

## **Center for Dark Energy Biosphere Investigations (C-DEBI)**

**A center for resolving the extent, function, dynamics and implications of the *Subseafloor Biosphere***

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The Earth's "deep biosphere" includes a variety of subsurface habitats on Earth, such as mines, aquifers, and soils in the continental realm, and sediments and igneous rock in the marine realm. It has been estimated that nearly *half of total biomass on Earth resides in the deep biosphere* [1]. Subsurface biosphere sites examined to date have been selected for scientific interest and opportunity, but have been limited to relatively few locations and shallow drilling, because of technological hurdles and a lack of interdisciplinary coordination during the early phases of project design and development. These problems have hindered deep biosphere research, skewing data sets towards environmental accessibility, and precluding the development of a more accurate global census. Even less is known about the *identity* of these subsurface microbial communities or the critical *abiotic* and *biotic processes* within this biosphere. The last decade has produced a tremendous increase in deep biosphere studies, proposals, publications, working groups, field opportunities, and technologies available for sampling, monitoring, and experiments (*e.g.*, [2-10]). Although the field is still young, it is maturing from principally isolated, opportunistic investigations toward coordinated, targeted research. *We lack the infrastructural coordination mechanisms, however, to guide and support the research for transformational advance.*

*The largest potential subsurface biome is also the least accessible: the subseafloor biosphere, harboring an estimated 1/3 of all biomass on Earth* [1]. Owing to its vast size and intimate connection with the water cycles, the subseafloor biosphere has enormous potential for influencing global-scale biogeochemical processes, including carbon, energy, climate, and nutrient cycles. The subsurface biosphere may extend to a depth of 5-10 km or more, depending on local geothermal gradients, and occupy a volume several orders of magnitude greater than the continental biosphere [1]. Rock outcrops serve as conduits of fluid flow between the "sub-seafloor ocean" and the ocean basins, and offer windows into the subseafloor (*e.g.*, [8, 11-13]). Fluid flow in the global basaltic rock aquifer—considered a superhighway of fluid flow—mediates elemental exchange between crust and seawater, and as consequence, the chemical composition of the oceans [14, 15]. The fractured rock medium that provides conduits for the superhighway of fluids may also serve as an incubator for life. Examinations of the rock-hosted oceanic deep subseafloor biosphere as a realm of study is just beginning [16], but similar to deeply buried sedimentary habitats (*e.g.*, [5]), it holds promise for revealing new and remarkable information about uniquely remote life on Earth and the possibilities for life on other planetary bodies.

### **INTELLECUAL MERIT**

*C-DEBI proposes to seize a unique opportunity to bundle US-lead diverse deep subseafloor biosphere projects, coordinate them with international partner project, to accomplish an integrated, global scientific mission to solve the most vexing problems of this field.* This virtual center will be multi-institutional with international partnerships, with additional science and engineering liaisons and partnerships from a host of for- and not-for-profit agencies and a national laboratory. C-DEBI will integrate scientific projects across two deep subseafloor biosphere environments (igneous ocean crust and sediments) that have historically been studied independently, and among locations that span the globe.

*Life in deeply buried marine sediments.* Marine sediments can accumulate in km thick sequences in coastal areas, margin terrain, and abyssal plains of the ocean. These sediments are mineralogical and geochemical reservoirs of information about the environment in which each layer was deposited. Chemical processes in sediments are often dictated by diffusion and reaction kinetics, which operate very slowly over long length scales. As such, sediments record Earth's history, containing information about, for example, past glaciations and deglaciations and climactic and geochemical events. However, since the discovery of extant, metabolically active microbial life harbored within deeply buried sediments to at least 1km depth below the seabed [2], it is now known that they represent a complex reservoir of past and present life processes and biogeochemical activity, as well as localized time-capsules of microbial evolution.

***Life in igneous ocean crust.*** The igneous ocean crust is composed of porous and permeable volcanic rock, principally basalt, which outcrops at mid-ocean ridges (MORs) where frequent eruptions build new crust. The crust moves off-axis and typically remains uncovered by sediments for thousands to millions of years on the flanks of the MORs, before being blanketed in the abyssal plains of the ocean, and eventually subducted at trenches. The upper ~500 m of igneous crust is fractured and permeable to fluid, and hosts the largest aquifer on Earth. Most of the oceanic crust is hydrologically active (at least 60%; [17]) and the fluid flux through the ocean crust rivals global riverine input to the oceans [18]. Solutes and colloids—microbes included in this fraction—circulate actively through the crustal aquifer, but the degree to which microbes “take seed”, colonize, alter, and evolve in subsurface rock is not known.

***An integrative approach to deep seafloor biosphere research: A community-initiated vision for C-DEBI.*** C-DEBI will catalyze research that will bridge the crust and sediment marine realms, through scientific integration of independently-developed US-lead deep seafloor biosphere projects that have recently progressed through the Integrated Ocean Drilling Program System, in order to conduct an integrated global mission: to resolve the extent, function, dynamics and implications of the seafloor biosphere. The three US-lead that form the core of our mission were developed by the PI group: Edwards (USC) and Wheat (UAF) (North Pond, mid-Atlantic); Fisher (UCSC) and Cowen (UH) (Juan de Fuca, Pacific NW); D’Hondt (URI) and Edwards (USC) (South Pacific Gyre). C-DEBI will serve as: (1) a coordination and cyber infrastructural hub for an international community of researchers; and (2) a scientific incubator that will and revolutionize efforts to develop additional field, laboratory, and modeling experiments. C-DEBI will integrate and collaborate with German, Japanese, Danish, and Chinese researchers on this project, and bring deep seafloor marine biosphere projects developed in those countries into the C-DEBI framework. C-DEBI will serve as a bridge between the scientific community of seafloor biosphere researchers and drilling partners (Integrated Ocean Drilling Program, Ocean Leadership, industry). ***C-DEBI comprises an international model for project coordination and integration, establishing the intellectual, educational, technological, cyber-infrastructural, and collaborative framework needed for transformative experimental and exploratory research on the seafloor biosphere.***

## **BROADER IMPACTS**

C-DEBI creates distinctive educational programs at the K-12, undergraduate, graduate, and postdoctoral levels in order to train and foster the next generation of deep seafloor biosphere researchers. This is a highest priority to ensure the robust continued development of this new field, and will arm the field with the brightest and most creative young minds that can take what has been built over the past decade, to expand it in this decade via C-DEBI. C-DEBI researchers feel strongly that it is also fundamentally crucial that to translates knowledge of the deep seafloor biosphere and ocean sciences to the broader public. We will accomplish this in part through core education programs (which will interact with public policy, administration, and other education fields) and also by diverse lecture programs and other outreach mechanisms that promote broad dissemination of information and increased awareness of the existence and potential importance of the seafloor biosphere.

C-DEBI will support undergraduate, graduate, postdoctoral studies and research broadly across with collaborating investigator laboratories. C-DEBI will develop programs within the COSEE-WEST framework, and those of other existing programs in order to integrate C-DEBI faculty, postdoctoral, and graduate students into K-12 science education. As part of C-DEBI, faculty will work with COSEE-West staff and K-12 teachers to create new curriculum elements and lesson plans that explore the topics of C-DEBI research and link it directly to the California State Science Standards. In addition, Co-PI institutions will each contribute distinct components to these objectives. Example additional programs that will be lead at C-DEBI collaborating institutions include as teacher-at-sea programs and partnerships with REU projects such as the *Transforming Undergraduate Laboratory Experiences* project for underrepresented groups (TULES at UCSC), the *Summer Undergraduate Research Fellowships in Oceanography* (SURFO at URI), and K-12 technology outreach at C-DEBI affiliated marine technology centers (Monterey Bay Aquarium Research Institute).

## Center for Dark Energy Biosphere Investigations (C-DEBI)

### (A) Rationale for Center Concept

**WHY a deep subseafloor biosphere STC?** In a provocative 1992 essay, Thomas Gold postulated the existence of a “deep, hot biosphere”, supported by geological energy sources [19]. Whitman *et al.*, [1] expanded this concept, collating available data on aquatic, soil, and **subseafloor** microbes, and concluded that the majority of biomass on Earth may be harbored below the surface of the Earth. The ramifications of a massive buried biosphere of “intraterrestrial microbes” are significant (*e.g.*, global carbon budgets and cycling), leading to paradigm shifts in our thinking in the biosciences and geosciences [20, 21].

Owing to the vast size of the subseafloor reservoir in the global Earth system, most intraterrestrial microbes reside below the bottom of the **OCEANS**, in sediments and rock. The potential for the oceanic deep biosphere to influence global biogeochemical processes **scales with the size of the subseafloor as a habitat**. Oceans cover over 70% of the Earth’s surface, and 70% of the rock underlying the ocean represents an actively flowing aquifer system—the largest on Earth. Fluid flow in the oceanic aquifer mediates elemental exchange between crust and seawater, and consequently, affects global ocean chemistry [14, 15]. Herein, we propose to create a Science and Technology Center to resolve the **extent, function, dynamics** and global **implications** of what may be the largest biome on Earth, the subseafloor intraterrestrial deep biosphere. This center will have the capability of affirming or concretely re-defining the conjectures of Gold, Whitman and others with unprecedented global impact.

**WHY now?** Over the past decade, deep biosphere studies have focused on enumerating cells in relatively shallow marine sediments or in terrestrial mines, wells, and drill-core samples. Sites have been targeted based on interest and opportunity, but have been limited because of technological hurdles and a lack of interdisciplinary coordination during the early phases of project design. Consequently, despite the potentially profound implications for the existence of a deep biosphere, existing data are skewed toward accessibility and do not permit significant refinement of the global census of subseafloor biomass [1]. Little information exists about the identity of these microbial communities or the abiotic and biotic processes within this biosphere—information that is critical to link intraterrestrial microbes with global processes and to understand the significance of subseafloor biomes in the development and evolution of life. These shortcomings, in their essence, reduce to a lack of prior integration and coordination within this new field; C-DEBI will allow transformative advancement through collaboration, coordination, and support, enabled by recent opportunities.

We are at a crossroad in our quest to resolve the major questions in deep subseafloor biosphere research. Only **one** dedicated subseafloor biosphere-focused drilling project has been mounted to date [22]. However, **three new US-lead IODP projects for deep subseafloor biosphere research are poised for drilling** before 2013, headed by our executive committee members and involving many of our science participants. These projects developed independently, with specific sites and scientific objectives. C-DEBI will seize a unique opportunity to bundle these diverse projects, to accomplish an integrated, global scientific mission. Our first major science objective is to **coordinate, integrate, support, and extend** the science associated with these three projects, establishing a new model for conducting internationally coordinated collaborative research in the deep subseafloor biosphere. C-DEBI will establish the technological, collaborative, and cyber-infrastructure that is needed to effectively plan, execute, and maximize returns for deep subseafloor biosphere research—now and into the future. Our second major science objective is to foster and educate an interdisciplinary community of researchers in deep subseafloor biosphere research, with a focus on students and junior researchers. C-DEBI will nurture **new** projects, through collaboration and networking between new deep subseafloor biosphere enthusiasts and researchers with experience in the logistical and technological “how’s” for mounting and executing an IODP project—thereby ensuring precision use of scarce resources and well-informed project development for answering critical global science questions. Our education and diversity objectives are to educate, inform, and translate knowledge of the deep subseafloor biosphere via a coordinated program across primary, secondary, and higher education programs, and for C-DEBI scientific participants to learn how to be more effective in communicating scientific and technical results to a broader audience.

**(B) Management Plan**

Our management plan will facilitate the achievement of the principal scientific, education, and diversity goals for C-DEBI:

- (1) Support and intertwine the science associated with our three main field projects (yrs 1-5) at North Pond (NP), Juan de Fuca (JDF), and South Pacific Gyre (SPG) in order to conduct a global-scale, international, coordinated mission on the seafloor biosphere;
- (2) Grow, educate and nurture the community of deep seafloor biosphere researchers, advance the suite of scientific tools brought to bear on questions concerning this biosphere, and develop the next phase (yrs 5-10) of project development;
- (3) Train and educate a new, diverse generation of undergraduate, graduate students and postdoctoral deep seafloor biosphere researchers within an integrated and collaborative multidisciplinary community;
- (4) Translate knowledge of the deep seafloor biosphere and ocean sciences generally to a broad and diverse community, through targeted programs with K-12 teachers and informal science venues throughout the country.

The major administrative and science committees for C-DEBI members are presented in Table 1; Interactions between C-DEBI groups are depicted in Figure 1.

**Executive Committee.** The Executive Committee (*ExCom*) is comprised of the STC co-PI group,

**Table 1.** Listing of the principal membership of the research, administrative, and education committees. Note full C-DEBI science participants, liaisons, evaluators, industry, national laboratory, and international participants are included in the required supplemental “Institutions and Affiliations” document.

	<b>Name</b>	<b>Institution</b>	<b>C-DEBI Science and Administration Role(s)</b>	
<b>ExCom</b>	Katrina Edwards	USC	North Pond Research Project Lead	
	Jim Cowen	UHI	JDF Associate Lead; Instrument and Technology	
	Steve D’Hondt	URI	South Pacific Gyre Research Group Lead	
	Andy Fisher	UCSC	Juan de Fuca (JDF) Group Lead	
	Geoff Wheat	UAF	NP Associate Lead; CORK development	
<b>C-DEBI Administration</b>	Katrina Edwards	USC	C-DEBI Director/DEBI RCN co-Director	
	Jan Amend	WUSL	DEBI RCN co-Director/C-DEBI meetings coordinator	
	Ann Close	USC	C-DEBI Managing Director	
	Linda Duguay	USC	C-DEBI Research Coordinator	
	Rosalyn Lee	USC	C-DEBI Associate Managing Director	
	TBN	USC	C-DEBI Education Administrator	
	TBN	USC	C-DEBI Diversity Administrator	
<b>Education Instructors &amp; Advisors</b>	Steven Finkel	USC	Minority Course Advisor	
	John Heidelberg	USC	Minority Course Instructor	
	Eric Webb	USC	Minority Course Instructor	
	Jennifer Biddle	UDel	Postdoctoral Committee	
	Dave Caron	USC	Postdoctoral Committee	
<b>SciCom</b>	Wolfgang Bach	Bremen	<b>Crust Steering Committee</b>	Geochemistry
	Brian Glazer	UHI		Biogeochemistry
	Julie Huber	MBL		Microbial Ecology
	Olivier Rouxel	WHOI		Isotope Geochemistry
	Everett Shock	ASU		Geochemistry
	Matthew Schrenk	ECU		Geomicrobiology
	William Berelson	USC	<b>Sediments Steering Committee</b>	Geochemistry
	Pete Girguis	Harvard		Microbial Ecology
	Kai Hinrichs	Bremen		Organic Geochemistry
	Karla Heidelberg	USC		Genomics
	Steve Lund	USC		Sedimentology
	Axel Schippers	BGR		Geomicrobiology
	<b>Theme</b>	Wiebke Ziebis		USC
<b>Team</b>	Andreas Teske	UNC	Theme 2 Lead: Biogeography and Dispersal	
<b>Leaders</b>	Tom McCollom	UCO	Theme 3 Lead: Limits of Life in the Deep Biosphere	
	Bill Nelson	USC	Theme 4 Lead: Evolution and Survival	

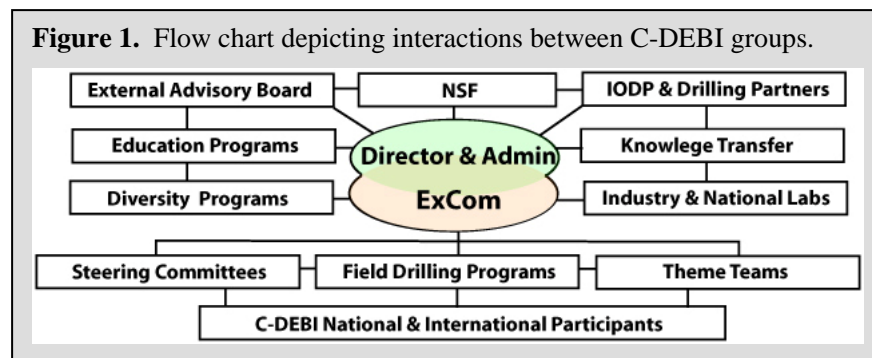
charged with overseeing the C-DEBI research and education programs, and is ultimately responsible for making sure that the STC is run efficiently and effectively in close coordination and communication with

C-DEBI administration (Fig. 1). **ExCom** is comprised of leaders from diverse disciplines that have spearheaded the major US-lead deep seafloor biosphere research projects that comprise the core initial focus for C-DEBI. The **primary responsibility of the ExCom** is to lead our major scientific projects that are described herein. D'Hondt, Edwards, and Fisher are the research project leaders for the SPG, NP, and JDF IODP projects, respectively. They are the "lead proponents" (~PI) of these IODP projects and as such are the principal contacts and coordinators for them. This involves project coordination with the IODP, Ocean Leadership, Texas A&M University (TAMU), and NSF. Co-PIs Wheat and Cowen will serve as associate leads for the technically and logistically complex NP and JDF observatory projects, respectively. Wheat will serve as lead for CORK technological development (section F), and will be the C-DEBI knowledge transfer coordinator for the scientific portion of these objectives (section F). Cowen will serve as lead of instrument and technology development for ocean crust observatories, also coordinating with our liaisons and industry partners.

In addition to leading and managing the science of our core projects, **ExCom** will (1) work with other C-DEBI members (see supplement listing) and groups (science steering committee (**SciCom**) and theme teams (**TT**)), which are our principal mechanisms for project integration and science oversight; and (2) foster and nurture the development of competitive new projects, as discussed below. This role is based on the **ExCom's** experience in navigating the IODP system, including, project development and coordination, proposal preparation and scientific planning, site surveys, engineering design and implementation, experiments, and observatory creation. C-DEBI will serve as a "scientific incubator" for both *existing* and *newly developed* projects (see pg. 6-7). **ExCom** will also oversee the development of an external advisory committee (EAC) comprised of leaders in oceanography and other leaders in Center-level programs. **ExCom** will ensure NSF diversity in representation criteria are met for this committee. For succession of the director, nominations should come from **SciCom** and **TT** leaders; a voting majority within **ExCom** will decide new directorship.

**Administration.** Day-to-day C-DEBI administration will rest with Edwards (Director). Edwards has lead efforts to organize this community, first with the NP project (initiated in 2005), followed by the activities (meetings and coordination efforts discussed below) that have coalesced and are herein expressed as the community scientific vision for C-DEBI. Edwards will benefit from close collaboration with an experienced administration team represented by Ann Close (Managing Director), Dr. Linda Duguay (Research Coordinator), and Dr. Rosalynn Lee (Associate Managing Director). Close has played a similar role at the USC Wrigley Institute for Environmental Studies (WIES; \$3-\$5 million per year with

a faculty of 20 and a staff of 45), and has organized and managed the daily activities of that center for over a decade. Duguay has years of experience in leading local and national programs at USC, NSF, and other organizations. Currently she is the Research Director of WIES, and director of



SeaGrant COSEE-West (see below and biosketch). Lee was recently recruited due to her experience in the development of the NSF denitrification research coordination network at Rutgers (lead by Dr. Seitzinger), with particular expertise on cyber infrastructure and meeting planning.

Close and Duguay will coordinate and integrate the daily activities of C-DEBI. Close will oversee site communication and coordination. Close will direct the education and diversity administrators at USC in coordination with the education, outreach and communications liaisons at Partner Institutions. Duguay will integrate the research themes into the education, diversity and knowledge transfer components of our programs. Duguay, with assistance from Lee, will also manage fiscal aspects of research proposals from C-DEBI community members (as described below), *i.e.*, student, postdoctoral support and etc. Lee will be

responsible for web site development and management (see section F). The Education and Diversity administrators (positions to be filled) will work with our external education program evaluator, Dr. Beth Rabin, to insure timely evaluations and rapid implementation of any recommendations on our education programs (sections D & F).

Yearly C-DEBI STC meetings will be coordinated and managed by C-DEBI administrative personnel. Dr. Jan Amend and Edwards are Co-Directors of the NSF-funded DEBI Research Coordination Network, which has partial support for yearly meetings in each of the next five years starting in 2009 (see section F). Amend is the principal meeting coordinator, and will work closely with Lee, Edwards, and local organizing committees on program development, fundraising, advertisement, and venue logistics.

Drs. John Heidelberg and Eric Webb, who have experience in teaching related classes at USC, will teach our undergraduate minority summer course. Dr. Steve Finkel will advise them on the development of this course; Finkel has run a summer course that similarly targeted undergraduate minorities and has five years of experience with all aspects of development, implementation, evaluation, networking and advertising. Drs. Jennifer Biddle and Dave Caron represent our postdoctoral committee; they will be responsible for oversight and management of the postdoctoral fellowships to ensure implementation of our mentoring program (see supplemental document), and will be overseen by **ExCom**.

**Science Steering Committee (SciCom).** The crust and sediment **SciCom** are advisory committees to **ExCom**, and have two principal charges: (1) Review proposals and applications for C-DEBI sponsored support (research, instrument, travel, etc) and make recommendations to the **ExCom**; and (2) Meet at the annual C-DEBI meeting and at another yearly event (major national scientific meeting) to discuss the confluence or lack thereof between the science proposals and C-DEBI objectives. Each **SciCom** member also will participate in a **TT**, and make recommendations to **ExCom** during conference calls. Each advisory committee consists of six members that span a range of disciplines. Members will serve two-year terms, after which new **SciCom** members will be identified by **ExCom** with input from current **SciCom**. This model—small groups, with targeted missions and short terms—will enable broad-based participation and supply a constant flux of fresh perspectives to science proposal evaluations and to **ExCom**. Members presently identified have, and will in the future, be chosen from the broader listing in the supplemental “Institutions and Affiliations” document, which delineates C-DEBI science personnel. For the sediments group, we have initially selected several “local” (USC) **SciCom** members for this team, for accessibility to the director during the building phase of the center (first 2 yrs). C-DEBI is intended to integrate across the sediment/crust division for deep seafloor biosphere projects—two sub-fields in the seafloor biosphere that have historically operated independently. However, four members of **ExCom**, including the director, focus on crust. Local access and expertise on sediments within **SciCom** during C-DEBI formation is critical to insure balance and representation in project development and science support. **SciCom** includes currently, and will in the future, two continental drilling liaisons (Schippers and Shock) for science coordination and knowledge transfer between continental and marine drilling projects.

**Science Theme Team (TT) Leaders.** Four C-DEBI cross-project research “Themes” are discussed below; they aim to integrate research projects within C-DEBI. C-DEBI science participants affiliate with one of these themes, becoming part of a **TT**. Each **TT** will have a leader, charged with creating the means to (1) develop core science foci for the particular theme they lead; and (2) bring new researchers—*i.e.*, those not already associated with one or more of our specific field projects, as well as *outside* experts from *related fields* (*e.g.*, continental deep biosphere) to C-DEBI—to broaden existing projects and develop new ones. Specific mechanisms for accomplishing these charges are discussed in section F. **TT** leaders will also consult experts from the broader research community to establish new partnerships for effective response to new challenges in the field. **TT** leaders will form ad-hoc task forces to formulate technical advisory panels (**TAPs**). **TAPs** will be used to focus and advance research, tools and advisory activities in each area, for science advancement in the four Theme areas. Community membership in themes may change (see supplemental listing) but it is anticipated that to achieve these objectives, **TT** leaders will hold these positions for at least three years.

## **(C) Research Objectives of the Center**

### **Preamble.**

In February 2008, the University of Southern California (USC) with support from WIES, sponsored an international workshop with the participation of 30 pre-eminent American and German deep subseafloor biosphere researchers. This community proposed an NSF Center in order to coordinate, integrate, and collaborate on research to resolve the **critical** outstanding research questions concerning the *largest biome on Earth*, its *biological implications* and its *consequence* for the balance of present, future, and past global biogeochemical cycles and elemental budgets. C-DEBI science is global in scale, international in scope, and transformative in impact; *the deep marine subseafloor biosphere is a global-scale enigma that requires an internationally coordinated research Center to tackle it comprehensively.*

Director Edwards and Jan Amend successfully acquired an NSF grant for a DEBI Research Coordination Network (RCN)—critical for the realization of C-DEBI by partially funding future annual meetings, based on the Catalina workshop model but to be held at C-DEBI partner institutions (across the US and Germany). The next DEBI meeting will be Oct. 09 (section F) in Hawaii (Cowen, host); Amend, Cowen, Fisher and Glazer submitted a proposal for supplemental funding for this meeting April 1, 2009 to Ocean Leadership's US-Science Support program.

### **Overview.**

*The most pressing questions in marine deep subseafloor biosphere research.* Deep subseafloor biosphere studies seek to answer questions that range in nature from exploratory and census-level to the most complex and fundamental in the Earth and life sciences. Deep subseafloor habitats are vast in scale—it is estimated that up to *1/3 of the Earth's biomass* is harbored in the deep *marine subseafloor* [1]—and are physically and chemically vastly diverse. A common feature among all deep subseafloor biosphere habitats is that they exist in the *dark*, one or more steps removed from the photosynthetic activity that fuels the surface biosphere. *Energy* and *carbon* cycling in the deep subseafloor biosphere are potentially important issues in solving global *redox* and *carbon* budgets [23]. However, quantification of the magnitude and activity of this dark biosphere and its organic versus inorganic energy and carbon sources is difficult, owing to a dearth of data concerning the nature of these deep ecosystems. Fundamental questions that have far reaching consequences for life on Earth and beyond include: What is the nature and extent of life on Earth? What are the physico-chemical limits of life on Earth? How metabolically active is the deep subseafloor biosphere, and what are the most important redox processes? Are there exotic metabolic processes occurring? How are microbes dispersed in the deep subseafloor biosphere? How does life evolve in deeply buried geological deposits beneath the ocean floor? These questions are diverse and demand interdisciplinary research approaches in microbiology, molecular biology, geology, geochemistry, engineering, hydrology and more. Our research findings have the potential to impact major current questions such as energy creation, climate change, and the very nature of evolution of life on Earth. To address these challenges, we focus and integrate across four broad **C-DEBI research Themes:**

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

We propose to address questions within these themes by *linking deep subseafloor biosphere projects* into a coherent deep-biosphere program, C-DEBI. The linked C-DEBI projects will embrace a strategy of "contrast, compare, and integrate" between deep subseafloor biosphere sites where specific environmental controls, processes, and dynamics relating to C-DEBI research themes can be resolved. *Our ambitious cross-site research agenda can only be accomplished via an integrative center infrastructure, which will fundamentally change the nature of how deep subseafloor biosphere research is conducted, resulting in transformative advances in this field.* Integrating multiple projects within C-DEBI allows us to adapt to changing field schedules (which we cannot control), new discoveries (which we cannot always

predict), and to set strategic research priorities for C-DEBI. The C-DEBI field projects can be completed in virtually any sequence, and will dovetail (and involve participation) with new projects as they develop.

**Research projects that will address key questions over the next 5+ years.** Study of life in the deep subseafloor biosphere is technologically and analytically among the most challenging in the Earth and life sciences. Accessing samples requires a *drill ship* supported by the IODP. The US has emerged as a leader in developing projects in the deep subseafloor biosphere. Only four deep subseafloor biosphere projects internationally are ranked within the IODP system as “ready to drill”, to be scheduled before 2013; we refer to these project herein as “mature”. Three of these projects are led by US PIs, with significant collaborations with scientists from other countries such as Germany and Japan:

1. **JDF; Co-PI Fisher (UCSC; lead) & Co-PI Cowen (UHI)**
2. **NP - Mid-Atlantic Ridge; PI Edwards (USC; lead) & Co-PI Wheat (UA)**
3. **SPG; Co-PI Steven D’Hondt (URI; lead), & PI Edwards (USC)**

These projects emerged independently with well-developed hypotheses, objectives, additional collaborators (many C-DEBI investigators), and specialized components. Each has been through the complete IODP review process and is ranked “Tier 1”, which represents the highest priority IODP projects for scheduling. While the full proposal and evaluation process cannot be described here in detail, briefly, all proposals have been: i) through multiple iterations of science review (many years); ii) requiring preliminary data, or “site-survey” sea-going data (with support from NSF for science and/or ships); the sea-going site-surveys are complete for all projects; (iii) additionally considered by IODP technology and safety panels; (iv) ranked globally with all other IODP proposals (from all disciplines and countries that have similarly passed these other panels).

Our international C-DEBI partner, Ken Takai, is the lead proponent of the only other mature deep-biosphere IODP project in the IODP system, focused on the Okinawa Trough. We fully intend to use C-DEBI as a coordinating mechanism to integrate the research and personnel engaged in that project into this global subseafloor biosphere mission, and to foster additional international collaboration.

**IODP Science: Drilling Platform vs. Research Support.** These mature projects bring *drill ship access* to C-DEBI for all three of the above projects, which enables them to be mounted, samples accessed, and experiments started; however, the IODP does not support *science costs* associated with drilling, which instead is supported by normal grants to individuals or small groups of PIs within the countries involved. Presently, no mechanism exists for coordinating and planning between scientists before a drilling expedition<sup>1</sup>, or performing the science after an expedition beyond individual small research grants (2-3 yrs). Hence, drilling projects have historically operated independently of one another, addressing limited sets of specific, relatively short-term research objectives relating to a single site or region that can be accomplished rapidly. ***C-DEBI represents a novel approach to deep-drilling science, because it enables us to integrate data from many sites and conduct experiments/monitor conditions for long time frames*** (see below), ***which is paramount for comprehensive understanding of the deep subseafloor biosphere.***

This is a critical interval of time for deep subseafloor biosphere research. Never before have so many deep-biosphere IODP projects reached maturity simultaneously, which motivates us to capitalize on this rare opportunity to create C-DEBI. We intend to establish a new model for deep subseafloor biosphere research, adopting an **Earth system science** approach to addressing key questions in our field, which are embodied within our themes. *C-DEBI will enable transformative science to emerge through research integration in a collaborative environment where complex logistical, technological, scientific and analytical know-how, research, and developments are supported and coordinated.*

**Research projects that will address key questions over the next 6-10 years.** From the brief description above of the IODP proposal process, it may be appreciated that it is complex and lengthy.

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<sup>1</sup> IODP supports limited operational planning in coordination with drilling engineers and technicians, generally with the lead PI for a project.

The three C-DEBI projects described above were initiated in IODP between 2003 and 2005. The length and complexity of this process has hindered the rise of new deep biosphere projects internationally, even though the IODP research theme “Deep Biosphere and Subseafloor Ocean” has been prioritized since 2003 [24]: the four projects discussed above are the *only ones that have emerged globally during IODP*. The lack of deep biosphere proposals has concerned the IODP and supporting agencies (e.g., Ocean Leadership) enough to support measures to help specifically encourage this community, including support for numerous workshops, for example one on “Subseafloor life” (Lead by Co-PI D’Hondt and others; [25]), another on the “Energy Limits of Life” (lead by B. Jørgensen & T. Hoehler; [26]), and one on “Exploring the Deep Biosphere” (lead by J.A. McKenzie; [27]). Additionally, the IODP has developed a standing “Task Force” for the deep subseafloor biosphere (D’Hondt, Edwards, Ferdelman, Inagaki, Kallmeyer, Orphan, and Takai are members). It is our assessment that this community may be best fostered by direct support and collaboration within the community; *C-DEBI is the community-initiated means of providing the collaborative framework and support that we believe is needed for new research projects to be developed in the deep subsurface biosphere.*

C-DEBI will support research that leads to the development of key new projects during the first five years, with the goal of moving them toward scheduling of drilling expeditions by phase II (yrs 6-10). The scientific rationale for these sites and projects has been emerging within the community for several years (not discussed in detail here), and through C-DEBI support, they may most effectively build the preliminary and justifying datasets, and develop/coordinate the IODP objectives for a proposal that will successfully traverse the IODP system. These projects include, but are not limited to:

**4. Guaymas Basin; Lead by Andreas Teske (UNC) and Adam Soule (WHOI)**

**5. Dorado Seamount; lead by co-PIs Wheat and Fisher**

A pre-proposal was submitted to the IODP April 1, 2009 for Guaymas, and a US-lead site-survey proposal was submitted to the NSF Feb. 15, 2009 for Dorado. As with our core projects (above), broad community interest in these systems exists among C-DEBI participants. Other opportunities for project development include the South Chamorro Seamount on the Mariana forearc; this is a system that has been extensively studied by geologists and geochemists, but has not received significant attention from microbiologists. C-DEBI participants (Moyer, Takai, and Inagaki) are beginning to mount efforts that could develop into major C-DEBI-wide field project. Additionally, international participants have recently initiated proposals for projects in the Arabian sea (Schippers) and the Shimokita Peninsula, Japan (Inagaki, Takai), that would benefit, and benefit from, C-DEBI as an international coordinating entity.

C-DEBI will *generally* support new and emergent field studies; the afore examples of where momentum appears to be gathering (note as with our three core projects, 3-5 year “incubations” are normal), but they are not exclusive; other areas C-DEBI would support include deep subseafloor H<sub>2</sub>-based ecosystems associated with water-rock reactions in ultramafic crust (e.g., Lost City hydrothermal field [28]), and other timely topics. C-DEBI will reach out to continental drilling programs and projects (see sections B and F) and aid in coordinating technology transfer and science integration as appropriate. C-DEBI will provide the logistical, networking, and research support to enable microbiology-led objectives to emerge as leading charges in drilling science. The creation of a center to provide this overarching support role backed by experience and fundamental science is wholly novel.

***Emergent new research within Deep Biosphere research.*** Though our field is inherently interdisciplinary, there are clear absences in the suite of tools and questions in deep biosphere research. For example, questions of evolution in microbiology: the time frame over which the deep subseafloor biosphere operates (geological) and long-term conditions of starvation and isolation of living cells, immediately bring to mind questions of evolution, [29], survival [30], paleobiology [31] and paleosignatures [32] to the forefront. These questions are *not* being addressed explicitly through existing projects. C-DEBI will support these new directions among current and future members of our community. The impact of this field is dependent on adaptation to new questions about the functionality and consequence of the deep subseafloor biosphere, rather than being only a field of research involved in a “census” of subseafloor life.

## **C-DEBI Research Themes and Unique Features of the Deep Subseafloor Biosphere.**

### **(a) Background: Subseafloor characterization**

The deep subseafloor biosphere falls into two overarching provinces: (i) *igneous crust systems (crust)*; and (ii) *sedimentary systems (sediments)*. Our means of accessing samples and studying these biome end-members differ significantly. For example, drilling in crust is technologically challenging and slow, and as consequence, only a few holes are generally drilled for any project over a limited geographical region. Studies in the crust also use *observatories* (NP, JDF) as a key research tool (see below). In contrast, sediments can be drilled more easily, and observatories for study of the sedimentary subseafloor biosphere have not yet been used. Sites targeted for sedimentary drilling can also cover an extensive area, and dozens of drill holes can be spudded in a typical 60 day drilling voyage; for example, an area twice as large as North America was traversed for the SPG site-survey cruise in Jan. 2007.

We summarize briefly the objectives for these projects, focusing on topics that relate most directly to our research themes (outlined below). We highlight areas of overlap, synergy, and intersection between projects, and emphasize the natural environmental continuum that exists among them, presenting opportunity for comparisons and broader meaning to be extracted. ***This distillation of research across projects can only be accomplished via C-DEBI.*** We focus on hallmark experimental approaches that exemplify the power of project integration, which will enable rapid and transformative advances.

***Crust Overview.*** The JDF ([33] and refs therein), NP ([34] and refs therein), Dorado (*e.g.*, [12]), and SPG [35] projects represent a continuum of crust habitats, or biomes, with regional-scale environmental parameters (temperature, pH, salinity, oxygenation, hydrological regime) influencing the microbial communities inhabiting them. JDF is the youngest (~3Ma), warmest (~60°C) and most chemically reducing (sulfidic) crustal biome, with these latter properties resulting from heavy sedimentation at the continental margin of the Pacific northwest of the US (sediments act as a thermal insulator) and sluggish fluid flow, resulting in long transport times between inflow and outflow. JDF is the best-studied crust system among all sites (*e.g.*, [8, 10, 36-39]). NP, by contrast, is older (~8 Ma), colder (~15°C), with rapid fluid flow, shorter residence time, and chemically oxidizing conditions [40-43]. Dorado is a seamount that outcrops basement on the Cocos Pacific plate; this seamount is vigorously venting cold water (4°C) from old, sedimented crust (~24 Ma) [12]. Finally, the SPG sites include the oldest (~100 Ma) and most oxidized crustal biome on Earth, with O<sub>2</sub> penetrating through much of the overlying sediment [44], and with active fluid flow occurring throughout the entire span of crustal ages to be cored (7 Ma to ~100Ma) [35]. This diversity of sites and range of conditions provides ripe opportunity for joint analysis and cross comparisons via C-DEBI.

***Sediments Overview.*** Our knowledge of sedimentary microbial communities, while more extensive compared to crust, is highly skewed towards shallow depths (<1 m) and coastal/continental margin sampling. Collectively, marginal sites are just one small part of the range of sedimentary conditions that exist globally, from extremely low nutrient and carbon regimes to extremely high organic matter regimes. *Oligotrophic regimes by area represent the largest sedimentary habitats on Earth.* Data available on the microbiology and activity in sediments from continental-margin to open-ocean sites based on ODP Leg 201 sediment coring indicates major distinctions in population size (biomass), structure (taxa), and activity (low), with major consequence to global biogeochemical activities (*e.g.*, [5, 7, 45-48]). *C-DEBI will focus on those environments most poorly represented in deep sedimentary subseafloor biosphere studies to-date:* the carbon and nutrient starved “open ocean gyres” such as the SPG and the Tropical North Atlantic Gyre (NP sediments). We will compare and contrast these oligotrophic sites from these two separate major ocean basins to address questions about the major drivers in dictating oligotrophic deeply buried sediments in the global Earth system. We will compare these carbon-starved biomes with the distinct environments represented by Guaymas Basin (*e.g.*, [49, 50]), a sediment-covered, organic-rich hydrothermal vent site in the central Gulf of California, characterized by hydrothermal alterations of buried sedimentary organic matter [51], and JDF, a sediment-covered organic-poor hydrothermal vent site.

## **(b) Specialized Methods for Observatory Science in the Deep Subseafloor Biosphere**

Major components of our crust projects rely on subseafloor observatories known as “CORKs”. **CORK observatories**, or “Circulation Obviation Retrofit Kits”, are essentially undersea labs that put hardware and experimental instrument packages into boreholes that are sealed (CORKed) so that *in situ* conditions can develop post-drilling. CORKs have been used for over a decade, but their technology is constantly evolving in response to new needs in the research community and new capabilities in drilling techniques and instrumentation (*e.g.*, recent CORK installations on the JDF: [52]). In ocean crust, solutes and colloids (such as microbes) are transported advectively, principally along fissures, cracks, and pore spaces. Drilling fluids also take this exact path during drilling operations, hence contaminating rock in most regions where microbes are likely to occur indigenously. CORK observatories have been adopted recently by deep subseafloor biosphere researchers (*e.g.*, [53, 54]) because they allow *in situ* conditions to be *re-captured post drilling* and thereby circumvent some of the contamination problems. Furthermore, the realization by deep subseafloor biosphere researchers that observatories could be used to do *time-series experiments in situ* – coupled with measurements and monitoring – suggests *CORK observatories potentially represent the most powerful and scientifically transformative means of studying the deep subseafloor crust biosphere.* Observatory science in oceanography is well established, for example, the Hawaiian Ocean Time Series (HOTS), and the Bermuda Atlantic Time-series study (BATS) stations, but it is *completely new* to subseafloor biosphere studies. For example, *in situ* aquifer fluids can be pumped through borehole experiments or to the ocean floor to conduct experiments to examine transport times for fluids and colloids, microbial colonization rates on crustal rocks, and activities of endolithic microbes in the crust. Such studies are *essential* to answering fundamental questions about microbial life in crust— for example, determination of how large the crustal biome is. The oft-cited paper by Whitman *et al.*[1] does not consider any life that may exist in crust, either within the fluids or on the surfaces of the porous rock matrix. The opportunities afforded by CORK observatories in the challenging-to-access crust underscore the significant, groundbreaking discoveries that are certain to be made through these projects.

Our industry partner Pettigrew and several of our liaisons at TAMU (Miller) and IODP-MI (Myers) represent our core CORK engineering and science partners. Pettigrew, an engineer, designed and developed all CORKs in use today. Myers supports the development of new tools and technologies for scientific drilling within IODP. Miller manages projects associated with IODP drilling. These are critical partnerships for observatory creation: Over the past 17 years CORK technology has evolved rapidly, requiring upgrades and modifications to previously deployed CORKs. We recognize the need to expand upon the engineering capacity offered by the C-DEBI institutions to develop new tools, sensors, and experiments. We have, for example, engaged the engineering faculty at USC, which has supported underwater acoustics, communications, and robotics programs, to tackle C-DEBI-related needs for experimental system design. C-DEBI will exploit this collaborative model to explicitly encourage the development of new tools and technology that will be needed for the next generation of CORKed observatories, to answer the next generation of deep biosphere researchers most critical questions.

## **(c) C-DEBI Research Themes**

Our C-DEBI research themes will cut across our projects, providing a common basis for making key comparisons. *This will transform the original scope of each project*—with individualized science objectives and sometimes provincially derived questions—into a truly integrated global-scale scientific mission for understanding the deep subseafloor biosphere. Additionally, these themes provide mechanisms for growth in our investigator base. Some of our participants, such as some of the engineering and genomics researchers, are not associated with any particular site, but may get involved via participation in these themes—and grow the type of scientific questions considered.

**Research Theme I. Activity in the deep subseafloor biosphere: function & rates of global biogeochemical processes.** Subseafloor microbial processes exert fundamental influence on the biogeochemistry of the ocean and atmosphere. For example, sulfate reduction coupled to metal sulfide (*e.g.*, pyrite) precipitation in sediments is a major sink of sulfate from the world ocean and potentially a significant source of ocean alkalinity on geological timescales (ka to Ma) [55]. Oxidation of organic

carbon leads to a major source of dissolved inorganic carbon (DIC) to the ocean. Because the geographic distribution of organic carbon degradation as well as sulfate reduction and sulfide precipitation is poorly quantified, the global effect of these coupled processes is not well known. As another example, water-rock weathering reactions in the ocean crust impose significant negative feedback on atmospheric CO<sub>2</sub>, accounting for ~30% of the silicate-drawdown globally [56]. Microbes are known to promote these reactions in the laboratory [57], and at the seafloor [58], but the degree to which they influence these processes *in situ* in the subseafloor remains unknown. Through targeted support of research aiming to quantify geographic distributions of subseafloor sedimentary respiration, rates and magnitude of microbial crustal alteration, energy sources and carbon flow, C-DEBI will enable robust analyses linking subseafloor processes to global scales and biogeochemical cycles.

The paradigm of the global carbon cycle, distilled to its most simplistic form, involves the net balance between photosynthesis and respiration, and what escapes this efficient cycle via export from the upper ocean to deep marine sediments. As a first-order bookkeeping approach, this paradigm works well for establishing mass-balances. However, the apparent success of such simplifications does not establish their adequacy—the magnitude and consequence of a viable and active deep subseafloor biosphere is not considered at all. We emphasize that this is problematic and not scientifically justified. For example, estimates based on the few measurements of respiration rates in the deep sedimentary subseafloor biosphere [5], by comparison to projected estimates of chemoautotrophic primary production in the crust [59], suggest a significant subseafloor carbon cycle, but the balance between production and respiration is too poorly constrained for solid implications to be inferred. There is also increasing evidence that the global redox state of the near Earth's surface (atmosphere, oceans, and upper lithosphere) is unbalanced, in part influenced by processes in the deep subseafloor biosphere such as ocean crust alteration, with consequence for the evolution of both the near surface (atmosphere) and deep Earth (upper mantle) [60].

Pore water chemical profiles from sediments in low productivity regions in the SPG, the Dorado outcrop and sediment filled ponds at the Mid-Atlantic Ridge (NP) suggest a range of diffusive, advective, and diagenetic influences, including evidence for upward fluid seepage, sea water intrusion and flow along basaltic aquifers [5, 61]; this “bottom up” supply of electron acceptors—invokes paradigm shift in our understanding of sediment biogeochemistry: Do autotrophic pathways play a much greater role and mass and energy transfer than is recognized (*e.g.*, [21])? *These hypotheses can only be tested explicitly through comparative studies at the different sites planned via C-DEBI.* Further, with information on the extent, limits and biogeochemical processes occurring in the deep subseafloor biosphere, conceptual models can be developed and expanded holistically to quantitative models. This will enable true predictions about the consequence of biogeochemical activity in the deep subseafloor biosphere and the role microbes play in global sulfur, carbon, and iron cycles.

**Research Theme II. Extent of life: biomes and the degree of connectivity (biogeography and dispersal).** We are now aware of the basic fact that there is a deep subseafloor biosphere—intraterrestrial microbes that appear to represent a significant biosphere in sediments (*e.g.*, [5]) and rock (*e.g.*, [16]) below the bottom of the ocean. How microbes are transported and dispersed in the deep subseafloor biosphere—the biogeography of microbes—is an open and intriguing problem. Questions concerning biogeography speak to the *most fundamental problems in microbiology* (*e.g.*, as discussed in [62, 63]), and date at least back to the Baas-Becking hypothesis that 'everything is everywhere, *but*, the environment selects' [64]. The variety of dispersal mechanisms for microbes to deep subseafloor habitats, and the vast spatial- and time-scales we consider, presents opportunities to address fundamental questions in this field.

As discussed above, it is well documented that tremendous volumes of seawater infiltrate the crust and hence, seawater is likely a source of inoculum “seeding” subseafloor biomes. The transport time for fluid to travel through different crustal aquifers varies enormously, as do the physical and chemical conditions of these fluids and any microbiology they carry [14]. Deep sea sediments remain in exchange with seawater at their top and bottom layers via the overlying water column and deep crustal aquifers. What microbes take seed and why? What are the most significant physical and chemical controls of these colonization processes? How similar or different are the resulting crustal and sedimentary ecosystems from deep subseafloor ecosystems and from each other? We expect that geochemical and physical site

parameters will shape the patterns of archaeal and bacterial community compositions. *Questions relating to biogeography are a cornerstone component of C-DEBI, because it is only through inter-project comparisons that true headway in comparing these ecosystems may be made.* Each site and project is an island in and of itself, but when compared with this disparate set of habitats, will coalesce as a global model for biogeography of microbes below the ocean floor.

These examples and others can potentially be tested, and we are working on datasets that test and support specific pathways. For example, the International Census of Marine Microbes (ICoMM) has been supporting the development of datasets for these types of cross comparisons (see [http://icomm.mbl.edu/microbis/icomm\\_status/](http://icomm.mbl.edu/microbis/icomm_status/)) among some C-DEBI participants (Biddle, Caron, D'Hondt, Edwards, Huber, Teske). Similar integrative and cross comparative studies will be a major focus of C-DEBI and we emphasize that *ultimate resolution* of issues relating to transport and biogeography appear to hinge on comparisons *between sites*: Comparisons between deeply buried sediment communities that are in similar carbon/nutrient regimes and comparisons between ocean crust biomes and the sediments that directly overlie them; such as the planned projects at NP and the SPG sites. C-DEBI will specifically enable and foster these cross-comparisons so that critical issues relating to biogeography and dispersal in the deep seafloor biosphere can be resolved.

**Research Theme III. Limits of life: extremes and norms of carbon, energy, nutrient, temperature, pressure, pH.** What are the factors that fundamentally *limit* the existence and diversity of life within seafloor sediments and ocean crust? High temperature is probably a critical limitation in many areas, although the impact of temperature on the distribution of life is likely to be convolved with other factors. For example, survival at high temperatures may depend on the capacity of organisms to repair the damage caused by thermal degradation of cellular components [65], so it may be possible for microbes to exist at higher temperatures in environments that supply more metabolic energy than in those where the supply is less. Most seafloor sediments exhibit low thermal gradients (1–30°C per km), but the highest temperature documented for microbial activity to date (~122°C) [66] is exceeded at shallow depths at certain sediment-covered mid-ocean ridges such as the JDF, Okinawa Trough, and Guaymas Basin. Drilling along a temperature gradient in deeply buried, organic rich sediments, such as at Guaymas Basin (where the availability of organic C should *not* be a limiting factor) will enable questions relating to the thermal limit of life in deeply buried sediments to be addressed empirically.

Low availability of electron donors may limit the distribution of life in the seafloor within marine sediments. In sediments, buried organic matter from the surface photosynthetic world is the principal source of electron donors (*e.g.*, [5, 67]). Within the SPG, where the burial rate of organic matter is two orders of magnitude lower than in other regions that have previously been explored for life in seafloor sediments, analyses of shallow cores obtained as part of an NSF-sponsored site survey cruise in 2007 revealed that only  $10^3$ – $10^4$  cells/m<sup>3</sup> survive in shallow sediments [68]. If low organic matter availability ultimately sets a limit to life in marine sediments, active cells may be absent from the deeper sediment column in the SPG.

Different factors are likely to define the ultimate limitation to life in the igneous ocean crust and in marine sediments. Sources of metabolic energy may not be a limiting factor in the ocean crust, as reactions between the reduced ocean crust and circulating fluids may supply chemical energy to support primary carbon fixation *in situ* (*e.g.*, [59]). One proposed hypothesis is that microbes may be active throughout the upper ocean crust wherever there is active hydrology with temperatures below ~120°C, until the crust undergoes subduction in ocean trenches. In one study supporting this idea, textural and isotopic evidence suggested that microorganisms are active in ocean crust aged over 1000 Ma [69]. However, another study that examined textural features thought to be attributable to microbial activity suggested that the features were established early in the history of the crust (~<10 Ma) and then changed little afterwards [70]. Evidence for the timing of oxidative alteration of the ocean crust, which may support chemosynthetic biological activity, also indicates that most alteration appears to occur early and then slows or ceases as the crust ages [59]. Thus, an alternative hypothesis is that life may be most active early in crustal evolution, and fades out well before subduction. The C-DEBI related projects and field

sites, which span nearly the entire age range of ocean crustal rock, will allow these conflicting possibilities to be directly and explicitly tested.

In addition to field observations, unraveling the limitations on growth and existence in the seafloor will require contributions from both laboratory and theoretical approaches. For instance, laboratory studies on the rates of chemical reactions and on microbial energy requirements will provide constraints on the balance between the supply and demand of metabolic energy sources in seafloor environments [26, 71]. Questions about the role of pH and pressure on limiting deep seafloor communities may similarly be augmented via laboratory investigations. Activities within C-DEBI will bring together scientists working in these different disciplines, providing opportunities to develop new insights into the *defining drivers* that effect the distribution of life in the seafloor, which will link findings concerning the limits of life to other themes, such as Theme I, the global biogeochemical consequence of the deep seafloor biosphere, and Theme II, the biogeography of microbes.

**Research Theme IV. Evolution and survival: adaptation, enrichment, and repair.** The seafloor environments being investigated by C-DEBI present challenges to life that are distinct from most other known Earth habitats. This raises questions of how microbes survive in the face of these challenges, and what evolutionary forces are at work in the deep seafloor biosphere.

The question of persistence of life from the perspective of metabolic processes and growth can be distilled to the concept of survival at the edge of bioenergetics and redox processes [26]. The metabolic rates proposed for subsurface microbes are up to six orders of magnitude below respiration rates observed in microbial cultures and in environmental microbes in surface sediments [72] and challenge our current understanding of the functioning of life (*i.e.*, having enough energy to maintain charge potential across a cell membrane). Observations of living cells [48] with intact polar membrane lipids [73] leads to the inference that seafloor sedimentary microbes must persist at extremely low rates of activity per cell. Additionally, studies have shown that the seafloor hosts extremely unique microbial communities that are distinct from surface habitats [73-75]. Why are these microbial groups so prevalent in the subsurface? Are there distinct adaptations that are common to the seafloor biosphere?

Since most subsurface microbes are recalcitrant to cultivation, answers to questions about their adaptation, evolution and survival need to be answered through genetic analysis. Genetic-based studies of deep seafloor biosphere to date have used targeted polymerase-chain reaction (PCR) based approaches to examine phylogenetic genes (*e.g.*, [45]) and on occasion, ribosomal sequencing and analysis has been performed [76]. More rarely, PCR based approaches for looking at functional genes encoding for important biogeochemical processes (methane, iron, etc.) have been targeted (*e.g.*, [77, 78]). However, research concerning questions about survival and evolution in the seafloor has not yet emerged among the core foci in seafloor biosphere studies, nor have research approaches that take a broader-scale view of the genetic content of microbes buried beneath the seafloor. We envision Theme IV studies will embrace a compare-and-contrast approach across our C-DEBI field projects examining the total gene content of the deep seafloor biosphere using metagenomics-based approaches (*e.g.*, [79]). The term “metagenomics” includes a variety of whole-genome approaches such as shot-gun sequencing, *i.e.*, [80], vector-based library tools [81], whole-genome amplifications [82] and other specialized methods.

Our first-glimpse at use of metagenomics in the deep seafloor biosphere illustrates its potential power for evolutionary questions. As part of the initial “census” of life in seafloor sediments [1], it has emerged that globally, cell abundances decrease logarithmically with depth [83]. A consequence of this decrease is that with depth, microbes become increasingly isolated from each other, owing to the fact that chemical exchange in sediments is dictated by diffusion, which operates slowly over long length scales. Hence, we may hypothesize that an evolutionary consequence of this increasing isolation may be the loss of genes for functions such as chemotaxis and quorum sensing, which may not be needed as cells become isolated. Indeed, metagenomics surveys of sediments from the Peru Margin do show that genes for chemotaxis decrease with depth [75], hinting that further metagenomics surveys and cross-comparisons may yield exciting new insights on microbial evolution on Earth. *Through project integration with C-DEBI, we will be able to integrate and compare these findings with metagenomics*

*surveys at other sites, and in distinct biomes.* For example, in the crust, where microbes exist in cracks, pores, and crevices through which seawater flows vigorously, there is less of the systematic isolationism with depth. Comparisons across the range of crust and sediments habitats may illuminate evolutionary trends that are a consequence of the increasing isolation of microbial cells. Are there systematic changes in gene content as a function of depth, distance from a spreading center? Do we see similar trends in the oligotrophic SP and NP sediments? Are there significant differences in the ability for viruses and predators to attack between oligotrophic (SPG & NP) and carbon-rich sediments (Guaymas)?

**(d) C-DEBI Research Support Mechanisms.** Each PI has budgeted support for research costs associated with major components of the three core research projects. Additionally, all senior research personnel laboratories are eligible through the C-DEBI Research Support program to apply for small grants in support of projects relating to C-DEBI research themes. Our C-DEBI program office will manage applications, which involves a two-page summary description of the project and time-frame (1-2 yrs of support). We anticipate supporting >700,000 / yr in research costs, and 300,000 / yr for instrumentation grants (postdoctoral, Student, and other C-DEBI support means are discussed below).

**C:DEBI: Community-Initiated Collaborative Research in the Deep Subseafloor Biosphere.**

This STC Proposal articulates the rationale for the establishment of C-DEBI, which can be summarized as:

**Timing:** In the history of drilling for scientific research, there has only been one project drilled with deep subseafloor microbiology as the major objective [22]. However, *three* US-lead and *one* Japanese-lead project will be drilled before 2013; hence, we stand to fundamentally increase our knowledge and understanding of the deep subseafloor biosphere by at least four-fold in a science-as-usual mode of operation, where individuals and small groups each conduct their own specific science objectives at discrete sites. The alternative mode of operation is the development, in essence, of a *collaboratory* to accomplish a coordinated mission in deep subseafloor biosphere research, as represented by C-DEBI. C-DEBI will enable integration, coordination, and moreover, the development of international trust between researchers in this fledgling field, for transformative advances in our understanding of one of the largest biomes on Earth.

**Maturity:** Though our field is new, this community has been working towards center-like modes of operation for years. Other initiatives are on the rise on an international basis. For example, Dr. Bo Barker Jørgensen, the director of the Max-Planck-Institute for Marine Microbiology, is in the process of starting a new center at the University of Aarhus. In this case a physical center is being created, embodied by a moderate sized research faculty that will focus in part on the deep subseafloor biosphere. This and other examples of emerging focus groups for study of the deep biosphere are great assets to the development of our field. However, we present the case that the need for a virtual center, such as C-DEBI represents, is critical to coordinate this international community of researchers. C-DEBI presents the opportunity for the US to lead this international coordination effort, which is warranted at this time given the predominance of the US in leading deep subseafloor IODP proposals in the system today. The meeting we held at Catalina in Feb. 2008 evidences other indications of our readiness for center-level interactions—long prior to this present STC call we were in motion towards achieving this end goal. This is an active, motivated, self-assembling community of researchers, poised to produce high return on a center's capital investment.

**Opportunity:** There is a stunning need to educate beyond traditional undergraduate and graduate levels about Earth and Ocean Sciences today. Capturing public attention concerning ocean sciences can be difficult—people are distracted and busy and ocean science is not often the focus in the popular press, even for its critical role in, for example, carbon cycling, climate change, ocean chemistry and energy production. Here we underscore that the “deep-hot biosphere”, even where it is cold, continues to capture imagination and excitement at a level that is rarely seen in ocean sciences—it *is* the current “wild west” in oceanography. It will not be so forever, if we are successful in our mission; the opportunity to seize this for public education in science and oceanography is *NOW*.

## **(D) Education and Human Resource Development Objectives**

### **Overarching Goals.**

Our *highest priority goal* is to create distinctive, targeted education programs at the K-12, undergraduate, graduate and postdoctoral levels in order to train and foster the next generation of deep seafloor biosphere researchers. This is first and foremost to ensure the robust continued development of this new field, and to arm the field with the brightest and most creative young minds that can take what has been built over the past decade and greatly expand it in this decade via C-DEBI.

We will create broad based educational opportunities that allow the Center's newly generated knowledge to thrive, and we will design special programs to provide opportunities for all segments of our society. We are committed to making sure that future scientists are representative of the full diversity of our society. These students will become the next generation of deep seafloor biosphere researchers who fully integrate the Center's tools and technology into their science. Additionally, we must translate knowledge in and of our field to the broader public, in part through our core education program (which will flow to public policy, administration, and other education fields in addition to academic fields)—but also via programs that promote broader dissemination of information and increased awareness to the public about the tremendous fraction of life on Earth that appears to be buried below the seafloor in sediment and rocks. The Research, Education, Knowledge Transfer and Diversity goals for the Center are closely inter-connected to ensure we meet these goals.

The Center's education and diversity programs are designed not only to improve the educational pipeline (*particularly for students from under-represented groups*), but also to help form a community of young scholars. Given the Center's location and contacts in Los Angeles, our K-12 programs place a special emphasis on the disadvantaged students of many different ethnicities and economic levels in the Los Angeles Unified School District and across the country.

### **K-12 Education.**

Our primary goal for K-12 teachers and students is to introduce them to this emerging field of deep seafloor biosphere research and encourage them to incorporate this research into their classrooms. We will use the NSF Centers of Ocean Science Education Excellence (COSEE) framework to connect deep seafloor biosphere research and our community of scholars (PIs to undergrads) to K-12 science education. For the past seven years, USC has been the home to COSEE-West. One of the key programs in COSEE-West is the teacher-training (**TeT**) program. COSEE-West (<http://www.usc.edu/org/cosee/cosee-west>) develops connections and interactions between cutting edge university research and **TeT** workshops and training programs through lecture series and in-person and on-line workshops that enhance the teachers' instruction. We will develop (1) on-line teacher workshops, (2) a series of lectures, (3) on-site teacher training programs, (4) provide grants and "kits" for hands-on modules, and (5) collaborate with the Deep Earth Academy (DEA), which focuses on scientific deep sea drilling, providing numerous avenues for education and outreach (see below).

C-DEBI faculty will work with COSEE-West staff and K-12 teachers to create new lesson plans that explore the topics of our research and link it directly to State Science Standards and the principles of ocean literacy (<http://www.collegeofexploration.org/oceanliteracy>). C-DEBI will work with COSEE-West to develop and host annual **on-line teacher workshops** on the deep seafloor biosphere. Previous COSEE-West on-line workshops have reached between 100-600 teachers. C-DEBI faculty, postdoctorals, and students will work with COSEE-West staff to develop a series of taped lectures and presentations which will be uploaded to the The College of Exploration (TCOE) web site, home to the COSEE-West online lecture series ([http://www.collegeofexploration.org.cosee\\_west](http://www.collegeofexploration.org.cosee_west)). After the teachers view the presentations, the faculty and graduate students have set times available for the teachers to interact and ask questions on their topics of interest. Teachers may sign up through the Cal State system to receive 1 unit of credit for the workshop. Teacher's interactions are tracked throughout the experience, so that we may evaluate their participation and follow their progress through pre- and post-workshop evaluations (section F). COSEE-West staff will follow-up with the teachers to evaluate use, and assist in integrating the new information and activities into their classrooms. Local C-DEBI graduate students will be

available to interact with the teachers in their respective regions and will provide additional connections into the teacher's classroom as part of a College Mentors program where personal connections to students facilitate the likelihood that they will see college as a logical career choice. By knitting our activities into the COSEE-West framework, we will participate in their professional assessment process. Each COSEE center has a formal assessment activity that uses various approaches to document the extent to which the activities have a positive impact on the stated program goals and to guide further improvements.

Our educational programs require both the personal commitments of the PIs and a small investment in funds. The PIs will participate in the **lecture process** and **lesson plan development** each year, and we will disseminate this information and solicit input and contributions from our senior researchers and science **TT**'s. We will ensure that all C-DEBI supported graduate students and postdoctoral students commit to participation in this process, and will encourage broad participation among all graduate and postdoctoral scholars working in C-DEBI laboratories. Each of these lecture modules requires staff support and coordination by COSEE-West staff.

This community of teachers would then be encouraged and made aware of opportunities to participate in **on-site teacher training programs** at our partner institutions. For example, the University of Hawaii's Astrobiology Laboratory Institute (ALI'I) for Instructors is a week-long training course for grade 7-12 teachers. The deep seafloor biosphere is an integral part of the ALI'I workshop. One of the requirements for admission into this program is a commitment from the teacher to conduct workshops back in their home school district.

For further assistance with implementing lesson plans in their classrooms, we will provide **small grants** to select teachers who have attended our on-line workshops. Additionally, teachers may apply to receive **deep biosphere "kits"** that will be developed, including lesson plans and classroom supplies. Many of the technological-based modules require substantial materials, which school systems cannot afford, store or repair.

We will also partner with the Deep Earth Academy, DEA (<http://www.deepearthacademy.org>), a program of the Consortium for Ocean Leadership (COL) that facilitates and develops activities and materials based on authentic data from shipboard research expeditions to strengthen students' mathematics, science, and analytical skills for a lifetime of learning. They work to equip K-12, university, and informal educators with materials to teach about the Earth using exploration of the world around us as a model to help students become better decision makers, problem solvers, science-literate citizens, and stewards of our planet. In so doing, DEA will be responsible for coordinating learning activities focused on the scientific processes and outcomes afforded by IODP's United States drilling vessel and long-time geoscience workhorse, the *JOIDES Resolution (JR)*. These include the new *JR* web portal ([www.joidesresolution.org](http://www.joidesresolution.org)), live video broadcasting from the ship to school and informal audiences, teachers and educators at sea on every expedition, and the popular shipboard "School of Rock" professional development program for teachers, faculty, and museum educators ([http://www.oceanleadership.org/learning/teachers/school\\_of\\_rock](http://www.oceanleadership.org/learning/teachers/school_of_rock)).

All expedition-based content is made available through the *JR* website, and much is published and distributed through outreach conducted by School of Rock participants. School of Rock 2009 will be taught in part by UC Santa Cruz C-DEBI Co-PI Andy Fisher and will include IODP deep biosphere themes that can begin to prepare C-DEBI for a long-term partnership. C-DEBI and DEA represent an ideal partnership for each of the C-DEBI IODP deep seafloor biosphere expeditions. The DEA is poised to facilitate, support, and maximize the efforts of the scientists and educators involved. They are prepared to work with C-DEBI to plan expedition-based programs originating with the *JR*, including educators at sea, live ship-to-shore events, and School of Rock either aboard the *JR* or at a C-DEBI partner institution.

In addition to the *JR*-focused activities at sea that are supported by the DEA, many C-DEBI sea-going research efforts will be mounted in association with our three major projects. Though all site-survey work is now completed, we will use US ships for post-drilling work such as servicing our CORK observatories. In addition, our developmental projects are certain to have site-survey sea-going work in upcoming years. All PIs and many of our C-DEBI investigators actively engage in teacher-at-sea

programs. C-DEBI will serve as a networking hub to link these various programs and the products of these activities in with the rest of our K-12 programs.

### **Undergraduate Education.**

**Fellowships:** Our activities for undergraduates involve not only classroom education, but hands-on research as well. It is critical for young researchers to become part of the intellectual community of the C-DEBI laboratories and to get a certain amount of ownership of the research and discoveries. To this end, we propose the formation of the “C-DEBI *“Deep Scholars”* program, available at all levels of undergraduate study. During the Spring and Fall semesters, students will get hands-on experience in faculty laboratories under the mentorship of faculty and graduate students.

Several options will be available to students during the summer months. In addition to USC’s own Summer Undergraduate Fellowship Program (SURF), we will coordinate with several of our partner institutions that already have such programs in place, such as the ten-week summer programs at the University of Rhode Island (Summer Undergraduate Research Fellowships in Oceanography), and the Monterey Bay Aquarium Research Institute. We will digitally unite students across the country to share experiences via teleconferencing and through our Virtual Deep Biosphere Community.

**C-DEBI Inspired Courses:** Key Center faculty have already begun to bring deep seafloor biosphere research into existing undergraduate courses, primarily through guest lectures. Some key personnel already teach undergraduate courses whose focus is shifting increasingly towards C-DEBI related topics—we estimate that we are currently reaching several hundred undergraduates each year.

At USC, we are creating a new undergraduate summer course in *Deep Marine Genomics and Evolution* (DMGE; linking to our science Theme 4). The course, taught by Drs. John Heidelberg and Eric Webb, will be targeted at underrepresented minority students (discussed further in the Diversity section), and geared towards upper level (junior/senior) undergraduates and Masters level students. This course will be developed based on the structural scaffold of a very successful NIH-funded Genomics Research Experiences for Undergraduates (GREU) program at USC, which has been running for several years. It will be open to 15 diversity students from any academic institution. We will recruit students from our partner institutions, as well as Historically Black Colleges and Universities (HBCU; <http://www.ed.gov/about/inits/list/whhbcu/edlite-list.html>) and other Minority Serving Institutions (MSI’s; <http://www.ed.gov/about/offices/list/ocr/edlite-minorityinst.html>).

Students will receive an introduction to marine genomics and metagenomics with a special emphasis on their application to the deep seafloor biosphere, training in the current web-based bioinformatics and genomics tools and an introduction to Perl programming. They will attend weekly seminars featuring presentations from researchers representing a wide range of disciplines in the biological sciences. This course will earn four units of transferable college credit.

This introductory course is designed to provide students with an exposure to basic concepts in microbial genomics and metagenomics as well as provide examples of the application of those concepts to deep-sea microbiology. The web-based bioinformatics and genomics are designed to familiarize the student with a wide variety of available tools for bioinformatics analysis. One of the goals of this section is to enable students to use these tools to their fullest with hands-on interpretation/discussion and experimentation, rather than just using the “default” lecturing settings.

The six-week class is divided between the main USC campus and the USC Wrigley Marine Science Center (WMSC) on Catalina Island. The time on Catalina is critical since it takes both the students *and* faculty out of the “typical” learning environment and places them in one where there is far more interaction between students, faculty and graduate teaching assistants—this is not only an important first initiation to the structure and atmosphere of graduate school, but a perfect way to build a tight, long-lasting community.

An interactive seminar series will encourage participation of the students to the fullest. The seminar includes reading a recent paper, chosen by the seminar speaker, to provide background to the discussion topic. Prior to the seminar, the students and instructors discuss the paper in a “Journal Club” format. This prepares the students for the seminar with the external speaker; by using this format it is our

hope the students will be empowered to participate in the more formal seminar, as well as giving the students crucial experience in reading/interpreting scientific articles.

While USC is taking the lead on the formation of this new course, all core institutions are committed to creating new curricular opportunities at their home institutions for their own students and to recruiting minority students for the USC program. For example, Fisher plans to newly incorporate C-DEBI themes into a ground water modeling class (Eart220) at UCSC.

### **Graduate Education.**

**Training:** Within their own institutions, each of the PIs has support for training of graduate students— in total 30 graduate years of support (six per year) are budgeted across the co-PI institutions. Additionally, all senior personnel laboratories are eligible through the C-DEBI Graduate Fellow Program to apply for graduate student funding. The application procedure involves a two-page summary description of the project and time frame (1-2 yrs of support/fellow) and two letters from supporting faculty, at least one of which must be a C-DEBI investigator. Applications will be reviewed by the standing steering committee. We anticipate supporting approximately 20 graduates in total between PI and Senior Investigator labs.

**Courses:** We will work with existing programs to integrate C-DEBI research into graduate thematic focus courses in which our faculty are heavily engaged. USC C-DEBI faculty (Berelson and Corsetti) are the co-Directors of the Agouron International GeoBiology course, and many C-DEBI faculty have been involved as faculty for lectures and other teaching activities for this course. We have a history of highlighting deep seafloor biosphere research via special symposia in this course and will integrate emergent C-DEBI themes. C-DEBI faculty will work with the organizers of other graduate courses such as the Hopkins Microbiology Course (lead by C-DEBI faculty Spormann), and the MBL Microbial Diversity Course (many C-DEBI faculty have/do teach in this course) to incorporate emerging deep subsurface biosphere research and technology.

As with our undergraduate programs, all key personnel will work to integrate C-DEBI research into existing graduate courses such as USC's GEOL 601, Topics in Geobiology.

**Small Grants:** Finally, we will award small research and travel grants (up to \$5K) for graduate students affiliated with the Center. These grants may be used to support research, travel for presenting C-DEBI research at meetings, or travel exchanges to other partner institutions or institutions that have new tools and techniques that can be applied to C-DEBI research.

### **Postdoctoral Program.**

The C-DEBI Postdoctoral Scholar Program will be an internationally advertised program to bring postdoctoral researchers into C-DEBI laboratories at US institutions. Our program will allow postdoctoral scholars to apply to work within any C-DEBI senior investigator laboratory. Postdoctorals that work between several laboratories will be encouraged to support synergy between laboratories. The application procedure is identical to the graduate student application described above excepting the addition of a two page CV for the applicant, and three letters of recommendation in total, one of which must be from the applicant's graduate advisor, and one other be the intended C-DEBI sponsor.

### **Public Outreach.**

**Lectureship series:** A unique feature of the C-DEBI community is our spatial distribution across the United States and beyond. While this presents challenges to this community—coordinating projects and research, for example—it also provides opportunity for public dissemination of knowledge of the field. We strive not only to reach those already involved in the field, but of equal importance, those who are not familiar with the complexities and importance of the deep seafloor biosphere. We propose to develop a lecture series that is modeled after the NSF RIDGE 2000 distinguished lecture series (<http://www.ridge2000.org/dls/>). Small colleges and universities, particularly ones without existing science programs, are the targets for these lectures, which are given by RIDGE scientists. Lecturers prepare two separate presentations: one geared for a scientific audience, and one for the general public, which is critical for attracting future students into the field. C-DEBI PI's and scientists will work with their local regional partners to provide lecture series to small colleges, aquaria and informal science

centers.

***Museum and Aquaria Exhibitions:*** Through COSEE-West and the USC Wrigley Institute's K-12 education programs, we have created excellent partnerships with the Los Angeles County Museum of Natural History, the California Science Center, the Cabrillo Aquarium, the Long Beach Aquarium of the Pacific and the Santa Monica Pier Aquarium. We will build on these connections to create public education opportunities that use the scientific discoveries from C-DEBI to educate the general public. This would come through C-DEBI scientists participating in public lecture series and collaborations on possible displays and educational materials for guests and teachers.

The USC Wrigley Institute has partnered with the USC Division of Animation and Digital Arts (within the School of Cinematic Arts) on a number of science communication projects in the past. We will work with faculty and graduate students to create short animations that will explain the complex subject of life in the deep seafloor subsurface. These can be distributed over the web and can be incorporated into scientific presentations and displays in museums and aquaria. Similarly, partner institutions will work with their local educational centers. For example UH C-DEBI co-PI will work with education specialist from NASA Astrobiology Institute, the Center for Microbial Oceanography Research and Education, Waikiki Aquarium, and the Bishop Museum. In this way, the displays, animations and other education materials produced via COSEE-West and other C-DEBI member institutions will achieve greatly extended reach.

***Science At-Sea Outreach:*** The deep seafloor biosphere captures the interest and imagination of the general public in a significant way, as exemplified by a recent New York Times blog on "The Intraterrestrials" (<http://judson.blogs.nytimes.com/2008/06/10/meet-the-intraterrestrials/>). The subsurface biosphere being the source of a NYT blog is notable in and of itself—but the public commentary, which can be viewed in posted responses, is simply amazing. "*So, let's see here... billions of bacteria per ounce of rock, not just surviving but thriving in every imaginable corner and crevice of the ocean floor... exploiting many, unexpected sources of metabolic activity... and having multiple effects on the chemical and geological composition of the Earth, and even on its magnetic fields...*"; and, "*it is amazing to know how that "aliens" reach the energy from other sources*"; as just a few examples.

C-DEBI seeks to capitalize on this current enthusiasm. USC's communication director of research communications Carl Marziali will coordinate with communication liaisons at our partner institutions for further dissemination of expedition-based web-content to a broad variety of public scientific outlets, for example science blogs and general science articles featuring C-DEBI research. This will include the *JR*-expedition focused programs facilitated by the DEA, and other non-*JR* expeditions associated with C-DEBI research. For example, site-survey and CORK observatory cruises that use other research platforms within the US or abroad.

Edwards and Marziali, in collaboration with C-DEBI participants, recently tested this model of science based on a site survey expedition in the Atlantic for the C-DEBI NP project. This cruise was a German-American collaboration that utilized the German research vessel *Maria. S. Merian*. USC hosted a NP blog (<http://northpondexpedition.usc.edu/>) that was authored by Edwards with content and photos from the shipboard science party (including C-DEBI faculty Bach, Biddle, Ferdelman, Schippers, and Ziebis). Marziali worked with a number of other media outlets for additional dissemination of this blog, for example, Scientific American (<http://www.sciam.com/blog/60-seconds-in-north-pond/>), and the NSF's new "Science 360" daily news site (<http://news.science360.gov/archives/20090223.aspx>) which rapidly spread throughout the science media world. Marziali also facilitated a "Behind the Scenes" feature, authored by Edwards, in *LiveScience*, an online science news wire that feeds MSNBC, Yahoo! and other outlets (<http://www.livescience.com/environment/090424-bts-ocean-science.html>). This was an unusually successful experiment, attracting significant attention to the deep seafloor biosphere and the NP project. As with the NYT blog, response comments such as: "*I was totally unaware of this aquifer under the ocean. That is something that should be studied for sure*"; were common.

## **(E) Diversity Objectives**

### **C-DEBI Core Diversity Goals.**

The Diversity goals for the Center are to: (1) Increase the diversity of participants in all levels of C-DEBI from undergraduate, graduate and post-docs through to participating researchers and staff; (2) educate and work with 50 to 75 teachers each year about C-DEBI research; we will especially target teachers who specifically work within large populations of underrepresented minorities; (3) visit and provide lectures on C-DEBI research programs at 2-3 HBCU/MSI campuses each year; (4) provide a unique educational experience in the form of a special summer course for 15 undergraduates from underrepresented groups each year.

**Table 2.** Data for C-DEBI PI and Co-PI students completing MS or PhD April 2006 through April 2009.

M.S. Students					Ph.D. Students				
G <sup>1</sup>	E <sup>2</sup>	D.S <sup>3</sup>	N <sup>4</sup>	#Y <sup>5</sup>	G <sup>1</sup>	E <sup>2</sup>	D.S <sup>3</sup>	N <sup>4</sup>	#Y <sup>5</sup>
F	White	No	US	2.3	F	Asian	No	China	5.3
M	White	No	US	2	F	White	No	US	5.5
M	White	No	US	3	F	White	No	US	6
M	White	No	US	US	F	White	No	US	6
M	Latino	No	US	2.5	M	White	No	US	6
F	Latino	No	X <sup>6</sup>	5	M	Iran	No	US	7
F	N.A. <sup>7</sup>	No	X <sup>6</sup>	4					
M	White	No	US	2.5					

<sup>1</sup>Gender; <sup>2</sup>ethnicity; <sup>3</sup>disability status; <sup>4</sup>nationality; <sup>5</sup>years to degree completion; <sup>6</sup>no data; <sup>7</sup>Native American

Table 2 presents a compilation of data concerning graduate degree completion from each of the PI and Co-PI institutions.

USC has a strong commitment to diversity at all levels of the academic community and throughout society. USC, as a private university, continues to promote affirmative action in student recruitment. When USC was named the 1999 Time Magazine *College of the Year*, it was attributed to USC's efforts to improve the lives of inner-city youth and to promote diversity across the campus. Gender diversity

has improved markedly in recent years, but significant improvements can still be made. USC's Marine Environmental Biology doctoral Program currently has 39 graduate students, 24 women and 15 men with one African American, one Latino student and one Native American. USC's Earth Science Program has 54 doctoral students with 24 women, 28 men and one Latino student. C-DEBI's goals for advancement of women will also benefit from the existence of the USC Women in Science and Engineering program (WiSE). A primary goal of WiSE is to prepare the next generation of women tenure-track faculty in science and engineering disciplines, through a host of creative programs designed to address subtle biases and inequities that hinder women's career advancement. Working with the math, science, and engineering departments across USC, WiSE matches and augments financial support to women graduate students, encouraging their research, enabling their travel to scientific conferences and meetings, and rewarding their achievements. WiSE will work in synergistic collaboration with C-DEBI to recruit and retain high-quality young women scientists as well as to provide them with versatile career paths.

Even in these times of great economic stress at public universities, UCSC recently created a Chief Diversity Officer position, a new position within the Chancellor's office for coordinating and managing diversity programs at the university. Example programs to foster diversity at UCSC include a program for *Academic Excellence* (ACE) for Science, Technology, Engineering, and Mathematics (STEM) education, which is designed to foster success among diverse undergraduate populations in large lecture classes. *ACCESS* is a academic bridge program to facilitate community college students transferring to UCSC. *California Alliance for Minority Participation* (CAMP) represents a program that puts undergrads in research labs and in the field. *California State Summer School for Mathematics and Science* (COSMOS) represents four-week summer residential program in education and research that is available to UCSC students. Other examples of programs in place and available to C-DEBI may be found at UCSC's website (<http://www2.ucsc.edu/eoo-aa/>).

URI has a breadth of existing multi-pronged programs for enhancing, recruiting, and supporting diversity growth. A prominent example at the undergraduate level is the URI Talent Development Program, which supports students of color and disadvantaged students. URI also hosts a nationally competed URI Summer Undergraduate Research Fellowships in Oceanography (SURFO) Program, which engages students in cutting-edge research directly. On average, women comprise 65 % and

members of under-represented groups comprise 20 to 25% of the SURFO students. A faculty-initiative is also provided by the NSF-sponsored *ADVANCE* program, focused on increasing representation and advancement of women in academic science and engineering careers. To enhance the number and quality of minority students in its graduate programs, URI utilizes a wide variety of mechanisms, including dedicated minority student support programs, (New England Board of Higher Education & a Minority Doctoral Scholars Program). In addition, the URI Graduate School participates in New England regional activities to increase retention of minority students.

The *UH* brings a distinct multicultural learning environment to C-DEBI that is founded on in its Hawaiian, Asian, and Pacific orientation and international leadership role. The UH motto is “Above all nations is humanity” and is reflected in the rich ethnic diversity of UH students: 22 percent Caucasian, 16 percent Japanese, 13 percent Filipino, 14 percent Hawaiian or part Hawaiian, five percent Chinese, 12 percent mixed ethnicity, and 18 percent other. The mission of the UH system is to provide quality education and training, to create knowledge through research and scholarship and to contribute to the cultural heritage of the community. UH encourages and fosters higher education for underrepresented groups through programs such as the Kua’ana Student Services, which facilitates entry of Native Hawaiians into UH (tutors, peer support, financial aid workshops). The Office of Multicultural Student Services provides employment, training and educational support to UH students who intend to tutor and advise minority-dominated public school students, and actively recruits ethnic minorities to apply for admission to UH. The Office of Student Equity, Excellence and Diversity also coordinates efforts to support students with disabilities, Native Hawaiians and ethnic groups, and women underrepresented in higher education. In further support of the educational goals of C-DEBI and is described in UH cost share support for a minority graduate student.

Given the many remote villages and towns in Alaska, many of which are located along the extensive coastline and support subsistence populations, in 1969 *UAF* developed a Rural Service Center, which is committed to responding to student needs by providing quality services to Native and rural students in the pursuit of higher education and its opportunities, and more recently UAF opened the Office of Multi-Cultural Affairs. UAF’s commitment to academic and vocational education and outreach that promote workforce preparation, economic development, life-long learning, and community development through Alaska, with an emphasis on Alaska Natives and underserved communities, is the focus of six satellite campuses that geographically serve nearly two-thirds of the state, representing more than 160 primarily Native Alaska communities, and state-of-the-art distant learning programs and technology. Other programs related to C-DEBI include the Alaska Native Science and Engineering Program, a STEM program, and the Alaska Experimental Program to Stimulate Competitive Research.

C-DEBI, its faculty, and all participating institutions are firmly committed to improving diversity at all levels of research and education and we are all committed to implementing innovative and effective programs so that C-DEBI is seen as a model for other Centers and institutions. The diversity objectives will be accomplished through an intensive effort to reach out to underrepresented minority groups through a variety of targeted activities outlined below.

### **K-12 Programs.**

Our K-12 program is centered on reaching teachers and informal educators at aquaria and science centers through on-line workshops and lecture series. In past teacher workshops sponsored by COSEE-West, we have had up to 30% participation by minority teachers (COSEE-West NSF Annual Reports). Most of the local districts within the Los Angeles Unified School District (LAUSD) are minority-serving schools with a predominantly Latino/Hispanic majority (73.7% in 2007-2008), as well as significant populations of African Americans (10.9%). COSEE-West manages a list serve, *Oceanlist*, with 660 participants nationwide and uses *Scuttlebutt* from the National Marine Educators Association (NMEA) to announce activities and opportunities for teachers and informal educators to participate in. We will work closely with the recently established COSEE Diversity Working Group of the COSEE Council to develop mechanisms to effectively reach and engage minority teachers as well as those who teach in minority serving districts. The COSEE-West program will support three

Hispanic/Latino teachers to attend the National Marine Educator's Association meeting in Monterey this summer, and C-DEBI will likewise support travel scholarships for minority teachers to attend annual meetings and present activities where appropriate. C-DEBI partner institutions will work to facilitate participation of teachers from minority-serving schools in local COSEE-West teacher workshops; for example, most Hawaii schools serve students of Native Hawaiian and other Pacific Island communities.

We will also promote C-DEBI research and programs at the *Society for Advancement of Chicanos and Native Americans in Science* (SACNAS) annual meetings through participation and presentations at the meeting by C-DEBI faculty, students and education and diversity staff (<http://www.sacnas.org/>). USC faculty representatives from earth science and marine biology, with a COSEE Council representative, have participated in this meeting for the last several years in order to engage the SACNAS community. SACNAS represents an excellent venue to recruit students, faculty, and teachers to the C-DEBI programs.

### **Undergraduate.**

***Undergraduate Summer Program:*** Dr. Steve Finkel (USC) has created an education program for traditionally underrepresented minorities in the fields of genetics, computational biology and molecular biology. As described in the Education Section, Drs. John Heidelberg and Eric Webb will be modeling their introduction to microbial genomics and evolution summer course, *Deep Marine Genomics and Evolution*, on this very successful program.

The six-week course will be composed of five diverse students from USC and ten diverse students from other institutions across the country. Recruitment for the course will be via a number of methods: (1) Through USC's partnership with SACNAS, we will post announcements on their website and send announcements via email to their 20,000 members through their "e-nouncement" system, (2) Through a booth at the annual SACNAS conference, (3) through on-campus minority clubs, (4) by providing C-DEBI faculty with an advertising slide to add to presentations, and (5) by email distribution by C-DEBI faculty and minority serving institutions. Stipend support is included in this program.

Student participants will have a unique introduction to the C-DEBI community. Because half of the course is at the USC Wrigley Marine Science Center on Catalina Island, students will get to know their instructors (both the main instructors and visiting lecturers, many of whom will be diverse) in a different way than the standard classroom. By learning and living together, the students will be much more engaged in the Center's activities, and with the participating graduate students and faculty. Those students enrolled at USC or partner institutions will be invited to participate in the C-DEBI Deep Scholars program for undergraduates so that they may continue their involvement throughout the school year.

To reach an even larger pool of underrepresented students, 3-4 instructors will be invited from California community colleges to evaluate how much of the Center approach and content can migrate into community college courses and to explore mechanisms for taking the excitement of our faculty and students and bringing it to these students. Under-represented minorities dominate community colleges in most of California and the science programs in these schools play key roles in determining if their students choose to continue in science at a 4-year institution.

### **Graduate Students.**

To both recruit and retain minority students in our Ph.D. programs, we are offering two-year Student Research Assistantships each year. Our hope is that we can use these fellowships as recruiting tools particularly for underrepresented students – the fellowships will allow the students to focus on their own dissertation research early in their graduate studies. Our undergraduate programs will be used as active recruiting tools for underrepresented groups to C-DEBI institutions and research. USC, UCSC, URI, UH and UAF *all* offer University wide competitive graduate fellowships for incoming minority students each year – these will also be available for C-DEBI recruited students.

Recruitment of C-DEBI graduate students for these fellowships will be via a number of methods similar to those used to attract undergraduates: (1) Through partnership with SACNAS, we will post announcements on their website and send announcements via email to their 20,000 members through their "e-nouncement" system, (2) Through a booth at the annual SACNAS conference, (3) by providing C-DEBI faculty with an advertising slide to add to presentations, and (4) by wide email distribution by C-

DEBI faculty to minority serving institutions as well as visiting and presenting C-DEBI research at HBCU's, MSI's, and other minority serving institutions.

### **Postdoctorals & Faculty Advancement: A C-DEBI Focus on Women in Science.**

Our fellowship program will take special measures to ensure advertisement and recruitment of



**Figure 2. C-DEBI Faculty: our women postdoctorals at sea.**

Left to right: postdoctorals Nina Knab (Edwards laboratory), Jennifer Biddle (Teske laboratory; starting Asst. Prof. Univ. Del 1/2010), Aude Picard (Ferdelman laboratory) sample sediment core with Edwards (right) aboard the research vessel *Maria S. Merian* (German fleet) during the Atlantic expedition to NP in Feb. 2009 that is described in the education section. This expedition also included (not shown) postdoctoral Anna Blazejack (Schippers laboratory). Photo Credit: A. Teske.

underrepresented groups, through broadly disseminated canvassing and advertisement both through traditional media (e.g., advertisement in ASM's Microbe magazine, postings on our websites) and some of the aforementioned avenues used for graduate recruitment where they apply. In addition, **C-DEBI will specifically emphasize career advancement for women in science, and recruitment of women into deep subseafloor research and ocean sciences generally.** The transitions from student to postdoctoral, and from postdoctoral to faculty/career scientist are well documented "attrition points" for young women, especially in the natural sciences and engineering. We will provide numerous opportunities at all levels for women to advance into leadership roles in our science committee's. This commitment is evidenced in the leadership roles

women are playing in this center: Edwards (Director), Biddle (Asst. Prof.; postdoctoral program committee), Ziebis (Asst. Prof.; *TT* leader), Huber (Asst. Sci; *SciCom* member and meeting co-organizer), K. Heidelberg (Asst. Prof. and *SciCom* member), and Rogers (Asst. Prof.; meeting aid). Hence, C-DEBI features six women at different career stages in influential positions. Commitment by the PI's, to advancing women in the sciences, and **C-DEBI wide commitment to this objective** is also evidenced by ongoing recruitment and mentoring in our laboratories (Fig. 2).

From the PI's laboratory in recent years, three women postdoctorals and one female Ph.D. graduate have been placed in competitive faculty positions at Harvard Univ., Univ. of MN, Univ. of DE, and the Marine Biological Laboratory. Postdoctoral Orcutt will soon transition from Edwards' lab to a competitive position in Jørgensen's new Center at Aarhus (discussed above). Of these women, two (Chan and Toner) were recruited to deep-sea research from outside fields (terrestrial aquatic geomicrobiology and soil chemistry, respectively), and now in initiating their own laboratories have a major focus on deep sea/subseafloor biosphere research. **C-DEBI faculty include 10 women at the Assistant Professor (or equivalent) career stage and 17 total women across C-DEBI (35% of senior participants in the US).** With these levels of women participation across all career stages, C-DEBI will serve as a "career incubator", supporting the career development of female postdoctorals and the current cadre of young women faculty through career advancement to senior faculty positions. The community building that will be fostered by creation of C-DEBI will help ensure advancement successes and increased diversity in the sciences and engineering.

## (F) Knowledge Transfer Objectives

We have three knowledge transfer objectives: (1) *training* and *fostering* a diverse new community of deep seafloor biosphere researchers with an emphasis on building an expertise base in young scientists; (2) *communicating* exciting results and new frontiers of research pertaining to the deep seafloor biosphere to the broader public and education communities.; and (3) *information sharing* concerning strategies to conduct C-DEBI-related research within national funding agencies and the IODP structures. Methods that will be used to achieve these objectives are described below (for (2), many of specific programs and methods for education and outreach are described in section D).

**Research Exchanges: Promoting student-postdoctoral-faculty interactions and fostering collaborative intra- and inter-university research.** C-DEBI will facilitate scientific coordination and collaborations by supporting student, postdoctoral, and faculty exchanges to build, educate and train the deep seafloor biosphere research community. Exchanges will establish direct linkages among groups within individual institutions participating countries, which are intended to result in a well-connected

<b>Expertise</b>	<b>Geochemistry</b>	<b>Geobiology</b>	<b>Molecular Bio</b>	<b>Theory &amp; models</b>	<b>Field Work</b>
<b>Technique</b>	Lipids Isotopes Microsensors OSMOs	Culturing Activity rates Experiments Microscopy	Sequencing Metagenomics Quantification FISH	Energetics Hydrogeology Reactions Modeling	CORKS Expeditions Equipment Site Surveys
<b>C-DEBI members</b>	K. Hinrichs O. Rouxel T. Ferdelman B. Orcutt	H. Cypionka W. Ziebis M. Schrenk K. Edwards	J. Huber J. Heidelberg F. Inagaki A. Schippers	E. Shock A. Fisher W. Bach T. McCollom	G. Wheat A. Teske S. D'Hondt J. Cowen

<sup>a</sup> representative examples only; see information on our full C-DEBI community and projects/expertise from our personnel listing and biosketches.

community and the development of future deep seafloor biosphere researchers and leaders. Exchanges will allow a C-DEBI researcher (student /postdoctoral

/faculty) to spend 1-6 months at a participating C-DEBI host laboratory to carry out experiments, use analytical equipment, learn a new tool, and/or join a research cruise. C-DEBI participants have embraced the concept of hosting research exchanges (*e.g.*, sample structure presented in Table 3). Exchanges may operate between any willing C-DEBI collaborating laboratories. Financial support for exchanges through C-DEBI will be ~50% of the total cost. Matching funds would be required, for example, a travel award from any program that supports student awards in this way (*e.g.*, Geological Society of America, NASA Lewis and Clark fellowships), or by other means, such as matching support from the researcher's institution or from a postdoctoral supervisor. We anticipate ~10 awards of \$0.5K-5k will be granted annually. Applications will be managed by our C-DEBI program office, reviewed by the SciCom and ExCom, and awarded annually. A complete application will consist of: (1) a two-page research proposal, which outlines the intended objective and anticipated outcome of a research exchange; (2) a one-page budget outlining expected costs of the exchange as well as other sources of funds which will be used to support the exchange; (3) two letters of support (4) a one-page CV; and (5) a confirmation of financial commitment for the matching funds. Recipients of the exchange awards will be required to present their findings at the subsequent annual C-DEBI meeting. In addition, they will prepare a short summary of their exchange experience for display on the C-DEBI website. Acknowledgement of NSF and C-DEBI support is mandatory in all associated oral and poster presentations and publications.

**Phone Conferencing:** Phone conferencing will be a major mode of routine communication among C-DEBI groups. *ExCom* and *SciCom* will have regularly scheduled phone conferences, both independently and jointly. *TT* leaders and *ExCom* will phone conference ~ quarterly. The subjects of these conferences will vary from administrative to science planning.

*TT* are the major mechanism of scientific exchange between the diverse C-DEBI communities and are anticipated to be our principal science incubator. *TT*'s will have monthly to bi-monthly phone conferences in order to discuss plans, progress, obstacles, other coordination and knowledge transfer issues. Additional *TT ad-hoc* groups will be formed for specific tasks (*TAPs* – see section B). Members

of the DEBI community (Bach, Becker, Cowen, Edwards, Fisher, Girguis, Glazer, Huber, Schrenk, Orcutt, Pettigrew, and Wheat) have demonstrated the successful utility of this mode of information transfer and decision making: For example, we have a standing CORK advisory group (*TAP*-like) group that has phone-conferenced monthly (since Feb. 08, coordinated by Orcutt) to aid with development of CORKed observatories for the NP and JDF sites. Similar *TAP*s are envisioned to develop from the *TT*'s for other technical, logistical, or scientific needs. Teleconferences will be organized by a C-DEBI postdoctoral fellow using freely available online meeting planning and teleconferencing software—a model that has worked well for use for the CORK *TAP*. This allows the postdoctoral fellow to gain practical experience in organizing and managing conferences, and it also serves to foster collaboration, communication, and integration of young scientists into complex science projects.

**Videoconferencing.** Videoconferencing will be an integral component of C-DEBI's objective to spread information amongst our geographically widespread participating institutions. We will host monthly virtual meetings/videoconferencing for science presentations from our *TT*s (rotating between themes), modeled after the successful *NASA Astrobiology Institute Seminar Series* concept, of which many of us have participated. Video seminars will focus on research results and activities of C-DEBI teams among the partner institutions. These seminars may also include invited talks, graduate student and summer student presentations and workshop plenaries to encourage interdisciplinary collaboration of those involved in deep seafloor biosphere research. To engage the larger deep seafloor biosphere community, the seminars and their closing question and discussion sessions will be recorded for public viewing on the website. *Adobe Connect* will be used for web conferencing and desktop sharing between meeting participants at their home institutions. USC manages an *Adobe Acrobat* server, which can be accessed with *Adobe Flash* via the internet (at <http://breeze.usc.edu>) for real-time visual and audio communication; image, text and video exchange; annotation; notes and more.

**C-DEBI Website, Cyber-infrastructure:** In collaboration with the USC Southern California Earthquake Center (SCEC) in Earth Sciences and TCOE liaisons, Tina Bishop and Peter Tuddenham, C-DEBI will develop and maintain a website for public access and data sharing among the C-DEBI research community. SCEC has been developing cyber-infrastructure for this center for well over a decade, and will serve as a model of website structure and function (<http://www.scec.org/>). TCOE will partner with C-DEBI in order to develop the architecture for our online communities for collaboration and learning for two principal objectives: 1) to support the connection among scientists and others in the C-DEBI project research community and 2) to foster the connections between C-DEBI scientists and educators through the online learning workshop program (section D). TCOE will provide an online project collaborative environment, a virtual C-DEBI Center, in which C-DEBI scientists, committee members, project leaders and others have the opportunity to dialogue in a private, password protected online space in an asynchronous format, with options for synchronous (real-time) exchange as desired. This will serve as an online meeting hub for collaboration, information and data exchange, planning, learning, and joint decision making for C-DEBI partners spread out across geographic distance. This would help the project meet its goal of supporting the C-DEBI collaborative framework for new and existing research projects.

In addition, cyber-infrastructure and databases are a well-established component of the IODP and its predecessor programs for facilitating coordination of complex logistical and technological aspects of deep seafloor biosphere research. While the information and resources are pre-existing in many cases, navigating the IODP system is not always easy, particular for the unacquainted. The C-DEBI website can serve as a facilitating agent to the broader community, for example, by collating deep seafloor biosphere proposals and communication among proponents and IODP committees on our C-DEBI website, and providing “tools” resources pages that are specific to deep seafloor biosphere research.

**Meetings:** The field of deep seafloor biosphere research is young; hence, in addition to phone and videoconferencing, direct interaction between our members is crucial for success. Five annual meetings are planned beginning in 2009 with funds from the DEBI RCN (discussed above). Meetings will be held at various locations, each organized by a local host and science team (with other local aids TBD), supervised by J. Amend (Table 4). Three-day meetings will have equal time for science

conferencing and a training workshop. Topics covered will span the range embodied within C-DEBI

Location/yr	Theme	Host	Science Aids
UH/2009	CORKs, Hydrogeology	Cowen	Fisher, Glazer
UNC/2010	Sediment Microbiology	Teske	Schrenk
Bremen/2011	Drill Cores/Biogeochemistry	Bach	Ferdelmann, Hinrichs
WHOI/2012	Microbiology of Crust	Huber	Rouxel, Girguis
WUStL/2013	Marine/Contin. integration	Amend	Rogers, Schulte

discussed in this proposal; year 5 we plan a joint marine-continental integration meeting. By 2013, we anticipate that then current needs for coordinating that science will dictate the future

science themes and potential locations for meeting (2013- meeting topics TBD).

**Industry, National Lab, Drilling Partner & Liaison Coordination:** Wheat will lead efforts to ensure that our industry and drilling partner institutions are involved in C-DEBI activities and promote critical knowledge transfer among the organizations. This includes overseeing *TAP* development and facilitating the appropriate partner or liaisons involvement. For example, Industry Partner Pettigrew’s involvement in the CORK *TAP* conferencing is facilitated by Wheat. Some C-DEBI meeting topics are also appropriate for engaging partners and liaisons. IODP-MI liaison Greg Myers, in his capacity as engineering manager, will attend the Hawaii DEBI-RCN meeting (Table 4).

Edwards will serve as principal contact for our national laboratory partners at the ALS, with whom we have been developing methods for analysis of deep sea and seafloor samples. Brandy Toner and Edwards are writing a proposal (June 2009) for long term “program” for the beamlines we use. This would result in a resident block of time at the ALS each year for us that we could in part be used to do

“test” analysis for C-DEBI (users from any country can apply for instrument time).

**Education Evaluation Program.** Formal evaluation of our program will help fine-tune the experiences for participants, maximize impact, and ensure knowledge transfer to our intended audiences. Follow-up contacts with participants will measure the impact of the program, months and in some cases, years later. Table 5. outlines the proposed evaluation plan for this multifaceted education program (to be conducted by B. Rabin; see section B).

Component	Method	Evaluation Questions
K-12 Online Teacher Workshops	Pre/post online survey	<ul style="list-style-type: none"> <li>• What have the participants learned?</li> <li>• How has the experience changed attitudes toward the content?</li> <li>• What were the most/least effective aspects of the training?</li> <li>• What are the main suggestions for improving the program?</li> </ul>
K-12 Online Teacher Workshops	Online survey 3-6 months after program	<ul style="list-style-type: none"> <li>• How have teachers used the material into their classrooms?</li> <li>• Are there differences in usage/satisfaction grade levels?</li> <li>• What are the main suggestions for improving the program?</li> </ul>
C-DEBI Scholars	Online or paper survey at the end of the school year	<ul style="list-style-type: none"> <li>• What aspects of the program worked best/least well?</li> <li>• In what ways do students think the program will impact them?</li> <li>• What suggestions do students have for improving the program?</li> </ul>
C-DEBI Scholars	One-time retrospective online survey after 5 years	<ul style="list-style-type: none"> <li>• What are participants doing now, career-wise?</li> <li>• In what ways did the program influence their career choices?</li> <li>• How do they see the program helping them in the future?</li> </ul>
Deep Marine Genomics & Evolution	Paper survey at the end of the summer	<ul style="list-style-type: none"> <li>• What aspects of the program worked best/least well?</li> <li>• In what ways do students think the program will impact them?</li> <li>• What suggestions do students have for improving the program, with specific attention paid to URM issues?</li> </ul>
Deep Marine Genomics & Evolution	One-time retrospective online survey after 5 years	<ul style="list-style-type: none"> <li>• What are participants doing now, career-wise?</li> <li>• In what ways did the program influence their career choices?</li> <li>• How do they see the program helping them in the future?</li> </ul>
Graduate Student Funding	Paper or online survey of PI	<ul style="list-style-type: none"> <li>• How has the student contributed to the field?</li> <li>• What presentations has the student given in the calendar year?</li> <li>• What papers has the student published in the calendar year?</li> <li>• What is the student’s next career move?</li> </ul>
Postdoctoral Scholars	Paper or online survey of primary supervisor	<ul style="list-style-type: none"> <li>• How has the postdoc contributed to the field?</li> <li>• What presentations has the postdoc given in the calendar year?</li> <li>• What papers has the postdoc published in the calendar year?</li> <li>• What is the postdoc’s next career move?</li> </ul>

All evaluation projects include questionnaire development in conjunction with the STC administrative and *ExCom* teams, data collection and online survey programming /monitoring where applicable, analysis of both qualitative and quantitative data, an executive summary of results, and complete data (for C-DEBI, NSF, and the EAC).

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