter and Simmons, 1974). Thermal expansion coefficients measured on rocks with thermal cracks will be too large, as compared with the weighted average of the coefficients of the minerals (Cooper and Simmons, 1977); conversely, pre-existing cracks reduce the thermal expansion because of closure of the cracks. Wong and Brace (1979), in measuring the thermal expansion of several crystalline rocks over the temperature range 2-38°C and under sufficient confining pressure to eliminate the effects of the pre-existing cracks and thermal cracking, find that the thermal strains are reversible and that the measured coefficients fall close to the theoretical bounds for polycrystalline aggregates calculated by Walsh (1973) from single-crystal data.

Porosity and Permeability

The porosity of massive crystalline rock masses is less than 5 percent and is associated primarily with microcracks, the occurrence of which depends on the history of the rock mass. Fracturing can result from tectonic stresses, thermally induced internal stresses, volume changes associated with metasomatic alterations of minerals, or thermally induced phase changes; Solomon and Kerrick (1976) observe volume increase on the alteration of biotite to vermiculite in NaCl solutions at elevated temperatures. Porosity and permeability increase as a result of either dissolution or fracturing; porosity and permeability reduction can occur by compaction, by the growth of secondary minerals in void spaces, or by the effects of pressure solution and cementation. A comprehensive review of porosity, permeability, and fluid flow is given in Chapter 3 of this report.

Flow of an aqueous solution through hot crystalline rock occurs in a number of natural and man-initiated, thermal-convective circulation systems of economic and engineering significance. Geologic evidence and direct observations indicate that fluid flow through crystalline rock masses is dominated by flow along macroscopic fractures (Norton and Knapp, 1977), for which the permeability of 2 to 3 orders of magnitude greater than that for intact rock, at low pressure. The flow of hot aqueous solutions through rock fractures is expected to change the intact rock and the fracture permeabilities as a result of the water/rock interactions, but the amount of change will vary with rock type, initial fluid composition, and temperature and pressure conditions.

Potter (1978) measures the permeability of the Westerly granite and two adamellites as a function of effective pressure (stress difference minus pore pressure) to 35 MPa and temperature to 200°C. By using short-term experiments, chemical interactions of distilled water with rock were reduced. At a constant effective pressure, permeability initially decreases with increasing temperature to 100-150°C, after which the permeability increases with temperature. At the lower temperatures, differential expansions of neighboring minerals result in narrowing of grain-boundary cracks (the primary flow channels); above 150°C, differential thermal expansions result in thermal cracking, which creates an irreversible increase in permeability. Corroborative results are obtained by Bauer and Johnson (1979) to 660°C and 35 MPa (Figures 8.4 and 8.5).

The flow of hot aqueous solutions through fractures is expected to increase flow apertures, and thus the permeability. Water/rock interactions can result both in dissolution of rock minerals and in the formation of secondary minerals. Shear and effective-normal stresses acting across the fracture may be a significant factor if pressure solution takes place. Permeability of sandstone to liquid water can decrease by 50 percent or more with increases in temperature from 20 to 150°C (Weinbrandt *et al.*, 1975; Muhammadu, 1976; Danesh *et al.*, 1978); the reversibility of the permeability degradation is unknown. Permeability decrease is not observed when inert gases are used as the fluid. Preliminary explanations focus on physicochemical weakening and particulate plugging associated with the rock itself or experimental system corrosion products.

Balagna *et al.* (1976), using distilled water, measure the changes in permeability with time of a sample of "granite" heated to 260°C, which was subjected to alternating periods of fluid flow and rest. After periods of rest of about 13 days, permeability decreases from 7.6×10^{-18} m^2 to 3.8×10^{-18} m^2; after forced flow for approximately 1/2 day, the permeability increases to 4.4×10^{-18} m^2. The decrease of permeability during the rest phase is interpreted to result from clay formation in the flow channels along grain-boundary cracks. After flow of distilled

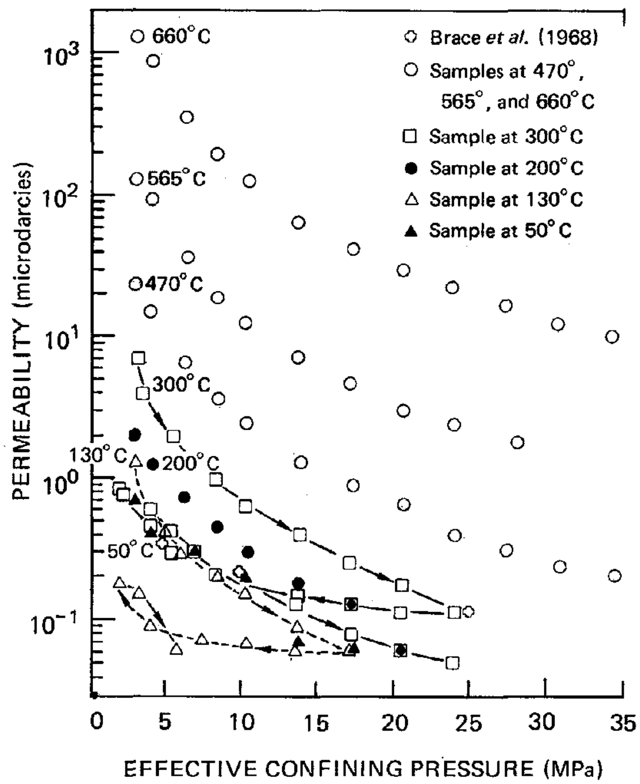

FIGURE 8.4 Permeability of thermally cycled Westerly granite as a function of confining pressure. Arrows indicate confining pressure load path (Bauer and Johnson, 1979).

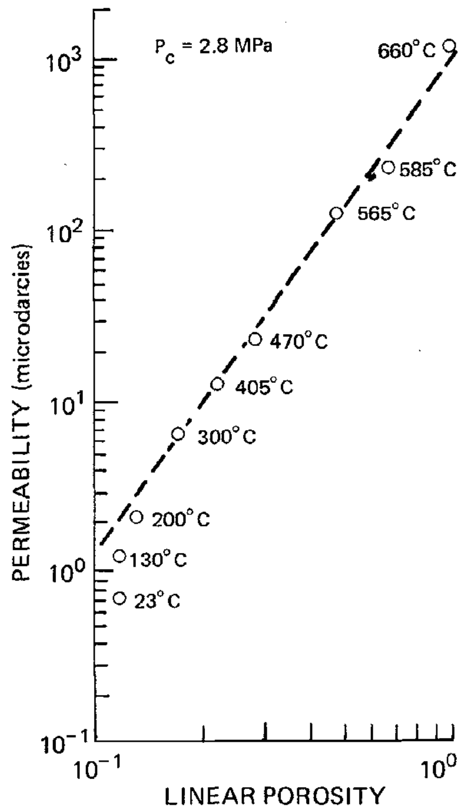

FIGURE 8.5 Increases in permeability and linear porosity with cycled temperature under 2.8 MPa confining pressure (Bauer and Johnson, 1979).

water for 5 days through adamellite samples at 200°C, permeability increases over an effective-pressure range to 20 MPa (Potter, 1978), which is attributed to the dissolution of quartz. Summers *et al.* (1978) measure changes in permeability during the flow of distilled water through Westerly granite for periods up to 17 days at temperatures between 100 to 400°C, with constant confining pressure of 50 MPa, differential stresses of 0 to 350 MPa, inlet pore pressure of 27.5 MPa, and outlet pressure of 0.1 MPa. In all experiments, permeability decreases significantly as a result of plugging of flow channels at the outlet by secondary minerals. Dissolution of quartz and feldspar is evident near the inlet.

THERMOMECHANICAL PROPERTIES

The effect of temperature on the mechanical properties of rocks is an irreversible thermal cracking if the rocks are not under some minimum confining pressure; similar cracks are induced by pore pressure. As Ide (1937) found long ago, grains in heated, unconfined rock expand differently in different directions, depending on composition and orientation, and create internal cracks; on cooling, the cracks remain and so the grains are more loosely joined and the rock stiffness is permanently reduced. If the integrity of the intergranular bonding is preserved from thermal cracking by confining pressure, the effects of temperature on elasticity, strength, and ductility of the rock can be predicted reasonably well. For comprehensive reviews, see Birch (1966) and Handin (1966). Brittle fracture and plastic flow in heated rock are the major categories of thermomechanical properties for consideration. Effects of fluids in rocks are evaluated more clearly as thermochemical properties, but they are also important mechanically. Additional discussion of thermal cracking appears in Chapter 6 and Chapter 7.

Brittle Fracture

The effect of increasing temperature on massive silicate rocks is a decrease in their strength, depending on the rock type and the confining pressure; the effect on ductility appears to be small for dry, crystalline, silicate rocks under moderate confining pressures (Friedman *et al.*, 1979; Lindholm *et al.*, 1974). A confining pressure of 10 to 20 MPa nullifies the effect of thermal cracking on compressive strength (Bauer and Johnson, 1979); however, this confining pressure does not remove the effects of thermal cracks on elastic moduli, thermal expansion, and fluid transport. Strength is reduced by heating under moderate confining pressure because fracture energies are temperature dependent. Bauer and Johnson (1979) find that thermal cracks dramatically reduce tensile strength. Stress-corrosion cracking and thermally activated fracture in noncorrosive environments also reduce tensile strength.

Deformation at existing discontinuities in heated rock has received recent experimental attention. Stesky *et al.* (1974), studying the frictional behavior of seven rocks at 700°C and at pressures from 250 to 600 MPa, observe that the transition between stick-slip and stable sliding is temperature dependent, varying with rock type. Above 600°C, the frictional strength of saw-cuts in Westerly granite decreases and is closely associated with the fracture strength. In two experiments to 265°C, under confining pressure of 300 MPa, and at 10^{-4} cm/sec sliding rate, water was found to have little effect on the frictional behavior of faulted Westerly granite. In subsequent studies of frictional sliding of faulted Westerly granite, Stesky (1978) finds that at $T < 500$°C deformation is brittle with an activation energy of 125 kJ/mole, and that at $T < 500$°C quartz adjacent to and within gouge exhibited plastic flow with an activation energy of 365 kJ/mole.

THERMAL CRACKING

Thermal cracks in rock are caused by thermal stresses resulting from mismatch of thermal expansions of adjacent grains with different or anisotropic coefficients. If the temperature change is sufficient, the stresses will exceed the local fracture strength, and grain-boundary and intragranular cracks will develop. The degree of thermal cracking sustained by a rock is a function of mineralogy, fabric, grain size, previous thermal and stress history, residual-strain state, and confining pressure. Only preliminary investigations have been made on these topics. Thermal cracking of crystalline rock is studied theoretically by Devore (1969), Johnson *et al.* (1978), and Bruner (1979) and experimentally by Barbish and Gardner (1969), Perami (1971), Richter and Simmons (1974), Johnson *et al.* (1978), Cooper and Simmons (1978), Kern (1978), and Bauer and Johnson (1979).

Fracture studies of ceramics indicate that as the crack porosity increases due to thermal cracking, the fracture toughness decreases (Simpson, 1974). By thermodynamic relations, fracture-surface energy is expected to decrease linearly with increasing temperature (Swalin, 1962). Wiederhorn *et al.* (1973) determine that the fracture-surface energy in single crystals of alumina decreases linearly with temperature to 600°C and that plastic deformation by dislocation or twinning plays no role in the fracture process. This reduction of fracture-surface energy with temperature has yet to be studied for minerals.

STRESS-CORROSION CRACKING

Fracture is a thermally activated rate process, although the details of the fracture process are dependent on whether a chemically active pore fluid is present. The presence of polar fluids, especially water, even in small amounts, markedly enhances crack growth; this process is called stress-corrosion cracking. Extensive experimental and theoretical studies of this cracking have been conducted for ceramic materials; research has begun on rocks and minerals, including quartz, marble, gabbro, Westerly granite, and Arkansas novaculite (Martin, 1972; Scholz, 1972; Martin and Durham, 1975; Henry *et al.*, 1977; Atkinson, 1979a, 1979b). Theoretically, there should be a threshold value to the stress-intensity factor at which stress corrosion will result in crack growth, the value of which can be estimated from fracture toughness and fracture-surface energy.

EFFECTS OF WATER IN POROUS ROCKS

The effects of interstitial fluid on the mechanical properties of heated sedimentary rocks are important in all excavations for practical purposes. Many of the problems involve phase equilibria and so are considered in the section on thermochemical properties. Some mechanical properties are listed in Table 8.1; chemical interactions of the fluids with rocks may occur. Temperature effects on the properties given in the table include increased effective stresses, decreased load-bearing capacity, and increased fluid/rock interactions and consolidation. Temperature effects on the load-bearing capacity of a rock matrix involve mineral dissolution, hydrolytic weakening, inelastic deformation, fluid-transport cementation factor, and apparent fluid viscosities near grain boundaries.

FATIGUE

The effects of temperature and water on time-dependent, load-bearing capacity have been studied in silicate glass and quartz crystals (Griggs, 1974; Weidmann and Holloway, 1974). Hydrolysis of silica at stressed tips of microcracks reduces strength and enhances microcrack-propagation velocity; the reduction in surface free of energy is temperature dependent. Porous rocks under thermal or mechanical compressive loads become unstable by intragranular fracturing resulting from grain-boundary extensional stresses (Gallagher *et al.*, 1974; Simmons *et al.*, 1979). Moderate-temperature static fatigue may be a contributing factor to porosity and permeability reductions and to increased aggregate consolidation. Mechanical dynamic fatigue has been experimentally observed (Hocking, 1979;

TABLE 8.1 Effect of Temperature Increase on Properties of Rock Saturated with Liquid Water

Property	Temperature Effect	References
Elasticity, yield strength	Decrease	Martin, 1972
Bulk compressibility	Increase	Von Gonten and Choudhary, 1969
Bulk density, thermal diffusivity	Increase	Somerton, 1975
Permeability (water)	Decrease	Weinbrandt *et al.*, 1975
Permeability (oil/water)	Increase	Lo and Mungan, 1973
Irreducible water saturation	Increase	Sanyal *et al.*, 1974
Mineral solubility, reaction rates	Increase	Rittenhouse, 1971

Haimson, 1978) in experiments on porous rocks at a loading frequency of 1 Hz, at room temperature.

Creep and Plastic Flow

At low homologous temperature (ratio of observed temperature to melting temperature), $T/T_m < 0.1$, permanent strain in most silicate rocks is produced at stresses greater than half their breaking strengths. This permanent strain is produced by the formation of microcracks, which are preferentially oriented parallel to the maximum compressional stress. Tests indicate that under constant load, creep rates decrease monotonically with time, except under high stress levels leading to rupture; Kranz and Scholz (1977) suggest that a critical dilatant volume of microcracks may produce tertiary creep and rupture. In the presence of fluids, the effect of temperature on stress corrosion is important, and temperature controls the chemical-reaction rates at crack tips. In dry samples under conditions of moderate homologous temperature ($0.1 < T/T_m < 0.5$), at atmospheric pressure, transient creep occurs by thermally activated microcracking; grain-boundary sliding occurs at higher temperatures (Carter and Kirby, 1978). Significant dilatation also develops but with small activation energies (4-13 kJ/mole). Creep under confining pressure results from combined plastic flow and brittle fracture (Carter and Kirby, 1978).

SILICATE ROCKS

Plastic flow of rocks, which involves the transport of material to produce a change of shape, is achieved by several thermally activated processes. Dislocation motion, twinning, and kinking are the dominant flow mechanisms at $T < 600°C$; diffusional processes and shear on grain boundaries become significant at $T > 600°C$ (Carter and Kirby, 1978). Diffusional processes become effective at lower temperatures if pore fluids are present. Griggs and Blacic (1964; 1965) and Carter (1976) demonstrate that above a critical temperature and depending on OH ion content, strain rate, and orientation, water promotes the mobility and multiplication of slip dislocations in quartz and olivine. Shear on grain boundaries is suppressed by increasing confining pressure; thus, it occurs at moderate temperatures and at low confining pressure.

CARBONATE ROCKS AND ROCK SALT

At a temperature of about 300°C, the yield strengths of calcite marble and rock salt are markedly reduced; however, the yield strength of dolomitic marble increases because of the increase of the critical shear stress for slip on the basal plane. The effect of temperature on work hardening in dolomites is small, so the ultimate strength increases with increased ductility. In calcite marbles, heating decreases the yield strength and so has little effect on work hardening. In rock salt, an increase in temperature lowers the yield strength and reduces work hardening. Very large plastic strains can be achieved because recovery processes are active.

Carter (1976) and Carter and Kirby (1978) contend that below 600°C crystalline silicate rocks, excepting quartzites, will exhibit only transient creep (where failure is precluded) under typical geologic conditions, whereas steady-state creep will dominate in natural deformation of rock salt and calcite marble. Prediction of closure of cavities in bedded salt and dome salt is important for nuclear-waste isolation and for storage of oil and other substances underground. Extensive research being conducted at a number of academic and national laboratories is developing many of the behavioral parameters for salt.

THERMOCHEMICAL PROPERTIES

The thermochemical properties of anisotropic minerals differentially affect the degree to which minerals react in geochemical processes. Perturbations of pressure, temperature, and composition, combined with kinetic constraints in some chemical systems, control mineral stabilities. Many important reactions cannot be investigated directly in the laboratory because of either time restrictions or kinetic constraints. Therefore, scientists are asked frequently to predict the consequences of varying intensive parameters and to determine mineral equilibria not amenable to experiment.

The computer models that have gained much prominence and acceptance in the last decade have been limited to a large extent to using equilibrium thermodynamic theory as a basis and generally restricted to describing dilute-solution behavior (Potter, 1979). In addition, the ability to make accurate predictions of natural phenomena through these models has been hindered by the lack of thermodynamic data for some phases and solution species, by inconsistencies in the thermodynamic data base chosen for the model, and by incomplete understanding and description of the mechanisms controlling the natural processes.

A variety of temperature-related phenomena have the potential to perturb the fundamental properties of consolidated and unconsolidated aggregates, as well as permeable intact rock. Among these phenomena are hydrothermal and metamorphic alteration, dissolution and cementation, mass transport, vaporization and dehydration, and bulk and boundary-layer viscosity changes.

Thermodynamic Data

Numerous tabulations of "critically" evaluated thermodynamic data may be found in the literature. However, differences in chosen or derived reference states for one or more of the elements within or between several of these tabulations preclude the indiscriminate mixing of enthalpy and free energy of formation data. The references cited in Table 8.2 are

TABLE 8.2 Recommended Sources of Thermodynamic Information and Data

Source	Type of Data[a]							Comments
	C	S	H	G	V	P	U	
Robie *et al.* (1979)	X	X	X	X	X	b	J	Thermochemical data for phases of geologic importance; large reference list.
Stull and Prophet (1971)	X	X	X	X		A	k	Thermochemical data for inorganic chemical substances; large reference set.
Langmuir (1978)		X	X	X		A	k	Thermochemical data for uranium minerals and ionic species.
Cordfunke and O'Hare (1978)	X	X	X	X		A	J	Thermochemical data for uranium and thorium compounds.
Helgeson *et al.* (1978)	X	X			X	A	k	Best source of references to experimental phase-equilibrium data in the geologic literature. Substantial differences in the reference state for several elements preclude direct mixing of the enthalpies and free energies of formation reported by Helgeson *et al.* (1978) with other tabulations listed in this table.
Lindroth and Krawza (1971)	X							Heat-content values for six common rock types.

[a]C, heat capacity or heat content; S, entropy; H, enthalpy and G, free energy of formation; V, volume; P, pressure units (b, bar; A, atmosphere); U, units (J, joules, k, calories); X, data contained in reference.

recommended to minimize the potential for incorporating inconsistent data. Hemingway and Robie (1977) and Hemingway *et al.* (1978) discuss the inconsistencies between several tabulations of thermodynamic data as applied to data for aluminum-bearing phases.

Two methods are used currently to evaluate thermodynamic and phase-equilibrium data and to generate an internally consistent data base. The older method employs the stepwise development of the data base through analysis of the experimental data for a given phase or related group of phases. The evaluation yields the "best values" for the thermodynamic properties of each phase, which are then added to the data base. Examples of this method may be found in the tabulations of Stull and Prophet (1971), Wagman *et al.* (1968), Helgeson *et al.* (1978), and Robie *et al.* (1979). A method proposed recently by Haas and Fisher (1976) provides for the simultaneous evaluation and correlation of all types of experimental thermodynamic data. Their method is extended by Haas *et al.* (1979) to include, as nearly as possible, analysis of the directly observed data from each experiment. Of the two methods currently in use, that of Haas *et al.* (1979) provides for the greater number of tests for internal consistency.

A substantial body of thermodynamic data derived from calorimetry (e.g., Robie *et al.*, 1979) and phase-equilibria studies (e.g., Helgeson *et al.*, 1978) exists for phases that can be expected to be important in reactions occurring from the shallow crustal environment through the upper mantle. As noted earlier, many of the differences in the reported enthalpies and free energies of formation of these phases frequently can be attributed to differences in the chosen reference states derived for these phases and can be eliminated by simultaneous multiple regression (Haas *et al.*, 1979).

Thermodynamic and phase-equilibrium data for phases important to surface and shallow crustal-reaction processes (e.g., zeolites and clay minerals) are limited; those that exist are largely unevaluated. Substantial differences exist in data derived from calorimetric experiments and from solubility studies, suggesting either that errors exist in the measurements or the ancillary thermodynamic data or that the solubility reactions or the derived solubility values are defined improperly.

Empirical and theoretical models have been developed to estimate thermodynamic properties of phases for which no experimental values are available. The empirical procedures developed by Helgeson *et al.* (1978) are fairly standard and are useful in deriving values for the entropy, heat capacity, and volume changes of a phase as a function of temperature. Theoretical models (Kieffer, 1979) for the same thermodynamic parameters are more cumbersome to use and offer no advantage over empirical models.

Procedures for estimating the enthalpy or free energy of formation of a phase have met with limited success. For simple systems, such as the halides, Latimer (1952) and Rossini *et al.* (1952) have been reasonably successful using empirical models. For more complex systems, such as the silicates, empirical models have been developed that attempt to relate the free energy of reaction from a selected set of component reference compounds (Tardy and Garrels, 1977; Chen, 1975; Mattigod and Sposito, 1978). Estimates of enthalpies and free energies of formation generally contain substantial errors that limit their usefulness.

The estimated thermodynamic values and the procedures developed to predict such values generally have been ignored in studies that evaluate thermodynamic data. An extensive discussion of the state of thermodynamic data is given in *Report of the Conference on Thermodynamics and National Energy Problems* (Holley and van Olphen, 1974). An annual summary of work in progress, together with a list of the personnel and programs, for domestic and international laboratories engaged in the acquisition or evaluation of chemical thermodynamic data is found in the *Bulletin of Chemical Thermodynamics* (Freeman, 1978).

Hydrothermal and Metamorphic Alterations

Hydrothermal mineral alterations and associated water-quality changes have been the focus of numerous theoretical, laboratory, and field investigations (Chernosky, 1979). Unfortunately, much of this effort has involved chemical equilibrium alone or has been directed at measuring only one thermochemical property at a time. The resulting inconsistencies of thermodynamic data have caused significant errors in several past investigations (Chernosky, 1979).

The composition of natural metamorphic fluids in equilibrium with mineral assemblages can be determined, in principle, if such systems contain exchange reaction, buffer, and fugacity indicators (Chernosky, 1979). The success of this approach is limited by the lack of thermodynamic data for aqueous species at high temperatures and pressures and also by the lack of appropriate mixing models for multicomponent fluids. In aqueous solutions, ionization tends to become less favored with increasing temperature, whereas ion association or complexing tends to increase. In turn, this results in significant changes in the solubilities of many minerals in contact with the solution. A knowledge of dissolution, metasomatic alterations, and secondary mineral formation in rock/fluid systems at elevated temperatures is essential to understanding porosity and permeability changes that will occur for prescribed pressure and temperature conditions and fluid composition.

Dissolution and Cementation

In studies of the geochemistry of mineral dissolution and precipitation, more emphasis is needed on temperature-enhanced pressure solution at grain boundaries. Changes in the shape of individual grains occur by grain-boundary dissolution and diffusion, predominantly from areas of high stress concentrations to areas of lower stress, at grain pore interfaces. In nature, this process may occur at temperatures substantially lower than those required for inelastic grain deformation (e.g., Coble creep, Nabarro-Herring creep, and superplastic flow). Diffusive mass transport is assisted by the presence of water at grain boundaries, high stress concentrations, and elevated temperatures. In the aqueous phase, effective diffusivities at temperatures of about 200 to 400°C may be of the order of solid-state diffusivities at much higher temperatures (Rutter, 1976). Temperature-enhanced pressure solution could include both compaction and cementation and could be manifested in nature as a reduction in the available fluid-storage and transport capabilities and an increase in subsidence. Thus, this phenomenon may be of importance to moderate-temperature underground technologies such as geothermal compressed-air energy storage, solar-heat storage, and nuclear-waste disposal.

Vaporization and Dehydration

The elevated-temperature structural stability of typical reservoir cap rocks, such as shale, is of concern to several energy-storage and recovery technologies. A greater understanding both of the mechanism of vaporization and desaturation in small-diameter pores and of contraction and fracture development subsequent to dehydration is important. It has been demonstrated that cracks up to 1 mm wide can be developed in argillite by nonuniform heating and dehydration, and decrepitation of the free surface of wellbores has been observed.

Retardation of Hazardous Constituents

The effects of temperature on adsorption of potentially hazardous trace constituents onto geologic materials need study. Ames and McGarrah (1979) and Erdal *et al.* (1979a; 1979b) find no trends in perturbation to radionuclide retardation coefficients with temperature. Problems arise from the competing relationships of solubility, complexing, ion exchange, and surface adsorption and their respective temperature dependencies.

TABLE 8.3 Outline of Recommendations—Thermophysical Properties

	Purpose		Where Done		Experimental Variations							Problem Areas					
Thermophysical Properties	Estimation	Monitoring	Laboratory	*In Situ*	Temperature[a] L, low; H, high	Pressure[b] L, low; H, high	Term s (short) < 10^6 sec > l (long)	Heat Capacity	Enthalpy of Formation	Solubility	Rock CR, common rocks, including salt	Nuclear-Waste Disposal	Geothermal Development	Waste-Fluid Injection	Liquid and Gas Storage	*In Situ* Resource Recovery (Oil and Gas)	Earthquake Prediction and Hazard Mitigation
Fluid-Rock Heat Transfers	X		X	X	L	L	s				Granite	X	X	X	X	X	X
Heat transfer, heated rock to water, geothermal development in hot, dry rock																	
Heat transfer, hot water to rock, hot springs interpretations																	
Solid Heat Conduction																	
Thermal conductivity, in boreholes	X			X	L	L	s				CR	X	X	X	X	X	X
Thermal conductivity, porous sedimentary rock, influence of micas on anisotropy	X	X	X		L	L	s					X	X		X	X	
Mechanisms of conduction in mineral crystals, rock-forming minerals	X		X		L-H	L	s						X				
Wave-Propagation Velocities																	
Longitudinal and shear-wave velocities	X	X	X	X	L-H	L-H	s				CR	X	X	X	X	X	
Permeability and Porosity																	
Pressure solutioning, cementation, effect of temperature	X		X	X	L	L	s, l			X	CR	X	X	X	X	X	X
Solubility of minerals on fractures and gouge, with temperature	X		X	X	L	L	s	X	X	X	CR	X	X	X	X	X	X

[a]Temperature: L (low) < 400°C > H (high).
[b]Pressure: L (low) < 100 MPa > H (high).

TABLE 8.4 Outline of Recommendations—Thermomechanical Properties

	Purpose		Where Done		Experimental Variations							Problem Areas					
Thermomechanical Properties	Estimation	Monitoring	Laboratory	*In Situ*	Temperature[a] L, low; H, high	Pressure[b] L, low; H, high	Term s (short) < 10^6 sec > l (long)	Heat Capacity	Enthalpy of Formation	Solubility	Rock CR, common rocks, including salt	Nuclear-Waste Disposal	Geothermal Development	Waste-Fluid Injection	Liquid and Gas Storage	*In Situ* Resource Recovery (Oil and Gas)	Earthquake Prediction and Hazard Mitigation
Thermal Cracking, Studies of the Mechanical Effects of Heating Rock, with Comparisons before, during, and after Heating																	
Crack permeability and porosity, liquid or gas	X		X	X	L	L	s, l				CR	X	X	X	X	X	X
Monotonic temperature change																	
Cycling of temperature																	
Effect of confining pressure																	
Irreversible thermal expansion	X		X	X	L	L	s				CR	X	X		X	X	
Elastic/inelastic stress and strain, compressibility	X	X	X		L	L	s				Granite, Basalt	X	X	X	X	X	X
Effect of confining pressure																	
Effect of mechanical cycling																	
Crack propagation velocity																	
Wave attenuation, compression or shear	X	X	X		L	L	s				Salt, Granite, Basalt	X	X	X	X	X	X

Elastic/inelastic strain, compression	X	X		X	L	L	s	Salt, Granite, Basalt, Shale	X	X	X	X	X	X
Strength, compression or shear Monotonic temperature change Thermal cycling, fatigue strength	X	X	X		L	L	s		X	X	X	X	X	X
Stress-Corrosion Cracking, with Heating of Rock														
Effects of water and brine on crack extension, chemical reactions at crack tips	X		X		L	L	s	CR	X	X	X	X	X	X
Subcritical crack growth, thermal activation mechanisms	X	X	X		L	L		CR	X	X	X	X	X	X
Creep and Strength Studies with Heating of Rock														
Creep, compression	X	X	X	X	L	L	l	CR	X	X	X	X	X	X
Effect of water on creep in rock salt	X	X	X	X	L	L	s		X	X	X	X	X	X
Water-weakening of crystals of rock-forming minerals	X		X		L-H	H			X	X	X	X	X	X
Frictional sliding, including the effect of water	X	X	X		L	L	s		X	X	X	X	X	X
Mechanical-fatigue strength, compression	X		X		L	L		CR	X	X	X	X	X	X

[a]Temperature: L (low) < 400°C > H (high).
[b]Pressure: L (low) < 100 MPa > H (high).

TABLE 8.5 Outline of Recommendations—Thermochemical Properties

Thermochemical Properties	Purpose: Estimation	Purpose: Monitoring	Where Done: Laboratory	Where Done: *In Situ*	Experimental Variations: Temperature[a] L, low; H, high	Pressure[b] L, low; H, high	Term s (short) < 10^6 sec > 1 (long)	Heat Capacity	Enthalpy of Formation	Solubility	Rock CR, common rocks, including salt	Problem Areas: Nuclear-Waste Disposal	Geothermal Development	Waste-Fluid Injection	Liquid and Gas Storage	*In Situ* Resource Recovery (Oil and Gas)	Earthquake Prediction and Hazard Mitigation
Calorimetry and Solubility Research (in each study, the different experimental techniques should be applied to portions of the same initial sample of each phase)																	
Thermochemistry of clay minerals, especially halloysite, endellite, and hisingerite	X		X	X	L	L	s	X	X			X	X	X		X	
Solubility at several temperatures																	
Heat capacity from 5 K to break-down temperature																	
Enthalpy of formation at 298.15 K																	
Thermochemistry of zeolite samples, clinoptilite, heulandite, laumontite, phillipsite, and chabazite	X		X		L-H	L-H		X	X			X	X	X	X	X	
Solubility at several temperatures																	
Heat capacity from 5 K to break-down temperature																	
Enthalpy of formation at 298.15 K																	

Thermochemistry of montmorillonite change composition by exchange techniques Enthalpy of formation at 298.15 K Solubility at several temperatures Heats and entropies of mixing	X	X	X	L-H	L-H		X	X		X	X	X	X	X	
Thermochemistry of water in clays and zeolites Field effect for bound water Stability and water loss	X	X	X	L	L		X	X		X			X	X	
Thermochemistry of amorphous precursors of clay minerals and zeolites, e.g., imogolite Solubility at several temperatures Stability range	X	X	X	L	L		X	X	X	X	X	X	X	X	
Stability of Minerals in Porous Sediments															
Vaporization in small pores, dehydration effects	X	X	X	L	L	s				X			X	X	
Theoretical Research	X	X		L-H	L-H					X	X	X	X	X	X
Evaluate and tabulate thermodynamic data for rock-forming minerals; list of references															
Evaluate and tabulate thermodynamic data of geologically important ionic species at moderate pressure and temperature. Compare calorimetric and solubility measurements															
Assess chemical-heat production of large volumes of rock, interacting with moving fluids															
Evaluate changing rock/fluid interface with time and temperature															

[a]Temperature: L (low) < 400°C > H (high).
[b]Pressure: L (low) < 100 MPa > H (high).

RECOMMENDATIONS FOR RESEARCH

In the foregoing description of present understanding of the thermophysical, thermomechanical, and thermochemical properties of rocks, the relative current importance to national needs was not presented. However, in making recommendations for research, priorities for national needs must be considered. The problem areas include those associated with supplemental and primary energy sources—specifically nuclear-waste disposal, geothermal development, liquid and gas storage, and *in situ* oil and gas recovery. Other areas are ground-failure hazards, reinjection of waste fluids, and earthquake prediction and control.

The recommendations for research, presented in Tables 8.3, 8.4, and 8.5, are listed in order of importance to national needs within each property type—thermophysical, thermomechanical, and thermochemical—showing applications to problem areas. As an example of how to interpret the experiments outlined, consider the entry on thermal-crack permeability and porosity (Table 8.4). Either or both laboratory and *in situ* studies are needed, using either a liquid or a gas, at room temperature or higher, at room pressure or higher, for both short and long periods, and on some common rock. The effects on crack growth of raising temperature slowly, or of repeated cycling of the temperature to some nominal value and down, and of applying an increasing confining pressure in successive experiments would yield important results. The conditions would be chosen by the investigator both for feasibility and for significance in one of the problem areas.

The example of thermal-crack permeability can be made more specific. To study the enhancement of hot dry rock, laboratory experiments could be planned using water to create cracks in heated granite—heating slowly to 100, 200, 300, and 400°C, until thermal equilibrium is attained, under 50-MPa pressure; hydrofracing pressures could be simulated by applying pore pressure at 0.1, 2, 5, 10, and 20 MPa.

The choice of experiment inevitably is determined by the source of funding and by feasibility. The accompanying recommendations merely provide guidelines.

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9
Numerical Modeling

INTRODUCTION

The word "model" has several interpretations, but in the context of this chapter it is taken to mean a "hypothetical or stylized representation" of some prototype. In rock mechanics the prototype is rock and rock mass, albeit on scales that vary from the molecular to the continental. Many different types of model are used, and these may be categorized as conceptual, physical, analytical, and numerical.

Conceptual models provide a framework for investigation. Physical-, analytical-, and numerical-modeling activities rely on selection of an adequate conceptual model of the prototype. Indeed, a major objective of such activities may be improvement of the conceptual model.

Physical models continue to play an important role in rock mechanics, even though their application is usually qualitative rather than quantitative. Important restrictions arise because of scale effects and the complex nonlinear behavior typically exhibited by the prototype. These restrictions, coupled with the high cost and inflexibility of large-scale physical-model studies, have led to increasing emphasis on numerical models.

The division between analytical and numerical models is indistinct. The former are generally presumed to rely on the application of a closed-form solution to the problem. When an appropriate closed-form solution is available, it can provide a powerful and economical method of analysis. However, derivation of the necessary closed-form solution is often difficult or even impossible, and the numerical effort necessary to evaluate certain mathematical functions may be excessive. Nevertheless, closed-form solutions for more and more complex problems in rock mechanics should be sought as they provide a basis for validation of more-general numerical models.

This chapter addresses only numerical modeling. The activity is taken to include development of a conceptual model, selection of an appropriate numerical procedure or computer code, construction of the numerical model, and its subsequent application to the solution of the problem. Necessary research relating to this entire activity is proposed. Further, some specific recommendations are made regarding necessary developments of particular numerical procedures. The basis of these recommendations is that numerical-modeling capability is currently restricted by limitations in available computer codes.

The purpose of this chapter is to define necessary research in numerical modeling as applied to rock mechanics. In meeting this objective, each area of rock-mechanics application is reviewed and computational features required for any investigation are assessed. The extent to which available numerical procedures meet the requirements is then discussed. This is done by making reference to specific computer codes considered to be typical of current computational capabilities in the field of rock mechanics.

COMPUTATIONAL FEATURES REQUIRED IN ROCK-MECHANICS INVESTIGATION

In the preceding chapters of this report, specific areas for rock-mechanics research are proposed. The primary objective of several of those research areas is to improve the model of the prototype. Such models often form part of a total numerical-modeling effort. In some instances, numerical modeling itself will form an important part of the research activities. Specifically, further development of rock-fragmentation methods will rely heavily on comprehensive computer models of fracture and comminution processes. Similary, problems of scaling laboratory-test results to field problems should be investigated using appropriate numerical models.

Although research specific to areas discussed in the previous chapters could be cited, the function of this chapter is interpreted more broadly. Accordingly, investigative areas of rock mechanics are considered. These areas are broken down into sufficiently narrow classifications so that characteristic features and behaviors can be identified. The classifications are defined below, and necessary computational capabilities for comprehensive numerical-modeling activities are identified.

Rock-Mechanics Concerns

Four important areas of rock-mechanics investigation are resource recovery, subsurface utilization, geological processes, and explosion effects. Each of these major areas is then subdivided in the following manner.

RESOURCE RECOVERY

Solid mining is intended to mean all mining that results in winning of solid material of some value. There is a division between surface and subsurface techniques on the basis that there are important differences in problems between open-pit mining and underground mining. There are also important similarities; for example, in both cases it is essential that rock be broken in some manner.

In situ recovery includes mineral extraction by solution mining, leaching, and retorting or gasification. It may or may not require preparatory underground development, but it does result in direct extraction of a mineral product.

Natural oil and *natural gas* extraction might be considered under the classification of *in situ* recovery methods. The difference lies in the fact that the latter all imply some kind of *in situ* processing, whether it is as simple as controlled solution or as complex as retort construction and operation.

Geothermal energy is considered to embrace both natural geothermal sources and petro-geothermal resources. The former are not considered independently because they form a relatively minor part of the total, potential geothermal resource.

SUBSURFACE UTILIZATION

Waste disposal embraces both nuclear and chemical wastes. The major difference between these two is that the former generates heat. (Radiation effects may also be present in the case of nuclear wastes, but they are not considered in this study.) Apart from the thermal effect, the problems are the same for all waste forms, and both nuclear and chemical wastes may remain potentially hazardous for a long time. Also, in both cases the major release mechanism is groundwater flow.

Storage of energy in all forms is considered. Underground storage of liquids, including oil and liquid gas, presents different problems than storage of natural gas or compressed air. In particular, the latter type of facilities could be subject to relatively rapid cycling. For example, the case of compressed-air storage as a means of smoothing peak power demands would be quite different from strategic storage of hydrocarbons. Heat storage concerns the direct storage of heat energy in heat accumulators, which may be naturally porous or artificially fractured materials and perhaps graded materials as well. The most likely heat-transfer medium is air, but water is a possible alternative. Pump storage, another means of energy-demand smoothing, can require construction of underground powerhouses and high-pressure tunnels.

Transportation, resource access, and *utilities* make up a major group that covers many areas of civil engineering. It embraces the problems of excavation in permafrost regions, which could be necessary in connection with petroleum production and other resource extraction from Arctic regions. It also includes undersea excavation for offshore development of mineral resources.

Foundations are identified as distinct from transportation, resource access, and utilities, as the latter are all underground. Problems that might be unique in this area include interaction between a rock foundation and a structure, such as a large building or dam, during seismic loading.

GEOLOGICAL PROCESSES

Earthquake concerns are subdivided into generation, far-field effects, and near-field effects. The first of these relates primarily to earthquake prediction. The second and third relate to impact on buildings and other structures, both surface and underground.

Diapirism is a geologic process of some practical importance when disposal of nuclear waste in salt domes is considered. In particular, the origin and long-term stability of these structures must be understood.

Global tectonics may appear to be of little direct concern in engineering. However, understanding of the large-scale, long-term movements in the earth's crust is essential to earthquake prediction. It may have some practical implications as far as mineral-resource exploration is concerned and also bears on a proposed scheme for nuclear-waste disposal involving burial in a subduction zone.

Basin development completes the group of geological processes. The understanding and successful modeling of this and other geologic processes may not be major concerns in other areas, but they would contribute substantially to the credibility of numerical models for application in areas involving very long time periods. Basin development is of major concern in the field of petroleum geology.

EXPLOSION EFFECTS

Containment refers specifically to containment of underground explosions. Historically, this has concerned underground testing of nuclear explosives, but it could include application of either nuclear or conventional high explosives for preparation of ground for *in situ* extraction on a large scale.

Cratering also refers specifically to the explosion of nuclear devices. Numerical models developed in this field have application in conventional blasting as well, provided that appropriate cognizance of scale effects is taken.

Subsurface facilities or hardened facilities refer to underground construction intended to be capable of withstanding major dynamic loading, presumably as a consequence of a nuclear explosion.

Computational Features

Computational features are those features that are required of numerical models in order to be able to address specific rock-mechanics concerns.

Five major groups of features are geometry, equations of motion, kinematics, constitutive behavior, and special features. Important features within each of these groups are discussed briefly in this section before matching rock-mechanics concerns with computational features.

GEOMETRY

Plane, axisymmetric, and *three-dimensional* analyses are required in differing circumstances. In some cases, analysis using plane geometry is of limited practical application, whereas in other cases the three-dimensional characteristics of the problem are relatively unimportant. When there is rotational or spherical symmetry in a geometrical and material sense, three-dimensional problems reduce by one or two dimensions, respectively, with significant cost advantage. Problems with rotational symmetry are referred to as axisymmetric.

Discrete jointing refers to cases when there are pre-existing fractures or discontinuities that make a rock mass discontinuous. The jointing is said to be discrete when it is necessary to recognize specifically the location and orientation of the joints. In some cases there are relatively few discontinuities whose presence can be recognized by some modification of an otherwise continuum approach to modeling. Examples of this approach include all interface procedures in finite-element and finite-difference models. In other cases, the rock mass is sufficiently broken by existing fractures to make it more meaningful to treat the mass as an assembly of blocks or particles. This approach is appropriate when components of the system are free to translate and rotate with respect to each other.

Discrete cracking refers to cases in which crack formation or propagation is of concern. In some circumstances such cracking leads to the formation of a discretely jointed system that must be modeled accordingly.

EQUATIONS OF MOTION

It is apparent from the classes of problems that are of concern in rock mechanics that heat transfer and fluid flow may be important components of the system. In some cases, heat transfer and fluid flow are interrelated and also are important parameters determining the mechanical behavior. In such cases the system is considered to be coupled, and it may be necessary to work with a computer model that specifically recognizes this coupling. Such a model might account for the interrelationships expressed diagrammatically in Figure 9.1. In other cases the coupling between processes is weak, and the necessary mechanical, thermal, and fluid-flow analyses may be carried out essentially independently. Such coupling needs are not specifically detailed in the prepared correlation of rock-mechanics concerns and computational features because the required level of coupling is poorly understood at present.

Within the grouping of equations of motion, three significantly different types of behavior are recognized: static/steady state, transient/

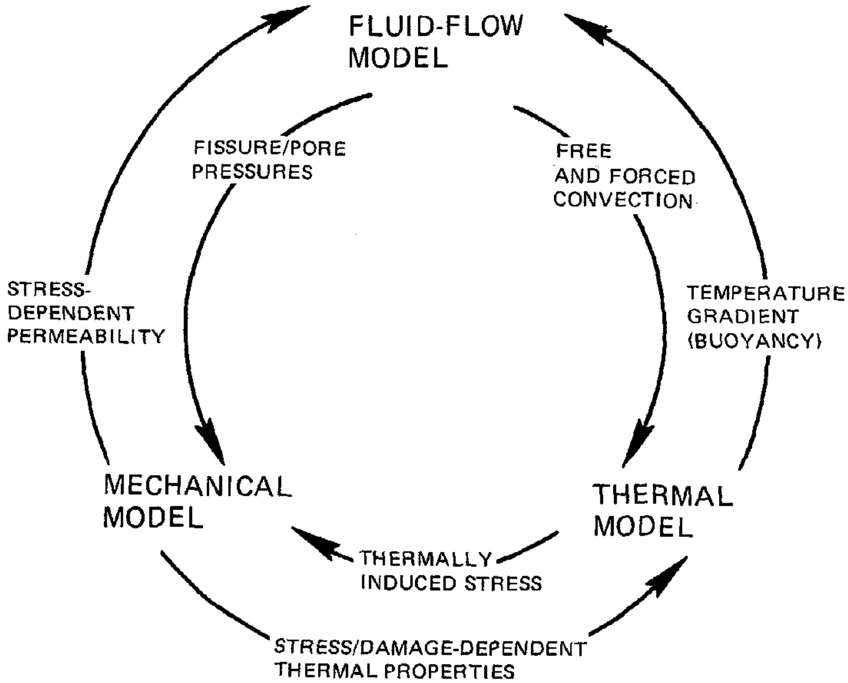

FIGURE 9.1 Some interactions for coupled systems.

noninertial, and transient/inertial. These distinctions are made on the basis that there are important differences in the numerical models used for the different classes of problems.

Static/steady-state processes are those in which time plays no part. Interactions between mechanical behavior, fluid flow, and heat transfer may still be present.

Transient/noninertial processes are those in which changes occur with respect to time, but sufficiently slowly that inertial terms may be ignored. Under these circumstances a boundary-value problem, identical to that for a static system, is solved to determine the mechanical behavior. The loading system, which may be determined by fluid or thermal input, can be constant (as in the case of time-dependent material behavior) or can vary in time.

Transient/inertial processes occur with sufficient rapidity that inertial effects for solids and fluids in the system cannot be ignored.

KINEMATICS

Finite- or infinitesimal-strain theory may form the basis of a numerical model. Three categories of model are considered, as follows:

Small strain/small displacement, in which the infinitesimal-strain theory is used and displacements of the system are sufficiently small that geometric changes can be ignored.

Small strain/large displacement, in which the infinitesimal-strain theory is applicable but geometric changes, particularly associated with rotation components of displacement, can be large. The numerical procedure adopted consists of progressively updating the geometry during deformation.

Large strain/large displacement, in which the finite-strain theory must be used, the assumptions made in infinitesimal-strain theory being inappropriate.

CONSTITUTIVE BEHAVIOR

Several different types of constitutive behavior are considered to be important. They vary from linear elastic to elasto-visco-plastic. The former implies that all deformation is linear and fully recoverable; the latter implies that there is recoverable elastic deformation, permanent time-independent or plastic deformation, and time-dependent or viscous deformation.

Special classes of constitutive behavior are also considered. In some cases these may be implicit in a given constitutive model, but they are listed independently to emphasize the importance of certain types of behavior.

Anisotropy may be present whether the material behavior is elastic, plastic, or viscous. The properties governing fluid flow and heat transfer may also be directional.

Dilatancy is taken here specifically to refer to volumetric expansion during failure. This is implicit in some failure models but should be controlled independently of other material properties.

Thermal dependency is an important component in the coupling indicated previously in Figure 9.1. It is included here to emphasize the importance of the heat-transfer calculations.

Damage model refers to the need to represent substantial changes in material properties and behavior during failure. Of particular significance is the decreasing load-bearing capacity of most geologic materials during failure. This decrease may be sudden and result in unstable collapse if there is sufficient energy release.

SPECIAL FEATURES

This category has been included because there are certain necessary computational features that may be absent from models that otherwise satisfy criteria in terms of geometry, type of motion, kinematics, and constitutive behavior. Reasons for omission of these features from a model may be that the model was developed for application in a field other than rock mechanics or that the rock mass interacts with some other system.

Stochastic processes are those in which the behavior of the system is determined to some extent by a statistical description. This may occur because of variability in real material behavior, uncertainties in material characterization, and in some areas of fracture mechanics where fracture-growth direction is not unique.

Initial stress and strain are recognized explicitly because they represent important conditions that must be taken into account properly. Initial stress is relatively seldom encountered in other branches of solid mechanics, so it is often not included in computer models developed for application outside the field of rock mechanics.

Structural components include all methods of rock support. In general, the method used to represent the rock mass is not appropriate for structural elements such as rock bolts, steel liners, concrete lining, and steel arches. It is implicit that appropriate means of interfacing the structural components to the rock must be provided.

Addition and removal of material is another feature that is unusual in solid mechanics. Where nonlinear material behavior is involved, the loading history may be important in determining the rock-mass response. In some circumstances the load history can only be represented adequately by simulating the progressive addition or removal of material.

Multiphase flow refers to conditions when the fluid component of the system exists in more than a single phase.

Chemical or radiation effects refer to modification of rock-mass behavior in response to chemical changes or radiation damage. For some areas, including nuclear-waste isolation, geothermal-energy extraction, and secondary recovery of petroleum resources, geochemical effects may be extremely important and must be an integral part of a numerical-modeling study.

Explosive loading is a special dynamic-loading condition. Input would be from some model predicting the pressures and temperatures during detonation of an explosive or would be obtained from field observations.

Assessment of Need

The listing and discussion of each rock-mechanics concern and computational feature that could be required of numerical models provides a basis for Table 9.1. This table assigns a priority to numerical-modeling capabilities. Category 1 implies that the capability is considered to be essential to any numerical model of the problem area identified. Category 2 implies that the capability is desirable, while Category 3 indicates the capability would be useful if available. A blank indicates that the capability is considered to be relatively unimportant or inappropriate.

The objective of Table 9.1 is to highlight areas where numerical models can make important and obvious contributions. Clearly, there will be some aspects of each study area that will need modeling capabilities different from those indicated. Indeed, in many instances problems can be solved without recourse to extensive numerical-modeling activities. Hence, the table is not intended to be exclusive. It does, however, provide a means of quickly assessing whether a particular approach to numerical modeling is likely to be applicable in some given area.

TABLE 9.1 Assessment of Computational Needs in Rock Mechanics

Rock-Mechanics Concerns	Geometry: Plane	Geometry: Axisymmetric	Geometry: Three-Dimensional	Geometry: Discrete Jointing	Geometry: Discrete Cracking	Equations of Motion, Static/Steady State: Solids	Static/Steady State: Heat	Static/Steady State: Fluid	Noninertial/Transient: Solids	Noninertial/Transient: Heat	Noninertial/Transient: Fluid	Inertial/Transient: Solids	Inertial/Transient: Fluid	Kinematics: Small Strain/Small Displacement	Kinematics: Small Strain/Large Displacement	Kinematics: Large Strain/Large Displacement	Constitutive Behavior: Linear Elastic	Nonlinear Elastic	Linear Viscoelastic	Nonlinear Viscoelastic	Elasto-Plastic	Elasto-Visco-Plastic	Anisotropy	Dilantancy	Thermal Dependency	Damage Model	Special Features: Stochastic Processes	Initial Stress and Strain	Structural Components	Material Addition and Removal	Multiphase Flow	Chemical or Radiation Effects	Explosive Loading
Resource Recovery																																	
Solid Mining																																	
Surface	1	2	1	1		1			2			2		2	1		1				1	1		1	3	1		1		1			2
Subsurface	1	2	1	1	2	1			2			2		1	2	2	1	2			1	1	1	1	3	1		1	1	1			2
In Situ Recovery																																	
Oil shale	1	2	1	1	2	1			1	1		2		1	2		1				1	1		1	1	1		1	1	1			2
Coal gasification	1	1	1	1	2	1			1	1				1	2		1				1	1	1		1	1		1		1			
Solution mining/leaching	1	1	1	1	2	1		1	1		1	2		1	2		1		2	3	1	1	1		1	1		1		1	1		2
Natural Oil	1	1	2	2	2	1	1	1	2	2	1			1	2		1				1	2			2	2		1			1		
Natural Gas	1	1	2	2	2	1	1	1	2	2	1			1	2		1				1	2			2	2		1			2		
Geothermal Energy	1	1	1	1	1	1	1	1	1	1	1	2		1	2		1				1				1	1		1			1		2

Computational Features (First, Second, Third Priority)

Subsurface Utilization																																	
Waste Disposal																																	
Nuclear	1	1	1	1	3	1		2	1	1	1			1	3		1		2	1	1	1		2	1	1		1		2	2	1	
Chemical	1	2	1	1	3	1		1	1		1			1	3		1				1				3	1		1		2		1	
Storage																																	
Oil/liquid gas	1	1	1	1		1	2		1	2				1			1					1			2	1		1		2			
Natural gas/compressed air	1	1	1	1		1	2		1	2				1			1		2	3		1			2	1		1		2			
Heat storage	1	1	1	1	3	1	1		2	1	2			1			1				1			2	2	1		1		2	1		
Pump storage	1	1	1	1		1			3		3			1			1				1				3	1		1	1	2			
Transportation, Resource Access, Utilities	1	1	1	1	3	1			1		3			1	3		1	2			1		2		3	1	3	1	1	1			2
Foundations	1	2	1	1	3	1			1					1			1	2			1		1		3	1		1	1				1
Geological Processes																																	
Earthquake																																	
Generation	1	3	1	1	1				3			1	3	1	3		1				1		2			1	2	1					
Far-field effects	1	2	3	1	3				3			1	3	1			1				1		2			1	3	1					
Near-field effects	1	2	2	1	3				3			1	3	1	3		1				1		2			1	3	1					
Diapirism	1	1	2	1					1					1	1	1	1		1	2		1			1	2		1					
Global Tectonics	1	3	2	1	3				1	2				1	1	1	1		2			1			1	2		2					
Basin Development	1	2	3	1					1					1	1	1	1		2			1			1	2		2					
Explosive Effects																																	
Containment	1	1	1	1	1							1	1		1	1	1				1			1		1	2	3		1			1
Cratering	1	1	1	1	1							1	1		1	1	1				1			1		1	2	3		1			1
Subsurface Facilities	1	1	1	1	1							1	1		1	1	1				1					1	3	2	1	1			1

NUMERICAL-MODELING CAPABILITY

Historically, development of numerical models for rock mechanics has drawn heavily on other branches of solid mechanics. Accordingly, several of the computer codes that will be identified by name in this section were not developed specifically for geotechnical purposes. These models often are capable of treating only a restricted class of problems because they may not be able to describe adequately the behavior of geologic materials.

In this section, the various types of numerical model are described briefly. This discussion is an essential prerequisite to a discussion of the applicability of different numerical models to the various areas of investigation in rock mechanics. Finally, a number of numerical models are listed together with indications of their capabilities. The listing is obviously incomplete and the classification scheme inadequate to define each model fully, but it does provide an indication of the current level of development.

There are two fundamentally different methods of viewing a geological material. Both of these recognize geologic materials as being discontinuous as a consequence of the presence of faults, joints, bedding planes, and other fractures. However, one approach treats the rock mass as a continuum that may be intersected by a number of discontinuities, while the other views the rock mass as an assembly of independent particles. A combination of these two approaches is possible to achieve by coupling of two models and is discussed briefly below.

The two basic approaches are classified as continuum and discontinuum. The various methods available as a basis for models for both types have a bearing on the possible application of the models.

Continuum Models

Continuum models of two important types are used: differential and integral. Differential models are characterized by the need to approximate mathematically or physically the entire region of interest. In finite-difference methods, a numerical approximation of the governing differential equations is used. In finite-element methods, a model is constructed from elemental components, the properties of which may be determined readily. Combinations of finite-element and finite-difference methods are frequently used. Indeed, finite-element models for transient behavior generally use a finite-difference form of the equations of motion (Zienkiewicz, 1977), even though treatment of time as another variable in the finite-element scheme is possible (Cushman, 1979).

For modeling of transient behavior—initial-value problems governed by hyperbolic and parabolic partial differential equations—two basic solution strategies are used. The solution procedure may be implicit or explicit with respect to time (Desai and Christian, 1977). The important distinction is that in the implicit methods a set of simultaneous equations defining a new state is formed and solved. In the explicit methods, equations explicitly defining the new state directly from the former are obtained. Implicit algorithms often exhibit improved stability over explicit algorithms, permitting large time steps to be taken unless material nonlinearity is such as to require detailed simulation in time. Explicit-solution procedures are less demanding for computer storage because a large set of simultaneous equations is never formed. However, stability criteria enforce time-step sizes that may be uneconomically small in some circumstances.

Both finite-element and finite-difference models may be formulated using either implicit or explicit procedures. Also, in both cases steady solutions may be obtained with computer models originally devised for transient analysis, by use of appropriate damping terms (Otter *et al.*, 1966).

Finite-difference and finite-element methods permit the introduction of interfaces within the continuum. These take the form of slidelines in the case of finite-difference methods and special elements in the case of finite-element methods (Zienkiewicz, 1977; Goodman and St. John, 1977). In either case, the constitutive behavior of these interfaces must be defined and special provisions must be made to accommodate large relative movements. Crack propagation can be handled by progressive growth of interfaces within the continuum.

Integral or boundary-element procedures differ fundamentally from differential methods in that discretization is necessary only along interior or exterior boundaries (Brebbia and Walker, 1978). The interfaces between different material types and discontinuities are treated as internal boundaries that must be made similarly discrete. Volume discretization, necessary for differential methods, is only used in some procedures for handling transient or nonlinear behavior (Banerjee, 1978).

Two distinct boundary-element methods are used. These have been referred to as direct and indirect methods. In the former case, use is made of the reciprocal theorem to obtain a solution directly in terms of the unknown variables, which in the case of a boundary-element procedure for stress analysis may be a combination of forces and displacements. Indirect methods, namely fictitious-force (Hocking, 1978) and fictitious-displacement (Crouch, 1976a) methods, make use of supplemental solutions that generally have no physical significance.

Like the differential methods, the boundary-element methods treat discontinuities as interfaces within the continuum. In both cases this treatment means that it is impractical to treat a true discontinuum. However, it is possible to use these continuum models in conjunction with discontinuum models when truly discontinuous material needs to be represented over only part of the region.

Discontinuum Models

In a true discontinuum model, the rock mass is treated as an assembly of independent blocks or particles. A numerical procedure identical to an explicit finite-difference scheme is adopted (Cundall, 1976), but the equations of motion are now those of particles rather than the continuum, and the constitutive equations refer to interparticle relationships. In its simplest form, the model assumes that the particles are rigid and remain intact. All deformation then is restricted to the contact points or surfaces. It is possible, however, to make the blocks deformable and to allow them to fracture according to some failure criterion. Because this modification requires stress analysis, one of the continuum methods discussed above must be used; for example, each block could be divided into a number of finite elements or its surface could be divided into boundary elements.

APPLICABILITY OF NUMERICAL MODELS

In the previous section, numerical models were divided into those that basically describe a continuum and those that simulate a true discontinuum. The model type used depends primarily on the problem being investigated, but it may also depend on the level of detail being sought. For example, granular flow of ore in a stope, or roof collapse behind a longwall face, involves large translational and rotational movements of discrete blocks of rock. To gain an understanding of the mechanisms involved, a true discontinuum model should be used (Cundall and Strack, (1979). However, from a modeling point of view, the behavior of this material might be described adequately by treating it as a large-strain problem involving some nonlinear material behavior.

With the above proviso, it is recommended that discontinuum models should be used whenever independent rock-block movements must be recognized specifically. This generally will be the case in any stress field insufficient to prevent large translations and rotations of the units defined by pre-existing geologic discontinuities or by stress- or blasting-induced rock fracture. Examples of this include simulation of rock-slope failure, tunnel collapse, and caving. The common feature of these problems is failure within a low stress field. Table 9.1 refers to this type of behavior as "damage," implying a fundamental difference in material behavior that results from rock-mass failure. This is also observed in connection with modeling of explosive effects when there is a transition from a continuum to a fragmented material.

Continuum models should be used whenever the rock is essentially continuous, even though traversed by one or more discontinuities or cracks. They should also be used when detailed representation of strongly discontinuous material is not required. If there is only one set of strong discontinuities, the fractures may be characterized without reference to specific location. The rock mass then may be considered to be anisotropic, with both its deformability and strength reflecting the properties and orientation of the discontinuities in the dominant set (Goodman and Duncan, 1971).

Which of the several continuum models to use for a particular problem depends largely on the constitutive behavior and the degree of inhomogeneity to be represented. Boundary-element procedures are most appropriate for modeling linear systems. Simple inhomogeneities may be handled, but the methods lose their advantages as soon as it becomes necessary to include many internal surfaces to represent the interfaces between different materials. Transient problems not involving inertial terms may be handled by the means of Laplace transform and subsequent inverse transform (Shippy, 1975). Companion methods are available for fluid flow and heat transfer, but only very simple coupling can be achieved because of the practical restriction on treatment of material inhomogeneity. Problems in linear thermoelasticity can be handled quite simply because the temperature changes result in thermal stresses that become additional boundary conditions.

Certain forms of nonlinearity may be treated by boundary-element methods. Elasto-plastic behavior can be handled using a method equivalent to the initial-stress approach in finite-element procedures, coupled with zoning of the plastic region (Banerjee, 1978). Any type of nonlinear behavior may be ascribed to interfaces or internal boundaries. This procedure has been used for simulating discontinuities and also partial extraction of tabular ore deposits (Crouch, 1976b). In the latter case, the remnant material is ascribed properties that define boundary conditions for the interface. Those boundary conditions may be time dependent, as in the cases of transient thermal response and viscous behavior of the remnant material.

In summary, boundary-element procedures are ideal for problems in linear elasticity. Material anisotropy presents no additional difficulties, and inhomogeneities may be considered. Discontinuities, either existing or resulting from fracture propagation, may be included and ascribed arbitrary properties. Within these restrictions, the boundary-element procedures provide economical means of two- and three-dimensional analysis of rock masses. They are uniquely suitable for use when conditions at the boundary are of most concern. This is often the case in rock-mass modeling because the infinite or semi-infinite domain of the problem is included implicitly. With differential methods, the domain is often arbitrarily limited in the interest of economy (St. John *et al.*, 1979).

Finite-difference and finite-element methods have similar characteristics and, in fact, can be shown to be identical in some circumstances. Both may be formulated to be implicit or explicit with respect to time for transient problems, so superficially there would appear to be little to choose between the two approaches. However, the finite-element methods remain uniquely capable of handling complex geometries and inhomogeneities. Additionally, different types of structural components can be handled with ease. For example, a tunnel support or borehole liner possessing flexural rigidity may be represented by elements with the appropriate properties in bending. Also, using the special interface elements (Goodman and St. John, 1977), blocky systems defined by intersecting discontinuities may be represented. However, analysis of such systems is restricted to consideration of small displacement fields because of difficulties of remeshing when a previously continuous feature is broken by a series of offsets. Obviously, when there is only one set of parallel features, such as might occur with a single joint set, this problem disappears and displacements of any magnitude can be handled easily.

TABLE 9.2 Examples of Codes Intended Specifically for Applications in Solid Mechanics: Summary of Code Capabilities

	Code Features: Geometry					Equations of Motion: Noninertial/Steady State			Noninertial/Transient			Inertial/Transient		Kinematics			Constitutive Behavior										Special Features							Numerical Procedures					
Code Name	Plane	Axisymmetric	Three-Dimensional	Discrete Jointing	Discrete Cracking	Solids	Heat	Fluid	Solids	Heat	Fluid	Solids	Fluid	Small Strain/Small Displacement	Small Strain/Large Displacement	Large Strain/Large Displacement	Linear Elastic	Nonlinear Elastic	Linear Viscoelastic	Nonlinear Viscoelastic	Elasto-Plastic	Elasto-Visco-Plastic	Anisotropy	Dilantancy	Thermal Dependence	Damage Model	Stochastic Processes	Initial Stress and Strain	Structural Components	Material Addition and Removal	Multiphase Flow	Chemical or Radiation Effects	Explosive Loading	Finite Element	Finite Difference	Boundary Element	Distinct Element	Explicit	Implicit
ADINA + ADINAT	◆	◆	◆			◆	◆		◆	◆		◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆	b		◆	◆	◆				◆				◆	◆
ANSYS	◆	◆	◆	◆		◆	◆		◆	◆		◆		◆	◆		◆	◆	◆	◆	◆	◆	◆		◆			◆	◆			◆		◆					◆
BMINES	◆	◆	◆	◆		◆			◆					◆			◆	◆	◆	◆	◆	◆	◆			b		◆	◆	◆				◆					◆
COUPLEFLO	◆	◆				◆	◆		◆	◆		◆				◆			◆	◆					◆			◆						◆					◆
DBLOCK	◆			◆	◆	◆			◆			◆		◆	◆		◆									◆											◆	◆	
FINEL	◆	◆	◆	◆		◆	◆		◆	◆		◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			◆		◆				◆				◆	◆
HONDO II	◆	◆		a								◆		◆	◆	◆	◆		◆		◆													◆				◆	
MARC	◆	◆	◆	a		◆	◆		◆	◆				◆	◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	b			◆					◆				◆	◆
MINAP	◆			◆		◆								◆			◆				◆		◆					◆		◆						◆			
MSEAMS	◆					◆								◆			◆											◆		◆						◆			
SANCHO	◆	◆		a		◆			◆			◆		◆	◆	◆	◆		◆		◆													◆				◆	
SPECTROM 11	◆	◆				◆								◆			◆				◆		◆					◆		◆				◆					◆
SPECTROM 21/22	◆	◆		◆		◆			◆					◆			◆		◆	◆			◆		◆			◆		◆				◆					◆
SPECTROM 41/341	◆	◆	◆				◆			◆															◆									◆					◆
STEALTH	◆	◆		a		◆	◆		◆	◆		◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆			◆							◆			◆	

[a]Frictional interface.
[b]Cracking model for concrete.

NOTES AND REFERENCES TO TABLE 9.2

Examples of Codes Intended Specifically for Applications in Solid Mechanics

ADINA + ADINAT: Two reports document these companion codes, which are available through K. J. Bathe, Massachusetts Institute of Technology.
K. J. Bathe, "ADINA. A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis," MIT Report 82448-1, December 1978.
K. J. Bathe, "ADINAT. A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis of Temperatures," MIT Report 82448-5, December 1978.

ANSYS: Extensive documentation, of which the User's Manual is the first volume, is provided by Swanson Analysis Systems Inc.
G. J. DeSalvo and J. A. Swanson, "ANSYS Engineering Analysis System User's Manual," Swanson Analysis Systems, Inc., July 1979.

BMINES: The BMINES code has been developed for the U.S. Department of the Interior, Bureau of Mines, by Agbabian and Associates.
D. E. VanDillen, R. W. Fellner, and R. W. Ewing, "User's Guide for BMINES–A Computer Program for Analytical Modeling of Rock/Structure Interaction," Agbabian and Associates, November 1980.

COUPLEFLO: Developed at Sandia National Laboratories for coupled creeping viscous flow and conductive-convective heat transfer.
P. R. Dawson and P. F. Chavez, "COUPLEFLO–A Computer Code for Coupled Creeping Viscous Flow and Conductive-Convective Heat Transfer." Part I, "Theoretical Background," SAND 78-1406. Part II, "User's Manual," SAND 78-1407. Sandia National Laboratories, November 1978.

DBLOCK: A version of the Distinct Element Method codes that incorporates deformability and fracture of blocks. RBM, which is a simple version for which deformation is restricted to block interfaces, is documented in the same report.
T. Maini, P. A. Cundall, J. Marti, P. Beresford, N. Last, and M. Asgian, "Computer Modelling of Jointed Rock Masses." Technical Report N-78-4, prepared for Defense Nuclear Agency by Dames and Moore, August 1978.

FINEL: Developed at Imperial College as a user-orientated package allowing a wide range of finite-element analyses of problems including thermal-stress analysis and structural dynamics.
D. Hitchings, "Student's Introduction to FINEL," Imperial College Integral Report, London, England, 1978.

HONDO II: A finite-element program for calculation of large-deformation elastic and inelastic transient dynamic response of two-dimensional solids. Closely related to the earlier code TOODY II, which uses a finite-difference formulation.
S. W. Key, Z. E. Beisinger, and R. D. Krieg, "HONDO II, A Finite Element Computer Program for the Large Deformation Dynamic Response of Axisymmetric Solids," SAND 78-0422, Sandia National Laboratories, October 1978.

MARC: A linear and nonlinear structural analysis program developed by MARC Analysis Research Corporation. "MARC-CDS, General Purpose Finite Element Analysis Program. Vol. I, Users Information Manual." Control Data Publication 17309500, Rev J, November 1977.

MINAP & MSEAMS: Two codes, based on the displacement discontinuity method, developed by S. L. Crouch at the University of Minnesota. Two- and three-dimensional versions incorporating analytical solutions for heat sources have been used for thermomechanical analysis.
S. L. Crouch, "Analysis of Stresses and Displacements Around Underground Excavations: An Application of the Displacement Discontinuity Method," University of Minnesota Geomechanics Report, November 1976.

SANCHO: A code similar to HONDO II that uses dynamic relaxation so that it can be applied to quasi-static problems.
S. W. Key, C. M. Stone, and R. D. Krieg, "Dynamic Relaxation Applied to the Quasi-Static, Large Deformation, Inelastic Response of Axisymmetric Solids." Sandia National Laboratories, 1980.

SPECTROM: The SPECTROM series of finite-element codes has been developed by RE/SPEC Inc. The codes have been extensively used within the National Terminal Waste Storage program of the Department of Energy and are being documented at present.
J. R. Wayland and L. D. Bertholf, "A Comparison of Thermomechanical Calculations for Highly Nonlinear Quasi-Static Drift Calculations," SAND 80-0149, Sandia National Laboratories, 1980.

STEALTH: A finite-difference code that will have capabilities for thermomechanical hydraulic analysis. It has been prepared by Science Applications Inc., and is distributed by the Electric Power Research Institute. The capabilities of the currently released two-dimensional version are listed in the table.
R. Hofmann, "STEALTH, A Lagrange Explicit Finite-Difference Code for Solids, Structural and Thermohydraulic Analysis," EPRI NP-176-1, Electric Power Research Institute, Palo Alto, California, June 1976.

In explicit methods, both for finite-element and finite-difference schemes (Hughes *et al.*, 1979; Cundall, 1976), the equilibrium equations and the constitutive equations are separated, permitting the selection of any arbitrary constitutive behavior. This suggests that explicit procedures may be uniquely capable of handling complex systems involving fluid flow, heat transfer, and mechanical deformation. However, either explicit or implicit procedures may be used. Indeed, the latter are likely to exhibit improved stability characteristics, an important consideration for coupled systems because the stability criterion may prove to be extremely complex.

Combinations of integral and differential methods have already been investigated (Zienkiewicz, 1977). These permit modeling in detail of some restricted region using a differential method, while the integral technique provides improved boundary conditions and perhaps approximate analyses of other parts of the system whose behavior is relatively unimportant and for which the material response may be considered to be linear. Similar coupling between continuum and discontinuum models has been noted already.

SURVEY OF COMPUTER CODES

A large number of computer codes for solution of problems involving mechanical behavior, fluid flow, and heat transfer—either independently or in some coupled manner—have been prepared. To list even a significant proportion of them would be of limited value since many are inadequately tested or documented or are applicable to a restricted class of problems. However, it is desirable to obtain some measure of definition of the current state of the art of computer codes applicable to problems in geotechnical engineering. To achieve this end, 15 codes considered to be representative of the state of the art for mechanical or thermomechanical modeling are listed in Table 9.2. A set of notes and references that indicate sources of additional information on the codes forms part of the table.

It should be stressed that inclusion of a particular code in Table 9.2 does not imply any endorsement of the code, nor should the assumption be made that the code necessarily offers any unique capabilities. However, in most instances, uses of the codes have been quite widely reported; also, the codes are reasonably documented and are supported by some continuing research effort.

RESEARCH NEEDS

Earlier in this chapter, rock-mechanics concerns were divided into four areas: resource recovery, subsurface utilization, geological processes, and explosion effects. Each major division was subdivided into what were considered to be important areas of investigation. By considering typical problems in each of these subdivisions, necessary computational capabilities were identified. Table 9.1 summarized the results of this analysis, ascribing a measure of necessity to each computational feature for a particular area of rock-mechanics investigation. A rating of 1 on this table implied that a particular capability was essential, a rating of 2 that the capability was desirable, and a rating of 3 that the capability could be exploited usefully. Table 9.1 is therefore a measure of research needs, if read in conjunction with Table 9.2. However, these tables do not indicate the extent to which the numerical-modeling research is essential for development of rock-mechanics investigations in each area. Furthermore, in some cases the major limiting factor is considered to be the understanding of the physical processes involved. Theoretical, laboratory, and field understanding of the physical processes are required before major advances can be achieved by the appropriate use of numerical models. (Some of these issues are raised in other chapters of this report.) Table 9.3 summarizes the issues considered to be essential for development in each area of investigation. It should be observed, however, that continued model development and application are important even where modeling is not identified currently as the critical issue.

TABLE 9.3 Assessment of Limitations to Rock-Mechanics Investigations

Investigative Area	Assessment of Limitation
Resource Recovery	
Solid mining	Computer codes are well developed for many material behaviors. Model application is required.
In situ recovery	Computer codes are well developed for a restricted class of problems. Model application is required.
Natural oil Natural gas	Rock-mechanics aspects of recovery are poorly understood. This limits the role of numerical models.
Geothermal energy	Rock-mechanics aspects are poorly understood. Fully coupled codes incorporating fracture propagation are required.
Subsurface Utilization	
Waste disposal	Computer codes are well developed for restricted classes of problems. Fully coupled models including geochemical effects are required.
Storage	Computer codes are adequate for some problems. Other problems require coupled models.
Transportation Foundations	Computer codes are well developed for most cases. Model application is required.
Geologic Processes	
Earthquakes	Physical processes are poorly understood. Numerical modeling should be used to improve this understanding.
Diapirism Global tectonics Basin development	Finite-strain models incorporating realistic material behaviors are being developed. Application is required.
Explosive Effects	
Containment	Mechanisms are poorly understood. Numerical models should assist investigation.
Cratering	Simulation of fracturing and comminution is inadequate. Improved models are required.
Subsurface facilities	Models are well developed. Application is required.

Although the above discussion refers to needs for specific study areas, it is possible to identify a number of more-general objectives. For the purposes of this discussion, three areas of necessary activity are considered: model development, model application, and model validation.

These three activities are important components in an approach to numerical modeling that recognizes the objective of providing the rock-mechanics community with the necessary computational tools for both design and research. The relationship between components is illustrated in Figure 9.2, which also identifies the major objectives to be met by research in numerical modeling. The objectives are to provide, in addition to the models themselves, recommended procedures and strategies for modeling, recommendations regarding optimum use of models, and validation of models to be used subsequently for design.

Subdivision of modeling activities into three areas does not imply an equal level of effort in each area. Rather, the division is intended to draw attention to the fact that modeling research is not complete when a code is developed. Model use must extend into the laboratory, field, and design office.

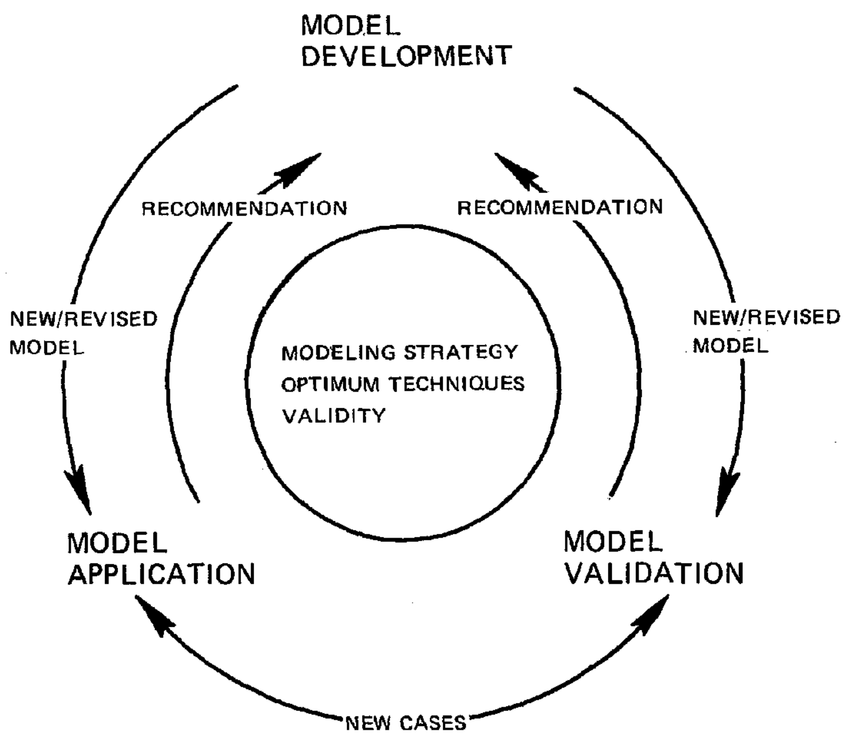

FIGURE 9.2 Summary of basic and applied research in modeling.

Model Development

For model development to proceed in a rational manner, it must be related closely to both model application and verification. However, there are several obvious weaknesses in existing model capabilities and these should be addressed by immediate, basic research.

Tables 9.1 and 9.2 indicate that immediate, basic needs for research are the following:

- *Improvement in three-dimensional capabilities.*
- *Development of large-strain models.*
- *Extension of yield criteria to fracture and damage.*
- *Further development of crack propagation models.*
- *Development of models to predict adequately unstable behavior such as necking, folding, buckling, or rock bursts.*
- *Improvement in models of discontinuity behavior.*
- *Further development of models of highly jointed or blocky systems.*

It is apparent that much of future modeling activity will be in cases where deformation, heat flow, and fluid flow are coupled to some extent. In many instances the coupling may be quite simple, for example, as in linear thermoelasticity, but in other cases the coupling may be complex. In the former case, models may be run essentially in parallel. However, there are relatively few instances when companion models for thermal and fluid-flow analysis can be identified. There is an immediate need to provide efficient coupling of mechanical models to others for thermal and fluid-flow analysis. Such coupling will be adequate when behavior is linear or weakly nonlinear. When the behavior is strongly nonlinear, single models incorporating all physical processes will be required. The level of coupling necessary for any particular problem is not clear at present, and, in many instances, this issue cannot be addressed until satisfactory, fully coupled models have been developed.

An examination of the research efforts identified above reveals that the predominant concern is constitutive behavior of geologic materials. The necessary experimental of field data must be available to support model development, because the constitutive models must be based on a sound understanding of the physical processes involved.

A second area of model development is required. This should concentrate on numerical procedures because it is not evident that the most appropriate or economical approaches to modeling have been identified. In particular, current state-of-the-art models appear to be highly structured and may reflect historical development rather than systematic investigation of alternatives. There is considerable scope for application of different numerical procedures and also combinations of two or more models. Possible areas for development include the following:

- *Explicit finite-element and finite-difference procedures.* These naturally separate the equilibrium equations and constitutive relationships, which allows simple simulation of complex nonlinear behavior. The application of these methods to problems in the field of rock mechanics requires further investigation. Additionally, the methods need to be compared critically with the implicit procedures that are currently in more general use.

- *Stability criteria for explicit schemes.*

These criteria require further investigation, particularly in the context of nonlinear behavior and coupled physical processes. Techniques, such as density scaling and time scaling, that are used to increase artificially the time-size for pseudo-static problems should be carefully evaluated.

- *Boundary-element methods for all small deformation problems in rock mechanics.*

These methods are singularly appropriate whenever the boundary conditions are of most interest. They provide potentially economical means of solving problems in three dimensions in cases where some inhomogeneity and nonlinearity are involved.

- *Methods of interfacing boundary-element methods, differential methods, and discontinuum models.*

These methods should be investigated further. Such interfacing appears to be a most promising approach to the solution of large detailed problems in both two and three dimensions.

- *Methods for automatic remeshing for continuum models.*

Such methods need to be established. Remeshing may be dictated on economic grounds, such as when the level of detail may be reduced with time, or may be required for large strain/large displacement fields.

The above listing of basic research activities is neither exhaustive nor complete. However, it provides a basis for discussion and indicates that a considerable research effort is needed. This need is real and arises because the complexity of the problems to be addressed within the field of rock mechanics has increased markedly in recent years. At the same time, there is also a need for simple models, perhaps subsets of more comprehensive codes, that can be used when detailed study is either uneconomic or inappropriate. Examples of such cases include parametric studies, in which certain essential physical characteristics are maintained and the data defining the problem are inadequate to support a major computational effort. The use of this type of model would be one area addressed during research in model application or model applicability.

Model Application

It is evident, from even a cursory survey of numerical models that have been used within the field of rock mechanics, that a wide range of modeling capabilities exists. Many of these were developed in a problem-oriented environment, and often the potential applications in different areas have not been realized. A research effort is needed to draw together the models and the problems. Such research should make use of state-of-the-art models and should contain the following steps:

- *Definition of critical problems in each area where numerical models may be used to aid understanding either in an engineering sense or of the physical processes involved.*
- *Identification of possible modeling techniques.*
- *Analyses of critical problems using identified models.*
- *Conclusions regarding the problem studied.*
- *Conclusions regarding deficiencies of the models.*
- *Recommendations regarding applicability of the models to the problems selected.*

Tables 9.1 and 9.2 are intended to initiate the first two activities in this listing.

If this type of study were carried out systematically in all areas discussed in this report, there should be an additional important outcome —namely, some direction for potential modelers regarding strategy for prototype characterization. For example, questions concerning boundary conditions, necessary level of detail, effect of orientation and spatial distribution of discontinuities, validity of equivalent continuum approaches, and the need to model the rock mass as a true discontinuum all need to be addressed. Currently, there are no clear statements, or even rational discussions, concerning these issues.

Model Validation

It is essential that the validity of numerical models be accepted by both the technical and nontechnical communities. Model verification must be undertaken in a relevant context and on appropriate spatial and temporal scales. Formulation of such verification studies is itself a research topic. Execution of such studies and conclusions regarding validity, or recommendations for further model development, would be a second stage.

The end result of such studies should be well-supported statements concerning the capabilities and limitations of a particular numerical model. The conclusions would be based on investigations intended to show that the model is both internally consistent and adequately representative of the real process for its intended purpose. Internal consistency, which implies that the model is mathematically and computationally correct, would be demonstrated by comparison with available closed-form solutions and other numerical models that assume the same physics but preferably make use of different numerical procedures. Demonstration of overall adequacy can be achieved only by observation of real behavior, both in the laboratory and in the field. In the former case, it is essential that experimentation be designed specifically to test critical components of the computer model. In the case of field studies, careful comparison of field observations with numerical simulations should lead to identification of the critical components governing the behavior of the prototype. If the model adequately includes these components, then it may be considered to be verified for application to that particular class of problems. The key issue is adequacy, the assessment of which will depend on the purpose of the modeling and the technical, economic, or political consequences of inaccuracy in prediction.

RECOMMENDATIONS

The development, application, and validation of numerical models are considered to be essential components in the advance of rock mechanics in all areas of its practice. Research in numerical modeling should neglect none of these complementary areas of investigation and should proceed with the final objectives of defining the following:

- *Appropriate strategy for modeling in given circumstances.*
- *Optimum numerical techniques for particular classes of problems.*
- *Validity of numerical models for prediction.*

It is recommended that clearly identified and possibly independent research efforts be supported in each of these areas. The applied research involving use of existing models is at least as important as the basic research involved in model development, and it should be funded accordingly.

In the preceding section of this chapter, specific recommendations were made regarding model developments that are considered to be necessary to meet the need to solve problems of increasing complexity. Two aspects of these recommendations are apparent:

- *Constitutive behavior.*
- *Numerical procedures.*

By necessity, many current models are making use of constitutive relationships that have little experimental basis. Future laboratory- and field-experimentation programs should relate closely to needs identified by the numerical-modeling community and provide a sound physical appreciation of the mechanisms that the models attempt to reproduce. In some instances, numerical models themselves may be used to develop constitutive equations. Such an approach is being used with considerable success in a study (Cundall and Strack, 1979) aimed at developing constitutive equations for granular materials such as soils. Another area in which this approach should be used is in the determination of the relationship between laboratory determined parameters and *in situ* performance. In this case, it should be practical to carry out laboratory investigation of each component that controls the behavior of the *in situ* rock mass. These components may be represented individually in a numerical model of the entire system that will reproduce the *in situ* behavior. Subsequent numerical modeling may use a simplified description of the constitutive behavior of the *in situ* material but will, nevertheless, be based on a sound appreciation of the physics of the situation.

Several specific areas for development of models were identified in the predecing section of this chapter. Included among them were the following:

- *Improvement in three-dimensional capability.*
- *Development of large-strain models.*

- *Extension of yield criteria to fracture and damage.*
- *Development of models to predict unstable behavior.*
- *Improvement in models of discontinuity behavior.*
- *Further development of models of highly jointed or blocky systems.*

In most instances these objectives could be met by modification of existing numerical models.

However, there is also an immediate need for models that adequately couple mechanical behavior with fluid flow and heat transfer, and there are some areas where specific numerical procedures require investigation. Areas for such development are identified as follows:

- *Explicit finite-element and finite-difference procedures for complex, nonlinear behavior.*
- *Boundary-element methods.*
- *Interfacing of different numerical techniques in a single model.*
- *Automatic remeshing.*

In general, modeling development should proceed so that a wide range of capabilities is available for use in both research and engineering practice. At one extreme, models capable of fully coupling all physical processes occurring during mechanical deformation, fluid flow, and heat transfer are required; at the other, simple models with clearly defined applicability are required to support relatively routine rock-mechanics investigations.

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