U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

CHALLENGING QUESTIONS FOR GEOLOGY AND GEOPHYSICS IN THE 21ST CENTURY

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Open-File Report 92-515

Prepared for the University of Oklahoma Centennial
and delivered November, 1990

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INTRODUCTION

When one reviews the advances of the last 50 years in the earth sciences, one recognizes the hazard of trying to forecast advances over the next 10 years much less into the next century. But trying to do this is irresistible, and it may be a valuable exercise in getting ready for a new century. In addition, there were speculations by some during the 1970s that, in the 21st century, geologists would become the equivalent of the lawyers of the 20th century. So let's proceed. In doing so, let's not forget the famous quote of von Neumann (1955) regarding the development of nuclear energy, "Consequently, a few decades hence energy may be free -- just like the unmetered air -- with coal and oil used mainly as raw materials for organic chemical synthesis, to which, as experience has shown, their properties are best suited."

We must consider that some major challenges of the past have been answered to the maximum degree that they can be answered. For instance, we are unlikely to discover any new stable elements. Another good example is the age of the earth which was determined nearly 40-years ago to be 4.5-billion years (Patterson, 1953). Efforts have been made to refine this age; however, careful modeling suggests that it took tens of millions of years for the earth to approach its present size. Thus if one wants to refine the age of the earth further, then one will have to state the stage in the accretionary formation of the earth that is being considered. A second complexity arises from the vast amount of ongoing research in the earth sciences. Currently, it is hard to think of a topic so unusual that it doesn't have at least one symposium and at least one book devoted to it. Although some major advances seem to be discovered by accident -- e.g., the impact theory of extinction being one (Asaro, 1987) -- most actually occur in programmatic areas -- such as plate tectonics in the years of the Upper Mantle Program. So if we can guess the likely major programmatic areas, then we can probably get some idea at least of the challenges if not the specific accomplishments that will occur. First, let's see if we can identify some things that are bound to happen.

I. GLOBAL POPULATION GROWTH

As a starting point, all the experts seem to feel that global population is bound to increase at the current rate until the middle of the next century, if not longer, thus more than doubling the present number of over five billion. So, the first challenging question is, "How does a more than doubling of global population impact the earth sciences?"

A. Food Production

The first challenge that comes to mind is how such an immense population will be fed? The effects of global population growth on the earth sciences could be less than we might at first think. In England, Malthus (1798) was postulating increasing starvation with increasing population growth because population was growing geometrically while he presumed that agricultural technology grew arithmetically. Certainly the population of England has increased considerably since then, but probably fewer British are starving today than there were then. To be sure, starvation is present in the world, but it seems to be less than in the days of the great famines in India, in spite of major global population growth. Starvation today is more a problem with global food distribution than with global food production. Indeed, U.S. farmers have been badly affected by competition from new food production lands in India and Brazil and are frantically pursuing alternative uses for agricultural products.

Although one reads that all the best agricultural land is now in production and that the limits of the green revolution are at hand, one suspects that such forecasts have long been the norm. Do we really know the limits of gene splicing on agriculture, for example? So far, technology has done a remarkable job of increasing food production. For example, rice has been developed that can be grown on dry land, removing the need for familiar rice paddies. The challenge in food production for the earth sciences lies in the area of making fertilizer usage more efficient, and perhaps in making the nutrients in soils that currently are not available to plants more accessible. One recent example involves application of certain zeolite minerals to help retain nutrients and to cut down on the over-application of fertilizers.

Much of the increase in global food production is attributed to so-called high-tech agriculture that relies heavily on the use of commercial fertilizers -- such as nitrogen, phosphorous and potassium -- and pesticides. Although uneven global distribution of fertilizer deposits has presented problems, shortages have not yet appeared. In fact, a major phosphate deposit in Saudi Arabia is yet to enter production. Problems with supply of natural fertilizers may develop before the end of the 21st century; however, the need for some fertilizers may actually decrease because of technological advances. For example, some feel that it may be possible to develop plants that acquire their nitrogen from the atmosphere through respiration, just as they do now for carbon. Development of the use of nitrogen-fixing rhizobial bacteria by nonlegumes, including rice, currently shows some promise (Moffat, 1990). Although sulfur is not a normal component of commercial fertilizers, it is considered to be number four on the list of essential nutrients for plants. Some vegetation apparently has converted to obtaining sulfur from the atmosphere, the sulfur coming from atmospheric pollution. One of the fascinating aspects of modern times is the recognition of just how interactive so many things are. For example, in removing sulfur emissions from the atmosphere, many plants may be put under sulfur-deficiency stress.

B. Natural Resources

1. Water Resources

The availability of water for the populated drier areas of the United States and the world is unquestionably the major resource problem of the future. As water resources are being consumed faster than they are being replenished, it is more proper to talk of water as being mined than as a renewable resource. As the global population grows, the water problem can only increase. The challenge to the earth sciences is not so much to find new water resources because the major resources are reasonably well known, but to find new ways of better storing water, to retain water where it is needed (In the United States, agriculture consumes about half the water used.), and to forecast future climatic conditions.

2. Mineral Resources

Forecasts were made in the 1970's that mineral resources would begin to be scarce early in the 21st century (e.g., Folinsbee, 1978); however, mineral problems are not serious at present because of the use of alternative materials for metals and abundant supplies of fertilizers. Increased use of alternative materials can be expected to continue -- e.g., the ceramic automobile engine and perhaps rare-earth elements in electric power production. In addition, conventional ore deposits of great size and high grade (e.g., the Red Dog Creek zinc-lead-silver deposit in the Brooks Range of Alaska) are still being brought into production. Some political problems occur associated with the uneven distribution of minerals around the globe, just as there are with most other natural resources. Exploration indicates, however, that for at least one strategic metal with a highly localized production, platinum, new sources may well be discovered. For example, the United States now produces platinum from the Stillwater complex in Montana, and showings of platinum mineralization occur in the Duluth gabbro of northern Minnesota. And every so often a new kind of mineral deposit is discovered, recent famous examples being the polymetallic Olympic Dam deposit in Australia and the rare-earth deposit of Bayan Obo in China. A number of unconventional resources are yet to be touched -- sea-bed mining is perhaps the most prominent example and could yield more than 1,000-years supply of some elements (e.g., manganese, nickel, and cobalt from manganese nodules in the Pacific Ocean (Mining Industry Council, 1990)). Such mining likely will be fraught with political and environmental problems.

I don't mean to say there are not some challenges. For example, even if the global growth in consumption of copper or zinc during the rest of this century is only about 1.5 percent rather than the 2.5 percent growth rate in the interval from 1965 to 1988, the <u>increased</u> annual production needed will almost equal the output of the 10 largest mines of copper or zinc today (Mining Industry Council, 1990). In addition, the need for new and improved methods of exploration for concealed mineral deposits is well recognized. To find concealed deposits, a better understanding is needed of the entire ore-forming process -- from source through transport to deposition and to post-depositional aspects. A particular challenge is improvement of our abilities to find high-grade, high-tonnage mineral deposits (e.g., Red Dog Creek), not only for economic reasons but for environmental reasons as well.

3. <u>Energy Resources</u>

Energy resources may be more tricky to forecast. Coal will continue to be the main source of basic energy in the world for at least the next 20 years. Fortunately, global coal resources seem adequate for that period and maybe the century. Oil and gas resources have been studied more extensively than other natural resources and may be more limited globally than coal or minerals. The estimated maximum petroleum reserve has held steady at about 2000-billion barrels for considerably more than a decade (Masters et al., in press). As examples, Folinsbee (1978) estimated the maximum figure for oil to be 1,814 billion barrels, whereas the 1985 figure from Masters et al. (1987) was 1,744 billion barrels. In addition, the uneven global distribution of oil and gas also leads to periodic problems. The trend is of particular concern in the United States because we use 26 percent of the world's oil consumption, two-thirds of which is used in transportation. Our average annual decline in oil production has been 1.6 percent over the last decade (Energy Information Administration, 1990). Production is expected to drop steeply in the United States and the Soviet Union early in the 21st century and in the Middle East later in the century. These trends could be somewhat ameliorated but not reversed by enhanced oil recovery techniques and fuel conservation measures. Some alternative fossil fuels may help with a transition (e.g., the supergiant unconventional deposits in places like the Athabasca tar sands of Canada and the Orinoco extra-heavy oil belt in Venezuela, as well as unconventional natural gas resources). These unconventional sources, however, require major technological breakthroughs to achieve substantial resource production. The energy equivalency of conventional natural gas is about equal to that of petroleum (Masters et al., in press); however, a breakthrough in producing natural gas from tight sands, coal, shale, or hydrates could increase reserves in a major way. Although much is known about these commodities, fundamental knowledge of the sources, the reservoirs, the migration pathways, and the chemistry of the fuels themselves still needs to be gathered.

Earth scientists will be challenged to provide the basic data and interpretations needed to assess, identify, and recover the changing sources of fossil fuels. In addition, some research is going on in several countries to produce energy that is low in carbon-dioxide emissions by what is called hot-dry rock (HDR) geothermal power which should help with basic energy production and heating applications (Batchelor, 1987). In the HDR method, water is pumped underground in one well, is transmitted through fractures where it becomes heated, and is extracted from a second well. Although the greatest potential of HDR is in areas of high heat production, in theory it could apply anywhere by drilling deeper holes. There is a long way to go before HDR is a reality; however, if we talk in terms of the 21st century, then the current small efforts on the HDR method may bear fruit. There is also the possibility that fusion power may come on line, but the time frame for energy production has been 30 years for many years. The impacts of this energy source on the earth sciences are yet unclear.

Pursuing the complexities of our modern world, energy is interconnected with mineral resources and agriculture. For example, high-grade, high-tonnage mineral deposits save on energy because less rock must be mined to obtain a ton of metal, and, of course, there is also less polluting waste. Although there are objections to supersonic air transport because of sound and stratospheric ozone layer pollution, it is the high cost of fuel that has made supersonic transport impractical.

C. Environmental Concerns

As the global population increases, the big challenge for the 21st century undoubtedly involves growing environmental concerns, or what I have called "The Challenge of Global Housekeeping" (Doe, 1990a). Many of us grew up thinking of geology as an historical science; we might study the present, but most often it was to gain a better understanding of the past. As environmental concerns increase, a major part of geology has been transformed into a predictive science, with the twist that the present and the past are being studied to understand the future (Doe, 1983). In addition to its predictive nature, environmental earth science is also refocussing emphasis on time scales of less than one-million years. The concerns involve those of a local nature involving natural phenomena (such as earthquakes) and anthropogenic influences (such as quality of water as a result of waste disposal). Past environmental movements have usually dealt with environmental concerns as local initiatives --e.g., the closing of many smelters in the 1920s by county or State governments.

Increasingly, we are becoming aware that many anthropogenic influences also are of a global nature and are gaining increased attention from national governments. The seriousness of these many concerns has given rise to a new and rapidly growing field of scientific endeavor -- environmental geochemistry (e.g., Doe, 1990c). Earth scientists are particularly well equipped for integrating the chemical, the biological, and the geological aspects of these complex problems. We may have a good vision of the challenges to the earth sciences in environmental concerns. Some of these are as follows:

1. Greenhouse Gas Buildup In The Atmosphere

A good example of global concern is the buildup of so-called greenhouse gases in the atmosphere (e.g., carbon dioxide, methane, nitrous oxide, chlorofluorocarbons or CFCs, and tropospheric ozone). Although the buildup of these gases is a fact, the effects of the buildup are less clear because of the complexity of nature. The best estimates are that the global atmospheric temperature is rising, about 1/2°C during the last century. But there are disturbing aspects to the estimates. One is that the carbon dioxide buildup in the atmosphere is only about one-half what calculations from organic carbon consumption figures indicate it should be. Where the other half is going is not yet clear. Initially researchers assumed that it was being absorbed into the ocean; however, at least one study disputes this hypothesis and suggests that land plants must be more important than thought (Tans et al., 1990).

Another aspect is that the temperature rise is only about one-half what General Circulation Models calculate it should be. The solution to that observation also is not clear. The usual speculations are that heating is being counteracted to some degree by buildup of low-level clouds or by absorption into the oceans. One recent paper finds a buildup of nonvolcanic stratospheric sulfuric acid, which would have a cooling effect to counter a tropospheric temperature rise (Hofmann, 1990). Presumably, this sulfur comes from burning fossil fuels and deforestation, but increased air travel near the tropopause should also be considered.

Some researchers even question the linkage of the greenhouse gas buildup to the temperature rise and suggest that it is still a rebound from the Little Ice Age that ended less than 100-years ago. The problem is further confused by the inability of researchers to explain the global cooling period from 1940 until about 1970 and an inability to find a long-term temperature increase in North America. So the important challenges remain -- How much will the temperature rise and how fast will it occur?

Other concerns, however, transcend temperature rise. According to Dyson (1990), for example, the missing carbon dioxide may have profound consequences depending on where the carbon is going. A few other of these concerns are: whether glaciers will increase or decrease, whether atmospheric storms will increase in number and severity, whether droughts will increase in number and severity, and whether sea level will rise drastically. Because humanity tends to concentrate near the oceans, what happens along the coasts is of particular importance. In fact, nature could counteract a global temperature rise if she wished, through increased cloud cover or increased absorption of heat by the oceans, but there are likely to be effects from greenhouse gas buildup anyway. Little thought has been given to the nature of such effects (Doe, 1990b).

Acid rain has shown again how environmental concerns are interconnected. Although there is a negative free energy in the reaction of sulfur dioxide to sulfuric acid in nature, it is not large enough for the reaction to proceed spontaneously. Nitrous oxide and tropospheric ozone (the prime atmospheric oxidants) appear to enter into the reaction to catalyze it, and ozone is consumed in the conversion of sulfur dioxide to sulfuric acid in the production of acid rain. It has been suggested that taking sulfur-dioxide emissions out of the atmosphere may worsen the tropospheric ozone problem. Many of us are not used to thinking of atmospheric sciences as geophysics, but we should recall that the American Geophysical Union has long had a section of atmospheric sciences.

Solid-earth science has much to contribute to the issue of global climate change. One easily could come up with models that the earth's climate is perfectly buffered were it not for studies of the geologic record. At one time, glacial ages were considered to be a great mystery, and still are to a considerable extent. In his landmark study on the effect of carbon dioxide on global climate, Arrhenius (1896) tried to determine if variations in atmospheric carbon dioxide could cause such events as the glacial ages. The geologic record shows evidence of global temperatures as great or greater than the present, and carbon dioxide levels presumably greater than the present. Paleoclimatology provides many interesting challenges. These include obtaining better methods of determining ancient atmospheric carbon-dioxide levels and determining if the fluid inclusions in amber really do give accurate measures of ancient oxygen level. Perhaps the greatest challenge lies in determining paleocloudiness. No good ways even have been proposed on how to make this measurement even though clouds play a key role in climate. A similar major challenge is provided by ancient solar luminescence. Because many of these kinds of studies rarely have been considered in the earth sciences, they provide new and exciting research frontiers that were considered the most basic of basic science just a few years ago.

2. Natural Hazards

Local damage problems (e.g. landslides, earthquakes, volcanic eruptions, violent storms) also turn out to be of global concern. Landslides and other forms of mass movement, for example, occur over much of the surface of the earth. Some other problems are more restricted in location, such as earthquakes and volcanos; however, humanity also tends to concentrate near these locations of natural hazards so they have a disproportionate effect. Once again we discern interconnections among the concerns. Many landslides are triggered by earthquakes, for example. Forecasting natural hazard occurrences remains a key issue. Considerable progress has been made in landslide and volcanic eruption forecasting, but earthquake forecasting remains in its infancy although we seem to be creeping up on it. Progress involving recognition of such factors as recurrence intervals, seismic gaps and quiet zones, magnitude frequencies, and characteristic earthquakes is helpful but has not made reliable forecasts possible.

3. Water Quality

Pollution of ground and surface water and estuaries continue to be of growing concern, which can only be expected to grow as the global population increases and its standard of living rises. Because estuaries are commonly population centers, all estuaries even now may suffer significant pollution problems. It may be that only five or 10 percent of the ground water is contaminated, but people are concentrated around where the contamination occurs. A challenge is to determine when unconventional water resources, such as very deep aquifers, should be developed, and when expensive treatments of conventional but polluted water resources or desalination of brackish or sea waters will be advisable.

The challenge to the earth sciences in agriculture, for example, is not so much in the area of food production but in agrochemical pollution. Little is known about how fertilizers, especially nitrates, and pesticides migrate through and, more particularly, to the water table. Little is known about how chemicals in general are taken up or released by geologic materials, such as clays. Some anthropogenic effects normally thought to be more local in nature are being found to spread farther than one would have thought -- e.g., pesticides. Others, like acid rain, may not be global in nature but can and do cross many political boundaries. A number of these kinds of pollution will disappear in time, but will this be years, decades, centuries, or longer? Determination of such natural mitigation will require a better understanding of chemical and physical hydrology.

Paleohydrology is a growing field that is involved with past fluid flow in the rocks and with the effects of rock-water interactions as various elements and compounds migrate. The topic is finding increasing emphasis in energy and mineral resources, as well as in pollution concerns.

4. Radioactive Waste Disposal

In contemplating radioactive waste disposal, someone, in say 1950, who said that he was trying to forecast climate for the next 10,000 years, would have been considered to be very much in an ivory tower. In the late 20th century, however, radioactive waste disposal has come into the regime of applied science, along with many other "rate" problems such as rates of uplift or volcanic activity. Because of the length of time being considered, safe disposal of radioactive waste -- and the fear the public has of anything radioactive -- pose the biggest challenges of all. There is a great fear about the geologic storage of radioactive waste; in particular, the best disposal sites are not where the nuclear power plants are. This fear of radioactive waste probably will not be solved in the next decade and, thus, disposal of radioactive waste remains a challenge for the 21st century.

In the United States, focus on radioactive waste disposal has become concentrated on the unsaturated zone, which has been little studied in hydrology. Because a great unknown in agrochemical pollution also involves the unsaturated zone, it forms an important challenge for research in the 21st century.

A discovery made while evaluating granite as a radioactive waste disposal repository in Canada has led to a topic of broad interest. The hydrology of granite has been little studied in the past because granite is not a major source of ground water. In the Canadian study, it was found that the water in Archean granites at depth are often brines. Current thought is that these brines come from dissolution of Paleozoic evaporite deposits in the geologic sediments above. Because the brines are dense, they sink and displace any preexisting water in the granites, and, may sit in the granites for very long periods of time, perhaps millions of years or longer. If the thermal pulse from radioactive waste does not cause significant brine flow, then the brine horizon in granite may be an attractive site as a disposal media. Finding brine in granite is not only of interest to radioactive waste disposal, but to other fields as well. Because of anion complexing, the brines are often rich in heavy metals and form a latent ore-fluid awaiting some geologic event to mobilize the brines into some site favorable for deposition of an ore body. A better understanding of brines in ancient granites is another challenge for the 21st century.

5. Essential Elements and Toxic Substances

Earth scientists can contribute to concerns involving essential elements and toxic substances in many ways (Doe, 1990c). Emphasis on the character of soils and other surficial deposits can be expected to increase. Many elements that are toxic in high concentrations are essential for life in low concentrations; selenium and copper are good examples. In many parts of the world, some of these essential elements are in inadequate abundances, and people and livestock can suffer from dietary deficiencies in them. Geochemical maps of soil chemistry can be helpful in dealing with the problem. Some minerals are thought to be harmful (e.g., some rare types of asbestos) as well as are the natural distribution of radioactive emanations (e.g., radon), and their distribution will need to be determined. Geophysical methods (e.g., ground-penetrating radar and complex resistivity) are able to trace ground-water pollution plumes. Maps of glacial till and other surficial sediments can outline likely pathways for shallow ground water. A number of other challenges are given in the section on water resources.

6. Conservation

The quickest way that humanity can approach many problems associated with increasing population is through improved conservation of all commodities, including water. Conservation is a perplexing problem for earth scientists because so many considerations involve the manufacturing process (e.g, recycled materials, more efficient powerplants, higher mileage automobiles, etc.) that few opportunities seem to exist for earth science contributions. Challenges exist nevertheless. As high-grade, high-tonnage ore deposits generate less waste and consume less energy, they tend to be more environmentally "friendly" than their more ordinary counterparts. Increasing grade of ores remains a vital goal for resource explorationists despite huge strides in mining- and resource-recovery technology.

7. Conclusions

Although some interesting challenges await us in the areas of agricultural food and mineral-resource production, the biggest challenges are likely to come in the relatively new area of environmental concerns as a consequence of increasing global population and as third-world societies strive to attain a Western style of living. Perhaps the most important lesson that we are beginning to learn is how broadly interconnected so many things are. Consequently, we are going to have to learn how to treat the earth as a system, and not just deal with individual problems. There is already a name for this -- Earth System Science.

II. INFORMATION AGE

Perhaps nothing is more astounding than the influence of the computer in our lives. To think that one can go to a bank or even a grocery store at anytime of the day or night and withdraw money, deposit money, transfer money, or find out the sums in one's accounts is an extraordinary reality. During the mid-1970s, the U.S. Geological Survey bought one of the first VAX computers. It came with 4 - 64 kilobyte boards for 256 kilobytes of random access memory (RAM) at a cost of hundreds of thousands of dollars. This computer needed a large room of conditioned space. Less than two years ago, however, one easily could buy microcomputers of the 286 class that would operate at 12-megahertz speed with one megabyte of RAM and a good printer for less than $3000. This microcomputer could easily sit on a desktop and operate on house electric power under normal room conditions. Now one can buy 386 class microcomputers for the same price that are faster, 16 megahertz, and have two megabytes of RAM. In the meantime, the 286 class of microcomputer has dropped in price by about $1000. Performing at least elementary Geographic Information System analyses has become possible for the individual. Can one doubt that progress will continue in reducing size and cost while increasing capacity, reliability, and convenience of computers? Surely over the next century, voice recognition computers will find great utility.

In order to handle most significant geologic problems, however, one rapidly outstrips the capacity of even the largest and fastest of the vector processing supercomputers and massive parallel processing computers. General Circulation Models in climate investigations can involve millions of equations and rapidly exceed the capabilities of even the current top-of-the-line computers. One cannot get very far into three-dimensional studies before supercomputers are needed. A few of these topics involve basin analysis, migration of seismic data, seismic tomography, and hydrologic modeling. As new equipment is developed, the earth sciences are bound to make use of them, but a number of important challenges need attention.

Enormous amounts of data already exist relating to an abundance of topics. A major challenge is how to utilize this data to the maximum and to build upon it rather than always starting from scratch. In one example, although geochemical exploration data are not as precise as is usually required for environmental issues, some geochemical exploration data was found to be of value in giving an initial assessment of the cause of the selenium problem at Kesterson Reservoir in California. Further, samples were already collected that could be reanalyzed for a second level of assessment by more precise methods and for elements of concern not previously measured in order to identify the source of the problem. In another example, a project being carried on for uranium resource purposes in Pennsylvania was rapidly reprogrammed into a radon emanation study when the household radon concern arose during the mid-1980s.

A major concern in computer applications is that the ability to perform calculations has outstripped the ability to assure that data of adequate quality are being processed. This concern is only going to grow. The problems are manyfold. It is not necessarily that bad data are entered into the data banks (although that is a problem), but that data that were adequate for the purpose for which they were originally collected are not entirely suitable for new applications. Sometimes machine processing of data can eliminate unsuitable numbers; other times machine processing of data causes an important observation to be missed. For example in processing satellite data over the South Pole, any anomalous data outside certain limits were automatically eliminated. Consequently the ozone hole over the South Pole was originally missed. The need for large data sets is clear. The challenge of properly utilizing them is a problem that is far from being satisfactorily solved. Thus, the information age enables us to answer some very difficult questions, but, not surprisingly, poses others of even a more complex nature.

Data are becoming so abundant that there is a real hazard of trying to overpower problems with data and substitute data for thought. The converse is also true -- the data available is so massive that there is a tendency to overly edit data and use only one's own and that of a few colleagues.

III. <u>INSTRUMENTATION</u>

Earth science is at an interesting watershed in its history. For the first time, the instrumentation exists to obtain all the principal kinds of data that are needed; for example, all the elements at ambient levels and all the principal isotopes can be directly analyzed. In seismology, high quality, mobile seismic systems are available. In active tectonics, high quality, portable Global Positioning Systems also are available. Various electrical properties are being measured in abundance. As of the 1980s, all the pre-1940s instrumentation of physics was being used in the earth sciences, even the synchrotron and the Van der Graaff generator. Some developments of the 1940s, such as aeromagnetic surveys, have been in use for decades. Many post-1940s instrumentation is already in abundant use in the earth sciences. Some of these are nuclear magnetic resonance (NMR), Auger, Raman and Mossbaur spectrometers, ground-penetrating radar, airborne gravity gradiometry, tandem-accelerator mass spectrometers (TAMS), proton-induced X-ray emission accelerators (PIXE), atomic absorption (AA), induction-coupled plasma mass spectrometers (ICP-MS), and so forth. Many of these have not achieved a mature usage status.

A major trend has been towards use of various kinds of microprobes. Although the electron probe has been in use for 30 years, other kinds of microprobes had to await the growth of the computer industry, which requires such instrumentation and which finally crystallized in the 1980s. Examples are the PIXE probe, the SHRIMP-class ion-probe mass spectrometer (SHRIMP stands for Sensitive High Resolution Ion Microprobe), and synchrotron light. Nearly every field saw great advances in instrumentation in the 1980s. Other examples are the global seismic array, the diamond-anvil high-pressure press, the hypersonic impact gun, portable Global Positioning Systems, and deep continental drilling to depths greater than 10 km. We have experienced difficulty in getting many of these kinds of instruments into United States earth science facilities at all or in adequate numbers; however, all such instrumentation is in use in some laboratory in the world.

Some of the advanced instrumentation exists in abundance. Electron probes and automated multicollecting mass spectrometers (either for light-stable isotopes such as oxygen, or for radiogenic isotopes such as lead) may be as common in laboratories today as X-ray diffractometers were in the 1950s. Rather than a need to develop new instrumentation, the challenge is more to obtain an adequate quantity of the new instrumentation of the 1980s and also to upgrade outdated equipment in laboratories.

Some frontiers remain. Perhaps the most notable of these is the resonant-ionization (or laser-ionization) mass spectrometer (RIMS), which has been used for analyzing the osmium-rhenium isotopic system, but is gradually finding usage for other applications, such as light-stable isotopes. The potential of every new instrumentation may not be yet achieved -- e.g., the scanning-tunneling microscope -- but every new technique cannot be expected to lead to major usage. An example of one that hasn't, although it has been in existence for many years, is neutron diffraction, which has found some use in locating hydrogen atoms in mineralogy.

Over a 100-year period, there is always the possibility of some new phenomena being discovered. Consider 1890, for example, an even 100 years ago -- X-rays were not discovered by Roentgen until 1895, and Becquerel did not discover radioactivity until 1896. Thus one probably cannot forecast methods of measurement on a 100-year timetable. The proper approach is to estimate what we would like to measure rather than how we might measure it. One might have guessed in 1890 that we would like to estimate geologic time better and construct a quantitative geologic time scale or determine mineralogy better or analyze trace-element contents. And of course, methods were discovered in the 20th century to solve all of these desires. For an example regarding the 21st century, a new way of imaging the earth's interior would be valuable. Perhaps neutrinos or some as yet unknown phenomena will be found to fulfill this need.

Many breakthroughs occurred during the 1970s and 1980s that increased the ability to produce data in quantity and high quality while reducing sample size. Such advances can revitalize mature techniques. A good example is applications of radiocarbon research since the introduction of the tandem-accelerator mass spectrometer in the late 1970s which allowed radiocarbon to be measured for individual microfossils. We have probably not seen the end of this sort of advance.

Although there is still much value in increasing precision in many kinds of measurements, we are approaching the point where that is not necessarily going to lead to new scientific breakthroughs. When the measurement of radiogenic isotopes becomes precise enough to include effects of isotopic fractionation, further improvement in precision will have limited value, at best. For some of the isotopes of some of the elements like strontium, however, the natural fractionation may be removed by normalization. Once distances can be measured down to values involved in tidal effects, further gain from increased precision may have limited value. From this standpoint, it is interesting that horizontal distances can be measured about an order of magnitude better than vertical distances. Thus there is a challenge of being able to measure vertical distances as well as we can horizontal distances.

IV. BASIC SCIENCE

There are so many interesting and fundamental questions being asked by societal needs that applied research today has blurred the distinctions between basic research and technology. The challenge will continue to exist in technology transfer of findings in fundamental research to practical uses. It even can be hard to know how to classify things, however. So here are included some broad topics that might well be mentioned in an applied research section as well as some fundamental topics of no known application. Below are capsule comments on just five major challenges that are rather new to the earth sciences.

A. Mantle seismic tomography.

One of the most exciting developments of the 1980s was studies of mantle seismic tomography. We seem to be on the verge of being able to map circulating cells within the mantle and perhaps to resolve the problem of whether there is a one- or a two-layer mantle or whether it is a "plum pudding". The full importance of mantle plumes is just becoming apparent (To what extent are the surface expressions of plumes (hot spots), earth equivalents of sun spots?). The most interesting work done so far largely has used existing data collected over long time periods by various kinds of instruments. Not surprisingly, such data are not fully capable of being used to solve the key questions, although they point in certain directions. Further significant advances must await modern data taken with the new generation of equipment.

B. Thermal Structure of the Crust

The thermal structure and thickness of the crust are topics that might be classified as either applied or basic research. To what extent does the thickness of the crust depend on the thermal structure of the crust? The thermal structure is a key variable governing the state of stress and attenuation of seismic energy in the crust. It and its relation to rock rheology and tectonic structures, are also important but little understood parameters in intracontinental deformation. The role played by thermal structure on movement of fluids in the crust needs to be determined. In addition, such studies will be important in evaluation of the economic potential of low carbon dioxide energy generation from geothermal resources (e.g., hot-dry rock).

C. Fluids in the Lithosphere

Because the study of water in the earth has such practical applications, again one is uncertain how to classify fluid research. Brines in granite already have been mentioned. The role played by fluids in the evolution of the thermal structure in the lithosphere is another interconnection of topics. Another aspect is determining the extent to which pore pressure explains the low shear stress along the San Andreas fault and what role pore fluids play in rock rheology and intraplate deformation. Recent studies even shed optimism that the time of rock-water interaction through dating the formation of alteration (diagenetic) minerals (e.g., potassium feldspar and clays) will be determined. These studies promise to shed much light on the origin of natural resources, but they also bear on such societal concerns as toxic and radioactive waste disposal. Not all the emphasis is on water. Fluids produced in metamorphism are just beginning to be understood and are often carbon-dioxide rich. Carbon-dioxide-rich fluids appear to play an important role in the formation of many gold deposits.

D. Impact History and Extraterrestrial Flux

According to Marvin (1990), the extraterrestrial or bolide impact history of the earth ultimately may have a greater intellectual influence on the earth sciences than plate tectonics. She also points out that bolide impacts violate the law of uniformitarianism. It will be a challenge to the profession to test this opinion. The current popular theory for the origin of the Moon is that it was formed by a giant impact of a planetismal with the earth, thus making the Moon a hybrid body. One presumes that a consensus is achievable on the origin of the moon, and that achieving this may not be too many years or decades off. There is a constant bombardment of the earth with an extraterrestrial flux. An indication that this flux has important things to tell us comes from the iridium anomaly at the Cretaceous-Tertiary boundary. That is, the extraterrestrial flux can have compositions different from what we find naturally on earth. Indeed, the original intent of the study of the boundary clay at the Cretaceous-Tertiary boundary was to determine the rate of deposition of the clay through dilution of the extraterrestrial flux in it and not that the boundary clay might have an iridium excess (Asaro, 1987). Making sense out of this flux is certainly going to carry into the next century.

E. Solar System Evolution

The earth has experienced many changes due to external forces during its history -- e.g., the increasing length of the day, decreasing tidal forces as the Moon recedes from the earth, and a presumed increase in solar luminosity. At present, little independent evidence of such changes is found in the geologic record, and some researchers are looking into these sorts of influences as a frontier in the earth sciences. One recent interesting study used General Circulation Models from climatology to see what they might tell us about climate in the Archean when days were much shorter than they are now (Jenkins et al., 1990). Rhythmic banding in sediments is being used to try to learn more about the Milankovitch effect in nonglacial times (see Williams, 1989; review by Fisher, 1986). The Milankovich effect deals with possible climate influences from the systematic changes in earth's orbit around the Sun, the inclination of the earth's equator to the plane of the ecliptic, and the precession of the earth's axis. Solar system evolution offers many challenges for research in the 21st century and some investigations already have begun.

IV. CONCLUSIONS

As we look at the 21st century, it appears that the major challenge is going to come as a result of population growth. Within this context, the major concerns for the earth sciences are probably going to involve such environmental factors as ground water supply and pollution, radioactive waste storage, natural hazard concerns -- such as earthquakes, landslides and volcanism -- and global climate change. Such considerations will continue the transformation of the earth sciences into a predictive science with emphasis on less-than-one-million-year time scales.

This is not to say that natural resources will be without their challenges. The changing mix of energy sources as the century evolves will certainly challenge the earth sciences. Better ways need to be found to discover covered mineral resources that will require an understanding of the total process of mineralization. There is a major challenge to find more energy and mineral resources in environmentally less sensitive and politically stable areas of the earth. The information age certainly includes a growing share of challenges as more and more complex problems are considered and larger and larger data sets are utilized. As to instrumentation, the 1990s will be a watershed decade in which the introduction of major new kinds of instruments not before used in the earth sciences will be superseded by an age where obtaining improved instrumentation in adequate quantities is the challenge.

There will still be much to do in basic research. Some of the challenges involve mapping the mantle by use of seismic tomography (and neutrinos ?), and determining the thermal structure of the lithosphere, the behavior and effect of fluids in the crust, the role of extraterrestrial impacts and flux on the earth, and the evolution of the solar system , particularly solar luminescence.

The evolution in scientific knowledge and instrumentation that has occurred during the last half century is extraordinary. Concurrently, there is an equally significant change in human ethics toward the earth and therefore in the role earth scientists will play in the ethic of Global Housekeeping. This change will become increasingly evident in the years to come. Humanity will become increasingly aware of the interconnections among societal concerns, and of how the concentration of population along coasts and in zones of natural hazards (like earthquakes, landslides, volcanism, and severe storm areas) maximizes the impact of these natural hazards. Earth scientists will be right in the middle of the controversies that develop and will be expected to respond in thoughtful, non-cynical, and responsible ways to these challenges.

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