The Environmental Crisis: Quantifying Geosphere Interactions

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Summary. Because of increasing population, human activity has become a dominant process modifying the continents and their environment. Understanding the new environmental stresses includes studies of interface processes on all scales. The present scientific effort is inadequate and is not providing the data necessary for rational decision-making in critical areas, such as global energy production, land use, and resource development.

Despite all the advances in science and technology, man is feeling the limitations of his planet. Such limitations have been dramatically brought into focus by the recent *Global 2000 Report to the President* (*1*). This report predicts a 50 percent increase in population by the year 2000, a population that must be sustained by a 4 percent increase in arable land. In the 1977 report of the Club of Rome (*2*, p. 1) it is stated that "no longer can we afford to live in a world where a few prosper and most are near starvation." C. P. Snow has written (*3*, p. 27) that "local famines will spread into a sea of hunger." The President's committee on the health and environmental effects of increased coal utilization has identified two major global environmental problems, one of them acid precipitation and the other the increased emissions of carbon dioxide, with their potential effects on climate (*4*). Woodwell (*5*, p. 43) has said "carbon dioxide, until now an apparently innocuous trace gas in the atmosphere, may be moving rapidly toward a central role as a major threat to the present world order." One could go on, but the simple fact is that man is perturbing natural systems that once were assumed to have essentially infinite buffering capacity. As the perturbations have become recognized, our basic lack of knowledge of many fundamental environmental processes has become obvious.

In view of our present social and political situation, it seems inevitable that the human population will exceed 10 billion by early next century. Man of the modern industrial developed world uses 2×10^7 grams (20 tons) of new mineral material annually (*1*). For a billion people, about 15 percent of the global population by 2000, this annual usage (2×10^{16} grams) about equals in mass the most impressive geological processes of our planet, that is, ocean crust formation, erosion, and mountain-building rates. If we add to such a figure the amount of earth moved in agriculture, then there is no doubt that man has become the most important agent modifying the surface of our planet. We must understand the effects of this new situation where "environmental, resource, and population stresses are intensifying and will increasingly determine the quality of human life on our planet" (*1*, p. iii). It will be the responsibility of geochemists to provide much of the basic data necessary for adequate planning to minimize the strains.

One of the ultimate objectives of geochemistry is to understand the detailed history of the chemical elements as they take part in the major terrestrial processes. Most of our present approaches were established in the classic studies of Goldschmidt (*6*). According to the early concepts of the geochemical cycle (*7*), it was thought that, for the surface environment, the main processes consisted only of reactions of the hydrosphere, atmosphere, and crust. Influences of the deeper mantle were underestimated by orders of magnitude. Goldschmidt appreciated that the biosphere was of great significance, and he recognized that living organisms could be important in the concentration of some metallic species. But, for most earth scientists, these processes were believed to be of secondary importance to the major inorganic processes. It is only now that we are beginning to study the major chemical flux rates between the major geospheres (atmosphere, hydrosphere, biosphere, crust, and mantle). It is these rate processes that ultimately provide the global buffer systems. We now know that man is perturbing some of these rates on a scale that is easily observed.

Almost all the problems associated with understanding the rate processes that control environmental stability concern interfaces. There are the great interfaces between the atmosphere and the oceans, rainwater and the continental crust, ocean water and sediments, the living cell and the hydrosphere, and the crust and the deep interior. We are also concerned with the interface between the atmosphere and the radiation field of space.

Only in the past decade have earth scientists begun to appreciate earth dynamics and the scale of the interactions. We now know that the earth is a vigorously convecting body. One of the most spectacular discoveries of recent years was that the crust of the ocean floor, covering 70 percent of the surface, is geologically young, and that this crust is almost quantitatively recycled back into the mantle, to depths perhaps as great as 700 kilometers. The light material of the continents floats on heavier mantle and is modified by erosion and reconstructed near its oceanic margins. It is fascinating to look back at texts of the 1950's and 1960's (*7*, *8*), and to note that estimates of the quantitative influences of volcanism on crust formation were low by one or two orders of magnitude. The basic convective flux between the deep earth and the surface crust is now reasonably quantified, but there are still great gaps in our knowledge.

Geosphere exchange processes ultimately control the human environment, whether we are concerned with resources for energy, metals, agriculture, or with processes that lead to earthquakes and other geological hazards. But real understanding of these processes inevitably leads to considerations of interface processes on the atomic-molecular scale. The formation of soils and soil fertility depend on surface reactions between the minerals of a rock and ground water. The transport of a toxic metal may depend on its fixation in the cell wall of a microorganism. Our understanding of such interface problems,

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which control chemical transport, mobilization of the elements, and their subsequent fixation in new rocks and minerals, is inadequate. I recall from my student days a distinguished chemist who lectured on "terra incognita," the surface of the reacting solid. The geochemist is only now beginning to explore this land of surfaces, which control our environment.

Table 1. Natural and man-made fluxes of metals into the oceans (× 10^3 tons per year) (*1*).

Element	Natural	By man
Iron	25,000	319,000
Manganese	440	1,600
Copper	375	4,460
Zinc	370	3,930
Nickel	300	358
Lead	180	2,330
Molybdenum	13	57
Silver	5	7
Mercury	3	7
Tin	1.5	166
Antimony	1.3	40

Observation

The most urgent problem facing geochemists is quantification, on every scale, of the interactions that control our environment. There is reason for optimism that the required progress is possible. The geochemist must develop the data that will allow rational decisions to be made on global environmental problems.

Such optimism is based on the phenomenal advances in our ability to observe and describe natural systems on all scales. Exploration of the solar system is producing data on planetary atmospheres and surfaces which sharpen our ideas on the development of our own planet and the factors leading to the existence of life. Every space flight has produced scientific shocks. Observation of more than one planet is necessary if we are to begin to quantify the variables controlling the evolution of our planet. In more distant regions of space, modern spectroscopic techniques have revealed a host of complex organic molecules (*9, 10*), leading to the development of new hypotheses about the precursors of life (*11*).

For the first time, we can observe all of the surface of our planet. By use of the full spectral range of observation from satellites, we can monitor the atmosphere and the land surface, the distribution of soil moisture or salt, the growth of coral reefs, the destruction of forests or the development of deserts, and the motion of great faults. The nature of the atmosphere, with its multitude of complex photochemical processes (*12*), is being intensively studied; but, as the debate on stratospheric ozone concentrations has shown, these observations are not adequately understood, and recently (*13*) it was shown that changes in the carbon dioxide concentration may also change the ozone content of the atmosphere. The state of the art is shown by the fact that only now do we have the first measurements of sulfuric acid concentrations in the stratosphere (*14*).

The crust under the deep oceans is now being directly observed, and during the past year (*15*) the first submarine discovery and sampling of a rich sulfide ore of zinc and copper has been reported. The models for ore genesis in submarine environments, developed by economic geologists over the past decade (*16*), are being confirmed by direct observation.

At the core of the great advances in modern geochemistry are the advances in instrumentation for describing the chemistry and structure of inorganic and biological materials of the earth. It was not long ago that basic tools were restricted to the classical solution methods of inorganic chemistry, combined with optical spectrography and x-ray diffraction techniques. The techniques generally demanded tedious mineral separations, the scale of observation was often too large to permit resolution of the actual mechanisms of processes, and techniques for studying an interface or surface were almost nonexistent.

The advances in electron optics, photonics, mass spectrometers, their detectors, and the computers that are used in conjunction with the instruments, have brought us to the point where few systems cannot be realistically described. But the cost of solving the problems has also increased with the sophistication of the instrumentation.

Scientists at a modern versatile institute for geochemistry will require access to instruments such as electron microprobes, ion microprobes, x-ray fluorescence, and inductively coupled plasma and mass spectrometers. The new generation of electron microscopes, with transmission, scanning, and analytical capability, allows description of the nature of particles at the level of 20 to 50 angstroms, a vital requirement for many biomineralization processes. Modern mass spectrometers, coupled to small accelerators which eliminate molecular species, have detection levels close to one atom (*17*). Studies of the chemistry of the outer few atomic layers of a surface are becoming routine, through modern ESCA (electron spectroscopy for chemical analysis) and Auger techniques. In summary, we have tools from satellites to submersibles to electron microscopes with which to see our planet and its materials. Given the support, we can now begin to describe the phenomena that control our environment.

Energy and the Environment

If C. P. Snow's predictions are to be avoided, global energy production must increase twofold in the next two decades. Every energy option is associated with an environmental or resource stress. The data necessary for an intelligent choice among the various options are not available.

From the most recent report of the Club of Rome (*18*), one must conclude that, for the next decades, there will be increased use of fossil carbon in all forms and that nuclear fission will be used as an energy source. Although the options chosen by any nation are constrained, for the geoscientist the problems are global. In almost every issue of *Science* or *Nature*, articles appear that express the complex concerns of the scientific community in relation to the various forms for energy production. But the level of research, and the number of adequately equipped laboratories, does not match the scale of the problems.

Most of the flood of recent discussions on the problems associated with the utilization of fossil carbon fuels have focused on two outstanding aspects: the increasing concentration of carbon dioxide in the atmosphere (*5*) and the increasing acid precipitation related to emissions of sulfur and nitrogen species (*4*). The present rate of carbon emission to the atmosphere from all forms of combustion is about 5×10^{15} grams per year (*5*), another reflection of the scale of human activity (compare the rate of formation of new ocean crust, 3×10^{16} grams per year). The atmospheric carbon reservoir is about 7×10^{17} grams, so that human activity injects almost 1 percent of this reservoir mass per year. Atmospheric monitoring clearly shows that the buffer systems are not coping with this addition, and most recent work predicts temperature increases of the order of 2° to 3°C by the middle of the next century. Wigley *et al.* (*19*, p. 17) have recently written on the "scenarios for a warm, high-CO_2 world." In *Global 2000* (*1*, p.

37) we read, "a carbon dioxide–induced temperature rise is expected to be 3 or 4 times greater at the poles than in the middle latitudes. An increase of 5°–10°C in polar temperatures could eventually lead to the melting of the Greenland and Antarctic ice caps. . . ." But such views are frequently challenged, and Idso (*20*, p. 1463) claimed that "a doubling of the atmospheric CO_2 concentration would produce a change in T_0 [surface air temperature] practically indistinguishable from climatic 'noise.' " In view of the immense complexity of upper atmosphere photochemical processes [McEwan and Phillips (*12*) listed some 400 or so of importance], it is no surprise to find that, if the carbon dioxide concentration changes, concentrations of all species, including ozone, will also change (*13*).

The exact understanding of the consequences of increased carbon dioxide injection on climate and our survival involves a host of factors, including influences of volcanism, biomass fixation, ocean-atmosphere exchange, chemical weathering, biomass sedimentation, and dust production by man (*21, 22*). The interplay of these factors is not quantified. And, in addition to the basic planetary processes, one must recognize changing human activity. Will the Amazon forest system exist in the next century? If it does not and the green hell becomes the red desert (*23*), how will increased Atlantic sedimentation rates, promoted by increased erosion, change the environment? A recent report (*24*) indicates that deforestation is already increasing flooding in the Amazon.

The increased acidity of rain is directly coupled to fossil fuel and biomass burning (*4, 25*). Typical of the state of knowledge is the comment (*26*, p. 1): "the effects of acid rain on the Great Lakes region are not fully understood. The Great Lakes themselves are not in danger, but the threat to small rivers and lakes and river tributaries makes acid rain a concern for the Great Lakes ecosystem."

The solubility and the oxidation-reduction rate processes of almost all minerals and man-made materials are changed drastically by the unit change in the *p*H of rain that has occurred in the western United States over the past decade (*27*). For most sulfide ore minerals that release toxic metals (mercury, lead, cadmium) into the environment, solubility depends on the second power of the *p*H. Present-day monitoring of such processes is not adequate, nor are data for soil-rock-water buffer interactions.

Although these problems are widely recognized, the overall geochemical impact of fossil fuel and biomass combustion processes are only beginning to be emphasized (*28*). All biomass requires a wide range of trace metals to flourish. This is well illustrated by the chemical recipes used for productive growth media (*29*), which contain organic metal complexing reagents to maintain adequate concentrations of copper, zinc, and the like. The biomass and its debris, cycled at a rate of about 6×10^{16} grams per year, is one of the most significant metal transport mechanisms for the crust-hydrosphere system. Although such metals are frequently listed as either essential or nonessential, the common biological molecules are capable of complexing almost all metals, even the classic refractory immobile elements of the geochemist, such as titanium and zirconium, which are complexed by polysaccharide molecules (*30*). Coal typically contains a host of rare elements at elevated concentrations (boron, fluorine, nickel, copper, zirconium, lead, and uranium), perhaps a reflection of carbon filtration processes which enhance the original concentrations in plants and occur because of the high permeability of coal strata during the metamorphic processes that form coal. Thus coal mining moves to the surface and into the atmosphere about 20,000 tons of uranium per year, about 7 percent of the present world resource estimates (*1*). Recent studies of the nature of coal fly ash (*31*) showed the enrichment of mercury, lead, and uranium in this material.

For this most common energy source, mined in quantities of about 3×10^{15} grams per year, our knowledge of its chemistry, chemical structure, and the geologic factors bearing on such data, is totally inadequate. Our laboratory recently received some standard coal samples from the National Bureau of Standards. For these standards, the concentrations of only 14 elements are listed with reasonably certain values. Coals show great variation in composition (*32*), which must be fully understood in relation to the various options for coal utilization.

Through the use of coal and modern industry, man is again perturbing the mobilization of metals in the surface environment. Wood and Goldberg (*33*) reported that modern Baltic sediments contain seven times the cadmium, four times the lead, three times the zinc, and two times the copper content of a century ago. They also reported that the flow of mercury to the oceans has increased fourfold over the level before man was present. Table 1 illustrates the situation. But if the global acidity of rain continues to increase, such changes will further intensify.

The full potential of modern instrumentation for observation is not being used on problems of fuel chemistry. We must know exactly how elements are sited in the fuels: Are they in the minerals of the ash fraction, are they in organometallic complexes, can they be separated before or after utilization? The basic data are often lacking. If some of these impurity elements could be separated from the mass presently being utilized, they could supply much of the world's needs for copper, nickel, uranium, fluorine, and probably other elements.

The study of the detailed structure and chemistry of modern and fossil biomass is essential to an understanding of chemical transport processes in the surface environment. Present technology requires such knowledge, but the advances will also have profound implications for our understanding of this part of the geochemical cycle of the elements. Mass relations show that biological transport processes are quantitatively dominant for many elements.

Climate and the Geological Record

When one discusses the possible perturbations on climate that may be induced by man's activity, or natural phenomena such as volcanism, it is clear that the earth scientist has a unique role. Recently, it has been suggested that both our planet and Mars may have had "greenhouse" stages in their early evolution (*34–36*). It has also been suggested that early life on our planet may have initially been confined to thermophilic microorganisms (*9*) and that evolution was controlled by gradually decreasing ocean temperatures.

Numerous studies of the oxygen isotope systematics of ancient and modern siliceous sediments (cherts) indicate that the ancient oceans may have approached their boiling temperature 3.8 billion years ago (*34, 37*). Even though there is room for argument about the significance of such data, it is also clear that ancient ocean sediments in the predominantly volcanic environment of the Archean were significantly different and, for example, contained large amounts of the mineral talc, which now is only found associated with a few submarine hot springs (*38*). It has been proposed (*34*) that talc formation may be related to the injection of silicon dioxide into the oceans by hot springs, which then reacts with magnesium bicarbonates [for example, $4SiO_2$ (soln) + $3Mg^{2+}$ + $6HCO_3^- \rightarrow$ $Mg_3Si_4O_{10}(OH)_2$ (talc) + $6CO_2$ + $2H_2O$]. The reaction liberates carbon dioxide, and from estimates of heat production and volcanic intensity for the ancient earth (*39*) it can be shown that the rate of carbon dioxide emission by such a mechanism is of the order of 10^{15} grams of carbon per year, close to the present man-made injection rate. Although such observations are at present subject to various interpretations, they do indicate how the geologic record may be used to provide evidence on possible "greenhouse" mechanisms.

Nuclear Waste

At the present time, about 300 nuclear reactors produce approximately 6 percent of the global electricity needs. In France and the United Kingdom, 8 to 10 percent of the electricity was produced by nuclear reactors in 1973 (*40*). In the report of the Club of Rome (*18*, p. 96–97), it was stated that "at present the only alternative energy source to fossil fuels which is both technically feasible and economically viable is nuclear fission . . . a further development of nuclear fission energy today represents an unavoidable choice for industrialized nations. The development of nuclear energy is then to be regarded as a choice limited in time and space, to be utilized to fill the energy demand gap during the passage from today's oil era to a new one based on a wide spectrum of primary sources."

For the earth scientist and the geochemist in particular, the fact is that nuclear wastes exist and must be safely stored. Even if alternative energy sources fill the needs during the next century, the problem is now with us and must be solved. The increasing mass of nuclear power wastes and military nuclear wastes must become an increasing source of anxiety. The geologist is being asked to dispose of materials, some of which will be dangerous in a million years. But the problem is not new. Toxic materials, such as mercury, arsenic, and lead, have infinite lifetimes. Solving the radioactive waste problem will also solve a host of other toxic waste problems, even if man seems less alarmed by those that are nonradioactive.

The problem of nuclear waste disposal nicely illustrates the interaction between an urgent environmental problem and basic knowledge in the earth sciences. At a recent meeting of the International Council of Scientific Unions working group on the terrestrial disposal of radioactive wastes, a number of fundamental gaps in basic knowledge were brought into focus (*41*). All agree that we should dispose of nuclear wastes in sites where the crust is stable. But what is stable crust? For many, stable crust represents crust with very old rocks. But in the disposal context, stability implies low permeability to fluids for long periods of time and the selection of regions where any reasonable perturbation on hydrogeologic regimes from factors such as climate change with induced seismicity or even meteoric impact will not enhance the permeability. The general state of stress in the crust becomes of great importance. Climate changes may drastically change the hydrogeologic regime and the distribution of population.

Discussions of the "ideal host rock" for disposal also show how little is known about the permeability of continental rocks in the depth range from 0 to 4 kilometers, and particularly how little is known about reactions between rocks and ground water at low temperatures. At present a great deal of laboratory effort is being devoted to the study of exchange reactions between minerals in rocks and fluids carrying toxic elements, a process that it is hoped will reduce the flux rate to the biosphere. However, techniques for studying silicate reactions at 0° to 100°C are not satisfactory. Laboratory studies may be quite misleading, but the study of natural systems may provide data with appropriate time scales. Studies of the tropical weathering of rocks, or of submarine weathering, may provide realistic distribution coefficients between solids and fluid phases for a very wide range of elements. Data so derived should withstand some of the present criticisms regarding the reality of laboratory experiments extrapolated in time by factors of 10^6 to 10^8.

The impact of such research on basic earth science may be immense. First, we should begin to understand the weathering process in great detail. Quantification of fluid flux and heat flux regimes on continents will add to our understanding of tectonics on continents, as it already has done on the ocean floors. We must learn much more about the importance of biomolecular transport of toxic elements, a problem of critical importance to the study of pollution from uranium mining wastes.

On the positive side, the geologist knows that the problem can be solved. Delicate molecules and compounds are stored in rocks for millions or even billions of years. Fine filaments of native copper remain uncorroded for a billion years; amino acids are stored in rocks for billions of years. Studies of such processes of preservation in rocks can guide us in our search for safe methods of disposal.

Resources

At the heart of the global problems arising from the inequalities of life and opportunity of man is the inequality in the distribution and utilization of resources. Understanding the limitations of resources requires that we know exactly how they are formed.

If, during the next century, renewable energy resources are to be developed at reasonable economic levels for the benefit of all the members of the human race, the availability of inorganic materials in the earth places definite constraints on development. Such limitations show clearly in biomass productivity and food resources. I recently examined the optimum recipes for algal growth media (*29*). To provide the metals needed for the complex biocatalysis systems of the living organism, complexing reagents such as ethylenediaminetetraacetic acid are added, to keep key metals in solution in phosphate media. Carbon, nitrogen, oxygen, and hydrogen alone do not make man; at least 20 metallic elements are also essential, at well-controlled concentrations.

Malnutrition exists at catastrophic levels in tropical regions. There is an impressive correlation between global tectonics and agricultural production. Old stable shield regions, under conditions of tropical weathering, are unproductive; active volcanic regions or regions of high elevations, where new rocks with a wide spectrum of trace metals are renewed, are far more productive (*42–44*).

There are few major food production processes for which adequate mass balances for the reactions between rock, soil, soil water, and living organisms are available. Chemical analyses of soils from the Amazon Basin illustrate the critical problem. In that region major nutrients such as calcium, magnesium, potassium, and phosphorus are often present at the part-per-million level (*45*). Key micronutrients (*46*) such as zinc, copper, cobalt, and nickel are present at concentrations far below the levels of fertile soils. Such soils, although productive for a short time after the burning of the old forest, can hardly sustain long-term food production unless very sophisticated fertilizers are designed for the total balance of the inorganic needs.

The Amazon system is being perturbed, and it is out of chemical balance. If a major effort is not made in balancing the laws of conservation for productivity, the rate of erosion in this system, from which 20 percent of the world's river waters flow to the oceans, could be dramatically changed (*24*). In light of such problems, the geochemist, hydrogeologist, soil scientist, and biologist must join forces to describe and solve the problems.

Traditionally, the geochemist, petrologist, and mineralogist searched for the rocks that are considered to have the most simple history, that is, fresh rocks. Such rocks provide the best indications of primary origin. The geologist concerned with mineral deposits must understand alteration processes and must examine altered rocks. Ore deposits are always associated with altered rocks, and, perhaps for this reason, the economic geologist was placed in a lower class in the geological hierarchy because he studied rocks that often had been changed beyond recognition of their original state. The fact is that far more complex chemical changes are occurring in the alteration processes, which make their study extremely difficult. The situation has changed; new analytical techniques, including the study of fluid inclusions, stable isotopes of oxygen, sulfur, and hydrogen, have allowed a new analysis of the problem of the formation of an ore deposit, and the same techniques, applied to fresh rocks, have shown that these are often not so uncontaminated as was once thought (*47*).

Perhaps the greatest recent advances in our understanding of the chemical transport processes that lead to ore deposits have come from the study of the alteration of sea-floor crust and the correlations between heat flow and fluid flow patterns (*38*). The fluid-cooling processes occurring at ocean ridges, where new crust is cooled by circulating seawater, are another of the most massive chemical exchange phenomena on earth. Any component, present in moderate concentrations in seawater (sodium, potassium, magnesium, oxygen, sulfate, uranium, strontium, rubidium, and the like), is likely to be enriched in the basaltic crust. In exchange, virtually the entire transition-metal series is leached from the basalts and transported to the seawater-sediment interface. Modern metal deposits have been found by submersibles (*15, 38*), and there is little doubt that these processes contribute to the copper, nickel, cobalt, and manganese in marine sediments (*48*). The views of economic geologists on the origin of ore deposits, such as the classic ores of Cyprus or Oman, have been confirmed. Concepts of renewable versus nonrenewable resources are being challenged, for at least some important metal resources are now forming in the oceans.

It has been estimated that some 30 percent of the present earth's surface participates in the deep convective circulation of marine waters (*49*). For the ancient earth, when most of the crust was submarine and igneous activity was four to five times more intensive, the entire surface must have been involved, and the common occurrence of rich deposits in Archean terrains is not unexpected.

Although recent research has focused on submarine phenomena, continental situations, where the fluid flow of meteoric water is driven by gravity and thermal convection, exhibit similar metal transport processes. The study of all such flow processes is only beginning, but it seems likely that by using chemical data, coupled with isotope systematics, researchers will be able to unravel the processes. The understanding of the relations between fluid input and the focused discharge where ore deposits form has defined new targets for prospecting. Most of the estimates of resource limitations proposed 20 years ago are proving to be very pessimistic.

For many metals (for example, copper, zinc, gold, and uranium) the flow dynamics and geochemical processes leading to deposits are becoming understood; for some metals (for example, tin, tantalum, and chromium) our knowledge is not adequate. The possibility of extracting many metals from by-products of energy production (coal, tar sands, shales) must be carefully studied, for these fossil biomass systems concentrate an impressive range of metals (*21*). In our search for the best sites for nuclear waste disposal, sites where fluid flow is minimal, we are bound to increase our knowledge of flow regimes and to increase knowledge related to the search for ore deposits. Appreciation of the relations between fluid flow and heat flow and tectonics in all crustal situations will expand, if such lines of research are well correlated. With all the techniques of modern earth sciences and intelligent conservation, the resource outlook for a population of 10 billion is one for optimism.

Geosphere Exchange

The significance of the exchange processes of the outer systems of the earth, oceans, atmosphere, biomass, sediments, and rock is obvious. But one of the greatest problems for the modern geochemist is the quantification of exchanges between the outer layers and the deep earth. There is an almost quantitative return of the new ocean floor rocks to the mantle by convective processes. Because of the suface reactions with seawater, the rock that returns is chemically changed: it contains more potassium, sodium, uranium, sulfur, carbon dioxide, and water (*38*). Such recycling must maintain some constancy in the composition of the upper mantle. The scale of these recycling processes can be impressive. Water added to the ocean crust, in minerals such as chlorite, serpentine, and amphibole, is recycled in quantities that would remove the oceans in a billion years or so and thus there must be return flow (*50*). We do not know how much sedimentary material is recycled, but mechanisms for dragging light materials into the deep mantle have been discovered (*51, 52*). These return-flow processes present one of the greatest gaps in modern geochemical knowledge. The search for the answers will require a much larger program of drilling and geophysical studies, in regions where the convection cells turn back to the interior. At the same time, careful study of the rocks near trenches will show what is, or is not, easily subducted. As understanding of the recycling process increases, the present confusion on the chemical origin of the many types of magmas should be resolved.

Geological Education

If we are to solve the urgent geochemical problems of the next decades, we require a new breed of geochemist and we will require such people in large numbers. To make progress on these complex problems team effort will be required as seldom seen before in earth sciences, with the possible exceptions of ocean and space research. The environmental and interface problems will need sedimentologists, geochemists, hydrogeologists, biologists, geomorphologists, geophysicists, structural geologists, and tectonic experts who can communicate.

If fruitful communication is to be achieved, some traditional fields of concentration in geological education may no longer dominate. The geochemist will need education in hydrogeology, biochemistry, and microbiology. The student with the double major across geology-biology-chemistry-mathematics will be of particular value and such a person with a 5-year bachelor of science degree may be of more value than one with the standard master's degree in geology.

In this article, I have chosen to stress the geochemical problems of the environment. They are problems which must be solved. Their solution will surely advance our total appreciation of our planet and our neighbors. There is little purpose in science if we are not here to enjoy our universe. The human biomass has become one of the major influences shaping the planet Earth and, perhaps in the future, it will be the single greatest influence. We cannot afford the extinction of "15 to 20 percent of all species on earth" by the year 2000, as predicted in *Global 2000* (*1*, p. 37).

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Micromorphology and Tectonics of the Gorda Ridge

The Gorda Ridge is an active medium-rate spreading ridge located between 160 and 330 kilometers off the coast of northern California and Oregon. A prominent axial rift valley runs along the crest off the Gorda Ridge between the northern termination of the ridge at the Blanco Fracture Zone and the southern termination at the Mendocino Fracture Zone. At the northern end of the Gorda Ridge, the rift is located in a water depth of 3500 meters (or 1000 meters below the crustal height of the ridge). A multibeam, narrow beam, bathymetric survey system with acoustic beams 2⅔ degrees wide, was used to carry out a detailed study of the rift valley and Blanco Fracture Zone intersection. The SEABEAM system, mounted aboard the NOAA ship, *Surveyor*, shows an interesting mode of development off the Gorda Rift at this site. The rift valley has, in general, the bathymetric characteristics of the Mid-Atlantic Ridge, namely, the presence of a 250-meter-high ridge located centrally within the rift valley. This rift valley ridge is interpreted to be the site of active submarine volcanism and hydrothermal activity. The rift valley is flanked by steep rift valley walls located along normal faults. Polymetallic sulfides, if present, could be located along the base of these faults. The width of the rift valley varies from 7 kilometers at the Blanco Fracture Zone to less than 2 kilometers at a distance of 24 kilometers south of the Blanco Fracture Zone. Differential spreading rates along the rift (in a north-south direction) are suspected of having generated this wedge-shaped rift valley.

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