Towards coordination and integration of deep marine biosphere research: the Dark Energy Biosphere Institute (DEBI)

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Summary. The 2003-2013 phase of the IODP brought platform integration and broad-scale international participation to ocean drilling, but it also targeted new scientific pursuits—including a focus on the subseafloor biosphere. There has been a high level of activity and excitement within the IODP for this new direction with workshops, working groups, and special sessions at conferences encouraged and supported by various agencies in a number of countries. Despite the demonstrable support, few new viable drilling programs have emerged during this IODP phase, particularly ones targeting the deep biosphere. In fact, no programs with this theme as the driving force have been drilled or scheduled for drilling before 2013. The reasons for this are both numerous and complex, but the lack of proposals from microbiologists and/or with microbiology as a leading scientific theme is certainly noteworthy and worth considering and asking the question "why". One obstacle to microbiology emerging as a mature, core science driver for ocean drilling lies in the organization and implementation of projects at the large scale required for drilling expeditions. Scientific drilling is well integrated into the Earth and marine geological sciences, but remains enigmatic in the life sciences. To help organize and mount coordinated efforts in the deep marine biosphere, we have launched a five-year National Science Foundation (NSF) supported Research Coordination Network (RCN - Biological Sciences Directorate). The immediate objective is the creation of the Dark Energy Biosphere Institute (DEBI) to build and coordinate research activities and the exchange of ideas between microbiologists, geochemists, hydrogeologists, and engineers. Our end objective is for DEBI to be a self-sustaining, dynamic umbrella organization that fosters and supports marine subsurface biosphere studies at the international level.

State of the field. In a 1992 essay, Thomas Gold postulated the existence of a "deep, hot biosphere", supported by geological energy sources (GOLD, 1992). Whitman et al. (WHITMAN et al., 1998) expanded this provocative concept by collating all available data on aquatic, soil, and subsurface prokaryotes, and concluded that a majority of biomass may be harbored in the subsurface. The ramifications of a hidden biosphere are numerous, leading to paradigm shifts in the biosciences and geosciences. The potential contribution to the global budget and cycling of carbon is just one of many examples. Owing to its vast size, the biosphere buried beneath the ocean harbors great potential for influencing global-scale biogeochemical processes, including the carbon, energy, and nutrient cycles. The subsurface biosphere may extend to a depth of 5-10 km, or more, and occupy a volume several orders of magnitude greater than the continental biosphere. Gas seeps, hydrothermal vents, and fresh rock outcrops serve as windows into this subsurface, and determining the biological processes and rates there is now at the forefront of deep biosphere studies. Additionally, these rock outcrops serve as conduits of fluid flow between the "sub-seafloor ocean" and our ocean basins (FISHER, 1998; FISHER and BECKER, 2000). Fluid flow in the oceanic aquifer in ridge flanks largely balances and controls elemental exchange between crust and seawater, and as a consequence, global ocean chemistry (BACH et al., 2004, and references therein). The porous rock medium that provides conduits for the superhighway of fluids may also provide safe havens for life. Examinations of the rock-hosted oceanic deep biosphere (e.g., Fisk et al., 1998), like studies of deeply buried sedimentary habitats (e.g., D'Hondt et al. 2004), are only just beginning, but they hold promise for revealing new and remarkable information about remote life here on Earth.

Deep biosphere studies seek to answer questions that range from exploratory and census-level to some of the most complex and fundamental in the Earth and life sciences today. It starts at a specific location or on a particular sample with 'who is there?', 'who is active?', and 'what are they doing?'. The investigations then drift to global concerns. What are the nature and extent of life on Earth? What are the physico-chemical limits of life on Earth? How metabolically active is the deep biosphere, and what are the most important redox processes? What are the dispersal mechanisms for life in the deep biosphere? How does life evolve in deeply buried geological deposits that can occur more than a km beneath the ocean floor? These questions are very diverse, and the underlying research approaches are highly interdisciplinary. Overarching themes that emerge include:

- ***Activity*** in the deep subseafloor biosphere: function and rates of global biogeochemical processes;
- ***Extent*** of life: biomes and the degree of connectivity (biogeography and dispersal);
- ***Limits*** of life*:* extremes and norms of carbon, energy, nutrient, temperature, pressure, and pH;
- ***Evolution and survival****:* adaptation, enrichment, and repair.

To date, deep sub-seafloor biosphere studies have focused, often by necessity, on enumerating cells in relatively shallow marine sediments, which does not permit a true global census of subsurface life. Even less is known about the activities of this biosphere – in function or in magnitude – or the identity of these microbial communities. The last decade has produced a tremendous increase in deep subseafloor biosphere studies, many that derive from the ground-breaking Leg 201 expedition and a few opportunities that we have had to look into the biosphere in CORKed holes (e.g., BIDDLE et al., 2006; COWEN et al., 2003; D'HONDT et al., 2004; INAGAKI et al., 2006; KORMAS et al., 2003; ROUSSEL et al., 2008; TESKE and SORENSEN, 2008). Although the field is still in its infancy, it is starting to mature from predominantly opportunistic investigations (often piggy-backing on other science) to targeted research.

The need for DEBI? Experienced drilling scientists are well aware of the fact that drilling projects are logistically complex, requiring close coordination and detailed planning – often involving many years of lead time prior to an expedition. All projects rely on dedicated drilling platforms, but often also require additional research cruises for site surveys, specialized instrumentation (e.g., CORKs), submersible vehicles, highly trained technical staff, long-term observatories, and substantial financial commitments. To a microbiologist new to the IODP, drilling projects bear little resemblance to any programs in life sciences, marine or terrestrial. In fact, they are perhaps more akin to flight missions in the space sciences. The high costs and low funding rates, the need for international cooperation, and the exceedingly long planning stages can be daunting for even the most integrated of scientific groups within the drilling community – for example, the paleoceanographic community. Many microbiologists are unfamiliar and daunted by this lengthy and complex proposal process. We note again that though the deep biosphere has been one of the three major themes of the IODP 2003-2013, remarkably few projects have been proposed, and fewer have successfully transitioned to even the initial stages of implementation. A better understanding of the deep marine biosphere requires a tighter coupling of microbiology-driven research within this field, to foster its development into a mature research discipline.

Microbiology-led deep-sea drilling projects are very recent developments that require extensive communication, detailed planning, and careful execution. This coordination is absolutely critical. While some aspects of planned expeditions will be "project specific", others will certainly benefit related, future drilling investigations. However, during the brief history of deep biosphere research, this type of inter-project (program-level) coordination,

collaboration, and information-sharing has been haphazard at best. There must be corporate memory pertaining to the logistics of science operations. Technical and scientific successes and failures from one project must be readily accessible to the next generation of researchers and engineers. DEBI is poised to be one vehicle for developing this type of information sharing, as a community-instigated initiative.

DEBI can also promote interest and awareness among students and young researchers in deep biosphere studies. These early-career scientists can then be integrated with those at mid-levels and the relatively limited senior leadership. The logistics of navigating the complex drilling program may hinder the rise of new leaders, especially in microbiology.

A brief history of DEBI. To initiate coordination among scientists interested in the deep biosphere, an exploratory three-day meeting was held February 17-20, 2008 at, and supported by, USC's Wrigley Institute for Environmental Studies. About 30 scientists from 15 institutions in the USA and Germany developed an agenda for promoting research on microbial processes in the deep subsurface. Two core agenda items that resulted from this meeting were: 1) develop the concept for an institute (later to be named DEBI) to help integrate and support a young and dynamic community characterized by small and discrete collaboratory groups, and 2) use the momentum generated by this fledgling community to raise seed funding for establishing the DEBI virtual institute.

What will DEBI do? DEBI was initiated to develop and support a growing community of marine-focused deep-biosphere scientists. Our main objectives are to:

- ***Develop*** an interactive community of deep-biosphere researchers
- ***Facilitate*** coordination of science between deep-biosphere drilling projects;
- ***Stimulate*** interaction and education among the disparate disciplines involved in deep biosphere research;
- ***Enable*** synthesis and integration of data and technology advances generated from deep biosphere projects.

How will DEBI do this? The principal mechanisms we are using to achieve these objectives include:

- ***Annual meetings:*** these are part science synthesis and part education workshop – focused on key topics in deep biosphere research;
- ***Student exchanges:*** provide financial support to enable visits to another deep-biosphere research laboratory to learn new skills, carry out experiments or analyses, participate in a research cruise or other field work;
- ***Cyberinfastructure***: a website for community building, coordination, advertisement, and branding;
- ***Special sessions*** at international conferences to provide platforms for presentation of deep biosphere research, education, and public outreach;
- ***Publications*** that are both integrative and outreach-oriented for scientific and public/policy/community awareness;

The DEBI annual meetings: You are invited! To advance our understanding of microbial processes in the deep subsurface, a coordinated effort of theoretical, field, and laboratory investigations is required. We have raised partial support from the NSF and Ocean Leadership to hold five annual, theme-based meetings. These meetings will enable scientists and students to exchange ideas in deep biosphere studies, to learn about practical developments and study opportunities in the field, and to coordinate research and education activities. Each meeting will focus on a specific theme within deep biosphere research and will be part scientific conference and part training workshop. The conference portion

provides a forum to present research activities and findings to a broadly trained, but scientifically focused audience. The aim is to present objectively the key research techniques and methods commonly employed, to discuss the pros and cons for specific applications, to produce consensus recommendations, and to make available detailed lab and field protocols.

Themes and locations were selected, in part, based on what we currently know, where we think we will be in the near future, and the expected timing of certain drilling programs, and will be implemented by hosts, a local organizing committee, with assistance of DEBI (Table 1).

The future of DEBI. Anticipated immediate and long-lasting results include:

- ***Technology and information transfer*** between existing and future deep biosphere projects and research groups;
- Cross-disciplinary ***networking and education advancement*** across all levels of participation (student-postdoc-career scientist);
- ***Collaborations*** among deep biosphere researchers at an international level of participation;
- Support and promotion of new projects in deep biosphere research, under the direction of ***new leaders*** who may emerge from within DEBI;
- To become a self-sustaining, dynamic, and international ***Institute*** for deep biosphere research that will provide long-term community support and infrastructure.

Table 1. DEBI Meeting themes, locations, and principal coordinators.

Location/Yr	Theme	Host	Local Committee
Univ. Hawaii/2009	CORKs, Hydrogeology	J. Cowen	A. Fisher, B. Glazer
Univ. N. Carolina/2010	Sediment Microbiology	A. Teske	M. Schrenk
Bremen/2011	Drill Cores/Biogeochemistry	W. Bach	T. Ferdelmann, K. Hinrichs
WHOI/2012	Crustal Microbiology	J. Huber	O. Rouxel, P. Girguis
Wash. Univ. St.L./2013	Marine & Continental Integration, Bioenergetics	J. Amend	K. Rogers, M. Schulte

Table 2. DEBI Steering Committee.

Name	Affiliation	Expertise
Bach, Wolfgang	Univ. Bremen	Marine geology, geochemistry
Cowen, Jim	Univ. Hawaii	Subsurface microbiology, borehole observatories
Fisher, Andy	Marine Biol. Labs	Subsurface microbiology, basement fluids
Orcutt, Beth	Univ. So Cal/Aarhus	Methane hydrates, subsurface experiments
Shock, Everett	Arizona St. Univ.	Extremophiles, theoretical geochemistry
Teske, Andreas	Univ. N. Carolina	Deep subsurface sediments and archaea

Concluding Statements. Scientific drilling has a long history of confirming major hypotheses in the Earth Sciences (e.g., plate tectonics) and with deep biosphere research holds the promise to be equally transformative in the life sciences. We need long-term means of enabling life-science research within ocean drilling, so that this field can realize its full potential. DEBI is one mechanism to catalyze, energize, integrate and coordinate this community to reach these promising ends.

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Appendix Table 1.

Name	Affiliation	Name	Affiliation	Name	Affiliation
Katrina Edwards	USC	Pete Girguis	Harvard	Olivier Rouxel	WHOI
Jan Amend	Wash. U.	John Heidelberg	USC	Axel Schippers	BGR
Wolfgang Bach		Kai Hinrichs	U. Bremen	Matt Schrenk	ECU
Keir Becker	U. Miami	Greg Horn	USC	Mitch Schulte	U. MO
Will Berelson	USC	Julie Huber	MBL	Everett Shock	ASU
Joan Bernhard	WHOI	Tom McCollom	U. CO	Jason Sylvan	USC
Pete Countway	USC	Jim McManus	OSU	Andreas Teske	UNC
Jim Cowen	U. Hawaii	Bill Nelson	USC	Hongmei Wang	China Univ.
Andy Fisher	UCSC	Beth Orcutt	USC	Geoff Wheat	U. AL
Brian Glazer	U. Hawaii	Karyn Rogers	U. MO	Wiebke Ziebis	USC