

Message from the DOEI Director



Photo by Amy Nevala, WHOI.

This year marks the seventh anniversary of the establishment of the Ocean Institutes at Woods Hole Oceanographic Institution (WHOI). There is no doubt that the Ocean Institutes have made a significant contribution to the intellectual and fiscal growth of the Institution, and have paved the way for new research endeavors across many scientific disciplines.

Over the past seven years, the breadth of talent and ingenuity of WHOI scientists and engineers conducting deep ocean research has been phenomenal. Scientific creativity has led to new insights about the animals, microbiological diversity and geochemical processes at hydrothermal vents; novel instrumentation to measure and sense chemical and biological processes *in situ*; and a broad range of geological, geochemical and geophysical investigations of the seafloor throughout most of the world's oceans.

The broad themes of the Deep Ocean Exploration Institute (DOEI) include developing novel instrumentation to study deep ocean and

seafloor processes, understanding fluid flow in geologic systems, and exploring the deep biosphere.

In this year's annual report, we highlight three recent projects, one conducted by our current Fellow, Wenlu Zhu, and the other two by DOEI researchers, Laurent Montesi and Sheri White.

Sheri is an MIT/WHOI Joint Program graduate and an Assistant Scientist in the Applied Ocean Physics & Engineering Department. She began studying the remote sensing of chemicals in the ocean with specialized equipment as a graduate student and continues this line of research in her current studies. Sheri is developing techniques to use laser Raman spectroscopy with submersibles to study chemical processes where they are taking place – at hydrothermal vents and on the deep ocean floor. Her work is breaking new ground in taking measurement devices to the seafloor, rather than collecting samples and analyzing them back in the laboratory. Making observations on site, under the pressure and temperature conditions of these remote locations will yield new insights into the biogeochemical processes taking place in the deep ocean.

Wenlu Zhu is a specialist in rock mechanics and an Associate Scientist in the Geology & Geophysics Department. She studies the physical properties of different rock types to determine how they control Earth processes as well as how they react to different physical settings on and within Earth's crust

and mantle. Her DOEI fellowship has enabled her to collaborate with specialists in industry who use rock properties, specifically porosity and permeability, to exploit hydrocarbon and mineral deposits and properly engineer buildings to withstand earthquakes. Wenlu has been applying this diverse knowledge base to a wide range of topics, including deep sea hydrothermal vent mineral deposits – the subject of her article.

Finally, geophysicist and Associate Scientist, Laurent Montesi discusses how modeling can provide new insights into the processes that supply magma to ultra-slow-spreading ocean ridges. His innovative use of the characteristic features and geometry of these ridges is an excellent example of the “puzzle-solving” that drives all earth scientists – using the clues that are presented by Mother Nature to figure out how Earth systems work. – Dan Fornari

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DEEP OCEAN EXPLORATION INSTITUTE
www.whoi.edu/institutes/doei

Dan Fornari dfornari@whoi.edu
Audrey Rogerson ... arogerson@whoi.edu
Andrew Daly..... adaly@whoi.edu
Editor: Alison Kline ... akline@whoi.edu

Techniques for Analyzing Dissolved Gases in Seawater

Laser Raman Spectroscopy

Advancements in the development of deep submergence platforms such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) are giving scientists greater access to the deep ocean. Likewise, seafloor observatories provide newly emerging opportunities to monitor seafloor environments over sustained time periods. These technologies are enabling ocean scientists to move away from mere *sampling* (bringing back samples from the deep ocean for analysis in the lab) toward *sensing* (measuring actual processes in real-time on the seafloor).

Hydrothermal vent systems are the subject of a great deal of interdisciplinary research and a key topic for the DOEI. A variety of dynamic processes occur at these sites that support life and influence ocean chemistry and seafloor geology. Located on seafloor spreading centers, rising magma at vent sites heats and alters seawater percolating through the ocean crust. The hydrothermal fluid emerging from the seafloor is super hot and contains high concentrations of metals and dissolved gases. Some of these are greenhouse gases, such as carbon dioxide (CO₂), methane (CH₄) and hydrogen sulfide (H₂S).

Currently, scientists study these fluids by collecting samples in gas-tight bottles and returning them to the surface for analysis in the laboratory. However, new technologies are being developed that will allow hydrothermal fluids to be analyzed *in situ* – on location. These techniques include *in situ* mass spectrometry (like instruments being developed by Rich Camilli; see the 2006 DOEI annual

report) and laser Raman spectroscopy, which I employ.

Laser Raman spectroscopy is a non-invasive, non-destructive technique that can identify a range of solids, liquids and gases. It is a useful tool in a variety of fields, including medicine, pharmacology, materials science, biochemistry and geochemistry. It can be used to identify drugs and explosives and for various types of industrial process monitoring. Because it is rapid and requires no sample preparation, laser Raman spectroscopy is well suited for *in situ* oceanographic analyses. A number of oceanic targets of interest can be analyzed by this technique, including the dissolved gases and minerals (sulfides and sulfates) released from hydrothermal vents.

In this technique, a laser is used to “excite” a sample at the molecular level. The back-scattered light from the illuminated spot is collected with a lens and sent to a spectrometer, where the intensity at various wavelengths is recorded. Most of the light is elastically, or “Rayleigh” scattered – that is, light is scattered back at the same wavelength as the incident light.

However, a small amount is inelastically, or “Raman” scattered – the light is shifted in wavelength due to its interaction with the molecule. The shift in wavelength (or energy) is equal to the vibrational energy of the molecule. So, the Raman spectrum serves as a “fingerprint” of a molecule by providing chemical and structural information about the molecule.

Many of the gases in hydrothermal fluids are Raman-active, such as CO₂, CH₄ and H₂S. DOEI support is allowing me to perform laboratory experiments with these dissolved gases to determine calibration curves for the chemicals in seawater. The methods ironed out during this project will allow future development of a new sea-going Raman system that is optimized for the real-time *in situ* analysis of dissolved gases in the deep ocean. These instruments will be deployed on AUVs, ROVs and at seafloor observatories. Using these instruments, scientists will be able to better elucidate the concentration of these chemicals around vent sites and the relative sources and sinks for greenhouse gases in the ocean.

– Sheri White

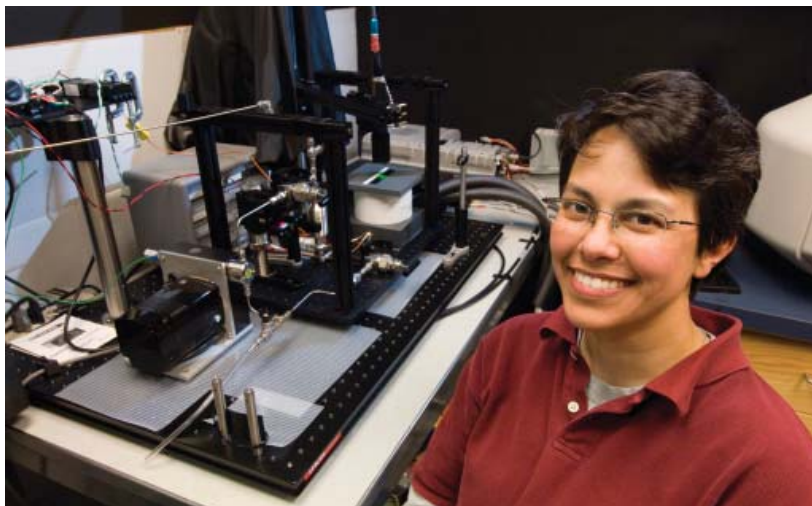


Photo by Tom Kleindinst, WHOI.

Microstructure of Rocks

Porosity and Permeability of Rocks and Vent Deposits

All rocks are porous to some degree – varying from joints in natural rock formations to microcracks and tiny pores in some specimens. Porosity affects fluid transport in rocks and is important to many science and engineering problems, including earthquake and fault studies, oil and gas recovery, reservoir architecture, groundwater contamination control, and nuclear waste deposit monitoring.

The key physical property that affects fluid transport in rock is permeability, or the ability of a rock to transmit fluid. However, to estimate permeability is challenging, because it varies a great deal in different rocks. To make matters more complicated, Earth is a dynamic environment, which means that there are huge variations in pressure, temperature, fluid chemistry and other environmental conditions.

My research focus is to investigate the relationship between permeability and pore structure in a wide range of geological materials, including sedimentary rocks (sandstones and limestones), partially molten rocks (mantle peridotite and harzburgite) and hydrothermal vent mineral deposits. My approach is to use both experimental and theoretical methods to provide better data on rock permeability and to determine how permeability changes under different conditions.

Since arriving at WHOI, I started an exciting collaboration with Meg Tivey, a geochemist and a former DOEI fellow (June 2001 - May 2004). Meg specializes in the study of active seafloor hydro-

thermal systems, where metal-rich vent deposits form from complex interactions among hot (~350°C) vent fluid, cold (~2°C) seawater, and previously deposited material. These deposits are analogs of ore deposits present on land, and host unusual biological communities, including microorganisms that thrive at high temperatures (up to 120°C).

Like most people who are aware of seafloor hydrothermal vents, I am fascinated by black smokers, white smokers and the amazing creatures that live at vent sites. But a not-so-common aspect of my interest in vent systems is that, to me, it is a natural factory where materials with ever-evolving pore structures are fabricated. Because vent fluids and seawater flow through the changing pores, it is important to accurately estimate permeability of vent deposits and to understand how it affects fluid flow, thus influencing the growth of vent structures and the

animals that live there.

Because permeability is closely related to porosity – a physical parameter that is much easier to measure – efforts have been made to establish permeability-porosity relationships. As a DOEI Fellow, in collaboration with Meg, I obtained permeability-porosity measurements and conducted microstructural analyses on three large vent deposits from the Juan de Fuca Ridge (off shore of Washington state). We found that the connections between permeability and porosity can best be described by two different power law relationships. The difference in the two permeability-porosity relationships reflects different mineral precipitation processes, as pore space evolves within different parts of the vent structures. In one process, angular sulfide grains deposited as aggregates block fluid paths very efficiently. In the other process, amorphous silica coats existing grains



Wenlu Zhu in her lab working with a Helium Porosimeter. This instrument provides accurate data on grain and pore size in rock samples.

Photo by Laurent Montes, WHOI.

Microstructure of Rocks (continued)

and reduces fluid paths more gradually, thereby reducing flow through the structures. These findings are published in our recent paper in the *Journal of Geophysical Research*.

Our results suggest that, while there is not a single “universal” permeability-porosity relationship, there are good correlations between permeability and porosity for some types of samples, particularly when pore evolution processes – the processes that change pore space – are considered. Types of pore evolution processes relevant to vent deposits include precipitation and dissolution, and formation of cracks from thermal cracking. These processes destroy and/or create porosity.

Identifying which processes result in changes in porosity and permeability is accomplished by making

microstructural observations, for which we use reflected light microscopy to examine grain size, pore size, pore distribution and connectivity. Identification of different evolution permeability-porosity relationships (EPPRs) provides information about how different portions of vent structures form over time. They also tell us what processes are responsible for changes in porosity and permeability, and, thus, the ease with which fluid flows through parts of the vent deposit.

Based on our success in quantifying permeability-porosity relationships on vent deposits, we plan to conduct further experimental and microstructural measurements on a full range of vent structure types with samples recovered from many different active seafloor vent sites.

Our data and observations will be used to identify ranges of permeability and different EPPRs, which we hypothesize will correlate with distinct textures that reflect different physical and chemical processes (e.g., thermal cracking vs. precipitation of blocky grains vs. precipitation of mineral coatings).

Results from my DOEI study will be used in models of fluid transport and to examine feedback processes that are crucial in simulating flow within vent structures. Our study will address a key question about many hydrothermal structures – whether there are cascading feedbacks that lead to clogging, or, alternatively, whether the feedback is such that fluid flow is maintained in certain portions of the structures.

– Wenlu Zhu

Volcanism at Ocean Ridges

Volcanism at the Slowest Spreading Ocean Ridges

The strong outer shell of Earth, the lithosphere, is broken into rigid plates that move away from each other at mid-ocean ridges and collide at subduction zones. Although we have unmistakable proof of this motion, it is still unclear how this global process of plate tectonics functions. One popular idea is that plate motion is lubricated, both at the base of the plates and at the margins between plates, by fluids – either water or magma. What happens, then, at the slowest spreading ridges, where very little molten magma appears to make it to the surface? How much magma is actually present beneath the surface, and how is it distributed?

Answering these questions requires a combination of data collection and numerical modeling. I was fortunate to

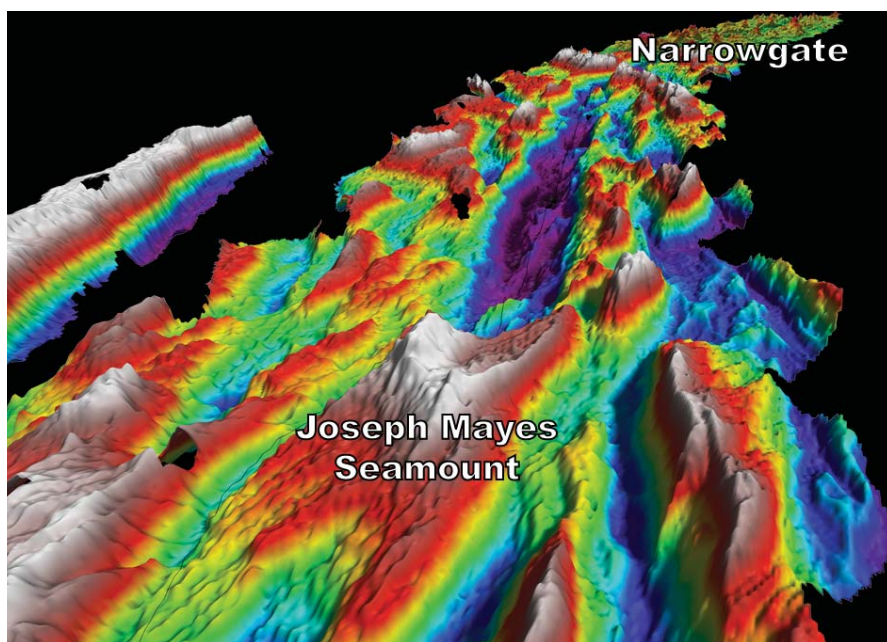


Image by Laurent Montési, WHOI.

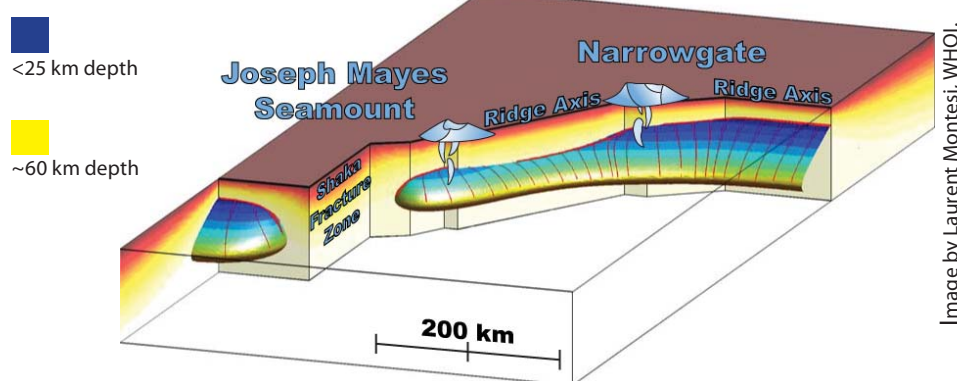
3D bathymetric image of the southwest Indian ridge, an ultraslow spreading mid-ocean ridge. The colors represent bathymetry (seafloor terrain) from purple (deeper than 4500 meters) to white (shallower than 2000 meters). The deepest parts of the ridge axis show no signs of volcanism. Instead, all the magma reaches the surface via large seamounts, shown in gray-white. (Scale: the distance from Joseph Mayes Seamount to Narrowgate is 236 kilometers.)

Volcanism (continued)

receive a grant from DOEI to develop a general modeling toolkit to address the generation and propagation of magma at mid-ocean ridges. The results of this study, which have been submitted to the journal, *Geophysical Research Letters*, show that magma is probably present at depth but cannot traverse the thick, cold lithosphere of the slowest spreading ridges. Plate lubrication appears possible, even though little volcanism is visible at the surface of the ocean ridge.

The slowest spreading ridges on Earth tend to be in rather inaccessible locations, such as underneath the Arctic ice or in the harsh environment of the “Furious Fifties” in the waters south of Africa. In spite of the difficulties, WHOI mounted several expeditions to the southwest Indian ridge in the early 2000s. These expeditions, headed by geologist, Henry Dick, revealed a new type of seafloor spreading, now qualified as “ultra-slow,” in which much of the ridge axis is covered not by oceanic crust but by mantle rock. Instead of being distributed along the axis, volcanism is concentrated in very large seamounts – underwater volcanoes.

What does this paucity of volcanism mean? At mid-ocean ridges, mantle melts as it rises to fill the gap between spreading plates. The magma then collects to form the oceanic crust. However, if the spreading is relatively slow, the hot mantle should cool down as it rises and melting should stop. Are ultra-slow ridges so cold that no magma is being produced? Together with WHOI geophysicist, Mark Behn, we reexamined estimates of how much magma is produced. In fact, enough magma should be produced



Modeled image of an ocean ridge where magma is produced beneath the lithosphere. The magma melt moves along the base of the lithosphere. Our models show that magma is produced everywhere under the ridge but is focused upward in the locations of large seamounts, such as Narrowgate and Joseph Mayes.

at ultraslow ridges to create 3-kilometer-thick crust continuously along the axis. But this crust is not observed geophysically. We realized that, at ultraslow ridges, the magma is produced entirely at depths greater than 25 kilometers. Therefore, it seems that magma has trouble traversing the thick, cold lithosphere and is, instead, trapped along the way.

Magma produced underneath a mid-ocean ridge is lighter than the mantle from which it is extracted. Furthermore, it is somewhat corrosive. Therefore, it is expected that magma will follow porous channels, migrating rapidly up toward the surface until it reaches the cold lithosphere. There, it either forces the opening of a crack and continues to move upward or travels instead along the base of the lithosphere, searching for the point where the lithosphere is thinnest. At the slowest ridges, the lithosphere is so thick that cracks are unlikely to form. Therefore, it should be possible to test whether the magma, impeded by thick lithosphere, spreads out and pools at the points where the lithosphere is thinnest. Will ascending magma manage to find these locations and collect to form a seamount?

DOEI funding enabled me and collaborator Mark Behn to test this hypothesis using a model in which we analyzed seamounts at an ultraslow ridge. Our model indicates the movement of magma in three dimensions underneath a ridge. We found that the seamounts are, in fact, located at portions of the ridge where the lithosphere is thinnest.

This work not only sheds new light on magma movement beneath the slowest spreading ridges, but also can be applied to many other places. The 3D modeling capacity developed for this project has enabled MIT/WHOI Joint Program Student Trish Gregg to estimate the thermal state of many mid-ocean ridges all over the globe. By comparing it to the gravity field of these ridges, she inferred different modes of magma transport in the crust at fast and slow ridges. This work was published in July in the scientific journal *Nature*. Finally, the initial work conducted with this DOEI support was key to obtaining a grant from the National Science Foundation to relate magma movement to the geochemistry at ultraslow and other mid-ocean ridges.

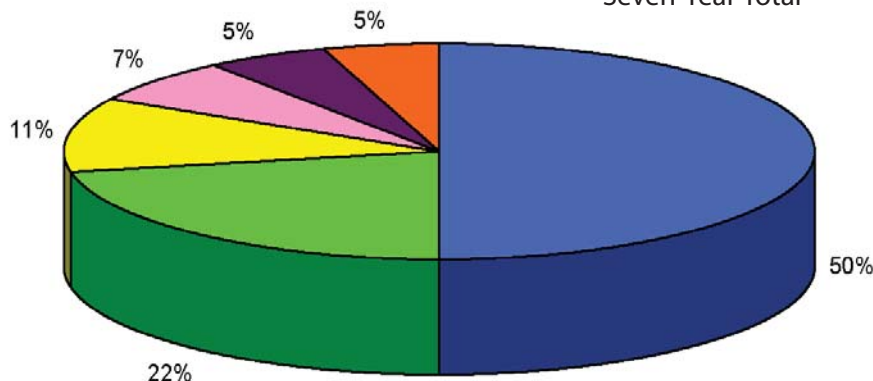
– Laurent Montesi

Image by Laurent Montesi, WHOI.

Financial Information

DOEI Funding History 2001-2007

\$4,858,208
Seven-Year Total



■ Research Projects	\$2,428,023
■ Fellows	\$1,067,549
■ Postdoctoral Scholars	\$535,770
■ Graduate Students	\$330,674
■ Seminars & Workshops	\$254,325
■ Other	\$241,867

Allocation of DOEI Funds

DOEI funding supports research in a variety of topics related to the Institute's themes. Decisions on these grants are made through a peer-review process by the DOEI advisory committee.

Over the past seven years, the majority of funds (50%) have been awarded to individuals or teams of researchers for specific projects. All WHOI departments are represented in the pool of awarded investigators, whose projects often span interdisciplinary topics.

Fellows have received the second largest portion of funds, followed by postdoctoral scholars and graduate students. DOEI funding also contributes to other WHOI programs such as the Geodynamics Seminar, various other seminars and workshops, and public outreach such as the Dive and Discover™ Web site. Additional information on the specific projects funded this year as well as in past years can be found at: <http://www.whoi.edu/page.do?pid=7795>.

Campaign Update

As of June 30, 2007, the Depth of Leadership Campaign has raised \$162M toward our \$200M goal. Highlights of the campaign over the past few months include grants from philanthropies such as the Richard King Mellon Foundation, David and Lucile Packard Foundation, Edwin S. Webster Foundation, McKnight Foundation, Comer Science and Education Foundation, and Swordpoint Foundation. Corporate donors include, Fugro Robertson, Inc. In addition, many of our trustees, corporation members, and associates have contributed substantial gifts, including Peter and Erika Aron, Frank and Lisina Hoch, and the estate of Claudia Heyman.

Leveraging

The funds provided by DOEI to its fellows and researchers have paid significant dividends by providing the seed monies that have led to 5 to 8 times more funding in grants from traditional government agencies like the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA)-Ocean Exploration program, and the National Aeronautics and Space Administration (NASA).

Campaign Funds Raised to Date

\$162,380,865

As of June 30, 2007

