The Biosphere Is Going Deep

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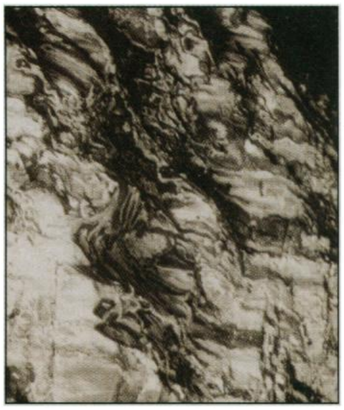
Earth system science investigates the interactions between the solid Earth—from crust to core—with the atmosphere, hydrosphere, and biosphere. In the past decades it has become increasingly appreciated that on a planet cooling by convection, all geospheres mix (*1*). The influence of the biosphere has long been recognized, particularly since the classic work of the great geochemist V. M. Goldschmidt, but the scale of this influence is only now being appreciated.

It was Goldschmidt who first used the classification term "biophile" (*2*) for elements that were enriched in living organisms. We now know that the oldest rocks on this planet that could possibly contain preserved organisms do so (*3*). The work of the late H. Lowenstam showed that in the marine sedimentary environment, for most new minerals, their formation is biocatalyzed. I remember a lecture he gave at the University of California, Berkeley, when he asked, "Is any mineral at the Earth's surface produced by purely inorganic processes?" And Abelson (*4*) showed that, given the present mass of living cells and their recycling rates, if life has been more or less constant, then the mass of living cells integrated over 4 billion years would be similar to the mass of Earth. Given the average chemical composition of living matter and the Earth, for many elements (such as potassium) there is a good chance that they have spent part of their lifetime on the planet inside a living cell (*5*). Recent work has also shown that the synthesis of many interesting organic polymers can be induced on the surface of minerals. As stated by Ferris *et al.* (*6*), minerals on the primitive Earth would have provided a "library" of surfaces for the exploration of molecular evolution.



Making minerals. In a cave on the Hawaiian island of Kauai, all surfaces are covered with new minerals, such as silica and Ca-Mg carbonates. These surfaces, assisted by microorganisms, fix carbon in the rocks. Can such processes be used to dispose of combustion gases from stationary fossil fuel–burning energy systems?

The generally accepted diagrams of the carbon cycle (*7*) show that most of life is in the hydrosphere and very near surface regions of Earth, soils and the like. But as the problems of secure nuclear waste isolation evolved, new questions about the location of life were asked. If such wastes are to be packaged in metals like copper, are there possibilities of corrosion by biological processes at depths of hundreds of meters below the surface? Several nations then undertook studies to see if there were populations of microorganisms in the cracks and pore spaces of rocks at depth. The unexpected presence of deep life has been well summarized by Pedersen (*8*). At the present time the world record for diverse colonies is at a depth of 4.2 km and a temperature of 110°C. Recent work on the chemistry of the North Sea oil and gas fields also confirms that thermophilic organisms are very busy at depths of several kilometers (*9*). As deep scientific drilling is developed, a host of observations show the products from the deep biosphere. Indeed, if there is a cavity of appropriate size with sufficient water, life will be present.

Microorganisms are everywhere there is a fluid and temperature not greatly exceeding 100°C. Thus, the ultrasaline calcium chloride waters of Antarctica are alive, as are the ocean ridge cooling systems; black smokers are thriving, and given its large crack porosity, probably the top few kilometers of the entire basaltic ocean crust is alive with the sulfate reducers, methane and H_2 producers, and similar microbes (*10*). Recently Thorseth *et al.* (*11*) and Staudigel *et al.* (*12*) have described the important role of microorganisms in the chemical alteration of ocean crust, observations confirmed by direct experiment on volcanic glass. It is clearly demonstrated that the minerals formed and the behavior of the chemical elements and their isotopes are strongly influenced by the organisms. Many of the classic ore deposits formed in the near-surface environment clearly show the important role of microorganisms. These can influence the oxidation-reduction state of fluids and act as ion-exchange collectors and nucleation sites (*13*, *14*).

The new discoveries of the deep biosphere open up a host of new technological opportunities. Can we mine sulfide ore bodies underground by using microorganisms to oxidize the sulfides and then pumping out the acidic, metal-rich solutions? Can we produce gases like CH_4 and H_2 in appropriate source rocks in situ? Can we use organisms to clean polluted ground waters, as with the arsenic-contaminated waters in the Calcutta region of India (*15*)? Can we use microorganisms to catalyze the reactions of toxic chemicals like organo-halogens with appropriate common sodium silicate minerals to produce graphitic compounds and NaCl, reactions generally thermodynamically favorable?

The list of such opportunities is vast, but one process that is attracting increasing global attention is the possibility of the subterranean disposal of combustion gases from stationary fossil-carbon–burning power plants. In the deep caves in Hawaiian basalts, every crack and pore space is covered with a white substance that includes complex assemblages of Ca-Mg carbonate minerals (see figure). The fluids from the forest cover on the surface, loaded with organics, penetrates the permeable lava flows and react with the basaltic silicates to produce carbonate minerals, in a process that appears to be biologically mediated. The same would be true for the acids SO_x and NO_x from combustion. If such processes can be developed for these combustion products, many of the transient energy problems of the world could be eliminated, as with the future needed use of coal in nations such as China and India (*16*).

The study of the nature and activity of the deep biosphere is perhaps one of the most exciting developments in modern Earth science and points the way to find life in places like Mars. No clever species would live on the surface of a planet during the early chaotic formation period—but perhaps in a period of stability. Such work also shows the rewards of cooperation between specialists—geochemists, hydrogeologists, and microbiologists. We must understand the deep biosphere if we are to correctly describe the carbon, nitrogen, and sulfur dynamics of Earth.

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