DEEP OCEAN DRILLING REVEALS MICROBIAL POPULATIONS BENEATH THE SEA FLOOR

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Summary One of the major achievements of the Ocean Drilling Program (ODP) has been the discovery that bacteria are not only present at much greater depths (>750 meters) beneath the deep seafloor than was previously thought but actually thrive there in colossal numbers. Sampling deep within the oceanic sedimentary section and in basaltic crust has revealed a complex and very active microbial fauna. Results to date indicate that the deep sub-seafloor microbial ecosystems found in both oceanic crust and the deep subsea sediments comprise a hidden world entailing a new form of life, previously unrecognized. The extent of this major biosphere and the nature of the "extremophiles" living there are essentially unknown. Deep ocean drilling offers the potential to probe this unexplored world of the deep sub-seafloor, which represents a unique habitat that couples biosphere/geosphere cycles.

Introduction One of the fundamental, unanswered questions facing Earth scientists today is the nature of the Earth's deep, sub-seafloor biosphere. The extent of this hidden biosphere and the character of the "extremeophiles" populating it are essentially unexplored. During the last decade of the 20th century, the ODP has made a concerted effort to begin the exploration and sampling of the deep sub-seafloor biosphere. A Pilot Project was initiated in the current phase of the ODP to meet the emerging challenges in the study of the deep biosphere.

Results to date indicate that the deep sub-seafloor microbial ecosystems found in both oceanic crust and the deep subsea sediments comprise a new world entailing a new form of life, previously unknown. Full appreciation of this unexplored biomass and its role in global biogeochemical cycling are currently beyond our grasp. Any satisfactory understanding of these biota and processes will alter our views of our dynamic Earth and, undoubtedly, of life itself.

Deep Sub-seafloor Biosphere Before the discovery of the deep sub-seafloor biosphere, bacteria isolated from hydrothermal environments had already made a big impact on biotechnology, for example in providing enzymes for the polymerase chain reaction which has galvanised molecular genetics. Some hydrothermal bacteria can not only just survive but also are biochemically active at temperatures up to at least 120 ^{o}C and there may be bacteria able to be active at even higher temperatures. This is significant as bacteria are likely to be present several kilometers beneath the surface despite temperatures increasing around 30 ^{o}C /km. In addition, bacteria may be involved in the formation of fossil fuels at depth as the "oil window" occurs between 100 to 150 ^{o}C and large bacterial populations emerge with production fluids from some oil reservoirs. It also looks likely that the deep biosphere will provide an even more diverse source of bacteria than the hydrothermal environments and as a result have a much greater impact on biotechnology.

Through continued deep sampling it is becoming increasingly obvious that subsurface microbiotic communities play an active role in elemental cycling. At the sediment-hard rock interface bacteria interact strongly with hard rock mineral phases thus catalyzing "weathering reactions" that have been traditionally viewed as abiotic. Although sulfate-reducing bacteria are among the most numerous, it has been shown in some settings that acetate is the main substrate, the sources of which (thermogenic or biogenic) are poorly known. Also, methane and other gases are an important energy source for methanotrophic bacteria, fueling communities from the seafloor to great depth. Downward into gas hydrate deposits and deeper free gas zones, a complex consortia of microbes exists. The relationships between various bacteria, their depth ranges, and their interaction with surrounding sediment and pore water are topics of current discussion.

Future IODP Drilling The study of the deep sub-seafloor biosphere has considerable overlap between pure and applied science. The integrated size of this microbial population is enormous. It conservatively comprises two thirds of Earth's bacterial biomass. The synthesis and maintenance of this huge biomass from the presumably deprived resources that exist at these great sedimentary depths is remarkable and poses major questions for biochemistry, microbial physiology, and microbial ecology. For example, it seems that some bacterial populations have survived on buried organic material for millions of years and so must have evolved some metabolic processes and enzymes that are unknown in the surface biosphere. Unraveling these processes will be of interest for pure science while also perhaps yielding new materials and ideas for biotechnological applications.

Recent sampling efforts have demonstrated that uncontaminated samples of the microbial fauna can be recovered from the deep sea for laboratory study. The next phase of deep ocean drilling, currently designated the Integrated Ocean Drilling Program (IODP), will emphasize a major new initiative to explore for new species of ancient, but still living biota that lie deep within the Earth, and decipher their physiology and life cycles. Defining the environmental boundary conditions which support and limit the existence of the deep, subsurface biosphere are of primary importance to future research and require well-designed deep Earth sampling strategies. Global mapping, both with respect to depth and geographic extent, of these populations is needed through a tight network of carefully chosen drill sites to refine our present estimates of the integrated global biomass in the deep bacterial biosphere. Integration of such global assessment initiative with tectonically oriented drilling programs will make it possible to examine the influence of tectonic settings at passive *vs.* active margins and spreading centers on the structure, size and turn-over rates of subsurface communities.

Acknowledgments This extended abstract represents a compilation of ideas from numerous contributors to IODP scientific planning documents on the deep sub-seafloor biosphere, all of whom are gratefully acknowledged.