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Perspectives in Geology

Invited papers presented at a symposium in observance of the 75th anniversary of the Illinois State Geological Survey

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ILLINOIS STATE GEOLOGICAL SURVEY
Natural Resources Building
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Foreword

The papers in this booklet were presented at a symposium *Perspectives in Geology,* held October 9 and 10, 1980, in observance of the 75th anniversary of the Illinois State Geological Survey. About 300 persons attended the anniversary activities.

The nine speakers who participated in the symposium with Chief Jack A. Simon are former staff members of the Geological Survey. They were selected to present diverse perspectives in geology, mineral resources, paleontology, and environmental concerns. Eight of ten papers at the symposium are presented in their entirety in this booklet; only the abstracts of the papers by Heinz A. Lowenstam and Gordon W. Prescott were available.

I am grateful to these former staff members, all distinguished scientists, for helping make our 75th anniversary a memorable occasion. Their careers offer a worthy goal for emulation by the staff of the Geological Survey.

Robert A. Bergstrom
Chief

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The Illinois State Geological Survey– The Next Quarter Century

Jack A. Simon

The present Illinois State Geological Survey was established by an Act of the General Assembly in 1905. In this 75th anniversary year, some past achievements will be recognized, but of greater importance in this milestone in history is the opportunity to consider some new challenges and directions for research and service that will influence the course of the Survey from now until its centennial year. A few glances back, however, are appropriate since future directions will be influenced by where we are now and where we have been.

Nearly 130 years ago, in 1851, the General Assembly of Illinois established the first Illinois State Geological Survey. The State Geologist was directed to study the stratigraphy and structure of Illinois, discover its mineral resources, make chemical analyses of the rocks and minerals, determine the topography of the state, submit annual progress reports, and make a final report to the governor. The Survey was also charged to collect rock, mineral, and fossil specimens for a state collection.

Establishment of the Geological Survey was a response to similar interests that had evolved in a number of other states and a great awakening of interest in science in the United States. Recognition of the economic potential for discovering and delineating valuable mineral deposits certainly was important in enlisting legislative support. The broader science charge to the State Geologist reflected more than just an economic motivation. Although appropriations ceased in 1875 and the Survey was thus terminated, it had been blessed with imaginative leadership that went well beyond the legislative charge.

An analysis of the geologic work of the original Survey, particularly that under the direction of A. H. Worthen, indicates that implementation of the goal of identifying "the extent of her mineral riches" was broadened by extensive basic geologic studies, particularly paleontology. Worthen had come to his position with an excellent background in paleontology which strongly influenced his view of the Survey and the nature of the specialists he enlisted for its work. This broad view of the nature of a State Geological Survey, firmly established by Worthen, I believe had its impact on the character of the present Survey when it was reestablished in 1905.

During the 30 years when there was no State Geological Survey, geologic work was advanced at several academic institutions in the State, including the University of Chicago, Northwestern University, University of Illinois, and Augustana College, and the newly created Illinois State Museum. The new U.S. Geological Survey, established shortly after the demise of the first Illinois State Geological Survey, also conducted geologic studies in Illinois. In this period, important contributions were made that later greatly strengthened the program of the new state survey, including collection of data that permitted publication of a state geological map (ISGS Bulletin 1) in its first year of operation.

THE PAST

1905-1930 (first 25 years)

Reasons for support for establishment of a new geological survey in 1905 was certainly as varied as those for the first Survey but were perhaps even more broadly based. As a science, geology was better established and was formally a part of the curricula of universities of the State. Of comparable importance was a vigorous state mineral industry and engineering and agricultural establishments that recognized and were supportive of economic geology as well as other geologic studies.

In addition to interpreting geologic data, the original Geological Survey emphasized data gathering. The new Geological Survey of 1905, recognizing the fundamental importance of a data base, immediately undertook acquisition of information from diverse sources, particularly drill hole records from the mineral industry and basic geologic data from all practical sources. Many Survey research activities also added significantly to an essential data base.

Much of the earliest work of the modern Survey was devoted to studies of oil, gas, and coal with much more diversity in this work than characterized the original survey. For example, in the coal industry studies were conducted to determine the quality, coking character, gas-making properties, combustion characterisitics, occurrence of sulfur, and beneficiation of coal. Similar detailed geologic studies of the newly discovered oil fields of east-central Illinois were made as well as studies of extraction of oil from shale.

As the Survey grew, work expanded in stratigraphic studies and studies of industrial and metallic minerals (limestone, sandstone, sand and gravel, clays, lead, zinc, fluorspar, tripoli, and others). The mission of the Geological Survey continued to have a strong emphasis on the State's mineral resources.

By the end of the first quarter century, the research and service programs of the present Geological Survey had largely evolved, particularly in areas of mineral resources, fundamental geology, and service. Major new programs reflected new directions although the basic programs of generating and assembling data on the State's geology continued. In 1927, what has been recognized as the first formal designation of the field of engineering geology occurred with establishment of such a division at the Survey. Although the value of chemical data was recognized even by the original Survey, being dependent on outside sources for analyses was a major constraint. In 1931 Geochemistry, Physics and Mineral Economics Divisions (now called sections) were created.

The Survey celebration of a milestone anniversary is shared by the Educational Extension Unit, which this year is celebrating its fiftieth anniversary. Its annual program is designed to provide earth science field trips in different parts of the State for the public, including high school teachers and their students.

1930-1955 (second 25 years)

The Survey's second 25 years saw a considerable expansion in scope of programs and service activities. This was greatly enhanced by construction in 1940 of the Natural Resources Building, which houses the principal research offices and laboratories of the Geological Survey and the Natural History Survey. A special laboratory for pilot scale research was completed the next year for the Geological Survey for large scale research in coal utilization.

Geologic studies by the Survey in Illinois resulted in the finding of significant quantities of oil and gas. The discovery of major occurrences of oil in the deeper part of the Illinois Basin in 1937 resulted in the significant increase in oil production, from fewer than 5 million barrels in 1936 to nearly 150 million barrels by 1940. Pilot scale studies that demonstrated practical use of major percentages of Illinois coal in blends to produce metallurgical coke were highly successful.

Through the second quarter century of the present Geological Survey, delineation of mineral resources remained a high priority program although many geologic and geochemical studies of more fundamental character also grew steadily. This period also saw a large growth in acquisition of drill hole records. In addition large numbers of samples—particularly cores and rock cuttings—were added to Survey collections.

During this period, the Survey achieved international recognition in several areas of study including stratigraphy and paleontology but particularly for its diverse program in coal geology and notably in paleobotany (palynology) and coal petrology. Work of the geochemistry group received recognition in coal carbonization, fluorine chemistry, and methods of analysis.

1955-1980 (third 25 years)

In the past 25 years, a number of significant changes have had important effects on the Geological Survey programs. During this period a third major building was constructed to house the large collections of drill-hole samples, rocks, minerals, fossils, and miscellaneous collections, an important part of the Survey's data base.

Throughout much of the history of the present State Geological Survey, mineral industries and land owners were perhaps the prime users of data generated. Major segments of the state's citizenry and agencies of government often were not aware of the kinds of geologic data that were available to them; indeed many were not aware of a need for geologic information. In this past quarter century, there has been greatly heightened public awareness of geology in Illinois and the part geology has to play in broad aspects of meeting societal needs.

Included in the program of the original State Geological Survey and in subsequent Survey programs were detailed studies of the glacial deposits that blanket most of Illinois. These deposits are important sources of groundwater, sand and gravel, and clay. Through the history of the Survey, there was considerable growth not only in resources studies of glacial deposits, but also in fundamental geologic studies of these deposits. The development of technically qualified planning agencies in cities, counties, or other regions of Illinois has focused attention on land uses that are affected by geologic conditions, particularly the glacial deposits that form much of the land surface.

Nearly 20 years ago, these developing interests resulted in formal recognition by the Survey of a field to which we applied the name environmental geology. Original studies were designed to provide basic geologic data in a format that could be used by engineers, planners, public officials, and other nongeologists for assessment of such factors as engineering conditions, waste disposal siting, water supply, and mineral resources.

Of major importance in the increased need for geologic data has been the evolution of requirements for geologic input under many regulatory procedures. This includes such considerations as mineral evaluations for areas that might through their land classification be precluded from mineral development; the recently enacted Surface Mining Control and Reclamation Act of 1977, which requires the development of hydrogeologic data for mining and land reclamation; assessment of geologic hazards for major plant siting such as nuclear power plants; geologic suitability of sites for hazardous and toxic wastes disposal; and geologic assessments of possible subsidence from underground mining, recognized in the new subsidence insurance legislation in Illinois. Greater numbers of environmental impact statements require development of more geologic data. Such legal requirements for geologic data are likely to increase in the future.

THE FUTURE

1980-2005 (the next 25 years)

For many years, the Illinois State Geological Survey has had as a prime objective the capability of being rapidly and authoritatively responsive to requests for information on geology of Illinois. This capability has been possible because of the acquisition of a very large mass of geologic data and maintenance of a staff qualified to utilize such a data base. Much of the success that the Survey has enjoyed in meeting objectives has resulted from data gathering and research well in advance of the time it would be needed to answer demands from the public we serve. Significant also is the support provided by the Survey to geologic research at universities and other research laboratories in the state.

Some changes in the past in the field of geology were related to legislative requirements. This will most certainly be true of the future. Geologists are now engaged in many areas that were outside the realm of interests of most geologists in the earlier years. Governmental laws and regulations related to energy, environment, and mining have resulted in geologists being hired by a number of governmental regulatory agencies. Although geologists have been involved for many years in exploration and development of minerals other than coal, many are now employed as coal geologists by that industry. Engineering consulting firms have proliferated, and a large percentage employ more geologists than in former years. Geology has been expanded in many other research facilities such as those of the U.S. Department of Energy National Laboratories. Major new coal research laboratories have been established in a number of coal producing states as well as in newly established mining and mineral research institutes.

I believe that there will be a change in the next 25 years that will be greater than that which has characterized comparable periods of history. The Illinois State Geological Survey possesses a unique advantage in geologic research that should enable it to respond to any changing role in meeting future geologic needs of the State.

The unique advantage is the geologic data base generated over the past 75 years and a qualified staff familiar with its use. The data base, staff, and means for disseminating geologic information provide important support to geologic research at other facilities in the state. Interdisciplinary research with the other two scientific surveys, the State Natural History Survey and the State Water Survey, and the State Museum, which also have appropriate data bases, is providing growing opportunities.

Some aspects of future directions and needs for geologic research in Illinois will undoubtedly be addressed in the "perspectives" presented by other contributors to this symposium. With no intent to suggest an exhaustive list of future geologic needs, I perceive several areas as requiring greater efforts in the next quarter century, to which the State Geological Survey should be a contributor.

Underground space. There has been a long history of limited use of underground space for such works as subways, water conveyance and sewers, warehouses, utility lines, and gas storage. For a number of reasons, I believe that we will see in the future much greater use of underground space for residential, commercial, and industrial purposes. Use of such space provides a relatively simple mechanism for heating and cooling at minimal expenditures of energy. As the population has grown, there has been increasing concern for loss of agricultural lands. Greater use of the subsurface, I believe, may well be expedited because of energy considerations and desire for greater economy in use of land area. Any such major developments will require detailed information on geology and hydrogeology.

Industrial, mineral, municipal, and other potentially toxic wastes. Problems of toxic waste disposal by burial or deep well disposal are currently of major interest. The nature of such problems of disposal of wastes has only recently been widely recognized. Any level of growth in industry and population will result in even larger quantities of such materials being generated. Many factors may be involved in an environmentally satisfactory solution of toxic wastes disposal, but I believe none to be more fundamental than geology. Through geologic studies, sites can be selected that have earth materials possessing the capacity to contain wastes for treatment or to attenuate toxic materials as they migrate.

Nuclear waste disposal. Expansion of nuclear energy has slowed considerably from the level projected only a few years ago. Energy developments in this same period, however, increase the likelihood that there will be a substantial expansion of nuclear energy until at least early in the next century. The safe disposal of both high-level and low-level hazardous wastes has most generally been considered contingent upon the discovery of suitable geologic containment of such materials. If nuclear energy supplies even a modest increment of increased demands for energy, the satisfactory resolution of the problem of disposal of wastes will be a significant challenge for geologists. In Illinois, identification of suitable sites for low-level radioactive waste disposal will be a principal need.

Land-use planning. These words have been used in a wide variety of ways in different disciplines. Environmental geology provides basic data on earth properties, which should be a major consideration in land-use planning. Implementation of environmental geology studies on a statewide basis for use in sound land-use planning should provide an important area of programs during the next 25 years.

Coal mining. Beginning in the late nineteenth century, there was a large growth in coal mining in Illinois. After some significant fluctuation, coal production is now hovering close to the average production of the past 50 years. Because of the vast coal reserves in Illinois, most of which must be acquired by underground mining, there are many aspects of geologic research that can profitably be expanded and applied in mining. Quality of mine roof and floor, mining hydrogeology, geologic features disturbing coal seams, physical and chemical properties of coal including noncombustible constituents, and coal mine subsidence are subjects of current investigation. If there is major expansion of coal production in Illinois within the next 25 years, greatly increased levels of research will be needed. Despite nearly 130 years of systematic investigation of coal resources in the state, relatively little is known about coal resources of stratigraphically lower seams in major areas of Illinois.

Oil and gas exploration. Historically, activity in geology of oil and gas has included not only geologic studies to discover areas favorable for oil occurrence, but development of new basic principles of such occurrence. In Illinois, most recent activity has been related to attempts to find additional oil and gas in situations similar to earlier finds. Improved methods of secondary and tertiary recovery will be a major research activity in the next 25 years.

Future discoveries most likely will involve the complexities of identifying favorable sites at greater depths. Detailed and broad area geologic studies will be undertaken to assess prospects of deeper oil and to identify types of geologic occurrence that may be new or that have not been adequately understood in the past.

Occurrence of gas in Illinois has been of minor concern because of relatively small amounts discovered. Greatly increased prices of natural gas and needs for indigenous sources of even relatively small amounts of recoverable gas will result in diverse geologic investigations to identify favorable sources from geologic occurrences such as coal seams, black shales, and compact sandstones.

Industrial minerals and metallic minerals. Throughout most of the past 25 years, work on industrial minerals and metallic minerals in Illinois has mirrored national attitudes that have resulted in reduced levels of geologic research. Foreign competition for ores of lead, zinc, and fluorspar have significantly constrained exploration and development of these resources in Illinois. Recognition of the need to greatly reduce dependence on foreign sources for a large number of minerals will, I believe, result in much higher levels of exploration and development in the future.

Although there is still some uncertainty regarding properties of carbonates for purposes such as scrubbers in flue gas desulfurization and in fluidized bed combustion techniques, a variety of special limestone uses will require much more sophisticated investigation of the properties of such resources. The possible presence of mineral resources must be considered a factor in making final land-use decisions. Possible sequential or multiple land-use strategies can only be considered with knowledge of geology and mineral resources.

Geologic hazards. Generally, Illinois has not been recognized as having major geologic hazards. I believe that in the future we will see much greater activity in this subject area—not because the hazards are necessarily greater, but because there is greater recognition that such hazards exist. These include phenomena such as slumping and landslides in more dissected terrain near major rivers and in certain surficial geologic materials. Seismic hazards are being increasingly considered because of strict building requirements for some types of facilities. Impact of mining on surface subsidence is intimately associated with the geologic character of strata in mines and between the mines and the surface. A great expansion in mining will greatly increase need for geologic input to minimize or control mine subsidence.

Computer-based research. The Illinois Geological Survey pioneered in utilizing electronic data processing for geologic data more than 40 years ago and is now extensively using computers in support of research efforts. The computerization of major data files will be essential to maximize their future use and value. The size of the files mandates that they be rendered to machine processable form in order to carry out timely research to a level that has not been practical in the past.

SUMMARY

Major research and service activities, some of which have persisted through the history of the Survey, must continue in the future. It is essential that we continue to add to the bank of geologic knowledge that is represented by our data base, if we are to be successful in meeting future requirements. Thus research in stratigraphy, sedimentation, studies of environments of deposition or accumulation, mineral resources mapping, paleontology, geochemistry of earth materials, economic analysis of mineral resources and acquisition of log files, samples, and descriptions of geologic materials must continue. All of the new or expanded applications of geology referred to previously rely on such fundamental geologic data.

Geologic research and services will be exciting and challenging in the next quarter century. The papers of this symposium will affirm this statement. The role of the Illinois State Geological Survey will be a major contributor to meeting many of these challenges in Illinois.

Coal Geology—Who Needs It?

Harold J. Gluskoter

Pere Marquette and Louis Joliet conducted their famous exploration of the Wisconsin, Illinois, and Mississippi Rivers from Lake Michigan to the Arkansas River during 1673. On a map dated 1674, Joliet indicated the occurrence of coal, "charbon de terre," on the north side of Illinois River at a point near Ottawa (Bement, 1929, p. 12). This outcrop of what was to become known as the LaSalle (No. 2) Coal was the first report by a European of coal-in-place in the New World. The natives knew it was there all the time. As a matter of fact, there is indication that coal was used in firing clays by the Indians in western North America as early as the 11th century (Lindbergh and Provorse, 1977); however, they and the early European settlers initially depended on wood for their source of heat.

The use of coal surpassed that of wood in the mid 1800s when railroads expanded across the country. By 1890, more than 200 million tons of coal were consumed in the United States. When the modern Illinois State Geological Survey was formed in 1905, Illinois was producing 37 million tons of coal per year. In 1920, the U.S. annual consumption reached 569 million tons and Illinois production was 90 million tons. At that time coal was the dominant source of all the energy used in this country.

When the Illinois State Geological Survey was first established, coal research had high priority. Bulletin 3, published in 1906, was "The Composition and Character of Illinois Coal" by S. W. Parr, a member of the faculty of the University of Illinois who had a long association with the Survey.

That same year, Dr. Gilbert Haven Cady was appointed to the staff of the Survey, beginning a tenure that would continue, with a few interruptions, until his death at age 88 in 1970, 19 years after his official retirement as Head of the Coal Section. Through his activities at the Survey, and through other professional contacts, his influence on coal geology of North America was extensive. Most of this influence was directed through individuals, and except for those who have come into the science in the past decade, there are very few coal geologists in this country who have not been affected by Cady's professional activities and personality.

The Illinois State Geological Survey has had an active coal geology program for the last 75 years. Studies of coal chemistry were given high priority from the very beginning of the Survey, as were evaluations of coal resources and reserves, which required knowledge in stratigraphy obtained through field mapping. Innovations in the field of coal geology were developed at the Survey, and ISGS researchers were also quick to apply promising new techniques developed elsewhere. Studies in paleobotany included investigations of coal balls, compression floras, and spores; in petrography, studies of the inorganic and organic geochemistry of coal were prominent. Scores of publications were produced and numerous papers were presented to state, national, and international societies.

From 1900-1975, the U.S. Geological Survey, the U.S. Bureau of Mines, other state surveys, individuals in academic institutions, and researchers in the steel companies also maintained active research programs. But there were relatively few coal geologists; even in the 1960s, the coal geologists required only a very small room in which to hold their sessions at the national meetings. Although there were extremely competent coal geologists conducting well designed investigations in their disciplines, there was only modest support for their efforts. Coal geology did not develop and support professional staffs to the extent that petroleum geology did in the oil industry. The reason for this was largely economic; support for science in industry or in state and federal agencies is motivated principally by economic factors.

ECONOMICS

The basic reason for the lack of whole-hearted support for coal geology in the past was that most coal companies were operating with a low-profit commodity and did

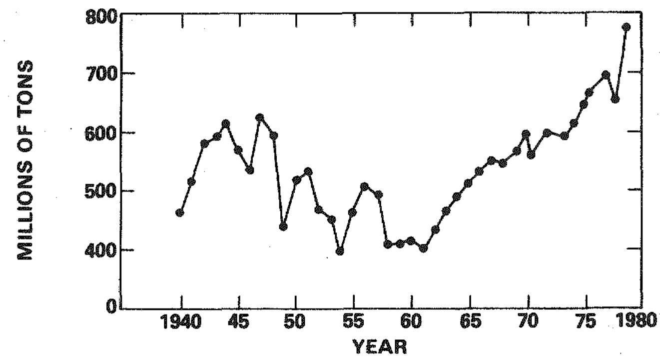

Figure 1. Production of coal in the United States, 1940-1979. (Source: Tables prepared by National Coal Association, published in Keystone Coal Industry Manual, 1980.)

not consider geologic studies by geologists worth the extra cost when the basic geologic work could be handled by mining engineers or other company personnel. Coal mining was usually done by small to modest-sized companies with limited resources, rather than by corporate giants.

There are several reasons for this condition of the coal industry. Coal production declined from about 1940 to 1960 and then began a rise that carried through the 1970s (fig. 1). Within the past seven years the rate of increase in production of coal has been more rapid, partly because of international policies and the increasing price of energy in general. However, the price paid for a ton of coal during that period of time did not follow the trend of production (fig. 2). Coal sold for $4 to $5 a ton for 20 years. Allowing for inflation during the period 1945 to 1970, it is apparent that coal companies recieved less and less of real value for their product over that period of time.

After the oil embargo of 1973, the price structure changed significantly, keeping ahead of inflation for the first time in several decades. The increased use of coal in the 1960s and beyond was predicted by some mineral economists. Figure 3 shows actual consumption of energy from 1900 to 1960 and projects consumption forward

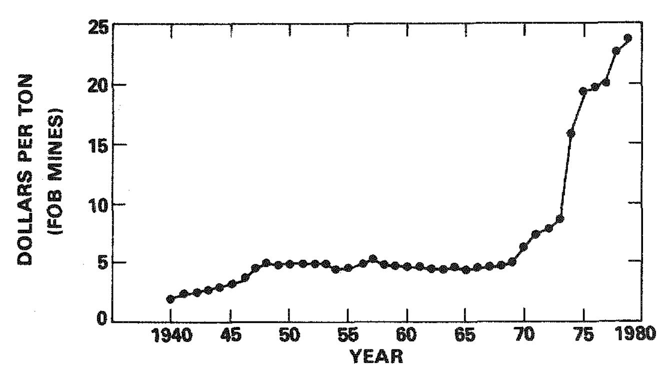

Figure 2. Average price per ton of coal in the United States, 1940-1979. (Source: Tables prepared by National Coal Association, published in Keystone Coal Industry Manual, 1980.)

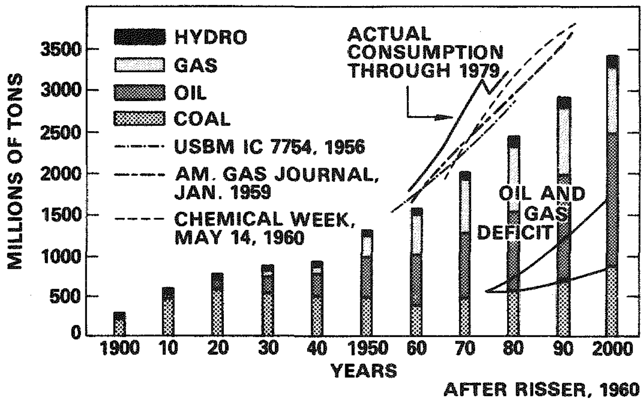

Figure 3. U.S. consumption of energy (tons of coal equivalent). (After Risser, 1960, actual consumption through 1979 added.)

to the year 2000 (Risser, 1960). In 1960, when U.S. coal production was at a near 20-year low, Risser projected major increases in energy usage in the United States and major increases in coal consumption as well. He postulated that by the middle 1970s—as the result of a declining availability of oil and gas—new markets for coal would open up and old markets would be regained. Hubert Risser was correct in his prediction of the energy crisis, although he was slightly conservative in his estimation of the rate at which the national energy consumption would rise.

Recent projections of the U.S. energy supply to the year 2000 by Exxon USA (1979) predict doubling of energy usage by the end of this century, a 3.5 percent average annual growth rate. Coal's share will increase from 19 to 33 percent (fig. 4). This will require a tripling of coal production in a 20-year period (a 5.6 % annual growth rate). There is an associated decrease in the absolute amount of oil and gas to be produced. It seems likely that there will be an opportunity to market coal at prices that will produce a reasonable return on investment.

This combination of factors has been sufficient to arouse the interests of some large energy companies. The top 20 companies holding coal reserves in the United States as listed by McGraw-Hill in the 1980 Keystone

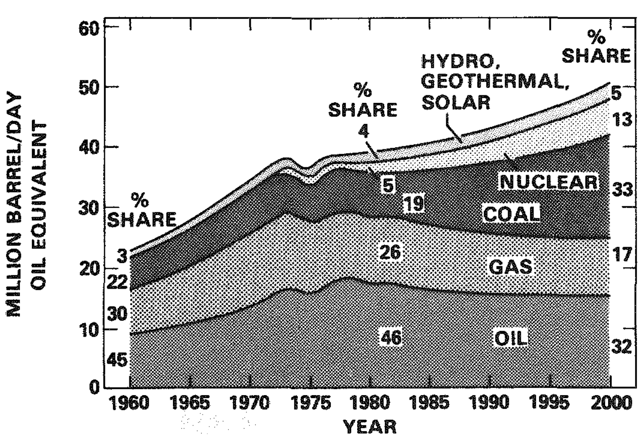

Figure 4. U.S. Energy Supply, 1960-2000. (From Exxon USA, 1979.)

Coal Industry Manual include 11 that are readily recognized as major energy companies that have oil and gas holdings as well as coal reserves. Among the remaining nine are two railroads, two steel companies, and one power company. The four others of the top 20 are mining companies, two of which were originally coal mining companies. These larger companies are able to make major capital investments in coal properties and coal projects. As the approach to coal recovery and utilization becomes larger in scale and more sophisticated economically, the concern for avoiding technical pitfalls increases.

COAL GEOLOGY TODAY

The geologist in general and the coal geologist specifically must have a grasp of the character and composition of the material with which he is dealing. Coal characterization, both physical and chemical, is basic to all aspects of his work. The coal geologist is adapting the wide variety of recently developed instrumental analytical techniques to his studies. Coal exploration and evaluation require not only that the geologists identify the presence of coal but they also require the prediction of the specific characteristics of coal. The geologist is asked to locate or predict the location of the thicker coal seams or coals in which the seam is continuous. These data are required also to calculate accurately the amount of coal resources and reserves in any area. The geologist may be asked to predict something about the floor or roof conditions that will affect the minability of the coal. Coal rank and ash content are significant factors to be determined in advance of mining.

Various aspects of the chemical composition of the coal may be critical in some areas. Since the sulfur content of the coal is the singlemost detrimental factor limiting the possible utilization of many of the coals of the world, including those of Illinois, it is very important to be able to predict where coals low in sulfur content can be found.

Other chemical parameters such as the alkali content, chlorine content, and trace element content may also be important. Inorganic constituents, including minerals present in coal, are significant for environmental reasons as well as for their possible effects on conversion. For example, certain metals may counteract the effect of catalysts in some coal conversion processes. Macerals, organic materials in coal distinguishable by electron microscopy, are useful in determining whether coals can be made into metallurgical coke. They may also be useful in determining whether a coal may be appropriate for conversion to liquids or gases. Many of these geologic factors can adversely affect the ability to utilize the coal and therefore the ability of the producer to market a particular coal. The geologists' ability to predict these and other characteristics of coal requires that they understand (1) the environments of deposition of coals, (2) the geochemical history of the coal from the time of the coal-forming peat swamp to the present and (3) the structural history of the coal during its entire existence.

COAL MINING GEOLOGY

It is possible to discuss coal mining geology as distinct from coal geology, although in practice the two cannot be separated. Various geological and engineering factors influence adversely the minability of coal. It would be of much benefit to be able to predict many of these geologic factors before mining the coal. One of these factors is the amount of coal present in an area (which is basically the thickness of the coal and its continuity). The continuity of the seam is also important for other reasons in mining (e.g., one wants to know if there are interruptions, such as concretions or clay dikes, in the seam). Other factors one would like to be able to predict are the character of the roof and the floor of the mine, the presence or absence of zones of structural weakness, and the groundwater conditions to be expected in a mine. Many of these factors are important for surface mines as well as for underground mines. Many of the major adverse factors that influence coal mining are geologic in origin, and although we are not yet sufficiently knowledgeable as to the controls of their distributions, the geologist, by virtue of his training, certainly has a good chance of being able to predict them in advance of mining.

GEOPHYSICS AND LOGGING

A number of geophysical and logging techniques are currently being applied to coal exploration and evaluation, and other techniques are being investigated including: seismic techniques, both surface high resolution methods and subsurface methods; resistivity; gravity; magnetic methods; radar and other electromagnetic methods; and down-hole geophysics. To date, seismic methods are the most advanced and have been used to identify the presence of a coal seam, the location of faults, and the presence of sandstone channels and other similar cutouts within the seam.

A rather sophisticated suite of logs is currently being run by a number of companies on holes drilled for the purpose of coal exploration. These logs are used primarily to identify the presence and the thickness of the coal seam and the presence or absence of partings within the seam. A number of other coal parameters are determined on the basis of drill cores taken from the same drill holes in which the logs were made.

The coal is analyzed in the laboratory for ash, moisture content, heating value, sulfur, and many other parameters. It is possible to predict the ash, moisture, and heating value content from some of this suite of logs. Research is currently under way to develop new devices that allow for the direct measurement of sulfur and other elements by logging methods. Geotechnical data can also be obtained directly from logs and can be used to identify problem areas prior to mining.

FUTURE OUTLOOK

Prognosticating the future carries with it the risk of eventually being judged as to degree of accuracy. Time has proven that Hubert Risser was quite accurate, as was the 1972 article by Major and Simon, "The Impending Energy Crisis—A Look at the Coming Decade."

Exxon Corporation's projection of the world's coal demand by the year 2000 is given in figure 5. Electric power generation is projected to maintain its position as leader in coal usage. A significant contribution by synfuels to the total amount of coal consumed is also projected. We will see a continuation of the trend to larger coal mines with their associated high capital costs. Large energy companies with a history of using sophisticated methods in their operations will produce much of that coal. The present demand for coal geologists, including stratigraphers, sedimentologists, geochemists, geophysicists, petrographers, engineering geologists and others, will not only continue but will increase. Unless unforeseen political events occur, the increased energy resource activities during the next several decades will create an exciting time for the coal geoscientist. These activities will be supported by state and federal agencies as well as industry as all recognize that they can benefit directly from coal geology.

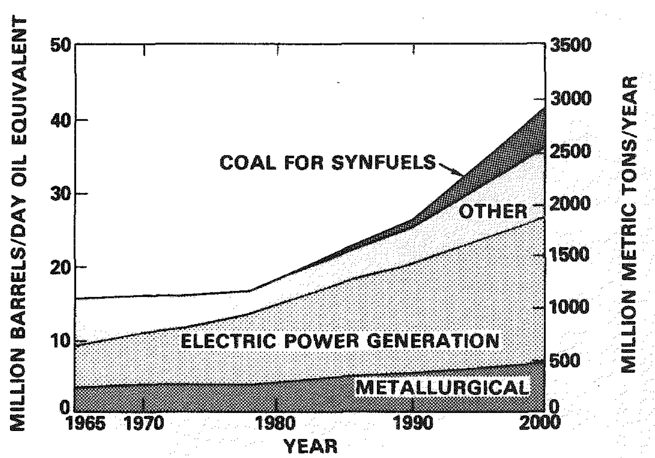

Figure 5. World coal demand, excluding USSR, Eastern Europe, and the Peoples Republic of China. (From Exxon Corporation, 1980.)

REFERENCES

Bement, A., 1929, Illinois coal: Illinois State Geological Survey, Bulletin 56, 123 p.

Exxon Corporation, 1980, World energy outlook: Public Affairs Department, Exxon Corporation, New York, Background Series, 32 p.

Exxon USA, 1979, Exxon USA's energy outlook 1980-2000: Exxon USA, Houston, 18 p.

Keystone Coal Industry Manual, 1980: G. E. Neilsen [ed.], McGraw-Hill, New York, 1364 p.

Lindbergh, Kristina, and Barry Provorse, 1977, Coal: a contemporary energy story: Scribe Publishing Co., Seattle, 207 p.

Major, R. L., and J. A. Simon, 1972, The impending energy crisis: a look at the coming decade: Illinois Business Review, Bureau of Economic and Business Research, University of Illinois College of Commerce, v. 29, no. 6, p. 6-8.

Parr, S. W., 1906, Composition and character of Illinois coals: Illinois State Geological Survey, Bulletin 3, 86 p.

Risser, H. E., 1960, Coal in the future energy market: Illinois State Geological Survey, Circular 310, 15 p.

U. S. Petroleum Exploration–Likely Targets 1980-2000

Richard F. Mast

During the last 100 years, domestic exploration for petroleum has been carried out primarily in the onshore and offshore domestic basins where the regional geologic settings have been reasonably simple. Early surface and subsurface geologic and geophysical exploration for oil and gas concentrated on large shallow structural anomalies and later moved toward investigating deeper targets, locating smaller and smaller geologic anomalies, and testing more complex targets that combined stratigraphic, structural, and hydrodynamic trapping mechanisms. This path was generally followed into the 1970s. Since the long-term expectation for the discovery of oil and gas is constantly decreasing—if not in number of fields, then in the size of the accumulations discovered—further exploration will also undoubtedly be carried out in the traditional producing areas. These discoveries will yield an important and dependable future source of domestic petroleum, and the production resulting from these discoveries, although not great, should be reasonably predictable with various types of discovery rate models. However, this approach to exploration will not solve our national oil and gas supply problem.

United States imports of oil and gas in the 1970s grew to more than 50 percent of our liquid petroleum supplies. As a result of the formation of the OPEC cartel, the cost of obtaining foreign oil has risen dramatically from less than $2/barrel in the early 1970s to $30 to $40/barrel in the world market today. The impact of increasing world prices has been to increase our domestic price of oil and gas in essentially the same time frame.

During this period we have also effectively increased our oil and gas exploration effort; as a result, exploration in new oil and gas provinces onshore and offshore has already begun. Although some of the initial results of offshore exploration have not been encouraging, we are really just beginning to search outside the traditional offshore producing areas of the western Gulf of Mexico, offshore southern California, and the Cook Inlet of Alaska. Onshore exploration has also begun to move into areas once considered too risky to explore, and some siginificant discoveries have been made outside the historical producing areas, particularly in the Overthrust Belt of Wyoming and Utah.

This change in strategy appears to offer the best hope for the United States to develop significant new supplies of oil and gas; however, it is too early to tell what the impact will be. It generally requires some 7 to 10 years to discover and develop new petroleum supplies outside the existing producing areas. In some of the new areas to be explored, difficult technological problems will have to be solved to develop and transport the oil and gas to consumers; these problems could further delay the production from new discoveries. One way to address the question of where exploration will take place in the next 20 years is to look at the appraisals of undiscovered recoverable oil and gas resources.

ESTIMATING UNDISCOVERED OIL AND GAS

Over the years, geoscientists have developed many methods of estimating the quantities of undiscovered oil and gas that may be contained in petroleum basins or provinces.

Volumetric method

One of the oldest of these techniques is the area or volumetric method, in which the ratio of the volume of oil and gas discovered in a basin or province to the explored rock volume or area is applied to the remaining unexplored volume or area to calculate the volume of oil and gas remaining to be discovered; there are many variations on this technique. One major problem with the method—which as been discussed in some detail by Hubbert (1974)—is that the technique usually assumes a constant discovery rate. Because the larger accumulations are usually discovered early, a greater proportion of the oil and gas in a basin is discovered during the early phases of exploration rather than during the later phases. This tends to make the volumetric appraisals of undiscovered oil and gas too large; volumetric estimates tend toward the optimistic side.

Process rate method

A second method for estimating undiscovered oil and gas volumes is the process or discovery rate method. In this technique, the volumes of discovered resources are plotted against some measure of exploration effort (usually the drilled footage of exploration wells), and on the basis of the past discovery history, declining discovery volumes are extrapolated into the future. By using this technique it is possible to avoid the problem of declining discovery rates noted with the volumetric method but it is difficult to assess exactly the volume of rock that is actually being appraised. The method generally produces conservative estimates of undiscovered resources.

Analog method

A third method is the analog or comparison method. In this technique, comparisons are made of undrilled or frontier petroleum provinces with geologically similar explored provinces, and resource estimates based on the degree of geologic similarity are then developed. Several analogs can usually be applied and a fairly wide range of estimates can result.

U.S.G.S. method

The U.S. Geological Survey (Miller et al., 1975) utilizes all of the above methods that are applicable to a given region to develop its estimates of undiscovered oil and gas in a province or basin. The results of the volumetric, discovery rate, and analog methods are used to gain insight as to the amount of hydrocarbons that may be contained in a province. Using these data, experienced estimators then make individual estimates of the volumes of undiscovered recoverable oil and gas contained in the province; these estimates are called subjective or expert assessments. The estimates are made at different probability levels to allow the estimators to express uncertainty about the geology (and therefore the uncertainty above the volumes of oil and gas that may be contained in a petroleum province). Log normal curves are then fitted to these estimates to develop the final expression for the undiscovered resources. These fitted distributions are then used to determine the statistical mean estimates, which provide a starting point to discuss sites for future exploration. It is only a starting point, because many other factors are involved over and above the general expectation for discovery of new resources.

AREAS FOR FUTURE U.S. OIL AND GAS EXPLORATION

In January 1981, the U.S. Geological Survey released revised estimates for the outer continental shelf (OCS) oil and gas

TABLE 1. United States offshore basins or provinces ranked by volume of estimated mean undiscovered recoverable oil and gas resources.

	Mean crude oil (billion barrels)		Mean nonassoc. gas (trillion cu ft)
Shelf (0-200 meters water depth)			
Beaufort Sea*	7.0	Western Gulf of Mexico	38.1
Western Gulf of Mexico	2.8	Beaufort Sea*	23.9
Eastern Gulf of Mexico	1.2	Mid-Atlantic	4.7
North Chukchi*	0.8	Navarin Basin	4.0
Navarin Basin	0.8	North Chukchi*	2.2
Mid-Atlantic	0.8	Central Chukchi*	2.1
Slope (>200 meters water depth)			
Western Gulf of Mexico	2.4	Western Gulf of Mexico	21.9
Mid-Atlantic	2.3	Mid-Atlantic	5.9
Beaufort Sea*	0.8	Beaufort Sea*	3.1
Santa Barbara	0.7	North Atlantic	2.1
Carolina Trough	0.6	Carolina Trough	2.1
Santa Maria	0.5	North Chukchi	0.8

(Dolton, 1981)

* These quantities can be considered recoverable only if technology permits their exploration beneath Arctic pack ice—a condition not yet met.

resources (Dolton et al., 1981). A review of these published estimates (table 1) shows that, on the basis of the estimated mean values for undiscovered recoverable oil, the six most promising areas for future oil exploration offshore to a water depth of 200 meters are the Beaufort Sea, the Western and Eastern Gulf of Mexico, the North Chukchi Sea, the Navarin Basin, and the Mid-Atlantic. On the basis of the sum of mean values given in Dolton et al. (1981), 13.4 billion barrels of oil and 64.4 trillion cubic feet of gas are the potential volume targets on the shelf in those six areas. For the OCS petroleum provinces of the United States, this represents (again based on mean values) approximately 77 percent of the 17.5 billion barrels estimated mean undiscovered recoverable oil assessed on the continental shelves (0-200 meters water depth) and 73 percent of the 88.1 trillion cubic feet mean estimated undiscovered recoverable gas for the same area. Comparison of these values to the American Petroleum Institute (API) statistics published in June 1980 for the year ending December 31, 1979, shows that the total mean oil estimated for the shelf area is only about 12 percent of the 148 billion barrels of ultimately recoverable oil already discovered in the United States and about 65 percent of our current reserves of 27 billion barrels of oil. The same comparisons for gas are 8.7 percent of 768 trillion cubic feet ultimately recoverable gas already discovered and 45.1 percent of our current gas reserves of 195 trillion cubic feet. (Past production plus proved reserves is equal to ultimate recovery using the API terminology.)

Gulf of Mexico

Of course offshore exploration will proceed most rapidly in areas surrounding the conterminous United States, in particular in the Gulf of Mexico. The long-range exploration trend will be to move toward the Arctic environments where the expectations for large oil resources are good offshore in water depths of less than 200 meters.

Offshore Alaska

Specific technological and climatic problems will have to be dealt with for exploration and development to proceed, especially in the Beaufort Sea, Chukchi Sea, and Bering Sea areas. In my opinion exploration will proceed most rapidly in the Beaufort Sea area (at least out to a water depth of 20 meters, where pack ice is not a problem) for the following reasons:

1. A number of discoveries have already been announced along the north Alaska coast, generally to the east of Prudhoe Bay, in rocks the same age as those that will be explored offshore.
2. Large structures offshore within the 20-meter isobath could be developed from a technological standpoint, on the basis of past experience in the MacKenzie delta and the Prudhoe Bay area.
3. Discoveries in the Beaufort Sea should support the costs of development even in these extreme environments, on the basis of (a) predictions of reservoir quality from drilling onshore in northern Alaska and offshore on the MacKenzie delta, and (b) the area's proximity to the Trans-Alaska Pipeline System.

The next most likely area for exploration will be in the Bering Sea, where operation and technological problems will be similar to those in the North Sea. At this time very little information is available on the quality of the reservoir rocks that will be encountered, but sediment thicknesses are large and thermal maturity of organic matter with the attendant hydrocarbon generation should have been achieved. There are also large structures that, if productive, could support the establishment of this area as a petroleum producing province.

Finally, as the technology is developed to handle pack-ice problems, exploration should spread into deeper water on the Beaufort shelf and into the Chukchi Sea area.

Offshore Atlantic coast

One other area that deserves special mention is the deep-water (>200 meters) area off the Atlantic coast. For several years we have interpreted a thick Jurassic carbonate shelf margin and an overlying thin Lower Cretaceous reef from seismic data. This reef structure with its associated fore reef and back reef facies and growth faulting between the present-day shelf and the buried reef complex is an attractive oil and gas setting. The major problem in the development of the area is the water depth, which can be more than 6,000 feet over the reef itself.

Much of the geochemical evidence supports the idea that if there is production in this region, it will be gas. Evidence from source rocks on the shelf shows that the source material is of primarily terrestrial origin (woody and herbaceous), and samples from the Deep Sea Drilling Project of correlative deep sea sediments are also of the type that generate predominantly gas. The Cretaceous slope environments have not yet been sampled, and one might expect that if marine-derived organic matter were preserved, the slope environment would be the most likely setting for anoxic conditions and maximum source-rock potential for oil generation.

Whether the reef itself will be highly porous and permeable is another question. Evidence from the Golden Lane region in Mexico, where there are very large, highly productive accumulations both in the reef and fore reef facies, suggests that significant karstification of those rocks took place before they were buried. Although Cretaceous rudist buildups are initially porous, early diagenesis commonly destroys porosity, and karstification may be required to develop a laterally continuous and effective porous system. In general, uplift related to tectonism or salt movements can be used to explain this karstification in the Golden Lane region. A counter-example is the Cretaceous Edwards reef complex in the Edwards Limestone of Texas, where karstification was not a major factor and where large oil accumulations in reef or reef-related environments have not been discovered. There is not enough evidence from the Atlantic margin to tell if parts of that reef were subjected to karstification in the geologic past. A few salt diapirs have been identified on seismic sections in the Atlantic region, and movement related to salt tectonics could have induced some natural fracturing. It is likely that these questions can be answered only by drilling.

In summary, a potential exists for significant discoveries in the deep water areas off the Atlantic coast in reef and reef-related facies that extend for almost 2000 miles parallel to the coast. Although exploration would take place in very deep water, the rig capability already exists to explore in water depths more than 6000 feet, and the technology for deep water drilling and production is expanding rapidly. There seems to be little doubt that during the next 20 years, explorationsists will test several times the deep-water Jurassic-Cretaceous shelf areas along the Atlantic margin.

New areas onshore

What about future exploration trends onshore? We know that the North Slope of Alaska will be an important exploration area over the next 20 years; however, rather than discuss the onshore drilling in known producing areas, I will focus on the search for new areas—in a sense the surprises—that may be only partly reflected in conventional thinking.

The best example of these is the Western Overthrust Belt in Wyoming and Utah; although this area had been explored over a long period, significant resources were not discovered until January 1975 when the Pineview field was drilled. That discovery was in the Triassic (?) and Jurassic (?) Nugget Sandstone, interpreted to be of eolian origin. Since that time new discoveries have been made in rocks ranging in age from the Ordovician Bighorn Dolomite (gas) to the Cretaceous Kelvin Formation (oil). Discussions with the "old timers" in the industry indicate that the exploration did not proceed rapidly in the belt prior to 1975, for at least two reasons: (1) results from many of the older wildcats that had been drilled were not encouraging; (2) the geology was rated as complex, so the risk was extremely high. One lesson probably learned from this experience was that, regardless of structural complexity, regions that have all the ingredients necessary for oil generation and accumulation must be thoroughly tested.

These discoveries also reflect the improvement over the years in the seismic data acquisition, processing, and interpretation, which now allows for better siting of wells, especially those targeted at underlying thrust sheets. Partly because of the experience gained in the Wyoming-Utah-Idaho portion of the belt, explorationists have expanded their horizons and have begun to look at these kinds of regions much more intensely.

Exploration activity in the Appalachian thrust belt has also begun to expand, and reservoirs have been found that are unrelated to the surface anticlines in décollement zones and in fractured rocks overlying or associated with thrust ramps. Thrust belts have much to recommend them in terms of petroleum geology. The tectonic style allows reservoirs and source rocks of widely different ages and depositional environments to be placed in close association with one another, and the compressed sections offer the possiblity of a wide variety of stratigraphic traps within individual thrust sheets, as well as intense fracturing and deformation within the thrust sheet themselves.

Since 1974 seismic investigations by both the U.S. Geological Survey (Harris and Bayer, 1979) and COCORP (Cook et al., 1979) have shown that the Appalachian Thrust Belt may extend significantly farther to the east than previously thought. Seismic data suggest that under the crystalline rocks of the southern Blue Ridge may lie several thousand feet of sedimentary rocks that have hydrocarbon potential, primarily for gas. Leasing activity has increased significantly in the belt; it has been reported that ½- to 1-million acres have been leased in Virginia alone and suggested that more than 10 million acres have been recently leased (or leases have been applied for) in the Appalachian Basin. Seismic data east of the Blue Ridge indicate that several thousand feet of crystalline rock, perhaps as much as 6,000 to 10,000 feet, would have to be penetrated before the suggested sedimentary section would be encountered. Similar developments have occurred in the Western Overthrust Belt.

More than a year ago, Anshutz Corporation released a seismic line in southern Arizona, traditionally considered to be in the Basin and Range province, in which they interpreted a thrust province, again overlain by several thousand feet of crystalline rocks. The section shows the presence of some very large structures. There has been much subsequent geologic discussion regarding the geologic validity of these hypotheses. The first well drilled was disappointing because it reportedly encountered 18,000+ feet of igneous rocks. A second well is now being drilled. I personally am a proponent of the concept that in the future we will see a significant expansion of exploration into thrust terrains, all of which may not yet be fully recognized and delineated.

One additional resource type that will probably be explored for may be representative of many of the "reservoirs" of the future. Major resources are thought to exist in the greater Green River Basin, the Uinta-Piceance Basins, and the Northern Great Plains region of Montana, North Dakota, and South Dakota. These resources are usually in Upper Cretaceous and Tertiary nonmarine rocks in which gas has apparently been generated from organic matter within the units or from the maturation of interstratified coals. In some cases there is evidence that part of the gas is biogenic.

On the basis of the U.S. Geological Survey's work in the Uinta-Piceance Creek Basins and the greater Green River Basin, almost 80 percent of the pore space in these rocks is thought to be secondary. We need to increase our understanding of the geologic processes that develop secondary porosity in these kinds of rocks so that at least the "sweet spots" can be explored for and developed. There are also problems in identifying the completion intervals within the hydrocarbon-saturated sections that are often more than 1000 feet thick. Furthermore we must improve the hydraulic fracturing technology so that continuity and communication with the well bore in these kinds of rock can be enhanced.

The Northern Great Plains is a "tight sand" area that the U.S. Geological Survey has also been investigating. One unit of interest in the area is the Gammon Shale or the Gammon member of the Pierre Shale, a silty mudstone of marine origin that covers a wide area in eastern Montana and the western Dakotas. The gas in the Gammon has been shown from isotopic studies to be of biogenic origin, so that its distribution can be presumed to be widespread. In fact, the burial history of the Gammon indicates that the gas could not be thermogenic. Recently we were able to acquire a core from the Gammon. The log and core analysis indicated that the Gammon above 1270 feet had high water saturation and below 1270 feet had high gas saturations; therefore the interval below 1270 feet was completed. The well from which the core was obtained came in at about ½ million cubic feet of gas per day after hydrofracturing.

We studied the entire core in detail to see if we could find any differences between samples above and below the 1270-foot level, which for all practical purposes were lithologically the same. The only difference we could find was that the dominant exchangeable cation on the montmorillonite clays above 1270 feet was sodium and below 1270 feet the dominant exhangeable cation was calcium. Further verification of the phenomena is certainly needed. If these phenomena can be verified, the ability to map regionally the distribution of sodium and calcium montmorillonite in the region would be a significant aid in the appraisal of the amount of shallow low-volume gas that could be developed in the northern Great Plains area from the Upper Cretaceous Gammon Shale. This example amplifies the importance of understanding the geology of these accumulations as a basis for resource appraisal.

SUMMARY

Past records, especially those of over the last few years, indicate that we produce our reserves at approximately the rate of 1 barrel of oil per 10 barrels of remaining reserves. Our current consumption of liquid petroleum is about 6.5 billion barrels of oil/year. At our current consumption rate, to be self-sufficient through new discoveries we would have to discover the equivalent of three Prudhoe Bay fields in one year and begin to deliver that oil to market in the next year. Our undiscovered resources of oil and gas, as we now estimate them through resource appraisal, are definitely not large enough to provide energy self-sufficiency through new discoveries alone, primarily because of the time required to discover and develop new large resources in most of the frontier regions.

On the other hand, although there are some very interesting and exciting places both onshore and offshore left to explore, much of the easy-to-find oil has been discovered. This emphasizes the country's need for well-trained geologists and geophysicists with the imagination to improve the efficiency of the discovery process, and well-trained technologists to make inroads on the oil and gas development and production problems in these new areas.

Of great importance today, and in the next 20 years, is our ability to assess accurately the magnitude of the undiscovered resources in the United States so that we can wisely plan for the future. New data from drilling, especially in the frontier regions, will help with such an assessment, but better predictive methods are truly needed. Geologic research directed toward understanding our future resource potential in deep-water areas off the shelf is also needed so that we can more accurately predict the source and reservoir potential before drilling actually commences. The development, refinement, and application of the continental drift model could respond in many ways to these kinds of problems.

Although we cannot reasonably hope to achieve energy self-sufficiency through exploration for new conventional oil and gas supplies alone, I believe that we have plenty of exploration room onshore and offshore, and we have the ability to improve our resource position through the vigorous exploration for new conventional supplies over the next 20 years.

SELECTED REFERENCES

American Petroleum Institute, American Gas Association and Canadian Petroleum Association, 1980, Report on proved reserves of crude oil, natural gas liquids, and natural gas in the United States and Canada—annual volume for the year 1979: American Petroleum Institute, New York.

Cook, Frederick A., et al., 1979, Thin skinned tectonics in the crystalline southern Appalachians—COCORP seismic-reflection profiling of the Blue Ridge and Piedmont: Geology, v. 7, no. 12, p. 563-567.

Dolton, G. L., et al., 1981, Estimates of undiscovered recoverable resources of conventionally producible oil and gas in the United States, a summary: U.S. Geological Survey Open-File Report 81-192, 17 p.

Harris, Leonard D., and Kenneth C. Bayer, 1979, Sequential development of the Appalachian orogen above a master décollement—a hypothesis: Geology, v. 7, no. 12, p. 568-572.

Hubbert, M. K., 1974, U.S. energy resources, a review as of 1972, Part 1, *in* A national fuels and energy policy study: U.S. 93d Congress, 2nd session, Senate Committee on Interior and Insular Affairs, Comm. Print, Serial No. 93-40 (92-75), 267 p.

Miller, B. M., et al., 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U.S. Geological Survey Circular 725, 78 p.

Perspectives in Groundwater

George H. Davis

The science of finding groundwater is one of the world's oldest professions. Development of groundwater was the key to the spread of mankind, permitting men to move campsites from where they were tied to perennial streams to towns and finally civilized society as we know it. In examining perspectives in groundwater, it is appropriate to look back to the origins of the science.

The use of groundwater supplies from springs and wells dates back to prehistoric times. The oldest works of the Bible contain many references to the digging of wells by the early Hebrews, as in Genesis 26:18, "and Isaac digged again the wells of water, which they had digged in the days of Abraham his father." This testifies to a widespread practical knowledge of the occurrence and development of groundwater. The Romans, in similar fashion, made widespread use of groundwater supplies; indeed some of the aqueducts that supplied ancient Rome tapped spring zones. What little we know of the culture of the Celts in Western Europe is based largely on the discovery of ancient springs and wells containing votive offerings.

Good evidence of the appreciation of groundwater phenomena by the Romans of the Empire period can be gained from the writings of Frontinius (A.D. 97) who served as the water commissioner of Rome in the latter first century A.D. He related that, from the founding of the city up until about 313 B.C., the Romans depended on water from the Tiber or from wells or springs. He notes that springs commonly were associated with the supernatural, having holy names, being objects of veneration, having the repute of healing the sick, and being the dwellings of nymphs. Herschel (1899) in his commentary on the water supply of the City of Rome observes that the Vestal Virgins were forbidden to drink the profane waters of the aqueducts, and instead drank only water from sacred springs.Herschel also reports on the practice of throwing votive offerings into springs that were sacred to the gods or were famous for their therapeutic properties. One such sacred spring on the shores of Lago de Bracciano was excavated in 1852 in clearing the mouth of the main spring (Herschel, 1899). The workmen found a nearly complete collection of coins extending from brass and silver coins of the fourth century A.D., through silver and gold coins of the early Empire period and bronze coins of the early Republic. Below this were found shapeless copper fragments, a kind of currency that preceded formal coinage, and finally arrowheads and knives of polished stone offered to the sacred spring by the half-savage people who preceded the Romans.

Despite the efforts of Saint Augustine and his contemporaries (Herschel, 1899) to break up the ancient veneration of springs, old customs die hard as indicated by the modern custom of tossing of coins into fountains for luck, and by an almost fanatical belief, held to this day in parts of Europe, in the sacred therapeutic qualities of certain springs (Lourdes in France and Mariazell in Austria, for example).

While we modern-day scientists scoff at supernatural attributes of groundwaters, many laymen still employ water witches to locate wells with their supposed supernatural powers.

Although the ancients clearly had a good practical knowledge of finding and developing groundwater supplies, there is no evidence that they had any understanding of geology or the occurrence and movement of groundwater. It wasn't until the seventeenth century that significant advances in scientific knowledge of groundwater occurred.

DEVELOPMENT OF THE SCIENCE OF HYDROLOGY

Perrault (1678) and Marriotte (1686), both concerned with the flow of the Seine, concluded from measurements of precipitation and river flows that much of the precipitation over the basin of the Seine must infiltrate to recharge groundwater. This key finding, which was contrary to the accepted wisdom of the time, led both these men to additional findings—with practical application—on groundwater movement and discharge.

Surface-water hydrology advanced by leaps and bounds during the eighteenth century, but groundwater hydrology was not advanced significantly until the fundamental principles of geology were established near the end of the century. William Smith in England did pioneering work in applying geology to groundwater questions. Understanding the principles of groundwater occurrences then advanced rapidly in the first half of the nineteenth century, culminating with the work of Darcy (1856), who established the law of the flow of groundwater in porous media. Darcy was the first to define the relationship between velocity of groundwater flow and permeability and head differences, a truly fundamental finding that provided the base for modern hydrology and petroleum engineering.

The latter half of the nineteenth century was marked by an acceleration of knowledge, particularly in Europe with Adolph Theim's (1870) introduction of field methods for tests of groundwater flow and Ghyben's (1888) and Herzberg's (1901) separate discovery of the balance between sea water and fresh water. In the United States, studies of groundwater lagged behind those in Europe but picked up in the latter part of the century with Chamberlin's treatise on artesian flow (USGS, 1885). Many able geologists, including Hill, Russel, Darton, Leverett, and Norton directed their attention to groundwater near the end of the century, and notable work was done on groundwater hydraulics by Hazen, King, and Schlichter.

The twentieth century can be looked upon as the age of quantitative hydrology. The foundations laid by Darcy and others in Europe were followed up in America by King with laboratory experiments of flow through natural materials, and by Schlichter with laboratory experiments and field experiments on velocity of groundwater flow. If I had to single out the five most far-reaching developments in terms of impact on groundwater science in the first half of the twentieth century, I would select the following:

1. Gunter Theim's (1906) application of the Dupuit formula (1863) to the problem of determining permeability of water-bearing materials by means of pumping tests and observations of the drawdowns in observation wells.
2. O. E. Meinzer's (1923) definition of the concepts of specific yield and specific retention, which laid the foundation for evaluation of groundwater storage capacity of broad areas.
3. Meinzer's (1928) and Russel's (1928) independent recognition that artesian aquifer systems do not perform like rigid conduits, but are subject to compression and compaction with decline of head. This laid the basis for understanding land subsidence due to water and petroleum production,

and to more valid quantitative analysis of artesian systems.

4. C. V. Theis' (1935) application of mathematical theory of heat conduction to groundwater flow for determining the drawdown of the water level in the vicinity of a discharging well. His formula is known as the nonequilibrium formula because, unlike other earlier formulas (including Theim's), it does not depend on the hydraulic system's reaching a state of equilibrium. With a properly managed aquifer test, both transmissibility and storage coefficient could be obtained. This development formed the foundation of modern aquifer-test analysis.
5. M. King Hubbert's (1940) development of an integrated analytical treatment for groundwater flow based on potential theory. This laid the basis for analytical analysis of groundwater flow problems, which ultimately led to the modern development of computer models.

With the end of World War II, we entered what might be termed the modern era of groundwater development. During the world depression of the 1930s and the War, there had been little new economic development. The end of the war revealed a pent-up demand for water supplies, and groundwater developments proceeded apace. From 1950 to 1975 we witnessed nearly a tripling of groundwater withdrawals (USGS, 1980). Much of this represented irrigation of new lands, but a significant proportion of the industrial and suburban growth of the past 30 years was supplied by groundwater. Groundwater science likewise grew tremendously. In 1950, the USGS and Illinois State Geological Survey were almost the only public agencies carrying out broad studies of hydrogeology and groundwater hydrology on a regular basis; now, nearly every state has some such inhouse capability, and studies are funded through the Water Resources Institutes and carried out in dozens of universities. With the recent growth of concern at the national level about contamination of groundwater supplies, we can expect continued growth of interest in groundwater science.

MODELING OF FLOW SYSTEMS

In the period since World War II, the greatest advances in the field of groundwater unquestionably have been in the area of modeling of flow systems. Some of the earliest work was in the allied field of soil drainage problems, where Luthin (1953) applied resistance-capacitance modeling to analysis of transient flow. Specific application of modeling of groundwater flow, however, dates from Stallman's (1956) introduction of numerical methods to groundwater hydrology. The earliest flow models used the analogy of electrical flow to fluid flow and employed conductive paper and a sensing probe to measure potential distribution throughout the conductive paper. Such models were limited to homogeneous, isotropic systems in two dimensions and were quickly superseded by resistance-capacitance networks in which transmissivity was simulated by resistors, and storativity was simulated by capacitors. In these models an electrical pulse is fed to a specific terminal that represents a well, and the time voltage graph taken at another point in the network represents the time-drawdown of an observation well. Any pumping rate could be simulated by varying the input current; results were generally shown in the form of maps predicting water-level drawdowns at future times. The greatest drawback of the method lay in the expense of construction of large networks and the difficulty of making adjustments once the networks were constructed.

Almost before electrical analogs were well developed they were superseded by numerical simulation models employing digital computers. Models employed in hydrology tend to fall into three classes: deterministic models in which known physical principles and boundary conditions permit accurate description of system behavior; stochastic models in which systems are assumed to be random and thus cannot be described by deterministic methods; and parametric models in which empirical relations among system variables are sufficiently known so that system behavior can be predicted. Groundwater systems generally are too heterogeneous for application of purely deterministic models. At the other extreme, stochastic models have little application because some parameters do not vary in a random fashion.

Most groundwater models can be described as quasi-deterministic, with case-by-case empirical determination of some parameters whose behavior may be random and thus not subject to detailed analysis. Much research is aimed at developing computerized procedures to calibrate groundwater models. Methods have been developed for steady-state flow problems to estimate values of parameters describing aquifer properties, hydraulic stresses, and boundary conditions on the basis of observation of dependent variables. Such methods test model fit, determine the reliability and significance of the model and the parameters of the model, and estimate the reliability of the predictions made. Research continues on similar application to transient flow problems.

Groundwater models generally are based on the principle of dividing the system to be studied into a finite number of blocks or elements. Each block has its own hydrogeologic properties and a node at its center where head is defined for that block. Finite difference or finite element equations are then used as a basis for computer simulation of flow in the aquifer system.

One of the most exciting areas of flow modeling research is the development of transport models to simulate movement of dissolved constituents in groundwater flow. Such models employ the advection-dispersion equation to describe the movement of both reactive and nonreactive dissolved constituents. These numerical simulation models offer a tool to evaluate conceptual models and to test hypotheses. They do not replace field data but they can help to guide the design of more efficient data-collection programs. Transport modeling is still in an early stage of development and no single model is best suited for all problems, but developments are coming at a rapid rate (see Steele and Stefan, 1979).

Transport models are of particular interest in analyzing movement of slugs of contaminants down gradient in the groundwater flow system. They have obvious and important application to problems of subsurface disposal of radioactive and other noxious wastes.

We appear to be on the threshold of developing complete models of saturated-unsaturated systems in which multiphase flow is simulated both above the water table and below. Freeze (1971) and Rubin (1968) have suggested approaches to this problem, but the complexity of calculations has deterred practical progress so far. Tremendous advances have been made in the field of flow and transport modeling in a brief time, but much remains to be done. Major policy issues, such as radioactive waste containment, and assessing impacts of surface development on groundwater supplies require long-term modeling with reasonable accuracy and knowledge of output uncertainty. This challenge must be met on a case-by-case basis and will require interdisciplinary efforts at all levels of technology.

Despite my emphasis here on numerical modeling, let me emphasize that a simulation model is only a tool for translating concepts and data into usable results. There is no magic to modeling that in any way improves on the underlying concepts and data. If the latter are defective, the outputs of the simulation model surely will be defective also. Indeed, thanks to rapid advances in modeling technology and digital computers, we find ourselves today in the curious condition that these tools are tending to outrun our basic knowledge of hydrogeology and the field data needed for input to models. This situation stems primarily from the high cost of acquiring groundwater data, particularly when extensive drilling is required. In many practical situations we are still hobbled by poor understanding of the details of the hydrogeologic regime and lacking in critical point data needed for viable models. Nevertheless, there is still much that could be done along the line of applying available science to the problem of improving the data base for modeling at reasonable cost. I refer particularly to the related fields of geochemistry and geophysics as offering such data that could be integrated with hydrologic data to improve numerical models. This, of course, requires involving specialists in these related fields in groundwater modeling.

As an example of the application of geophysics to groundwater modeling, I believe we could do much more in applying surface electrical and seismic methods to outlining subsurface deposits of significance in simulation modeling. Too often, the modeler relies on a few scattered drill records to formulate his concept of the subsurface regime, when for a relatively modest cost he could vastly improve his geologic model. The ISGS has long been a leading institution in the United States and the world in application of geophysical techniques to hydrogeologic problems.

Important progress has been made in understanding the geochemistry of groundwater systems, but much remains to be done. Most of the focus in the past decade has been in the development of chemical equilibrium models and in the modeling of solute transport through porous media. We also need to do much more in applying geochemical concepts and field data to improve our understanding the details of groundwater systems; too often, we are using groundwater hydrology to predict the movement of a slug of contaminant, without fully utilizing environmental chemical information to improve our understanding of the groundwater regime. In the past, hydrologists were generally limited to analyses of the six commonest ions in groundwater, but rapid advances in analytical techniques make possible the testing of a broad spectrum of elements at modest cost. The trace metals, for example, offer great potential for application to improving understanding of the groundwater regime.

A special area of hydrogeochemistry that offers great opportunity for future development is isotope hydrology. The isotope ratios of special interest to groundwater scientists are H/D, $^{16}O/^{18}O$, $^{13}N/^{14}N$, $^{32}S/^{34}S$, $^{12}C/^{13}C$, $^{12}C/^{14}C$ and $H/^{3}H$. All but the latter two are of stable isotopes, although ^{14}C and ^{3}H decay radioactively once the water is removed from atmospheric influence. A knowledge of the behavior of the stable isotopes of oxygen and hydrogen is of great value in increasing understanding of the source and timing of recharge and mixing phenomena. The behavior of carbon and sulfur isotopes can yield information about chemical reactions between water and rock materials, and the behavior of nitrogen isotopes aids in detecting contamination. Because the isotopes ^{14}C and ^{3}H decay radioactively, they provide unique information on time of travel of groundwater over long distances that cannot be obtained any other way. Isotopic analysis represents a wondrous new (since 1950) bag of tricks of chemical tracers quite independent, for the most part, of other solute reactions. A knowledge of their behavior provides an independent resolution of questions that can confirm conclusions arrived at by conventional hydrologic analysis. In many cases it helps in deciding among alternative hypotheses.

FUTURE CONSIDERATIONS

I would like to highlight some topics of continuing interest in groundwater science which promise major growth in the future. Currently, about half the people and four-tenths of the irrigation in the United States are supplied by groundwater, and in many areas groundwater is the only economical source of high-quality water. Accordingly, considerations of supply and quantity will continue to be of great importance as groundwater reservoirs are stressed to an even greater extent than now. Problems of conjunctive operation of surface water and groundwater systems will no doubt assume greater importance as we more fully utilize all our water resources.

Hydrologic work related to problems of permanent disposal of high level radioactive wastes from nuclear reactors may well hold the key to the growth of nuclear power generation in the United States. Several states have already taken the position that no nuclear plants should be built within their boundaries until a long-term solution is reached to the problem of permanent disposal of the highly poisonous, long-lived isotopes included in high-level wastes. While it is generally agreed that the answer lies in below ground repositories, a thorough knowledge of the hydrogeology of the repository sites and proper engineering of the disposal will be required to ensure that dangerous isotopes will not be transmitted away from the site as a result of leakage to groundwater. Work along these lines will be intensive for several years, but will continue indefinitely as the number of reactors generating wastes increases.

The large number of groundwater contamination cases discovered in recent years has already focused the attention of the media and the public on this long-standing problem. Federal and state efforts to assess and address the problem are only partly mobilized, and even the magnitude of the problem is not well-known. In the present climate of public concern, we can look forward to a flowering of policy, management, regulatory, and public-information initiatives. All these, of course, will depend for technical support on groundwater data. Because of past lack of public concern, contamination problems have had little study, and knowledge of the geochemistry of chemical wastes in groundwater is rudimentary at best.

Regardless of the level of public concern, groundwater contamination is deep seated and not amenable to the "quick fix" approach. It will be a real challenge to groundwater scientists to help maintain a rational perspective and provide practical solutions to this widespread, perplexing public problem. Long-term, expensive, and complex protective, preventative, and corrective measures face society. To be effective and affordable, these measures must be designed around a working knowledge of the controlling conditions—socioeconomic, hydrologic, and geographic.

REFERENCES

Chamberlin, T. C., 1885, The requisite and qualifying conditions of artesian wells: U.S. Geological Survey Annual Report, p. 125-173.

Darcy, H.P.G., 1856, Les fontaines publique de la ville de Dijon: Paris.

Dupuit, J., 1863, Etudes theoretiques et pratiques sur le mouvement des eaux les canaux decouverts et a travers les terrains permeables: Dunod, Paris.

Freeze, R. A., 1971, Three dimensional, transient, saturated-unsaturated flow in a groundwater basin: Water Resources Research, v. 7, p. 347-366.

Frontinius, Sextus Julius, A.D. 97, The water supply of the City of Rome: [Translation and explanatory chapters by C. Herschel.] (Republished by New England Water Works Assn., 1973.)

Ghyben, W. B., 1888, Nota in verband met de voorgenomen putboring nabij Amsterdam: Tijdschrift van Let Koninklijk Inst. van Ing.

Herschel, Clemens, 1899, Translation into English and explanatory chapters of Frontinius' two books on the water supply of the City of Rome: Dana Estes & Co., Boston. (Republished by New England Water Works Assn., 1973.)

Herzberg, A., 1901, Die Wasserversorgung eineger Nordseebader: J. Gasbeleucht. Wasserversorg, v. 44, p. 815-819.

Hubbert, M. King, 1940, Theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. I, p. 785-944.

Luthin, J. N., 1953, An electric resistance network for solving drainage problems: Soil Science, v. 75, p. 259-274.

Marriotte, Edme, 1686, Trates du mouvement des eaux et des autre corps fluides: Published in Leyden, 1717.

Meinzer, O. E., 1923, The occurrence of groundwater in the United States, with a discussion of principles: U.S. Geological Survey Water-Supply paper 489.

Meinzer, O. E., 1928, Compressibility and elasticity of artesian aquifers: Economic Geology, v. 23, no. 13, p. 263-291.

Perrault, Pierre, 1678, De l'origine des fountaius: Paris.

Rubin, J., 1968, Theoretical analysis of two-dimensional transient flow of water in unsaturated and partly unsaturated soils: Soil Science Society of America Proceedings, v. 32, p. 607-615.

Russel, W. L., 1928, The origin of artesian pressure: Economic Geology, v. 23, no. 2, p. 132-157.

Stallman, R. W., 1956, Use of numerical models for analyzing data on ground water levels: International Association of Scientific Hydrology Publication 41, p. 227-231.

Steele, T. D., and Stefan, H. G., 1979, Water quality in U.S. National Report to the IUGG: Reviews of Geophysics and Space Physics, v. 17, no. 6, p. 1306-1334.

Theim, Adolph, 1870, Uber die Ergiebigkeit artesische Bohrlocher, Schachtbrunnen, U.S.W.

Theim, Gunter, 1906, Hydrologische Methoden: Leipzig.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysics Union Transactions, p. 519-524.

U.S. Geological Survey, 1880, Ground water: our priceless resource: Ground Water Age, April.

Perspectives in Non-fuel Minerals

Allen F. Agnew

The term nonfuel minerals is slowly beginning to achieve national exposure in the press and on radio and television. In the years ahead, most citizens of the United States will understand what that term means, and some people will even understand how the pieces that make up the minerals-policy puzzle can be put in place.

Unfortunately, the decibel level of this cry for national attention to nonfuel minerals has always been lower than many people felt necessary—if the public was to be adequately informed. However, despite lack of public awareness, policy actions have been taken—especially during wartime—by the U.S. government, and the mineral needs of the moment were satisfied. But in the past, the international setting was also different; the United States had carrots on its stick, and it also had clubs that it was willing to brandish to ensure that favorable action took place.

One of the traditional problems of the minerals sector has been its failure to communicate with the public. There has been no shortage of published articles pointing out the strategic importance of mineral resources, but these learned papers routinely have appeared in publications read mainly by engineers and geologists involved in the minerals industry. In short, we have spent too much time talking to ourselves.

Thanks to the shock of the OPEC oil embargo of 1973-74, we as a nation suddenly became aware that things had changed and that we might actually be faced with shortages of other imported commodities because of cartel-like actions. The nontechnological press began to take notice of the nonfuel minerals. The public's awareness of present and future minerals problems in the United States is evidently increasing. But to many of us, that increase is still too small and too slow. Therefore, we professional geoscientists must all become more involved in communicating with the many nonmineral publics—all of whom have an interest in our national nonfuel minerals situation and in the means to solve our nonfuel minerals problems.

THE PAST

Minerals issues have been discussed in the past (along with other natural resources), and these discussions must have had some impact on national policy. Flawn (1966, p. 183-235), in his discussion of "Minerals and Government," commented on the New Conservation Movement of the early part of this century:

> The Conference of Governors and the North American Conservation Conference called by President Theodore Roosevelt in 1908 and 1909, respectively, marked the beginning of a nationwide awareness of natural resource problems.... Between 1910 and World War II, the conservation movement was concerned mainly with preventing the destruction and waste of natural resources—with soil erosion, deforestation, and the waste of mineral resources. Since World War II, a new dimension has been added to the conservation effort—cleanliness and beauty—and, for the first time air and water have been a major focus of attention (p. 184).

The conservation movement actually had its roots in the writings of John Muir and John Wesley Powell during the last two decades of the nineteenth century. As it evolved, it was joined by conservation-minded geological giants such as C. R. Van Hise in the 1910-1930 decades and C. K. Leith in the 1930s.

Most people seem to think that the consideration of minerals-policy issues began in 1952 with the Paley Commission. This is not completely true, however; in 1947 the materials-availability activities of the Department of the Interior were reviewed in Congressional hearings on national resources (U.S. Senate, 1947). An extensive appendix to the report on those hearings, "Mineral Position of the United States," was prepared by staffs of the U.S. Bureau of Mines and the U.S. Geological Survey (p. 165-338).

The Paley Commission on Materials Policy worked during the period 1950-52 to prepare its often quoted 5-volume report (Paley, 1952); in this report, the extrapolation of statistics for future United States materials requirements (based on the 5-year period 1947-51) "give a frightening picture of exhaustion and foreign dependence; [furthermore] extending the figures of per-capita consumption in the United States to the rest of the world suggested that total world exhaustion of many materials would not be long delayed" (CRS/SPRD, 1977, p. 26).

Minerals-policy matters have been intertwined inextricably with those of other materials, as noted by Huddle (1976), who showed that a number of policy reports and decisions have been made in the years since the Paley Commission and are being made in the Congress today.

Having watched the recent and rather unproductive 18-month exercise known as the President's Nonfuel Minerals Policy Review, Phase I (Agnew, 1979), I find it refreshing to reread Flawn and other geologists. Their numerous published papers and speeches on this subject of minerals policy during the past couple of decades presented blueprints of the future as seen through the eyes of perceptive geologists. We should be reconsidering what these men said rather than consigning their work to the archives.

THE PRESENT

Minerals provide the natural materials that are the basis for construction, for manufacturing, and for the metallurgical industries. The demands of technology in the United States and other developed countries, plus those of the less-developed countries, are causing increasing rates of worldwide mineral consumption (NAS/COGS, 1972, p. 13, 61).

Except for a few metals, a substantial share of the raw materials or finished products used in the United States must be imported. However, despite its dependency on imports of many mineral commodities, the United States is one of the world's most self-sufficient nations; most countries are just as dependent, or more so, on foreign sources. "These facts emphasize the importance of effective governmental policy and foreign relations in assuring a continuing mineral supply....and the need for developing greater self-sufficiency whenever possible" (NAS/COGS, 1972, p. 77).

The fact that the United States must import significant percentages of a number of minerals is of serious concern to students of such matters (Morgan, Jr., 1980; Park, 1978; Meadows et al., 1974; CENS, 1980). But, we must be careful to distinguish between mere *physical* shortage of mineral supplies and shortages due to *nonphysical* factors such as economics or politics. (See McKelvey, 1975, a geologist; Skelding, 1976, a mining engineer; Malenbaum, 1978, an economist, Govett & Govett, 1978, geologists; and the B/NAC, 1976.) According to the Govetts, mineral supply is solely a matter of economics:

> Whereas the ultimate world supply of minerals is controlled by geological factors, the actual supply at any particular time is controlled by economic factors (1978, p. 106).

The B/NAC report made a more involved analysis:

> The recent wave of popular fears of "running out of mineral supplies" proved short-lived. The "Club of Rome" analysis was not substantiated and no longer holds the field. A better understanding of the widespread physical availability of mineral resources and of the potential substitutability of most mineral supplies contributed to removing such fears (1976, p. 3).

That B/NAC report continued: "the major nonfuel minerals on which our industrial society is based (iron ore, bauxite, and copper) are distributed widely among both the industrialized and the developing countries." The report admitted that the industrialized world does have some problems—with chromium, tin, tungsten, manganese, and cobalt—and stated that the picture is "more mixed" for other metals such as columbium, molybdenum, vanadium, nickel, and the fertilizer minerals potash and phosphate (1976, p. 3-4). According to the report, public concern about the availability of minerals and their increasing cost has stimulated interest in: (1) conservation; (2) improved technology that will enable utilization of lower grades of ore; (3) substitution of more available minerals for those in short supply; and (4) the use of recycled secondary minerals. Thus, the B/NAC report concluded, "systematic review of the physical availability of minerals indicates that our industrial society is not likely to exhaust its supplies." It cited no less than 17 references to back up that conclusion (B/NAC, 1976, p. 4-6), yet warned that, "physical availability does not automatically imply 'availability for use'." Unfortunately, that report went no further with this very important caveat, so the reader is likely to underestimate its significance to our discussion.

Geologist Earl Cook looked at the matter in another way. Although to the mining engineer the profit of exploiting a mineral resource is the difference between the price received for his product and the costs of recovering the natural material and transforming it into a marketable product, society looks at it differently. Society, he argued, sees the profit from mining as either: (1) an energy surplus from exploiting a fossil fuel deposit or (2) a saving in work (the decreased expenditure of human energy and time when steel is used in place of wood in tools and in structures). Cook said that the "exploitation of earth resources" for display, adornment, or monetary backing is a deficit operation, financed by energy profits from other kinds of mining (Cook, 1976, p. 677):

> The ultimate limit to exploitation of earth resources then is the limit of net energy profit (or work savings)...[or] the limit to a resource also may be determined by the unwillingness of society to pay the cost of its exploitation, even though an energy surplus (or saving) might be obtained thereby.

It is instructive to examine the mineral raw materials requirements for the development and production of energy. Large quantities of minerals are essential in energy production because they are needed to produce energy-related hardware, according to a recent report of the U.S. Geological Survey (Goudarzi et al., 1976). This report said that the United States is totally dependent on imports of four of these mineral commodities: chromite, cobalt, manganese, and niobium (columbium); that imports provide a significant part of the supply of four others (aluminum, fluorite, nickel, and tungsten); and that reserves of only seven commodities (barite, bentonite, copper, iron ore, lead, molybdenum, and zinc) are adequate to meet demands in the United States during the 15-year period, 1975-1990. Thus,

> significant increases in production above that of 1973 for six commodities...are needed to satisfy the demand by the energy industries...so research is essential to increase U.S. resources and reserves for many commodities... (Goudarzi et al., 1976, p. 1).

One aspect of the energy/minerals relationship that has not received adequate attention pertains to solar energy. Many proponents of solar energy—especially among the general public—believe that since the sun is "free" there are no (or relatively little) significant costs or requirements except those involved in ensuring that the solar line-of-sight is not obstructed by trees or buildings. However, a report by the U.S. Geological Survey shows that the six main types of solar energy technologies will require in the first ten years (1980-1990) huge quantities of aluminum, concrete, copper, glass, iron, and manganese (Albers et al., 1976, p. 15; table 28). Of those six commodities, two are supplied to the United States almost totally by imports—aluminum (93%) and manganese (98%); about 28 percent iron ore, 13 percent of the copper, and 10 percent of the cement must be imported.

Another aspect of minerals supply is the environmental effect of minerals extraction and use. Some people blame the increased costs of environmental protection in recent years for a large part of the increased cost of products derived from mineral supplies—such as automobiles—because of the decreased productivity that allegedly results from industry's compliance with environmental requirements. The effect of the tension between minerals production and consumption on the one hand, and environmental quality on the other, was discussed perceptively a few years ago by Richard A. Carpenter:

> Neither exploitation nor preservation is dominant as a concept; a continually refined balancing among many goals is what is called for...Trade-offs are to be made explicitly and in a process open to the public. The marketplace, with its time limitations and imperfect information about environmental impacts, has been augmented (or perhaps supplanted) by a growing array of assessment procedures and regulations. In fact, the single greatest source of tension between availability of materials and environmental quality may well be the increased difficulty and time lag involved in reaching acceptable decisions (1976, p. 665).

Carpenter also recognized a second major problem—the dearth of complete, accurate, and timely information. He concluded, nevertheless, that "ingenuity and a more complete understanding of the parts and interactions of the energy, materials, and environment system can do much to reduce [these] tensions...and bring about equitable trade-offs..." (Carpenter, 1976, p. 668).

Some people have charged that when companies in the United States increase their investment in mineral production and processing facilities in foreign countries—to escape the strict environmental regulations in this country—they are simply transporting their environmental problems abroad. Although such a charge may have been valid a few years ago, it is losing some of its impact today by the fact that foreign countries are also becoming more environmentally conscious. Nevertheless, this is an issue that must be considered when contemplating alternate United States sources of supply where its domestic capability is inadequate.

THE FUTURE

In order to meet the growing worldwide demand for both metallic and nonmetallic minerals, additional deposits must be located and mined and major advances must be made in recovery and reuse of metals.

It seems obvious that we *do* have a problem, after all. But how significant is this problem, and how can it be overcome?

How significant is the problem?

Many minerals experts claim that the problem is significant, requiring close attention by government policy makers, industrial suppliers, and end-use consumers. Others, mostly economists, assume a more relaxed attitude.

For example, a recent study by Resources for the Future concluded that the United States faces only one major mineral-supply problem—an undue vulnerability, in the case of certain minerals, to contingencies that might seriously disrupt supplies or cause sharp upward movement of prices, with serious economic impact (RFF, 1979, p. ES-1). The RFF study was restricted to only seven mineral commodities; of these, only chromium presents a major problem; problems connected with aluminum, cobalt, copper, and lead range from major to minor, and problems associated with manganese and zinc are minor because substitutes are available and shortages of these commodities would have a relatively small impact.

One of the reasons for this seemingly complacent RFF attitude is the fact that almost all previous projections of world mineral consumption have been too high—mainly because of over-estimating the long-term growth rates in gross economic output of countries that are the principal consumers of minerals (RFF, 1979, p. ES-2). The RFF study itemized several short-term problems including: actions by foreign governments, intended to disrupt supplies or raise prices; actions or events that might disrupt supplies incidentally; generalized demand surges; and natural disasters. Long-term problems itemized in the study included: monopolistic control of prices; long-term exposure to short-term supply contingencies; declining processing capacity in the United States; steep rises in prices; depressed prices; price instability; and physical supply stringency. Most short-term contingencies fall within the bounds of normal business risks that do not require government attention; others arise out of large deviations from trend.

Since World War II, mineral considerations have had only limited influence on our foreign policy, despite our substantial reliance on imports for many minerals. This laissez faire policy is based on the assumptions that: (1) worldwide investment in mining capacity by United States companies would be adequate to meet world demand, and that (2) United States industry would be able to compete freely for the resulting mine output.

However, growing nationalization of mineral operations (and other unilateral revisions in mineral concessions) resulted in a marked decrease in the flow of United States capital into direct investment in mining abroad. Then in the 1970s new concerns arose, including the risk of cartel actions, boycotts, and other supply interruptions (RFF, 1979, p. ES-16).

The RFF report concluded that "none of these developments [occurring over the past 30 years] justify an overriding concern for mineral supply problems in U.S. foreign policy," although they do suggest the need, said the report's authors, for a "more elaborate policy than [simply]...'the equal access' doctrine," which had proved sufficient in earlier decades (RFF, 1979, p. 17-19).

The high degree of our dependence on Southern Africa for minerals—especially the chromium and platinum-group metals—coupled with the potential use by the USSR of its mineral exports as a political weapon have been recognized by the RFF report as problems, especially when the changing situation with the Peoples Republic of China is added to the brew. As a result, a process of adaptation has begun, as follows:

- Some investment by private companies has occurred by diversifying risks;
- International financial institutions have expressed willingness to participate in minerals financing;
- New minerals projects have been organized in some of the more advanced countries under the control of State mining companies (using debt capital borrowed in the international capital market).

Opportunities thus exist for United States foreign policy "to facilitate adaptation to changed environment, and thereby to increase and accelerate the process of exploration, development, and production." However, as the RFF report pointed out, if the United States diplomatic establishment is to offer such support, it will need to become much better informed about minerals exploration, production, and marketing. "Developing credence for its good offices will undoubtedly place considerable strain on its diplomatic talents...It will require both knowledge and serious analysis, to make a proper assessment of the...constraints...; it will require that, plus an extra dose of imagination, to divine the opportunities (RFF, 1979, p. 17-25 and 26).

How can these problems be overcome?

As the RFF study suggests, we can sit back and relax and watch the variety of innovative arrangements crop up, as part of the process of accommodation that has already begun (RFF, 1979, p. 17-24). But, as economist John Tilton has pointed out, whether the shortage is a physical one or an economic one, the end result of nonavailability of supply could be devastating in terms of dislocation and hardship and changes in life-style (Tilton, 1977, p. 5).

There are a number of positive actions we can take. In addition to cutting down on our use of mineral commodities, we can also conserve what we do use and recycle more of what we have customarily thrown away in such a cavalier manner. Recycling of many mineral commodities is already practiced and the recycling of several of these commodities could be greatly increased.

According to Dresher (1975, p. 10), chemical engineers and metallurgists should rise to this challenge, which has three components: recycling, substitution, and efficient design. Substitution has many proponents—several of them evangelistic. Goeller and Weineberg, for example, have portrayed a future society that could subsist on renewable resources and on elements (such as iron and aluminum) that are practically inexhaustible; they admitted, however, that most of what they contended is speculation (1976, p. 688). But, let us return to Dresher's argument. He said that, although the recycling problem is largely one of economics, technological problems do exist and must be solved. He warned metallurgists and chemical engineers that the substitution of plentiful metals and other materials for scarce ones will also offer new challenges to the technologist, and he challenged designers to ensure that machinery and even household appliances are "designed for optimum performance, for reliability, and for ease of recycling."

The problem of dissipation (or loss of potentially recyclable materials through dilution) was the subject of a study that examined in considerable detail the dissipative uses of 11 metals that are returned to the environment "in a form so dilute that there is no possibility of recovery" (NATO, 1976, p. 1). The report stated that:

> In the free economy of the Western world many policies and lines of action are the natural consequence of the profit incentive. Many of these are of course beneficial to society in every way...[and] self-optimizing.
>
> However, there are other areas where short-term public interests are not identical...[and thus] non-self-optimizing. For example almost 40% of current zinc production is used in galvanizing and is irretrievably lost. It is unreasonable to expect the galvanizing industry to support research on alternative methods of corrosion protection when the success of such research would serve only to put them out of business.
>
> Other examples appear where recyling is a technical possibility but is not currently practiced due to lack of responsibility or economic incentive. Here much of the difficulty arises because the product changes hands. The foundries have an obvious interest in collecting and sorting their in-house scrap for recyling, and to a lesser extent the same applies to large users. But it applies hardly at all to the ultimate individual consumer. And when the product becomes junk..., it usually becomes the (unwanted) property of a government echelon whose mission makes no provision for salvage or re-use (NATO, 1976, p. 1-2).

This is the challenge for metallurgist, chemical engineer, and designer. But, what about the geoscientist? Bender (1977) attempted to answer for the geologist the question: How large are the resources that we can reasonably expect to find in the earth's crust, and are they amenable to exploitation? He concluded, in answer to economists and others who promote the cubic-mile-of-rock concept, that because "an enrichment factor of some nineteen to twenty times that of the crustal average is...required statistically, it is thus quite obvious that the imposingly vast tonnages of metal contained in the upper crust, or even within rock masses of greater than average content, constitute but examples of theoretical and scientific interest that are of no practical importance whatever for the future supply of metal" (Bender, 1977, p. 121).

According to Bender (1977, p. 127) we can surely expect to be able to double or triple the "reach" of our exploration methods in the future, which should certainly increase the available reserves of nonfuel minerals. These more sophisticated exploration techniques will undoubtedly be accompanied by more sophisticated thinking by geologists about the genesis of metallic ores and their nonmetallic counterparts. The definition of prospective areas will consequently be revised, so that there will be an increase in the size and number of areas where there is a likelihood for discovering a deposit.

The relationship of metallogenesis and plate tectonics is a key concept being investigated today, that will undoubtedly bring new discoveries of metallic and nonmetallic minerals. Recent advances in our knowledge of stratiform ore deposits will undoubtedly stimulate even more interest in those potentially huge deposits.

Marine geology and ocean-floor mineral resources will take on a legitimacy that can come only when the legal/political problems of access and ownership to these potential reserves underneath international waters are solved. Mineral and chemical resources from the oceanic areas can be sought from (1) sea water itself; (2) placer deposits within or beneath submerged beach or stream deposits; (3) sediments other than placers, together with sedimentary rocks that overlie crystalline rocks both on continental shelves and slopes and also beyond continental margins; and (4) crystalline rocks exposed on the sea floor or lying beneath sediments both on continental margins and beyond (Cloud, 1969, p. 137).

However, one must beware of getting carried away by the economics of extracting minerals from that hostile environment of great water depth, underwater currents, and surface storms. Thus, as Cloud pointed out (1969, p. 153-154):

> What we must avoid is to succumb to the misleading notion that a great variety of resources are available in large volumes, such that when we run out of terrestrial resources we can simply turn to the sea...A 'mineral cornucopia' beneath the sea thus exists only in hyperbole. What is actually won from it will be the result of persistent, imaginative research, [of] inspired invention, [of] bold and skillful experiment, and [of] intelligent application and management—and resources found will come mostly from the submerged continental shelves, slopes, and rises...It is a fair guess that they will be respectably large; but if present conceptions...are even approximately correct, minerals from the sea are not likely to compare in value with those yet to be taken from the emerged lands. As for seawater itself, despite its large volume and the huge quantities of dissolved salts it contains, it can supply few of the substances considered essential to modern industry.

The State Geological Survey

In working out solutions to our mineral problems, the U.S. Geological Survey and the U.S. Bureau of Mines, as the major mineral resource agencies of the Federal government, will play a major role; we depend heavily upon their analyses of the occurrence and distribution, extraction, processing, and recovery of mineral commodities.

But we also lean heavily upon their counterparts in the States. Most such agencies, as in Illinois, are called state geological surveys; however, in eight states a bureau-of-mines function is also included in the state geological survey (California, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Virginia). In Texas and West Virginia, the word "economic" is incorporated with geology in the survey's title.

State geological surveys are focused on state problems, and much of their work tends to be of a resource assessment and economic evaluation nature. Although mineral resources produced in one state enter national and international trade, most of the emphasis of a state geological survey is on the service it can provide to its own citizens. The Illinois State Geological Survey, for example, has published a large number of bulletins, reports of investigations, circulars, and mineral notes dealing with at least two dozen separate mineral commodities, and it responds daily to requests for information on Illinois minerals.

As we enter the last two decades of the twentieth century, I wish to pose a challenge to state geological surveys: that the state geological surveys attempt, to the extent possible as governed by manpower and financial resources available, to look at their mineral resources from the standpoint of their national implications also. Many surveys, including the Illinois State Geological Survey, have published reports that dealt with regional economic implications (in two, three, or even more states) of some of their studies—so, perhaps this challenge does not call for as great a change in course as some people might think. In a sense, my challenge is for the state geological surveys to provide an answer to the question raised by Charles H. Smith, Assistant Deputy Minister of the Canadian Department of Energy, Mines and Resources, who said at the dedication of the U.S. Geological Survey's new building in 1974:

> Can a geological survey produce the timely and meaningful analyses required for the resource and environmental policies of the next decade? For geological surveys to rise to this increasing responsibility will require the focusing of talents and efforts in a manner not unlike that of wartime, but the possibilities of disaster warrant such a reaction, even if only to prove the predictions to be unfounded or premature (1974, p. 5).

Communication

Paul Barton recently spoke of several instances in which we geoscientists and engineers have not done even a passable job of getting the necessary knowledge across. As a result, he mentioned (Barton, 1980, p. 802) the uproar about strip mining of coal—whereby "the net result of well-meaning, but uninformed people is to *maximize* the very long range effects they sought to eliminate."

Barton next spoke of asbestos, a subject about which the experts, in this case medical doctors, "have proven that a little knowledge is a dangerous thing." Stating that "it has been known for some time that crocidolite, the fibrous sodic amphibole that is sometimes used as asbestos, when inhaled as small particles, all too often does lead to mesothelioma and to lung cancer, the latter especially among smokers. In contrast, good evidence shows that the major economic asbestos mineral, chrysotile, is *not* carcinogenic when dust control is held to 2 to 5 fibers/cc...Nevertheless, for reasons known only to themselves the cancer crusaders lumped the apparently guilty crocidolite with the innocuous chrysotile; in addition, they have included nearly every other fibrous mineral, including some zeolites, that has the prerequisite fine-grained, acicular morphology—calling them all 'asbestos.'"

Barton went on to cite a number of other instances of misinterpretation and overzealous application of inadequate knowledge in governmental regulation of the minerals industry, in the name of environmental protection. He cited a conversation he had had with a well-educated, socially responsible person about energy or mineral shortcomings—who, it turned out, was interested not in how to *develop* a deep-sea manganese nodule industry in an environmentally responsible manner, but rather, in how to *prevent any development* at all of this "dreadful" industry (Barton, 1980, p. 803).

So I will conclude this discussion of our need for communication with the 80 million or so people of voting age in the United States by quoting a most important paragraph from Barton's paper:

> I want to emphasize...*education* of decision makers *and* the electorate that supports them. *It is as important for the future*

voter to appreciate the realitites of our resources-environment situation as it is to be able to read the ballot...our principal hope lies in education—at all levels; in grade school, in junior and senior high schools, in colleges, in the public at large (804-805).

A postscript

For some stimulating and provocative reading, I recommend that you look up Ridge's paper (1974, p. 13) on grid drilling of the United States, and Muessig's paper (1979) on art (not science) of exploration. Then you might reread Merriam's paper (1974, p. 43), in which he took a hard look at data and retrieval, philosophy of search, applied methods, and education, and concluded: "I look for geologists to meet their responsibilities and commitments with foresight and ingenuity. The future looks bright for the Geological Survey to continue to fulfill its role..." So do I, on both counts; just as Merriam was referring to the U.S. Geological Survey in its 95th year, so am I referring to the Illinois State Geological Survey, on its 75th Anniversary.

I agree with Merriam. Despite the temporarily curtailed programs in 1980, as all parts of the nation adjust to the current straitened economic circumstances, the nation's future need for nonfuel minerals paints a bright picture, indeed, for those who can do the necessary research.

REFERENCES

Agnew, Allen F., 1979, Summary comments on President's nonfuel minerals policy review report (draft) of August, 1979. Library of Congress, Congressional Research Service, unpublished report, 15 p.

Albers, John P., W. J. Bawiec, and L. F. Rooney, 1976, Demand for nonfuel minerals and materials by the U.S. Energy Industry, 1975-90: U.S. Geological Survey Professional Paper 1006-A, 19 p.

Barton, Paul B., Jr., 1980, Public perspective of resources: Economic Geology, v. 75, p. 801-805.

Bender, F., 1977, An earth scientist's view of metallic resources: *in* F. Bender [ed.], The importance of the geosciences for the supply of mineral raw materials (Processing International Symposium, Hannover, Federal Republic of Germany, Oct. 25-26, 1976): Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, p. 117-136.

B/NAC, 1976, Mineral development in the eighties; prospects and problems. (British-North American Committee): National Planning Association, Washington, D.C., 54 p.

Carpenter, Richard A., 1976, Tensions between materials and environmental quality: Science, v. 191, p. 665-668.

CENS, 1980, The "resource war" and the U.S. business community: the case for a Council on Economics and National Security: National Strategy Information Center, Washington, D.C., June, 52 p.

Cook, Earl, 1976, Limits to exploitation of nonrenewable resources: Science, v. 191, no. 4228, p. 677-682.

Cloud, Preston, 1969, Mineral resources from the sea: *in* NAS/CORAM, Resources and Man (National Academy of Sciences, Commission on Resources and Man), W. H. Freeman & Co., San Francisco, p. 135-156.

CRS/SPRD, 1977, Materials policy handbook: Legislative issues of materials research and technology (Prepared by Congressional Research Service for Subcommittee on Science Resources and Technology): United States 95th Congress, 1st Session, House Committee Print, Series C, June, 205 p.

Dresher, William H., 1975, Technology—the future of raw materials supply: Arizona Bureau of Mines Field Notes, v. 5, no. 2, p. 1-3, 9, 10.

Flawn, Peter T., 1966, Mineral resources: geology, engineering, economics, politics, law: Rand McNally & Co., Chicago, 406 p.

Goeller, H. E., and A. M. Weinberg, 1976, The age of substitutability: Science, v. 191, p. 683-689.

Goudarzi, Gus H., L. F. Rooney, and G. L. Shaffer, 1976, Supply of nonfuel minerals and materials for the U.S. Energy Industry, 1975-90: USGS Professional Paper 1006-B, 437 p.

Govett, M. J., and G.J.S. Govett, 1978, Geological supply and economic demand; the unresolved equation: Resources policy, June, p. 106-113.

Huddle, Franklin P., 1976, The evolving national policy for minerals: Science, v. 191, p. 654-659.

Malenbaum, Wilfred, 1978, World demand for raw materials in 1985 and 2000: E/MJ Informational Services, Inc., New York, 126 p.

McKelvey, V. E., 1975, One nation in one world: *in* NAS/NAE National Materials Policy: NAS, Washington, D.C., p. 23-27.

Meadows, D. H., D. L. Meadows, et al., 1974, The limits to growth: Universe Books, New York, 2nd ed., 205 p.

Merriam, Daniel F., 1974, Resources and environmental data analysis: *in* USGS Symposium on Earth Science in the Public Service: USGS Professional Paper 921, p. 37-45.

Morgan, John D., Jr., 1980, Minerals availability—the mineral position of the U.S.: Mining Congress Journal, February, p. 49-54.

Muessig, Siegfried, 1979, The art of exploration: Economic Geology, v. 74, p. 732-734.

NAS/COGS, 1972, The earth and human affairs: National Academy of Science Committee on Geological Science, Canfield Press, San Francisco, 142 p.

NATO, 1976, Rational use of potentially scarce metals: NATO Scientific Affairs Division, Brussels, Belgium, 129 p.

Paley, William S., 1952, Resources for freedom: Report of the President's Materials Policy Commission, U.S. GPO, Washington, D.C., 5 volumes.

Park, Charles F., Jr., 1978, Critical mineral resources: Annual Review of Earth and Planetary Science; Science, v. 6, p. 305-324.

Resources for the Future, 1979, Major mineral supply problems: Study prepared for the Office of Science and Technology Policy for the President's Nonfuel Minerals Policy Review, NTIS Publication PB 80-117674, Springfield, VA, 1090 p.

Ridge, John D., 1974, Mineral-resource appraisal and analysis: *in* USGS Symposium on Earth Science in the Public Service: USGS Professional Paper 921, p. 12-16.

Skelding, Frank H., 1976, The U.S. and the world mineral economy: *in* Alfred Weiss [ed.], World Mining and Metals Technology: 2 volumes, p. 1066-1081.

Smith, Charles H., 1974, Geological surveys in the public service: *in USGS Symposium on Earth Science in the Public Service*: USGS Professional Paper 921, p. 2-6.

Tilton, John E., 1977, The future of nonfuel minerals: Brookings Institute, Washington, D.C., 113 p.

U.S. Senate, 1947, Investigation of National Resources: Hearings, May 15, 16, and 20, 1947, Senate Committee on Public Lands: United States 80th Congress, 1st Session, 388 p.

Geological Problems in the Geochemistry of Sediments

Raymond Siever

Sedimentary geochemists explain in chemical terms the ways in which the detrital and chemically precipitated components of sediments may form, alter, or disappear in the course of the sedimentary cycle. Those changes may result from subaerial or marine weathering; transport; continental or oceanic deposition in a wide variety of environments; and diagenesis under many different kinds of burial regimes. We study modern processes and we infer ancient ones, including those that occurred early in the history of Earth before any preserved record of sedimentary rock deposition. Geochemical reactions have an immense range of speeds. Among the fastest are biochemical pathways, mediated by enzymes, by which minerals such as carbonates, phosphates, iron oxides, and fluorite are precipitated. Some are of moderate speed, such as the ion-exchange of clay minerals when river water meets sea water. Most are slow, like those reactions by which disordered, impure phases of micrometer size grow to become ordered, relatively pure phases of millimeter size—transformations typical of carbonate and silica minerals. Temperatures at which these reactions take place range from 0°C or colder to 250°C at the bottom of a deep drillhole, and from 1 bar to many kilobars.

EVOLUTION OF MODERN GEOCHEMISTRY

We have moved through several stages in the evolution of sedimentary geochemistry. The earliest stage, in the 19th and early 20th centuries, was concerned with the bulk chemical analysis of materials of Earth. The culminating work of this effort was Clarke's "Data of Geochemistry" (1924); from it we could quote the composition of the average shale and of many other rocks and fluids in rocks. The study of crystal structures and crystal chemistry so important to sedimentary mineralogy and chemistry began in 1912 with von Laue's first proposal of x-ray diffraction by crystals and culminated, in a way, in 1930, when Linus Pauling published a remarkable paper on the structure of the micaceous minerals. Bulk chemical analysis has now been overshadowed by the detailed microanalysis of individual textural constituents of rocks by the electron probe, the ion microprobe, and other methods of analysis. Isotopic analyses of extremely small amounts of material are now done with high precision. The study of environmental geochemistry has stimulated chemical analysis of the highest sensitivity and accuracy that has been applied to the study of sediments as we attempt to increase our knowledge of the distribution of trace quantities of specific elements and compounds.

The second stage of geochemistry in this century was the study of equilibrium states by classical methods of thermodynamics, pioneered in this country for the igneous rocks by N. L. Bowen (1915) and his associates at the Geophysical Laboratories in Washington and later at the University of Chicago. Although this stage started near the beginning of the century with the notable work of van't Hoff and others (1905) on a sedimentary deposit—the Stassfurt salt deposits—the work continues as we seek even more accurate determinations of thermodynamic properties of geologically important materials. Many materials, particularly those of variable composition and intimate phase mixtures, are yet to be carefully determined. The thermodynamics of concentrated solutions, such as deep subsurface formation waters, is still problematic.

The third stage, one we are barely entering, is concerned with the kinetics of reactions by which we can tie the sequence or timing of geochemical changes to geological changes.

THE RELATION TO PURE CHEMISTRY

As sedimentologists moved out into modern sedimentary environments to study the processes by which sediments are formed, sedimentary geochemists did the same, measuring the chemical variables: concentrations of dissolved substances, bulk chemical compositions of solids, adsorbed surface phases, isotopic and trace element ratios, and pressures of gases such as carbon dioxide, hydrogen sulfide, and methane. Developments of the last few years have allowed us to make these measurements in the field and in the laboratory more sensitively and accurately than ever before. By contrast, our study of ancient rocks remains more circumscribed. The fluids in rocks can be measured only in deep drillholes or mines where representative sampling is difficult. Remaining as a central problem is our desire to understand not so much the state of the rock in its present surroundings as the geochemical history by which it reached the present state.

Our knowledge of pure chemistry is an enormous help in tracing this history. Great strides have been made in pure chemistry in the interval during which sedimentologists were investigating the compositions of sediments. We now draw on a solid background of generations of careful work in analytical and physical chemistry. Although we know much about crystal chemistry, there is still much research to be done on the relationship between disordered crystallographic states of minerals and their chemical composition. Such studies are especially relevant to some of the most abundant sedimentary minerals, the clays, carbonates, and silica minerals. We know well the thermodynamics of pure phases. The theoretical analysis of non-ideal solutions is well-advanced. But, contrary to the impression of many physical chemists, thermodynamics is not a completely finished science. There is still much to learn about the thermodynamics of solutions, especially some of the solutions most important in geology—aqueous solutions such as concentrated formation waters, sea water, and magmatic and hydrothermal waters. The physical chemistry of surface phases is also of great interest to geochemists, because it is on the surfaces that reactions start. Surface chemists have yet to arrive at fully satisfactory theories for any but the simplest materials. Although there is much research in chemical kinetics, the study of heterogeneous kinetics of chemisorption at temperatures characteristic of Earth's surface is still largely empirical. The geological problems related to kinetics assume great importance as we study the rates of feldspar weathering, clay mineral alteration, coalification, oil and gas formation, and bacterial processes of sulfate reduction. Geochemists must rely on all the newer developments in pure chemistry to supply the theoretical tools with which to proceed.

THE GEOLOGICAL BACKGROUND

The geological background of sedimentary geochemistry involves well-known principles; however, the ways in which these principles are applied frequently need to be recast. A geological material cannot be described without reference to its past history as well as its present surroundings. Rocks are not reagents on a shelf. It is not merely that we want to understand history; we need to know it in order to understand the present. Geological history is based on stratigraphy, paleontology, and sedimentology; to it we must link a geophysical history: paleotectonics, magnetic stratigraphy and apparent polar wandering paths, and estimates of past heat flow regimes. The geochemical history we seek to understand includes the history of pressures, temperatures, and bulk and phase compositions of solids and fluids. Such histories include non-uniformitarian aspects as we infer processes that occurred before the diatoms and pelagic foraminifers evolved in the Cretaceous oceans, before the vascular plants evolved early in the Paleozoic and before the metazoans evolved late in the Precambrian. The geochemistry of the Precambrian, which had an atmosphere that may have varied from our present one and a lack of metazoan life on land or in the sea, presents more complex questions. We may infer that much higher heat flow regimes, more extensive volcanism, and a style of tectonics unlike the plate motions of today occurred in the earlier Precambrian.

GEOCHEMICAL CYCLES

Many sedimentary geochemists see the analysis of geochemical cycles of elements and compounds as a way to identify important geological and geochemical processes affecting various sedimentary environments at or near the surface of Earth and fluxes to and from the various reservoirs (Garrels and Mackenzie, 1971). Thus far, geochemical cycle studies have been concerned primarily with global patterns and, necessarily, our models have been simplified. These first approximations based on assumed steady state conditions are now shifting toward considerations of the effects of perturbations, such as the current changes in CO_2 concentrations in the atmosphere. Increasing interest in environmental geochemistry has stimulated the study of cycling and mass balances on a smaller scale (i.e., the primary object of study may be a local drainage basin or lake). Because of the continuing interest in solution geochemistry, there has been a corresponding geologic emphasis on hydrology and on the atmospheric sciences as we have begun to realize how much chemical transport takes place at different levels of the atmosphere.

THE SEDIMENTATION DIAGRAM

One way to illustrate the geological background of a sedimentary geochemical problem is by the analysis of the geological history of a sediment following its deposition; we can then connect that history with chemical changes occurring during diagenesis. We will start with the diagram originally called an "oscillogram" (fig. 1) by its originator, von Bubnoff (1954). It has since been called a sedimentation diagram or geological model, but neither term is entirely appropriate. It is a time-depth curve, in which the depth with respect to sea level of a particular formation is given as a function of its geological age. Since stratigraphers have seldom preoccupied themselves with this kind of reconstruction, constructing such a diagram is a non-trivial exercise. Most geophysicists' attempts have been too simple—perhaps because of the difficulty in handling the resulting calculations of geothermal gradients. A resasonably complete diagram should include the depth of the sediment-water or sediment-air interface with respect to sea level. This is not easy with our present knowledge of sedimentology, but we improve every year. We also have the consolation that for very thick sections (4-5 km deep), only the major differences between deep and shallow seas are of great importance.

A sedimentation diagram is not a cross section but a graph of the locus of the depth versus geologic age; this means that one must estimate *original* thicknesses as well as the amounts eroded during later erosional intervals. The present thickness, as logged from a drillhole, will generally be unsatisfactory. In working with outcrop sections for which little subsurface information is available, we find that the problem is more difficult, because the reconstruction must take place for a given point on the surface of Earth. Thus we must extrapolate and interpolate original thicknesses, information which must come from a careful study of facies and the general nature and specific course of subsidence. A careful assessment of unconformities must be included and specific estimates of the amounts of material removed by erosion. This estimate of materials removed will also involve an estimate of uplift during unconformity intervals.

A hazardous occupation at best, estimating heights of ancient uplifts or mountains can be done only by correlating present mountain heights with modern plate tectonic environments. Unfortunately, only a few modern examples of each type exist. The Himalayas may be considered representative of young mountains produced by continental collision. We may take as an upper limit on mountain heights the constraint of the strength of the crust in comparision to crustal thickness, which would limit the heights of mountains to approximately the present heights of the Himalayas, about 8-9 km above mean sea level. The Alps may be used as an example of not-quite-so-young collision-type mountains. Their heights range around 4-5 km, which can be considered representative of erosional lowering after initially higher regimes. Mountains formed by subduction zone orogenies in advance of continent-continent collisions may be illustrated by the Zagros Mountains of Iran, which are less than 1 km high, and the Cascades of Oregon and Washington, which may rise more than 4 km above sea level. The Andes, another example of subduction under a continent, include mountains that rise above 6 km. A re-examination of mountain heights in various tectonic regimes and of many erosional histories is clearly needed, but this brief scan shows some of the variation involved.

Histories of older mountains are more difficult to estimate because rates of erosion vary not only with height above base level but also with climate. The Appalachian Mountains are generally at a level of about 1 km, although they sometimes reach almost to 2 km. The Caledonian Mountains of Norway may exceed 2 km, but those of the Scottish Highlands are around 1 km. Intermediate-age mountains, such as those of the Rocky Mountains, may be higher than 4 km.

The elevation of mountains is the driving cause for the erosion of section and the stripping of overburden that are revealed by dramatic, extensive angular unconformities. Other unconformities are less spectacular but may nevertheless represent significant losses of stratigraphic section that may also be important in calculating overburden and geotherms. Local unconformities may be associated with onlap-offlap relations such as those recently being explored by the methods of seismic stratigraphy. Changing shoreline patterns that need not necessarily include changes in sea level may also lead to erosion, although the effects of this erosion may be exceedingly difficult to evaluate quantitatively. Submarine erosion can also eliminate significant thickness of sediment.

Estimates of amounts of erosion based on present-day denudation rates are not likely to give promising results, because present-day rates are strongly affected by agricultural and other anthropogenic activities (Judson and Ritter, 1964).

The process of estimating the erosion represented by an unconformity is illustrated in an ISGS study of the Mississippian-Pennsylvanian unconformity in the Illinois Basin (Siever, 1951). Mapping of the unconformity revealed that as much as 80 m of the upper part of the Mississippian were missing, presumably stripped during the post-Mississippian erosional interval. An analysis of the details of the sub-crop map of the Mississippian beneath the Pennsylvanian showed that the erosional interval was actually compounded of two episodes. The first episode was a beveling of a slightly deformed Mississippian terrain in which a more-or-less even, sub-planar topography was produced. The later episode occurred when further uplift with respect to sea level caused extensive channeling of the previously beveled surface. In this case, as in analyses of specific sandstone bodies in the Pennsylvanian, one can assume a shoreline at some distance south, perhaps 200 km, and estimate a longitudinal profile for the river system. The erosion in the upper reaches could then be correlated with base level lowering, and an estimate of sea level lowering during this period could be made.

This general way of proceeding leads to estimates of a few hundred meters of erosion of the section. This

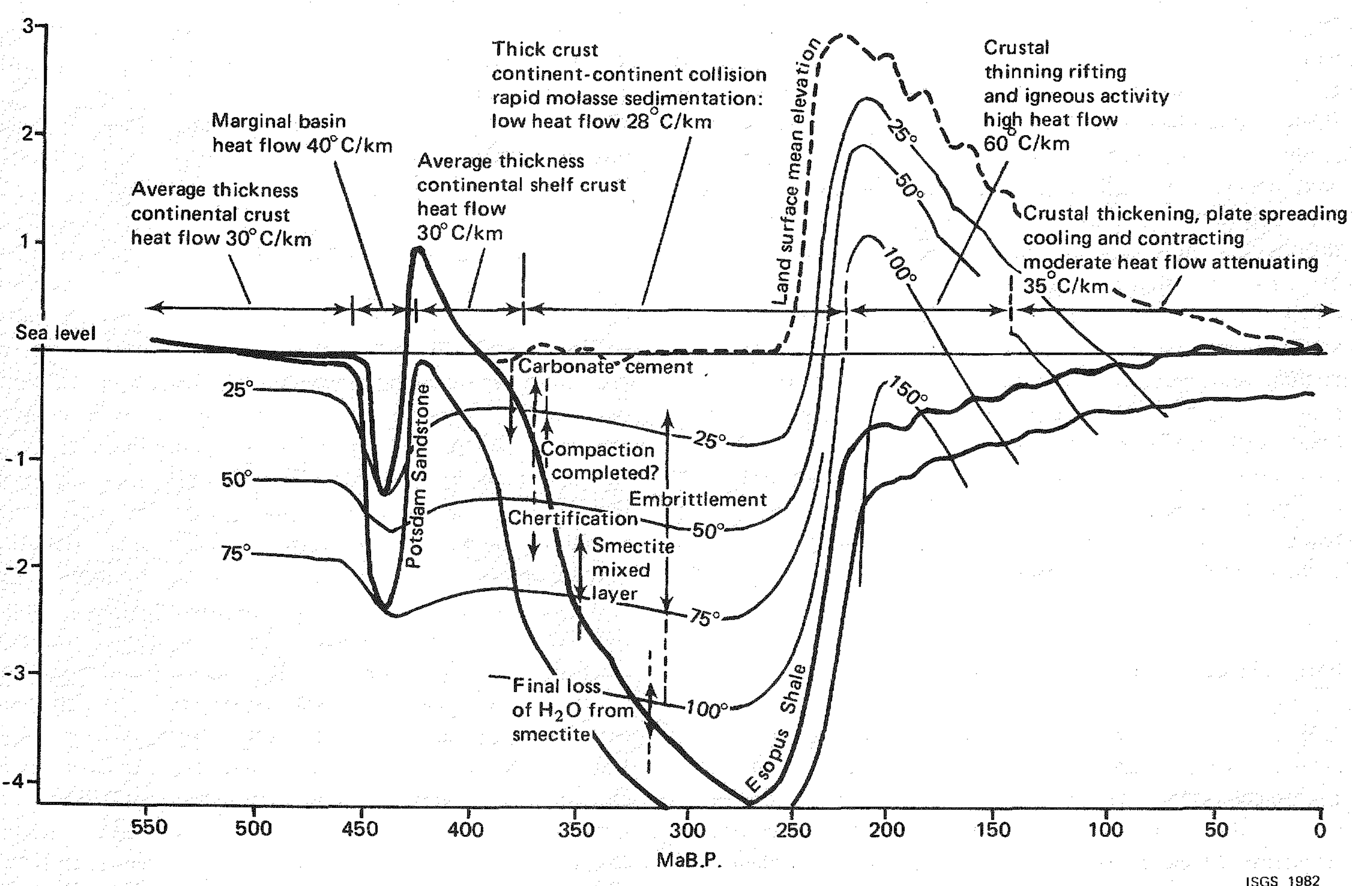

Figure 1. Sedimentation with estimated paleogeotherms for an area in eastern New York State, for two formations, the Potsdam sandstone (Cambrian) and the Esopus shale (Devonian).

amount of erosion may be negligible in the analysis of a basin section 10 km deep with only a few local unconformities, but as Sloss (1963) has pointed out, a great many unconformities can be found in shallow cratonic basins. Twenty such unconformities in a Paleozoic section of only 2 km can remove significant amounts of the original stratigraphic section.

ESTIMATION OF PALEOGEOTHERMS

Once the sedimentation-subsidence diagram has been constructed, one can proceed to the estimation of paleogeotherms. As a first approximation we assume no convective movement by groundwater that would lead to any heat transfer. Second, we assume that any volcanism would not transfer a significant amount of heat directly by mass transfer. On the basis of these assumptions, we treat only the uppermost 10 km of a static stratgraphic section that has heat sources only at depths greater than 10 km, presumably from a lithospheric crustal basement. Values for heat flow vary widely among continental regions. These variations are caused by regional differences in radioactive element content of the continental lithosphere (Roy et al., 1969) and by variations in mantle convection that lead to higher or lower heat flow in a region. Thus, a region of thick, old continental crust with much granitic material would be expected to have a relatively high heat flow from the indigenous radioactive material of the rocks, although the mantle convection sources may be small. Heat flow from a Precambrian shield area may be moderate and almost entirely from crustal radioactivity.

In contrast, heat flow would be very low in a basin located in a fore-arc region that overlies basaltic oceanic lithosphere with very low radioactive element content in a cold descending limb of a plate. Another area may be a rift region with thin crust and high mantle heat flow, similar in some ways to the Basin and Range Province of the western United States. From these generalized models, crude estimates of the heat flow into the top 10 km of sediments of a sedimentary basin can be made.

After the estimation of heat flow, average values for the porosity and thermal conductivity of the sedimentary section must be assumed. The surface temperature of the stratigraphic section is the only remaining variable to be estimated. Surface temperature depends both on latitude and altitude. One can infer the latitude at any given time by reference to continental drift maps derived from paleomagnetic apparent polar wandering curves and geological considerations such as paleoclimates, facies, continental fittings, and structural lineaments. Once the latitude is determined and the altitude is estimated from the sedimentation diagram, there is a further decision: whether Earth at the time was in one of its glacial periods or was ice-free. The latitudinal temperature distribution should remain approximately the same in character but be displaced toward warmer temperatures in the temperate and polar regions in nonglacial periods.

Although this procedure for estimating paleogeotherms involves many assumptions, it should be noted that the range of mean annual surface temperatures on the globe is not large, varying only from about 0°C at the bottom of polar oceans to about 30°C in the warmest regions of the continents. This range applies also to the variation from low to high altitudes.

Given surface altitude and latitude and thus surface temperatures, and estimated heat flow, one can then arrive at some idea of the paleogeotherms for a given time by using models for heat flow calculations. Models such as those given by Birch et al. (1968) allow us to calculate heat flow as a function of time, sedimentation, and erosion. Because of the long time scale for heat conduction, rapid sedimentation will result in cooler temperatures in the recently deposited section than at equilibrium. Slow sedimentation will result in more rapid equilibration and thus higher temperatures. Because of this lag in heat equilibration, the paleogeotherms will tend to be smoothed, and temporal and local variations of small scale will be ironed out.

One refinement of this procedure for estimating geotherms is the estimation of heat transfer by convection within the pore fluids of the top 10 km of the section. An average bulk permeability and a simple flow geometry can be assumed for the entire section and a Rayleigh number calculated to see if a critical value for convection is reached. Assuming a simple flow geometry, rates of water movement as driven by convection alone can be calculated. Further refinement would depend on evaluation of any hydraulic head that drives water circulation independently of convection. Given a certain amount of heat transfer by this method, then the paleogeotherms can be adjusted to arrive at a more realistic figure.

Given an estimate of the paleogeothermal history of the sediment pile, we can compare it with time-temperature curves for given reactions. To do this, one must measure rate constants for different temperatures—as Eberl and and Hower (1976) did for the conversion of one clay mineral to another. Once such determinations have been made, they can be plotted versus reciprocal temperature, an Arrhenius plot that gives the activation energy. We can convert this curve for activation energy to get an integrated time versus temperature curve instead of rate constant versus temperature. This curve would then give the time at a given temperature for a given yield of the reaction to be reached. A family of curves would describe different yields for the same temperature and another family of curves for different temperatures for the same yield. The geological choice is dictated by the fact that a given sedimentary rock may move slowly or rapidly from one temperature to another in comparison to the increase in rates. Thus as the rates increase with temperature, they must be compared with the rates at which the rocks move from one temperature regime to another. This leads to evaluation of a combination of the subsidence rate (or sedimentation rate if the two are equivalent) and the geothermal gradient. For example, a thermal gradient of 60°C/km will increase the temperature at a rate equivalent to a doubling of sedimentation rate at a gradient of 30°C/km. Thus a coupling of relatively low sedimentation rates with relatively low (continental average) heat flow would lead to relatively long times before a sediment heated up sufficiently to exceed the activation energy of many geological processes. Conversely, high sedimentation rates coupled with high heat flow rates such as those obtained in some rift valleys (when the sediments catch up on their heating from the heat flow lag caused by low thermal conductivity) would lead to rapid movement of the sediment into the thermal region of rapid chemical changes.

The complete formulation of the problem would include the continuous change in kinetics as the sediment heats up, with a calculation of the rapidity of sediment heating under a given thermal gradient and sedimentation rate.

SOME KINETIC DIAGENETIC PROBLEMS

A number of diagenetic transformations associated with deep burial have been investigated using some of these ideas. Perhaps the first modern attempt was Weyl's (1959) proposal for pressure solution of quartz grains as a function of overburden pressure, which led to a time-pressure diagram for the decrease in porosity caused by pressure solution. Pressure works exactly the same way as temperature for these purposes except that the lithostatic gradient is relatively invariant from place to place, dependent only on the average rock weight. The exception to this is in overpressured regions where hydrostatic pressures in pore spaces approach the lithostatic pressure. No exact determination of the activation energy for the pressure effect on the solubility of quartz is available, but we do know the activation energy for the dissolution of quartz in a hydrostatic field as a minimum (Stöber, 1967). The clay effect on pressure solution was visualized by Weyl as related to the number of channels offered for diffusion by the clay. As diffusion is itself temperature-dependent and can be analyzed as a kinetic process, an additional term for the increase in diffusion rate is required. The various processes are so interrelated that studies of one effect in isolation is nearly impossible.

A favorite mechanism used by geologists to produce silica-rich waters that would precipitate silica cement in sandstones is the expulsion of silica-rich formation waters from underlying or overlying shales (Johnson, 1920; Siever, 1957; Towe, 1962). The conversion of a silica-rich smectite or similar clay mineral to a relatively silica-poor illite or chlorite is a typical reaction that would liberate significant quantities of dissolved silica to the surrounding solutions; these solutions would then be expelled by compaction of the muddy sediment. A close inspection reveals how this can be treated as a kinetic problem. Hower and colleagues (1976) have evidence that for some Gulf Coast sediments depths of well over 5 km are required for the conversion of significant amounts of smectite to illite. Given this depth and the geothermal gradient for the Gulf Coast we can calculate backwards to an activation energy. At the same time, we would have to calculate the compaction of the shales as a kinetic process, using the classic data of Athy (1930) and Hedberg (1926) and a modern review by Meade (1966). We can thereby deduce the decrease in porosity and water content as a function of time-pressure, a relation qualitatively much like that for pressure solution but probably largely independent of temperature, at least at lower temperatures. For most shales buried in continental, low geothermal-gradient environments, a negligible amount of water of compaction is incrementally squeezed out at the great depths corresponding to smectite-illite transformations. Interlayer water from the smectite would be the only effective source of water for transporting dissolved silica and much of this interlayer water might also have been expelled at an earlier stage. Only with much more accurate data can we evaluate the plausibility of this mechanism.

I suspect that, in fact, the source of silica-rich waters lies in chemical dissolution reactions that take place during early diagenesis, when much water is still left to be squeezed out. Such reactions might be those related to dissolution of tests of diatoms and other silica-producing organisms that have been present in large quantities in many muddy sediments (at least since the early Cretaceous) or to sorption-desorption reactions of clay minerals and zeolites (Siever and Woodford, 1973). These two processes may in fact be related.

Reversible silica-carbonate cementation of sandstones may be traceable to hydrologic regime changes related to local unconformities produced during the sedimentation of a long-term platform sequence (Walker, 1962). Some of these rocks show early emplacement of secondary silica, replacement of this silica by carbonate, and a final episode of carbonate dissolution or decementation. We may hypothesize that the silica cementation occurred while the rock was undergoing early diagenesis. The first carbonate replacement may have come from meteoric water inflow while the sediment pile was exposed to erosion during the production of an unconformity. If the meteoric water traversed a carbonate sequence it would become saturated with respect to carbonate. As it moved deeper in the section in response to a hydraulic head it would heat up along the prevailing geothermal gradient. As a result of its decreased solubility at higher temperatures, carbonate might be precipitated at the same time that the solution (relatively undersaturated with respect to silica) dissolved some of the early quartz cement. The final episode, the disappearance of carbonate cement, we know occurs in some near-surface formations as a result of influx of meteoric water (Sedimentation Seminar, 1969, for example). Subsurface karstification is another example of carbonate dissolution from limestone formations shallowly buried beneath an erosion surface. We can only suggest the outline of these kinds of events, for we would need to know the appropriate solubilities as functions of temperature and ionic strength, the kinetics of dissolution of both carbonate and silica, and groundwater flow rates.

Clay mineral transformations are clearly reactions of much interest. A great many different compositional and structural phases of unstable clay minerals are found in most modern sediments. The kinetics of changes to stable species would give a family of curves in which each species would move through a series of increasingly more stable states, the rates of change depending, as before, on temperature. If these transformations are also a function of solution composition, particularly with respect to silica and Group I and II elements, the problem becomes more complex. We need to invent far more sensitive and quantitative analyses of the relative amounts of clay species to solve this problem in detail.

The chemical evolution of subsurface formation waters may be treated in a manner similar to that used for other diagenetic transformations. A single term-rate expression would not suffice; a combination of several would be needed. Thus the overall change in Ca/Mg ratio of a formation water as it evolves would be a function of the rates of the following reactions: (1) conversion of calcite to dolomite; (2) conversion of smectite to chlorite or illite; (3) precipitation of calcite; (4) precipitation of dolomite; (5) precipitation of anhydrite-gypsum; (6) dissolution of plagioclase feldspar; and (7) dissolution of diopside and other Ca, Mg pyroxenes, and amphiboles. Although the last two reactions are probably not of great importance in continental platform sequences, they may be significant in volcanogenic deposits of subduction zones. One may hope that the kinetics of these reactions would be sufficiently similar that they could be averaged to give an overall kinetic expression for the evolution of the formation water.

Analysis of burial history in relation to temperature has become common for study of the diagenic conversion of organic matter to oil and gas and their migration to reservoir rocks (Lopatin, 1976; Tissot and Welte, 1978; Hunt, 1979). One of the important coal macerals, vitrinite, has been extensively studied for increase in reflectance as a function of temperature increase, a relation that was implied by Hilt's "law" of increase in coal rank with depth (Stutzer and Noé, 1940, p. 292). The rate at which vitrinite reflectance increases is by no means a simple function of temperature. Although the process seems not to be pressure dependent to any significant degree, there may be some effect of the surrounding organic and inorganic constituents of the rock. There is also the possibility that the original derivation of the vitrinite from various mixtures of plant components may give slightly different compositions and structures that affect its rate of reflectance increase.

Many more diagenetic transformations can be analyzed in this way: the growth of zeolites and authigenic feldspars, phase transformations of the titanium oxides from rutile to brookite and anatase, and the rates of dissolution of unstable heavy minerals are all susceptible to this kind of analysis.

The ultimate goal of this kind of analysis is to calibrate our deductive paleogeotherms by a variety of diagenetic temperature scales. This would allow us not only to decipher the diagenetic history of the sediment but also to deduce fossil heat flows. If we can generate paleogeotherms from diagenetic markers, we can then calculate backwards to paleo-heat flow in the same way that we estimate the forward calculation. Ultimately, then, the kinetic analysis of diagenetic sedimentary transformations is a way of determining the large-scale tectonics of the Earth; such analysis is a companion to the use of more classical methods of sedimentary petrology to determine provenance and thereby sedimentary tectonics and paleogeography.

REFERENCES

Athy, L. F., 1930, Density, porosity and compaction of sedimentary rocks: Bulletin, American Association of Petroleum Geologists, v. 14, p. 1-24.

Birch, F., R. F. Roy, and E. R. Decker, 1968, Heat flow and thermal history in New England and New York: Studies of Appalachian Geology: Northern and Maritimes, J. B. Wiley and Sons, New York, p. 437-451.

Bowen, N. L., 1915, The later stages in the evolution of igneous rocks: Journal of Geology, v. 23, Supplement to no. 8, p. 1-91.

Clarke, F. W., 1924, Data of geochemistry: U.S. Geological Survey Bulletin 770.

Eberl, D. and Hower, J., 1976, Kinetics of illite formation: Geological Society of America Bulletin, v. 87, p. 1326-1330.

Garrels, R. M., and F. T. Mackenzie, 1971, Evolution of sedimentary rocks: W. W. Norton, New York, 397 p.

Hedberg, H D., 1926, The effect of gravitational compaction on the structure of the sedimentary rocks: Bulletin, American Association of Petroleum Geologists, v. 10, p. 1035-1072.

Hower, J., E. Eslinger, M. E. Hower, and E. A. Perry, 1976, Mechanism of burial metamorphism of argillaceous sediments: 1. Mineralogical and chemical evidence: Geological Society of America Bulletin, v. 87, p. 725-737.

Hunt, J. M., 1979, Petroleum geochemistry and geology: W. H. Freeman and Co., San Francisco, 617 p.

Johnson, R. H , 1920, The cementation process in sandstone: Bulletin, American Association of Petroleum Geologists, v. 4, p. 33-35.

Judson, S., and D. F. Ritter, 1964, Rates of regional denudation in the United States: Journal of Geophysical Research, v. 69, p. 3395-3401.

Lopatin, N. V., 1976, Historico-genetic analysis of petroleum generation: application of a model of uniform continuous subsidence of the oil-source bed: Akademia Nauk S.S.R., Izvestia, Seria Geologicheskaya, no. 8, p. 93-101.

Meade, R. H., 1966, Factors influencing the early stages of the compaction of clays and sands—a review: Journal of Sedimentary Petrology, v. 36, p. 1085-1101.

Pauling, L., 1930, The structure of micas and related minerals: Proceedings of National Academy of Science, U.S., v. 16, p. 123-129.

Roy, R. F., E. R. Decker, D. D. Blackwell, and F. Birch, 1969, Heat flow in the United States: Journal of Geophysical Research, v. 73, p. 5207-5221.

Sedimentation Seminar, 1969, Bethel Sandstone (Mississippian of western Kentucky and south-central Indiana, a submarine channel fill: Report of Investigations 11, Kentucky Geological Survey, 24 p.

Siever, R., 1951, Mississippian-Pennsylvanian unconformity in southern Illinois: Bulletin, American Association of Petroleum Geologists, v. 35, p. 542-581.

Siever, R., 1957, The silica budget in the sedimentary cycle: American Mineralogist, v. 42, p. 821-841.

Siever, R., and N. Woodford, 1973, Sorption of silica by clay minerals: Geochimica et Cosmochimica Acta, v. 37, p. 1851-1880.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America, Geological Society of America Bulletin, v. 74, p. 93-114.

Stöber, W., 1967, Formation of silicic acid in aqueous suspensions of different silica modification: *in* W. Stumm [ed.], Equilibrium concepts in natural water systems: American Chemical Society, Advances in Chemistry 67, p. 161-182.

Stutzer, O., and A. C. Noé, 1940, Geology of coal: University of Chicago Press, Chicago, 461 p.

Tissot, B. P., and D. H. Welte, 1978, Petroleum formation and occurrence: Heidelberg, Springer-Verlag, 538 p.

Towe, K. M., 1962, Clay mineral diagenesis as a possible source of silica cement in sedimentary rocks: Journal of Sedimentary Petrology, v. 32, p. 26-28.

Van't Hoff, J. H., 1905, Zur Bildung der Ozeanischen Salzablagerungen, Braunschweig.

Von Bubnoff, S., 1954, Fundamentals of Geology, 34d ed., translated by W. T. Harry, 1963: Oliver and Lloyd, Ltd., Edinburgh, 287 p.

Walker, T R., 1962, Reversible nature of chert-carbonate replacement in sedimentary rocks: Geological Society of America Bulletin, v. 73. p. 237-242.

Weyl, P. K., 1959, Pressure solution and the force of crystallization—a phenomenological theory: Journal of Geophysical Research, v. 64, p. 2001-2025.

Biominerals, Tracers of Evolution, Paleoecology and Impact of Life on the Biosphere

Heinz A. Lowenstam

A vast array of recent organisms are now known to precipitate minerals. The elucidation of the Phanerozoic history of numerous protists and many animal groups owes its documentation to phosphate, carbonate, and silica mineral-bearing skeletal remains. The existence of sulfate-reducing bacteria as old as 2 eons and possibly 3.2 eons B.P. has been established by means of $^{34}S/^{32}S$ ratios from sulfide minerals found in sedimentary Precambrian rocks.

Studies of crystal habits, trace element constituents, and stable isotopes in skeletal carbonate minerals, phosphates, and silica have shown that they embody genetic and environmental information. Biologic mass fixation of silica in the sea has resulted in undersaturation of ocean water and suppression of opal precipitation by inorganic processes. Mass fixation of carbonate minerals by planktonic protozoa has reduced inorganic precipitation of these minerals in the open sea to insignificant proportions. The carbonate sink of "coral reefs" in shallow seas has materially modified physical processes.

As to the geologic past, the data show that: (1) skeletal carbonate and phosphate mineralization mediated by organic matrices in eucaryotes was initiated rather late in the history of life—only about 6×10^8 yrs B.P.; (2) carbonate mineralization tended to replace that of phosphate in the course of the organisms skeletal evolution; (3) suppression of inorganic silica precipitation through skeletal fixation of their minerals, and progressive reduction of inorganic carbonate precipitation via expansion of skeletal fixation by eucaryotes is documented in the course of their evolution over the last 6×10^8 yrs B.P. Biologically "induced" mineral formation, as found in many extant procaryotes, was initiated prior to that of the "organic matrix mediated" process, at least as early as 2×10^9 yrs B.P.; but documentation is limited to sulfate-reducing bacteria and some questionable manganese oxide depositing bacteria. It is not known, however, whether intracellular membrane "mediated" mineralization by bacteria, which takes place today in a few groups, had already begun in Precambrian time.

In the last two decades our knowledge of the diversity of minerals formed by organisms has increased beyond expectation. Since I integrated, one year ago, contemporary knowledge of this subject (1981), numerous additional biominerals have become known. Of particular interest are a number of minerals that cannot be formed by inorganic processes anywhere in the biosphere. An example is magnetite, now known to be synthesized by bacteria and a variety of animal groups. Other newly discovered biomineralization products cannot be formed by inorganic processes in those environments in which they are synthesized by organisms. Another aspect worth mentioning is the difference in crystal habits between biologic and inorganic mineral precipitates. Striking examples are occurrences of needle-shaped fluorite crystals and teardrop-shaped magnetite crystals, which are formed biologically.

The data now at hand indicate that some of the minerals formed by organisms today can be distinguished from their inorganic counterparts by their crystal habits, their trace element chemistry, and their isotopic composition in that (1) they usually are non-equilibrium precipitates and (2) some of them can be solely be synthesized by life under biospheric conditions. The minerals further embody information on ecologic parameters and some can be further shown to have progressively modified chemical and physical processes in the biosphere. Thus the concept of the evolution of mineral-forming processes by life is emerging as a significant contribution to the evolution of life, its environmental framework, and its effects on the biosphere. Moreover, as the data base is extended to a wide range of biologically formed minerals, criteria should emerge to define the principles for the search of extraterrestrial life in non-anthropomorphic terms!

As of now, most of the known biominerals still lack physical and biochemical characterization and, most importantly, our knowledge of what biologically formed minerals encompass in toto is still very incomplete. This is even true for animals and protists—mineral-bearing sites are discovered almost daily. What is even more critical is that we know so little about the minerals and their physical and chemical properties formed by plants, fungi, and bacteria. Data to fill these gaps are decidedly needed to establish in the fossil record (1) the beginning of mineral forming processes by life in the Precambrian; (2) the history of its proliferation; and (3) the inception, mode, and spread of the more "sophisticated" biomineralization processes mediated by organic matrices.

REFERENCE

Lowenstam, H.A., 1981, Minerals formed by organisms: Science, v. 211, p. 1126-1131.

Perspectives in Engineering Geology

Gordon W. Prescott

Engineering geology can be defined as the application of geology to engineering practice. The engineering geologist must be involved in the planning, design, and construction of major projects. It is apparent, from a review of the past history of the profession, that geologists have often been limited in their contributions to engineering. Articles by both geologists and engineers emphasize that an engineering geologist must be a highly qualified geologist with sufficient education and training in engineering to appreciate the problems of the engineer. The curriculum for engineering geology should equip the graduate with a strong academic background to meet the needs of the increased complexity of engineering projects. Experience will add that important ingredient of judgement.

Engineering geologists have a wide range of employment opportunities with consulting firms, major construction contractors, universities, mining companies, petroleum companies, and government agencies. The increased interest in underground space will require the use of engineering geologists in the many problems of design and construction. The engineering geologist could be involved with design and development of special excavating equipment as well as design and installation of necessary support features. It is anticipated that engineering geology will play an increasing role in the disposal and control of liquid and solid waste. It naturally follows that many geologists will be involved with many phases of the energy problem. Finally, it is expected that engineering geologists will continue with increased contributions in the technical areas in which they are now active, such as foundations for all types of structures, highways, and construction materials.

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Radioactive Waste Storage in Mined Caverns in Crystalline Rock

Paul A. Witherspoon

Although several ideas for isolating radioactive wastes have been proposed, the idea of using underground excavations for deep geological disposal is receiving increasing attention (U.S. Department of Energy, 1979). Designing an underground repository to isolate radioactive wastes from the biosphere constitutes a unique problem for scientists and engineers. Three main types of rocks are now being investigated: granites, evaporites, and clays.

The need for a basic understanding of rock behavior under the special conditions that will arise in an underground repository cannot be overstated. These conditions include the presence of heat-generating, radioactive wastes, and the complex processes of waste migration (deMarsily et al., 1977) in slowly moving groundwaters. In addition to laboratory and theoretical research, field investigations will be needed in order to understand the magnitude and scope of such problems and to expedite development of the technology necessary to resolve this problem.

Since 1977, Lawrence Berkeley Laboratory (LBL) has been involved in a comprehensive series of field tests in an abandoned iron-ore mine at Stripa, Sweden, about 150 km west of Stockholm. A suite of experimental rooms has been excavated in an extensive mass of granite (quartz monzonite) adjacent to an iron-ore body (high-grade metavolcanics) at a depth of 338 m below surface (fig. 1). This work is part of a Swedish-American cooperative program of investigations on radioactive waste disposal (Witherspoon and Degerman, 1978). LBL's counterpart in Sweden is the Nuclear Fuel Safety Program (KBS). The LBL activities are under the direction of Battelle Memorial Institute, Office of Nuclear Waste Isolation, and are funded by the U.S. Department of Energy. The KBS activities are under the direction of the Swedish Nuclear Fuel Supply Company (SKBF).

A coordinated series of tests has been carried out on two key problems in using granite for underground waste isolation. The first is that of predicting the thermo-mechanical behavior of a heterogeneous and discontinuous rock mass. To do this, a series of electric heater tests is being used to simulate the energy released by the decay of nuclear waste. The second problem involves predicting the movement of groundwater that can transport radionuclides through fractures in the granite. A combination of borehole measurements and geochemical studies forms the basis of these hydrogeology tests. A new method of measuring the permeability of very large rock masses using a length of drift is also being developed. Results will be compared with those from conventional methods.

THERMO-MECHANICAL INVESTIGATIONS

Importance of thermo-mechanical effects

A geologic site identified as suitable for a radioactive waste repository will be subjected to two principal perturbations if used for that purpose. First, it will be necessary to sink shafts to the depths of the proposed repository and then make the excavations for the repository at this depth. With reliance on careful design and on the wealth of related experience in civil and mining engineering, it should be practical to accomplish this without significantly impairing the ability of the site to isolate wastes from the biosphere.

Second, as a result of the radioactive decay of the wastes, the subsurface media in the vicinity of the repository will undergo a thermal pulse. The geologic system will be heated to a maximum temperature at the depth of the repository within a century, depending upon the waste form, and subsequently will cool over a much longer period of time. To ensure that the repository will provide adequate isolation of nuclear wastes from the biosphere over these long periods of time, it is necessary to assess the effects of this thermal pulse. In general, this pulse will increase compressive stresses and water pressures in the heated zone of the rock mass around the repository and induce corresponding tensile stresses outside this zone.

An estimate of the magnitude of these effects can be calculated readily using a linear theory of thermoelasticity. First, temperature fields can be calculated as a function of time using conduction of heat. From the temperature field at any time, the thermally induced displacements and stresses can be calculated using the coefficient of thermal expansion, Poisson's ratio, and Young's modulus. Values for these coefficients as determined from laboratory measurements on small specimens of rock are available in handbooks (Clark, 1966). However, it is well known that the behavior of a large rock mass is seldom the same as that of small specimens of rock (Hoek, 1979). Accordingly, it is important to develop and verify models for predicting the thermo-mechanical response of an underground repository for nuclear wastes. To ensure that this is done in a meaningful and realistic way, relevant experiments must be done where rock stress, groundwater pressure, and other conditions are typical of those likely to be encountered at the depth of a repository.

The availability of a site at depth in water-saturated granitic rock at Stripa provided a unique opportunity for conducting three thermo-mechanical experiments under conditions encountered at representative depths: two full-scale heater tests in which the near-field response of the rock mass was studied under simulated short-term and long-term conditions, and an intermediate-term time-scaled experiment covering the major part of the heating-up period of the thermal pulse and interaction between adjacent heaters. By instrumenting these experiments to obtain comprehensive measurements of temperature fields, displacements, and stresses as functions of time and space, we have identified the data needed to predict the thermo-mechanical response of a repository. These results have shown that it is necessary to consider the geologic structure of the rock mass and the functional dependence of the coefficients of thermal expansion, Poisson's ratio, and

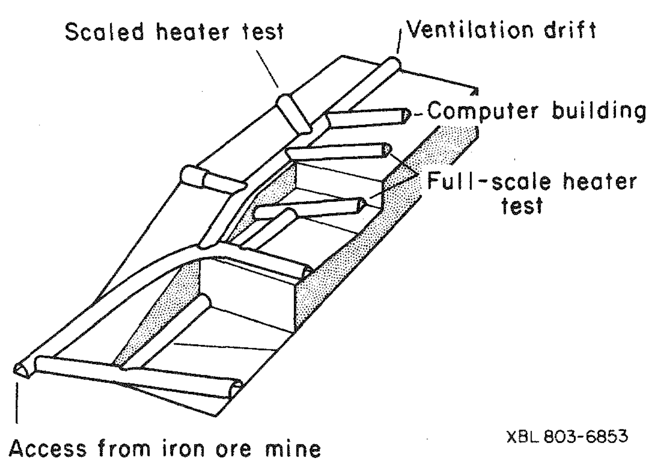

Figure 1. Location of experimental rooms excavated in granite (quartz monzonite) rock mass at Stripa, Sweden.

Young's modulus if predictions are to provide an accurate description of the response of a rock mass to the heat produced by the decay of radioactive wastes.

Full-scale heater experiments

The energy output from U.S. canisters containing high-level reprocessed radioactive waste could be as much as 5 kW per canister. This output drops significantly in the first few years after emplacement, but an energy release of this magnitude, when coupled to the rock mass, can produce temperature increases of several hundred degrees. It is therefore important that definitive field experience be gained concerning the thermal effects on the rock mass immediately adjacent to the canister.

Full-scale heater experiments have been designed to permit the investigation of the short-term effects of heat in granite. Electric heaters housed in a canister 3 m in length and 0.3 m in diameter have been used to simulate the power output of radioactive waste. Two such canisters, each containing four heating elements, have been positioned in 406-mm vertical holes drilled to a depth of 5.5 m in the floor of the full-scale heater drift (fig. 2). Details of the design and construction of these electrical heaters have been reported by Burleigh et al. (1979).

Figure 2 shows a cutaway drawing of the two full-scale heaters and some of the horizontal boreholes that have been instrumented from an adjacent lower level drift. The two heater holes are spaced 22 m apart so that the canisters have remained thermally isolated from each other for the duration of the experiment. This has enabled two separate experiments to be conducted in parallel. Power output for the canister-heater on the left side of figure 2 has been adjusted to 5 kW in order to represent a typical power level of reprocessed fuel after about 3 years. The other canister-heater, on the right, has been set at a power output of 3.6 kW to represent similar waste products approximately 5 years old at the time of emplacement.

The response of the mass adjacent to these two canisters has been monitored extensively. Rock displacements have been measured using extensometers, and thermally induced stresses have been determined from strain measurements using U.S. Bureau of Mines borehole deformation gages and IRAD (Creare) vibrating-wire gages. Each of these instruments has a thermocouple associated with it, and additional thermocouples have been positioned around each heater to obtain the temperature field in three dimensions.

It is known that, because of the low thermal conductivity of rock, temperatures, and therefore temperature gradients, within the rock in the immediate vicinity of the heaters will approach maximum values in a few months. Consequently, within a relatively short period, this test program has been able to provide important data for two values of power output in a typical hard crystalline rock.

Figure 3 compares predicted versus measured temperatures for the 3.6 kW heater in granite as a function of time. The length of the heating period was 398 days; the total length of this experiment was about 1½ years. Temperatures were calculated before the experiment started on the basis of a semianalytic solution, assuming intact rock and using laboratory measurements of rock properties (Chan, Cook, and Tasang, 1978). The laboratory

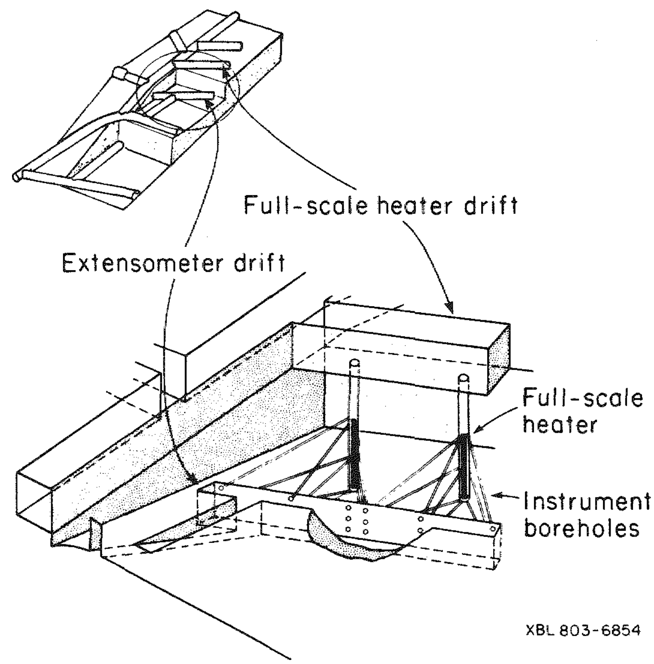

Figure 2. Arrangement of electric heaters in full-scale experiment room in granite showing location of instrument boreholes from adjacent extensometer drift.

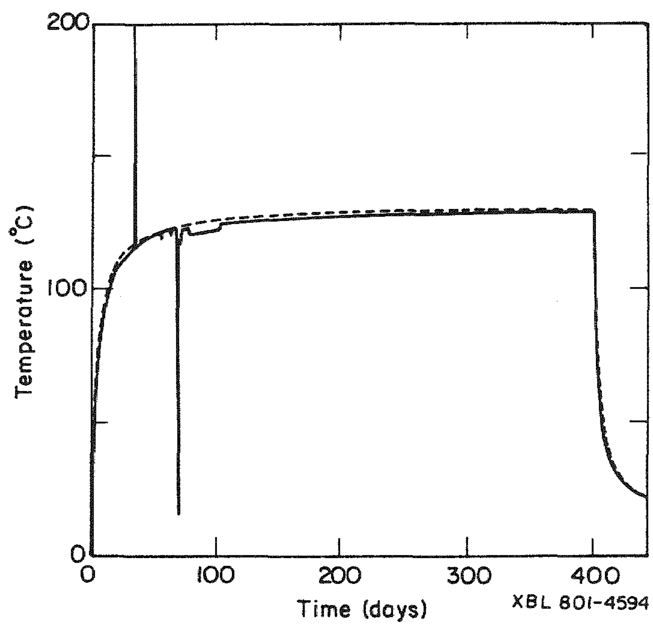

Figure 3. Predicted (dashed) and measured (solid) temperatures plotted as a function of time at a radius of 0.4 m from 3.6 kW heater along heater midplane. Variations in measured signals at early time caused by corrosion of stainless steel thermocouple sheath.

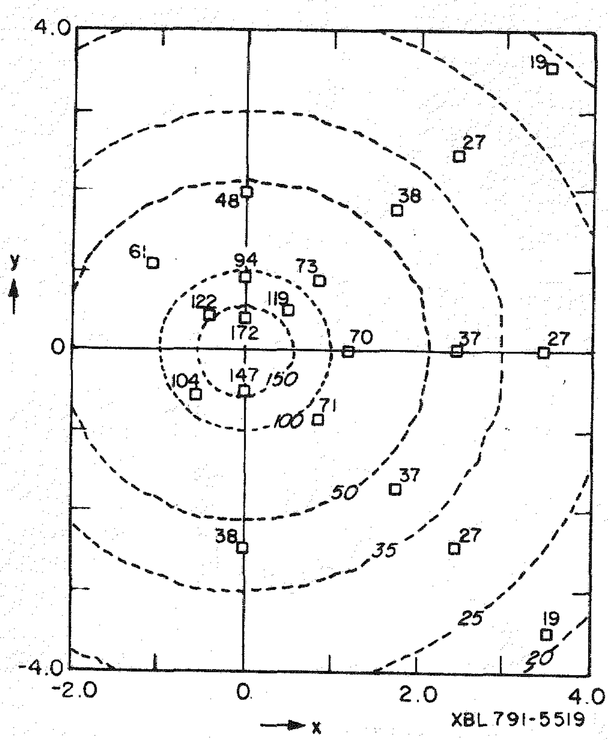

Figure 4. Predicted (dashed) isotherms and measured temperatures in a horizontal plane through the center of the 5.0 kW full-scale heater 190 days after starting experiment. Distances are in meters and temperatures are in degrees centigrade.

data were as follows: density, 2600 kg/m^3; specific heat, 837 J/(kg$^\circ$C); thermal conductivity, 3.2 W/(m$^\circ$C); and thermal diffusivity, 1.47×10^{-6} m^2/sec.

Figure 4 shows predicted isotherms and the spatial distribution of temperatures measured 190 days after heater turn-on on the midplane passing through the center of the 5 kW heater. As will be described later, this granite rock mass is extensively fractured and jointed. Careful examination of figure 4 reveals that, despite the presence of these discontinuities and the water that fills them, there is little, if any, effect on the thermal field. Note the excellent agreement between predicted and measured values in all directions away from the axis of the heater. This is typical of the results that have been obtained throughout both full-scale heater experiments.

Time-scaled heater experiment

One of the more important factors in repository design is the effect of long-term thermal loading on the rock mass. A time-scaled experiment was designed to permit investigation of this long-term effect through the use of a scaled array of heaters. Calculations show that thermal interactions begin to occur between full-scale canisters in an actual repository within a period of 3 years if the canister spacing is 10 m. Thereafter, the effect of individual canisters diminishes and, in a period of 10 to 100 years, heat should flow upward and downward from a plane containing the canisters so that the 100°C isotherm will have migrated distances of the order of 50 m from the plane of the repository. The resulting thermal expansion of the roughly oblique spheroid of rock with these temperatures will be of the order of 10^{-3}, which is significant.

It is impractical to check these thermo-mechanical effects in the critical period from 10 to 100 years using a full-scale heater experiment. Fortunately, the laws of heat conduction allow for compressing the time-scale. The dimensionless quantity used in solutions of heat conduction calculations is the ratio of the linear distance to the square root of the product of time and the thermal diffusivity of the material. Therefore, in the time-scaled experiment at Stripa the times have been compressed in the ratio of 1:10—that is, each year of data from the time-scaled experiments is equivalent to 10 years of data from the full-scale setup. In order to accomplish this, the linear scale must be reduced to $1/\sqrt{10} \cong 0.32$ of the full scale, which still allows for realistic dimensions in the field. Measurements of rock temperatures and deformations have also been made in the time-scaled experiment so that these data can be compared with the full-scale results and with theoretical predictions of a repository over a period of several decades.

An array of eight heaters, spaced 7 m apart along the axis of the time-scaled heater room and 3 m apart in the other direction, has been used in this investigation (fig. 5). Appropriate scaling of the power output of these heaters shows that 1 kW is representative of an initial power output of 3.12 kW; this power level has been decreased during these tests to simulate the decay in energy output of radioactive waste.

The configuration of the heaters in the array shown in figure 5 was chosen to establish a three-dimensional pattern of thermal interaction between heaters and surrounding rock, such as may be found in a practical repository. We

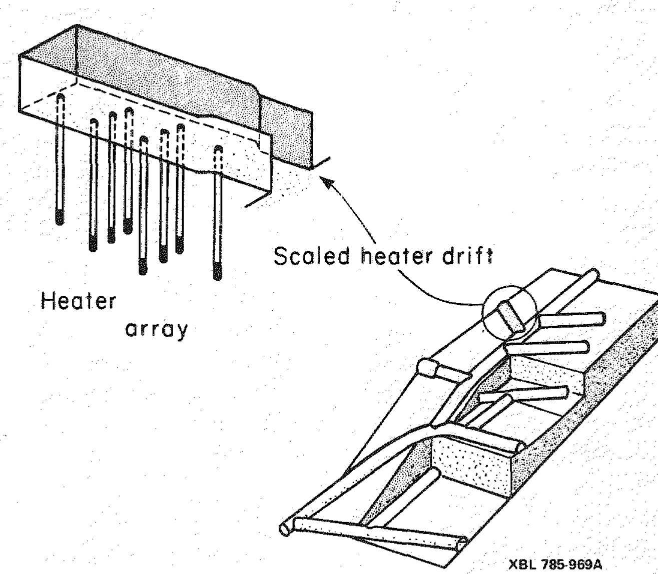

Figure 5. Arrangement of 1.0 kW electric heaters in time-scaled heater experiment. Heaters are 1.0 m long and have been placed so that the heater midplane is 10.5 m below the floor.

calculated that this interaction would occur within a few months of the start of this experiment. Figure 6 shows how this interaction has taken place. Predicted isotherms are compared with measured temperatures in a horizontal plane passing through the centers of all eight heaters 190 days after the experiment began. As in the case of the full-scale heater experiment, there is remarkably good agreement between measured and predicted rock temperatures.

Rock decrepitation

High temperatures were expected to occur in the rock immediately surrounding the electric heaters, resulting in large thermal compressive stresses in directions parallel to the axis and tangential to the surface of the borehole containing the canister (Cook, 1978). If these stresses exceed the uniaxial compressive strength of the rock, failure of the borehole wall will result. Although such failure is not likely to damage a well-designed canister, it may make retrieval of the canister a difficult operation. Thus the strength of the rock is likely to be the factor that limits the canister power output and therefore the minimum age before burial.

Theory predicts that the stresses at the borehole wall asymptotically approach a maximum value about 30 days after the start of the experiment; in the case of the 5 kW heater, this maximum stress is tangential and was calculated to be about 215 MPa at the heater midplane (Chan and Cook, 1980). This value is in the same range as the mean uniaxial compressive strength of the rock, which, by laboratory measurement, was found to be 208 MPa at room temperature; there are only small variations from this mean value at elevated temperatures (Swan, 1978). If the borehole were subject only to mechanical loading, failure would be expected to occur when the induced maximum compressive stress exceeded the uniaxial strength of the rock (Jaeger and Cook, 1979).

A special experiment conducted with the 5.0 kW full-scale heater produced very definite evidence of borehole decrepitation. During installation, a series of eight 1.0 kW electric heaters were equally spaced around a circle with a radius of 0.9 m from the axis of the 5.0 kW full-scale heater. These peripheral heaters were switched on at Day 204 in order to raise the ambient temperature of the rock mass by approximately 100°C in the vicinity of the full-scale heater. This also had the effect of increasing the compressive stresses on the surface of the heater hole.

Observations using a borescope revealed that serious deterioration of the 5.0 kW heater borehole occurred within a few days after the turn-on of the peripheral heaters. Initially this spalling was concentrated about the heater midplane and was characterized by the formation of rock chips 20-30 mm in diameter and 2-3 mm thick. Step increases in canister skin temperatures of 10° to 30°C evidently reflect the increased impedance to heat flow from the heater to the borehole wall as a result of the accumulation of rock chips in the annulus. Borehole decrepitation continued to increase both in extent of damage along the length of the borehole and in the size of rock chips. Much larger rock chips (up to 150 mm long) were observed, and eventually the annulus between the canister and the borehole became completely blocked with rock fragments, resulting in an increase in the skin temperature of the canister, for the same power output, of some 100°C. Calculated temperatures on the rock wall were in the range of 300° to 350°C during this period.

These results indicate that two distinct mechanisms are involved in this spalling phenomenon. First, the time-dependent behavior obviously is not explained by thermoelastic theory. Cook (1978) has suggested other mechanisms for thermal deterioration of rock, including dehydration of clay minerals and differential thermal expansion of individual crystals within the rock. At present, this behavior is not well understood and further investigation is required. Second, the gross failure appears to be a stress related event precipitated by a buildup in compressive stresses when rock temperatures exceeded 300°C. Further work will be necessary to better define the stress conditions beyond which rock decrepitation will occur.

Rock displacements and stresses

The thermocouple readings show that, in general, the rock temperatures are symmetrical around the heater midplanes and heater axes (fig. 4), and thus the heat flow is little affected by discontinuities in the rock mass (Hood, 1980). Furthermore, analysis demonstrates that the dominant mode of heat transfer is by conduction; for this reason the temperature field can be predicted by using relatively simple semianalytical methods (Chan, Cook, and Tsang, 1978).

Unlike the temperature results, the rock displacement findings are not consistent with values predicted before heater turn-on using linear thermoelastic theory (Chan and Cook, 1980). Six vertically oriented, multiple-rod extensometers, each with four anchor points, have been mounted in boreholes adjacent to each full-scale heater at different radial distances. In addition, nine horizontally mounted extensometers of similar design extend into the near

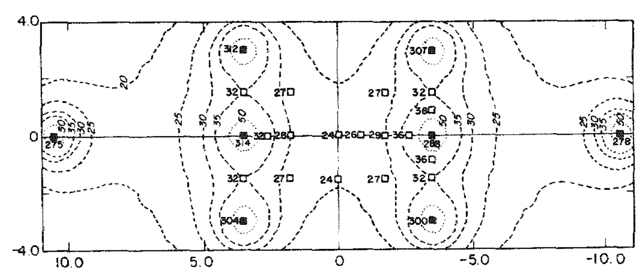

Figure 6. Predicted (dashed) isotherms and measured temperatures in a horizontal plane through the center of the time-scaled heaters 190 days after starting the experiment. Distances are in meters and temperatures are in degrees centigrade.

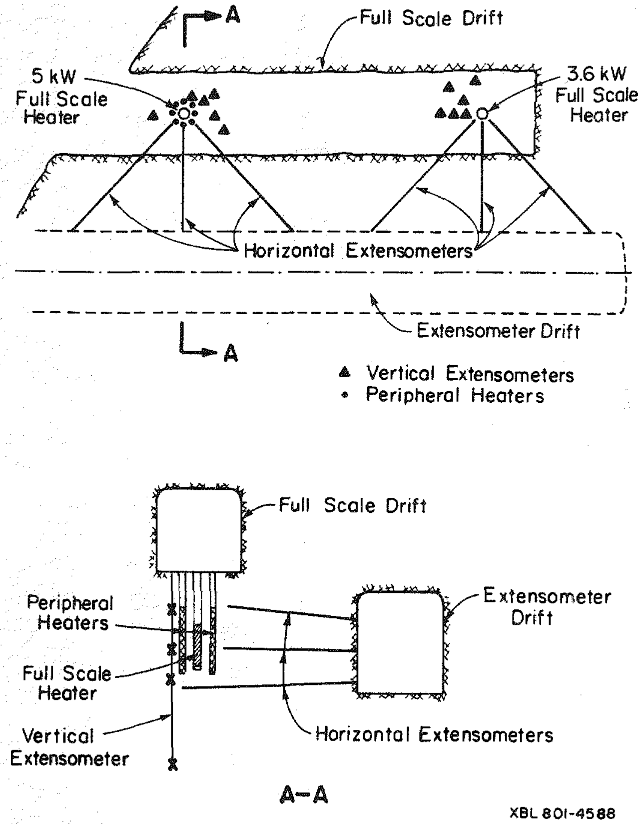

Figure 7. Arrangement of full-scale heaters, locations of extensometers in both vertical and horizontal boreholes, and locations of peripheral heaters surrounding 5.0 kW full-scale heater.

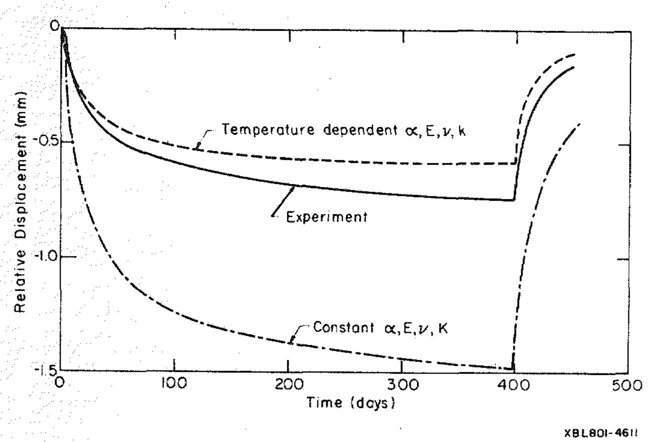

Figure 8. Measured rock displacements in a vertical direction between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1.0 m from the 3.6 kW full-scale heater. Also included are displacements predicted using constant as well as temperature dependent properties.

vicinity of each heater through boreholes (fig. 7). Details of this and other instrumentation are given by Kurfurst, Hugo-Persson, and Rudolph (1978).

The extensometer readings have yielded some puzzling results that reveal the complex problem of attempting to predict thermo-mechanical behavior of a discontinuous rock mass. As a first approach, the limiting case of a homogeneous intact rock was assumed and displacements were predicted before heater turn-on using the following constant material properties: thermal expansion, $\alpha = 11.1 \times 10^{-6}/^\circ C$; Young's modulus, $E = 51.3$ GPa; Poisson's ratio, $\nu = 0.23$; and thermal conductivity, $\kappa = 3.2\ W/m^\circ C$. These values are representative of average results over a temperature range of 100°-150°C.

The rock displacements show two types of behavior. During the first few weeks, the measured displacements were very much less than predicted by the theory of linear thermoelasticity. After this initial period, the measured displacements increased uniformly but at a more or less constant percentage of the predicted values. For many of the extensometers, the ratio of measured to predicted displacements during this second phase has been 0.4 (Hood, 1980).

An example of measured and predicted displacements for a vertical extensometer at a radial distance of 1.0 m from the 3.6 kW heater is shown in figure 8. Note that the experimental results show far less rock movement than one would predict from the theory of linear thermoelasticity for intact rock (Chan and Cook 1980). The temperature dependence of the material properties of Stripa granite is now being studied (Chan, Hood, and Board, 1980). On the basis of a limited number of laboratory tests on intact samples, a second set of displacements has been predicted using temperature dependent values of α, E, ν, and κ. Results are shown in figure 8. Note that although much better agreement with field data has been obtained, the predicted vertical displacements are now less than the measured results. This work is continuing, especially the study of the thermo-mechanical behavior of Stripa granite samples obtained from the careful core drilling of all boreholes at the test site.

The nonlinear deformation behavior of the rock observed shortly after the activation of the heaters deserves special attention. Some of this nonlinear rock behavior may be a result of the effects of pre-existing discontinuities. This thesis is supported by independent experimental evidence from cross-hole ultrasonic measurements in the rock adjacent to the 3.6 kW full-scale heater. Figure 9 shows some results from ultrasonic measurements in which a marked increase in wave velocities was observed during the early time period when rock displacements were exhibiting a nonlinear behavior (Hood, Carlsson, and Nelson, 1980). The increase in both S- and P-wave velocities probably indicates closure of fractures, especially in the rock between the transducer and the receiver.

Changes in stress in the rock mass computed from strain measurements using vibrating-wire Creare gauges show a trend somewhat similar to that of the extensometer results. The experimental values of stress have been consistently about one-half or less than one-half the values predicted using linear thermoelasticity and the constant values for thermo-mechanical properties cited above. Here too, a review of the material properties and their temperature dependence is needed. There is some indication that the predicted stresses are still significantly higher than the measured values even after the temperature dependence of rock properties has been taken into account (Chan, Hood, and Board, 1980). Nevertheless, the stress results support the conclusion from extensometer measurements that the induced thermo-mechanical effects in the rock mass (away from the decrepitation effects at the heater hole) are signifcantly less than predicted by available theory for intact rock.

Fracture mapping

The above results clearly indicate that the granite rock mass at Stripa, when subjected to a thermal pulse, does not behave in a linear isotropic manner. The reason, of course, is that the system discontinuities play a major role in controlling thermo-mechanical behavior. Study of the behavior of the rock mass in situ raises a difficult question: at what level of detail must one investigate the geometry of the fractures? A comprehensive program of fracture mapping has therefore been carried out in addition to a general description of the geology at Stripa (Olkiewicz et al., 1979).

Thorpe (1979) has described the methods that he employed in studying the rock fracture system in the time-scaled heater room. First, major discontinuities were identified in the test area so that they could be modeled as discrete elements of weakness (Goodman, 1976). Although these features probably play a major role in the rock mass behavior, they comprise only a small percentage of the total fracture system. Most of the other fractures are discontinuous in their own planes: therefore, the second aspect of the characterization involved defining all fractures through careful measurement of orientation, spacing, and joint length. It is presently impractical to model such ubiquitous joints as they actually exist; techniques are being developed to represent them stochastically (Glynn, Veneziano, and Einstein, 1978).

Heaters for the time-scaled experiment were placed 10 m below the floor of the drift (fig. 5), and the results of the fracture mapping indicate that only the most prominent and continuous features are likely to extend through the heated region. Accordingly, only the major fractures striking transverse to the drift were extrapolated downward and correlated with discontinuities found in the boreholes. Results of this discrete characterization are illustrated in figure 10, which shows the inferred profile of four shear surfaces that pass through the heater array. These fractures offset or truncate other discontinuities, whose positions are shown in each borehole, and their filling minerals of chlorite, calcite, epidote, and clay are several times thicker than the fillings of other fractures. Fault number 3, the most prominent and well-defined of the set, apparently offsets a pegmatite dike, 20 cm wide.

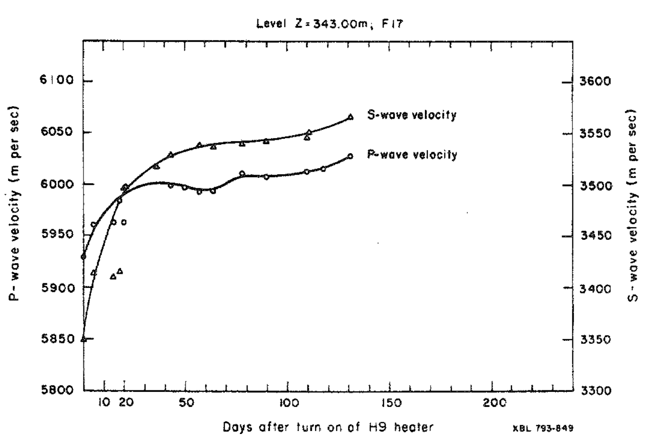

Figure 9. Ultrasonic velocity measurements between boreholes spaced 4 m apart at the heater midplane elevation in the rock mass adjacent to the 3.6 kW full-scale heater.

Thorpe (1979) has also made a statistical analysis of joint geometries by using results from both borehole and surface mapping. The jointing can be separated into four distinct sets, and these in turn have been found to correlate, to a degree, with the principal stresses as measured in the underground by Carlsson (1978). The mean pole of one of these joint sets corresponds to that of the four faults shown on figure 10. Resolving the principal stresses into shear and normal components on the mean fault plane yields a theoretical shearing azimuth of 242 degrees. From field observations, the azimuth of slickensiding on the faults was found to be 240 degrees.

Characterization of the fracture system is thus an important component in understanding the overall thermo-mechanical response in a discontinuous rock mass. Without the level of detail described above, it will not be possible to perform an analysis (such as is now underway) of those fracture displacements that control the near-field behavior of the overall system. Obviously, the comprehensive fracture analysis described above can only be made where one has access to an underground test facility, such as at Stripa.

Instrument problems

The heater experiments at Stripa have created some severe operating conditions for the instruments that were installed and expected to operate over a period of 1½ years (Binnall, DuBois, and Lingle, 1979). Measured heater skin temperatures approached 500°C, rock temperatures in the immediate vicinity of the heaters exceeded 300°C, and mechanical response had to be measured with rock temperatures exceeding 150°C. Few of the avilable instruments for measuring mechanical response are designed to operate with accuracy and reliability under such conditions.

Four types of instruments have been used at Stripa: 389 thermocouples for temperature, 35 rod extensometers for displacement, 30 U.S. Bureau of Mines (USBM) borehole deformation gauges, and 26 IRAD (Creare) vibrating wire gauges for stress determination. These sensors have been installed in vertical and horizontal boreholes strategically located around the vertical heater boreholes (Schrauf et al., 1980). The sensor signals (>750) were digitized

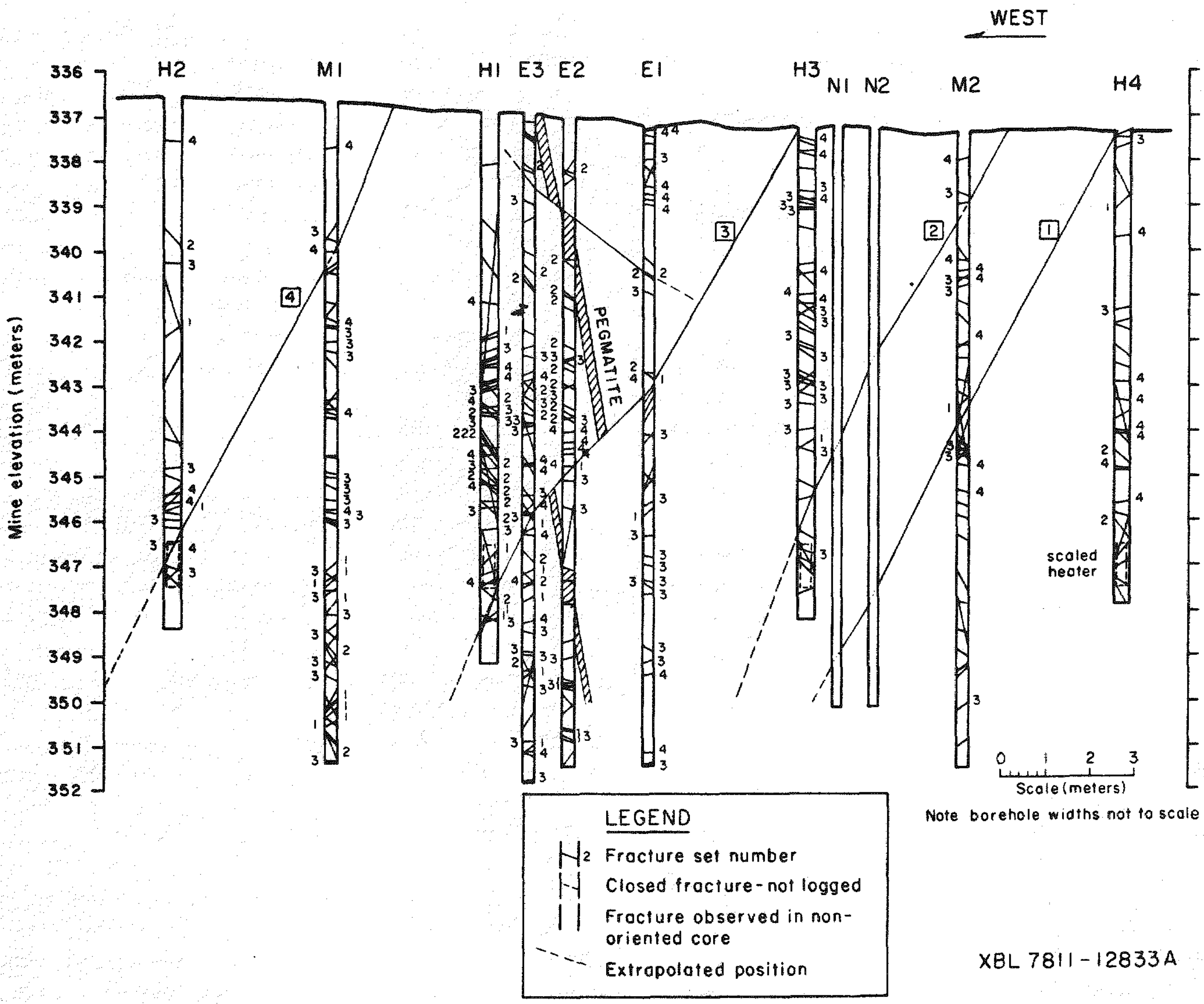

Figure 10. Vertical profile of major fractures along centerline of time-scaled heater room.

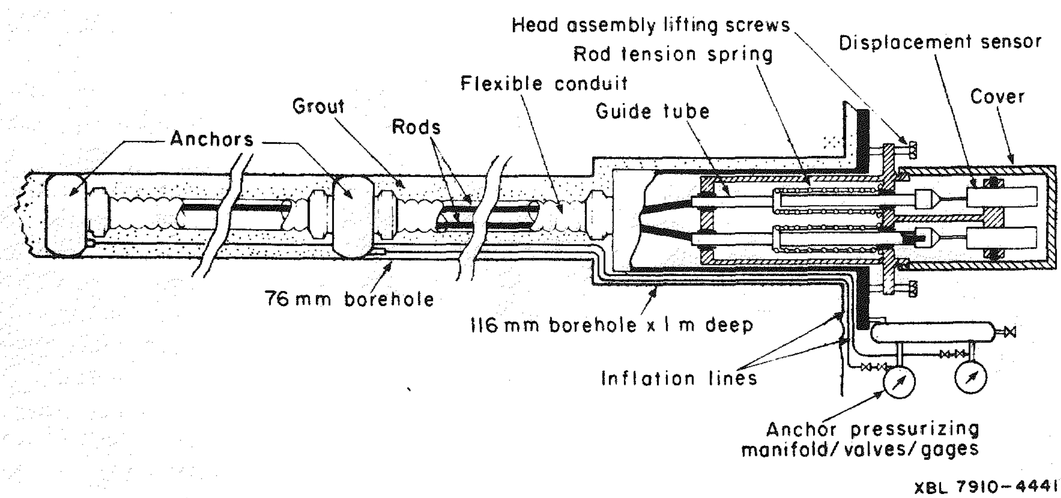

Figure 11. Sectional view of rod extensometer, two-anchor version.

and transmitted to a Modcomp IV computer (McEvoy, 1979) located in a nearby building underground (fig. 1).

The major instrument problem has been with the USBM gauges, which use pairs of opposed cantilever beams to sense changes in borehole dimensions from which stress may be computed. The gauge was originally designed to operate at ambient temperature (Hooker, Aggson, and Bickel, 1974), and it was thus necessary to incorporate high-temperature components for operation up to 200°C. Sixteen of the twenty gauges installed in vertical holes and two of the ten gauges installed in horizontal holes have failed in service, some of these more than once. The failures have been caused by water entering the gauge housings, causing short circuits and open circuits due to corrosion. These leaks occurred in spite of a regular dewatering operation that ensured that water levels in the instrument boreholes remained below that of the gauges. Corrective measures have been taken to provide soldered internal connections and improved hermetic seals at cable connections. After passing a leak test, the improved gauges have been reinstalled, and we are now gathering data to assess whether performance will be improved.

The second method of determining stress using the IRAD (Creare) vibrating wire gauge (Hawkes and Bailey, 1973) has failed only three times. However, these gauges must be individually calibrated and the calibrations are temperature dependent. Once installed, the gauges can be used only to detect a change in stress, and thus, an independent measure of in situ stress is needed when information on the total stress field is required. In spite of the calibration, considerable uncertainties remain in the calculated stress change, particularly under conditions of varying temperature and cyclic loading (Binnall, DuBois, and Lingle, 1979).

The rod extensometer is a common device for measuring changes in the axial length of a borehole (Committee on Field Tests, International Society for Rock Mechanics, 1978). Basically, these instruments have performed well with interim maintenance and minor field modifications. The major elements of these extensometers (fig. 11) are: (1) the anchor system; (2) the anchor-to-collar rod connection mounted inside a waterproof flexible conduit; (3) a head assembly, which includes the rod tensioning system and the displacement sensors; and (4) several thermocouples for measuring the temperature profile along the connecting rods.

An arrangement with four downhole anchor points to measure displacements over a range of ±13 mm has been installed. Superinvar rods, heat treated at 225°C for 5 hours, were found to have a reproducible thermal expansivity, and thus corrections for rod expansion during temperature buildup could be incorporated into the data reduction process. At Stripa, this correction was as much as 20 percent of the gross displacement.

A few problems with extensometers have arisen and will require attention. One difficulty has been an internal friction that caused stepwise displacements of up to 0.08 mm. This friction could be released by simple tapping of the covers (fig. 11), and a routine of releasing the stored displacements several times per week in this fashion was found necessary. Another problem is the lack of precision of the instrument in measuring very small displacements. The present lower limit in extensometer precision is about 0.1 mm; because heater experiments in the future may operate at significantly lower temperatures, a much greater accuracy will be required.

FRACTURE HYDROLOGY INVESTIGATIONS

Importance of fracture hydrology

The most likely way radionuclides can migrate away from a deep geologic repository is in the groundwater that slowly seeps through the site after burial. Once the wastes are able to dissolve in groundwater, retardation in their rate of movement will depend on three basic properties: permeability, effective porosity, and sorptive properties of the host rock. Research in fracture hydrology at Stripa has been concerned with the permeability aspect of this migration problem.

Determining the permeability of a crystalline rock, such as granite, is essentially a problem of understanding the hydrological behavior of a complex network of fractures. Migration through the matrix will be relatively insignificant, and presumably a site with major zones of potential leakage (shear zones, faults, etc.) will be carefully avoided. Our knowledge of the permeability of fractured rocks has, until recently, been limited to borehole investigations in the upper few hundred meters of the earth's crust. In general, these investigations have been conducted under the assumption that the fracture system can be treated as a slightly different form of porous media. The needs of the nuclear waste isolation program require that investigations now be extended to depths of 1000 m or more in an effort to locate rock systems that are "nearly" impermeable (Office of Waste Isolation, 1977 and Lawrence Berkeley Laboratory, 1979). Under these conditions, the porous media assumption also needs to be justified.

These new programs require an accurate description of the hydrology of fractured rocks. Thus, one must develop a data base to provide answers to such questions as: (1) What is the role of discontinuities in determining the nature (isotropic or anisotropic) of fractured rock permeability? and (2) Under what conditions, if any, can fractured rock masses be treated as "equivalent" porous media? To answer the first question, we need methods of characterizing a fracture system and its role in determining the hydrology of such systems in order to provide a framework within which to interpret local and large-scale groundwater movements. Answers to the second question determine the type of borehole testing programs that must be undertaken in concept verification studies. These testing programs must provide the data needed to develop the hydraulic parameters that clearly describe how fluids move through fractured rock. Both of these questions become increasingly difficult to pursue in the field as permeability of the rock mass becomes vanishingly small.

In any crystalline rock mass, the fracture or joint system consists of several sets of planar openings, relatively parallel in orientation, most of which are involved in the flow properties of the rock. Several such groups of different orientations as well as randomly distributed fractures may exist at a given location. Velocity through a fracture is proportional to the square of the fracture aperture, and flux is proportional to aperture cubed (Witherspoon et al., 1979). If all fractures in a particular volume of rock could be described in terms of their location, orientation, aperture, and continuity, then it would be possible to develop a discrete model and analyze flow through that volume of rock.

It is essentially impossible to measure each and every fracture involved in regional groundwater movement. Because the actual three-dimensional system of fracture flow paths cannot be fully described in practice, this discrete approach has a significant limitation. However, in order to use a continuum analysis we must be able to demonstrate that equivalent porous media values will provide an accurate prediction of the flow system; then we must be able to measure the equivalent porous media properties in situ.

A comprehensive program of investigations has been organized at Stripa (Gale and Witherspoon, 1979) in an effort to understand the fracture hydrology of the granite mass. Three of the most important parts of this program will be discussed in this paper: (1) assessment of directional permeabilities; (2) large-scale permeability measurements; and (3) geochemistry and isotope hydrology.

Assessment of directional permeabilities

The mathematics of calculating directional permeabilities from fracture orientation and aperture data, using the parallel plate analogy for fracture flow, was first developed by Romm and Pozinenko (1963). Extensive work in this area has been performed by several others (Snow, 1965; Caldwell, 1971; Parsons, 1972; and Louis and Pernot, 1972). The approach consists of developing a permeability tensor from measured orientations and spacings of fractures and assumed aperture distribution models. Principal permeabilities and their directions can be calculated from the eigenvalues and eigenvectors of the tensor by following procedures outlined by Westergard (1964).

Our approach to assessing directional permeabilites of the fractured granite at Stripa is based on this earlier work. We are attempting to incorporate the effects of fracture continuity and fracture interconnection in the calculation of directional permeabilities. Basic data on fracture orientations, spacings, and continuity have been obtained by mapping the fractures in the surface outcrops and in the walls and floors of the subsurface excavations (Thorpe, 1979).

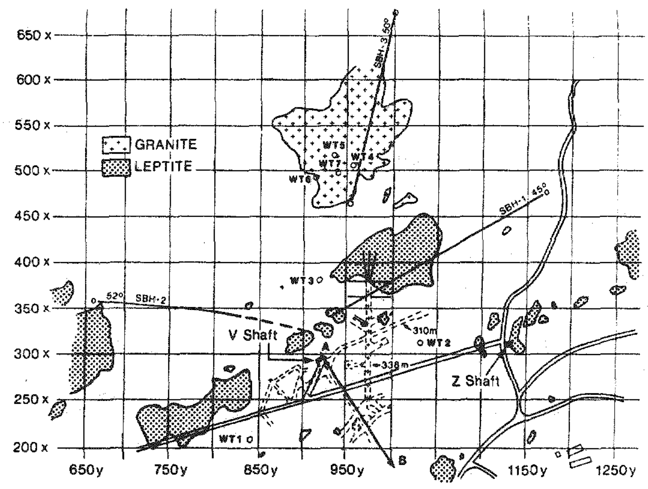

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Figure 12. General geology at Stripa mine and locations of hydrology boreholes relative to underground (dashed) experiments.

Another source of data has been obtained in a group of three oriented boreholes drilled from the surface down to the level of the experimental heater tests discussed previously. Careful core drilling, core reconstruction, and core orientation have been carried out in these boreholes to determine the variations in fracture geometry within the rock mass. The surface and subsurface data are now being combined with the borehole data in an attempt to define the three-dimensional fracture system.

Figure 12 shows the distribution of outcrops at Stripa and the locations of these hydrology boreholes in relation to the underground heater tests at 338 m. SBH-1, SBH-2, and SBH-3 are 76 mm core-holes that were diamond drilled at various angles from the horizontal as indicated on figure 12. Additional information has also been obtained from a series of seven relatively shallow, vertical boreholes (WT-1 to WT-7). The inclined surface boreholes were oriented to optimize their intersection with the major fracture sets. An example of results from SBH-1 is given in figure 13. Note that the effect of years of drainage into the nearby mine workings has decreased the water pressures below hydrostatic as depths increase below 100 m.

A borehole injection test program has also been developed to provide information on the distribution of effective fracture apertures. The basic test equipment consists of a two-packer assembly with downhole pressure and temperature probes. An example of injection tests results and fracture data from the interval 325 m to 355 m in SBH-1 is given in figure 14. By combining different flow rates with different packer spacings, it should be possible to develop fracture aperture distribution data for different parts of the rock mass from a statistical analysis of fluid pressures, flow rates, and fracture frequencies. This work is now under way (Gale et al., 1979), and the results will be incorporated into the analysis of directional permeabilites.

Large-scale permeability measurement

Three problems arise in determining flow parameters for low-permeability fractured rock. The first is to determine the minimum volume of rock for which the permeability tensor is representative of a larger rock mass and is amenable to a porous media method of analysis. The second problem is to determine this permeability tensor from field tests, such as those described above. The third problem is to assign permeabilities to the volumes of rock that are not directly examined in the field. The large-scale permeability experiment at Stripa is an attempt to increase our understanding of the first two of these problems.

As the volume of the fractured rock sample increases from zero, the average permeability will oscillate as either fractured or solid rock is added to the sample. When the volume of rock becomes sufficiently large that permeability is no longer sensitve to the effects of individual fractures, the oscillations will be subdued. An average permeability can then be assigned to that volume or rock which is called the representative elementary volume (REV). Theoretically, volumes of rock the size of the REV can be treated as porous media for regional groundwater flow analyses. Increasing the volume further may ultimately cause additional oscillations if a different realm of fracturing is encountered. When a single permeability measurement is made in an arbitrary volume or rock, there is no way of knowing a priori whether or not the measured permeability lies on the oscillating portion of the curve. A series of measurements on different scales must be made to determine if there is an REV smaller than the rock mass itself and to determine the permeabilites associated with that volume.

In fractured rocks in which the discontinuities themselves may occupy areas on the order of 10^2 m^2, it is reasonable to expect that REVs, if they exist, would be on

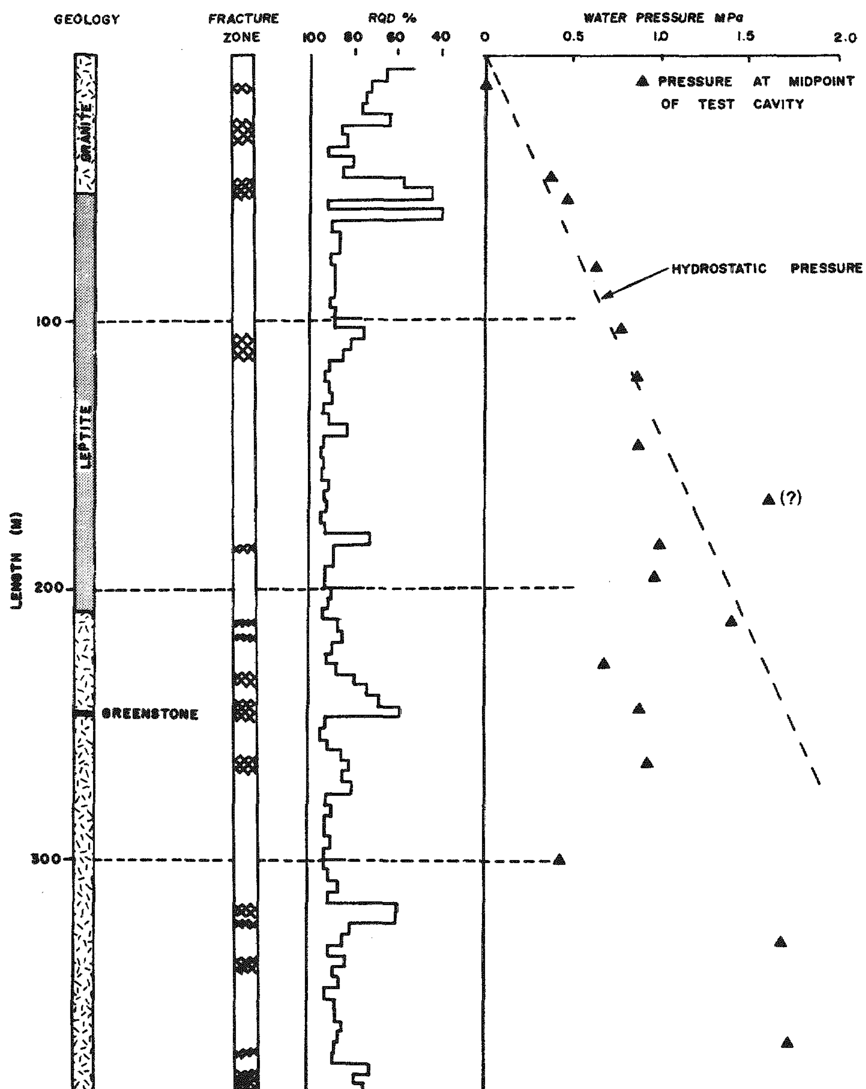

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Figure 13. Fracture hydrology results from SBH-1 showing general geology fracture zones, rock quality designation (RQD) values, and bottom hole hydrostatic pressures measured during drilling.

the order of 10^4 or 10^5 m^3 of rock. The large-scale permeability experiment at Stripa will permit a measurement of the average permeability of 10^5 to 10^6 m^3 of rock. There is no assurance that this volume will be as large as the REV; however, the experiment, taken along with other small-scale tests performed at the same site, should indicate the size and existence of the REV.

The second problem is to determine the permeability of these large rock volumes from in situ tests. In high permeability soils or rocks, conventional well tests suffice

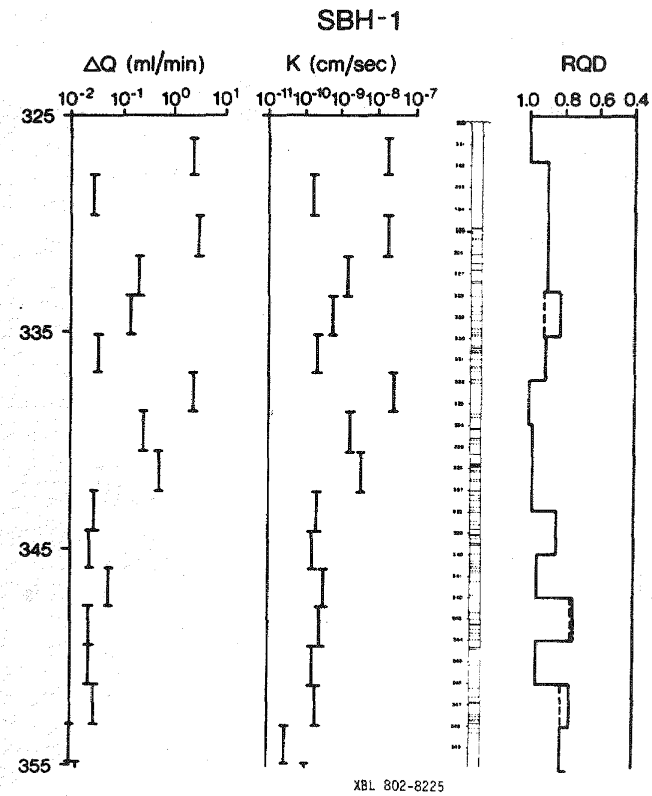


Figure 14. Injection test results and fracture data for the interval 325 m to 355 m in SBH-1.

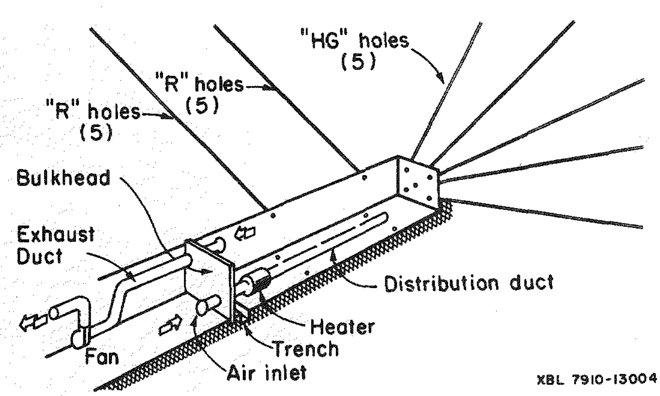


Figure 15. Large-scale permeability experiment showing instrumentation boreholes and system to capture water seepage through evaporation into a controlled pattern of air flow.

because they perturb a large volume of the flow system. In rocks of very low permeability, however, such tests may affect the flow system only within a few meters of the well. A determination of large-scale values of permeability can therefore be attempted in two ways. The first way is to synthesize large-scale values from an appropriate number of conventional (small-scale) tests in boreholes. The second way is to create a large-scale sink (or source) that will perturb a large volume of the flow system (i.e., a macroscopic permeability test).

At Stripa, a macroscopic permeability test is now being conducted by using the arrangement shown in figure 15. A 33-m length of the ventilation drift (fig. 1) has been sealed off and equipped with a ventilation system, the temperature of which can be controlled to evaporate all water seeping into the room. The water seepage is being determined from careful measurements of the mass flow rate and the difference in the humidities of entering and exiting air streams.

The pressure gradients in the rock walls are being measured in 15 holes that radiate out from the sealed room in all directions (fig. 15). Two groups of five "R" holes each have been drilled from the walls out to distances of 30 to 40 m. One group of five "HG" holes has been drilled at the end of the room. Each borehole has been sealed off with six packers placed so that pressure and temperature measurements can be made at intervals of approximately 5 m. Details of this experimental setup are given elsewhere (Witherspoon et al., 1980).

The results to date indicate that the experiment is developing in a very satisfactory manner. A dramatic indication of the degree of communication within this huge rock mass occurred in November 1979, just as the last of the 15 boreholes, R01, was packed off. Before instrumentation, when all the holes were draining freely, R01 produced about as much water as all the other 14 holes combined. Earlier injection tests in R01 resulted in pressure responses in many of the other boreholes in the ventilation drift. Consequently, we instrumented R01 last and monitored the effects in all other boreholes of the pressure buildup in R01.

Figure 16 illustrates the pressure profiles in radial holes R01-R05. Pressures increase with distance from the drift and are all about 1 MPa (145 psi) at a distance of 30 m. These unusually low pressures are a result of the drainage that has been taking place into the adjacent mine workings for some years. The dashed lines represent pressures measured on October 30, 1979, and the solid lines represent pressures measured on November 8, 1979. R01 was packed off October 31, 1979, so the stippled areas show how pressure increases occurred more or less uniformly throughout this fractured granite. Similar pressure increases were noted in all the other boreholes. This hydraulic response illustrates the complex nature of the fracture system in the granite at Stripa.

After all boreholes were packed off, a marked increase in drips and wet spots was observed. Concurrently, the seepage rate is about 50 mL/min, and on the basis of the observed pressure gradients, the average hydraulic conductivity of the surrounding rock is about 10^{-11} m/s. This new method of measuring permeability in situ could well provide an important advance in fracture hydrology. Obviously, an experiment such as this could never be carried out without access to a test facility such as at Stripa.

Geochemistry and isotope hydrology

Another important component of the investigations at Stripa is the geochemistry and isotope hydrology of the groundwaters. This work provides an independent approach to the problem of the overall permeability of a rock system. If there is rapid communication of surface waters to the 338-m level where the heater experiments were placed, similarities in chemistry and age between shallow and deep waters should exist. On the other hand, if the deep waters entered the groundwater system many thousands of years ago and have percolated downward at very low velocities because of inherently low hydraulic conductivities in the rock mass, there should be significant differences between waters at different depths. This approach must, of course, take into account the geochemistry of these systems because changes in the environment of groundwaters can also produce signficant effects.

A comprehensive program of investigations on the geochemistry and isotope hydrology of the Stripa groundwaters has been carried out by Fritz, Barker, and Gale (1979a). Water samples were collected from the surface, shallow private wells, and in boreholes drilled at the 338-m level where the heater tests were carried out. In addition, a deep borehole drilled by the Swedish Geological Survey from 410 m (the deepest operating level in the mine) to about 840 m below surface provided a further opportunity to examine whether evidence can be gathered for an increasing isolation of the groundwaters with depth. Analysis of the results has provided important information on the geochemical evolution, origin, and age of Stripa groundwaters (Fritz, Barker, and Gale, 1979a, 1979b).

Geochemical analysis of the groundwaters shows an increase in total dissolved solids with depth. This increase is due to a few elements only, notably calcium, sodium, and chloride. Bicarbonate (or total inorganic carbon) decreases dramatically below a depth of 100 m, and both magnesium and potassium contents drop from higher levels (2-10 ppm) in the shallow groundwaters ($>$100 m) to below 1 ppm in the mine waters.

Especially remarkable, however, is the rise in pH from around 7.0 in the shallow waters to as high as 9.8 in the deepest groundwaters (801-838 m). This is probably linked to the dissolution of primary silicates such as feldspars and the formation of clay minerals. These processes release calcium, which causes continuous saturation of the mine waters with respect to calcite.

The increased sodium concentrations at depth could be explained by plagioclase dissolution, but it is difficult to determine the origin of chloride; chloride concentrations increase from 2 to 5 ppm in shallow waters to more than 400 ppm in the deepest groundwaters. Simple mixing of freshwater and fossil seawater cannot explain the observed chemistry. The geochemical history of the deep groundwaters at Stripa is more complex than that of groundwaters from other localities in similar rocks (Jacks, 1973). It is tentatively concluded that the deep groundwaters at Stripa have a different origin and are not related to fossil seawater which would have infiltrated less than 10,000 years ago.

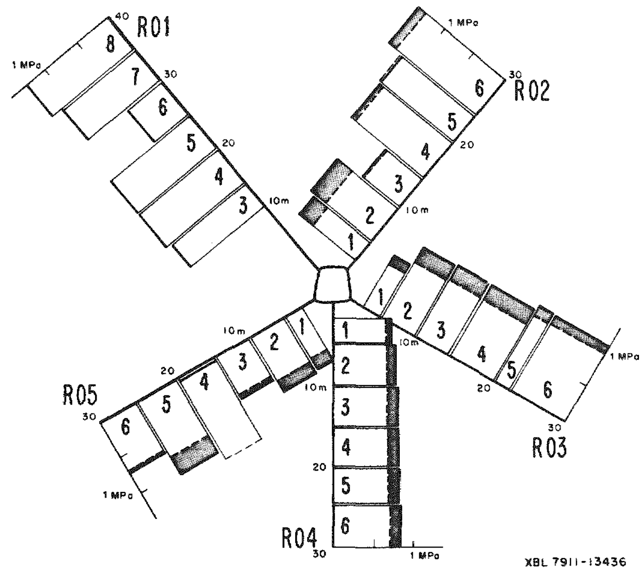


Figure 16. Pressure measurements in radial boreholes of ventilation drift at Stripa. Stippled area shows pressure increases eight days after packing off R01. 1 MPa = 145 psi.

The abundance of the stable isotopes ^{18}O, ^{2}H, and ^{13}C was determined to obtain information on the origin of these waters. The results of the ^{18}O and ^{2}H analyses are shown in figure 17, which illustrates that, except the surface waters, all groundwaters sampled fall close to the global meteoric water line. They are thus "normal" groundwaters for which ^{18}O and ^{2}H contents reflect climatic conditions in the original recharge area.

As a general rule, lower heavy isotope concentrations signify lower average annual temperatures at the recharge area. Therefore, the deep "saline" groundwaters, which have the lowest ^{18}O and ^{2}H contents, must have recharged at lower average annual temperatures than the shallower groundwaters. This has been confirmed by rare gas analyses performed on all samples (Fritz, Barker, and Gale, 1979a). One must therefore conclude that the deep groundwaters have an origin different from that of the shallower ones.

This conclusion is further substantiated by comparing ^{18}O with the chloride concentrations (fig. 18). Here it is apparent that the deep groundwaters, especially those at the bottom of the 410-m hole (801-838 m total depth), are different from the shallow groundwaters. In other words, the different fracture systems in the granite at Stripa carry different types of water because they are isolated from each other.

Because of the lower ^{18}O isotope contents in the deeper groundwaters, one could argue that this is an indication of subglacial recharge. This is not supported by the ^{13}C analyses; all waters from the mine levels have $\delta^{13}C$ levels close to or below -15‰. This indicates that biogenic carbon is present in the dissolved organic carbon, which would signify that these groundwaters infiltrated through soil horizons (that is, were generated during an interglacial period).

The most difficult and inconclusive part of this geochemical investigation was the attempt to date the groundwaters from the different mine levels (Fritz, Barker, and Gale, 1979a). Tritium levels approaching 100 TU were found in all shallow groundwater (<100 m) and, interestingly enough, even in the mine waters of the old workings. However, tritium was not encountered (<0.5 TU) in any of the deep groundwaters from the granite despite the drainage previously mentioned, which has decreased water pressure below hydrostatic (see fig. 13). This lack of tritium indicates that deep waters do not contain any surface water component younger than 30 to 40 years.

Major problems were encountered in attempting ^{14}C age dating because of the very low content of dissolved inorganic carbon; treatment of 2,000 to 3,000 liters of water was necessary to obtain sufficient carbon for analysis. The results indicate that waters at the 330-m level, and probably also from the 410-m borehole, were more than 20,000 years old. (Contamination problems with water samples from the 410-m borehole made these results unreliable.)

Three different approaches to age dating based on the uranium decay series were also investigated: (1) uranium activity ratios; (2) helium contents; and (3) radium-radon relationships (Fritz, Barker, and Gale, 1979a). The $^{234}U/^{238}U$ activity ratios in the groundwaters decrease from 10.4 at the 330-m level to about 6 at the top of the 410-m borehole to almost 4 in the high "saline" waters (fig. 18) at the bottom of this hole (811-838 m). This decay in activity ratio can be used to date water according to a method proposed by Barr and Carter (1978). Although the method is still under development and subject to some uncertainties, ages exceeding 100,000 years are obtained for the groundwaters from the 410-m borehole.

Somewhat lower ages were determined from the He concentrations. The atmospheric concentration at 5°C is 4.9×10^{-8} cm^3 He/cm^3 H_2O, whereas the concentrations in the groundwaters at Stripa are five orders of magnitude higher, ranging from 0.3×10^{-3} cm^3 He/cm^3 H_2O at the 330-m level to 1.4×10^{-3} cm^3 He/cm^3 H_2O in the 410-m borehole. On the basis of a method proposed by Marine (1976), ages can be computed from these data that range from tens to hundreds of thousands of years.

If ^{222}Rn accumulates as a recoil product and is in

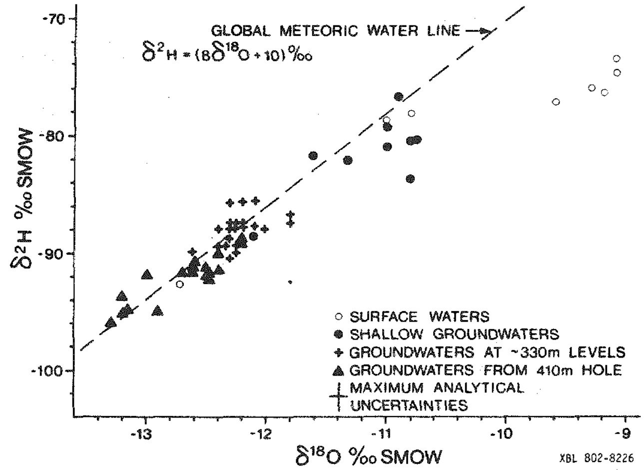


Figure 17. Comparison of $\delta^{18}O$ and δ^2H values for Stripa groundwaters. The analyses are reported as δ‰ values with reference to SMOW. A $\delta^{18}O$ of -10‰ signifies that the sample has 10‰ less ^{18}O than the reference standard, which closely reflects average seawater.

equilibrium with ^{226}Ra, then ^{234}U and ^{222}Rn activities may eventually reach equilibrium. Ages calculated by this model indicate 10,000 to 35,000 years for the different mine waters. An extension of this approach considers the ^{226}Ra concentrations in the rock minerals and the ^{226}Ra in the water. If equilibrium between the two exists, that is, if the recoil rate from the rock equals decay in the solution, then the waters must be at least 8,000 years old (five half-lives of ^{226}Ra). There is evidence that this is the case, again supporting the earlier results that the waters presently found in the deep granite rock mass at Stripa are indeed many thousands of years old. A careful investigation of geochemistry and isotope hydrology is an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the Stripa groundwater system.

IMPORTANCE OF FULL-SCALE FIELD TESTING

The results obtained at Stripa would not have emerged unless the experiments had been carried out underground at depths comparable with those envisaged for an actual repository. However, this creates unexpected and sometimes difficult problems that must be resolved if deep geologic disposal of radioactive waste is to become a reality. Scientific advances are needed in the laboratory, but these must be supported by meaningful field experiments.

The mechanical, thermal, hydraulic, and chemical behavior of a repository in a crystalline rock mass of low permeability is determined by the rock matrix properties and, more importantly, by discontinuities that pervade the rock mass. This raises a critical question: *Can one determine the geometry of fractures in sufficient detail using surface measurements?* Studies by Kendorski and Mahtab (1976) and Raven and Gale (1977) suggest that fracture orientations between surface and subsurface are similar. However, no data demonstrate that length and continuity of such features can be predicted reliably from surface measurements.

Fractures must be mapped so that the orientation, spacing, continuity, and aperture distribution are determined in sufficient detail to enable us to predict the total behavior of the rock mass. Over long time periods, this complex problem involves the thermo-mechanical response of the rock system and the hydraulic-chemical behavior of aqueous solutions migrating through the discontinuities. The magnitude of the thermo-mechanical response depends on the thermal loads imposed on the system and the material properties of the rock mass. The hydraulic-chemical behavior depends on the permeability and porosity of the system, the hydraulic gradients (natural and/or thermally induced), and geochemical reactions. These coupled effects are also influenced by the magnitude of the in situ stresses. The repository must be deep enough to keep the fractures closed and to maintain low permeabilities (even in a perturbed rock mass containing discontinuities) yet not so deep as to generate stresses that cause stability problems.

Much more work will be required to develop a reliable basis for predicting the thermally induced behavior of discontinuous rock masses. The mechanical and hydrologic effects of the discontinuities are not yet understood. After a repository has been filled with waste canisters, the rock will undergo a thermal pulse of increasing temperature extending out to distances well beyond the limits of the excavations. The magnitude of this effect is, of course, primarily dependent on the energy and spacing of the canisters. However, for high-level waste from light water reactors, this pulse reaches a maximum temperature in the plane of the repository between 10 and 100 years.

This thermal perturbation caused by the repository raises a second critical question: *How can we develop the technology to reliably predict the global thermal response of a repository in a discontinuous rock mass?* This can be carried out only in an underground test facility that has been properly designed and instrumented. Whether or not more than one type of crystalline rock needs to be tested in this fashion is difficult to answer because the physics of the thermomechanical and hydraulic-chemical behavior of large rock masses is not yet adequately understood. Because granite and basalt have distinctly different types of fracturing and are examples of massive versus bedded forms of igneous rock, they would appear to be prime candidates for underground investigations.

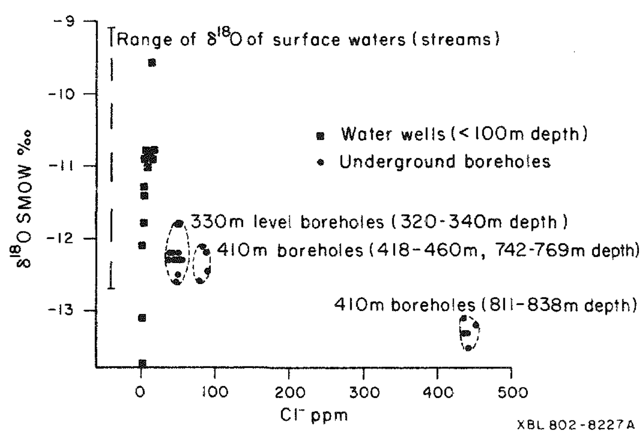


Figure 18. Comparison of chloride with $\delta^{18}O$ values shows that the different fracture systems in the Stripa granite carry different types of water.

Because the heat output of radioactive waste decays with time, the magnitude of the thermal perturbation depends on how long the emplaced waste was stored at the surface. This raises a third critical question: *What are the tradeoffs between minimizing the thermally induced effects and long-term surface storage of waste?* The decrepitation results observed at Stripa when rock temperatures near the 5.0 kW heater exceeded 300°C could undoubtedly be eliminated by keeping the temperature below some maximum value. This would be an important component of the field experiments suggested above. Low temperatures would also minimize effects on backfill materials and the possibility of generating thermal convection in the groundwater system. The answer to this third critical question will not be forthcoming until the ability to predict thermally induced effects is perfected through appropriate field tests underground.

Another area of investigation must be the hydrogeology of the rock mass and the geochemical behavior of aqueous solutions, including radionuclides, as they migrate through that mass. This hydraulic-chemical response is coupled to the thermo-mechanical response through the discontinuities. Fractures in any type of rock will deform under the influence of changes in rock stress, affecting the permeability of the rock mass. The magnitude of these changes in permeability may be very important and will depend on the effects of the thermal perturbation and the disturbance caused by the excavation itself.

All these concerns raise a fourth critical question: *How should we make field measurements of the rock properties we need in order to understand the hydraulic-chemical effects, specifically permeability (hydraulic conductivity), total and effective porosity, and sorption behavior?*

At Stripa, a careful measure of the permeability tensor is being attempted using conventional methods in inclined boreholes drilled from the surface. These methods seem to be working well, but the hydraulic conductivity at Stripa is about 10^{-11} m/s. Less permeable rock masses may have values two to three orders lower than this, and whether conventional methods will still give reliable results remains to be seen. On the other hand, the large-scale method of measuring permeability (Witherspoon, et al., 1980) should easily be adaptable to rock masses with permeabilities far less than at Stripa. Thus, the accuracy of borehole methods must be assessed by comparing the results with those from the large-scale method, which will certainly yield a good measure of the bulk permeability in the immediate vicinity of the repository. This information is needed to confirm the degree of isolation at a potential site. Conceptually, one could use this method to measure the permeability of the rock mass around individual drifts during their excavation. However, in the far field, where it is not practical to use the large-scale method, one needs to know the reliability of the various borehole testing techniques in measuring permeability.

In a rock mass with very low permeability, the problem of measuring the effective porosity using in situ tracer tests is not easily resolved. Because these tests involve rock at great depths and large enough to be representative of the total mass, they may take months or years to complete. Under such circumstances, conventional tracer tests in deep boreholes drilled from the surface are not likely to yield reliable results. On the other hand, an underground room, similar to that at Stripa (fig. 15), creates significant pressure gradients at the depths where a repository will be constructed. Movement of groundwater through the fracture system toward such an underground opening is greatly enhanced, and tests using tracers can be designed for use in very large volumes of rock. Actual velocities can be measured by introducing such a tracer at a point along a known flow path and observing time of arrival downstream. Although standard borehole tracer tests contribute to an understanding of fracture flow in higher permeability rock masses, we conclude that the only feasible approach in rocks with very low permeabilities is an underground tracer experiment run in conjunction with a large-scale permeability test.

Predicting the geochemical sorption behavior of aqueous solutions of radionuclides in contact with mineral surfaces is complicated by a lack of basic data. Much work is needed on the behavior of the actinide aqueous and solid species that are important in groundwater transport processes; there is also a dearth of information on the potential for actinides to form colloids in groundwater. Actinides may form complexes with organic materials that occur naturally in groundwater (Means and Hastings, 1979). The movement of dissolved species involves several mechanisms for retardation, such as sorption on mineral surfaces, precipitation, ion exchange, and diffusion into the rock matrix. Because of the small scale of these phenomena, they can be studied very effectively in the laboratory, and a large effort in this direction is now under way. Eventually, geochemists will require field tests to validate their laboratory findings. If underground tests facilities are already in operation for other purposes, various geochemical tests could be incorporated conveniently; such tests are already being planned for the Stripa project.

The critical importance of being able to determine the velocity of groundwater movement through a rock mass with very low permeability cannot be overstated. The study of the geochemistry and of the ages of the groundwaters at different points in the total system provides important data. There is also a need to integrate geochemical and isotopic data with the physical hydrology results, as is being done at Stripa. This raises a fifth critical question: *How should one gather groundwater samples for these investigations?*

The conventional approach to this problem is to collect water samples in vertical boreholes drilled from the surface. Drilling procedures normally cause contamination of the natural waters because of the pressures required for fluid circulation often exceed those of the fluids in the rocks being drilled. This is usually overcome before sampling by producing a sufficient volume of water from such rocks until the contaminants are removed. In rocks with very low permeability this may not be practicable because the influx of groundwater into boreholes may be very slow.

Experience at Stripa, however, has shown clearly the superiority of collecting groundwater samples from boreholes drilled from underground drifts and rooms. Hydrostatic water pressures in rock are about 1 MPa per 100 m of depth, whereas the pressure within the mined openings is only about 0.1 MPa (1 atm). Thus, any borehole that is drilled from an underground excavation into the rock mass around the opening encounters hydrostatic pressures that far exceed the pressure necessary to circulate the drilling fluids. This creates an artesian condition that minimizes contamination and greatly simplifies the subsequent problem of collecting water samples. Furthermore, both horizontal and vertical boreholes can be drilled from an underground location to provide data in three dimensions of the hydraulic environment. This approach to collecting water samples for geochemical and isotopic groundwater studies is far more effective than methods using boreholes drilled from the surface.

The effectiveness of backfill materials in isolating canisters of radioactive waste and plugging off underground openings is still another problem that must be investigated. This raises the sixth critical question: *What is the proper way to demonstrate the effectiveness of backfill materials?* As in the case of sorption behavior for aqueous solutions of radionuclides, many fundamental aspects can be investigated very effectively in the laboratory, especially in conjunction with the study of naturally occurring geological materials. A major effort in this direction is already under way. Ultimately, however, field tests will be required to demonstrate how such materials can be best used under repository conditions. It will be necessary to carry out field demonstrations on selected materials under appropriate levels of stress, temperature, and moisture content. This can be done meaningfully only in an underground test facility.

Answers to the preceding six questions cannot be found in terms of current experience or through numerical modeling alone; these problems will require investigations conducted in full-scale underground test facilities at depths and other conditions expected to be encountered in an actual repository. For speed and economy, preference may be given to the process of evaluating a repository site on the basis of detailed exploration and testing carried out at the surface or in boreholes drilled from the surface. Such techniques, however, cannot yield the data needed to assess the total behavior of discontinuous rock masses subjected to the perturbations of an underground waste repository. Experience with underground experiments at Stripa indicates that site evaluation must include extensive subsurface experiments, carried out in conjunction with measurements made at the surface. Much effort is needed at this stage to generate the technology that is required. The Stripa investigations are a beginning.

REFERENCES

Barr, C. E., and J. A. Carter, 1978, Uranium isotope disequilibrium in groundwaters of southeastern New Mexico and implications regarding the age dating of waters: *in* International Atomic Energy Symposium 228, Munchen, Germany, Manuscript 28.

Binall, E., A. DuBois, R. Lingle, 1979, Rock instrumentation problems experienced during in situ heater tests: Paper presented at International Symposium on the Scientific Bases for Nuclear Waste Management, Materials Research Society, Boston, MA, Nov. 26-30.

Burleigh, R. H., E. P. Binall, A. O. DuBois, D. U. Norgren, A. R. Ortiz, 1979, Electrical heaters for thermo-mechanical tests at the Stripa mine: Lawrence Berkeley Laboratory Report LBL-7063, SAC-13, Berkeley, CA, Jan.

Caldwell, M. A., 1971, The theoretical determination of the fluid potential distribution in jointed rocks: M.S. thesis, University of the Witwatersrand, South Africa.

Carlsson, H., 1978, Stress measurements in the Stripa granite: Lawrence Berkeley Laboratory Report LBL-7078, SAC-04, Berkelely, CA, Aug.

Chan, T., and, N.G.W. Cook, 1980, Calculation of thermally induced displacements and stresses for experiments at Stripa: Lawrence Berkeley Laboratory Report LBL-7061, SAC-22, Berkeley, CA, March.

Chan, T., N.G.W. Cook, and C. F. Tsang, 1978, Theoretical temperature fields for the Stripa heater project: Lawrence Berkeley Laboratory Report LBL-7082, SAC-09, Berkeley, CA, Sept.

Chan, T., M. Hood, and M. Board, 1980, Rock properties and their effect on thermally induced displacements and stresses: Paper presented at ASME Energy Sources Technology Conference, New Orleans, LA, Feb.

Clark, S. P., 1966, Handbook of physical constants: Geological Society of America Memoir 97, New York.

Committee on Field Tests, 1978, Suggested methods for monitoring rock movements using borehole extensometers: *in* International Society for Rock Mechanics Commission on Standardization of Laboratory and Field Tests: Pergamon Press, Great Britain, Document No. 5.

Cook, N.G.W., 1978, An appraisal of hard rock for potential underground repositories of radioactive wastes: Part I, Lawrence Berkeley Laboratory Report LBL-7073, SAC-10, Berkeley, CA, Oct.

deMarsily, G., E. Ledoux, A. Barbreau, and J. Margat, 1977, Nuclear waste disposal: Can the geologist guarantee isolation: Science, 197, 4304, p. 519-527.

Fritz, P., J. F. Barker, J. E. Gale, 1979a, Geochemistry and isotope hydrology of groundwaters in the Stripa granite—results and preliminary interpretation: Lawrence Berkeley Laboratory Report LBL-8285, SAC-12, Berkeley, CA, April.

Fritz, P., J. F. Barker, J. E. Gale, 1979b, Geochemistry, origin and age of groundwaters at the Stripa (Sweden) test mine: Paper presented at International Symposium on the Scientific Bases for Nuclear Waste Management, Materials Research Society, Boston, Nov. 26-30.

Gale, J. E., O. Quinn, C. Wilson, C. Forster, P. A. Witherspoon, and L. Jacobson, 1979, Hydrogeologic characteristics of fractured rocks for waste isolation—the Stripa experience: Paper presented at International Symposium on the Scientific Bases for Nuclear Waste Management, Materials Research Society, Boston, MA, Nov. 26-30.

Gale, J. E., and P. A. Witherspoon, 1979, An approach to the fracture hydrology at Stripa—preliminary results: Lawrence Berkeley Laboratory Report LBL-7079, SAC-15, Berkeley, CA, May.

Glynn, E. F., D. Veneziano, and H. H. Einstein, 1978, The probabilistic model for shearing resistance of jointed rock: Proceedings of the 19th U.S. Symposium on Rock Mechanics, Reno, NV.

Goodman, R. E., 1976, Methods in geological engineering in discontinuous rocks: West Publishing Co., St. Paul, MN.

Hawkes, I., and W. V. Bailey, 1973, Low cost cylindrical stress gage: U.S. Department of Commerce, Springfield, VA, NTIS PB243—374/A5.

Hoek, E., 1979, The role of modeling in the design of nuclear waste repositories—the design engineer's viewpoint: Proceedings of workshop on thermomechanical modeling for a hardrock waste repository, Berkeley, CA, July 25-27, UCAR-10043, pp. 33-43.

Hood, M., 1980, Some results from field investigations of thermomechanical loading of a rock mass when heater canisters are emplaced in the rock: Part 1, Lawrence Berkeley Laboratory Report LBL1-9392, SAC-26, Berkeley, CA, March.

Hood, M., H. Carlsson, and P. H. Nelson, 1980, The applications of field data from heater experiments conducted at Stripa, Sweden, to parameters for repository design: Part II: Lawrence Berkeley Laboratory Report LBL-9392, SAC-26, Berkeley, CA, March.

Hooker, V. E., J. R. Aggson, D. L. Bickel, 1974, Improvements in the three component borehole deformation gage and overcoring techniques: U.S. Bureau of Mines, Report of Investigations no. 7894.

Jacks, G., 1973, Chemistry of some groundwaters in igneous rocks: Nordic Hydrology, 4, 4, p. 207.

Jaeger, J. C., and N.G.W. Cook, 1979, Fundamentals of rock mechanics: 3rd Ed., Wiley, NY.

Kendorski, F. S., and M. Mahtab, 1976, Fracture patterns and anistropy of the San Manual quartz monzonite: Association of Engineering Geologists, v. 13, p. 23-52.

Kurfurst, P. J., T. Hugo-Persson, and G. Rudolph, 1978, Borehole drilling and related activities at the Stripa mine: Lawrence Berkeley Laboratory Report LBL-7080, SAC-05, Berkeley, CA, August.

Lawrence Berkeley Laboratory, 1979, Geotechnical assessment and instrumentation needs for nuclear waste isolation in crystalline and argillaceous rocks: Symposium Proceedings, Lawrence Berkeley Laboratory Report LBL-7096, Berkeley, CA, July 16-20.

Louis, C., and M. Pernot, 1972, Three dimensional investigation of conditions at Grand Maison damsite: Proceedings Symposium on flow through fissured rock, I.S.R.M., Paper T4-F, Stuttgart, Germany.

Marine, I. W., 1976, Geochemistry of groundwater at the Savannah River plan: DuPont de Nemours and Co., report no. DP 1356, Aiken, SC, 102 p.

McEvoy, M., 1979, Data acquisition, handling and display for the heater experiments at Stripa: Lawrence Berkeley Laboratory Report LBL-7062, SAC-14, Berkeley, CA, Feb.

Means, J. L., and D. W. Hastings, 1979, Status report on the importance of natural organic compounds in groundwater as radionuclide-mobilizing agents: U.S. Department of Energy, Office of Nuclear Waste Isolation, Report ONWI-84, p. 33.

Office of Waste Isolation, 1977, Summary review of workshop on movement on fluids in largely impermeable rocks: P.A. Witherspoon [ed.], Office of Waste Isolation report Y/OWI/SUB-77/14223, Oak Ridge, TN.

Olkiewicz, A., J. E. Gale, R. Thorpe, and B. Paulsson, 1979, The geology and fracture system at Stripa: Lawrence Berkeley Laboratory Report LBL-8907, SAC-21, Berkeley, CA, Feb.

Parsons, M., 1972, Determination of the hydrogeological properties of fissured rocks: Proceedings 24th Geologic Congress, Montreal, Sec. III, Hydrogeology, p. 89-99.

Raven, K. G., and J. E. Gale, 1977, Subsurface containment of solid radioactive waste: A study of the surface and subsurface structural and groundwater conditions at selected underground mines and excavations: Canadian Division of Energy, Mines and Resources, Report EMR/Gsc-RW (internal report).

Romm, E., and B. Pozinenko, 1963, Investigations of seepage in fractured rocks, Trudy VNIGRI, p. 214.

Schrauf, T., H. Pratt, E. Simonson, W. Hustrulid, P. Nelson, A. Du Bois, E. Binall, R. Haugt, 1980, Instrumentation evaluation, calibration and installation for the heater experiments at Stripa: Lawrence Berkeley Laboratory Report LBL-8313, SAC-25, Berkeley, CA.

Snow, D. T., 1965, A parallel plate model of fractured permeable media: Ph.D. thesis, University of California, Berkeley, CA, 331 p.

Swan, G., 1978, The mechanical properties of Stripa granite: Lawrence Berkeley Laboratory Report LBL-7074, SAC-03, Berkeley, CA, Aug.

Thorpe, R., 1979, Characterization of discontinuities in the Stripa granite—time-scaled experiment: Lawrence Berkeley Laboratory Report LBL-7083, SAC-20, Berkeley, CA, July.

U.S. Department of Energy, 1979, Management of commercially generated radioactive waste: Draft Environmental Impact Statement, April.

Witherspoon, P. A., and O. Degerman, 1978, Swedish-American cooperative program on radioactive waste storage in mined caverns—program summary: Lawrence Berkeley Laboratory Report LBL-7049, SAC-01, Berkeley, CA, May.

Witherspoon, P. A., J.S.Y. Wang, K. Iwai, and J. E. Gale, 1979, Validity of cubic law for fluid flow in a deformable rock fracture: Lawrence Berkeley Laboratory Report LBL-9557, SAC-23, Berkeley, CA, Oct.

Witherspoon, P. A., C. R. Wilson, J.C.S. Long, R. M. Galbraith, A. O. DuBois, J. E. Gale, and M. J. McPherson, 1980, Large scale permeability measurements in fractured crystalline rock: Paper presented at the International Geologic Congress, Paris, July 7-17.

Westergard, H. M., 1964, Theory of elasticity and plasticity: Dover, NY, 176 p.

Geology and Society

John C. Frye

The earth and its materials have played basic roles in the development of human society since the dawn of civilization. Soil and water, together with the energy from the sun, did, and still do, make life possible. In the most primitive societies, these elements were "givens"—that is, they were accepted without much thought.

The first deliberate use of earth materials in a social context may have been the fashioning of weapons and tools from glasslike, easily broken natural materials such as chert and obsidian and use of shaped fragments of rock for hunting and defense. In this sense we might claim that geology has had an impact on the development of society and civilization for at least 20,000, 30,000, 40,000 years, or more; however, we cannot claim that the science of geology existed until there was an organized body of knowledge and theory or speculation that could be used by a group or by individuals in a group. It is impossible to know when the beginning of a trend in this direction first existed, because by the time of the first well-documented history of civilized groups, the use of earth materials, and perhaps some understanding of their general characteristics and utilization, was clearly evident.

During the period of rapid cultural development in the eastern Mediterranean region 3,000 to 2,000 years ago philosophical speculations—sometimes in a religious context—about the earth and its materials were widespread. No organized body of observational and experimental knowledge or classification scheme was evident, and the societal utilization of earth materials continued to be on a trial and error basis.

Not until the emergence of western Europe from the "Dark Ages" did the writings of such men as da Vinci, Steno, and others begin to shape what we now call the science of geology. A. R. Palmer, describing the Geological Society of America-sponsored "Decade of North American Geology," rather eloquently describes this phase:

> As we move into the last part of the 20th century, the finite nature of the natural resources that support the highly technological cultures of our world is becoming increasingly apparent. Our effort to understand the origin of these resources, and thus to improve the efficiency of our search for more, is still far from complete. Nearly three centuries ago, Joseph Lister proposed to the fledgling Royal Society of London the idea of a geologic map as the "first step in a quantitative analysis of the earth's crust....Now if it were noted how far these (chalk, flint, sandstone, coal, etc.) extended, and the limits of each soil appeared on a map, something more might be comprehended from the whole, and from every part, than I can possibly foresee, which would make such a labor very well worth the pains." During these three centuries, knowledge of the Earth has increased at an exponential rate, and the labor of creating syntheses of geologic knowledge has become correspondingly complex, but Lister's philosophical justification remains unchanged.

As Lister clearly points out here, the science of geology began as an intellectual, philosophical exercise to attempt to understand what and how, with no plan of application or material reward. However, with the industrialization of the western world and the accelerated population increases that began more or less 150 years ago, we gradually learned that the study of the earth and its materials could aid in the discovery and exploitation of needed resources. Without realizing what was happening to their academic-intellectual exercises, geologists were generating information that had practical value.

An early example of the practical value of geologic knowledge was the recognition about 100 years ago of the Burning Springs-Fly anticline in West Virginia and Ohio and the subsequent development of the anticlinal theory of oil accumulation. Later followed I.C. White's carbon-ratio theory, and N. Wood Bass' shoe-string sands concept. These, and many other ideas, represented the application of basic geology to the exploration for mineral resources.

In the early 1900s it became evident that the formerly academic science of geology could be put to practical use in the development of mineral resources; this realization prompted many of the states (including Illinois) to establish state geological surveys to develop basic data that would lead to the development of mineral industries in the state. In several of these far-sighted states (including Illinois) this investment in scientific investigation has paid off handsomely in the development of the state's industries. Even the federal government recognized this potential and established a federal geological survey.

For the first half of the twentieth century the conventional wisdom was that geology was valuable to society in only two general areas: (1) as an intellectual stimulus in the realm of natural philosophy, or later as earth history, and (2) as the generator of the basic data needed for exploration and development of mineral resources.

During this period, Hilgard, Marbut, Thorp, and others, who were quietly developing the science of soils, began to rely heavily on a background of geology, particularly on surficial geology.

Another application of geology emerged in the 1920s—engineering geology. The Illinois Survey's George Ekblaw was one of the pioneers in the application of geology to engineering problems; in fact, he was far ahead of his time when he advocated the concept of multiple sequential land-use planning. The use of geologic data and advisory input from geologists in solving engineering problems involving the subsurface, groundwater flow, foundations, landslides, and similar problems and questions has since become routine.

The term environmental geology was introduced less than a quarter of a century ago—again, by the Illinois Geological Survey. Environmental geology is the application of geologic data, expertise, and advice to the adjustment of human activities to the opportunities and the limitations of the physical environment. Environmental questions and concerns go beyond the realm of geologic applications, of course, but many of them have an important component that is basically geologic. These areas include, in addition to the generally accepted problems of engineering geology and groundwater geology, such societal concerns as land-use planning, with all its ramifications: flood-plain zoning, foundation conditions, geologic hazards of landslides, earthquakes, volcanic activity, subsidences, undermined areas, waste management, geologic components in problems of air pollution and water pollution, and many local problems.

From the foregoing discussion it might appear that over the past hundred years geological science has evolved from an esoteric intellectual exercise to a fully applied science in the service of society. Unfortunately, I have the personal impression that this is not the case. For a body of knowledge, or science, to serve society properly there must be meaningful communication and mutual understanding, and it seems to me that this communication has deteriorated rather than improved during the past quarter century. Geology and geologists have become more specialized, their language more complex and obscure to the general public, their erudition more focused toward their scientific colleagues than on outsiders, and perhaps even their attitudes less focused on general societal concerns than on their own narrow self-interests.

This situation has led to a deplorable lack of transfer of information from the geologic community to the political decision makers. I hasten to add that this lack of information transfer is only half the fault of the geologic community, and there are some notable exceptions to the lack of effort on the part of the geologists.

In the next few decades, geologic data and advisory input will be needed more urgently than has ever been the case. Therefore, it behooves both geologists and public decision makers to enter into a serious dialogue for the transfer of basic information for the future wellbeing of society. By this I do not mean just the description of spectacular events such as the explosion of Mt. St. Helens, but rather, basic information for the general public—the ultimate decision maker—about the occurrences, extent, and availability of mineral resources, the character and necessary protective measures for natural hazards, the future availability of groundwater supplies, and basic principles of land utilization. When we view an exponentially increasing population set in apposition to finite mineral and land resources, the urgency of the situation becomes apparent.

Examples of the continuing lack of information transfer abound, but I will mention only a few to illustrate the point.

Public awareness of the problem of diminishing resources is probably the greatest in the area of energy availability; the public—including many public officials—understand least the basic data in the area of nuclear power. In this highly interdisciplinary activity geologists are vitally involved in several phases of the work: the discovery and production of the mineral raw material that becomes the fuel for the operation, the selection of sites for the power generating facilities, the engineering geology work in construction of the plants, and the disposal (in or on the earth) of the toxic waste products of the operation. The public is very concerned about nuclear power and there is a serious lack of understanding of the facts of the industry. In this field, the chemists, physicists, engineers, and biological scientists, along with the geologists, have a severe problem of information dissemination and public understanding. The lack of meaningful information leads to the development of widely held notions of unsolved problems and inescapable catastrophies, whereas solutions are indeed scientifically and technically achievable.

It is, of course, in the realm of fossil fuels that geology has its maximum interaction with society, yet information exchange here is still far from being adequate or satisfactory. This lack of communication was dramatically emphasized earlier this year when a vice-president of one of the big three auto manufacturers stated in a national television interview (in response to a question as to why these manufacturers had not started earlier to design fuel-efficient cars) that it was unreasonable to expect motor car manufacturers to anticipate drastic increases in gasoline prices when they were designing cars for the future. One can only ask if their heads were in the sand when M. King Hubbert, more than 20 years ago, made his forecasts of petroleum supply declines, or when shortly thereafter, Hubert Risser, principal mineral economist of the Illinois State Geological Survey, documented this problem with particular reference to midwestern United States. This was a dramatic example of failure of information transfer. One might contend that this failure was not the fault of geologists, but rather the fault of policy makers for not knowing the facts because the critical information had been published in the scientific literature.

This is an excellent illustration of the very point that I am attempting to make: geological scientists who talk only to other geological scientists have little impact on the society. It is only when such information is translated and transmitted to decision makers that the science of geology serves the needs of society. Whether or not we wish to admit it, that translation is the responsibility of geologists; the public and private decision makers are not equipped to do it.

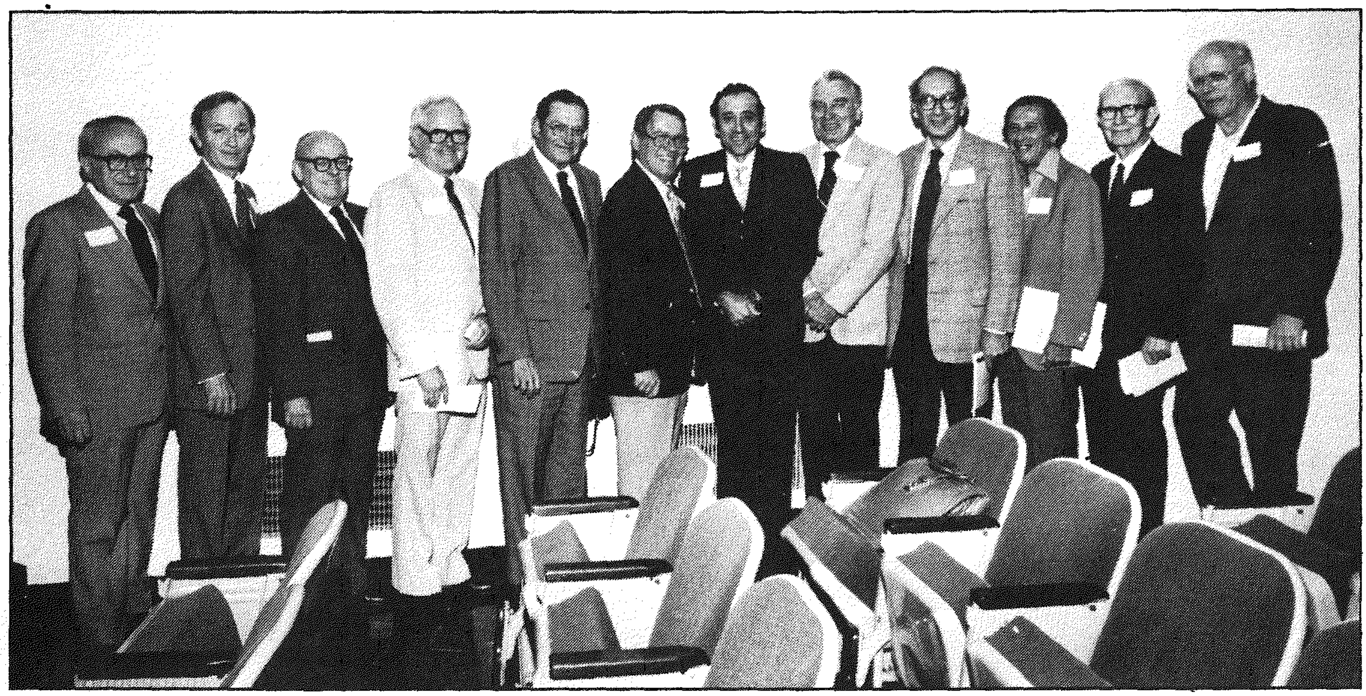
A totally different societal impact involving a different group of geologists exists in the area of land-use planning. During the first several hundred years of settlement of what is now the United States, land was the most expendable commodity imaginable. Vast areas of unsettled—and in some cases unexplored—land extended to the west. It was a commodity to be used or misused at will. During the last half century, land has become one of our most precious assets, to be used wisely and protected. Unfortunately, that message seems to be very slow in penetrating public consciousness. The science of geology provides data essential to sound decisionmaking about the use of our land resources—data on soils, minerals, and water are all of concern. Other factors to be considered are topography, subsurface characteristics, slope stability, flood plain characters, engineering and waste management considerations, and climatic and biological factors. Geologists pioneered in developing basic data essential to proper land-use management, but it is appalling how few public managers and decision makers know or use the geologic data essential to proper planning and zoning. Here again geologists must accept at least part of the responsibility for getting relevant geologic data to the people.

Problems connected with nonenergy mineral resources have attracted little public notice so far; nevertheless, this is an area that will have major societal impact in the not-too-distant future. Shortages of many essential mineral commodities either already exist or are developing in the western hemisphere, especially in the United States. Geologic investigation can generate data leading to the discovery of new domestic sources of these commodities or to ways of utilizing more efficiently the minerals we do have, thus decreasing our dependence on foreign sources of supply.

In recent years the science of geology has played a significant role in the study of extra-terrestrial bodies such as the Moon and Mars. Although the immediate impact on such study on society may not be particularly clear, it seems certain that it will in the future.

After enumerating the many areas to which geologic knowledge can apply and the economic advantages that can, and should, be derived from geology, let us not forget that the science of geology originated as an intellectual-philosophical experience and still has much to offer in increasing our understanding of the history of the Earth and the origin of its rocks, continents, and organisms.

The science of geology is vital for society. Geologists must be responsible for both the development of the science and the communication of their research.



Symposium participants (left to right): Jack A. Simon, John Hower, George H. Davis, Allen F. Agnew, John C. Frye, Richard F. Mast, Harold J. Gluskoter, Gordon W. Prescott, Raymond Siever, Heinz A. Lowenstam, H. B. Willman, and Paul A. Witherspoon.

Symposium Program

THURSDAY, OCTOBER 9

Registration, open house and tours, 8:00 a.m.-12:00 p.m.
Natural Resources Building

Symposium, 1:30-4:30 p.m.
PERSPECTIVES IN GEOLOGY
Law Building Auditorium
Chairman: John Hower, Chairman, Geology Department, University of Illinois

The Illinois State Geological Survey—The Next Quarter Century
Jack A. Simon, Illinois State Geological Survey

Coal Geology: Who Needs It?
Harold J. Gluskoter, Exxon Production Research Co.

U.S. Petroleum Exploration—Likely Targets 1980-2000
Richard F. Mast, U.S. Geological Survey

Perspectives in Groundwater
George H. Davis, U.S. Geological Survey

Perspectives in Non-fuel Minerals
Allen F. Agnew, Library of Congress

Reception, 5:30-6:00 p.m.
Levis Faculty Center

Anniversary banquet, 7:00 p.m.
Illini Union Ballroom
Master of Ceremonies: Frank H. Beal, Director
Illinois Insititute of Natural Resources

Geology in the 80s
Laurence L. Sloss, Northwestern University; Member, Board of Natural Resources and Conservation

FRIDAY, OCTOBER 10

Symposium, 9:00 a.m.-12:00 p.m.
PERSPECTIVES IN GEOLOGY
Law Building Auditorium
Chairman: H.B. Willman, Emeritus
Illinois State Geological Survey

Geological Problems in the Geochemistry of Sediments
Richard Siever, Harvard University

Biominerals, Tracers of Evolution, Paleoecology and Impact of Life on the Biosphere
Heinz A. Lowenstam, California Insitute of Technology

Perspectives in Engineering Geology
Gordon W. Prescott, Purdue University

Radioactive Waste Storage in Mined Caverns in Crystalline Rock
Paul A. Witherspoon, Lawrence Berkeley Laboratory, University of California

Geology and Society
John C. Frye, Geological Society of America

Open house and tours, 1:30-4:30 p.m.
Natural Resources Building