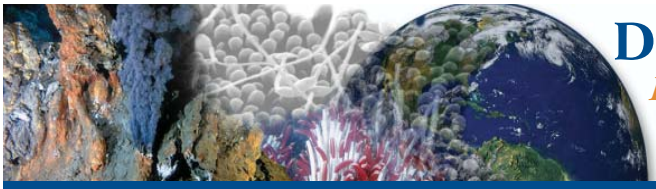

Deep Ocean Exploration Institute

Investigating Earth's Dynamic Processes

Annual Report ~ Summer 2006

Message from the DOEI Director

Photo credit: Mike Perfit, U. Florida

Many keys to unlocking Earth processes can be found deep under the ocean, on and within the seafloor that covers two-thirds of our planet's surface. The goals of the Deep Ocean Exploration Institute (DOEI) are to investigate these key planetary processes. They include understanding the flow of both magma and water within the planet; the nature and evolution of biological communities in the deep ocean and Earth's crust; and the characteristics of planetary processes that shape Earth. We also support the development of undersea technology and the establishment of seafloor observatories in various settings.

To fulfill its goals, DOEI relies on the ingenuity and critical thinking of engineers and scientists from all WHOI departments. Our graphics, Web, and communications groups help us convey this knowledge to students, colleagues, policy and lawmakers, and the general public – an important ancillary objective of DOEI-funded research.

"Ex calamitate intelligitur" – out of disaster comes understanding …

2006 has been an exciting year for DOEI research and me, personally. In April, seafloor eruptions in the western Pacific were observed by the WHOI *Jason 2* remotely operated vehicle team and scientists from NOAA and several universities. In May and June several WHOI scientists working on DOEI projects and I were able to conduct rapid-response surveys on the East Pacific Rise near 9° 50' N using the WHOI TowCam and *Alvin* to investigate a recent volcanic eruption there. Our observations have led to greater understanding of the dynamic eruption processes that shape the volcanic seafloor of the global ocean (see page 5).

In this annual report, we highlight three DOEI-supported research projects. For the past few years, Stan Hart has been studying volcanic and mantle melting processes beneath Samoa using a variety of techniques. Stan is a current DOEI Fellow, and his work has been greatly facilitated by the steady support fellows receive over their three-year tenure. Stan's field and laboratory studies represent innovative investigations of the processes that generate magma in the mantle, how magma is delivered to the surface, and how it acquires its particular geochemical traits. Stan has been mentoring MIT/WHOI Joint Program student Matt Jackson as part of this effort. The breadth of techniques they have used – submersible and ship-based studies, sophisticated analytical techniques based at WHOI's ICP-MS Neptune facility, and correlative seismic studies – point to the diverse approaches required to solve fundamental problems in Earth science.

Greg Hirth was a DOEI Fellow from 2002-2005, and his seminal work on rock mechanics and fluid flow through rocks has stimulated a broad set of research problems that are leading this field of inquiry. As detailed in Greg's report, the role that water plays in Earth's crust is far reaching, both mechanically and chemically. The high pressure experiments he is doing with his students and colleagues at MIT and the University of Paris and the modeling of those data promise to shed new light on how rocks in Earth's crust and mantle form, deform and transform through chemical processes. These largely hidden processes – and the clever methods that Greg and his colleagues use to investigate them – exemplify the innovative nature of DOEI research and the far-reaching implications of this type of work.

Rich Camilli has established a leading engineering program at WHOI by developing miniature chemical analyzers for deep ocean applications. Rich's work shows how far we have come in taking our laboratory capabilities directly to the seafloor, to make chemical measurements in situ (in place). With these new technologies, the combined effects of temperature and pressure at the seafloor can be integrated into a more comprehensive analytical framework. Rich's work is cutting-edge and will be used by many investigators worldwide when the next generation of ocean floor observatories is established.

– *Dan Fornari*

Table of Contents

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Volcanism and Plate Tectonics

Investigating the Plume Theory in Samoa

Despite remarkable advances over the past few years in our understanding of the dynamics and evolution of Earth's deep mantle, one major question has become increasingly contentious. Is oceanic volcanism fed by deep mantle plumes or not? Plumes, upwellings of abnormally hot rocks within Earth's mantle, have been a central tenet of the standard model of volcanism for the past three decades (see figure at right). But the Plume Model has been challenged recently by a "top down" model. This new theory posits that hot spot volcanism derives strictly from the upper mantle, via fracture tectonics of the surface plates. While the Hawaiian hot spot chain strongly supports the Plume Model, the Samoan chain is cited frequently as evidence for the "top down" model.

In order to tackle this problem, I have been using my DOEI Fellowship to initiate a wide range of coordinated studies of the Samoan volcanic chain. Our recent studies in Samoa show that, while fracture tectonics plays an important role in localizing volcanism, this volcanism is, in fact, part of a plume-driven hotspot.

Over the past year my research team has conducted three cruises to Samoa. In March 2005, we were able to explore for the first time the crater of an undersea volcano, Vailulu'u, with a submersible. Vailulu'u is a 15,000-foot tall submarine volcano anchoring the east end of the Samoan chain. We had discovered hydrothermal activity there during expeditions in 1999, 2000 and 2001. During the March 2005 dives, we were astounded to find that another 1,000-foot volcano had grown in Vailulu'u's summit crater since 2001! This new cone was named Nafanua for the Samoan Goddess of War (see figures at right). A series of current meters, temperature loggers and biological

In some seafloor regions, unusually hot areas of the mantle form narrow, isolated plumes that erupt through rigid oceanic plates to form volcanic islands and seamounts.

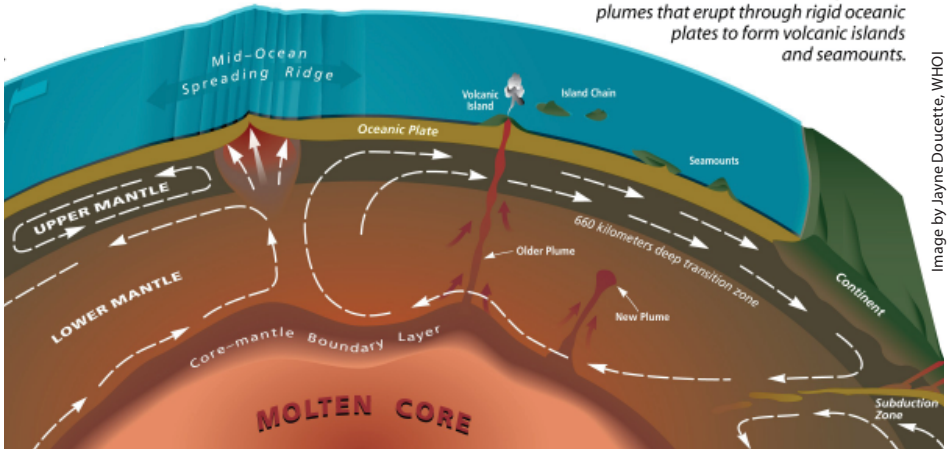


Image by Jayne Doucette, WHOI

The Standard Plume Theory of Volcanism posits that plumes of molten lava from deep in Earth's mantle rise to the surface creating hotspots where volcanic islands and seamounts form. Senior Scientist and DOEI Fellow, Stan Hart, investigates in Samoa with his research team.

experiments have now been deployed on and around Nafanua to monitor its growth.

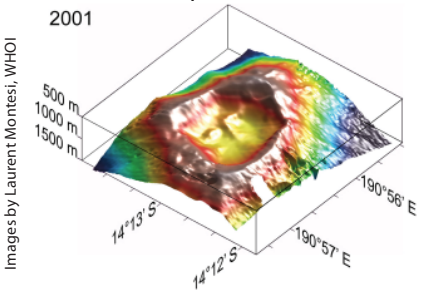
An April 2005 cruise followed, with 22 days of dredging along 1,000 kilometers of the Samoan chain. The recovered volcanic rocks are currently being dated to see if their ages increase systematically from east to west, as they should, according to the Standard Plume Model.

In July 2005 we returned to Vailulu'u for another submersible dive series, this time picking up the instruments deployed in March and exploring more of Nafanua and the summit crater. Many exciting discoveries were uncovered including: a "city" of eels living on Nafanua, a "death zone" in the crater bottom, hot springs of bubbly carbonated hydrothermal water, base-metal sulfides in active growth, and strong currents sweeping the crater walls.

While federal agencies supported the use of the ship and submersible assets, there was no support for my time at sea, so the DOEI Fellowship was critical to my participation.

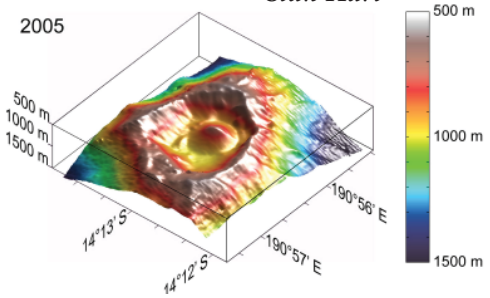
Also, a multi-institutional group of scientists convened in June 2005 to write a proposal for a large interdisciplinary study of the Samoa volcanic chain. A significant component of this project is the installation of a seismic network on three of the islands. With DOEI support, John Collins (Geology & Geophysics) and MIT/WHOI Joint Program student Matt Jackson were able to place four seismic stations in Samoa during November 2005, well in advance of outside agency funding. Samoan colleagues will maintain the stations to ensure reliable data transfer. The installation of these stations has allowed us to demonstrate the capability of our pilot project, thus greatly enhancing the prospect of funding this large proposal through federal agencies.

– Stan Hart



Images by Laurent Montesi, WHOI

Crater of Samoan undersea volcano Vailulu'u in 2001.



Nafanua emerging from Vailulu'u four years later.

Geological Fluid Mechanics

Water/Rock Interactions Deep Within Earth

Water plays a critical role in controlling the physical properties of Earth. Hence, there is a growing appreciation that interactions between the ocean and the outer shell of Earth (which we call the lithosphere) ultimately affect earthquake generation, magma flow to volcanoes, and the chemistry of the ocean itself. Furthermore, new discoveries from the ocean basins demonstrate that microbiological processes are strongly influenced by the movement of ocean water through cracks in the shallow lithosphere.

It is clear that our understanding of all of these things depends on developing theories for where, how and when water penetrates the lithosphere. In more technical terms, what is the permeability of the lithosphere, and how is this permeability created? With support from my DOEI fellowship, I have been studying these processes with colleagues. We are combining theories that were developed from material engineering research with new experimental data and high-magnification microscope analyses of rocks recovered during ocean drilling projects.

Our experimental results indicate that stresses resulting from rapid cooling of oceanic rocks play an important role in creating permeability. To study this "thermal cracking," we have applied theories that were developed for determining the optimal conditions to make industrial ceramics. Ceramics are used for many unique engineering applications because of their extremely high strength. They must be "hot-pressed" at high temperatures and pressures, and then brought back to average room conditions. The extreme changes in pressure and temperature can result in the formation of cracks that compromise the strength (and, therefore, usefulness) of the material. Theories demonstrate that cracks form because the grains within the ceramic exhibit "anisotropic thermal contraction" (which is a fancy way of saying that the grains do not shrink the same amount in all directions when they cool). In the end, these properties make ceramics very strong, but somewhat easy to break - like a brick. By contrast, steel is not as strong, but it is much harder to break. A steel beam, for example, is more likely to bend than break in half.

Earth works in much the same way. When rocks are at high temperature deep in Earth they behave like steel. After they rise to the surface and the temperature decreases rapidly, they act like ceramics, and cracks eventually form when the pressure also decreases. When the rocks crack under the oceans, water then penetrates in, further changing their physical properties.

Together with MIT/WHOI Joint Program graduate student Brian deMartin and our MIT colleague Brian Evans, we are studying this thermal cracking process in the lab. We are now also testing the applicability of these experimental results with rocks that we recovered during the Integrated Ocean Drilling Project (IODP) Expedition to the Mid-Atlantic Ridge during Fall 2004. The key to this test is that the rocks undergo chemical reactions forming new minerals when they come in contact with water, and the composition of the new minerals depends on the temperature in which they form. Therefore, by measuring the composition of the rocks we can determine at what point in the cooling history they began to crack. These chemical measurements are combined with observations made under the scanning electron microscope (SEM) to provide a robust test of the theoretical models under the more extreme conditions experienced in Earth. In this way, we are actually pushing the boundaries of materials research while at the same time studying fundamental geologic processes.

The fun is only beginning once the water actually gets into the rock. Laboratory experiments are being conducted with our colleagues (and my former student) Javier Escartín (now working at the Paris Institute for the Physics of the Globe) and our recent Ph.D. graduate, Margaret Boettcher. Our experiments indicate that the presence or absence of the alteration minerals that form once water penetrates the lithosphere strongly affect the strength of the rocks and how likely these faults are to cause earthquakes.

– Greg Hirth

Photo by Brian deMartin, MIT/WHOI

Greg Hirth inserting a specimen into a high pressure experimental deformation apparatus.

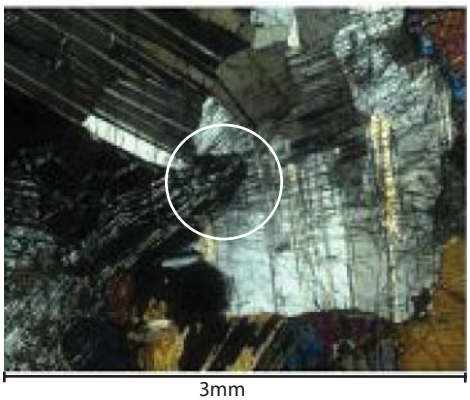


Photo from IODP Expedition 304/305, "Initial Results Volume"

Close-up of the tip of a serpentine vein (circled) from a piece of a core that was recovered during an IODP cruise. Serpentine veins and the microcracks that surround them are produced by hydrothermal fluid flow and cooling of oceanic crust.

Technology Advances

Miniature Chemical Analyzers for Underwater Exploration

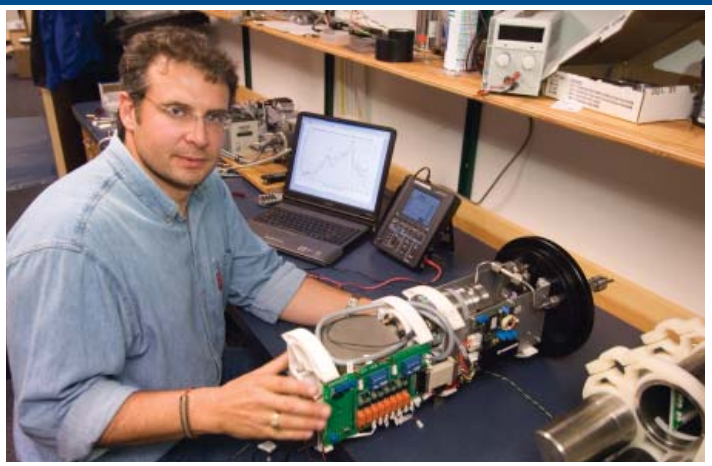


Photo by Tom Kleindinst, WHOI

Rich Camilli in the lab with Gemini, his miniature mass spectrometer.

From the beginning of my career at WHOI as a postdoc, the DOEI has supported my research program. This support has permitted me to pursue what, at the time, was regarded as a high-risk research endeavor – developing new technologies for in-situ chemical exploration and mapping. My plan was to focus on instrument development, devising sensors that could combine with navigation systems to automatically adapt the search and discover methods of autonomous underwater vehicles (AUVs) in reaction to environmental conditions.

Working with Jean Whelan (Marine Chemistry & Geochemistry) and Hanumant Singh (Applied Ocean Physics & Engineering), several of the systems that I developed over the past two years are now being routinely used for scientific deployments. The data that these technologies are now generating allow ocean scientists to examine previously unobservable phenomena in the deep ocean.

DOEI support has enabled me to pursue three closely related research themes: (1) development of mass spectrometers for in-situ chemical analyses; (2) development of an AUV-based embedded intelligence system that interprets in-situ chemical data in real-time and guides the AUV to seek out specific chemicals; and (3) development of an AUV-based water sampler that is triggered by the onboard chemical sensors and embedded intelligence to collect samples based on the mission directives.

Mini Mass Spectrometers

Gemini and TETHYS are small, portable, mass spectrometers used for in-situ chemical investigations. Gemini began as a conceptual design in 2004 and was successfully built and tested in mid-2005. It has now transitioned to an advanced chemical oceanographic sensor. To date we have used the instrument for scientific deployments in the Atlantic, Pacific and Mediterranean. Unlike most in-situ chemical sensors, which can only measure a single chemical at a time, Gemini can measure a broad spectrum of chemicals, including their isotopes. When deployed on a mobile platform, the Gemini mass spectrometer is well suited to identify and quantify cold seeps and volcanic vents, which often emit gases such as helium, hydrogen, sulphides, methane, carbon monoxide, ammonia, and carbon dioxide.

Gemini is also functioning as a testbed for developing the next generation mass spectrometer called TETHYS (TETHered Yearlong Spectrometer). Now funded through a federal grant, TETHYS is being designed for long-term measurement (months to a year) of dissolved biogenic, atmospheric, and noble gases as well as light hydrocarbon compounds. Like Gemini, TETHYS will have minimum limits of detection (on the order of parts-per-billion) and be capable of shallow-water to full-ocean-depth deployment. It will utilize techniques currently under development at WHOI to enable automated re-calibration in-situ.

Dynamic AUV Retasking

In parallel with the mass spectrometer development, DOEI support has allowed me to begin research into aspects of in-situ data assimilation and decision making by AUVs to increase the efficiency of data interpretation and utilization. By coupling chemical sensors with the navigation system of an AUV, the vehicle can intelligently search for and identify chemical and biological structures. This research, which started with DOEI postdoctoral support, has since been funded by a three-year NSF grant.

Autonomous Water Sampling

DOEI also funded the development of a gas-tight water sampler. The sampler is intended for operation on AUVs, allowing the vehicles to collect water samples based on in-situ data from the mass spectrometer and other real-time chemical sensors. This will enable the calibration of commercially available in-situ instruments (e.g., methane sensors and optical sensors such as fluorometers and turbidity meters) and provide ground truth for experimental instruments including Gemini and TETHYS. The sampler will allow multi-point correlation studies of in-situ data using laboratory analyses of the water samples, such as through the use of gas chromatographic analysis. Such a sampling system will provide a means for more-detailed lab investigations into the makeup of chemically unique areas. The water sampler is being tested and is expected to undergo sea trials in the coming months. We hope to routinely use this system on deployments at hydrothermal vents, and hydrate or cold seep sites. Upcoming cruises include the Gakkel Ridge in the Arctic (funded by NASA) and the Gulf of Mexico.

– Rich Camilli

Underwater Eruption on the East Pacific Rise

WHOI Part of Rapid Response Team to Investigate EPR Eruption

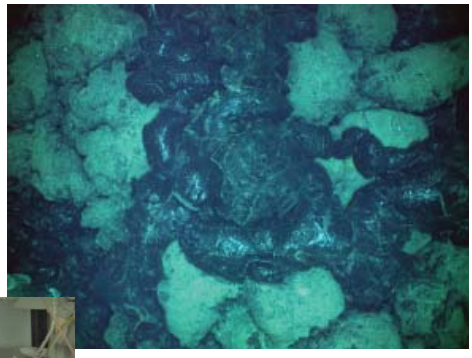
Image credit: http://www.ridge2000.org

Volcanic eruptions on the seafloor aren't rare, but catching one in action is. In April, oceanographers on R/V ***Knorr*** were recovering instruments from the East Pacific Rise crest, part of the global mid-ocean ridge system in the eastern Pacific, when they found telltale clues that an eruption had recently occurred. The clues came from ocean bottom seismometers (OBSs) that had been scheduled for routine recovery and redeployment. When the OBSs were recalled, only 4 of 12 instruments returned to the surface. Based on these observations, combined with some initial water-column data and one dredge that recovered very fresh lava, two more expeditions in May and June were organized as "response cruises" to find out what had happened. The May cruise used the Scripps Institution of Oceanography's ship R/V ***New Horizon*** to do preliminary surveys using CTD (conductivity-temperature-depth) sensors and TowCam (WHOI's towed underwater camera system). The June cruise employed WHOI's R/V ***Atlantis*** and the submersible ***Alvin*** to map the lava-covered seafloor and take photos and samples of the fresh lava. In addition, the science team used a new fiber optic TowCam developed with help from WHOI's Deep Submergence Lab specially for searching out the OBS instruments believed to be trapped in the lava and for mapping the new flows.

We had maps of the area before the eruption, and now we'll create new ones to see how the seafloor has changed. It has been a rare opportunity and a real luxury to begin examining how seafloor volcanism creates new ocean crust and how eruptions affect the chemistry of the ocean and the organisms that live at the hydrothermal vents at these sites.

This research is part of the National Science Foundation's Ridge 2000 Program and involves scientists from many different disciplines and universities throughout the US.

– ***Dan Fornari***

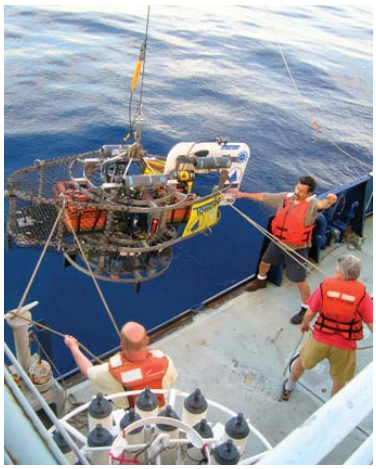


Photograph of pillow lava taken by TowCam at the site of a recent eruption on the East Pacific Rise.

Photos courtesy of Dan Fornari.

WHOI Event Response Team in front of ***Alvin*** aboard R/V ***Atlantis*** during an expedition to the EPR axis near 9° 50′ N in June 2006. From left, top row: Sean Sylva, Research Associate (Geology & Geophysics Dept.), Kate Buckman (MIT/WHOI Joint Program student), Steve Molyneaux, Stefan Sievert and Craig Taylor (all in the Biology Dept.); Bottom row: Breea Govenar (DOEI Postdoc, Biology Dept.), Adam Soule and Dan Fornari (Geology & Geophysics Dept.), and Tim Shank (Biology Dept.).

[Left]: Dan Fornari (center) and Tim Shank ready the towed-camera system, TowCam, for deployment. [Right]: TowCam being lowered into the ocean.



Financial Information

Allocation of DOEI Funds

Since its inception, DOEI has funded a total of seven fellows, seven postdoctoral scholars, three graduate students and thirty-six research projects involving fifty-one investigators (some on more than one project). These include seven new research projects funded in 2006 and a new Fellow – Whenlu Zhu of the Geology & Geophysics Department – funded by a generous gift from Claudia Heyman.

DOEI support for postdoctoral scholars and graduate students is intended to nurture fertile young minds for the oceanographic and engineering sciences. Karyn Rogers and Breea Govenar are the 2006 DOEI Postdocs. Karyn will be working with WHOI scientists Jeff Seewald and Stefan Sievert investigating the fine-scale nature of microbial interactions with their environment. Breea will be working with WHOI biologists Tim Shank and Hal Caswell on quantifying changes in hydrothermal communities and modeling their development.

DOEI also supports the Dive and Discover Web site and hosts a number of workshops, symposia, and seminars, including the Geodynamics Seminar series. Total investment in the activities of the DOEI already surpasses four million dollars.

DOEI Leveraging

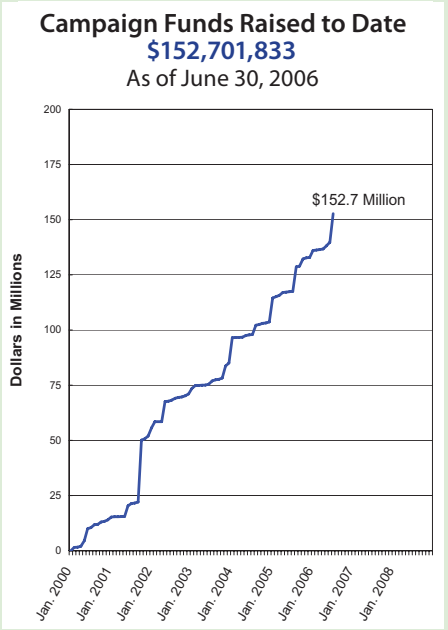
The three examples in this report of the research being sponsored by DOEI (see pages 2 - 4) are compelling proof of both the need for this type of funding and the success it has garnered in leveraging federal support. Over the past few years, these projects and numerous others with DOEI support have flourished into full-fledged, multi-year federally funded projects supported primarily by NSF and NOAA.

DOEI seed money for research projects and fellowship support has multiplied at an estimated 7:1 ratio. For every dollar of DOEI investment made, seven additional dollars are funded by federal agencies to the same scientists to continue their work. Needless to say, we are pleased with this trend.

Ruth and Jim Clark donated $10 million to the campaign for Arctic research. Photo by Tom Kleindinst, WHOI.

WHOI Campaign Update

As of June 30, 2006 our campaign total exceeded $152.7 million.



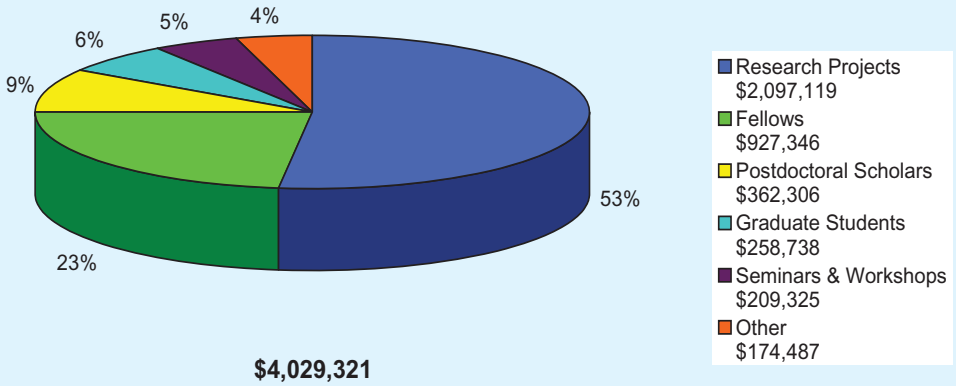
Honorary Trustee and former President of the Corporation Jim Clark and Honorary Member Ruth Clark have made a major commitment to WHOI that will bolster one of the Institution's interdisciplinary research strengths and enable us to take a leadership role in high latitude research entering the International Polar Year in 2007.

The Clarks have contributed $10 million to establish The James M. and Ruth P. Clark Initiative for Arctic Research. The gift was announced at the joint meeting of the Board and Corporation on May 19, 2006.

The funds are in the form of current money that will provide impetus for immediate and high impact advances in knowledge about Arctic ecosystems and their role in global environmental dynamics. The Initiative will be administered by the Director of Research through internal competitive awards.

This remarkable gift brings our campaign total to three-quarters of our $200 million goal.

DOEI Funding History 2001-2006



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