LAMONT-DOHERTY EARTH OBSERVATORY

2008–2010 Biennial Report

The mid-ocean ridge system encircles the entire globe. Mountains form as magma from the underlying mantle rises to fill the space between diverging plates. Most of these are underwater, but in a few places the ridges breach land. Shown here, the Mid-Atlantic Ridge straddles the island of Iceland.

Credit: Kim Martineau

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Cover image: NASA/Visible Earth

Since its inception 60 years ago, the Lamont-Doherty Earth Observatory has been at the forefront of scientific research to understand the Earth system in all its complexity. In that time, its researchers have made seminal breakthroughs in many areas of earth science, from imaging the structure of the seafloor, determining the mechanics of plate movement and interpreting ocean/atmosphere dynamics, to deciphering past and present climates.

Throughout the two years highlighted in this report, we've witnessed firsthand how these interconnected Earth processes impact some of the globe's most vulnerable areas: the earthquake that ravaged Haiti, Taiwan's typhoon-related landslides, and the steady melt of our planet's glaciers and ice sheets. Such environmental catastrophes have compromised innumerable communities.

The Observatory's research targets the science behind each of these events, systematically providing people with the insight to mitigate, and potentially prevent, future disasters. From investigations into fault ruptures in Haiti to the acidification of our oceans from carbon emissions, the implications of this work are timely and far-reaching.

It has been my privilege to serve as director of this world-class research institution for the past 10 years and to oversee the more than 300 researchers and university students who are dedicated to solving the environmental challenges we face. I've been impressed not only by the quality of their work, but also by the loyalty of our friends whose gifts sustain this research. As the economy faltered, their support these past two years enabled us to pursue critical projects, such as our community education initiatives and the construction of laboratories for sophisticated scientific analysis.

These new research facilities—so critical to securing the future of Lamont-Doherty—also received much-needed assistance from the American Recovery and Reinvestment Act stimulus package. Last year, the Observatory won two highly competitive federal infrastructure grants. One, from the National Institute of Standards and Technology, provides $1.4 million in matching grants for the construction of academia's largest ultra clean lab for geochemistry. A $7 million grant from the National Science Foundation will help fund the renovation of the Core Repository, home to the world's largest collection of deep-sea sediment cores.

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While my tenure as director ends, I am confident that Lamont-Doherty will achieve even greater success in the decades ahead. The recent creation of the Lamont Research Professor track—which confers greater stability and benefits to our researchers—will help secure the talent we've amassed and attract new minds. Our deep ties to the University's Department of Earth and Environmental Sciences, which provide optimal opportunities for students to study with our researchers, have grown still stronger. The National Research Council's assessment last year of 140 Ph.D. programs in the United States selected Lamont/Columbia as the premier earth science program in the country. These students are at the very heart of the intellectual vitality of the Observatory and a source of genuine pride to the Lamont-Doherty researchers who serve as their mentors.

Thank you to all of Lamont-Doherty's dedicated employees—researchers and administrators alike—whose hard work and vision have allowed us to maintain our long tradition of groundbreaking discovery.

G. Michael Purdy
Director
Lamont-Doherty Earth Observatory
2000–2011

It has been a privilege and a pleasure to work with G. Michael Purdy since my arrival at the Earth Institute in 2002. Columbia's President Bollinger has made an excellent choice in appointing Mike as the University's new executive vice president for research. Mike will build a new record of great accomplishment in this position. This final biennial report of his tenure at Lamont-Doherty highlights just some of the tremendous legacy he leaves behind.

- In 2008, the Observatory opened the Gary C. Comer Geochemistry Building, the first LEED-certified building constructed by Columbia University.
- Over several years, the Observatory oversaw the refitting and launch of the R/V *Marcus G. Langseth*, the only vessel in the U.S. academic fleet capable of sophisticated three-dimensional seismic imaging of the ocean floor.
- Last year, the National Research Council ranked the Lamont-Doherty/Columbia Earth and Environmental Sciences department at the top of 140 earth science graduate education programs in the country
- Mike led the effort to establish the Lamont Research Professor title, which supports the retention as well as the recruitment of new world-class researchers to Lamont-Doherty's roster of 130 Ph.D. scientists.

The common thread running through these achievements is the determined course Mike Purdy has charted for moving the Observatory into a new era of leadership within the global earth science community. We thank him for 10 years of extraordinary vision, and wish him well as he moves to the Morningside campus.

We also greet Professor Arthur Lerner-Lam, who takes up the helm as interim director. Arthur's 25 years of dedicated service at Lamont-Doherty—as researcher, administrator and as a renowned expert on understanding seismic events and their impacts on people—have earned him the respect of colleagues and peers around the world. While we conduct a search for a new director, one of the most prestigious positions in international earth science research, we are confident Arthur will build on the momentum Mike has set in motion.

As this report shows, there will be much for the new director to oversee. Every day, Observatory researchers are in the field or in the laboratory, involved in path-breaking analysis and discovery. No fewer than 300 separate research projects are undertaken at the Observatory at any given time. Humanity depends on the new knowledge these dedicated scientists are uncovering; on the successful dissemination of their findings; and on the education of a new generation, ready to take on the challenges presented by natural hazards, sea-level rise and mounting atmospheric carbon.

While the rate at which future changes will take place remains unclear, world leaders require ever more effective predictive models in order to mitigate human-induced environmental change and natural disasters and to adapt successfully to the dislocations that are already on their way.

Fortunately, we live in a time of greater scientific and technological capacity than ever before, and also very fortunately, we have at Lamont-Doherty the requisite talent for innovation and discovery to decipher the complex dynamics of our planet. The Earth Institute and the Observatory boast a unique approach—one that brings the force of scientific knowledge to bear on the development of essential new policies and practices for sustaining life on Earth. We are grateful to all who participate in and support this critical work.

Jeffrey D. Sachs
Director
The Earth Institute, Columbia University

In the chaotic aftermath of a natural disaster, immediate efforts are usually concentrated on tending to the wounded, clearing up debris, and rebuilding infrastructure. However, members of the Lamont-Doherty community are uniquely poised to provide more than humanitarian aid. Following the landfall of Typhoon Morakot on Taiwan in 2009 and the January 2010 earthquake in Haiti, two research groups at the Observatory—one focused on landslides and one focused on earthquakes—realized that quickly coordinated projects could uncover the mechanics of the extreme events and ascertain critical details about the earth processes responsible for such destruction.

Destruction of UN buildings in the aftermath of Haiti's January 2010 earthquake.

Credit: United Nations Development Programme

Fault Lines in Haiti

Within days of Haiti's catastrophic January 2010 earthquake, seismologist Leonardo Seeber and marine geologist Cecilia McHugh quickly applied for funding from the National Science Foundation (NSF) Rapid Response Research initiative to investigate the seafloor off Haiti. Both were familiar with this class of faults because they had studied similar tectonic regimes in Turkey's Marmara Sea. With several other scientists from around the country, they set off on a 20-day research cruise to the earthquake's epicenter.

"We needed to leave quickly, before fractures and other signatures of the earthquake were covered up by storm deposits or sedimentation processes," explained McHugh, the cruise's chief scientist.

The quake was thought to have taken place along the Enriquillo Fault, the boundary between two massive blocks of Earth's crust sliding in opposite directions. However, after surveying the seafloor near the epicenter, they were unable to find a fresh rupture caused by the earthquake. Researchers could not locate one on land either, which raised some concerns.

"When a fault breaks and the rupture reaches the surface, we know that the energy stored before the earthquake has been released," said Seeber, one of the cruise's principle investigators. "If we don't find evidence that the rupture has reached the surface, we aren't sure where this energy is being stored. And this energy might produce another powerful earthquake."

Seeber and McHugh set off on a 20-day research cruise to the earthquake's epicenter.

On board the NSF-owned research vessel *Endeavor*, McHugh and Seeber helped take an array of measurements that scientists expect will aid in better characterizing what happened during the January earthquake. Though no scar was found, images of the seafloor did reveal that the earthquake caused underwater slides and moved sediment from the fault zone in shallow water near the shore into deep water offshore. Sediment cores showed that these underwater landslide deposits contained distinct grains derived from basalt cliffs in Haiti's highlands. A similar pattern of sediment is seen in deeper and older portions of the cores, which may provide evidence of previously unknown earthquakes in the region.

Using data from this cruise, surveys on land, and analysis of the seismic waves from the main fault rupture and many aftershocks, researchers around the world are currently trying to pinpoint exactly how the 12 January earthquake ruptured. Deformation patterns associated with the earthquake and the geologic structure at the surface seem inconsistent with results obtained from seismic data. This has caused some to speculate that a new fault, undiscovered until this event, may be responsible for Haiti's devastation.

However, Lamont-Doherty seismologists, including Seeber, are skeptical and counter that the source of the earthquake is indeed the Enriquillo fault, but that the plate motion is being partitioned between this and another known fault system found underwater to the north of Enriquillo. Identifying the correct source of the earthquake is critical, and data from a recently installed local seismic network are expected to soon resolve this debate.

Locating Landslides From a Distance

While Lamont-Doherty's rapid response to Haiti's earthquake involved fieldwork within the affected area, other Observatory scientists can fully complete their analysis of a disaster from afar.

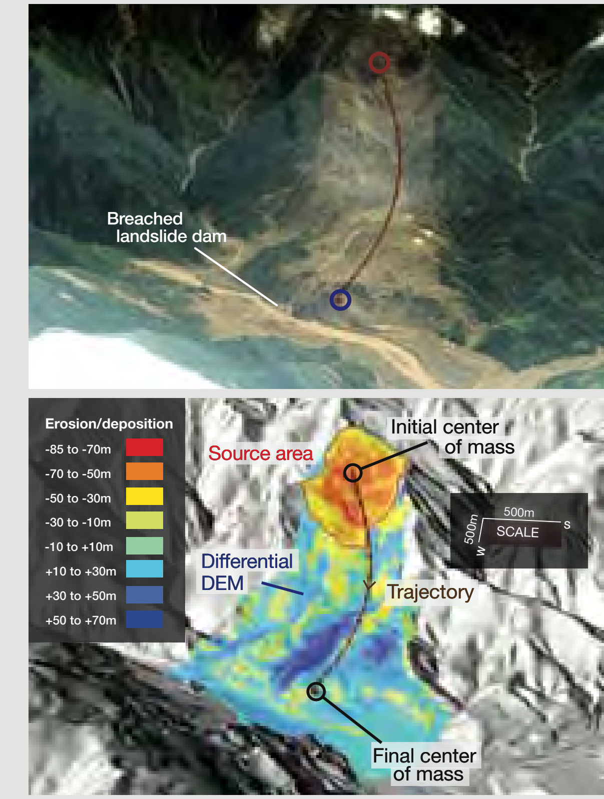
On the morning of August 8, 2009, Typhoon Morakot hit Taiwan, dumping between 50 to 100 inches of rain across southern Taiwan in a day, killing nearly 500 and wreaking more than $1 billion in damages. A few days later, seismologist Göran Ekström noticed a peculiar feature in the global seismic records he monitors weekly for earthquake activity: seismic waves originating in Taiwan with energies exceeding magnitude 5 earthquakes. He concluded that these events were likely caused by a surface rupture.

"Initially, no other agency had detected or located the four events that we had found, so it seemed very likely that we had detected something special," Ekström explained. "A closer look at the seismograms confirmed that they were landslides." Sure enough, within a few days the media began reporting on the devastation caused by huge landslides across the mountainous nation.

In one instance, a landslide near the village of Hsiaolin blanketed a nearby river valley in a thick carpet of debris. This slide was not known by officials until two days later, even though it occurred only about 30 miles from the bustling city of Tainan. "To be that close and not know that something catastrophic had happened is just amazing," said Lamont-Doherty geomorphologist Colin Stark. "But seismology allows us to report on such events in real time."

Ekström and Stark pieced together each landslide's trajectory and the total energy released during its slip.

By analyzing seismograms, Ekström and Stark calculated the forces involved with each landslide as it progressed. Coupled with an estimation of the landslides' masses based on maps of debris, Ekström and Stark pieced together each landslide's trajectory and the total energy released during its slip. Information about a landslide's force helps researchers predict how far a landslide will continue to travel, a factor vital to estimating how many people and how much territory will be affected by moving debris.



[top] Typhoon Morakot triggered several landslides in Taiwan, including this one that destroyed the village of Hsiaolin. The image shows the trajectory of the main slide inferred from seismic inversion. A natural dam created by the slide can be seen at the toe of the slope; downstream river gauge records indicate the dam was breached 40 minutes after it was formed. [bottom] A 3-D digital terrain model view of the Hsiaolin landslide's erosion and deposition, generated by differencing pre- and post-Morakot digital elevation maps (DEMs). The eroded volume calculated in this way was used to calibrate the seismic inversion to obtain the trajectory shown at top.

To perfect their method for detecting and quantifying landslide characteristics, Ekström and Stark are conducting retroactive analyses on large landslides that have occurred within the past decade in Taiwan, Pakistan, Canada and Tibet. They hope this will improve their assessments of landslide locations and energies as future events unfold.

Though ground verifications are needed for accurate scientific analysis, Ekström and Stark's quick method for estimating a landslide's scope has the potential to alert emergency responders within minutes of a landslide's occurrence and help them determine which population centers were in its path.

"Imagine if we are able to detect large landslides anywhere and report them to the media and local governments so that they can more quickly respond to those affected," Stark said. "Such a system would have tremendous utility."

Credit: Michael Studinger

During the most recent International Polar Year (2007–2009), Lamont-Doherty scientists spearheaded two ambitious projects at either end of our planet. Marine biologists led research cruises in the Bering Sea to unravel the complex inner workings of one of the world's most fertile ecosystems and to assess how it might be disrupted by impending climate changes. Lamont-Doherty geophysicists led an international team of scientists who used remote sensing to peer through the 2.5 mile thick East Antarctic Ice Sheet, revealing a major mountain range and a previously unknown system of rivers and lakes.

Life at the Ice's Edge

After long, dark Arctic winters in the Bering Sea, spring's return relaunches a cascade of events: Sunlight penetrates sea ice, spurring the growth of algae on its underside; rising temperatures melt the ice, releasing algae into the ocean and providing open waters for blooms of microscopic marine plants, or phytoplankton.

"These ice-edge blooms represent a huge production of organic matter," marine biologist Ray Sambrotto explained. It's a bonanza of food for tiny marine animals and seafloor-dwelling creatures such as fist-sized amphipods, low links in the food chain that feed those animals higher up: fish, seabirds, seals, walruses, polar bears and humans. The Bering Sea supplies nearly half the seafood consumed in the United States.

Like all plants, phytoplankton require nutrients to grow. Sambrotto and colleagues have collected hundreds of sediment and water samples from varying depths and locations to find out how essential nutrients such as nitrogen and phosphorus are supplied to fuel the blooms and how they disperse across the Bering Sea's extensive (roughly 1.9 million square miles) and shallow (60 to 200 meters deep) continental shelf.

Expeditions aboard the icebreaker *Healy* explored the fertile Bering Sea ecosystem.

Nutrients are brought from rivers discharging into the sea and from nutrient-rich waters flowing onto the shallow shelf from the deeper regions of the Bering Sea. A third source is existing plankton that are recycled back into nutrients to fertilize next year's bloom. Sambrotto's work should help distinguish how important each of these sources is to sustaining the Bering Sea ecosystem.

Sambrotto discovered that the ice itself plays a previously unknown role in this process. "The general idea was that all ice-edge blooms are extremely productive, but that's not what we've seen," he said. The key factor is where the sea ice originates. He found that ice formed in shallow regions produces the most intense blooms—most likely because the ice picks up trace metals, which phytoplankton need to grow, before it drifts out into deeper waters, melts and releases the nutrients that fuel the blooms.

Understanding such nuances will help scientists predict what will happen in the Bering Sea if climate changes hinder the formation of sea ice and alter its drift patterns. And this knowledge will inform strategies to help society manage or adapt to those changes.

Credit: Michael Studinger

Airplanes were equipped with instruments to measure properties of the ice sheet and of the rocks and mountains buried underneath it.

Peering Beneath the Ice

At the opposite end of the planet, Robin Bell, Nick Frearson and Michael Studinger were investigating a mystery: What might account for the presence of Antarctica's Gamburtsev Mountains, when the usual forces that form mountains—volcanic activity or continents colliding or rifting apart—haven't occurred for hundreds of millions of years?

Working for weeks in harsh conditions and temperatures averaging minus 30 degrees Celsius, researchers from seven nations used two airplanes to survey the East Antarctic Ice Sheet, an area the size of California. The planes were equipped with radar instruments to "see" through the ice—the geophysical equivalent of using MRIs or CAT scans to visualize the organs beneath patients' skin. The airborne instruments measured the magnetic and gravity properties of rocks under the ice; scanned the contours of the ice sheet's surface; measured ice thickness; and detected liquid water and layers within the ice. Traveling by plane, scientists also set out a network of seismometers to record sound waves that reveal the composition, age and structure of Antarctica's crustal rock.

What might account for the presence of Antarctica's Gamburtsev Mountains, when the usual forces that form mountains haven't occurred for hundreds of millions of years?

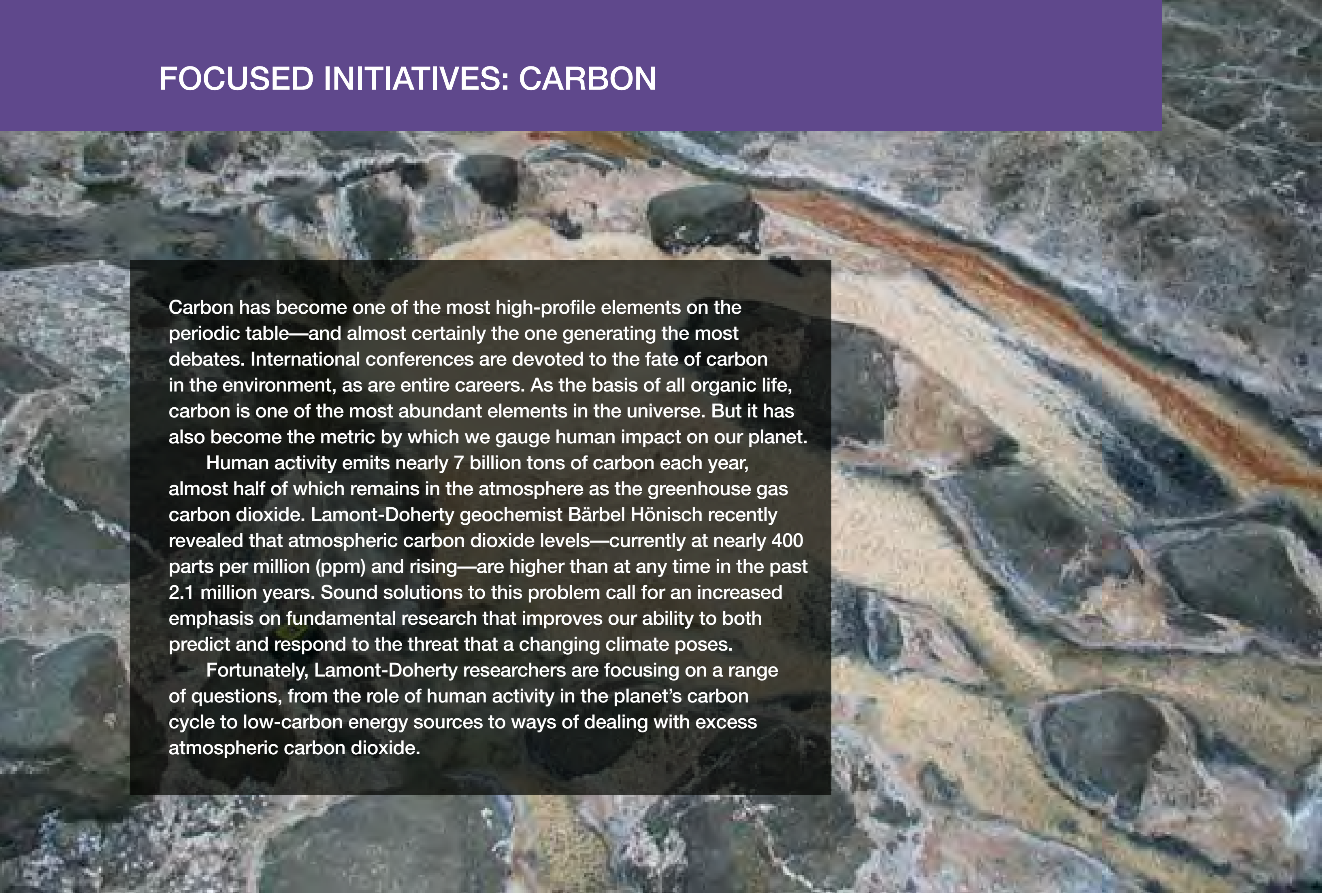
The instruments produced spectacular images of the ice-covered mountains in far greater detail than anything scientists had been able to get before. "It's like switching from a big, fat Sharpie pen to a fine-tipped pencil," Bell said. The images revealed that the Gamburtsevs were the size of the European Alps, with similar peaks and valleys.

The magnetic data indicates that the mountains were not made of rocks created by volcanic activity, though scientists have yet to determine how they were formed. And the images raised further questions about how the ice sheet developed above the mountain range. The range's deep valleys were likely carved by rivers long before glaciers began to form on the high summits roughly 35 million years ago. The mountain peaks suggest that the ice sheet may have grown rapidly, leaving no time for the peaks to erode into flat plateaus.

Perhaps most astoundingly, the scientists found water currently in a vast network of waterways hidden beneath the ice. The thick ice preserves their liquid state by acting like a blanket trapping geothermal heat and insulating the base from the surface's frigid temperatures. The pressure of the thick ice sheet pushes water through the system of deep valleys, sometimes downhill, sometimes uphill. Along the buried mountain peaks, water refreezes to the bottom of the ice sheet and thickens the ice sheet from below.

"The ice sheet has its own internal hydrological system that we never knew about before," Bell said. Knowledge about this underlying water improves scientists' understanding of ice sheet dynamics, ultimately providing insight into how quickly and extensively ice and water can be delivered into the ocean, raising sea levels.

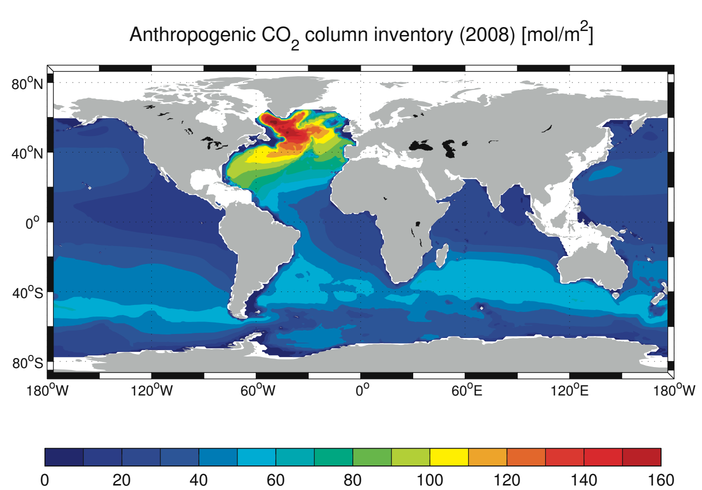
The Lamont-Doherty airborne ice-imaging system has worked so well the National Science Foundation has signed on to use it to explore other glaciers, including those on the edges of Greenland and Antarctica, in an effort to improve global forecasts of ice behavior.



Carbon has become one of the most high-profile elements on the periodic table—and almost certainly the one generating the most debates. International conferences are devoted to the fate of carbon in the environment, as are entire careers. As the basis of all organic life, carbon is one of the most abundant elements in the universe. But it has also become the metric by which we gauge human impact on our planet.

Human activity emits nearly 7 billion tons of carbon each year, almost half of which remains in the atmosphere as the greenhouse gas carbon dioxide. Lamont-Doherty geochemist Bärbel Hönisch recently revealed that atmospheric carbon dioxide levels—currently at nearly 400 parts per million (ppm) and rising—are higher than at any time in the past 2.1 million years. Sound solutions to this problem call for an increased emphasis on fundamental research that improves our ability to both predict and respond to the threat that a changing climate poses.

Fortunately, Lamont-Doherty researchers are focusing on a range of questions, from the role of human activity in the planet's carbon cycle to low-carbon energy sources to ways of dealing with excess atmospheric carbon dioxide.



A recent inventory by Lamont-Doherty's Samar Khatiwala and his colleagues found that the amount of anthropogenic carbon stored in the global ocean totaled 140 petagrams (150 million tons).

Ocean's Uptake of CO_2

Because of its chemical composition, seawater is able to absorb large amounts of carbon dioxide, making it one of the largest "sinks" of natural and anthropogenic carbon dioxide on the planet. But there are signs that the absorption process may be stalling, as the ocean takes up a smaller proportion of human CO_2 emissions. The reasons for this slowdown remain unclear. Some scientists attribute it to changes in ocean circulation as a result of global warming, others to the inability of the ocean to keep up with the large increase in emission growth rates over the past two decades. There is little debate however over the fact that the continued absorption of carbon dioxide by the ocean is making seawater more acidic and eventually less able to function as a receptacle for emissions.

Scientists also raise the disturbing possibility that a small change in the chemical and physical processes responsible for keeping carbon dioxide locked in the deep ocean might suddenly release large amounts of the gas back into the atmosphere.

The uncertainties associated with these scenarios are partly based on the fact that the ocean has only been studied systematically for less than 150 years. "For a long time, the ocean was thought to be a sluggish pool of water," said Lamont-Doherty geochemist Samar Khatiwala. "We know now that's not true. It's in fact a lot like the atmosphere: turbulent and dynamic. But we're still at a primitive stage in our understanding of the global ocean."

Fortunately, an increasing number of scientists are coming to realize the necessity of understanding the ocean's role in the carbon cycle and climate system. This realization is old news for Lamont-Doherty geochemist Taro Takahashi. For more than 40 years, Takahashi has headed an effort to determine the rate at which and direction in which carbon dioxide is exchanged between the ocean and atmosphere. Roughly every five years, he publishes an authoritative map pinpointing areas in the ocean that emit or absorb the greenhouse gas. These have become an invaluable tool for climate modelers and others who are attempting to forecast Earth's ability to handle increases in carbon dioxide.

Scientists at Lamont-Doherty and elsewhere are further learning to differentiate between natural and anthropogenic sources of carbon. Recently, Khatiwala and his colleagues succeeded in calculating the anthropogenic carbon content in the global ocean while tracking changes in human contributions from preindustrial times to the present.

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One of their more disquieting findings is that concentrations of both atmospheric and oceanic carbon dioxide, which had been rising together under human influence, now appear to be diverging. As the rate of emissions accelerates, it appears in recent years that the ocean is unable to absorb carbon at a fast enough rate.

"It's great that the ocean has been taking up so much CO_2," said Khatiwala. "But there may be limits to what even the ocean can do."

Converting Carbon Dioxide Into Stone

The fact that the ocean has a limited capacity to absorb carbon dioxide and that the growing acidification of seawater may be as disastrous for the planet as permitting the gas to remain in the atmosphere underscores the need for humans to modify their place in the carbon equation. Given the continued economic rise of populous nations like China, India and Brazil, emission cuts alone are unlikely to solve the problem. Managing atmospheric carbon dioxide rather than regulating it is the only other option, and for that, scientists are turning their gaze deep underground.

Earth's rocky outer lithosphere is believed to be the planet's largest storehouse of carbon. The solid carbonate minerals found there are also some of the most common and stable forms of known carbon. These, however, form very slowly. Several projects at Lamont-Doherty are looking at ways to speed up geologic time and efficiently turn carbon dioxide gas into a solid carbonate mineral more quickly. By targeting rocks such as basalt or peridotite, which are rich in magnesium and calcium, researchers hope that pumping carbon dioxide dissolved in water into the rock formations will produce the desired phase change, turning the carbonate ion solution into carbonate minerals and permanently sealing it away from the atmosphere and ocean.

One of these *insitu* carbon sequestration projects is run by geophysicist David Goldberg, head of the Borehole Research Group at Lamont-Doherty. In 2004, Goldberg and his colleagues conducted a low-volume test injection of carbon dioxide in solution *in situ* — essentially Perrier water, as Goldberg described it — into the test well on Lamont-Doherty's Palisades campus. The hole is drilled through the sill, a large formation of basalt similar to many others around the world that together could, in theory, have the potential to soak up all the carbon dioxide emitted by oil and coal reserves worldwide.

As possible storehouses, "Basalts are just too big to ignore," said Goldberg.

That initial test demonstrated that the concept could work, and Goldberg's group now plans to conduct further tests to determine the impact carbon dioxide injection may have on adjacent groundwater. If this proves successful, humanity may be one step closer to finding a long-term solution to one of our most pressing problems.

[left] White veins and terraces show where carbonate has formed in darker peridotite deposits in Oman. [right] Similar reactions in basalt formations in New York and New Jersey show promise for testing the ability of these rocks to permanently sequester excess carbon dioxide in the atmosphere.

Rosanne D'Arrigo
Associate Director, Biology and Paleo Environment

The Biology and Paleo Environment (B&PE) division is home to a diverse array of researchers seeking to gain understanding of Earth's atmosphere-ocean-terrestrial system. They are generating invaluable long-term records and analyses to improve our knowledge of climate change and to provide a context in which to assess recent anthropogenic influences. Toward this end, they use deep-sea sediment cores, geochemical markers, tree rings, pollen and corals to reconstruct climate and environmental conditions, sometimes spanning millions of years into the past.

B&PE investigators Dennis Kent and Paul Olsen, for example, are co-leading an ambitious drilling project on the Colorado Plateau. It will attempt to recover continental basin records for the early Mesozoic Era—a period dating back more than 200 million years that witnessed mass extinction events, the emergence of modern-day organisms, and significant climate changes.

The Lamont Deep-Sea Sample Repository, housed here at the Observatory and curated by Rusty Lotti, remains a world-class archive of sediment cores and other ocean records. Consisting of samples collected from every major ocean and sea, the repository is readily available to the world's research community. Many of our division's researchers make use of this extensive collection. B&PE paleoclimatologist Brad Linsley utilizes coral records to investigate linkages between the climate of the Pacific Ocean and the El Niño–Southern Oscillation. Paleoceanographer Peter deMenocal uses ocean sediment cores, with other geochemical and fossilized archives, to discern patterns of abrupt climate change in the Atlantic Ocean region and infer how past African climate variability may have influenced human evolution (page 11).

B&PE's biological oceanographers include Ajit Subramaniam who studies tropical river plumes and their impact on the global nutrient and carbon cycles (page 12). Andy Juhl and Ray Sambrotto have conducted research on microbes in the Hudson River estuary that can threaten water quality and harm public health. Sambrotto is also investigating biological productivity in the Bering Sea (page 6). O. Roger Anderson examines the physiological ecology of microbial organisms in aquatic and terrestrial environments, while Alex Chekalyuk has developed bio-optical technologies to measure fluorescence characteristics of phytoplankton, photosynthetic activity, pigmentation and organic matter.

Scientists in B&PE's Tree-Ring Lab (TRL), led by Ed Cook, are using annual growth measurements in trees to generate a new tree-ring data network, known as the Monsoon Asia Drought Atlas. Covering the past millennium, it sheds critical light on Asian monsoon climate dynamics, a key feature of the global climate system that impacts many millions of people. Brendan Buckley and colleagues have discovered ancient trees in Southeast Asian forests and other monsoon-affected locations that reveal evidence of severe megadroughts that may have contributed to the demise of ancient Asian civilizations. TRL researchers Kevin Anchukaitis and Laia Andreu are investigating new ways to expand the use of tree rings in Central America (page 13), while Neil Pederson studies the response of old-growth forests in the Northeastern United States and Mongolia to recent environmental and climatic shifts.

Other B&PE scientists exploring the terrestrial realm include palynologist Dorothy Peteet, who reconstructs the past vegetation and climate history of Alaska, Siberia, and the Northeastern United States. Natalie Boelman studies the effects of environmental change on migratory songbirds in Alaska and the role fire plays in the Arctic landscape. Kevin Griffin investigates patterns of tree ecophysiology in New York State, the paleoecology of vegetation in the Arctic, and environmental factors that affect the growth and physiology of forests in New Zealand.

In the future, our division looks forward to the major renovation of B&PE's New Core Lab and Core Repository and pursuing new avenues in global biogeochemistry research.

Climate Change and the Evolution of Humans

Researcher Peter deMenocal has been hot on the trail of a still-unsolved epic scientific detective story: How did humans evolve on our planet?

While archaeologists have pieced together fossils of our human ancestors to reconstruct an evolutionary tree culminating in *Homo sapiens*, deMenocal has found evidence in the oceans of dramatic climate changes that may have influenced how that tree branched out.

Analyzing sediments deposited on the seafloor off Northeast Africa, he and former graduate student Sarah Feakins employed a novel method to identify molecules from plant remnants blown offshore by winds. These "biomarkers" indicate that this area of Africa shifted away from woodlands and toward savannah grassland as its climate became drier in two big pulses, roughly 2.8 million years ago and, to an even greater extent, beginning 1.8 million years ago. Those times coincide with major evolutionary events: During the former, *Australopithecus afarensis* (referred to as "Lucy"), one of the first bipedal hominids, became extinct; the human family tree diverged into two branches including our genus, *Homo*; and the first stone tools were introduced. During the second major climate shift, humans' most immediate ancestor, *Homo erectus*, first appeared, and with it came the development of more sophisticated stone tools.

While this overall drying trend in Africa started sometime after 3 million years ago, no existing hypotheses could account for the climatic shift.

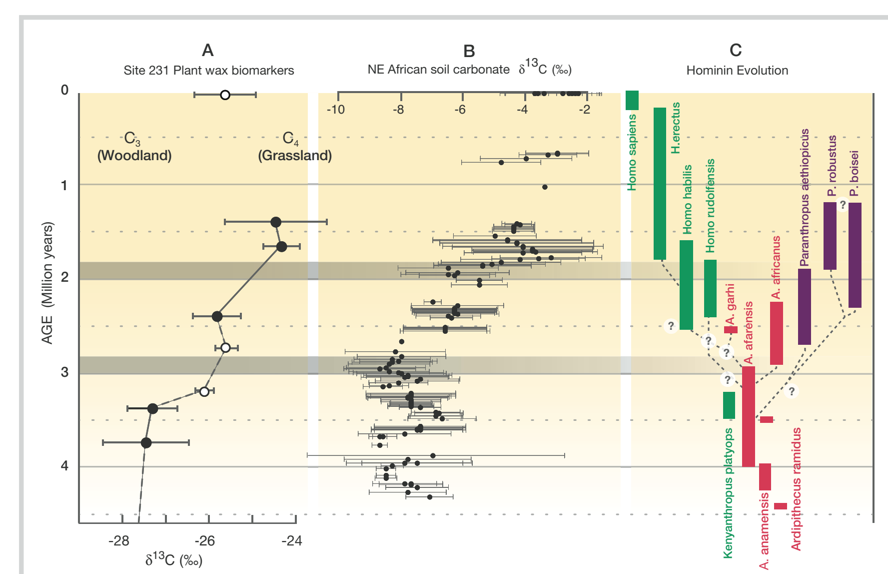
Building on work involving the El Niño–Southern Oscillation by his Lamont-Doherty colleague Mark Cane, deMenocal examined how past changes in tropical ocean temperatures may have affected African climate. Today, the eastern equatorial Pacific and Atlantic Oceans are relatively cool because trade winds blow warm surface waters westward, causing the upwelling of deeper, cooler waters to replace them in the east. The warmer waters in the western Pacific and Atlantic warm the air above, leading to convection and increased rainfall. This concentrates rainfall in the west, which accounts for the Southeast Asian and Amazon rainforests, but it denies rainfall to other regions, such as East Africa.

Examining seafloor sediments from the equatorial Atlantic, Pacific, and Indian Oceans, deMenocal analyzed the relative amounts of magnesium and calcium in the fossilized shells of organisms that once lived in the surface ocean. Since shells grown in warmer temperatures have a higher magnesium content, magnesium/calcium ratios can function as a proxy thermometer, revealing climate information that spans many millions of years.

He found that temperatures across the tropics in all three oceans were uniform from east to west between 3 and 4 million years ago, when Africa experienced moister conditions. Then, temperature gradients appeared in all three oceans: Waters in the western Pacific and Atlantic became warmer than those at their eastern ends. (The case was reversed in the Indian Ocean.) The emergence of these east-west temperature gradients coincided with the onset of drier conditions in Africa, possibly setting the stage for the major human evolutionary events that followed.

"The ocean began starving Africa of water around 3 million years ago," said deMenocal. He co-authored a report issued by the National Research Council in 2010 that summarized our current knowledge regarding climate's influence on human evolution and set forth a research plan for future investigation.

[below] Analyzing sediments blown off Africa, Peter deMenocal and former graduate student Sarah Feakins identified molecules from plant remnants (Col. A) and soil (Col. B), which indicated that Africa shifted away from woodlands and toward savannah grassland as its climate became drier in two big pulses, roughly 2.8 million years and 1.8 million years ago. Those times coincide with major human evolutionary events (Col. C).



Peter deMenocal uses seafloor sediment cores, like these stored in Lamont-Doherty's Deep-Sea Sample Repository, as archives of past climate changes.

River Plumes Supply Ocean With Vital Nutrients

Exploring the world's great rivers, marine biologist Ajit Subramaniam discovered that the Amazon and other large tropical rivers play a major—and previously unsuspected—role in fertilizing the ocean food chain, extracting the greenhouse gas carbon dioxide from the atmosphere and sequestering it into the sea.

To grow, microscopic marine plants (or phytoplankton) need nutrients such as nitrogen and phosphorus. They also use CO_2, which they get from the surface ocean, thus drawing more gas out of the atmosphere. But ocean scientists have long thought tropical oceans to be too deficient in nutrients to produce much phytoplankton growth and therefore not much of a repository for excess CO_2.

In a five-year study, Subramaniam and colleagues took water samples and studied satellite images of the Amazon plume discharging into the Atlantic. They found that for a few months a year during the rainy season, this Amazon plume extends more than 930 miles from the river mouth, reaching dimensions equivalent to twice the size of Texas.

Filled with decomposing vegetation, the Amazon delivers nitrates that spark blooms of phytoplankton called diatoms that use up nitrates quickly. Unlike in smaller rivers, the plumes of big rivers extend farther into the ocean and persist for many months. Stripped of nitrates by diatoms, the big-river plume waters are still rich in phosphorus, which sparks blooms of cyanobacteria, another kind of phytoplankton. Some cyanobacteria can convert nitrogen gas from the atmosphere into organic forms of nitrogen, thus providing a source of nutrients to fertilize additional blooms of phytoplankton. These, in turn, remove more CO_2 from surface waters, Subramaniam explained.

He and colleagues published their study in the July 29, 2008, issue of *Proceedings of the National Academy of Sciences*. Subsequently, they found that the world's second largest river, the Congo, operates similarly. Following Subramaniam's hypothesis, scientists from Puerto Rico and Germany found the same mechanism at work in the Orinoco and Mekong Rivers, the world's third and ninth largest rivers. Together, the findings are forcing scientists to look with new eyes at the roles rivers play in the earth system.

"We are still trying to understand the general rules that govern how various rivers deliver nutrients to the ocean and how those nutrients impact the growth of marine life," Subramaniam said. This fundamental knowledge would help researchers predict how rivers systems may alter as climate and river use changes in the future.

"Climate change will change rainfall patterns and stream flow," he explained. "And what people do on land—chopping down trees, adding fertilizers and pesticides for agriculture—will affect the chemical makeup of the rivers."

A satellite image shows tan-colored sediment from the Amazon River entering the North Atlantic [upper right] off the coast of Brazil at the end of the dry season. During the rainy season, plumes from major rivers like the Amazon can extend hundreds of miles into the ocean, which has a substantial impact on the ocean's ecosystem.

Credit: NASA/Visible Earth

Living Archives: Trees That Record Past Droughts and Rainfall

For decades, dendrochronologists in Lamont-Doherty's Tree-Ring Lab have analyzed concentric annual growth rings in trees to reveal how climate and environmental conditions have varied year to year—centuries into the past and in places throughout the world. Now, Kevin Anchukaitis is expanding the frontiers of dendrochronology into the tropical regions of Central America, where records of past climates are sparse and trees may not even grow annual rings.

Tropical trees may fail to form rings because they aren't subject to the fluctuating temperatures that accompany the winter and summer months. In the cloud forests of Costa Rica, Anchukaitis is pursuing what he refers to as "dendrochronology without rings." His technique involves using high-resolution measurements of oxygen isotopes in the wood of trees to reveal rainy and dry seasons, which have their own environmental and social impacts in these regions.

Central America has few reliable instrumental measurements of climate data. To fill that gap, Anchukaitis and colleagues are investigating new species of tropical trees that have recorded fluctuations in precipitation over the last several centuries.

"Changes to the frequency and duration of droughts will have the most direct and immediate consequences for human populations, posing threats to already stressed water supplies," Anchukaitis said.

Nearly all climate models predict declines in rainfall for much of Central America. A long-term record of past rainfall changes would give scientists and governments an improved sense of how Central American ecosystems have responded in the past and their vulnerability to drought in the future. And, integrated with climate models, such a record would provide insights into how changes in the ocean and atmosphere influence global and regional rainfall. But Central America has few reliable instrumental measurements of climate data, and what does exist extends only as far back as the 1970s.

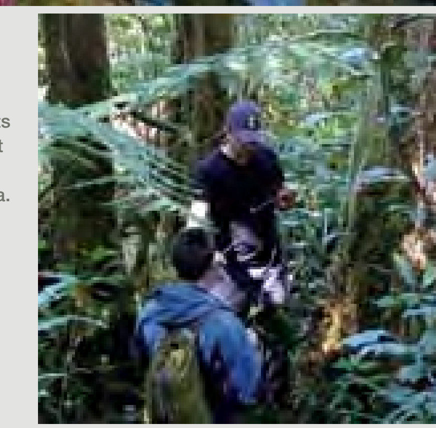
To fill that gap, Anchukaitis and colleagues are investigating new species of tropical trees that have recorded fluctuations in precipitation over the last several centuries. They have identified several candidate species, working at high elevations in the Cuchumatan Mountains with Mayan communities and with scientists at the Universidad de Valle in Guatemala.

In cloud forests, during dry periods, trees get moisture from the water vapor of clouds that condense against the high mountains. This water vapor contains higher concentrations of the oxygen isotope O^{18}. Conversely, rainwater, a lifeline to trees during the rainy season, has lower O^{18} levels.

By identifying and dating annual cycles of oxygen isotopes in tree wood, Anchukaitis can reconstruct a long-term record of precipitation in the region. A recent National Science Foundation grant to Lamont-Doherty provided instrumentation to expand this tropical isotope dendroclimatology work.

Anchukaitis and Michael Evans of the University of Maryland already used the technique to solve the mystery of widespread extinctions of amphibians in Central America in 1987–88. A leading theory blamed warming temperatures, which would have created optimal conditions for the growth of a lethal fungus. But Anchukaitis and Evans showed it was drying, not warming, that killed the amphibians.

Their tree records revealed that the 1986–87 El Niño caused one of the longest and driest periods in Central America in the last 100 years. That would have caused amphibians to coalesce around a few remaining wet habitats, where the fungus could spread rapidly through the populations and ultimately produce mass extinctions.



[top] Lamont dendrochronolgist Anchukaitis and students from the University of Denver work together with local Maya residents of nearby Todos Santos to collect tree-ring specimens in the Sierra de los Cuchumatanes, Guatemala. [right] Anchukaitis and colleagues gather tree-ring samples from centuries-old pine trees to reconstruct past climate variability in the Sierra de las Minas, Guatemala.

Credit: Matthew Taylor

William M. Smethie, Jr.
Associate Director, Geochemistry

Geochemistry is truly a planet-spanning discipline, and research in the Geochemistry Division at Lamont-Doherty covers a wide variety of topics, ranging from processes that occur in Earth's mantle to processes at its surface, including the ocean and atmosphere. Lamont-Doherty geochemists measure a variety of chemicals and isotopes found in crustal materials that reveal information about the composition of the mantle and exchange of materials between the core, mantle and crust. A study focusing on the movement of trace elements between the mantle and the crust is highlighted on the facing page.

Geochemists also have a long history of investigating climate change using a variety of stable and radioactive isotopes preserved in ocean sediments. Recent research by Bärbel Hönisch produced a 2.1 million–year reconstruction of atmospheric carbon dioxide, showing that today's atmospheric carbon dioxide concentration far exceeds the natural levels of Earth's recent history. The Cosmogenic Dating Group continued their study of glacial moraines, left in the wake of receding glaciers, which allow investigators to develop better records of glacier fluctuations. Highlighted on page 16 are the results from work by Bob Anderson and his colleagues to synthesize various climate records in an effort to explain how our planet emerged from past ice ages.

Research in the Geochemistry Division covers a wide variety of topics, ranging from processes that occur in Earth's mantle to processes at its surface.

Researchers are participating in several global-scale surveys that build upon the 1970s decade-long Geochemical Ocean Section Study (GEOSECS) program—the first global survey of anthropogenic tracers in the ocean, which was headed by Lamont-Doherty climatologist Wally Broecker. The course these substances navigate within the ocean help scientists trace such processes as large-scale ocean circulation like the meridional overturning (the great ocean conveyor) and the ocean's uptake of carbon dioxide. This work continues in the Climate Variability and Prediction Repeat Hydrography Program with Lamont-Doherty geochemists making many of the tritium, ^{3}He and CFC measurements.

Carbon dioxide's role in the solid earth, oceans and atmosphere occupies many different subdivisions within the field of geochemistry. Taro Takahashi has been measuring the distribution of carbon dioxide in the surface ocean for more than 40 years, providing a critical baseline from which to isolate changes caused by the burning of fossil fuels. This past year he published an update of his global database for surface carbon dioxide from 1957 to 2008, as well as a paper on changes in surface carbon dioxide over the past few decades. Samar Khatiwala and his colleagues recently reconstructed the uptake of anthropogenic carbon dioxide in the ocean (page 8) using Taro's database. Some Lamont-Doherty geochemists are investigating techniques to sequester carbon dioxide in natural mineral formations, which may provide a way to mitigate global warming caused by anthropogenic emissions. Three studies are currently underway, one at a well drilled into the Newark Basin (page 9), one in Iceland and one in Oman.

On the public health front, scientists here continue to research both arsenic contamination in drinking water and airborne particulate matter. The arsenic studies focus on both understanding the geological and geochemical processes that control the arsenic distribution in various types of aquifers and possible methods of preventing the contamination. Other geochemists study the concentrations of tobacco smoke and black carbon, formed by burning fossil fuels, which affect various populations in New York City.

Tracing the Path of Trace Elements

Recycling may be a relatively novel activity for many people, but Earth has been using and re-using roughly the same raw materials since it was formed. Now, geochemists are beginning to realize just how effectively elements cycle through the planet.

Scientists have known for nearly two decades that some chemical components of ocean sediments carried into the mantle at subduction zones return to the surface in the molten lava that volcanoes emit. In fact, seminal work conducted at Lamont-Doherty in the early 1990s documented how trace elements travel from the surface to the deep earth and back again. But the efficiency of this chemical recycling and the process by which it occurs have remained largely unknown.

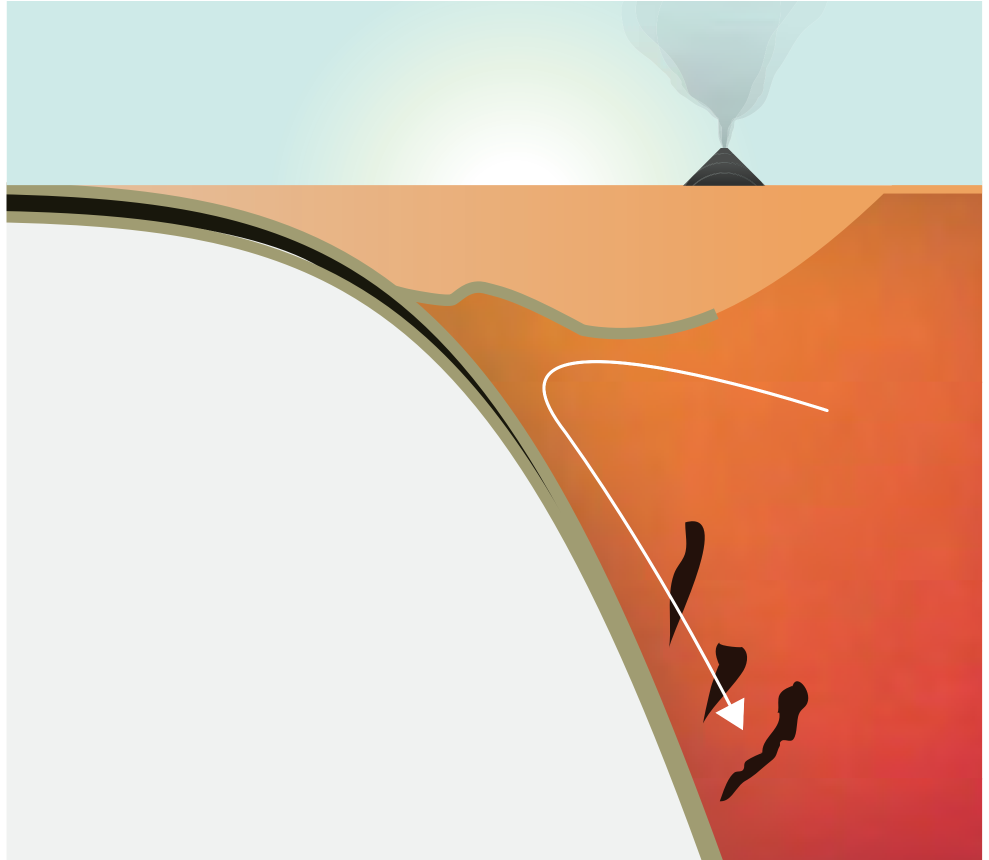
Recent work by the Geology, Petrology and Geodynamics Group, led by geochemist Peter Kelemen, has shown that the deep-earth processes that recycle trace elements are nearly 100 percent efficient. Their findings could lead researchers to rethink the conditions in the upper mantle in addition to granting a clearer understanding of how continental plates form and change at their margins.

In 1993, geochemists Terry Plank and Charlie Langmuir, working at Lamont-Doherty, first showed that some components of seafloor sediments carried down by subducting plates were returned to the surface at volcanic arcs in roughly the same proportions as they were consumed at subduction zones: When more barium- and thorium-rich sediments sank below the surface, more barium and thorium eventually reappeared in the lavas of nearby volcanoes. Neither scientist addressed the efficiency of this process, and it remained possible that the majority of subducted trace elements were mixed into the mantle and largely lost to the planet's surface.

Since then, scientists have identified metamorphic rocks known as ultra-high pressure metasediments—large pieces of shale and other relatively low-density sedimentary rock carried beneath the surface with subducting crust. These rocks are buoyant enough to slowly float back to the surface largely intact, though significantly altered by the extremely high temperatures and pressures they encounter along the way. Analysis of these metasediments indicates they have lost many of their original trace elements during the round trip.

Kelemen and his colleagues compared the chemical composition of lavas around the world to the known composition of ocean sediments being subducted at continental margins. They found that the amount of trace elements being subducted very nearly equaled the amount coming out of arc volcanoes. Ultra-high pressure metasediments were similarly depleted of trace elements.

For this to occur, Kelemen and his colleagues concluded that the metasediments must be detaching from the subducting plate at depths of roughly 60 to 100 miles and rising through the much hotter, intervening mantle to the surface. Along the way, the high temperature pressures they encounter cause them to relinquish virtually all of their trace elements, permitting the material to return to the surface, rather than being lost forever to the interior of the planet.



Sediments detach from subducting plates and rise through the intervening mantle, where heat and pressure strip the material of trace elements. These elements eventually return to the planet surface through volcanoes near subduction zones.

[opposite page]
The Cosmogenic Dating Group is currently studying glacier moraine deposits around Antarctica's Mount Achernar.

Emerging From Past Ice Ages

Earth scientists have long been aware that the planet's climate is an intricate, delicately balanced system. In two papers that appeared in *Science* in 2009 and 2010, Bob Anderson and his colleagues identified some of the interlinking conditions that helped Earth emerge from past ice ages. Once fed into climate models, their findings could provide a more thorough understanding of how the planet's climate system operates.

Their work reveals a number of essential elements necessary to bring an ice age to an end.

Winters in the high latitudes are generally cold enough to allow snow and ice to accumulate, while the intensity of summer sunshine controls whether ice sheets grow or retreat. Work by Lamont-Doherty's Jim Hays and colleagues in 1976 finally proved the long-held hypothesis that variations in Earth's orbit dictate the timing of the ice ages.

Although the theory is widely accepted today, some mysteries about ice-age periodicity have defied explanation. For example, why do ice ages in the Southern Hemisphere follow the same schedule as the Northern Hemisphere when the intensity of summer sunshine in each hemisphere is always in opposition? In addition, why does an increase in summer sunshine in the north terminate certain ice ages but not others?

In one paper, Anderson, together with Lamont Associate Research Professor Joerg Schäfer, Lamont-Doherty adjunct researcher George Denton, and others, illustrated a sequence of events linking changes in the Southern Hemisphere's climate to a southward shift, or intensification, of westerly winds. These winds warmed the Southern Hemisphere, while an increase in summer sunshine was melting the massive northern ice sheets.

Much of the resulting melt water flowed into the North Atlantic Ocean, sometimes accompanied by large numbers of icebergs. Together, the freshwater and ice inhibited deep mixing of the ocean at high latitudes, allowing winter sea ice to spread and creating extreme winter conditions that altered the north-south temperature gradients that regulate global wind systems.

This same reorganization of the Southern Hemisphere winds was invoked by Anderson and another group of colleagues in a second paper to explain a significant rise in atmospheric carbon dioxide at the end of the last ice age. They concluded that the altered wind pattern stirred up deep waters in the ocean around Antarctica, releasing carbon dioxide from the ocean depths into the atmosphere and contributing to atmospheric warming.

Their work reveals a number of essential elements necessary to bring an ice age to an end. First, ice sheets must be large enough that their weight depresses continents and creates drainage patterns that will sustain melting, once started, until most of the ice is gone. Second, the melting must be sustained over several thousand years to keep the winds around Antarctica in a position favorable to the release of carbon dioxide that, in turn, warms the planet even after the intensity of northern summer sunshine declines.

"Changes in the global wind systems can explain many features of the paleoclimate record," said Anderson. However, such changes have yet to be incorporated into climate models. "Comparing model output with paleoclimate records from the Southern Hemisphere will advance knowledge of the connections that link the entire planet during times of climate change."

One of the factors critical to the termination of ice ages was a large supply of icebergs and freshwater runoff from land to areas of deepwater formation. In the past, ice flows from Eurasia, North America and Greenland into the North Atlantic have fulfilled this role.

Lubrication of the San Andreas Fault

If getting blood from stone epitomizes the impossible, then getting water from solid rock is only a shade less difficult. But once extracted, the water can reveal a lot about the deep Earth.

In 2010, a team of researchers led by then-Columbia graduate student Shahla Ali first demonstrated a method of extracting fluids from solid rock samples. The group discovered that their method, which involved heating vacuum-sealed rock samples in a small, nitrogen-flushed oven, allowed them to extract both the fluid contained in the rocks' pores as well as any helium dissolved in the pore fluids. The latter enabled the team to identify the source of the fluids and the length of time the liquid had resided in the rocks.

Water plays an important role in Earth's crust, circulating minerals and permitting chemical reactions to occur at temperatures below the melting point of rocks. It also acts as a lubricant between faults, enabling tectonic plates to slip past one another without causing earthquakes. The absence of water can cause a fault to lock, making it more likely to rupture in a single, large earthquake.

Direct fluid sampling in active fault zones is an expensive and time-consuming endeavor, and liquid samples are often subject to contamination. Until now, researchers have been unable to obtain adequate fluid samples that would provide them with detailed information about fault conditions.

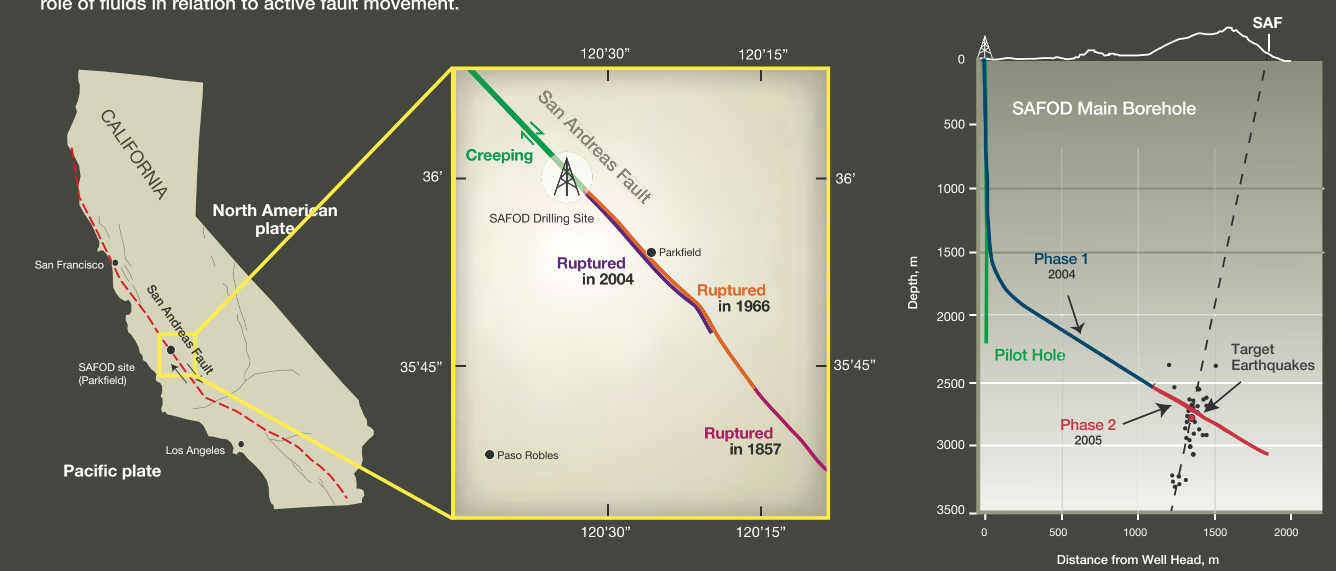
With the new sampling method in hand, Ali led a group of researchers from Lamont-Doherty interested in studying fluids trapped in sediments between the North American and Pacific plates. They extracted pore fluids from drill core fragments recovered by the San Andreas Fault Observatory at Depth (SAFOD) drilling project, an ongoing investigation in a region near the initiation point of 2004's magnitude 6 Parkfield earthquake. The location of the SAFOD project coincides with a section of the fault where the North American plate slides past the Pacific plate at an average rate of 1.5 inches per year, resulting in a series of events that have ruptured the fault five times since 1857. California's Parkfield region is the most extensively instrumented section of a fault anywhere in the world and has been the focus of intensive study for the past two decades.

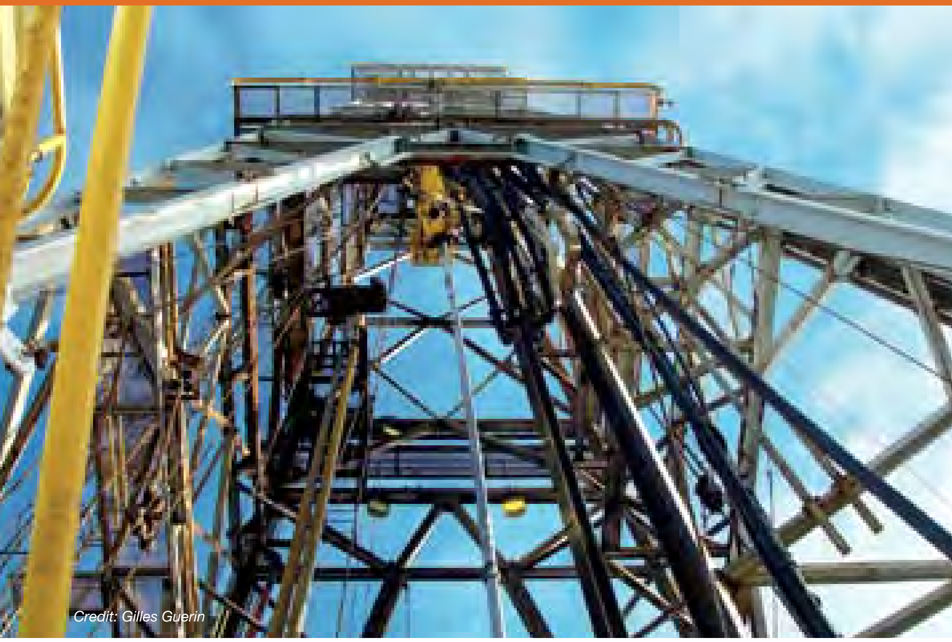
By helium dating the fluids extracted in their samples, the researchers concluded that the most recent fluid inflow into the fault happened less than 35,000 years ago. The liquid consisted of freshwater from the surface that made its way nearly two miles into the fault relatively quickly—most likely when the fault acted as a drain during a large earthquake event.

Since then, this fluid has led to the formation of clay minerals, which provide the necessary lubrication to allow the two plates to slide continuously past each other every year without producing regular earthquakes.

If getting blood from stone epitomizes the impossible, then getting water from solid rock is only a shade less difficult. But once extracted, the water can reveal a lot about the deep Earth.

Core samples retrieved during SAFOD drilling phases 1, 2 and 3 across the active fault zone demonstrate researchers' ability to extract usable fluids from rock samples and establish the role of fluids in relation to active fault movement.





Credit: Gilles Guerin

W. Roger Buck
Associate Director, Marine Geology and Geophysics

Most researchers in the Marine Geology and Geophysics (MG&G) Division got their start employing geophysical techniques to examine the sediments, crust and mantle beneath the oceans. In these pages we highlight several projects that continue to focus on processes at the seafloor, particularly those related to the creation of new crust at mid-ocean ridges. However, many MG&G scientists are applying the expertise they gained working in the oceans to other problems.

A prominent example is the growing group of scientists, led by Robin Bell and James Cochran, who are using radar and gravity to see though the Antarctic ice sheet to study the hidden lakes trapped beneath the ice. To monitor retreating ice sheets, Nick Frearson is leading a major push to engineer more sophisticated instruments that can be fitted to airplanes and drones on polar flights.

A large project led by Michael Steckler attempts to better understand the structural history of Bangladesh, a tectonically active region threatened by floods and earthquakes. Christopher Small continues to analyze satellite data with techniques he's developed to use marine geophysical data to estimate the number of cities with varying sizes within a given region. A group established by Suzanne Carbotte and William Ryan in an effort to archive marine geophysical data online has now formally amalgamated with a group led by Kerstin Lehnert to provide free access to petrologic and geochemical data.

Oceanographer Kim Kastens, recipient of the 2008 American Geophysical Union's Excellence in Geophysical Education prize, is the author of innovative science curricula, soon to be released by the National Science Teacher's Association Press. The book, *Earth Science Puzzles*, is comprised of actual earth science data collected by researchers at the Observatory and around the world; the exercises encourage students to think critically about earth processes and supplemental material helps educators introduce science more effectively in their classrooms.

Several groups in MG&G work on theoretical models to explain observations. For example, Colin Stark is using seismic data in an attempt to model how giant landslides happen. Alberto Malinverno has employed ideas from physical chemistry to explain why methane hydrates are concentrated in certain sedimentary layers recently measured in deep-sea cores. Working with seismologists at the Observatory, Eunseo Choi has developed three-dimensional numerical models to explain the deformation occurring in warped regions of strike-slip faults.

These ventures into other topics in earth science demonstrate the cross-disciplinary nature of the MG&G division. But marine research is still our core. Cecilia McHugh and colleagues' analysis of the history of deformation recorded in sediments off the coast of Haiti may provide insight into the frequency of earthquakes along Haiti's Enriquillo Fault. Additionally, new data from William Ryan pins down the age of a large and sudden flood—perhaps the source of ancient flood myths—during which the Black Sea opened to the Mediterranean and water level rose a hundred meters. Also, the borehole geophysics group led by David Goldberg took part in numerous sea expeditions on the reconditioned Integrated Ocean Drilling Program's ship, the *JOIDES Resolution*.

The division suffered a significant loss with the passing of John Diebold in early July 2010. He will be greatly missed not only as a friend to many but also as a superb scientist. Diebold did marine seismology the old-fashioned way: He understood every aspect of the field, from the mechanics of air guns to envisioning scientific problems best studied with the instruments at hand. To honor his memory, we hope to expand our curriculum by formally teaching students some of the techniques John developed.

Building New Ocean Crust

The longest mountain chain on Earth is not the Andes, but the mid-ocean ridge system, stretching nearly 50,000 miles and crisscrossing the ocean floor like the seams on a baseball. Here, below the water's surface, Earth's crust is splitting apart. Magma deep within the mantle seeps to the ocean floor as lava, and new crust is born. Understanding how this magma reaches the ridges may tell researchers how the seafloor forms and ridges spread.

On land, scientists can use a variety of instruments to measure the movement of magma below the surface, but probing the motion of underwater magma is more difficult—satellite signals for measuring subtle changes in elevations cannot penetrate water. Thus researchers lack details on the exact processes by which magma transforms into new crust.

Scientists at Lamont-Doherty have devised a way around this problem. By placing pressure sensors—similar to those used to detect tsunamis—along certain ridges, researchers can measure slight changes in water pressure and calculate changes to the seafloor's depth as the crust rises and falls from the oozing magma.

Scott Nooner, a marine geophysicist at Lamont-Doherty, is using pressure sensors to study Axial Volcano, located along the Juan de Fuca Ridge (roughly 270 miles off the coast of Washington) and fed by magma rising from within the mantle.

In 2007, researchers placed pressure sensors, equipped with new data recorders developed by Lamont-Doherty scientist Spahr Webb, along the East Pacific Rise. Nooner and Lamont-Doherty colleague Roger Buck want to see if over several years the sensors can detect subtle changes in seafloor depth, which would indicate how magma travels to the ridges. This may reveal why parts of ridges spread faster than others and how physical features such as strike-slip faults evolve on the ridges.

They also want to comprehend how magma travels through the crust and reaches the surface through dikes, which are fingers of magma pushing through the crust. Because monitoring dike formation underwater is so difficult, Nooner and Buck are studying Ethiopia's Afar region, one of two places in the world where a mid-ocean ridge intersects the land. In a 2009 paper in *Geophysical Research Letters*, Nooner, Buck and other collaborators found that a recent episode where several dikes formed in rapid succession might have caused a brief period of accelerated spreading at the ridge.

Nooner and Buck's research allows them to investigate the differences between spreading centers above water and at the ocean floor. For example, unlike the dike sequence studied at Afar, dikes at ridges under the ocean are thought to form one at a time, with up to 10 years between volcanic events. Because thousands of years from now Afar will be submerged by ocean as plates continue to split apart, Nooner and Buck hope to discover how magma supply to rifts changes in behavior once the rifts no longer have to tear through continental crust.

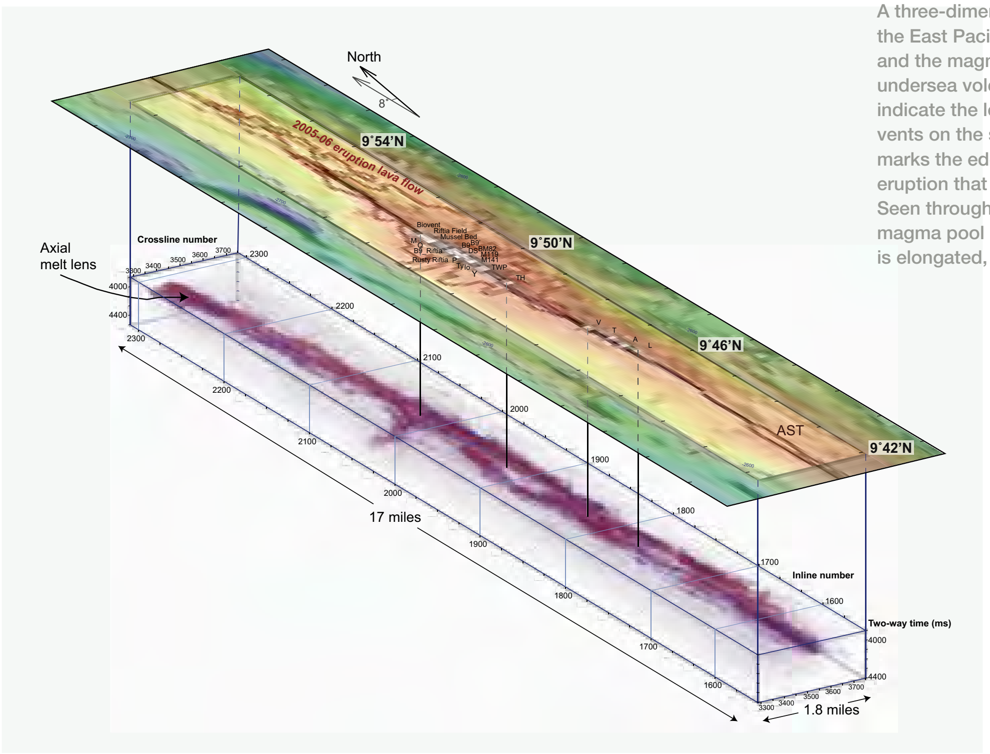
By placing pressure sensors—similar to those used to detect tsunamis—along certain ridges, researchers can measure slight changes in water pressure and calculate changes to the seafloor's depth as the crust rises and falls from the oozing magma.

In a 2009 paper in the journal *Geochemistry, Geophysics, and Geosystems*, Nooner reported that these sensors detected a short period of rapid swelling of the volcano followed by a decade of slower but steady uplift of the volcano surface. The rapid swelling is indicative of either drainage of nearby magma chambers into the main volcanic vent or movement within the crust in response to an eruption. The slow and steady uplift that followed was the result of magma rising from the mantle.

Videos taken by a remotely operated vehicle on the seafloor at Axial Volcano on the Juan de Fuca Ridge are streamed to a ship sailing above. The images captured include a pressure sensor (yellow) used by Lamont-Doherty researchers to study how seafloor depths change due to magma flowing underground.

[opposite page] Looking up into the derrick of the *JOIDES Resolution*

Ridges in Three Dimensions



A three-dimensional view of a region of the East Pacific Rise shows the seafloor and the magma about 1 mile beneath this undersea volcanic system. White stars indicate the locations of hydrothermal vents on the seafloor, and the red outline marks the edge of lava flow from an eruption that occurred in 2005–2006. Seen through this seismic image, the magma pool (red and blue blotches) is elongated, patchy and disjointed.

In the 1950s, scientists at Lamont-Doherty were the first to discover that the planet's submarine mountain chains were connected to one another and prone to earthquakes, observations that helped solidify the theory of plate tectonics. These mountain chains, known as mid-ocean ridges, mark places where the plates are spreading apart. More than 50 years later, Lamont-Doherty scientists are still at the forefront of this research, seeking new details on what drives plates to diverge and how magma is transformed into fresh seafloor.

In 2008, the Lamont-Doherty operated R/V *Marcus G. Langseth* became the first academic research ship to produce high resolution three-dimensional images of the sub-seafloor using state-of-the-art seismic techniques. The research vessel crisscrossed the diverging plate boundary at the East Pacific Rise, towing an array of instruments designed to reveal the rocks and sediments hidden deep beneath the ocean floor.

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On that 2008 voyage, marine geophysicists John Mutter, Suzanne Carbotte and Helene Carton, along with other collaborators, investigated magma pools situated roughly a mile below the ridge. Rather than finding one elongated sheet of magma feeding seafloor eruptions along the entire ridge, they discovered that the magma supply was disjointed, indicating that the ridge axis is composed of separate but elongated volcanoes rather than one continuous sheet of magma oozing up from the mantle as previously thought. Such a finding suggests that different regions of the ridge may evolve and erupt separately.

During the cruise, the scientists also found that magma pools can exist at least 11 miles away from the ridge. These pools of magma have different chemical signatures from lavas found at the ridge axis. Though prevailing ideas propose that all crust at ridges forms within the few kilometers separating the diverging plates, the new data suggests that magma may ooze through conduits and form new crust farther away. As a result, the unique biology found at ridges, fueled by hydrothermal vents (which are heated by magma below), may exist over a broader swath of seafloor than was previously assumed.

Carbotte and Carton's goal is to illuminate the extent of these satellite magma pockets, document how these pockets heat hydrothermal ecosystems, and discern how the disjointed magma pools beneath the ridge modulates volcanic eruptions. Because little is known about the dynamics of magmatic systems beneath underwater volcanoes, scientists from Lamont-Doherty hope to return to the East Pacific Rise soon to conduct new surveys.

The Flow of Fluid: Imaging Black Smokers and Oil Spills

Most of the ocean floor is barren. But in areas where submarine mountains rise, desolate landscapes give way to biological oases: forests of tubeworms, mats of microbial ooze, translucent crabs, shrimp, and ghostly looking fish.

Towering over these environments are tall spires called black smokers that spew clouds of water heated by hot magma just below Earth's crust. Bacteria feed on the chemicals contained in this mineral-rich water, forming the lowest link of the system's food chain. If one or more of the hydrothermal vents were to shut down, these oceanic oases would become ghost towns.

In addition to supplying life-sustaining minerals, the vents transfer heat between the lithosphere and the overlying ocean. Determining the rate at which fluid flows from these vents can help scientists understand how ocean crust forms.

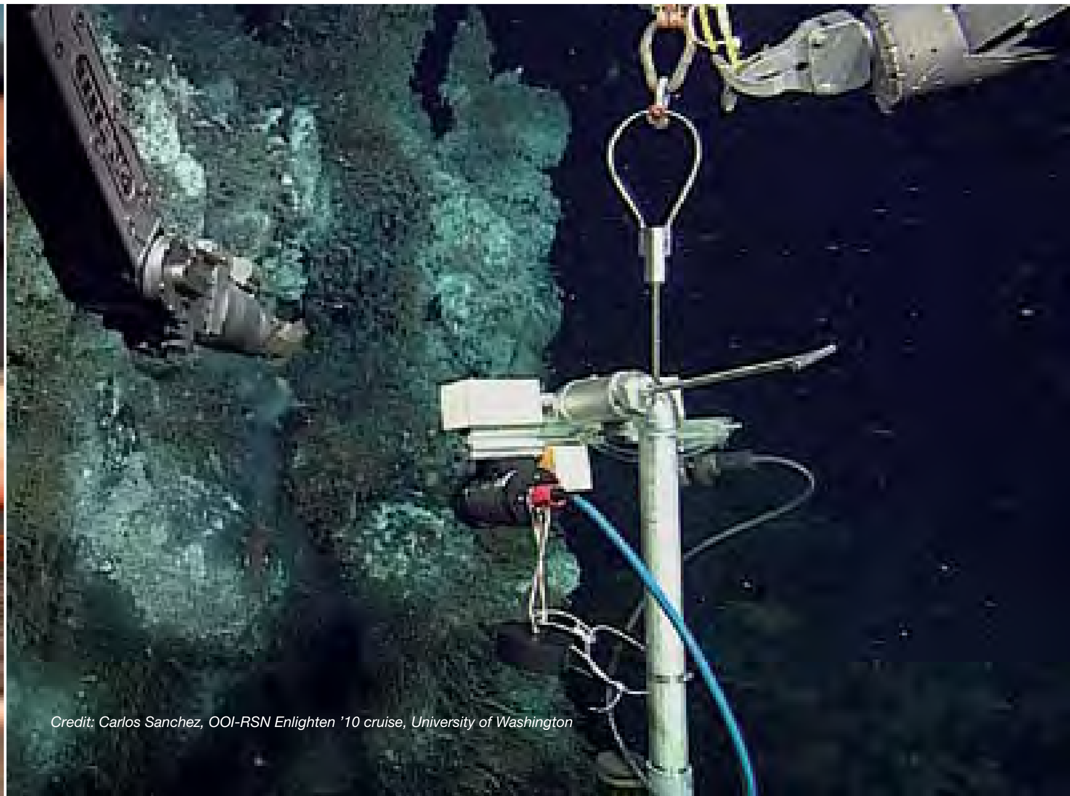
Lamont-Doherty marine geophysicist Timothy Crone has pioneered a way to more accurately measure how fast fluid is flowing from hydrothermal vents. In a 2008 paper in the journal *Experiments in Fluids*, he described a process of analyzing the flow rate of black smokers by employing a computer program to track—pixel by pixel—the swirling clouds of hydrothermal fluid released by the vents.

By applying this technique to video footage shot of a black smoker off the coast of Washington in the late 1980s, Crone verified previous conjectures that the rise and fall of tides affect fluid pressures within the vent, causing changes in its flow rate. He also determined that variations in flow rates were linked to earthquake swarms that frequently occur at divergent plate boundaries. These results were published in a 2010 paper in the journal *Geochemistry, Geophysics, and Geosystems*.

Crone's research received unexpected media attention after BP's Deepwater Horizon oil rig exploded in April of 2010. Watching footage of the oil plume on television, Crone realized the flow was similar to those that issue from hydrothermal vents. Applying his computer imaging technique to the BP spill, he calculated in June that nearly 60,000 barrels were leaking daily—an amount 12 times larger than the original estimate given by BP and the National Oceanic and Atmospheric Administration. Crone was one of the first scientists to offer an independent assessment, first on National Public Radio and later in *The New York Times*, CBS News and other news organizations.

Currently, Crone is working with Lamont-Doherty colleague Maya Tolstoy to construct models of fluid flow within the young crust at mid-ocean ridges, using data collected from hydrothermal vents along the East Pacific Rise, a ridge segment north of the Galapagos. Crone is also developing a camera, called VentCam, for installation at the seafloor that would capture around-the-clock footage of black smokers. He tested a prototype in a summer 2010 expedition to the Juan de Fuca Ridge and hopes it will eventually form part of the National Science Foundation's ambitious Ocean Observatories Initiative project to wire the seafloor for remote observation.

[left] Crone prepares the VentCam for a mission to the seafloor, where it will measure flow rates in a black smoker vent.
[right] Using the robotic arms of the ROV *Jason*, Crone and other researchers install VentCam near a black smoker on the Juan de Fuca Ridge.



Credit: Carlos Sanchez, OOI-RSN Enlighten '10 cruise, University of Washington

Credit: NASA/Visible Earth

Arnold L. Gordon
Associate Director, Ocean and Climate Physics

The footprint of human civilization on our planet is heavy indeed. Scientists, the public and governmental bodies are increasingly aware of likely anthropogenic changes to our environment: extreme droughts and floods that damage food supplies and displace populations, disappearing glaciers and associated rising sea levels, the future behavior of intense tropical storms, and the acidification of the ocean. There is broad consensus that the world 100 years from now will be a very different place, and in 1,000 years, a drastically altered one.

But all is not dire. There are solutions that can lead us into a sustainable relationship with our planet. They require an understanding of the complex interplay of the living and nonliving components of the total earth system. Scientists within the Ocean and Climate Physics Division (OCP) are actively engaged in this pursuit, striving to sharpen our projections of future climate and environmental conditions, so as to better guide remedial actions.

Changes in Earth's climate are nothing new; they have been occurring throughout the planet's long history and will continue. These changes are governed by complex interactions involving the atmosphere, hydrosphere (oceans), cryosphere (ice), biosphere (living things) and external sources, such as fluctuations of solar radiation and even an occasional asteroid impact. Understanding the natural variability of Earth's climate is complicated enough. But now humankind is adding a new dimension, superimposing powerful stresses on Earth's delicately balanced climate system.

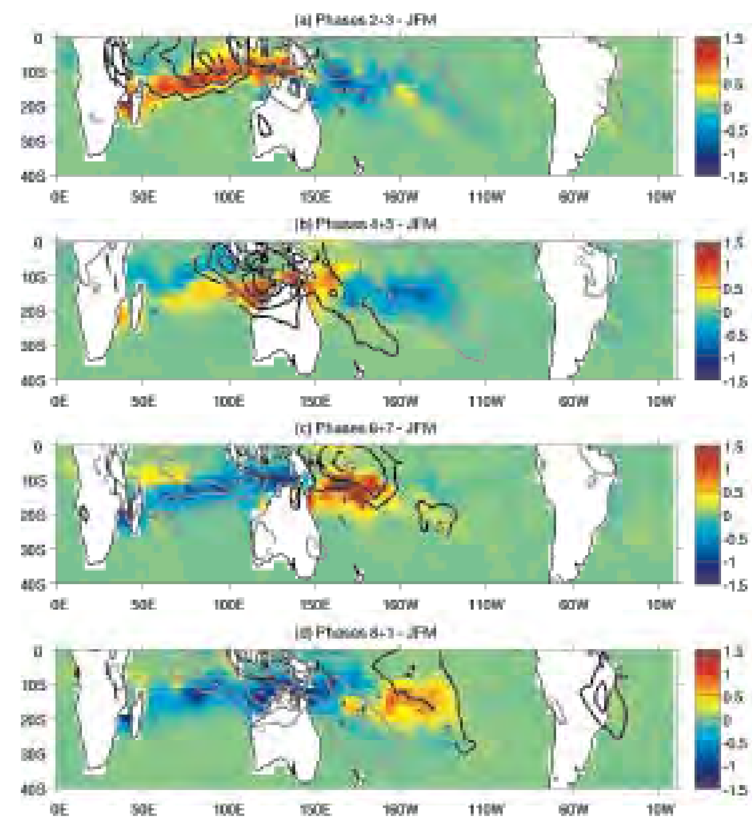
Close collaboration between observationalists and modelers, between oceanographers and climatologists, and with scientists from other divisions at the Observatory is one of OCP's hallmarks and has led to significant advancements in the field. OCP researchers investigate spatial and temporal patterns of climate change employing data obtained from the meteorological and oceanographic instrumental record, as well as the observational record, of roughly the last century and a half. They study atmospheric and oceanic dynamics to better understand the processes that govern climate change. These include recent efforts to understand intraseasonal oscillations that impact temperatures and rainfall at scales of less than 90 days (page 23) and efforts to unravel connections between climate swings in the tropics, Antarctic sea ice and the oceanography of the southern polar region (page 24).

These new insights can be effectively incorporated into global climate numerical models with higher resolution to produce more robust predictions, particularly at the regional level. To calibrate the models, we are also keenly aware that we need to develop more accurate reconstructions of past climates, research that engages other scientists within our division (page 25).

OCP researchers examine ocean behavior through seagoing expeditions, sensors deployed on moorings, and from remote data obtained from satellites—all placed in context with the decades of archived observations and ocean model output. Regional studies range from local estuary and coastal waters, to the frozen southern polar ocean, the broad sweep of the tropical ocean, and the balmy seas of the Southeast Asian archipelago.

Lamont-Doherty oceanographers also investigate the processes that govern the flux of heat, freshwater and gases across the sea surface, as well as deep-ocean mixing. Quantifying sea-air exchange and ocean mixing is not easy, but the task is essential if we want computer models to accurately depict the intertwined global network of ocean and atmosphere we call climate.

Cycle of Air-Sea Interactions Has Big Impact



Over each cycle of the Madden-Julian Oscillation, warm waters, clouds and rainfall propagate eastward from the western equatorial Indian Ocean, over Indonesia, and onward to the central equatorial Pacific, before the cycle repeats in the western Indian Ocean. This figure shows, for four "phases" of the MJO, a measure of the changes it causes in cloudiness and rainfall (greater rainfall in black and lesser in gray) and the change in the probability of tropical cyclone formation in colors (greater probability in red and lesser in blue).

From S.J. Camargo, M.C. Wheeler, and A.H. Sobel, "Diagnosis of the MJO modulation of tropical cyclogenesis using an empirical index," *Journal of Climate* 66, 3061–3074.

By now many are familiar with the El Niño–Southern Oscillation (ENSO) and its shifting winds, ocean temperatures and rainfall that affect weather and climate around the globe. Few people, however, have heard of another naturally occurring cycle of interacting ocean-atmosphere dynamics called the Madden-Julian Oscillation (MJO), whose impact is similarly of global proportions.

Roland Madden and Paul Julian first discovered the MJO in the early 1970s, but Lamont-Doherty climatologist Adam Sobel explained that "despite a huge number of observational, theoretical and modeling studies, there isn't a broadly agreed-upon description of the mechanisms that cause the MJO or govern its most basic properties."

Models have improved substantially in recent years, and Sobel and colleagues are testing them to see how well they can simulate the MJO.

Sobel has made it his research goal to elucidate this elusive oscillation in an effort to improve our ability to forecast the MJO and the weather it generates throughout the year.

This much is known: The cycle begins with an enhanced convection that spawns clouds and rainfall over warm waters in the western equatorial Indian Ocean. The clouds and rainfall propagate eastward over Indonesia and into the eastern and central equatorial Pacific. They dissipate as they move over the cooler ocean waters of the eastern Pacific, only to reappear in the tropical Atlantic and Indian Ocean. Each cycle lasts 30 to 80 days.

Traversing the equator, the convection system distributes moisture and rearranges atmospheric circulation. It not only affects local weather, it also influences the Asian and Australian monsoons, cyclones and hurricanes in the Pacific and Atlantic, rainfall and flooding on the West Coast of the United States—perhaps even El Niño itself.

Heretofore, numerical models that simulate climate dynamics haven't been able to capture the physics that generates the MJO. But models have improved substantially in recent years, and Sobel and colleagues are testing them to see how well they can simulate the MJO.

They are also conducting experiments with the models to try to isolate the mechanisms that drive the MJO. The researchers attempt this by systematically "turning off" individual physical processes in the model's simulation to see if the MJO ceases to exist or is strongly weakened.

Similar experiments could provide insights into such questions as: Why do these oscillations exist? What is their energy source? Why do they propagate eastward at a speed of roughly five meters per second?

Of course, more observations and measurements on the phenomenon would improve the models, and with that in mind, scientists from several nations are poised to launch a field program in the central equatorial Indian Ocean in 2011 and 2012 to collect data on the MJO in action. Sobel plans to participate in United States' contribution to the expedition, a program called Dynamics of the Madden-Julian Oscillation, or DYNAMO.

Earth's Climate: A Tapestry Woven From Sea, Air and Ice

Xiaojun Yuan has been on a decade-long quest to connect the dots in Earth's climate system by unraveling the oceanic and atmospheric pathways that link the tropics to the South Pole. She has traced how shifts in equatorial Pacific Ocean temperatures prompt atmospheric changes that ultimately impact both the sea ice in the Southern Ocean surrounding Antarctica and the deep circulation of the global ocean.

The Southern Ocean plays several key roles in global climate change—both in responding to it and in driving it. For example, white ice reflects solar radiation back into the atmosphere, but when enough warming causes large amounts of ice to disappear, the exposed areas of dark ocean water absorb heat and further amplify global warming.

When cold, dense waters produced during the formation of sea ice sink to the bottom of the ocean, they draw down large amounts of carbon dioxide from the sea surface. Changes in this circulation could influence the ocean's uptake of greenhouse gases and, consequently, the buildup of greenhouse gases in the atmosphere.

In the early 2000s, Yuan and Lamont-Doherty colleague Doug Martinson began correlating records of Antarctic sea ice and the El Niño–Southern Oscillation (ENSO)—the periodic shifts between warmer (El Niño) and colder (La Niña) sea surface temperatures in the eastern equatorial Pacific.

Yuan and Martinson proposed that the atmosphere served as a link between the tropics and the southern polar region.

They found that during an El Niño, temperatures rose and sea ice declined in the Pacific sector of the Antarctic, but colder temperatures and increased sea ice developed in the Atlantic sector of the Antarctic. These conditions flip-flopped during La Niña events. Yuan and Martinson called the phenomenon the Antarctic Dipole.

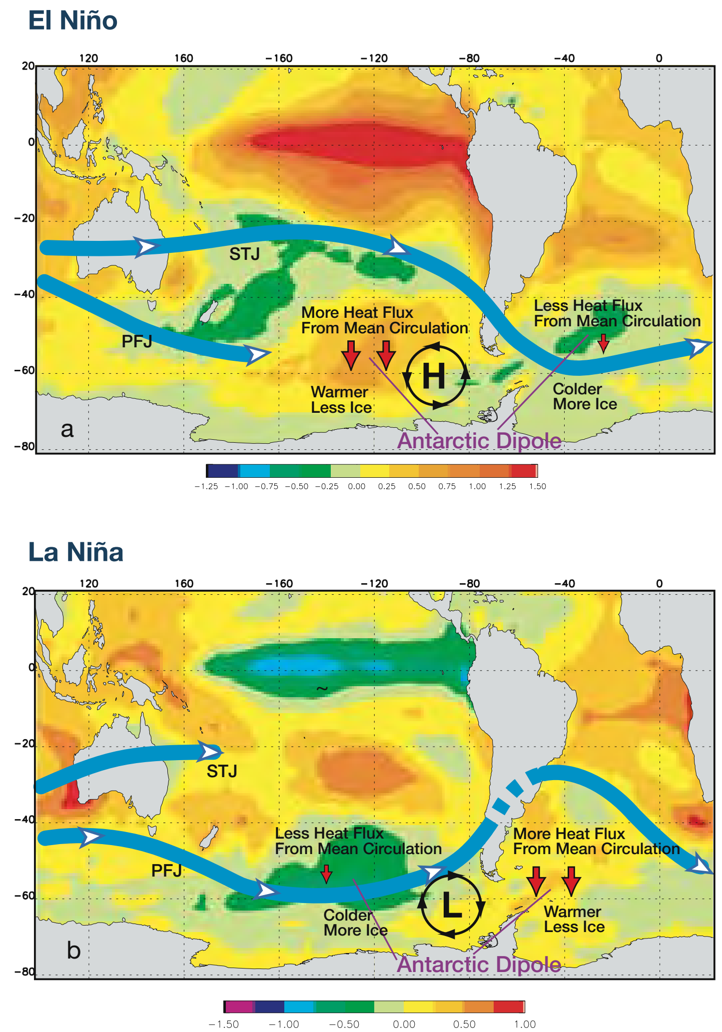
They proposed that the atmosphere served as a link between the tropics and the southern polar region. Warmer waters during El Niños transferred more heat to the air above the tropical Pacific, triggering a cascade of atmospheric changes that rearranged circulation patterns in the tropics, mid-latitudes and all the way south to Antarctica.

In 2004 Yuan and Lamont-Doherty colleague Dake Chen began using the patterns they identified in the Southern Ocean climate system to make some of the first successful forecasts of sea ice coverage around Antarctica.

In the latest phase of this research, Yuan followed the trail into the Weddell Sea, east of the Antarctic Peninsula, where voluminous masses of dense water form over the Antarctic continental shelf, sink rapidly, and spread in ocean depths throughout the world. She teamed up with Lamont-Doherty oceanographers Arnold Gordon, Bruce Huber and Darren McKee who had used subsurface moorings set in the Weddell Sea between 1999 and 2007 to measure changes in temperature, salinity and current velocities.

The moorings detected years when cold-water masses did and did not form in the Weddell Sea depths. The researchers tied these fluctuations to fluctuations in wind patterns over the Weddell Sea, which, in turn, they linked to ENSO and another periodic shift in atmospheric circulation known as the Southern Annular Mode.

Link by link, Yuan is unraveling the processes governing Earth's climate and identifying mechanisms that help scientists assess how our planet's climate might operate in the future.



Yuan and Martinson showed that during El Niños temperatures rose and sea ice declined in the Pacific sector of the Antarctic, but colder temperatures and increased sea ice developed in the Atlantic sector of the Antarctic. These conditions flip-flopped during La Niña events. They called the phenomenon the Antarctic Dipole.

Paleoclimatologist Jason Smerdon conducts numerical experiments to reduce uncertainties in climate reconstructions used to understand Earth's past climate variability.

Refining Our Recorders of Climate Change

Scientists use several tools to understand how Earth's climate has worked in the past and how it might change in the future. None is perfect; each has its pluses and minuses. Lamont-Doherty climatologist Jason Smerdon is exploring ways to combine the strengths of the different tools in order to diminish their weaknesses.

The surest tools at scientists' disposal are measurements of temperature, precipitation and other components of the climate system taken by modern instruments. But these records go back only 150 years or so, not long enough to characterize earlier climatic changes, such as those in the past 2,000 years (Smerdon's research focus), or to contrast natural and human-caused changes in preindustrial and postindustrial periods.

With no time machines at their disposal, scientists have extracted clues from a second tool: natural climate archives, or proxies, such as tree rings, coral skeletons, and cave formations, all of which grow in layers, whose formation is determined, in part, by the period's ambient temperature, precipitation and other climatic factors. Analyzing these proxies, however, involves inherent assumptions, statistical inferences, even biases and errors—in a word, uncertainties. These uncertainties are often at the heart of vigorous debates by scientists—and in some cases, the general public—about how to interpret proxy data and which data are the most accurate record of Earth's past climate.

A third tool utilizes simulations from climate models that mathematically incorporate the laws of physics and the myriad other variables that influence climate.

"Climate models are our best approximation of how we think the climate works," Smerdon said. Although imperfect, these models do a good job reproducing climate variability during the 20th century and have helped scientists understand important dynamical properties of the climate system. And model simulations spanning the last 1,000 years or more are beginning to offer clues about the causes of climatic change during that period.

Smerdon combines all of these techniques and often uses one method as a check against another. In an effort to test the accuracy of reconstruction techniques, he conducts what are referred to as pseudoproxy experiments. Model simulations spanning the last thousand years provide complete temperature and precipitation fields over time and space, but Smerdon subsamples these fields to mimic the limited measurements he would have from real proxies and modern observations. Operating a sort of numerical laboratory, Smerdon runs trial climate reconstructions with these subsampled data and compares his results to the known model fields to test the performance of various reconstruction methods. Using these pseudoproxy experiments, Smerdon and colleagues have characterized important uncertainties in the performance of climate-reconstruction methods currently used in his field.

Model simulations spanning the last 1,000 years or more are beginning to offer clues about the causes of climatic change during that period.

"This work helps us identify and characterize the strengths and limitations of state-of-the-art climate reconstruction methods so we can reduce their uncertainties and improve them," Smerdon said. The goal is a more detailed and verified climate atlas providing information on how Earth's climate varied over the last several millennia. That atlas, based on real data, will in turn help validate models used to project future climate changes.

Art Lerner-Lam
Associate Director, Seismology, Geology and Tectonophysics

Seismology, Geology and Tectonophysics (SG&T) encompasses research on earthquakes and Earth's structure. This includes studies of the evolution and deformation of continents as expressed in surface geology and sediments, examinations of the strength of Earth materials, characterizations and simulations of earthquakes, and detailed investigations of the deep Earth. Research approaches combine theory, observation and laboratory work.

The scientists here who study geodesy—the shape and deformation of the planet—led by Mikhail Kogan, Meredith Nettles, and most recently James Davis, will soon benefit from a new geodesy laboratory that will serve as the basis for fieldwork, instrumentation development and analysis. Modern geodesy has illuminated the motions of the tectonic plates for several decades, but recent work indicates that rigid plate motions tell only part of the story. Earth's crust is in fact deforming in amazing ways—slowly creeping, episodically trembling and shifting—and not just at major plate boundaries.

Moreover, new generations of instruments are capable of monitoring minute motions and sending data in real time to analytical centers. This new information supplies researchers with a record of deformation around major faults in unprecedented detail. The new data is both mysterious and enticing in its implications, with the promise of providing clues about the nature of earthquake cycles.

SG&T continues to monitor earthquakes globally, and the group headed by Göran Ekström—the Global Centroid Moment Tensor project—is responsible for calculating and disseminating detailed characterizations of large events. We also have operational responsibilities for monitoring quakes in the Northeast as part of the U.S. Geological Survey's national quake detection system. The staff, led by Won-Young Kim, provide critical details about significant seismic events to government agencies and first responders, the media, the public, and the broader scientific community.

Our seismology group is engaged in field work spanning the globe, from Papua New Guinea and Alaska to Africa. James Gaherty, Geoffrey Abers, along with their students and postdocs, have been investigating continental rifting and ocean subduction worldwide using high-fidelity instrumentation. Many of the land experiments are supplemented by deployments of ocean bottom seismometers (OBS), designed and constructed by our OBS Laboratory, which is managed by Andrew Barclay. Their work builds on Lamont-Doherty's long history of observational seismology, but is informed by a new understanding of the geochemical and geophysical signatures of plate tectonic processes.

Our scientists also interpret these new observations for insight about the behavior of the minerals that make up Earth's crust and mantle. Marc Spiegelman, Ben Holtzman and our new "rock mechanic," Heather Savage, work on the theoretical aspects and laboratory measurements of rock deformation, magma generation, and the interaction between Earth's solids and fluids. These studies should shed light on innumerable problems in seismology, petrology and geodesy. We are truly at the dawn of a new era of integration in solid earth sciences.

Our excitement about the potential for new science is always tempered by the tragic consequences of earthquake disasters, and the past two years have seen many. Though the earthquakes in Sichuan, Haiti and Chile were phenomenologically distinct, each had devastating consequences, including the extreme loss of life and livelihood for millions. The more we learn, the more we realize that we must fuse our scientific understanding with actionable advice to reduce the impact of future catastrophes.

[top] Satellite image of central Death Valley

Identifying an Unknown Plate

A map of earthquake epicenters spanning the last 50 years reveals narrow zones of seismicity across the globe. These zones trace the boundaries of tectonic plates—at these boundaries, plates are converging, diverging, or sliding past each other, generating quakes as they move.

But not all plate boundaries are marked by clear seismic zones. For example, the exact location of where the Eurasian plate ends and the North American plate begins is not clearly defined by seismicity. Lacking clear seismic expression, this boundary was marked in early tectonic maps along Siberia's Cherskiy Range. Maps traced the plate boundary through the Sea of Okhotsk, meeting up with the Pacific plate just north of the Japanese island of Hokkaido. According to these maps, the North American plate extended far into the Asian continent to include the eastern tip of Siberia, the Kamchatka Peninsula and the Kuril Islands.

Called the Bering plate, named for the Bering Sea, this new plate is important to understanding earthquake hazards in the northwest Pacific.

To Lamont-Doherty researcher Mikhail Kogan, this oddly shaped portion of the plate boundary presented an irresistible challenge. Over the past decade, he worked with colleagues at the Russian Academy of Sciences and at the University of Alaska Fairbanks to deploy networks of Global Positioning System (GPS) stations across the frigid landscapes of Siberia and Alaska, including the volcanic terrains of the Kuril Islands, Kamchatka and the Aleutian Islands. An orbiting constellation of sophisticated satellites tracks the motion of these stations, allowing scientists to measure precisely the present-day speed and direction of the plates.

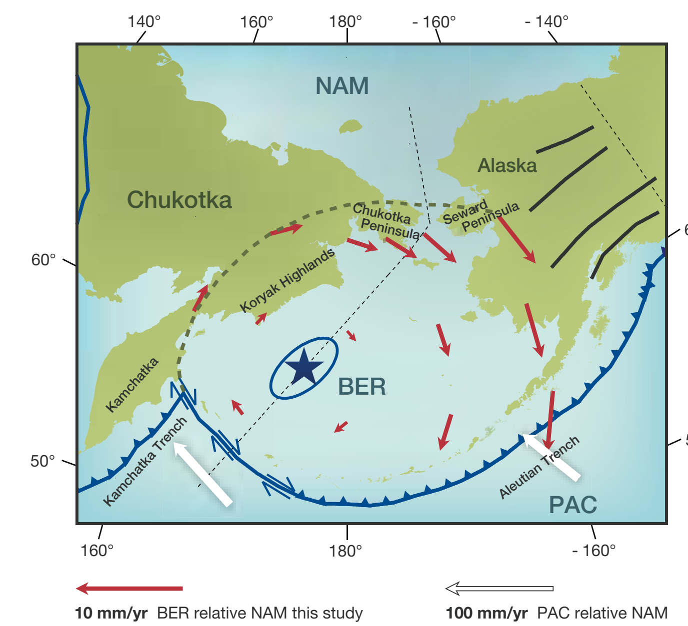
This group of scientists discovered that the easternmost section of Siberia is not only moving at a different rate and direction from Eurasia, but—along with the Bering Sea—it is moving at rates distinct from the rest of North America. This could only mean one thing: the region is its own plate rotating clockwise with respect to North America at a speed reaching several millimeters per year.

Called the Bering plate, named for the Bering Sea, this new plate is important to understanding earthquake hazards in the northwest Pacific. Earthquakes caused by the subduction of the Pacific Ocean beneath the Bering plate are known to be some of the most energetic in the world. Some, like the 1964 magnitude 9.2 Great Alaskan Earthquake, caused large tsunamis across the Pacific Ocean. The plate also lends credence to the idea that some of the large plates believed in the early days of plate tectonic theory to tile the globe are actually interacting assemblages of smaller plates.

Kogan's research in the multiyear Russia–U.S. project also reveals information about the nature of earthquake cycles in subduction zones bordering the northwestern Pacific Ocean. The GPS network recorded motions caused by a pair of great earthquakes that ruptured a large section of the Kuril arc in 2006 and 2007. The data indicates that both seismic events are closely related, suggesting that the earlier earthquake provoked the second.

Knowledge of strain patterns provides insights into the complexities governing the interface between subducting and overriding plates and may offer clues to the initiation, location and timing of the next rupture.

The GPS array installed by the Russia–U.S. team at the northwest Pacific Ocean margin will support future work on the precise location where the Kamchatka and Aleutian subduction zones intersect. Analysis supports the idea that at the point of intersection, a small sliver of the Bering plate has broken off along the western Aleutians. Whether this small sliver is being dragged along by the Pacific plate and smashing into Kamchatka will yield further insights into earthquake production in this region.



Tectonic sketch of the Bering Sea region. PAC, NAM and BER are the Pacific, North American and Bering plates, respectively. Motion of PAC and BER relative to NAM is shown at selected points. The motion of BER was estimated from GPS observations in Alaska, Siberia and the Bering Sea Islands. The blue star marks the approximate point about which BER is rotating. The barbed curve denotes subduction of PAC beneath BER and beneath NAM near Kamchatka.

New Instruments to Image an Underwater Fault

Major earthquakes regularly rupture Earth's surface: Since 1900, earthquakes of magnitude 8.0 or greater have happened roughly once a year somewhere across the globe. Those greater than 9.0 happen less frequently, about once every 15 years. These large seismic events release energies equivalent to 25,000 nuclear bombs—enough energy to power the entire United States for at least 52 days.

Earthquakes of this scale occur along subduction zones, places where large sections of oceanic crust are being thrust beneath continental crust. Plates in these zones are moving together continuously, causing friction to build in areas where they meet. If enough strain accumulates, the release of energy that ensues can be disastrous, as witnessed with the 2004 Great Sumatra–Andaman earthquake that, together with a deadly tsunami, killed nearly 300,000 people.

Scientists deploy the new trawl-resistant ocean bottom seismometers into Long Island Sound for testing.

Off the northwest coast of the United States, the Juan de Fuca plate is plunging beneath the North American plate at a rate of three to four centimeters per year, forming the Cascadia Trench. A great earthquake struck the region in 1700, producing a devastating tsunami in the Pacific Ocean. But little is known about this particular subduction zone, and researchers are unable to estimate when the next large earthquake will occur.

Scientists and engineers in Lamont-Doherty's Ocean Bottom Seismology (OBS) Laboratory develop unique ocean bottom seismometers capable of detecting seismic waves within a broad range of energies. Hoping that the instruments will help answer fundamental questions about earthquake hazards in the Cascade Trench, lab manager Andrew Barclay and colleagues, with the guidance of Lamont-Doherty scientists James Gaherty, Maya Tolstoy and Spahr Webb, are designing seismometers to image this underwater fault. Their work forms part of the Cascadia Initiative, a project funded by the National Science Foundation that aims to better understand subduction-zone faulting in this region.

A focus of the Cascadia Initiative is to study episodic tremor—seismic features recognized in this area only recently. Episodic tremor refers to a rate of seismic motion somewhere between the normal state of gradual plate motion and earthquakes, during which huge blocks of crust move several meters in just a few seconds. "Earthquakes happen on the cold, brittle and relatively shallow portions of this fault, but there appears to be a deeper zone characterized by episodic tremor where stress builds up over the course of about a year and then releases in ground motions that last for a week or so," explained Gaherty.

This newly discovered process in these more ductile zones may lead to a more detailed representation of what controls big earthquakes in adjacent brittle zones; tremor may increase the likelihood of a strong earthquake in specific brittle portions of the fault, while decreasing the likelihood in other areas. The new OBS instruments will help scientists understand the location and timing of tremor activity and its relationship with larger quakes.

Twenty of the 30 new instruments have been designed to resist being dredged up by the trawlers that collect fish along the coast of the Pacific Northwest. The loss of ocean bottom seismometers due to these trawlers represents a major risk—at almost $80,000 per instrument, the cost of losing one is a significant setback. Housed within sleek steel shielding, the new seismometers skirt the ocean floor, collecting data until they are retrieved by remotely operated vehicles. The trawl-resistant shield also deflects motion from ocean currents that can interfere with the sensitive seismometers they encompass.

The remaining 10 instruments will be deployed deep enough to render trawl resistance unnecessary, but they do include shielding to protect against ocean currents. Prototypes of the instrument packages are being tested by OBS staff in Long Island Sound, with the goal of deploying them by summer 2011.

Like Fireflies, Earthquakes May Fire in Synchrony

In 1665, Dutch scientist Christiaan Huygens noticed that two pendulum clocks hanging from the same wall swung in unison and would synchronize no matter how much the pendulums were disturbed. His observations led to the discovery that other seemingly random events could mysteriously align: from the chirping of crickets, or the flashing of fireflies, to the beating of two human hearts.

It turns out that earthquake faults may similarly rupture in synchrony, according to a June 2010 paper by Lamont-Doherty seismologist Christopher Scholz, published in the *Bulletin of the Seismological Society of America*.

Scientists have known for some time that large earthquakes can trigger aftershocks and additional big quakes along the same fault. But Scholz proposes that through a process called entrainment, big earthquakes can trigger other big quakes on nearby faults through the same mechanism that synchronized the swinging pendulums of Huygens' clocks.

Scholz became interested in this idea 30 years ago while researching how large ruptures in California and Nicaragua trigger aftershocks at nearby faults. He revisited the idea last spring when a student asked why two parallel faults in Nevada that usually rupture every 5,000 years had both fired off earthquakes in a matter of hours.

In another example, a 1992 earthquake near Landers, Calif., killed one and injured nearly 400 when the sub-fault—an offshoot of the San Andreas Fault—ruptured in a magnitude 7.2 event. Seven years later (and 15 miles away), the Pisgah Fault ruptured in a 7.1 event. The close timing of these earthquakes was curious: Based on paleoseismic studies, both faults rupture only once every 5,000 years.

Intrigued, Scholz took a closer look at earthquakes in Nevada's Basin and Range region, California's Mojave Desert and in southern Iceland. He found a similar pattern emerging, with a major earthquake following another on a nearby fault, even if both faults were known to rupture only every few thousand years. For Scholz, the earthquake sequences were too close in time to be coincidental. The faults, typically between 6 to 31 miles apart, had to be synchronized.

Scholz proposes that through a process called entrainment, big earthquakes can trigger other big quakes on nearby faults from the same mechanism that synchronized the swinging pendulums of Huygens' clocks.

Scholz hypothesizes that a simple mechanism is responsible. When any earthquake strikes, stress is released and moved to a different section of the fault. However, a tiny portion of this stress—around a fraction of one percent—can be transferred to nearby faults. Over time and many earthquakes later, this small transfer of stress builds up to the point that a large earthquake on the original fault could induce the nearby fault to finally rupture.

The Landers quake may have triggered another big quake, seven years later, at Hector Mine [above] near Joshua Tree National Park.

Credit: Chris Walls, Earth Consultants International/USGS

Just as Huygens' pendulum clocks only swing in synchrony if the pendulum lengths and weights of the bobs are the same, large earthquakes at the coupled faults must share common features. For example, both faults need to be slipping at a similar rate.

Prevailing thought has been that large earthquakes lower the risk of future seismic events because of the stress they release. But if Scholz's theory is correct, one big earthquake might actually increase the probability of another occurring nearby. "If so, our seismic hazard analysis techniques may need re-evaluation," Scholz explained.

MARINE DIVISION

Credit: Sandbox Studio SF/Eduardo Acorda

David Goldberg
Associate Director, Marine Division

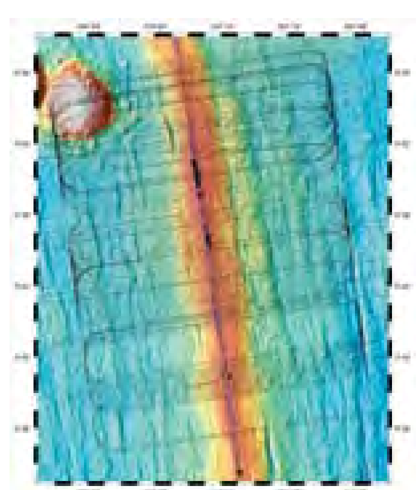
In 2009, Lamont-Doherty marked the first full year of science operations aboard the R/V *Marcus G. Langseth* with research cruises around the Pacific. Highlights included collaborations with Taiwan Integrated Geodynamics Research (TAIGER), a multi-institutional, land- and sea-based effort to study the formation of Taiwan, and trips to the East Pacific Rise (EPR) and the Endeavor segment of the Juan de Fuca Ridge. The EPR cruise, led by Lamont-Doherty's John Mutter and Suzanne Carbotte, was the first academic cruise to generate a three-dimensional seismic volume of the region.

Despite the unparalleled success of the cruise to the East Pacific Rise, it was not without tense moments. At one point, a compressor charging the ship's air guns failed and a backup proved inoperable as well. The ship eventually needed to return to port, but the situation brought out a true "all hands on deck" spirit with everyone on board working to coax the faulty compressors back to life. Conducting research at sea is a complex and fraught enterprise at times.

While operations got underway aboard the *Langseth*, Lamont-Doherty Director Michael Purdy initiated a review of the leadership of the Marine Division. For several years prior, he had been acting as the interim associate director for the Marine Division, while Paul Ljunggren led day-to-day office operations and Al Walsh oversaw the engineering and technical operations. Foreseeing an increasingly complex fiscal and regulatory environment for managing the *Langseth*, Purdy asked David Goldberg to take on the role of associate director of the Marine Division. In this capacity, Goldberg is developing a plan to address the future organization of the division as well as looking into expanding *Langseth's* base of support beyond the National Science Foundation.

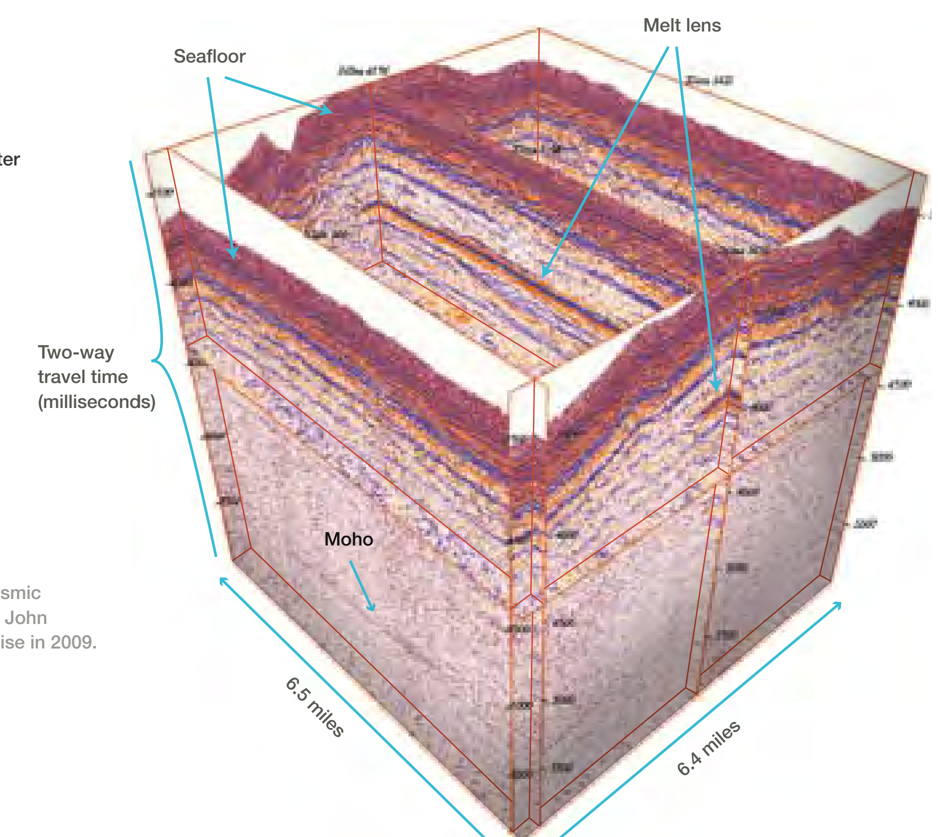
The first step toward implementation of that plan was the creation of a new position of director of the Office of Marine Operations to oversee the *Langseth's* scientific and operational management. In early 2010, Sean Higgins was appointed in this role. Already, he has enabled projects to be planned and managed more comprehensively, and he has enhanced our interactions with the National Science Foundation and the Marcus Langseth Science Oversight Committee (MLSOC).

Into this period of growth and promise within the Marine Division came the tragic deaths of John Diebold, a towering figure in the world of marine seismic imaging, and John Nicolas, a long-time marine mammal observer and shipmate aboard the *Langseth*. Their passing leaves a large hole in the community of scientists, engineers, and maritime researchers who look beneath the ocean floor for answers to questions about how our planet is constructed, how it continues to change, and how marine mammals behave. Both men's contributions to these fields will continue to resonate at Lamont-Doherty and beyond for many years to come.



The Carbotte/Mutter seismic survey of the East Pacific Rise [survey track lines, left] was the first true three-dimensional, multichannel (multisource/multireceive array) seismics survey ever carried out by a U.S. academic research vessel. The primary goal was to image the magmatic-hydrothermal system beneath the ridge [opposite page].

DATES	PORT(S)	PI(S)	PROJECT DETAILS
6/29/08–8/21/08	Manzanillo, Mexico	**John Mutter** and **Suzanne Carbotte** Lamont-Doherty Earth Observatory	3-D/4-D seismic reflection imaging of the magmatic-hydrothermal system at the RIDGE 2000 program's East Pacific Rise Integrated Study Site
9/10/08–10/6/08	Astoria, Oregon	**Sean Gulick** University of Texas at Austin	Seismic survey to examine crustal structure, fault patterns and tectonic-climate geohistory of Yakutat Bay, Alaska, as part of St. Elias Erosion/Tectonics Project
1/13/09–1/21/09	Nuku'alofa, Tonga	**Del Bohnenstiehl** North Carolina State University	Mooring deployment in the Lau Basin to examine T-wave processes and hydroacoustic monitoring capabilities
1/24/09–3/8/09	Nuku'alofa, Tonga, to Suva, Fiji	**Doug Wiens** Washington University in St. Louis	Seismic survey at the RIDGE 2000 program's Lau Integrated Studies Site involving deployment and recovery of 77 OBSs
4/1/09–7/25/09 (5 legs)	Kaohsiung, Taiwan	**Kirk McIntosh** University of Texas at Austin	Seismic survey to investigate processes of large-scale mountain building in the China and Philippine Seas as part of Taiwan Integrated Geodynamics Research initiative
8/22/09–9/19/09	Astoria, Oregon	**Doug Toomey** University of Oregon	3-D seismic tomography of sub-seafloor volcanic and hydrothermal features as part of Endeavour Seismic Tomography Experiment involving deployment and recovery of 64 OBSs



Carbotte/Mutter EPR 3-D Survey
A 6-mile by 6-mile section of 3-D seismic imaging from Suzanne Carbotte and John Mutter's survey of the East Pacific Rise in 2009.

Credit: Elena Steponaitis

Steven L. Goldstein
Chair, Department of Earth and Environmental Sciences

The Department of Earth and Environmental Sciences (DEES) received great news as this report prepared for press with the release of the National Research Council's (NRC) latest assessment of doctoral programs in the United States, which serves as the benchmark within academia for a program's performance. Out of 140 programs in earth sciences, we were proud to see ourselves ranked at the very top in overall program quality.

Rankings were last released in 1994, when Columbia ranked fifth in geosciences behind Caltech, MIT, Johns Hopkins and Berkeley. Our growth in this regard reflects the dedication and expertise of our faculty, research colleagues and talented students.

To most of the outside world, geosciences at Columbia University means Lamont-Doherty. Nevertheless, our educational and research offerings extend beyond the Observatory. The DEES instructional faculty consists of nearly 50 voting members, which includes the department's full-time faculty, all based at Lamont-Doherty, plus 15 of the nearly 70 Lamont Research Professors, as well as scientists from the NASA-Goddard Institute for Space Studies, the American Museum of Natural History, Barnard College and the International Research Institute for Climate and Society (IRI).

Moreover, the graduate research faculty serving as advisers and mentors to Ph.D. students includes many scientists who are not formal members of DEES. Many of the approximately 40 postdoctoral scientists mentor our students as well. Together we form a community of well over 150 professional scientists, covering a wide range of subjects, from the deepest Earth to the oceans and atmosphere, which is generating fundamental scientific contributions. The synergy between disciplines and the cooperation among these institutions provide our students with an array of opportunities that are hard to match anywhere. Herein lies the key to our success: The strength of our doctoral program reflects the shared efforts between the various research units at the University and beyond.

While we are pleased with the NRC ranking, it is based on data submitted in Fall 2006. Since then there have been 15 new appointments to the DEES faculty. In seismology: Professor Göran Ekström, Assistant Professor Meredith Nettles (both from Harvard), and Adjunct Professor Geoff Abers from Boston University; in paleoceanography: Professor Jerry McManus from the Woods Hole Oceanographic Institution and Assistant Professor Bärbel Hönisch from the Alfred Wegener Institute for Polar and Marine Research; in petrology-geochemistry: Professor Terry Plank from Boston University; in climate studies: Adjunct Associate Professors Gisela Winckler and Joerg Schaefer from Lamont-Doherty, Lisa Goddard from IRI, and Adjunct Professor Mingfang Ting from Lamont-Doherty; in marine geophysics: Associate Professor Maya Tolstoy; in remote sensing: Adjunct Professor Chris Small; and in biological oceanography: Adjunct Associate Professor Andrew Juhl.

Since 2006, DEES has seen the retirements of Dennis Hayes, James Simpson, David Rind, William Ryan and Paul Richards. Even with the departure of these singular figures, we are today a much larger, more diverse and interdisciplinary faculty than we were when the NRC data were gathered.

Undergraduate and Masters Programs

Over the last decade, one of the most dramatic changes in the department is our expanding undergraduate program, driven by the fact that students have become increasingly motivated by the potential impact of humans on the environment. Whereas previously DEES was largely a graduate department, over the last decade we have escalated our undergraduate recruiting efforts. As a result of our efforts to participate in the Frontiers of Science core curriculum course, every Columbia College student is now exposed to the geosciences. We also offer a taste of fieldwork with annual geological excursion courses during spring break, alternating between Death Valley, led by Professor Nicholas Christie-Blick, and the Mono Lake region, led by Professor Sidney Hemming.

Gone are the days when DEES and Lamont-Doherty were nearly invisible to undergraduates, as course enrollments have nearly tripled since 2004. Of course, along with our success come new challenges: Increased enrollments mean increased demand for teaching assistants, larger classes mean individual students get less attention from the professors, and few classroom options exist for courses with more than 50 students. We are struggling with these issues and, for the first time, are considering limiting the enrollments of some classes.

As a result of our efforts to participate in the Frontiers of Science core curriculum course, every Columbia College student is now exposed to the geosciences.

Along with increasing enrollments, DEES is witnessing an increasing number of undergraduate majors. There were 57 in the Spring 2010 term, up from 29 in 2007–2008. Carol Mountain, our undergraduate coordinator, has organized weekly Noon Balloon lunchtime science talks aimed specifically for undergraduates. Our majors have also organized an Undergraduate Student Committee in order to promote interaction among themselves and to give students the means to communicate their needs and concerns to the department. Over the last year, this group has expanded its activities and now plays a central role in the undergraduate departmental life.

With the influx of majors, we have expanded our undergraduate offerings, most notably with new 3000-level courses aimed at majors and concentrators. "Design and Maintenance of a Habitable Planet" by Professor Terry Plank and "Solid Earth Dynamics" by Assistant Professor Meredith Nettles have become successful bridges between the foundation courses and graduate courses. And an expanded summer intern program, partly supported by DEES, Lamont-Doherty, and the Earth Institute, has permitted the involvement of many more Columbia and Barnard students than was possible in the past.

With increasing demand for undergraduate research, one of the main obstacles for undergraduates is traveling to the Lamont campus to conduct research, while their class schedules require them to stay mainly at Columbia's Morningside campus. Recognizing this problem, we are working to facilitate portions of students' research in the city.

The 12-month master's program in Climate and Society headed by Professor Mark Cane and Adjunct Professor Mingfang Ting has shown tremendous growth from 18 students in 2004–2005 to 39 in 2009–2010. Students come from all over the world to learn the workings of Earth's climate system, assess its socioeconomic impacts, and consider ways to make climate information more usable to policymakers. On the other hand, our Earth and Environmental Sciences Journalism Program, despite its past success, was suspended in 2009–2010 by its director, Adjunct Professor Kim Kastens, in recognition of the poor outlook for employment in print journalism.

Columbia College undergrads now have the opportunity to experience geologic fieldwork at Mono Lake [left] or Death Valley [above].

General News

During the 2008–2009 and 2009–2010 academic years a large number of DEES faculty members received noteworthy awards and recognitions from the international community.

Adjunct Professor John Flynn and Hirschorn Professor Stephanie Pfirman of Barnard were inducted as Fellows of the American Association for the Advancement of Science. Newberry Professor Wally Broecker reached a milestone with the department, and in Spring 2010 we celebrated the 50th anniversary of his appointment to the Columbia faculty.

For a full list of awards won by faculty members connected with Lamont-Doherty, please see page 38.

A Climate Connection

It would be easy for any graduate student to turn inward during his or her time at Columbia, to focus solely on the long, rigorous task of publishing journal articles and completing the thesis. It would be easier still for a newly minted scientist to look anywhere other than his or her impoverished home country to launch a promising career. But Ousmane Ndiaye, a native of Senegal, isn't a typical graduate student.

As a student, and now scientist, Ndiaye has focused on developing better methods of forecasting short-term and seasonal climate variability in the African Sahel. Throughout his time at Columbia, he has been an active member of the Senegalese community in Central Harlem, where he and others in this tightly knit group help newcomers adapt to life in the United States, providing an informal safety net for those who fall on hard times. In many ways, these two parts of his life are inseparable.

Ndiaye's scientific work at the International Research Institute for Climate and Society (IRI) under the supervision of Neil Ward has centered around developing accurate ways to predict both the character of the rainy season in the Sahel and the onset of the rainy season over his native Senegal. For small farmers who make up the bulk of these regions' rural agricultural population, knowing when and what to plant often make the difference between a successful growing season and famine. It can also help countries and relief organizations anticipate and plan for an outbreak of climate-related diseases such as malaria—a need that Ndiaye knows only too well. "Everyone in the Sahel is affected by malaria in some way," he said. "I got it. Climate has a huge impact on our society."

Now Ndiaye's research stands to impact people all across the Sahel as well. His work revealed that the onset of the monsoon in the region is tightly linked to global sea surface temperatures (SST), while the onset in southern Senegal is tied most closely to the southern Atlantic dipole—a pattern of temperature differences involving the northern and southern tropical Atlantic. It is work that could easily catapult Ndiaye to a tenure-track position in the United States.

"Everyone in the Sahel is affected by malaria in some way. Climate has a huge impact on our society."

Undecided about his future plans after graduation, Ndiaye sought out the advice of Mamadou Diouf, the head of Columbia's Institute for African Studies. Even though the two men had never met before, it was natural for Ndiaye to approach the elder Diouf, because in the Senegalese tradition, age and experience garner real respect. Even in an emigrant community, social mores resonate. "Wherever we go, we recognize ourselves," said Diouf. "It's a way of rebuilding familiar ties."

Diouf didn't steer Ndiaye toward any one path, but, in conversation, it soon became clear that Ndiaye was intent on reconnecting with both his native Senegal and with the people who live in the Sahel. By the end of 2010, he plans to return to his home country to share his knowledge of the regional climate system.

"It's rare to see someone like him go back," said Diouf, sounding like a true elder brother. "But he knows the misery of the Sahel and he wants to contribute to the development of his country. I am very proud of him."

Following the Rocks

Almost any good geologist can tell a story by looking at rocks. Rocks hold the key to Earth's deepest past and reveal the monumental forces that have shaped the planet. They also tell us how the planet is changing beneath our feet, sometimes as we watch. Jill VanTongeren is discovering that some of these stories rival even the best mystery novels.

As an undergraduate at the University of Michigan, VanTongeren was preparing for a major in linguistics, but a suggestion by her father to fulfill her science requirement with a geology course opened a whole new world and set her on a different path. It also presented her with a ticket to visit some very exotic places. "There are rocks everywhere," she said. "You can go anywhere with geology."

Since graduating, VanTongeren has proved that statement true time and again, first venturing to Antarctica's Dry Valleys to study a stunning example of Earth's magmatic plumbing: When Gondwana, the supercontinent comprising many of Earth's present-day landmasses, began to break apart roughly 180 million years ago, it caused massive upwellings of magma that are still visible at the Antarctic. On the trip she met Lamont-Doherty senior adjunct researcher and American Museum of Natural History curator Ed Mathez, who eventually became her adviser at Columbia.

Since then, she has "followed the rocks" to Argentina, Mexico, Costa Rica and Oman. Most recently, in South Africa, she, Mathez and Lamont-Doherty geochemist and Columbia professor Peter Kelemen have been pursuing a mystery that involves nearly 250,000 cubic miles of rock. These particular rocks form the Bushveld Complex—the solidified remains of a massive magma intrusion that is the source of much of South Africa's

A suggestion by her father to fulfill her science requirement with a geology course opened a whole new world and set VanTongeren on a different path.

mineral wealth. A chemical inventory suggests that as much as 25 percent of the rock is unaccounted for.

While the Bushveld contains large quantities of platinum, vanadium and chromium, large amounts of zirconium and other elements that normally make up the uppermost layers of the ancient, solidified magma are nowhere to be found.

VanTongeren had a hunch that, like any good mystery, the answer lay right under her nose. She proposed they examine Bushveld's uppermost layers of lava that conventional wisdom had said were not part of the original intrusion.

Mathez, initially concerned the undertaking could lead VanTongeren down a blind alley, was hesitant to have her tackle the subject for her thesis. "Yet we couldn't find anything wrong with the idea, and so she convinced me to press ahead," said Mathez. "We could still be wrong, but it's no longer risky. We're simply following the science where it takes us."

In 2010, VanTongeren, Mathez and Kelemen published a paper in the *Journal of Petrology* showing how certain contents of this layer do indeed complete the chemical inventory of the formation.

The story almost certainly does not end here, but it is proof that rocks can lead one in some very interesting directions.

Credit: Kate Ronan

[above] Students participated in A Day in the Life of the Hudson River. [left] Lamont Associate Research Professor Tim Kenna working with summer intern Rodrigo Prugue.

"Our goal at Lamont-Doherty has been twofold: To generate fundamental knowledge that will inform environmental decisions at the global level and to build a comprehensive education and outreach program to foster a better-educated citizenry." — G. Michael Purdy

In 2009, a paper in *Science* co-authored by researchers at Columbia's Departments of Physiology and Cellular Biophysics found that the students of high school teachers who participated in university-led summer research programs performed better on the New York State Regents exams. At Lamont-Doherty, this conclusion was not surprising. For decades, the scientists and students here have devoted themselves to making their work accessible to generations of teachers and young people.

Later that same year, Lamont-Doherty geophysicist Kim Kastens was recognized by the American Geophysical Union with the Excellence in Geophysical Education Award. For years, Kastens has been researching how students process concepts in the geosciences and how teachers might translate the complex scientific ideas more effectively in the classroom. Together with Education Coordinator Margie Turrin, Kastens used her considerable insight into the way young people learn about the world to produce *Earth Science Puzzles: Making Sense of Data*, a book aimed at grades 8 through 12 published by the National Science Teachers Association.

Earth2Class

The monthly Earth2Class (E2C) science workshops for classroom teachers, organized by Adjunct Associate Research Scientist Michael Passow, reached a milestone during the 2009 to 2010 period by marking its 100th session. The program began in 1998, when Interim Director John Mutter gave Passow the go-ahead to host a Saturday seminar tailored for high school teachers and taught by research scientists active in the field. At the centennial meeting, Mutter presented a workshop on the role science plays in sustainable development. Today, the program's reach extends far beyond the roughly 20 local teachers who wake up early on a Saturday during the school year to drive to the Observatory; the E2C website (www.earth2class.org), which archives past presentations, averages more than 300,000 hits per month from teachers and students around the world.

A Day in the Life of the Hudson River

Formerly known as Hudson River Snapshot Day, this decade-long program educates participants on the environmental uniqueness of Lamont-Doherty's "backyard" as part of annual National Estuaries Week. The Observatory's central role in the estuary-wide celebration is led by Margie Turrin, who, along with her partners, helps organize research activities up and down the Hudson to create an environmental picture of the river from the Troy Dam to New York Harbor.

The event has grown nearly tenfold since its start, and now includes more than 3,000 students working at 62 different sites. Participants at each of these locations gather data, eventually sharing their results to gain a better understanding of the Hudson's dynamic ecosystem.

IcePod

Turrin and others have begun a four-year effort to improve science, technology, engineering and math (STEM) education in local schools as part of IcePod, an NSF-funded program led by Lamont-Doherty marine geophysicist Robin Bell to develop an integrated ice-imaging system to be deployed on polar research planes flown by the New York Air National Guard.

The education component of Bell's project is multifold: It will feature presentations by members of the National Guard about science-based careers, work with middle and high school teachers to integrate collected data into their classroom curricula, design hands-on activities and models to illustrate scientific concepts, and host a series of informational fairs in schools and within the wider community on the topic of climate science.

Secondary School Field Research Program (SSFRP)

In the summer of 2010, SSFRP—a six-week full-time summer internship program—celebrated its fifth field season. In that time, program director and Lamont-Doherty geochemist Robert Newton has enabled 65 low-income students and 12 teachers from eight high schools to take part in field-based scientific research. Students and teachers work alongside Observatory scientists, joining them on field expeditions or in the lab for data analysis.

The program results show promise: Twenty-seven of the student participants have gone on to college. Approximately half of these have declared science or engineering majors, and at least eight are majoring in marine or environmental science. SSFRP has also played an important role in leveraging three National Science Foundation grants to the Earth Institute totaling over $4.5 million.

Summer intern Hannah Perls explains her project to geochemist Jerry McManus.
Credit: Ronnie Anderson

Summer Interns

Every summer, college and university campuses around the country empty. A few students linger to take summer classes or to make extra money. At Lamont-Doherty, however, things only begin to heat up with the arrival each June of a new class of summer interns. Their presence signals the start of 10 weeks of hard work, tough questions and infectious energy.

"Every year I'm stunned," said geochemist Sidney Hemming, who in 2010 had three interns in her lab and who, over the years, has mentored nearly two-dozen summer students. "They come in knowing relatively little about what we do and by the end they're giving a polished report on the subject."

While the program began in the 1970s, the blueprint for its current incarnation was developed in the late 1980s, when Adjunct Research Scientist Dallas Abbott took the helm. Since then, the program has evolved steadily. Students are paired with a scientist mentor at the Observatory, and together they tackle topics such as the ice-age mega-floods of the Pacific Northwest or biogas emissions in New York's Hudson River.

The presence of undergraduates has become part of the summer rhythm on campus and an integral part of the research conducted both in the field and back in the labs.

The biggest challenge for these college students, Abbott explained, is not the transition from undergraduate coursework to graduate-level research, but rather the realization that they are no longer the smartest person in the room. "They're used to being the top student in class and knowing the answer to every question," said Abbott. "In actuality, no one may know the answer. Research is like that."

The program is funded, in part, by the National Science Foundation and draws on applicants from a range of sciences and with many different career plans in mind. Hannah Perls, a Columbia College senior majoring in Earth and Environmental Science, initially considered environmental science to be "for people who couldn't do calculus." She changed her mind during a class taught by Lamont-Doherty researcher Peter deMenocal. He was explaining how Earth's rotation affects the movement of water in the ocean. "About 10 minutes before he reached the point about the formation of the Gulf Stream, I got it," she recalled. "I went home and thought, 'My God, I understand how the world works!'"

This insight convinced Perls to enroll in the 2010 summer intern program, where she teamed up with Vetlesen Professor Mark Cane to study the role large-scale ocean circulation patterns play on temperature and precipitation in the Himalayas. Today, Perls is hoping for a job with the Environmental Protection Agency after she graduates.

Not every summer intern alum ends up in a science-related career, a fact that does not bother Abbott. In fact, she explained, one of the overarching goals of the program is to educate the general populace about the way science functions. If that means training a future doctor or entrepreneur how to conduct original research for a summer, then so much the better.

Aaron Lebovitz, Columbia College '92, came through the program after his junior year. "That summer made all the difference to my undergraduate experience," said Lebovitz. "The exposure to research helped me envision other contexts in which I could employ my talents." The mentoring relationship he developed with seismology professor Mark Anders continued until his graduation, adding dimension to his mathematics major that is still applicable to his work today as a partner in a Chicago trading firm.

EVENTS AND AWARDS

The 2008 Vetlesen Award ceremony
Credit: David Wentworth

2008 AWARDS

Uribe Guillermo, John Mutter, David Walker
CU's 25-Year Club

Maya Tolstoy
Women of Discovery Sea Award
Wings World Quest

Won-Young Kim
Jesuit Seismological Association Award
Seismological Society of America

Wally Broecker
Benjamin Franklin Medal in Earth and Environmental Science
Franklin Institute

Balzan Prize
International Balzan Foundation

Frontiers of Knowledge Award in Climate Change
Spain's Banco Bilbao Vizcaya Argentaria Foundation

Honorary Doctorate
Southern Methodist University

Mark Cane
Norbert Gerbier–MUMM International Award
The World Meteorological Organization

Robin Bell, Richard Seager
Named Palisades Geophysical Institute Senior Scientists

Cathy Troutman
Lamont Service Award

Veronica Lance, Robert Anderson, Andy Juhl
Advisory Board Innovation Fund Inaugural Grant

Brent Goehring
Goodfriend Prize

Kat Allen
Sara Fitzgerald Langer Book Prize

Natalie Boelman
Storke-Doherty Lectureship

Nicholas Christie-Blick
Best Teacher Award

David McGee
Best Teaching Assistant

2008 EVENTS

LDEO/DEES Retirement Party: Dennis Hayes, James Hays, Paul Richards, David Rind, William Ryan, Harry J. Simpson, Lynn Sykes
September 12

Lamont-Doherty Open House
October 4

Vetlesen Award Ceremony
The 2008 Vetlesen Prize was awarded to Walter Alvarez, University of California, Berkeley.
November 21

[left] Marine geophysicist Robin Bell

2009 AWARDS

Nicholas Christie-Blick, Mark Cane, Matthew Tucke
CU's 25-Year Club

Taro Takahashi
Dedication in the April issue of
Deep Sea Research II

Karen Wovkulich, Jenny Abruszewski, Janelle Homburg
Outstanding Student Paper Award
AGU

Wally Broecker
Honorary Doctorate
Cambridge University

Kim Kastens
Excellence in Geophysical Education Award
AGU

W. Roger Buck, Steven Goldstein
AGU Fellows

Peter deMenocal, Dale Chayes
Honorary Degree
St. Lawrence University

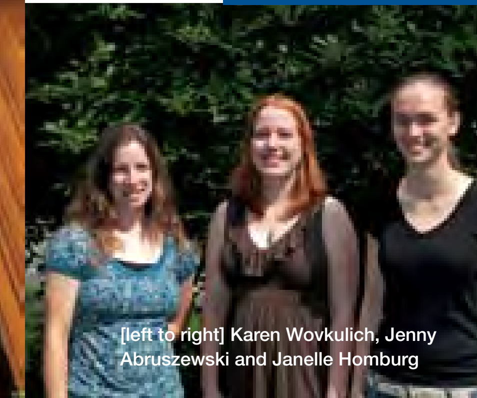
Gary C. Comer Geochemistry Building
2009 Lab of the Year prize
R&D magazine and the Scientific Equipment and Furniture Association

Sustainable Design Award
U.S. Environmental Protection Agency and the Boston Society of Architects

Alexey Kaplan
Excellence in Mentoring Award

Bonnie Deutsch
Lamont Service Award

Adam Sobel
The Clarence Leroy Meisinger Award
American Meteorological Society



[left to right] Karen Wovkulich, Jenny Abruszewski and Janelle Homburg

Geochemist Taro Takahashi

[left to right] Steven Goldstein, William Ryan, Lynn Sykes, James Hays, Dennis Hayes, Paul Richards, David Rind, Harry J. Simpson and G. Michael Purdy at the DEES retirement celebration.

A young science enthusiast at the 2008 Open House

2009 EVENTS

SPRING PUBLIC LECTURES

- Michael Studinger, "Extreme Science: An Antarctic Expedition in Search of Lost Mountains"
  March 15
- Dorothy Peteet, "New York's Piermont Marsh: A 7,000-year Archive of Climate Change, Human Impact and Uncovered Mysteries"
  March 29
- Nicholas Christie-Blick and Byrdie Renik, "Continental Stretching"
  April 19
- Brendan Buckley, "The Tree–Ring Project: Seven Centuries of Megadroughts in Southeast Asia and Their Impact on Regional Civilizations"
  April 26

Arthur D. Storke Memorial Lecture, Stephen Kestler, University of Michigan, "Estimating Earth's Remaining Mineral Resources"
May 1

Jardetzky Lecture, Penny Chisholm, MIT, "Too Small to See, Too Big to Ignore: What Prochlorococcus Has Taught Me About Life and the Ocean"
October 2

A Celebration Marking William Ryan's Contributions to Science and Research
October 23

Alumni Colloquium, Michael Bender, "Links between CO$_2$ and Climate throughout Earth's History"
November 20

2010 AWARDS

Danielle Sumy, Kaori Tsukui
Outstanding Student Paper Award
AGU

Adam Sobel
Excellence in Mentoring Award

Nick Shackleton
UK Postal Stamp

David Goldberg, L. Diane Hicks, Paul Olsen, Ray Sambrotto, Steward Sutherland
CU's 25-Year Club

Taro Takahashi
Champions of the Earth Award
UN Environmental Programme

2010 EVENTS

SPRING PUBLIC LECTURES

- Göran Ekström,"Detecting and Measuring Landslides with Seismology"
  March 28
- Jerry McManus, "Currents, Conveyors and Climate Change"
  April 11

Arizona State University President, Michael Crow

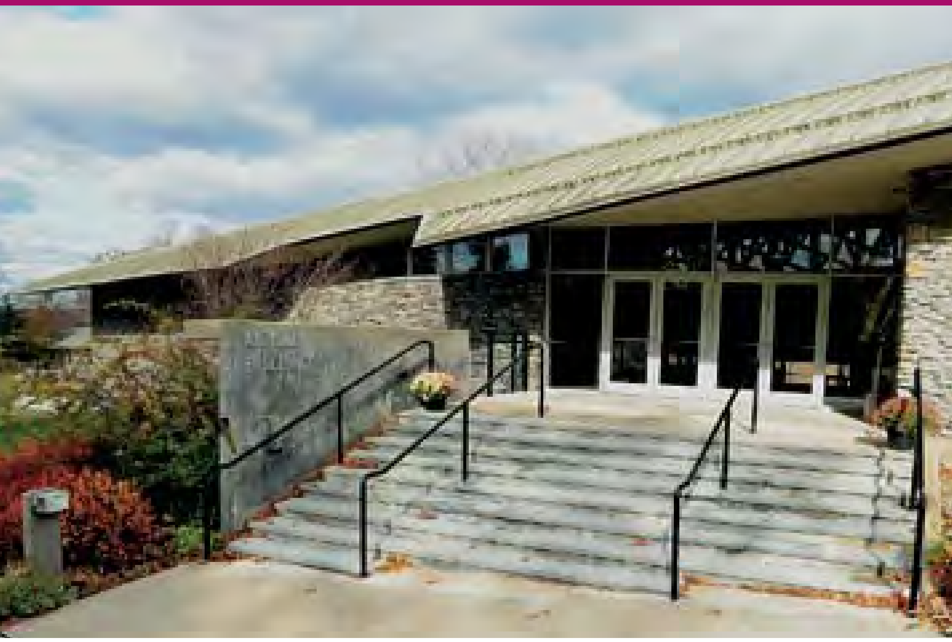
- Gisela Winckler, "Dust in the Wind: Dust, Stardust and Earth's Climate System"
  April 18
- Paul Heisig, U.S. Geological Survey, "Rockland County's Water Resources," followed by a panel discussion with Stuart Braman, Steve Chillrud, Brad Lyon and Martin Stute
  April 25

A Celebration Marking Wally Broecker's 50th Anniversary as a Professor in the Department of Earth and Environmental Sciences
April 16

Arthur D. Storke Memorial Lecture, Randy Udall, "The Carbon Shuffle and the Energy Challenge"
May 7

Director G. Michael Purdy 10th Anniversary Celebration
June 4

ACADEMIC AFFAIRS AND DIVERSITY



Kuheli Dutt
Assistant Director for Academic Affairs and Diversity

Despite concerted efforts to diversify the physical sciences, women and minorities remain underrepresented in academic and research institutions. Research shows mounting evidence of "leaks in the pipeline" as women leave academic and research institutions before attaining senior positions.

To tackle these problems, Lamont-Doherty established the Office of Academic Affairs and Diversity two years ago as a mechanism to institutionalize the Columbia University National Science Foundation–ADVANCE program, headed by Lamont-Doherty senior scientist Robin Bell. This program aims to increase diversity in the physical sciences through institutional transformation, with a focus on recruitment, retention and advancement of women and minorities.

From this early starting point, our mission has ballooned. The office is now fully integrated into key policy and decision-making areas such as appointments, promotions, salary structures, racial and gender diversity, and advancement of junior scientists. We aim to identify specific problems facing Lamont-Doherty and to devise individual strategies for change.

Any effort aimed at transforming an institution is only as successful as the institutional structure allows it to be. Closely related to the issue of diversity is the power structure within the institution, i.e., how academic affairs are governed and how decisions that affect the institution's community are made. Effecting changes in diversity necessitates effecting changes in power structures, and for maximum effectiveness the two must be tackled together.

A first step was to change key aspects of our search procedures for scientific appointments. This office became closely involved in all searches, from initiation to completion, providing input and guidance at each step. The results were dramatic, almost doubling the average diversity in the applicant pool, although the true test will be whether these increased applications translate into a diverse workforce. Current results show promise—four out of the seven most recent hires are either women or racial minorities.

Another focus has been the career advancement of postdoctoral researchers, currently the most diverse group at Lamont-Doherty with almost 50 percent women and 31 percent racial minorities. The creation of the Lamont research professor title, with improved benefits for junior scientists, will most likely increase our retention of postdoctoral researchers. Most recently, an institution-wide postdoctoral mentoring plan was implemented, which signals that the institution is placing increased importance on supporting scientists in their early careers.

Two new additional initiatives were introduced with junior scientists in mind. The Women Scientists Networking Event, where junior Lamont-Doherty women meet with senior women from both Lamont-Doherty and other institutions to gain insights on career advancement in male-dominated fields, was held in April 2010. This is expected to become an annual event. The other initiative, the Postdoctoral Lunch with the Director, allows postdocs to meet with Michael Purdy over an informal lunch and voice their concerns directly, will also be a recurring event. We continue to offer the prestigious Marie Tharp Fellowship that promotes the careers of female scientists.

Promoting openness and transparency, a document clarifying the Lamont-Doherty bylaws was disseminated to all staff, as was information comparing male and female salaries at every rank. Currently we are drafting new bylaws for the institution, with a goal to keeping them concise and transparent.

The fact that the scope and responsibilities of this office have grown so much within two years is a testament to our commitment to ensure a diversified workforce and, in the process, improve the quality of the work environment for all. We could not have achieved this much without the strong support of the Lamont-Doherty community.

DEVELOPMENT

Challenges and Opportunities

The two-year period from July 2008 to June 2010 was marked by tough challenges and inspiring opportunities. Over the first six-month period, we bade farewell to our two senior colleagues, Sarah Huard and Doug Brusa, and welcomed a new director for development, Barbara Charbonnet, and communications manager, Dove Pedlosky. While the economy showed signs of stress, we had fresh perspectives and renewed energy to meet that challenge and focus on a strategic fundraising plan.

At the forefront of the plan was our participation in the current Columbia Campaign to which Lamont-Doherty has made a significant contribution by raising the funds for the construction of the Gary C. Comer Geochemistry Building, the University's first new science building in several decades.

The Comer building opened on Lamont's campus in early 2008. Since then, the building has earned the prestigious Leadership in Energy and Environmental Design (LEED) certification, becoming Columbia University's first LEED certified project. In 2009, the building was named "Lab of the Year" by *Research and Development* magazine; it also won a Sustainable Design and Excellence in Architecture award from the Environmental Protection Agency and the American Institute of Architects.

But the Comer building is not yet complete! In early 2010, the National Institute of Standards and Technology (NIST) awarded the Observatory a $1.4 million matching grant to help support the construction of an ultra clean laboratory. This final Comer lab will be capable of providing the pristine conditions and advanced technology needed to conduct the complex chemical analyses necessary to understand Earth's past and to forecast future trends. We are very grateful to both an anonymous donor who pledged $400,000 and to the Botwinick-Wolfensohn Foundation, which pledged $200,000 toward the NIST challenge. Several dozens of alumni and friends also have made contributions ranging from $25 to $25,000. Thanks to their generosity, we are halfway to meeting the NIST challenge and to reaching our goal of building academia's largest and most sophisticated ultra clean lab for geochemistry.

[left to right] Jeffrey S. Sachs, Lee C. Bollinger, Walter Alvarez, Milly Alvarez, George Rowe and G. Michael Purdy

The development office recorded more than $5 million in new gifts, pledges and pledge payments from private donors during this two-year period. We are deeply grateful for the ongoing support of the G. Unger Vetlesen Foundation, whose gifts to support our core research activities have sustained our institution for more than four decades. Such leadership in funding earth science research is rare and cannot be acknowledged enough in this period of diminished income.

[left to right] Ronnie Anderson, Barbara Charbonnet, Stacey Vasallo, Dove Pedlosky

As further testimony to the Vetlesen Foundation's leadership, in November 2008, Lamont-Doherty was honored to host the presentation of the Vetlesen Prize—for the 16th time since the inception of the award in 1960—to University of California, Berkeley professor (and former Lamont Research Associate) Walter Alvarez. In the elegant setting of the Low Library rotunda on Columbia's Morningside campus, Alvarez graciously accepted the Vetlesen Prize, the most distinguished honor given in the field of earth science, with an eloquent narrative tracing his path to discovery of the massive meteor event that caused the extinction of the dinosaurs, some 65 million years ago.

> While the economy showed signs of stress, we had fresh perspectives and renewed energy to meet that challenge and focus on a strategic fundraising plan.

Two other important events took place in the spring of 2010. The first celebrated Wally Broecker's 50 years as a professor in Columbia's Department of Earth and Environmental Sciences (DEES)—and the even greater number of years he has been a member of the Lamont-Doherty research staff. Co-hosted by the development office and DEES, this event included tributes from former students, now eminent researchers in their own right, George Denton of the University of Maine and Michael Bender of Princeton University. Joining us as emcee was Earth Institute founder Michael Crow, now President of Arizona State University.

[bottom row, left to right] Gerry Lenfest, Joy Tartar and Frank Gumper.

Former Vice President Al Gore submitted a personal video tribute to congratulate Broecker, and Jeff Sachs, director of the Earth Institute, and Columbia president Lee Bollinger both lauded Broecker for his achievements. Two surprise guests were noted singer/songwriter Tom Chapin and Richard Alley of Pennsylvania State University. They recounted Broecker's achievements through original song (Chapin) and a witty rewrite of "Sixteen Tons" (Alley).

We were honored to have Columbia trustee Gerry Lenfest join us at the event. Lenfest has pledged a $250,000 challenge grant to name Wally's office, in perpetuity, Wally's Room. Upon his retirement, Broecker's office will be converted to a study lounge and meeting area, featuring memorabilia depicting Wally the man, Wally the mentor. At the close of the 2010 fiscal year, we received an anonymous gift to match $50,000 of Lenfest's generous challenge, and we hope to complete the challenge by the time of the next report.

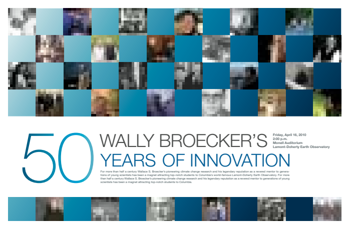
A second event, organized by members of the Observatory's senior research staff, was a surprise celebration in June 2010 to mark Mike Purdy's 10th anniversary as director and to acknowledge his many achievements over that period. These include most notably the launch of the R/V *Marcus G. Langseth*; the construction of the Gary C. Comer Geochemistry Building; and the creation of the Lamont Research Professor title, which brings greater recognition to the Observatory's scientists.

The occasion was marked by humor and heartfelt tribute. Sixty-seven gifts and pledges, totaling $200,000, were given by faculty, staff and friends of the Observatory to establish a future endowment fund to name a G. Michael Purdy Lamont Research Professorship upon the director's retirement.

As noted earlier in this report, educational initiatives continue to be one of the Observatory's highest priorities. The Henry L. and Grace Doherty Foundation completed its three-year $750,000 challenge grant for the establishment of a $1.5 million endowment to create a new position at the Observatory, the director of the Program in Earth and Environmental Science Education. To date, we have matched $120,000, thanks to the generous gifts of Frank and Joanne Gumper. We are extremely grateful to President Walter Brown and the trustees of the Doherty Foundation for their recognition of the economic challenges that have slowed progress on fulfilling this challenge.

While we actively seek to complete the Doherty Foundation challenge, we acknowledge Aaron Lebovitz and Donna Myers, whose generous gifts have supported the Observatory's long-standing summer internship program for undergraduates (page 37), and Frank Gumper, who gives generously of both his time and resources to expand our important educational initiatives.

Other notable gifts during the past two years have included the completion of a bequest from famed pioneer of modern marine geophysics, Marie Tharp, who died in August 2006. Tharp was one of the first members of our Torrey Cliff Society when she included Lamont-Doherty in her estate plans. Her generous final gift of $371,000 will help support in perpetuity a senior scientist at the Observatory. From across the sea, our friend John Maguire sent a gift of $101,000 to be used at the director's discretion to support research at Lamont-Doherty. Such funds have been critical over the last two years to bridge the gap left by the University's reduced endowment holdings.



We express our gratitude to several individuals and family foundations whose support made specialized research projects possible over the past two years: The Brinson Foundation, which supports a postdoctoral research fellow in seismology and provides resources for graduate students in our Earth Microbiology Initiative; the Schlumberger Doll Research Center for support of the work of Tim Kenna in the Geochemistry Division; and Google Inc. for their support of marine geophysicist Suzanne Carbotte's synthesis of global seafloor bathymetry.

Professor and geochemist Taro Takahashi received the prestigious UN Environmental Programme's 2010 "Champion of the Earth" award for his research on the oceans' uptake of carbon dioxide. He graciously donated his prize money to support the Observatory's earthquake-related work in Haiti.

We are grateful to Robert Kaplan for his continued support of Lamont-Doherty's research in carbon sequestration and to alumnus John Hall, whose gift allowed us to purchase equipment for Arctic research being conducted by Lamont Research Engineer Dale Chayes.

In addition to their success securing institutional grants from federal sources, several investigators were also able to raise significant private funding for their research, including generous grants from the Comer Science and Education Foundation and from the American Chemical Society.

Advisory Board

[left to right] Dennis Adler, Adam Wolfensohn, George Becker Jr., Walter Brown, Kathleen Semergieff, Frank Gumper (Vice-Chair), G. Michael Purdy, Quentin J. Kennedy (Chair), Barbara Engel, Florentin Maurrasse, Jeffrey Gould and Lawrence Lynn. Not pictured, William F. Baker, Edward Botwinick, Michael Cembalest, Daniel Lehrfeld and Barnabus McHenry.

Under the continued leadership of Advisory Board chairman Quentin Kennedy, several new members joined the Board over the last two years. In the fall of 2008, we welcomed Columbia University Trustee Emeritus and Lamont-Doherty alumnus Ed Botwinick. Over the course of the following year, he was joined by Columbia alumnus and investment adviser Michael Cembalest; Columbia alumnus and electronics engineer Dan Lehrfeld; Alpine, N.J., school superintendent Kathleen Semergieff; climate and energy entrepreneur Adam Wolfensohn; and, most recently, retired neurosurgeon and professor at Columbia's Neurological Institute George Becker, Jr.

The Board devotes its time, talent and philanthropic efforts assisting the director and his leadership team to advance the best interests of the Observatory. Members provide meaningful advice, bringing to bear their diverse areas of expertise—scientific research, academia, environmental activism, finance, fundraising, public relations—and serve as Lamont-Doherty's ambassadors in the greater community.

Highlights of their activities from 2008–2010 include a reception at the Knickerbocker Country Club in Tenafly, N.J., arranged by Quentin Kennedy, where professor Wally Broecker spoke about climate change to more than 50 club members and friends. The following spring, new Advisory Board member Kathleen Semergieff introduced the director and senior staff to members of the Alpine Educational Foundation. In October 2009, Michael Cembalest gathered more than 60 J.P. Morgan clients for a conversation about global warming and carbon sequestration with DEES professors Peter Kelemen and Peter deMenocal. In addition, Cembalest has twice featured Observatory researchers in his *Eye on the Market* newsletter, sent quarterly to thousands of the company's clients. Inspired by the success of the J.P. Morgan event, Vice Chair Frank Gumper arranged for a similar forum at Bernstein Global in April 2010.

These events have brought the Observatory to the attention of new audiences, and we look forward to further such introductions in the coming years.

Over the last two years, Frank Gumper has served as special adviser to the director for educational initiatives. In this capacity, Gumper has worked closely with the development office and with members of the Observatory's research staff to secure the resources for these important efforts. He has initiated collaborations with Liberty Science Center, the American Museum of Natural History, and the Alpine, N.J., school district where, in conjunction with Semergieff, he has arranged for a new Lamont Atmospheric Carbon Project monitoring station to be housed at the Alpine middle school.

Finally, as announced two years ago, members established, and have continued to finance, the Advisory Board Innovation Fund to make seed money available for the early stages of cutting-edge research projects not yet suited for more traditional sources of funding. Postdoctoral research fellow Veronica Lance won the inaugural award in 2008. Her study on the effects of elevated carbon dioxide levels on ocean ecosystems was published in EOS in July 2009, a good step toward securing future funding. A second award was made in the spring of 2010 to postdoctoral fellow and geophysicist Einat Lev to support the development of a video imaging technique to analyze the flow rate of volcanic lava.

Advisory Board members continue to give generously to Lamont-Doherty with 100 percent participation in the last fiscal year. Over fiscal years 2009 and 2010, Advisory Board members gave, pledged or secured gifts to the Observatory exceeding $1.15 million.

Special thanks to Carolyn Hansard, Neil Opdyke, Samuel Philander, Frank Press, Ian Strecker, Leon Thomsen and Seymour Topping for their service to the Advisory Board during its formative years from 2005 to 2008.

[left to right] Emma (Christa) Farmer, Michael Rawson, Rudi Markl, Joyce O'Dowd Wallace, Mary Ann Brueckner and Robert Kay. Not pictured, Louisa Bradtmiller, Steven Cande (Chair), Millard (Mike) Coffin, Stephen Eittreim, W. Arnold Finck, P. Jeffrey Fox, Arthur McGarr and Gregory Mountain

Alumni Association

Lamont-Doherty draws strength from the long history of spirited "Lamonters" who have either worked or studied at the Observatory. The Alumni Association was established in 1999 to facilitate a meaningful connection for these individuals—with each other as well as with the Observatory—and the Alumni Association Board assists efforts to encourage participation in Observatory activities at many levels.

Board membership reflects the research divisions at the Observatory and includes scientist emeriti, support staff, visiting professors and former graduate students. Because members are dispersed across the country, annual meetings take place on both coasts. The Board congregates three times a year: at the Open House in the fall, at the December American Geophysical Union conference in San Francisco, and at the alumni-sponsored Spring Public Lecture. With an eye to expanding its reach and numbers, current members have increased efforts to encourage Lamont-Doherty's recent graduates to join the Board.

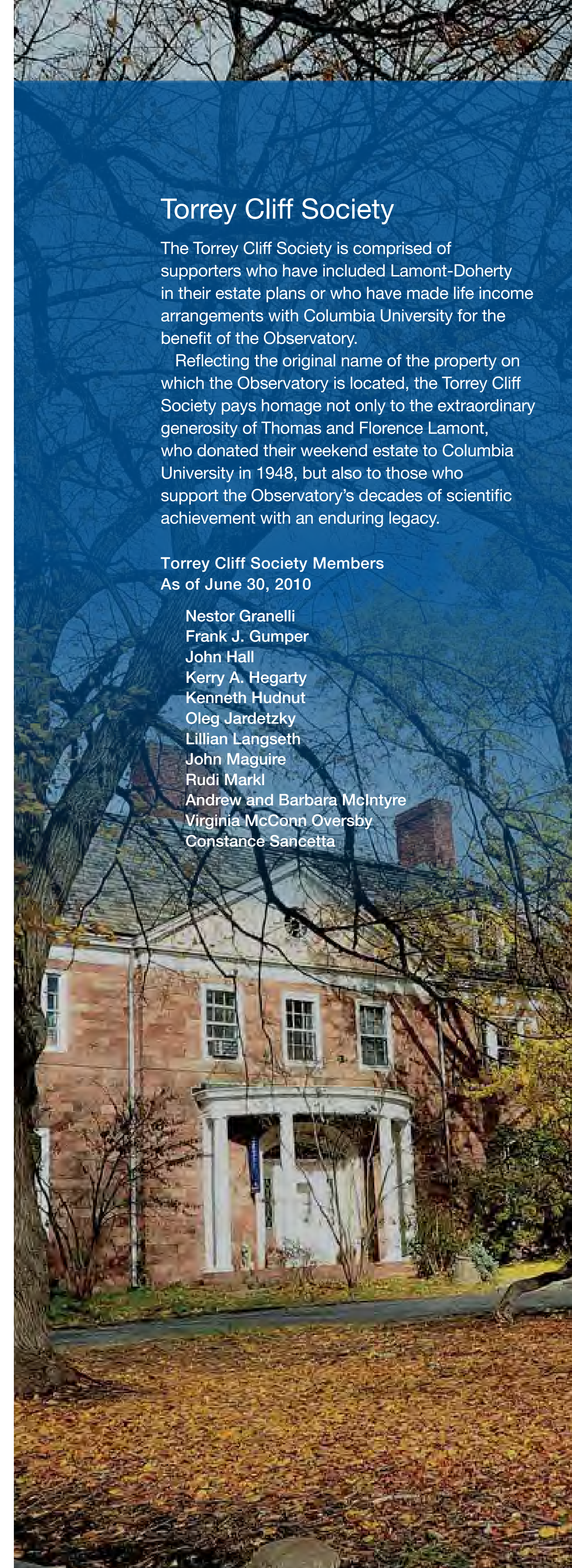
Under the direction of Alumni Association President, Steven Cande, the Board has strengthened its communication with alumni over the past two years by leveraging the power of electronic media and social networking. Alumni can now subscribe to a biannual electronic newsletter consisting of research and event highlights at the Observatory, in addition to receiving the printed *Alumni & Friends* publication. Alumni can also join the Lamont-Doherty Facebook page to stay abreast of current news and the Lamont-Doherty LinkedIn group to network professionally with other alumni. The Association has begun to send e-mails announcing lectures or events that might appeal to Lamont-Doherty's large alumni population. As part of this effort, the development office has been working with Columbia's Department of Earth and Environmental Sciences to collect updated and missing contact information for past graduate students.

The development office seeks to assist the Board in its efforts and, during this reporting period, has collaborated with staff at the University's alumni offices to learn best practices and to adapt University templates for our smaller-scale initiatives. In one example of this strengthened relationship, Lamont-Doherty liaised with Columbia University alumni officers, helping to organize an event for the Sarasota and Tampa chapters of the Columbia Alumni Association that featured a lecture on the earthquakes in Haiti and Chile by Lamont-Doherty's associate director for seismology, geology and tectonophysics, Arthur Lerner-Lam. This was followed by a trip to Miami where Alumni Board member Michael Rawson and his wife Martine (also a Lamont alumna) hosted more than a dozen Lamont alumni and friends for a sunset cocktail reception.

Several Alumni Board members have headed projects to restore or sustain cherished aspects of the Observatory. In September 2008 the Lamont-Doherty Historic Preservation campaign was officially launched when oceanographer Denny Hayes and alumni board member Arnold Finck sent fundraising appeals to alumni who might share an interest in preserving Lamont-Doherty's history. A small part of the $10,000 raised from this mailing was used to construct a display case populated with items relating to Marcus Langseth's lunar heat flow experiment. The goal is to raise enough funds to create exhibits highlighting more of the Observatory's early groundbreaking contributions to the field.

In another volunteer project, board member Mary Ann Brueckner has worked tirelessly to restore the campus' rose garden to its original splendor. This garden, along with the rest of the property, was designed in 1930 by the Olmsted Brothers Company—descendants of the great landscape architect Frederick Law Olmsted.

If you would like information on ways to engage in the Alumni Association's activities, please send an e-mail to alumni@LDEO.columbia.edu. You can subscribe to both our print and electronic newsletter on Lamont-Doherty's home page (LDEO.columbia.edu). Most importantly, the Alumni Association wants to hear from you! Please email us with your contact information and any news you'd like to share.



Torrey Cliff Society

The Torrey Cliff Society is comprised of supporters who have included Lamont-Doherty in their estate plans or who have made life income arrangements with Columbia University for the benefit of the Observatory.

Reflecting the original name of the property on which the Observatory is located, the Torrey Cliff Society pays homage not only to the extraordinary generosity of Thomas and Florence Lamont, who donated their weekend estate to Columbia University in 1948, but also to those who support the Observatory's decades of scientific achievement with an enduring legacy.

Torrey Cliff Society Members
As of June 30, 2010

Nestor Granelli
Frank J. Gumper
John Hall
Kerry A. Hegarty
Kenneth Hudnut
Oleg Jardetzky
Lillian Langseth
John Maguire
Rudi Markl
Andrew and Barbara McIntyre
Virginia McConn Oversby
Constance Sancetta

THANK YOU

We are ever grateful to the many friends who recognize the value of sustaining this vibrant research institution with their financial contributions. Your gifts ensure our endeavors in research and education and enable us to provide accurate, unbiased information that guides and informs both local and global communities.

July 1, 2008 through June 30, 2010

$500K +
The G. Unger Vetlesen Foundation
Anonymous

$100K +
American Chemical Society
Botwinick-Wolfensohn Foundation, Inc.
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ADMINISTRATION

[left to right] Patrick O'Reilly, Victoria Nazario, Wanda Diaz Maribel Respo, Howard Matza, Karen Hoffer, Richard Greco, Edie Miller and Thomas Eberhard. Not pictured, Virginia Maher

The primary responsibility of the Lamont-Doherty Earth Observatory's administration is to ensure compliance with the terms and conditions of our sponsored projects while facilitating the day-to-day work of the research scientists. To achieve this goal, Lamont-Doherty has created a multitiered administrative management structure that provides the checks and balances necessary to ensure appropriate stewardship of sponsored projects, endowments, gifts and other institutional funding. Although formally an extension of Columbia University's central operations, the Observatory's administration offers direct, on-site services to the research community on the Lamont campus.

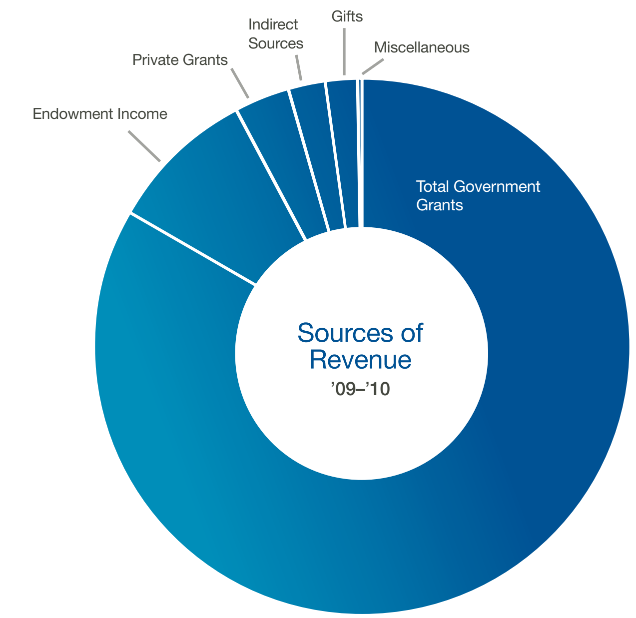
Lamont-Doherty's central administrative departments are responsible for a core set of activities including grants and contracts management, finance and accounting, purchasing, human resources, facilities management and engineering, shipping and receiving, and campus safety and security. Administrators also manage a range of ancillary services including food services and campus housing operations.

In addition to these central departments and activities, each of the five research divisions and Earth Institute programs located on the Lamont campus has an administrator and an administrative assistant who provide day-to-day support to scientists. Because of the complexity of our programs and the strength of our staff, the Lamont-Doherty Administration is routinely used by Columbia as a test site for new programs and initiatives. We are proud to provide quality services to Lamont-Doherty's scientific community and to be regarded as administrative leaders within the University.

Credit: Geoff Welch

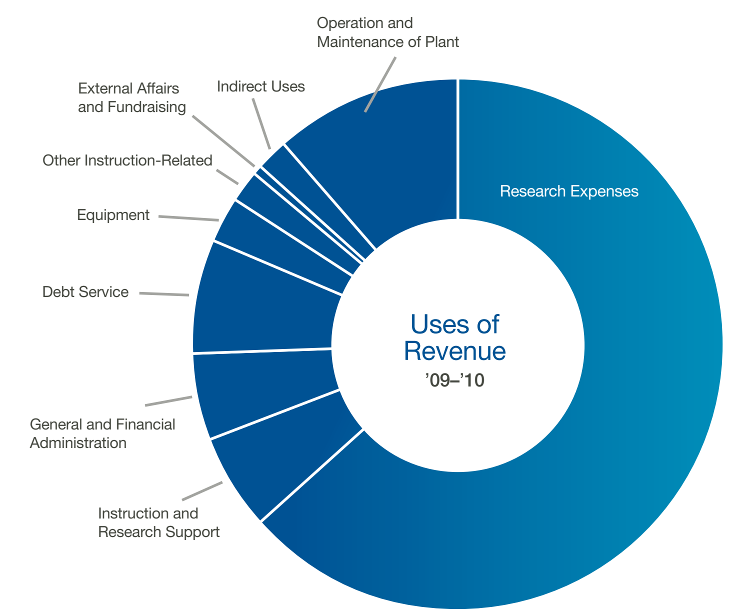
Statement of Activities (In 1,000s)

SOURCES OF REVENUE	'08–'09	'09–'10
National Science Foundation	30,368	31,642
National Oceanic and Atmospheric Administration	7,173	6,734
National Aeronautics and Space Administration	2,490	3,374
National Institute of Environmental Health and Safety	2,368	2,175
U.S. Geological Survey	763	662
Office of Naval Research	687	634
USDA	115	78
Department of the Air Force	127	122
New York State	103	174
Department of Energy	25	104
Government Funds via Subcontracts with Other Institutions	7,898	9,641
Miscellaneous Federal Funds	207	172
Total Government Grants	52,324	55,512
Private Grants	2,773	2,240
Gifts	1,274	1,255
Endowment Income	6,398	5,926
Miscellaneous	102	53
Indirect Sources	2,244	1,532
Total Sources	65,115	66,519



USES OF REVENUE	'08–'09	'09–'10
Research Expenses	44,383	40,891
Instruction and Research Support	4,213	3,743
General and Financial Administration	3,671	3,412
Operation and Maintenance of Plant	5,004	4,485
Equipment	2,779	1,805
Other Instruction-Related	(5,109)	1,224
External Affairs and Fundraising	948	522
Debt Service	1,095	1,095
Indirect Uses	7,300	7,336
Total Uses of Revenue	64,284	64,513

Net Operating Gain/(Loss)	831	2,007
Capital Expenses	(77)	221
Transfers From Endowment	(73)	104
Subtotal Nonoperating Expenses	(150)	325
Beginning Fund Balance	10,063	11,050
Ending Fund Balance	11,044	12,732



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[left to right] Beverly Wuerfel and Miriam Cinquegrana

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Duecker, M. Elias	Graduate Research Assistant
Jones, Miriam	Graduate Research Assistant
Levy, Jennifer	Graduate Research Assistant
Marlier, Miriam	Graduate Research Assistant
Sritrairat, Sanpisa	Graduate Research Assistant

SPECIAL RESEARCH SCIENTIST

Hays, James	Special Research Scientist
Hunkins, Kenneth	Special Research Scientist
Jacoby, Gordon	Special Research Scientist
Kukla, George	Special Research Scientist
Marra, John Frank	Special Research Scientist

LDEO ADJUNCTS

Anderson, O Roger	Adjunct Senior Research Scientist
Atkin, Owen	Adjunct Associate Research Scientist
Baguinon, Nestor	Adjunct Research Scientist
Baker, Patrick	Adjunct Associate Research Scientist
Boelman, Natalie	Adjunct Associate Research Scientist
Cherubini, Paolo	Adjunct Research Scientist
Cook, Benjamin	Adjunct Associate Research Scientist
D'Andrea, William	Adjunct Associate Research Scientist
Farmer, Emma	Adjunct Associate Research Scientist
Goes, Joaquim	Adjunct Senior Research Scientist
Hendy, Erica	Adjunct Associate Research Scientist
Heusser, Linda	Adjunct Research Scientist
Hoshina, Sadayori	Adjunct Research Scientist
Kent, Dennis	Adjunct Senior Research Scientist
Kjelgren, Roger	Adjunct Senior Research Scientist
Koutavas, Athanasios	Adjunct Associate Research Scientist
Kyaw, Nyi Nyi	Adjunct Associate Research Scientist
Lance, Veronica	Adjunct Associate Research Scientist
Langdon, Christopher	Adjunct Research Scientist
Laroque, Colin	Adjunct Research Scientist
Letourneau, Peter	Adjunct Associate Research Scientist
Liepert, Beate Gertrud	Adjunct Research Scientist
Linsley, Braddock	Adjunct Research Scientist
Livina, Valerie	Adjunct Associate Research Scientist
Lynch-Stieglitz, Jean	Adjunct Research Scientist
McCave, Ian	Adjunct Senior Research Scientist
Nachin, Baatarbileg	Adjunct Associate Research Scientist
O'Driscoll, Kevin	Adjunct Research Scientist
O'Mullan, Gregory	Adjunct Associate Research Scientist
Peteet, Dorothy	Adjunct Senior Research Scientist
Pross, Joerg	Adjunct Senior Research Scientist
Rainforth, Emma	Adjunct Associate Research Scientist
Rousseau, Denis-Didier	Adjunct Research Scientist
Schuster, William S.F.	Adjunct Senior Research Scientist
Smirnov, Alexey	Adjunct Research Scientist
Solomina, Olga	Adjunct Senior Research Scientist
Tissue, David	Adjunct Associate Research Scientist
Turnbull, Matthew	Adjunct Research Scientist
Vaillancourt, Robert	Adjunct Associate Research Scientist
Wiles, Gregory Carl	Adjunct Associate Research Scientist
Wilson, Robert	Adjunct Associate Research Scientist
Wright, William	Adjunct Associate Research Scientist

STAFF OFFICERS OF RESEARCH

Djukic, Ika	Staff Associate
Fang, Keyan	Staff Associate
Lotti, Ramona	Staff Associate
Mellendorf, Maren	Staff Associate
Wang, Peng	Staff Associate
Xie, Wenjing	Staff Associate

SYSTEMS ANALYSTS / PROGRAMMERS

Ho, Cheng-Chuan	Systems Analyst/Programmer
Pistolesi, Linda	Web Specialist

SUPPORT STAFF

Abel, Kali	Senior Research Staff Assistant
Anest, Nichole	Senior Research Staff Assistant
Esmay, Peter	Research Staff Assistant
Hsueh, Diana	Senior Research Staff Assistant
Knudson, Carol	Research Staff Assistant
Krusic, Paul	Research Staff Assistant
Lepre, Christopher	Research Staff Assistant
Lozefski, George	Research Staff Assistant
Malone, Patricia	Senior Research Staff Assistant
Mayernik, Andrea	Senior Research Staff Assistant
Mckee, Kali	Laboratory Assistant
Paulino, Mercedes	Administrative Assistant
Peters, Kenneth	Senior Research Staff Assistant
Saaby, Diana M.	Short-Term Casual
Su, Xiaoyang	Laboratory Assistant
Swenson, Kris	Research Staff Assistant
Yu, Winnie	Laboratory Assistant

Geochemistry

Smethie, Jr., William Massie	Associate Director
Tozer, Catherine	Division Administrator

SENIOR SCIENTIFIC STAFF

Anderson, Robert	Senior Research Scientist
Broecker, Wallace	Newberry Professor
Chillrud, Steven	Doherty Senior Research Scientist
Class, Cornelia	Doherty Research Scientist
Goldstein, Steven	Professor
Hemming, Sidney	Associate Professor


[left to right] Sandra Tiwari, Sarah Odland, Bonnie Bonkowski and Catherine Tozer. Not pictured, Heidi Marie Schow

Hofmann, Albrecht	Visiting Professor
Kelemen, Peter	Arthur D. Storke Memorial Professor
Khatiwala, Samar	Doherty Research Scientist
Licht, Kathy	Visiting Research Scientist
Longhi, John	Doherty Sr Research Scientist
Luz, Boaz	Visiting Senior Research Scientist
McGillis, Wade	Doherty Research Scientist
McManus, Jerry	Professor
Plank, Terry	Professor
Schaefer, Joerg	Doherty Research Scientist
Simpson, Jr., Harry James	Professor
Smethie, Jr., William Massie	Doherty Senior Research Scientist
Stein, Mordechai	Visiting Research Scientist
Takahashi, Taro	Doherty Senior Scholar
Van-Geen, Alexander	Doherty Senior Research Scientist
Walker, David	Higgins Professor
Winckler, Gisela	Doherty Research Scientist

JUNIOR SCIENTIFIC STAFF

Bostick, Benjamin	Doherty Associate Research Scientist
Hoenisch, Baerbel	Assistant Professor
Kaplan, Michael	Doherty Associate Research Scientist
Kenna,Timothy	Doherty Associate Research Scientist
Matter, Juerg	Doherty Associate Research Scientist
Mey, Jacob	Associate Research Scientist
Montagna, Paolo	Visiting Associate Research Scientist
Pahnke, Katharina	Doherty Associate Research Scientist
Straub, Susanne	Doherty Associate Research Scientist
Yan, Beizhan	Doherty Associate Research Scientist

POSTDOCTORAL STAFF

Arslan, Sebnem	Postdoctoral Research Fellow
Arsouze, Thomas	Postdoctoral Research Scientist
Borghini, Giulio	Postdoctoral Research Fellow
Bouimeterhan, Ilham	Postdoctoral Research Fellow
Bradtmiller, Louisa	Postdoctoral Research Fellow
Cai, Yue	Postdoctoral Research Scientist
Chang, Su-Chin	Postdoctoral Research Scientist
Cipriani, Anna	Postdoctoral Research Scientist
Gazel Dondi, Esteban	Postdoctoral Research Fellow
Goehring, Brent	Postdoctoral Research Fellow
Kai, Fuu Ming	Postdoctoral Research Scientist
Mangili, Clara	Postdoctoral Research Fellow
Marino, Gianluca	Postdoctoral Research Scientist
McGee, William	Postdoctoral Research Fellow
Mokeddem, Zohra	Postdoctoral Research Fellow
Moyer, Ryan	Postdoctoral Research Scientist
O'Shea, Bethany	Postdoctoral Research Scientist
Pena Gonzalez, Leopoldo	Postdoctoral Research Fellow
Radloff, Kathleen	Postdoctoral Research Scientist
Raitzsch, Markus	Postdoctoral Research Scientist
Rodriguez, Sedelia	Postdoctoral Research Scientist
Ruprecht, Philipp	Postdoctoral Research Scientist
Schimmelpfennig, Irene	Postdoctoral Research Scientist
Torfstein, Adi	Postdoctoral Research Scientist
Wang, Xianfeng	Postdoctoral Research Fellow
Yang, Qiang	Postdoctoral Research Scientist
Yu, Jimin	Postdoctoral Research Fellow
Ziegler,Martin	Postdoctoral Research Fellow

GRADUATE STUDENTS

Ali, Shahla	Graduate Research Assistant
Allen, Katherine	Graduate Research Assistant
Aziz, Zahid	Graduate Research Assistant
Bendersky, Claire	Graduate Research Assistant
Buono, Antonio	Graduate Research Assistant
Crowley, Meghan	Graduate Research Assistant
Du, Wei	Graduate Research Assistant
Hale, Sarah	Graduate Research Assistant
Hartman, Alison	Graduate Research Assistant
Hayes, Christopher	Graduate Research Assistant
Henry, Gene	Graduate Research Assistant
Homburg, Janelle	Graduate Research Assistant
Jones, Kevin	Graduate Research Assistant
Jweda, Jason	Graduate Research Assistant
Lloyd, Alexander	Graduate Research Assistant
Loose, Brice	Graduate Research Assistant
Mauldin, Abigail	Graduate Research Assistant
McGee, David	Graduate Research Assistant
Mihajlov, Ivan	Graduate Research Assistant
Orton, Phillip	Graduate Research Assistant
Paukert, Amelia	Graduate Research Assistant
Pierce, Elizabeth	Graduate Research Assistant
Schmieder, Paul	Graduate Research Assistant
Simons, Kyla	Graduate Research Assistant
Streit, Elisabeth	Graduate Research Assistant
Tsukui, Kaori	Graduate Research Assistant
VanTongeren, Jill	Graduate Research Assistant
Wovkulich, Karen	Graduate Research Assistant
Yanchilina, Anastasio	Graduate Research Assistant

SPECIAL RESEARCH SCIENTIST

Biscaye, Pierre	Special Research Scientist
Bonatti, Enrico	Special Research Scientist

LDEO ADJUNCTS

Barker, Stephen	Adjunct Associate Research Scientist
Bopp, Richard	Adjunct Senior Research Scientist
Bory, Aloys Jean-Mathias	Adjunct Associate Research Scientist
Brachfeld, Stefanie	Adjunct Research Scientist
Braman, Stuart	Adjunct Associate Research Scientist
Brueckner, Hannes	Adjunct Senior Research Scientist
Burckle, Lloyd	Adjunct Senior Research Scientist
Chaky, Damon	Adjunct Associate Research Scientist
Cheng, Zhongqi	Adjunct Associate Research Scientist
Cole, Jennifer	Adjunct Associate Research Scientist
Commins, Deirdre	Adjunct Associate Research Scientist
Dasgupta, Rajdeep	Adjunct Associate Research Scientist
Denton, George	Adjunct Senior Research Scientist
Ebel, Denton	Adjunct Associate Research Scientist
Grousset, Francis	Adjunct Senior Research Scientist
Hales, Burke	Adjunct Associate Research Scientist
Harlow, George	Adjunct Senior Research Scientist
Hemming, N. Gary	Adjunct Associate Research Scientist
Henderson, Gideon Mark	Adjunct Associate Research Scientist
Ho, David	Adjunct Research Scientist
Hohmann, Roland	Adjunct Associate Research Scientist
Kadko, David	Adjunct Senior Research Scientist
Kavner, Abby	Adjunct Associate Research Scientist
Keimowitz, Alison	Adjunct Associate Research Scientist
Kelly, Meredith	Adjunct Associate Research Scientist
Langmuir, Charles	Adjunct Senior Research Scientist
Langton, Christopher	Adjunct Research Scientist
Machlus, Malka	Adjunct Associate Research Scientist
Mandeville, Charles William	Adjunct Associate Research Scientist
Marcantonio, Franco	Adjunct Research Scientist
Mathez, Edmond	Adjunct Senior Research Scientist
Matsumoto, Katsumi	Adjunct Associate Research Scientist
Rinterknecht, Vincent	Adjunct Associate Research Scientist
Robinson, Laura	Adjunct Associate Research Scientist
Rutberg, Randye	Adjunct Associate Research Scientist
Shepherd, John	Adjunct Senior Research Scientist
Siddall, Mark	Adjunct Associate Research Scientist
Stute, Martin	Adjunct Senior Research Scientist
Sweeney, Colm	Adjunct Associate Research Scientist
Tomascak, Paul	Adjunct Research Scientist
Torgersen, Thomas	Adjunct Research Scientist
Turk, Daniela	Adjunct Associate Research Scientist
Van De Flierdt, Christina-Maria	Adjunct Research Scientist
Walsh, Daniel	Adjunct Senior Research Scientist
Webster, James Dale	Adjunct Research Scientist
Zellmer, Georg	Adjunct Research Scientist
Zheng, Yan	Adjunct Senior Research Scientist

STAFF OFFICERS OF RESEARCH

Aziz, Zahid	Staff Associate
Bolge, Louise	Staff Associate
Cai, Jing	Staff Associate

Camara Mor, Patricia	Staff Associate
Cook, Carys	Staff Associate
Cooper, Lauren	Staff Associate
Fleisher, Martin	Senior Staff Associate
Friedrich, Heinz	Senior Staff Associate
Garcia Barriga, Juan Luis	Staff Associate
Gorman, Eugene	Staff Associate
Griffiths, James	Staff Associate
Hyams, Orit	Senior Research Staff Assistant
Ladig, Kathryn	Staff Associate
Mcnally, Charles	Senior Laboratory Technician
Newberger, Timothy	Staff Associate
Protus Sr, Thomas	Senior Electronic Technician
Putnam, Aaron	Staff Associate
Roberts, Natalie	Staff Associate
Ross, James	Staff Associate
Saukel, Cornelia	Staff Associate
Schwartz, Roseanne	Staff Associate
Serno, Sascha	Staff Associate

SYSTEMS ANALYSTS / PROGRAMMERS

Lee, Hoyle	Systems Analyst/Programmer Intermediate

SUPPORT STAFF

Baker, Linda	Research Staff Assistant
Balletta, Marco	Laboratory Assistant
Bose, Sutapa	Senior Research Staff Assistant
Clark, Elizabeth	Senior Research Staff Assistant
Cox, Stephen	Research Staff Assistant
Criscione, Deborah	Administrative Assistant
Dachille, Anthony	Senior Research Staff Assistant
Dale, Cathleen	Research Staff Assistant
French, Melodie	Research Staff Assistant
Frisch, Jeremy	Laboratory Assistant
Fromentin, Daphnee	Administrative Assistant
Hanley, Jean	Laboratory Assistant
Hickey, Emily	Laboratory Assistant
Ilano, Arturo	Laboratory Assistant
Llaque Galvez, Claudia	Laboratory Assistant
Martin, Maxwell	Laboratory Assistant
Mendelson, Mieczyslawa	Senior Research Staff Assistant
Mesko, Gary	Research Staff Assistant
Palmer, Emerson	Research Staff Assistant
Penman, Donald	Research Staff Assistant
Pitiranggon, Masha	Senior Research Staff Assistant
Reid, Matthew	Research Staff Assistant
Rollins, Nathan	Research Staff Assistant
Sprecher, David	Laboratory Assistant
St Clair, Uranise Moanna	Administrative Assistant
Suriani, Arlene	Administrative Assistant
Sutherland, Stewart	Research Staff Scientist
Yoshida, Sandra	Administrative Assistant

Marine Geology and Geophysics

Buck, Roger	Associate Director
Odland, Sarah	Division Administrator

SENIOR SCIENTIFIC STAFF

Anderson, Roger	Doherty Senior Scholar
Bell, Robin	Doherty Senior Research Scientist
Buck, Walter	Doherty Senior Research Scientist
Carbotte, Suzanne	Doherty Senior Research Scientist
Cochran, James	Doherty Senior Research Scientist
Diebold, John	Senior Research Scientist
Goldberg, David	Doherty Senior Research Scientist
Hayes, Dennis	Professor
Hostert, Patrick	Visiting Senior Research Scientist
Kastens, Kim Anne	Doherty Senior Research Scientist
Lehnert, Kerstin	Senior Research Scientist
Malinverno, Alberto	Senior Research Scientist
Mutter, John Colin	Professor
Ryan, William	Doherty Senior Scholar
Small, Christopher	Doherty Senior Research Scientist
Stark, Colin	Doherty Research Scientist
Steckler, Michael	Doherty Senior Research Scientist
Studinger, Michael	Doherty Research Scientist
Tolstoy, Maria	Associate Professor
Weathers, Kathleen	Visiting Senior Research Scientist

JUNIOR SCIENTIFIC STAFF

Carton, Helene	Doherty Associate Research Scientist
Crone, Timothy	Doherty Associate Research Scientist
DeConto, Robert	Visiting Research Scientist

[left to right] Carol Mountain, Jean Leotte, Missy Pinckert and Mia Leo

Dyhrman, Sonya	Visiting Associate Research Scientist
Ferrini, Vicki Lynn	Associate Research Scientist
Flowers, Gwenn	Visiting Associate Research Scientist
Goodwillie, Andrew	Associate Research Scientist
Guerin, Gilles	Associate Research Scientist
Iturrino, Gerardo	Research Scientist
Kattoju, Kamesh	Visiting Research Scientist
Nitsche, Frank Oliver	Doherty Associate Research Scientist
Nooner, Scott	Doherty Associate Research Scientist
Shillington, Donna	Doherty Associate Research Scientist
Williams, Trevor	Research Scientist

POSTDOCTORAL STAFF

Choi, Eunseo	Postdoctoral Research Scientist
Cook-Yockey, Ann	Postdoctoral Research Fellow
Creyts, Timothy	Postdoctoral Research Scientist
Das, Indrani	Postdoctoral Research Scientist
Evans, Helen	Postdoctoral Research Scientist
Gregg, Patricia	Postdoctoral Research Fellow
Okay, Seda	Postdoctoral Research Scientist
Slagle, Angela	Postdoctoral Research Scientist

GRADUATE STUDENTS

Bagley, Katherine	Graduate Research Assistant
Barbour, Jonathan	Graduate Research Assistant
Bialis, Robert	Graduate Research Assistant
Borunda, Alejandra	Graduate Research Assistant
Chacko, Diya	Graduate Research Assistant
Cook-Yockey, Ann	Graduate Research Assistant
Fried, Rebecca	Graduate Research Assistant
Han, Shuoshuo	Graduate Research Assistant
Holmes, Robert	Graduate Research Assistant
Marjanovic, Milena	Graduate Research Assistant
Narayan, Adi	Graduate Research Assistant
Phillips, Veronica	Graduate Research Assistant
Smith, Adrienne	Graduate Research Assistant
Wolovick, Michael	Graduate Research Assistant
Zakharova, Natalia	Graduate Research Assistant

SPECIAL RESEARCH SCIENTIST

Hayes, Dennis	Special Research Scientist
Pitman III, Walter Clarkson	Special Research Scientist
Stoll, Robert	Special Research Scientist
Weissel, Jeffrey	Special Research Scientist

LDEO ADJUNCTS

Abbott, Dallas Helen	Adjunct Research Scientist
Block, Karin	Adjunct Associate Research Scientist
Bohnenstiehl, Delwayne	Adjunct Associate Research Scientist
Clarke, Garry K	Adjunct Senior Research Scientist
Herron, Michael	Adjunct Senior Research Scientist
Kane, Kimberlee Somers	Adjunct Associate Research Scientist
Karner, Garry David	Adjunct Senior Research Scientist
Kurt, Hulya	Adjunct Research Scientist
McHugh, Cecilia	Adjunct Senior Research Scientist
Mountain, Gregory	Adjunct Senior Research Scientist
Nagel, Thorsten	Adjunct Associate Research Scientist
Nedimovic, Mladen	Adjunct Research Scientist
Pfirman, Stephanie	Adjunct Senior Research Scientist
Robinson, Stuart	Adjunct Associate Research Scientist
Taramelli, Andrea	Adjunct Associate Research Scientist

STAFF OFFICERS OF RESEARCH

Agrawal, Shruti	Staff Associate
Baker, Ted	Senior Staff Associate
Brenner, Carl	Senior Staff Associate
Caso, Carlo	Staff Associate
Chayes, Dale	Senior Staff Associate
Cui, Xiangbin	Staff Associate
DeLeonardo, Susan	Staff Associate

Doermann, Lindsey	Staff Associate
Frearson, Nicholas	Senior Staff Associate
Gurcay, Savas	Staff Associate
Hussein, Tarik	Staff Associate
Kapoor, Geetika	Staff Associate
Liu, Tanzhuo	Senior Staff Associate
Malinverno, Cristina	Senior Staff Associate
Meissner, Eric	Senior Staff Associate
Mrozewski, Stefan	Senior Staff Associate
Perry, Richard	Staff Associate
Quoidbach, Daniel	Senior Staff Associate
Reagan, Mary	Senior Staff Associate
Sarker, Golam	Senior Staff Associate
Timur, Duygu	Staff Associate
Tinto, Kirsteen	Staff Associate

SYSTEMS ANALYSTS / PROGRAMMERS

Alsop, Joyce	Sr. Systems Analyst/Programmer
Arko, Robert	Lead Systems Analyst Programmer
Boivie, Ethan	Data Analyst
Chan, Sze-Man	Inter Sys & Network A/Programmer
Chan, Sze-Ling	Lead Systems Analyst/Programmer
Melkonian, Andrew	Systems Analyst/Programmer
O'Hara, Suzanne	Sr. Systems Analyst/Programmer

OFFICER OF ADMINISTRATION

Coplan, Justin	Programmer
Cox, Jack	Programmer/System Engineer
DeTemple, James	Prog Mangr Polar Geophysics Grp
Grames, David	Project Coordinator
Irukulapati, Naveen	Programmer/Systems Engineer
Nagao, Kazuko	Coordinator
Novikova, Natalia	Program Coordinator
Turrin, Margaret	Education Coordinator

SUPPORT STAFF

Bonczkowski, Juliet	Research Staff Assistant
Giacinto, Regina	Administrative Assistant
Johansson, Annika	Senior Research Staff Assistant
Masterson, Walter	Jr. Marine Tech
Meyer, Marsha	Secretary II
Morton, John	Data Manager Assistant
Pelowski, James	Data Manager Assistant
Rivera, Tiffany	Senior Research Staff Assistant
Simpson, Frances	Administrative Assistant
Spector, Perry	Senior Research Staff Assistant
Stolzmann, Andrew	Data Manager Technician
Weissel, Rose Anne	Senior Research Staff Assistant
Zemsky, Richard	Research Staff Assistant

Ocean and Climate Physics

Gordon, Arnold	Associate Director
Schow, Heidi Marie	Division Administrator

SENIOR SCIENTIFIC STAFF

Cane, Mark	Vetlesen Professor of Earth and Climate Science
Chen, Dake	Doherty Senior Research Scientist
De Camargo, Suzana	Doherty Research Scientist
Gordon, Arnold	Professor of Earth and Environmental Sciences
Jacobs, Stanley	Doherty Senior Research Scientist
Kaplan, Aleksey	Doherty Research Scientist
Kushnir, Yochanan	Doherty Senior Research Scientist
Martinson, Douglas	Doherty Senior Research Scientist
Ou, Hsien Wang	Doherty Senior Research Scientist
Seager, Richard	Doherty Senior Research Scientist
Sobel, Adam	Professor
Thurnherr, Andreas	Doherty Research Scientist
Ting, Mingfang	Doherty Senior Research Scientist
Yuan, Xiaojun	Doherty Research Scientist

JUNIOR SCIENTIFIC STAFF

Biasutti, Michela	Doherty Associate Research Scientist
Previdi, Michael	Doherty Associate Research Scientist
Smerdon, Jason	Doherty Associate Research Scientist
Zappa, Christopher	Doherty Associate Research Scientist

RESEARCH SCIENTIST

Naik, Naomi	Research Scientist
Susanto, Raden	Research Scientist

POSTDOCTORAL STAFF

Kim, Daehyun	Postdoctoral Research Scientist
Murukes, Nuncio	Postdoctoral Research Fellow
Ruiz-Angulo, Angel	Postdoctoral Research Scientist
Zhou, Lei	Postdoctoral Research Fellow

GRADUATE STUDENTS

Chen, Chen	Graduate Research Assistant
Diehl, Benjamin	Graduate Research Assistant
Dwyer, John	Graduate Research Assistant
Guan, Xiaorui	Graduate Research Assistant
Kelley, Colin	Graduate Research Assistant
Leonard, Katherine	Graduate Research Assistant
Liang, Xinfeng	Graduate Research Assistant
Pujiana, Kandaga	Graduate Research Assistant
Tessler, Zachary	Graduate Research Assistant
Tillinger, Debra	Graduate Research Assistant
Wang, Daiwei	Graduate Research Assistant
Webb, Lockhart	Graduate Research Assistant
Wu, Yutian	Graduate Research Assistant
Yang, Wenchang	Graduate Research Assistant

SPECIAL RESEARCH SCIENTIST

Houghton, Robert	Special Research Scientist

LDEO ADJUNCTS

Banner, Michael	Adjunct Senior Research Scientist
Clement, Amy	Adjunct Associate Research Scientist
Cook, Benjamin	Adjunct Associate Research Scientist
Curchitser, Enrique	Adjunct Associate Research Scientist
Eshel, Gidon	Adjunct Associate Research Scientist
Evans, Michael	Adjunct Associate Research Scientist
Ffield, Amy	Adjunct Research Scientist
Garzoli Sanchez, Silvia	Adjunct Senior Research Scientist
Gildor, Hezi	Adjunct Associate Research Scientist
Hall, Alexander	Adjunct Associate Research Scientist
Harnik, Nili	Adjunct Associate Research Scientist
Hellmer, Hartmut Heinz	Adjunct Research Scientist
Huang, Huei-Ping	Adjunct Associate Research Scientist
Jenkins, Adrian	Adjunct Senior Research Scientist
Kamenkovich, Vladimir	Adjunct Senior Research Scientist
Kang, In-Sik	Adjunct Senior Research Scientist
Karnauskas, Kristopher	Adjunct Associate Research Scientist
Paldor, Nathan	Adjunct Senior Research Scientist
Pullen, Julie	Adjunct Research Scientist
Reverdin, Gilles	Adjunct Senior Research Scientist
Robertson, Robin	Adjunct Associate Research Scientist
Stammerjohn, Sharon	Adjunct Associate Research Scientist
Stieglitz, Marc	Adjunct Research Scientist
Tourre, Yves Marcel	Adjunct Senior Research Scientist
Tremblay, Bruno	Adjunct Research Scientist
Visbeck, Martin	Adjunct Senior Research Scientist
Witter, Donna	Adjunct Research Scientist
Zambianchi, Enrico	Adjunct Research Scientist
Zheng, Quanan	Adjunct Senior Research Scientist
Ziv, Baruch	Adjunct Research Scientist

STAFF OFFICERS OF RESEARCH

Castagno, Pasquale	Staff Associate
Cullather, Richard	Senior Staff Associate
Giulivi, Claudia	Senior Staff Associate
Huber, Bruce	Senior Staff Associate
LeBel, Deborah	Staff Associate
Martin, Joseph	Staff Associate
Nakamura, Jennifer	Senior Staff Associate

SYSTEMS ANALYSTS / PROGRAMMERS

Correa, Gustavo	Lead Systems Analyst Programmer
Iannuzzi, Richard	Systems Analyst/Programmer
Li, Cuihua	Systems Analyst/Programmer
Mele, Philip	Systems Analyst/Programmer Senior
Rosen, Lawrence	Systems Analyst/Programmer Senior

OFFICER OF ADMINISTRATION

Barry-Biss, Laura	CICAR Administrative Officer

SUPPORT STAFF

Amrhein, Daniel	Research Staff Assistant
Arnold, Nathan	Research Staff Assistant
Brown, Scott	Senior Research Staff Assistant
Diblasi-Morris, Virginia	Senior Secretary
Lichtblau, Laura	Administrative Assistant
Manandhar, Deepa	Research Staff Assistant

Seismology, Geology and Tectonophysics

Lerner-Lam, Arthur	Associate Director
Bonkowski, Bonnie	Division Administrator

SENIOR SCIENTIFIC STAFF

Abers, Geoffrey	Doherty Senior Research Scientist
Anders, Mark	Associate Professor
Christie-Blick, Nicholas	Professor
Ekstrom, Goran	Professor
Gaherty, James	Doherty Research Scientist
Kim, Won-Young	Doherty Sr Research Scientist
Kogan, Mikhail	Doherty Research Scientist
Lerner-Lam, Arthur	Doherty Senior Research Scientist
Menke, William	Professor
Nettles, Meredith	Assistant Professor
Scholz, Christopher	Professor
Seeber, Leonardo	Doherty Senior Research Scientist
Shaw, Bruce	Doherty Research Scientist
Spiegelman, Marc	Professor
Waldhauser, Felix	Doherty Research Scientist
Webb, Spahr	Doherty Senior Research Scientist

JUNIOR SCIENTIFIC STAFF

Barclay, Andrew	Associate Research Scientist
Holtzman, Benjamin	Doherty Associate Research Scientist
Schaff, David	Doherty Associate Research Scientist
Yoshizawa, Kazunori	Visiting Research Scientist

POSTDOCTORAL STAFF

Calkins, Joshua	Postdoctoral Research Scientist
Diehl, Tobias	Postdoctoral Research Scientist
Hjorleifsdottir, Vala	Postdoctoral Research Scientist
Lev, Einat	Postdoctoral Research Fellow
Valoroso, Luisa	Postdoctoral Research Fellow
Zechar, Jeremy	Postdoctoral Research Fellow

GRADUATE STUDENTS

Almeida, Rafael	Graduate Research Assistant
Collier, Martin	Graduate Research Assistant
Foster, Anna	Graduate Research Assistant
Garroway, Jordan	Graduate Research Assistant
Jia, Tianxia	Graduate Research Assistant
Jin, Ge	Graduate Research Assistant
Li, Jiyao	Graduate Research Assistant
Madof, Andrew	Graduate Research Assistant
Moulik, Pritwiraj	Graduate Research Assistant
Newman, Kori	Graduate Research Assistant
Reitz, Meg	Graduate Research Assistant
Renik, Byrdie	Graduate Research Assistant
Shuler, Ashley	Graduate Research Assistant
Sumy, Danielle	Graduate Research Assistant
Templeton, John	Graduate Research Assistant
Vankeuren, Marc	Graduate Research Assistant
Veitch, Stephen	Graduate Research Assistant
Zha, Yang	Graduate Research Assistant

SPECIAL RESEARCH SCIENTIST

Jacob, Klaus Hans	Special Research Scientist
Richards, Paul	Special Research Scientist

LDEO ADJUNCTS

Aharonov, Einat	Adjunct Research Scientist
Cormier, Marie-Helene	Adjunct Associate Research Scientist
Dalton, Colleen	Adjunct Associate Research Scientist
Davis, James	Adjunct Senior Research Scientist
Katz, Richard	Adjunct Associate Research Scientist
Levin, Vadim	Adjunct Associate Research Scientist
Passow, Michael	Adjunct Associate Research Scientist
Pekar, Stephen	Adjunct Associate Research Scientist
Steblov, Grigory	Adjunct Research Scientist

STAFF OFFICERS OF RESEARCH

Andersen, Morten	Staff Associate
De Juan Verger, Julia	Staff Associate
Gassier, David	Staff Associate
Gold, Mitchell	Staff Associate
Koczynski, Theodore	Staff Associate
Mondal, Dhiman	Staff Associate
Renik, Byrdie	Staff Associate
Starin, Elizabeth	Research Staff Assistant

OFFICER OF ADMINISTRATION

Ranjeet, Niva	Coordinator

SUPPORT STAFF

Benedetto, Karen	Administrative Assistant
Contino, John	Senior Electronic Technician
Miller, Dana	Administrative Assistant
Oletu, Vincent	Junior Marine Technician II
Pugsley, Stephen	Jr. Marine Development Tech
Woodford, Kristen	Administrative Assistant

Marine Division

Goldberg, David	Associate Director
Cummings, Meagan	Marine Env. & Safety Coord.
Higgins, Sean	Research Scientist
Ljunggren, Paul	Senior Staff Associate
Meyer, Megan	Coord of Tech/Purchasing Svcs
Rupert, Jeffrey	Senior Staff Associate
Tallon, June	Financial Administrator
Walsh, Albert	Senior Staff Associate

STAFF OFFICERS OF RESEARCH

Johnson, Anthony	Chief Marine IT/Navigation Dep
Karlyn, Albert	Chief Engineer
Martinson, David	Science Officer
Pica, Stephen	Chief Engineer
Spoto, Thomas	Chief, Marine Sound Source Dep
Steinhaus, Robert	Senior Science Officer

SYSTEMS ANALYSTS / PROGRAMMERS

Aguilar, Elliot	InterSys & Network A/Programmer
Ng-Li, David	Systems/Analyst Programmer
Zhang, Zhi	InterSys & Network A/Programmer

SUPPORT STAFF

Ackerson, Steven	Administrative Aide (Jr Buyer)
Beck, Virginia	Coordinator
Dawe, Bradley	Research Staff Assistant
Domingo, Ellie	Administrative Assistant
Engelmann, Nicholas	Research Staff Assistant
Garland, Mercy	Administrative Assistant
Goodick, Brian	Mechanical Technician
Gutierrez, Carlos	Senior Data Technician 5
Hurley, Brendan	Research Staff Assistant
McKiernan, Bernard	Marine Tech III
Nicolas, John	Research Staff Assistant
White, Jennifer	Marine Technician

MARITIME

Acoutin, Clinton	Third Mate
Applewhite, Nicky	Ordinary Seaperson
Arthur, Robert	Able-Bodied Seaperson
Bakis, Matthew	Chief Mate
Baxter, Gordon	Able-Bodied Seaperson
Becker, Tamara	Chief Mate
Bell, Ethan	Able-Bodied Seaperson
Billings, Jack	Oiler
Billips, Charles	Oiler
Blackwood, William	Maritime Project Coordinator
Brodock, Gary	Steward
Cannon, Jeffrey	Ordinary Seaperson
Caseria, Michael	Second Assistant Engineer
Cereno, George	Able-Bodied Seaperson
Chase, Jerald	Oiler
Chizmar, Peter	First Assistant Engineer
Clark, Bernard	Able-Bodied Seaperson
Cobb, Malcolm	Oiler
Collier, Stephen	Oiler
Conrad, Paul	Shipboard Acquisition Asst
Crum, Breckenridge	Third Mate
De Whirst, Thomas	Second Assistant Engineer
Duffy, Michael	Cook
Eaton, Ryan	Shipboard Acquisition Asst
Ewing, Norman	Third Assistant Engineer
Fahey, Meagan	Oiler
Florendo, Rodolfo	Able-Bodied Seaperson
Gallant, Zachary	Third Assistant Engineer
Gasper, Nicholas	Third Mate
Gill, Matthew	Second Assistant Engineer
Glenn, Richard	Steward
Green, Travis	Oiler
Howard, James	Second Assistant Engineer
Jaunzemis, Randall	Second Assistant Engineer
Kanoute, Thidiane	Second Assistant Engineer
Kenny, Brian	Third Assistant Engineer
Landow, Mark	Master
Lapham, Trevor	Third Assistant Engineer
Lawson, David	Third Assistant Engineer
McLean Fuller, Hervin	Steward
Mitchell, Daniel	Oiler
Nadler, Marcus	Ordinary Seaperson
Neis, Philip	Junior Engineer
Oboza, Salvador	Able-Bodied Seaperson
O'Loughlin, James	Master
Paragas, Petronio	Able-Bodied Seaperson
Philbrick, David	Bosun
Pollock, Thomas	Third Assistant Engineer
Redito, Ricardo	Able-bodied Seaperson
Reed, Joshua	Second Assistant Engineer
Rimando, Inocencio	Able-Bodied Seaperson
Rios, Ricardo	Cook
Romero, Michael	Third Assistant Engineer
Schwartz, John	Chief Marine Electrician
Seyranian, Robert	Shipboard Acquisition Asst.
Singletary, John	Oiler
Sutton, Christopher	Able-Bodied Seaperson
Tatro, Michael	Shipboard Acquisition Asst
Tucke, Matthew	First Assistant Engineer
Tyson, Douglas	Bosun
Uribe, Guillermo	Oiler
Vetting, Ryan	Second Assistant Engineer
Webster, Jeromiel	Ordinary Seaperson
Widerman, Rachel	Third Assistant Engineer
Wolford, David	Second Mate
Woronowicz, Jason	Bosun
Zatwarnicki, James	Chief Mate
Zeigler, Stanley	Chief Mate
Zimmerman, Christopher	Second Mate

Computer Network Support Group

Bookbinder, Robert	Senior Staff Associate
Falerni, Ariana	Webmaster
Fitzpatrick, Philip	Systems/Network Analyst/Programmer
Kakascik, Robert	Systems/Network Analyst/Programmer
Lentrichia, David	Senior Staff Associate
Leung, Allen	Web Developer
Parsi, Mahdad	Lead Systems/Network Administrator
Shearer, Douglas	Senior Staff Associate

Dept. of Earth and Environmental Sciences

Leo, Mia	Academic Department Administrator
Leote, Jean	Administrative Assistant
Mountain, Carol	Program Coordinator
Pinckert, Millicent	Administrative Aide

Office of Administration

Miller, Edith	Asst Dir of Finance & Adminstration
O'Reilly, Patrick	Asst Dir Facilties & Engineering
Temple, Patricia	Administrative Aide

BUILDINGS AND GROUNDS

Greco, Richard	Manager
Baez, Bruce	Specialty Mechanic
Burke, Thomas	Mechanic Trainee
Casilli, Joseph	Mechanic A
Jones, Charles	Mechanic A
Morrone, Margaret	Administrative Aide
Muench, Herbert	Mechanic A
Murray, Jacqueline	Administrative Aide
Slavin, Raymond	Mechanic
Soto, Eric	Mechanic
Sullivan, Kevin	Specialty Mechanic
Sullivan, Leonard	Assistant Manager of Facilities
Trubiroha, Richard	Mechanic
Yano, Douglas	Assistant Mechanic

[left to right] Douglas Shearer, Robert Bookbinder, Mahdad Parsi, Ariana Falerni, Philip Fitzpatrick, Allen Leung and Robert Kakascik

CONTRACTS AND GRANTS

Respo, Maribel	Manager
Harding. Kristine	Administrative Aide
Higgins, Annette	Project Coordinator
Sencen, Theresa	Project Coordinator
Young, Rachel	Project Coordinator

DEVELOPMENT

Charbonnet, Barbara	Director of Development
Huard, Sarah	Director of Development
Anderson, Ronnie	Administrative Assistant
Brusa, Douglas	Associate Director
McGannon, Jessica	Development Assistant
Pedlosky, Dove	Communications Manager
Vassallo, Stacey	Development Officer

FINANCE

Nazario, Victoria	Manager
Calungcagin, Maria Angelina	Accountant
Dia, Wanda	Financial Analyst
Hicks, Linda	Budget Assistant
Kolacia, Paula	Travel Services Coordinator
Lamarque, Jessie	Administrative Aide
Rivera, Carla	Analytical Accountant
Sheridan, Linda	Coordinator of Accts Payable
Tavarone, Virginia	Financial Services Assistant

HUMAN RESOURCES

Maher, Virginia	Manager
Carlsen, Kathleen	Coordinator
Nurse, Cheryl	Benefits Manager
Vasquez, Katherine	Payroll & Benefits Manager
Verdin, Jennifer	Payroll Specialist

LIBRARY

Colwell, Miriam	Geology/Geoscience Librarian
Bielskas, Amanda	Librarian

MACHINE SHOP

Gallagher, Bernard	Senior Electronic Technician

PURCHASING

Hoffer, Karen	Manager
Barsky, Shelley	Administrative Aide
Bocsusis, Karen	Administrative Assistant
Deutsch, Bonnie	Analyst/Buyer

SAFETY, SECURITY, COMMUNICATION AND PROPERTY

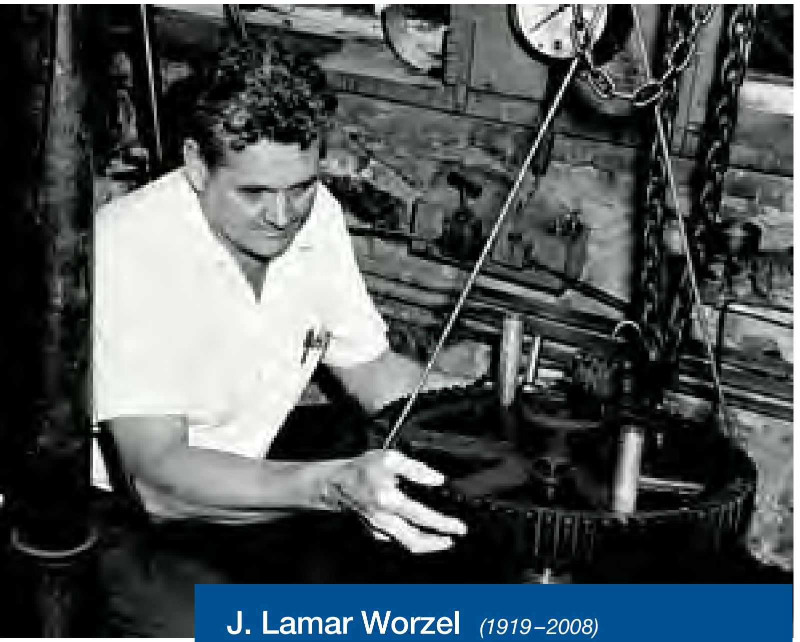
Matza, Howard	Manager
Troutman, Cathy	Assistant Manager
Hanneman, Maryann	Telephone Operations Coord
Weinstein, Stephen	Night Supervisor

TRAFFIC

Eberhard, Thomas	Manager
Ables, Patricia	Administrative Aide
Brothers IV, James	Driver
Daly, Robert	Supervisor
Deloatch, Antonio	Driver
Mack, Maurice	Driver
Murphy, Brendan	Driver
Torres, Juan	Driver

IN MEMORIAM

Lamont-Doherty is a singular institution, in part because it attracts singular people—staunch individualists who nevertheless share a certain ingenuity and willingness to get their hands dirty, solve problems, and make discoveries. Unfortunately, we've lost three such individuals since 2008.



J. Lamar Worzel *(1919–2008)*

Joe Worzel was an undergraduate at Lehigh University in 1936 when his physics professor, Maurice Ewing, received a grant to adapt land-based seismic methods to investigate the seafloor. Thus began a lifelong partnership between both men that led to the establishment of Lamont-Doherty—and to an entirely new scientific field.

"Geophysics as a science didn't really exist at the time," Worzel once said, and so the professor had little more experience than his student. "We were physicists and engineers, using our wits . . . to bring these sciences to bear on the study of the Earth, working out the methods as we went along."

They improvised novel instruments from materials at hand: underwater cameras using tin cans, ocean seismographs fashioned from pocket watches, and high-pressure testing devices out of surplus artillery shells. Using caps from toy pistols, they detonated homemade bombs in the oceans' depths and recorded the echoes to probe the seafloor.

On the brink of World War II, Worzel and Ewing made some fundamental discoveries about the way sound travels through the ocean, including underwater sound-resistant pockets or "shadow zones" and the "deep sound channel"—a narrow zone that transmits low-frequency sounds through thousands of miles of water with fantastic clarity. U.S. submarines used the former to elude enemies; the latter formed the basis of the Navy's Cold War program of underwater listening devices to track Soviet subs by their engine noise.

In 1948, Ewing, Worzel and a handful of graduate students founded Lamont Geological Observatory. Ewing's seminal ideas drove early systematic mapping of the world's oceans. But oceanographer Dennis Hayes, who worked with both men, said it was Worzel's unstoppable energy and mechanical ingenuity that brought many ventures to fruition.

In the early 1950s, Worzel obtained a series of research vessels, starting with the R/V *Vema*, outfitting these ships with scientific instruments. Worzel perfected a system to efficiently extract seafloor sediment cores, and he designed a system that could take precise measurements of Earth's gravity field from surface vessels. He also initiated the use of satellite navigation aboard research ships.

Lamont ships crisscrossed the oceans, relentlessly gathering depth recordings of the seafloor, seismic reflections of subseafloor layers, sediment cores, gravity, magnetic and heat-flow measurements. This data confirmed the revolutionary theory of plate tectonics and made Lamont-Doherty a global powerhouse in marine research.

"We never allowed ourselves to think that anything we decided to do was impossible," Worzel wrote. He died in December 2008.

John Diebold *(1944–2010)*

John Diebold was a college dropout in 1967 with a thin résumé of odd jobs and skills that included playing bluegrass and jug band music on guitar. Seeking seafaring adventure, he took a job in Lamont-Doherty's machine shop, where workers constructed and fixed seagoing instruments.

Diebold was sent on a 20-month cruise aboard the R/V *Conrad*, during which, among other duties, he took part in marine seismology experiments. "I personally detonated at least 50 tons of WWII-surplus explosives," he later said. Scientists used the echoes (or sound waves) from these explosions to map the underlying sediments, rocks and faults, revealing the structure of Earth's seafloor and crust.

Hooked, Diebold completed college, returning to Lamont-Doherty and earning a Ph.D. in geophysics from Columbia in 1980. Over the years, he became a sought-after expert in questions relating to sound's propagation through water and solid earth, and he helped pioneer methods and instruments used today in a wide range of marine research. Putting the era of explosives firmly behind him, he evolved into one of the world's authorities on air guns, which generate sound by releasing pulses of compressed air.

> A college dropout in 1967, John Diebold evolved into one of the world's most sought-after experts on questions relating to the propagation of sound through water and the solid earth.

Diebold helped design, test and refine air gun arrays, the hydrophones for receiving returning signals, and the complex software for rendering data into detailed three-dimensional pictures of the sub-seabed.

He served as chief scientist on many research ships around the world. By the 1990s, he estimated that his time at sea added up to at least six years, having crisscrossed the Pacific, Atlantic, Indian, Arctic and Antarctic Oceans, along with most of the world's seas. From such voyages, Diebold contributed to more than 60 scientific papers. He also played occasional public concerts with his longtime group, the American Standard String Band.

Diebold's last major project was a cruise in March 2010 off the coast of Haiti to image the undersea portion of the great fault that shook the capital of Port-au-Prince in January of that year. He could be seen at sunset on the fantail of the ship, playing his guitar. Then, he would take the midnight shift with the team working the air guns. He died in July 2010.

To commemorate Diebold's achievements, Lamont-Doherty has established the John B. Diebold Student Fellowship Fund, an endowed fund to provide support for Columbia University students to go to sea and participate in research expeditions.

Sam Gerard *(1926–2008)*

Robert (Sam) Gerard, a local young man with a master's degree in arctic geography, would occasionally visit the library at the Lamont Geological Observatory for a scientific reference. In short order, he was swept up by the vitality of research emanating from Lamont Hall and shipped out on the R/V *Verna*. That was in 1954.

"It was clear that [Lamont-Doherty] was the perfect place for him," said his wife, Alice. "He was constantly challenged, he had a chance to use his special mechanical talents, and he was working with many intelligent, unconventional scientists."

Ewing assigned Gerard to work on a new project for the Atomic Energy Commission, which was contemplating the deep sea as a repository for nuclear waste. To collect deepwater samples, he built what became an industry standard, the Gerard Sampler. Lamont-Doherty geochemist Wally Broecker applied new radiocarbon dating techniques to the samples, and he, Gerard and others co-authored seminal papers

revealing the chemical composition and circulation of the deep oceans.

Sailing continually on the Observatory's ships through the 1950s and 1960s and into the 1970s, often as chief scientist, Gerard introduced and refined tools and methods that were adopted by other scientific institutions. "Sam was known for his mechanical creativity and for his elegant solutions to engineering problems," said Director Michael Purdy.

Gerard continued to design, build and operate many pioneering oceanographic instruments, including the thermograd, a probe that obtained the first successful measurements of heat flow in the seafloor.

"If you didn't know how to make your own instruments and tools and use them and fix them, you weren't much use as a scientist. . . . That was how Lamont worked," Gerard once said.

> "If you didn't know how to make your own instruments and tools and use them and fix them, you weren't much use as a scientist."

In the 1970s Sam became Lamont-Doherty's marine superintendent and marine technical coordinator. His last major project before retiring in 1991 was to oversee the conversion of R/V *Ewing* into a fully outfitted oceanographic ship. He died in January 2008.

Celebrating **60** Years of Discovery

1949

Lamont Geological Observatory established on the grounds of the former Lamont estate overlooking the Hudson River.

Selected Contributions From Scientists at Lamont-Doherty Earth Observatory Over the Past 60 Years:

1950s

Established a physical basis for explaining phenomena such as the onset and termination of past ice ages, ushering in a new era of geophysical study of the planet.

Designed and deployed instruments, such as the piston corer, to collect sediment samples from deep beneath the seafloor. Established the Deep-Sea Sample Repository to house collected cores.

Laid the groundwork for modern geochronological dating methods, including radiocarbon and radiostrontium dating.

Developed the Press-Ewing seismograph, becoming the first to detect global seismic events by measuring vibrations in Earth's crust and supporting the establishment of the first global network of seismic monitoring stations.

Pioneered geophysical and oceanographic research from ice floes in the Arctic Ocean.

1960s

Published the first detailed maps of the global ocean floor, using data collected on Lamont-led expeditions.

Designed new pneumatic sound source devices (air guns) to improve depth and detail of seismic images of ocean crust.

Observed symmetric magnetic anomalies across mid-ocean ridges, confirming the hypothesis of seafloor spreading.

Observed earthquake mechanisms proving hypothesis of seafloor subduction and supporting plate-tectonic paradigm.

Demonstrated that underground nuclear detonations could be detected and measured seismically, setting the stage for monitoring of later international agreements, including the 1974 Threshold Test Ban Treaty.

Led systematic geophysical and oceanographic research in the Southern Ocean.

Pioneered use of deep-sea drilling to study ocean processes.

1970s

Developed lunar seismometers and conducted early analysis of the moon's structure.

Took leadership role in the multi-decadal Geochemical Ocean Section Study program, producing the first systematic analysis of chemical fluxes in the global ocean.

Demonstrated that variations in Earth's orbit dictate the timing of the planet's ice ages.

Pioneered the use of multichannel seismic techniques to study ocean crustal structure.

Reconstructed global patterns of climate conditions during the ice ages.

Demonstrated the links between plate tectonics and past variations in global sea levels.

1980s

Put forth paradigm-shifting theory that Earth's climate is bimodal, driven by reorganizations within the ocean-atmosphere system.

Made the first successful prediction of an El Niño event, as well as other regional weather anomalies associated with the phenomenon.

Documented evidence for global-scale ocean circulation.

Pioneered the use of satellite altimetry data to map global ocean floor topography.

Constructed a continuous, detailed record of sea level change over the past 17,000 years using corals found in Barbados.

Developed the experimental and theoretical foundation for the physics of earthquakes.

Demonstrated that variations in temperature of Earth's interior determine depth of the ocean floor.

Published first use of term "global warming" in describing anthropogenic climate change.

1990s

Developed the ocean's first global carbon budget.

Demonstrated importance of ocean-atmosphere gas exchange to the understanding of the global ocean carbon budget.

Discovered evidence for massive discharges of icebergs into the North Atlantic during the last glacial period.

Demonstrated a link between changes in past African climates and the evolution of early hominids.

Detected that Earth's innermost core is spinning at a faster rate than the rest of the planet.

2000s

Published tree-ring based, continental-scale drought atlases for North America and monsoon Asia and led the development of tropical dendrochronology.

Demonstrated a geochemical technique for geologic sequestration of anthropogenic carbon.

Inferred rate of accelerating glacial motion in polar regions.

Produced first multi-streamer 3-D seismic images of mid-ocean ridge magma chambers.

Quantified climate changes during the last millennium.

Lamont-Doherty scientists observe Earth on a global scale, from its deepest interior to the outer reaches of its atmosphere, on every continent and in every ocean. They decipher the long record of the past, monitor the present, and seek to foresee Earth's future. From global climate change to earthquakes, volcanoes, nonrenewable resources, environmental hazards and beyond, the Observatory's fundamental challenge is to provide a rational basis for the difficult choices faced by humankind in the stewardship of this fragile planet.

Lamont-Doherty scientists used geophysical survey aircraft equipped with radar, laser and other instruments to survey Antarctica's Gamburtsev Mountains, a mountain range buried beneath 2.5 miles of ice.
Credit: Michael Studinger

Editor
Dove Pedlosky

Writers
Ken Kostel, Mohi Kumar
Lonny Lippsett

Copy-Editor
Rita Augustine

Designer
Robert Gauldin

Art Director
Sunghee Kim

Content Director
Barbara Charbonnet

Portrait & Campus Photography
Eileen Barroso

Coordinators
Ronnie Anderson, Erika Freimuth, Stacey Vassallo

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61 Route 9W, P.O. Box 1000
Palisades, NY 10964