Ultra-Deep Biological Observatory White Paper

May 2, 2008

Prepared by the DUSEL Ultra-Deep Drilling and Exploration Working Group

The Ultra-Deep Biological Observatory will directly address the compelling research question, "How deeply does life extend into the Earth?" as well as all the other five major questions identified in the DUSEL S1 process.

Objectives are the following:

1. To understand factors controlling the distribution of life as a function of depth and temperature.
2. To observe the patterns in microbial diversity, microbial activity and nutrients along this gradient.

Expected Results (Hypotheses)

The following **biological hypotheses** will be tested at the Ultra-Deep Biological Obersvatory:

1. Temperature is the primary factor controlling the depth limit of the biosphere.
2. Chemoautotrophy increases relative to heterotrophy with depth.
3. Diversity declines, but phylogenetic novelty increases with depth.
4. Transfer of genetic elements is limited by low cell abundance and low nutrient concentrations.
5. Population sizes and/or the low rates of genetic recombination impose more rapid rates of protein evolution, resulting from inability to purge mildly deleterious mutations, as predicted by Neutral Theory and empirical data from surface ecosystems.
6. Energy and/or nutrient limitation select for high affinity uptake strategies coupled with motility and chemotaxis or long-term quiescence, maintenance, and passive dispersion strategies.

In addition, research made possible at the Ultra-deep Biological Observatory will also enable testing several **Geological Hypotheses**:

1. Proterozoic rock units at Homestake comprise the southernmost exposure of the Trans-Hudson orogen and are sandwiched between the Trans-Hudson and the Superior-Wyoming province. Consequently, understanding the stratigraphically lower rocks will have a major impact on the paleogeograhic reconstruction for the Proterozoic and possibly the Archean.
2. Stratigraphically and structurally lower Rock units (below Yates) are predicted to be Archean crustal and will be encountered at ~4000 meters drilled depth in a 60˚ angle borehole from the 8,000 ft. level.

   Alternative to this hypothesis include:

   a) the rocks beneath the Yates Formation are back arc basin basalts, gabbro, and possibly ultramafic rocks,

   b) a major thrust fault will be encountered at the base of the Yates that juxtaposes the Yates with younger proterozoic rocks with depth, and
   c) deep boreholes could encounter a large Tertiary rhyolite stock.
3. Horizontal-to-vertical stress ratio varies as a function of depth (directly test by hydrofracturing, examining disking/borehole breakouts)
4. Rock mass permeability decreases as a function of depth except for rare, high-permeability fractures that are typically isolated from the overall low flux through the rock.
5. Fluids in fractures below ~yyyy meters have been isolated for XXX millions of years.
6. Microorganisms at depth access microporosity only through diffusive mechanisms and this limits the rate of metabolism of deep subsurface communities.

The objectives of the Ultra-deep Biological Observatory require DUSEL-Homestake and can be addressed only at DUSEL-Homestake for the following reasons:

- DUSEL-Homestake will offer the deepest drilling platform in North America. Starting from the 2.4 km-deep 8000-level is much less expensive and minimizes the risk of drilling equipment failure compared to drilling from the surface.
- Homestake has a geothermal gradient that is close to the worldwide average. This contrasts with most environments (e.g., Yellowstone, Kamchatka, spreading centers) previously investigated for thermophiles. It is thus likely to be more generally representative of widespread deep earth systems that are not influenced by localized, anomalous geothermal systems.
- DUSEL-Homestake will provide four-dimensional access, i.e., X, Y, and Z directions plus time.
- DUSEL-Homestake will be the intellectual center for subsurface science and engineering and will thus attract the necessary interdisciplinary team required to conduct the research. Additionally, the proximity to other disciplines, e.g., high energy physics, sets the stage for unexpected synergies, for example:
  - generation of large quantities of ultra pure water that will be used for the Cerenkov counter but from which we can obtain drilling fluids,
  - Nearby earth system and physics research with ancillary technologies such as real time monitoring of drilling fluid tracers, low background radioactive decay counting systems, fiber optic temperature and deformation sensors

Approach

An array of three or more 2,500-m (8,200 ft.) boreholes, wire-line drilled from the 2,440 m (8,000 ft.) level at Homestake will probe to at least 16,200 ft. (4,940 m) below land surface, a depth at this location approaching the expected lower biosphere limit (e.g. the 120°C isotherm) (Figure 1). Cores will be collected aseptically and then fracture patterns (e.g., orientation, aperture, etc.) will be determined and fracture fluids will be intensively sampled over time. Cores and fracture fluids will be analyzed for indigenous microbial communities, including their genetic elements, metabolic processes, and biosignatures.

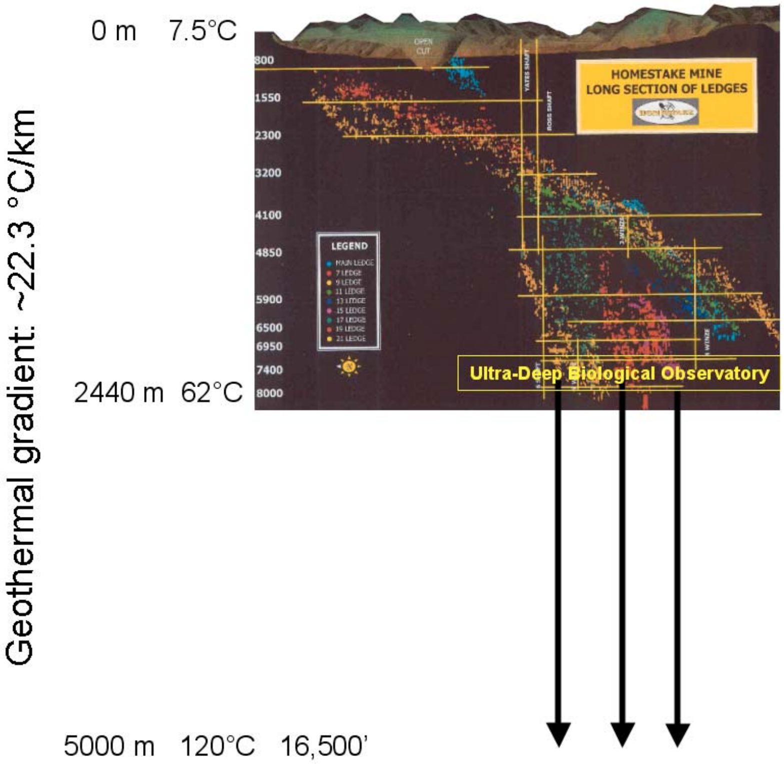

Figure 1. Conceptual diagram of deep drilling at DUSEL-Homestake showing the geothermal gradient.

Research at the Ultra-deep Biological Observatory will be inherently interdisciplinary, as outlined below:

- Drilling Technology
- Geophysics
    - Seismic monitoring
    - Cross-borehole tomography
    - Thermochronometry
    - FEC logging, rock physical properties
    - Cross-borehole tomography -- start with existing boreholes from 8000L - use to select sites/directions for deep boreholes
- Geohydrology - coordinate with Ambient Flow and Transport working group -- “hydraulic tomography”
- Geochemistry
    - Water samples, core samples
    - Down-hole instrumentation for measurement and monitoring
    - Stable isotopes

    - Geochronology
- Biology
    - Culture-independent approaches
        - Phylogenetic and functional gene analyses
        - Genomics, including single-cell genomics
        - Proteomics, metabolomics
        - Flow-cytometry
    - Culture-dependent approaches
        - Aerobes, anaerobes, high-throughput culturing methods
    - Viruses
    - Microbe-mineral interactions

Extraordinary care will be taken to avoid contaminating either the samples or the boreholes. Safety will also be paramount and will include blow out prevention, gas monitoring, and extensive training. Aseptic drilling will use the best available quality drilling fluid, potentially purified, degassed water generated using the same technology that may be implemented for filling a Cerenkov, large-cavity detector with pure water. The drilling rods will be steam-disinfected; chemical and particulate tracers will quantify drilling-associated contamination. The interiors of cores will be examined to quantify abundance, diversity, and activities of microbes as a function of depth. As the boreholes intercept subsurface fluids, aquatic chemistry (including isotopic measures), dissolved gases, and microbial community structure and function will be measured initially at multiple depths and tracked over time. Microbial community variables will be documented by multiple, state-of-the-art technologies, enabling the reconstruction within a geological context of metagenomes and metabolomes from presumably simple and verifiably subsurface-derived communities. Culture-dependent (dilution culture, enrichments, etc.) and culture-independent assays (lipid analyses, rRNA gene analyses, functional gene analyses, DNA arrays, metagenomics, and proteomics) will characterize microbial communities. Geochemical and microbiological data will be used to identify the dominant sources of energy, electron acceptors, carbon, and other nutrients along with the metabolic capabilities for accessing these resources. Chemolithouatotrophic energy sources, e.g., H_2, and CO, will be of particular interest. Viruses will be metagenomically surveyed for their abundance, diversity, rates of phage production, and rates of horizontal gene transfer. Imaging methods will elucidate spatial relationships of microbes to each other and to minerals. Borehole fluids will be isotopically dated as appropriate for the expected age of the water (e.g. ^{14}C, ^{36}Cl, noble gas composition). Solids will also be dated (e.g., U/Th). Wire line geophysics, borehole imaging, and cross-borehole seismic approaches will map the distribution of fractures. “Hydraulic tomography”, which entails a detailed measurement of temperature and strain using fiber optic instruments, will be used to characterize the flow fields. Geochronometric methods will recreate the thermal history of the deep rock. One borehole may be selected for rock mechanics studies and/or *in situ* stress instrumentation. Hole completion will include sterile, non-metal packer and multilevel sampling systems to isolate fracture zones. At least one borehole will be maintained at formation pressure for high-pressure flow experiments. Downhole instruments (e.g., UV, visible, Raman, and Mossbauer spectrometers) will be developed and tested for characterizing minerals, cells, and biosignatures.

The facility will be designed for decades of sampling and experimentation. Long-term experiments will include real-time monitoring of multiple parameters including pressure, temperature, water and gas compositions, etc. Fluids will be piped from isolated fractures into a mobile laboratory equipped with an anaerobic glove bag and flow-through cartridges to determine which factors limit the growth of indigenous microorganisms or hyperthermophilic strains from other extreme environments on the earth. This laboratory will be capable of performing these experiments under hyperthermic and high pressure conditions. Facilities will also enable the long-term study of *in situ* mineral weathering or precipitation experiments and organic/inorganic interactions.

Brief description of first suite of experiments:

1. Test technologies that will be used in the ultradeep boreholes at shallow drilling projects. The technologies include down hole detection methods for life (GOLD).
2. Use technologies to characterize the microbial contamination results from mining in the drilling projects occurring at the shallower levels.
3. Staged drilling program beginning with a pilot hole to characterize potential targets down to ~5 km.
4. Geophysical and geohydrologic testing using the pilot hole in order to gain as much information as possible about the lithology, fracture patterns, and fracture flow in the 2.4 to 5-km depth interval before conducting the first full diameter deep drilling/coring campaign.
5. First deep drill/core to ~5 km using aseptic techniques, purified water as drilling fluid, tracers in the drilling fluid, and complete geochemical and biological characterization of cores.
6. Geophysical and geohydrologic testing the first borehole.
7. Development of the well for multi-level sampling of the fracture water.
8. Decide on the location and orientation of the second full borehole based on the lithology, fracture patterns, and fracture flow data.

Development needs prior to conducting experiments at Homestake

- Review of all available information on the geology at Homestake beneath the 8000L (2.4 km depth).
- Critical decisions must be made regarding the drilling/coring technologies to use. Most of these can be addressed by gathering information on the available technologies, matching the highest priority objectives to the available technologies, considering the compatibility of various technologies, and considering cost factors. Decisions that need to be made include:
    - Number and orientation of boreholes
    - Borehole diameter: size HQ (~10 cm) may be possible. It may be necessary to start with a larger diameter and then step down to a narrower bore.

    - Selection of drilling fluid. Purified, degassed water generated by the same system used for a water Cerenkov detector would be desirable.
    - Quantity of drilling fluids. If the formations have as low a porosity as is expected, then 10 gallons per minute may be sufficient.
    - Disinfection of the drilling tools. Steam cleaning is an option.
    - Selection of tracers, both particulate and solute.
    - Circulating or single-pass for the drilling fluid?
    - Temperature stability of drilling materials.
    - Is blow-out prevention necessary and if so, what system(s) should be used?
- Packers and multi-level samplers will need to be selected and/or designed to meet the needs of the project. These will have to be of materials that are stable at high temperature. They may also need to be corrosion-resistant.
- Decisions will need to be made regarding the instrumentation for the MULE instrumentation specific to Ultra-Deep Observatory.
- If high-pressure coring is to be used, then the available technology (used by the IODP) will need to be adapted for use with the coring method to be used here.
- Several promising new technologies are in development that could aid in addressing the deep drilling objectives. These include downhole spectrometry instruments for geochemistry, fiber-optic approaches to geohydrology, and single cell genomics characterizing the microbial communities. Each of these technologies will require further development, especially for use in boreholes to 5 km depth.

S-4 activities currently under consideration:

- Systems design decisions
    - Drilling technologies
    - Sequence of deployment
    - Coordination of multidisciplinary approach
- Disciplinary meetings
    - Drilling/coring technology
    - Geology/geochemistry (to include review of existing data on the geology at Homestake at >2.4 km depths)
    - Geophysics/Geohydrology
    - Biology
- Capstone meeting
- WBS development
- Development/adaptation of promising new technologies, e.g., high-pressure coring and single-cell genomics.

Cost estimate:

S-4 costs: ~\$500k

Initial Suite of Experiments Project cost: ~\$10M

Tasks required to refine costs: Much of the S4 (and S5?) activity will involve selecting the appropriate drilling/coring technologies to meet our objectives, as described in the development needs section above.

Schedule:

Jul 2008	Submit S-4 proposal
Oct 2008	Begin S-4 project.
Jan 2009	Disciplinary workshops and meetings to make critical decisions about drilling/coring technology and to select and schedule geophysical, geohydrological, geochemical, and biological technologies.
Jul 2009	Capstone deep-drilling workshop.
Dec 2009	Submit Preliminary Design Report
2008-2012	Testing drilling technologies, downhole instrumentation, and biological characterization methods. PIs will be encouraged to support these activities with funding from various sources, e.e, NSF SGER grants, panel-reviewed NSF grants, and grants from other agencies.
2012	Drill pilot hole for initial characterization of the 2.4 to 5-km depth interval.
2013	Drill and core first full-bore borehole.
2014	Drill and core second full-bore borehole.
2015	Drill and core third full-bore borehole.

Facilities:

- Access to one or more boreholes drilled at intermediate depth during early development of DUSEL and in collaboration with other research groups. These will be useful for testing emerging technologies before the actual deep drilling process. The tested technologies can also be useful in surveying the extent of mine-induced contamination and testing for novel microorganisms.
- Access to the 8000L. This will require extensive infrastructure, including electricity, communication, air cooling, and ventilation.
- One or more drill sites with 6-12 m ceiling height and $\geq$100 m^2 area. Adjacent area for MULE and other equipment.
- If water from the purification system for a water Cerenkov detector is to be used, then plumbing will have to be provided. The distance could be 1-2 km.
- Mobile Underground Laboratory for Experiments (MULE).
- Sample processing capabilities at the mid-level campus and/or surface labs. This will include freezers for storing biological samples.

Broader Impacts: Education and Public Outreach (EPO)

The Deep Drilling Working Group is considering the following EPO activities.

- The Deep Drilling Working group is considering the following EPO activities:
- Target local Native American STEM students.
- Develop site Research Experiences for Undergraduates (REUs) and Research Experiences for teachers.
- Collaborate with Oregon State University/Portland State University Integrative Graduate Education and Research Traineeship (IGERT) Program on "The Subsurface Biosphere"
- Real-time data stream for classroom and visitor center use.
- DUSEL-Homestake Visitor Center displays

Risk identification and Management

Potential problems that could affect successful outcome

- The 8000 level at Homestake is never dewatered
    - This seems unlikely. SUSEL is committed to fully dewatering the mine.
- The 8000 level is never developed for extended scientific use.
    - This will be dependent upon the ability of DUSEL-Homestake PIs to make a strong case for developing the Ultra-Deep Biological Observatory. Assuming that there is a strong commitment to conducting major physics experiments at the 7400 level, the development of the 8000 level for biology and geology will require only modest additional funding.
- The deep borehole is a “dry hole”, i.e., the formation has extremely low porosity and therefore generates very little water for analysis.
    - There are almost certainly some fractures and even a small amount of water can be chemically and biologically analyzed. Moreover, we will have saturated core material to analyze.
- The 2.4 to 5-m depth interval has been geochemically and microbiologically contaminated by mining activities, including the original dewatering and subsequent flooding of the mine.
    - The fracture waters immediately below the 8000 level may be affected by mining activities, however, it is very unlikely that it has penetrated to than 1 km below the 8000 level. Larry Murdock is modeling the potential for vertical as well as lateral penetration of mine water and so we’ll have an estimate of this long before drilling. Even if these deep layers are contaminated, the geothermal gradient will still be in place such that we can test the lower limits of life and the effects of temperature on life.
- A borehole becomes contaminated by drilling/coring or sampling activities.
    - We will use tracers to enable tracking and quantification of any contamination. There will almost certainly be some small, manageable level

    - of contamination. If there were gross contamination of one borehoe, then we could drill a new borehole at some distance from the contaminated borehole.
- The borehole “flashes”, i.e, pressurized water is encountered, releasing hot water and steam.
    - This is a potential safety hazard. However, we will use all available and appropriate safety procedures, including use of bow-out prevention, as necessary.
- Dangerous gases are encountered, e.g., H_2S, CH_4, H_2, CO.
    - All available gas detection safety measures will be used.
- Drilling problems or even failures occur.
    - There will almost certainly be difficulties in drilling such a deep borehole for scientific purposes. These could include loss of fluids in the borehole, tools stuck in the borehole, etc. However, the funds for drilling will include contingency costs. The contracts with drillers will be written such that the drillers have necessary back-up equipment on site to minimize down time.

Potential problems that could affect other experiments or facilities

- Drilling/coring activities at the 8000 level negatively affect the physics experiments at the 7400 level.
    - This is extremely unlikely. The Ultra-deep Biological Observatory will be nearly 200 m deeper than the physics lower campus and will also be offset some distance laterally.

DUSEL Ultra-Deep Drilling and Exploration Interested Principals and Collaborators

Tom Kieft, (Working Group leader), New Mexico Institute of Mining and Technology geomicrobiology
Sookie Bang, South Dakota School of Mines and Technology, microbiology
Bruce Bleakly, South Dakota School of Mines and Technology, soil microbiology
David Boutt, University of Massachusetts, geohydrology
Nathan Bramall, NASA Ames Research Center, geochemistry
Rick Colwell, Oregon State University, geomicrobiology
Tom Daly, Lawrence Berkeley National Laboratory, geophysics
Hailiang Dong, Miami University, Ohio, geochemistry, geomicrobiology
Ken Farley, California Institute of Technology, thermochronology
Barry Freifeld, Lawrence Berkeley National Laboratory, geophysics
Tim Griffin, Golder Associates, drilling technology
Qiang He, University of Tennessee, molecular biology
Patricia Holden, University of California, Santa Barbara, geomicrobiology
Christian Klose, Lamont-Doherty Earth Observatory, Columbia University, geophysics
Phil Long, Pacific Northwest National Laboratory, geohydrology, geomicrobiology
Duane Moser, Desert Research Institute, geomicrobiology
Andrea Neal, University of California, Santa Barbara, geomicrobiology
Tullis Onstott, Princeton University, geomicrobiology, geochemistry, geochronology

Brent Peyton, Montana State University, geomicrobiology, engineering
Susan Pfiffner, University of Tennessee, geomicrobiology, education and public outreach
Tommy J. Phelps, Oak Ridge National laboratory, geomicrobiology, drilling technology
Roman Popielak, Golder Associates, drilling technology
Frank Robb, Center of Marine Biotechnology, University of Maryland, bacterial and eukaryotic molecular biology
Forest Rohwer, San Diego State University, environmentsl virology
Rajesh Sani, South Dakota School of Mines and Technology, chemical and biological engineering
Martin Saar, University of Minnesota, geohydrology
John Spear, Colorado School of Mines, geomicrobiology, molecular microbial ecology
Jim Staley, University of Washington, microbial ecology
Ramunas Stepanauskas, Bigelow Laboratory for Ocean Sciences, microbiology
Alexis Templeton, University of Colorado, geochemistry
Herb Wang, University of Wisconsin, geohydrology
Linda Wegley, San Diego State University, environmentsl virology