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The deep, hot biosphere

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ABSTRACT **There are strong indications that microbial life is widespread at depth in the crust of the Earth, just as such life has been identified in numerous ocean vents. This life is not dependent on solar energy and photosynthesis for its primary energy supply, and it is essentially independent of the surface circumstances. Its energy supply comes from chemical sources, due to fluids that migrate upward from deeper levels in the Earth. In mass and volume it may be comparable with all surface life. Such microbial life may account for the presence of biological molecules in all carbonaceous materials in the outer crust, and the inference that these materials must have derived from biological deposits accumulated at the surface is therefore not necessarily valid. Subsurface life may be widespread among the planetary bodies of our solar system, since many of them have equally suitable conditions below, while having totally inhospitable surfaces. One may even speculate that such life may be widely disseminated in the universe, since planetary type bodies with similar subsurface conditions may be common as solitary objects in space, as well as in other solar-type systems.**

We are familiar with two domains of life on the Earth: the surface of the land and the body of the oceans. Both domains share the same energy source—namely, sunlight, used in the process of photosynthesis in green plants and microorganisms. In this process the molecules of water and of CO_2 are dissociated, and the products of this then provide chemical energy that supports all the other forms of life. Most of this energy is made available through the recombination of carbon and hydrogen compounds concentrated in the plants with the oxygen that became distributed into the atmosphere and oceans by the same photosynthetic process. The end product is again largely water and CO_2, thereby closing the cycle.

This was the general concept about life and the sources of its energy until ≈12 years ago, when another domain of life was discovered (1). This domain, the "ocean vents", found first in some small regions of the ocean floor, but now found to be widespread (2), proved to have an energy supply for its life that was totally independent of sunlight and all surface energy sources. There the energy for life was derived from chemical processes, combining fluids—liquids and gasses—that came up continuously from cracks in the ocean floor with substances available in the local rocks and in the ocean water. Such sources of chemical energy still exist on the Earth, because the materials here have never been able to reach the condition of the lowest chemical energy. The Earth was formed by the accumulation of solid materials, condensed in a variety of circumstances from a gaseous nebula surrounding the sun. Much of this material had never been hot after its condensation, and it contained substances that would be liquid or gaseous when heated. In the interior of the Earth, heat is liberated by radioactivity, by compression, and by gravitational sorting; and this caused partial liquefaction and gasification. As liquids, gases, and solids make new contacts, chemical processes can take place that represent, in general, an approach to a lower chemical energy condition. Some of the energy so liberated will increase the heating of the locality, and this in turn will liberate more fluids there and so accelerate the processes that release more heat. Hot regions will become hotter, and chemical activity will be further stimulated there. This may contribute to, or account for, the active and hot regions in the Earth's crust that are so sharply defined.

Where such liquids or gases stream up to higher levels into different chemical surroundings, they will continue to represent a chemical disequilibrium and therefore a potential energy source. There will often be circumstances where chemical reactions with surrounding materials might be possible and would release energy, but where the temperature is too low for the activation of the reactions. This is just the circumstance where biology can successfully draw on chemical energy. The life in the ocean vents is one example of this. There it is bacterial life that provides the first stage in the process of drawing on this form of chemical energy; for example, methane and hydrogen are oxidized to CO_2 and water, with oxygen available from local sulfates and metal oxides. Hydrogen sulfide is also frequently present and leads to the production of water and metal sulfides; there may be many other reactions of which we are not yet aware. Of all the forms of life that we now know, bacteria appear to represent the one that can most readily utilize energy from a great variety of chemical sources.

How widespread is life based on such internal energy sources of the Earth? Are the ocean vents the sole representatives of this, or do they merely represent the examples that were discovered first? After all, the discovery of these is recent, and we may well expect that other locations that are harder to investigate would have escaped detection so far.

Bacteria can live at higher temperatures than any other known organisms; 110°C has been verified, and some biologists consider that the upper temperature limit may be as high as 150°C (providing always that the pressure is sufficient to raise the boiling point of water above this temperature).

There can be little doubt that venting of liquids and gases from areas of the Earth's mantle beneath the crust is not limited to a few cracks in the ocean floor. Indeed fossilized "dead" ocean vents have already been discovered (3), showing that the phenomenon is widespread and occurred in different geologic epochs. A similar supply of fluids seems to be widespread also in land areas, where it is much harder to investigate, but it has been noted that many areas of basement rocks contain methane and other hydrocarbons. This has been seen in numerous mining and tunneling operations for a long time. Major fault lines have been noted to be high spots of hydrocarbon seepage (4). Hydrocarbons have also been encountered in deep drilling in basement rocks, as in the Soviet superdeep well in the Kola peninsula and in the pilot hole of the German Continental Deep Drilling Project. The large quantities of methane hydrates (methane/water ices) found in many areas of the ocean floor, and thought to contain

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more methane than all other known methane deposits (5, 6), suggest a widely distributed methane supply from below.

In land areas, deep in the rocks, it would be much harder to discover and investigate biological activity than in the ocean vents. The pore spaces in the rocks are quite sufficient to accommodate bacterial life, and the rocks themselves may contain many of the chemicals that can be nutrients together with the ascending fluids. But, of course, there would be no space for larger life forms. Just as bacterial life in the ocean vents would not have been discovered had the secondary larger life forms not drawn attention to it, so any active bacterial life deep in the solid crust could have gone largely unnoticed.

The remains of bacteria in the form of molecules—"hopanoids" (derived from hopanes)—a material coming from bacterial cell walls, have however been found in all of the several hundred samples of oil, coal, and kerogen (distributed carbonaceous material in the crust) examined by Ourisson *et al.* (7). These authors note the widespread or apparently ubiquitous presence of these molecules in the sedimentary rocks, and they give an estimate of the total quantity as of the order of 10^{13} or 10^{14} tons, more than the estimated 10^{12} tons of organic carbon in all living organisms on or near the surface. They also note the virtually identical pattern of the chromatogram of these molecules in *oil* and in *coal*. Further they note that some of the molecules most commonly used to identify the presence of biological material in petroleum, such as pristane and phytane, are not necessarily derived from plant chlorophyll as is commonly believed, but could well be products of the same bacterial cultures as those that gave rise to the hopanoids. The presence of these biomolecules can therefore not be taken to prove a derivation of the bulk substance from surface biological debris.

What are the depths to which active bacterial life may have penetrated? Could bacteria get down into the deep rocks? Would this represent just a minor branch of all the surface biological activity, or could it be comparable with it in the total amount of chemical processing caused by it? How important would such life have been for the chemical evolution of the crust of the Earth?

An upper limit of the temperature of 110–150°C would place a limit on the depth of between 5 and 10 km in most areas of the crust. The mere question of access to such depths for bacteria would be no problem. Even just the rate of growth of bacterial colonies along cracks and pore spaces in which the requisite nutrients are available would take them down in a few thousand years—a very small fraction of the time span available. In fact, fluid movements in pore spaces would provide still much faster transport. The tidal pumping of ground water alone would be sufficient to distribute bacteria down to 10 km in less than a thousand years. Probably longer times would have been required to allow for the adaptation to the high temperatures.

The total pore space available in the land areas of the Earth down to 5 km depth can be estimated as 2×10^{22} cm^3 (taking 3% porosity as an average value). If material of the density of water fills these pore spaces, then this would represent a mass of 2×10^{16} tons. What fraction of this might be bacterial mass? If it were 1% or 2×10^{14} tons, it would still be equivalent to a layer of the order of 1.5 m thick of living material if spread out over all of the land surface. This would indeed be more than the existing surface flora and fauna. We do not know at present how to make a realistic estimate of the subterranean mass of material now living, but all that can be said is that one must consider it possible that it is comparable to all the living mass at the surface.

Together with this consideration would go the consideration of the cumulative amount of chemical activity that could be ascribed to this deep biosphere and with that the importance it may have had for the chemical evolution of the crust, the oceans, and atmosphere and the development of the surface biology.

The remarkable degree of chemical selection leading to concentrated deposits of certain minerals has long been an enigma. How can processes in the crust lead to the production of a nugget of gold or a crystal of galena when the refining process had to concentrate these materials by a factor of more than 10^{11} from the original elemental mix? How much of the concentrated metal minerals found have so far been explained satisfactorily? What energy sources were available to produce such large local decreases of entropy, and how was the necessary energy applied? Is this not a field where the complexity of carbon chemistry and biology, with their ability to be highly selective and to mediate chemical processes, may have had a much larger share than had previously been thought? It is characteristic, after all, for biology to generate important local decreases of entropy at the expense of energy absorbed and entropy rejected elsewhere.

If there exists this deep, hot biosphere, it will become a central item in the discussion of many, or indeed most, branches of the Earth sciences. How much of the biological imprint of material in the sediments is due to surface life and how much to life at depth? Do the biological molecules of petroleum and coal indicate now merely the additions from the deep biosphere to materials of primordial origin, rather than indicate a biological origin of the bulk of the substances themselves?* Many deductions that are firmly in the geological thinking of the present time may have to be reconsidered, if there is indeed such an abundance of life at depth.

One cannot discuss these possibilities without connecting them with the questions of the *origin* of life. Photosynthesis is an extremely complex process, which must lie some considerable way down on the path of evolution. Energy sources that were simpler to tap had to sustain life for all the time from its origin to the perfection of the photosynthetic process. Presumably these were chemical energy sources, provided by the substances of the Earth. Now one will want to examine whether these were perhaps the same as the chemical energy sources providing the life in the ocean vents and possibly the bacterial life in the rocks about which we are speculating here.

The rocks that have hydrogen, methane, and other fluids percolating upward would seem to be the most favorable locations for the first generation of self-replicating systems (9). Deep in the rocks the temperature, pressure, and chemical surroundings are constant for geologically long periods of time, and, therefore, no rapid response to changing circumstances is needed. Ionizing radiations are low and unchanging. No defense is needed against all the photochemical changes induced by ultraviolet light or even by the broad spectrum of visible sunlight.

Bacteriologists have speculated that, since a large subgroup of archaebacteria—the most primitive and judged to be the most ancient bacteria—are thermophiles, this may indicate that primitive life evolved at such high temperatures in the first place (10). If it did and if the archaebacteria are the

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*Robert Robinson, after studying the composition of natural petroleum, considered this possibility as likely. He wrote, "Actually it cannot be too strongly emphasized that petroleum does not present the composition picture expected from modified biogenic products, and all the arguments from the constituents of ancient oils fit equally well, or better, with the conception of a primordial hydrocarbon mixture to which bioproducts have been added" (8). Although there has been much detailed work since, demonstrating the variety of biological molecules that exist in most petroleum, none of this can make the distinction between the two opposing viewpoints. This work was frequently cited to support the bioorigin theory rather than the bioaddition, as a widespread microbiology at depth was not put under consideration.

earliest forms of bacteria, evolved at some depth in the rocks, they may have spread laterally at depth, and they may have evolved and progressed upwards to survive at lower temperatures nearer the surface. Some combination of lateral spread at depth and spread over the surface with subsequent readaptation to the conditions at depth will have allowed them to populate all the deep areas that provided suitable conditions to support such life. Of course now, when the surface is replete with bacteria of all kinds, it may be difficult to unravel the evolution in each of the domains.

If the deep, hot biosphere of microbial life exists in the rocks as well as at the ocean vents, what would be the consequences? Could we expect to have seen any evidence already?

Many reports have been published in recent times describing the discovery of bacteria in deep locations where they were not expected. The most striking example is the discovery deep in the granitic rock of Sweden. While drilling to a depth of 6.7 km in an ancient meteorite impact crater called the Siljan Ring, very large quantities of a fine-grained magnetite were encountered. Magnetite, a magnetic iron oxide, exists normally in the granite in the form of large crystals (≈ 1 mm) and at a low mean concentration. What was found was quite different from this. Grains in the micrometer size range were found in a thick sludge or paste, with a liquid binder that was a light oil. This was seen first at a time when the drilling fluid was water, with only occasional small additions of a plant oil as a lubricant. This sludge contained oil to the complete exclusion of water, and the oil was largely a simple, light, hydrogen-saturated petroleum, completely different from plant oils. (It is worth noting that no sediments of any kind had been encountered in the drilling, only granitic and igneous rock.) The magnetic grains were not only particularly small, but also had a different trace element content from the coarse magnetite grains in the granite. Neither the magnetite nor the oil had a simple explanation in terms of the material of the formation or of any of the drilling additives. The quantities of this sludge found in this first discovery were not small—60 kg of it filled a drillpipe to the almost complete exclusion of the water-based drilling fluid. Later a pump pumped up 15 tons of a similar oil, together with about 12 tons of the magnetite (11). Similar oil–magnetite pastes have been reported in several other oil drilling operations, and microorganisms have been identified that mediate the reduction of local ferric iron of the formation to the lesser oxidized magnetite, using the hydrocarbons as the reducing agent (12–14).

Later, when oil-based drilling fluid had been in use for several months, it was discovered that this had become loaded with many tons, at least 15 and possibly 30, of this fine-grained magnetite. It became clear that there was a phenomenon that occurred on a large scale and that was a major process in the rocks at a depth of between 5.5 and 6.7 km.

It is very difficult to see how concentrations of this material could occur without bacterial action; indeed, samples of it taken from a depth of 4 km or deeper have allowed several strains of previously unknown thermophilic, anaerobic bacteria to be cultured.[†] It will therefore be worthwhile to search for the presence of microorganisms in many other deep locations in the rocks where chemical energy is known to be available. The obvious locations for this are the deep oil or gas wells. Bacterial cultures can be attempted from samples taken with the necessary precautions (maintenance of temperature, pressure, and exclusion of oxygen) and using culturing media similar to the local chemical surroundings at the places of origin.

Although it had often been said that the presence of bacteria in oil can be identified by the chemical signs of "biodegradation" of that oil, we believe that this is misleading. Oil showing none of the known signs of biodegradation may still be coming from a region rich in bacterial life, and the oil may still have gained biological molecules from this without, however, having suffered any other changes. The reason for this is that microbial attack at depth is likely to be limited by the availability of oxygen and not by that of hydrocarbons; in that case, it seems to be the general rule that bacteria would first use the light hydrocarbons, the molecules from methane to pentane, before attacking any of the heavier hydrocarbons. If the light hydrocarbons are present in sufficient quantity to exhaust the locally available oxygen sources (iron oxides, sulfates, and perhaps other oxides with sufficiently low oxygen binding energy), then the liquid oils will not suffer any biodegradation. Under these circumstances, which are probably common at depth in petroleum provinces, oil will then commonly exist with additions of biomolecules and yet without any signs of biodegradation. It is the finding of apparently undegraded oil that nevertheless contained biomolecules that had been considered as the most compelling evidence for a biological *origin* of the oil itself. This consideration would no longer be valid, and a nonbiological origin for the bulk of the terrestrial hydrocarbons, just as for all the abundant hydrocarbons on the other planetary bodies, then seems probable. This is one example where the recognition of the existence of abundant microbial life at depth may change major considerations in geology and geochemistry.

Where we find "biodegraded" oil, it must have been subjected to conditions of greater availability of oxygen and lesser availability of the hydrocarbon gases; presumably, this occurs generally nearer the surface where atmospheric oxygen is available in ground water and where the concentration of the light hydrocarbons is low, as these are gases at the low ambient pressure.

It may be that we shall find a simple general rule to apply: *that microbial life exists in all the locations where microbes can survive*, that would mean all the locations that have a chemical energy supply and that are at a temperature below the maximum one to which microbes can adapt. There would be no locations on the Earth that have been protected from "infection" for the long periods of geologic time.

Chemical energy must be available, but it must not be liberated spontaneously without the intervention of the organisms. That means we have to be concerned with regions in which the chemical processes that can release energy would not run spontaneously; the temperature must be below the activation temperature for the reactions, or a set of reactions must be involved that give out energy on completion, but that require intermediate steps that absorb energy.

Research on the deep microbial life would allow one to judge the extent of it on the Earth, and with that one can expect to gain an insight into the extent to which microbial activity has contributed to the chemical evolution of the crust and its various mineral deposits. Prospecting techniques for minerals and for petroleum may be improved. The derivation of petroleum is a subject of great economic importance, and new information may profoundly influence the prospecting techniques and the estimates of the quantities of petroleum and natural gas that remain to be discovered.

The other planetary bodies in our solar system do not have favorable circumstances for *surface* life. The numerous bodies that have solid surfaces all have conditions of atmospheric pressure and temperature unfavorable for the presence of

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[†] U. Szewzyk at the National Bacteriological Laboratory (Stockholm) has cultured several strains of anaerobic, thermophilic bacteria from samples taken below 4000 m in the Gravberg borehole, Siljan Ring, Central Sweden (personal communication). Also K. Pedersen at the Department of Marine Biology of the University of Göteborg reports about deep ground water microbiology (15).

liquid water. Mars, deemed the least unfavorable in this respect, has been investigated (by the Viking landers), and no indications of any biological activity have been found. With this, it seemed that there was little or no chance of finding any other life in the solar system.

With the possibility of *subsurface* life, the outlook is quite different. Many planetary bodies will have temperature and pressure regimes in their interiors that would allow liquid water to exist. Hydrocarbons clearly are plentiful not only on all the gaseous major planets but also on the solid bodies (the large satellites, numerous asteroids, the planet Pluto, comets and meteorites); and there is every reason to believe that hydrocarbon compounds were incorporated in all of the planetary bodies at their formation. The circumstances in the interior of most of the solid planetary bodies will not be too different from those at a depth of a few kilometers in the Earth. The depth at which similar pressures and temperatures will be reached will be deeper, as the bodies are smaller than the Earth, but this fact itself does not constitute any handicap for microbial life. If in fact such life originated at depth in the Earth, there are at least 10 other planetary bodies in our solar system that would have had a similar chance for originating microbial life.

Could the space program ever discover this? Is there a possibility of finding life of an independent origin on some of the other planetary bodies?

We shall have to see whether microorganisms exist at depths on the moon, on Mars, in the asteroids, and in the satellites of the major planets. Such investigations may become central to that great question of the origin of life, and with that they may become a central subject in future space programs.

There is a chance that an independent origin could indeed be identified by a number of criteria: the discovery of opposite chiral asymmetries (50–50 chance in case of an independent origin, while the observation of the same chirality in just one other case would be uninformative); a different choice of basic molecules, or any of the criteria that have been used to show that all terrestrial life has one common origin. (Incidentally, as has often been discussed, this does not imply that there has been only one occurrence leading to an *origin* of life: if there had been several, the most successful would have supplanted all others, and after that there would be no possibility for a fresh start in competition with evolved biology).

It is difficult to foresee at the present time that the space program could proceed to the sophistication and power to perform very deep drilling operations on distant planets. However, there are other options. Deep rifts, such as the Valley Marinera on Mars, expose terrain that was at one time several kilometers below the surface. Samples from there, from the massive landslides in that valley, could be returned to Earth and analyzed for chemical evidence that living materials have existed there in the past. Similarly, one may sample lunar craters that have exposed deep materials fairly late in the lunar history or deep rifts and young craters on any of the other solid planetary bodies.

Since we recognize that even the seemingly most inhospitable bodies may harbor life, care would now be necessary to avoid contamination by terrestrial organisms. Manned expeditions, whatever other difficulties there might be with them, can certainly not be kept sterile and would therefore spoil such researches for all future times. Only very clean unmanned space vehicles going to planetary bodies that have not previously been visited by contaminated vehicles would qualify to bring back meaningful samples of a biology that resembles that of the Earth.

If life was restricted to the proximity of the surface of planetary bodies, then "panspermia," the transport of living material through space over astronomical distances, would be very improbable, as such living material would have to remain viable in a dormant form for very long times; in most of the suggested forms of panspermia, it would not be protected sufficiently well against the cumulative effects of the cosmic rays. Meteoritic impacts could well have exploded large chunks of rock from one planet, and such chunks may have escaped complete vaporization and excessive heating both during expulsion from one body and accretion on another. But unless the living organisms were deep inside of a rock, so as to be shielded by many meters of solids from the cosmic ray bombardment of space, there would be little chance of transferring functional living materials. Panspermia becomes a much more realistic possibility if there is abundant life at depth in the planetary bodies. There would have been a vastly greater number of opportunities for a transfer between planets in earlier epochs, when the rates of bombardment were much higher than they are now.

Meteorites are being collected at the present time that are thought to have derived from Mars (16) and indeed are found to contain carbonaceous material. Can one find traces of biological substances in them?

The surface life on the Earth, based on photosynthesis for its overall energy supply, may be just one strange branch of life, an adaptation specific to a planet that happened to have such favorable circumstances on its surface as would occur only very rarely: a favorable atmosphere, a suitable distance from an illuminating star, a mix of water and rock surface, etc. The deep, chemically supplied life, however, may be very common in the universe. Astronomical considerations make it seem probable that planetary-sized, cold bodies have formed in many locations from the materials of molecular clouds, even in the absence of a central star, and such objects may be widespread and common in our and in other galaxies. It is therefore a possibility that they mostly support this or similar forms of life. Panspermia not only over interplanetary but over interstellar distances would then be a possibility, and it would take the form of the distribution from one body carrying active living forms for indefinite periods of time and in a protected environment to another body capable of supporting similar life.

There is one further consideration that needs to be mentioned: the upper temperature limit of bacterial life may well be in the region of 120–150°C. But the availability of chemical energy sources will go down to much greater depths and much higher temperatures. Many chemical mixtures will not spontaneously run down to chemical equilibrium until temperatures more in the neighborhood of a 1000°C are reached. Therefore, underneath the type of biosphere that we have discussed here, there will generally lie a large domain that is too hot for the bacterial life we know, but that is nevertheless capable of supporting other systematic chemical processing systems that can mediate those energy reactions. Could there be such higher temperature systems that act in a way similar to life, even if we may not identify them as life? Perhaps their chemistry would not be based on carbon, like the life forms we know; the element silicon comes to mind as an element that can also form molecules of some complexity and frequently with a higher temperature stability than similar carbon-based molecules. Perhaps there are chemical systems that lack some of the properties we use in our present definition of life. Self-replication is a property possessed by simple crystal growth: it is only when self-replication is associated with an adaptive capability that the complex forms develop that we identify as life. In the case of unfamiliar circumstances and materials, we may fail to recognize these properties.

There is a lot of distance between plain crystallography and life. It is the bridging of this distance that forms the central piece of the theories of the origin of life. Should we perhaps look at this deeper, hotter domain to find the clues? This is a region where the conditions have remained constant for the longest periods and where the chemical energy sources have perhaps been most plentiful. Thermodynamics teaches us that a high degree of organization can develop only where there is a supply of energy, but we do not yet understand whether the availability of energy will itself promote the formation of such organized systems.

Cairns-Smith (17), writing about the origin of life, has pointed out that, once self-replicating adaptive systems have formed, they may well adapt gradually and change to a totally different chemistry. The chemistry of life we now know need not be the one associated with its essential origin. Thus if a higher temperature life (or pre-life) exists, based on a different chemistry, it may still have an evolutionary relationship with ours, and one cannot presume to know in which sense such an evolution may have taken place.

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