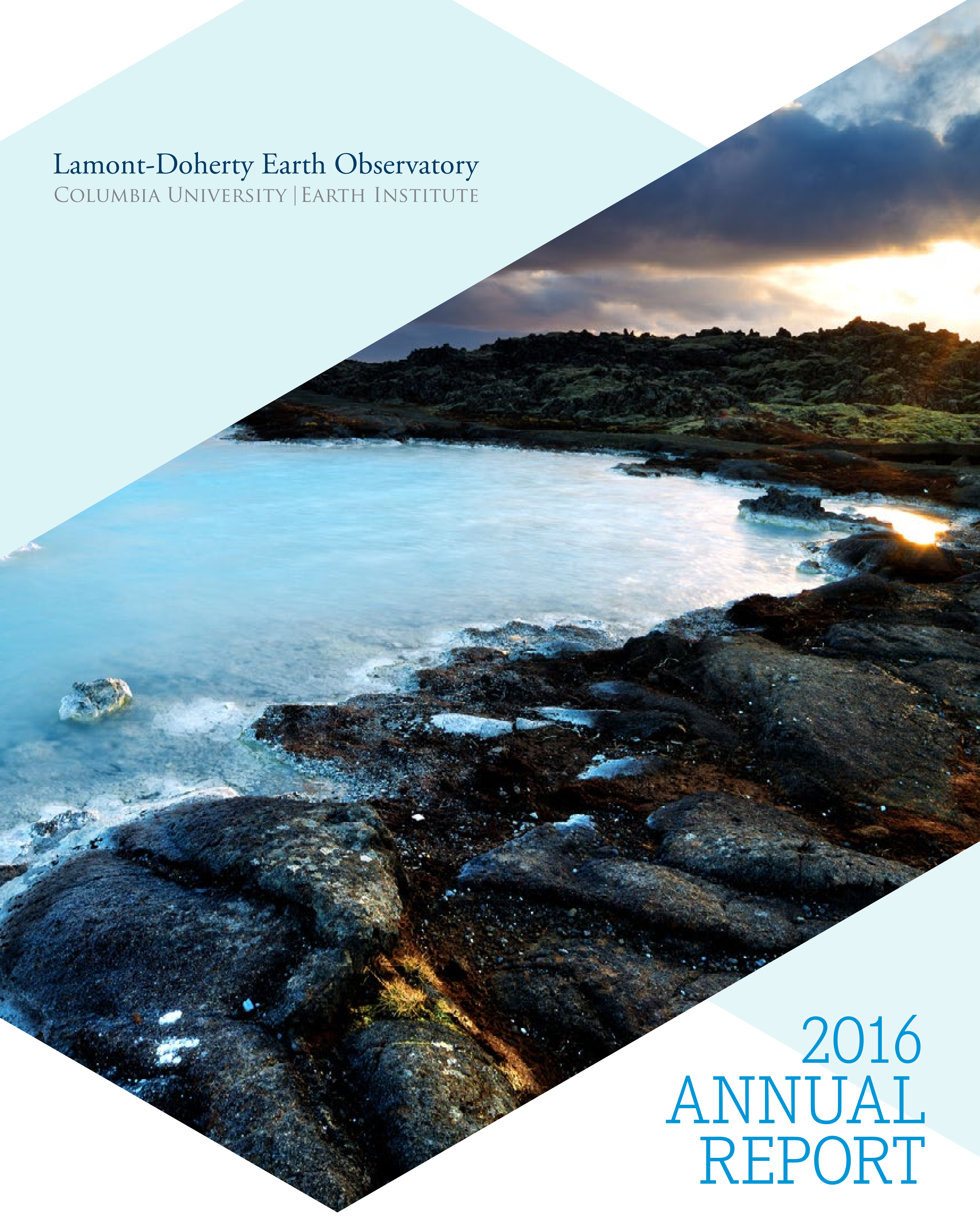
Lamont-Doherty Earth Observatory

COLUMBIA UNIVERSITY | EARTH INSTITUTE



2016 ANNUAL REPORT

Cover: Volcanic rocks at the edge of Blue Lagoon in Iceland. Lamont scientists are working with basalt deep underground to permanently store CO_2. (Anna Gorin)
This page: Kirsty Tinto and Nick Frearson set up a GPS station for use with IcePod flights mapping polar regions. (Margie Turrin)

Contents

STRATEGIC INITIATIVES

Lamont's strategic plan focuses on five multidisciplinary initiatives, each anticipating important near-term advances in basic science and addressing issues of societal importance. You will find these referenced throughout this report highlighting data and technology in the service of society.

CLIMATE & LIFE | REAL-TIME EARTH | ANTICIPATING EARTHQUAKES | CHANGING ICE, CHANGING COASTLINES | EXTREME WEATHER & CLIMATE

"Through data analysis and laboratory and field studies, we are beginning to solve what can feel like intractable societal challenges."

-Sean Solomon

Dear Friends,

This fall, our Polar Geophysics Group heads back to Antarctica to analyze the stability of the Ross Ice Shelf. They will be flying with the IcePod, an airplane-mounted science lab that was designed and built at Lamont to be packed with lidar, radar, infrared cameras, and other instruments for mapping the ice and Earth's surface below it. Each IcePod flight collects 2 to 5 terabytes of data. Seventeen flights in 2015 collected nearly 50 terabytes, and those flights were only the beginning of the surveys that will help us evaluate risks to Antarctica's ice sheet and to the future of sea level rise worldwide as temperatures rise.

The IcePod is a fraction of the massive volume of data that Lamont scientists collect and analyze every day as we work to solve the mysteries of the solid Earth, oceans, atmosphere, and the ecosystems they support.

In labs across campus, our scientists are mining deep data archives and real-time data streaming in from satellites, aircraft, ships, remote sensors, and seafloor observatories. We are building international archives of open data with the tools to facilitate multidisciplinary research in ways never before possible. Our scientists are also developing powerful computer models of increasing sophistication and resolution that allow us to glimpse the future of ice sheets, extreme weather, and sea level in a warming world.

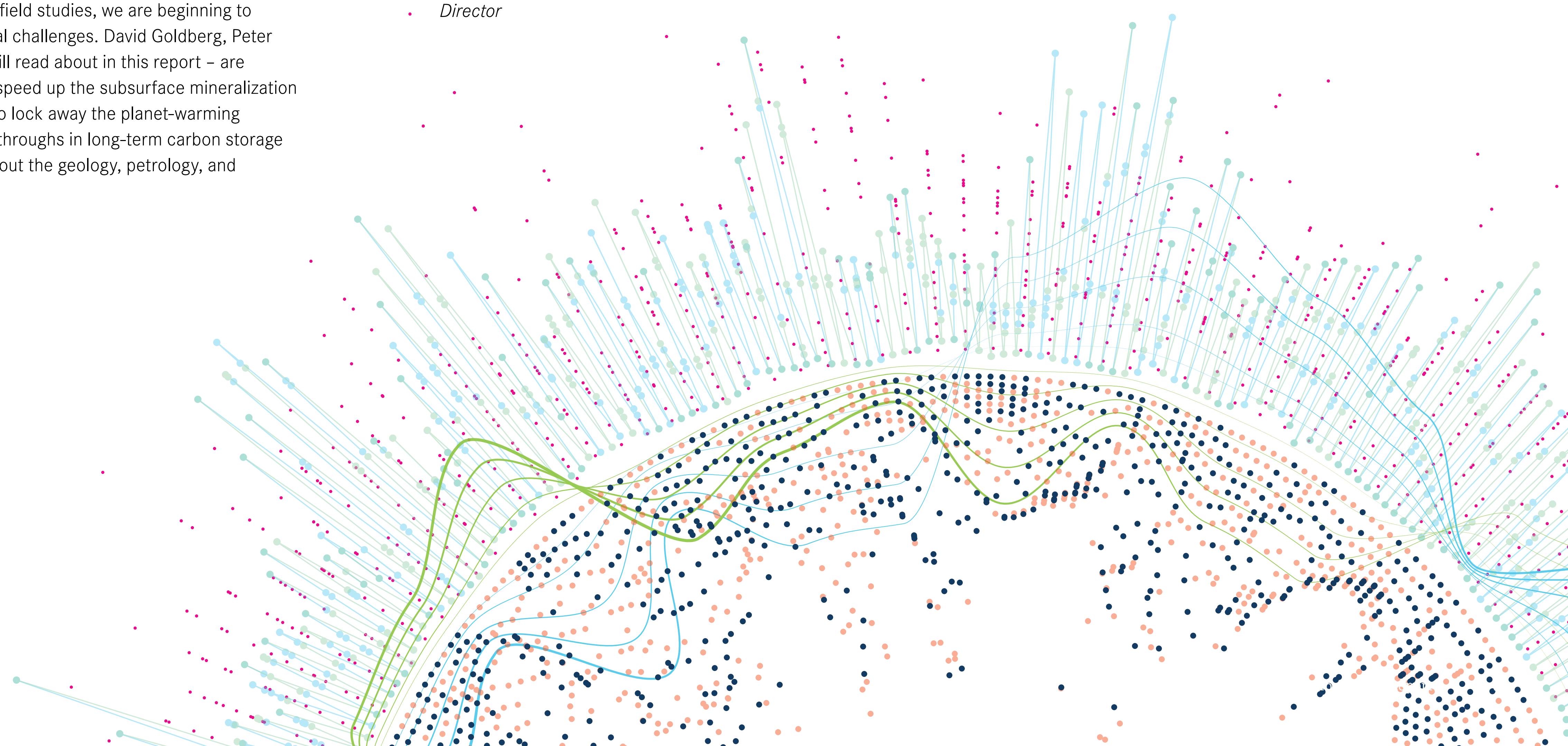
Through data analysis and laboratory and field studies, we are beginning to solve what can feel like intractable societal challenges. David Goldberg, Peter Kelemen, and Martin Stute – whom you will read about in this report – are leading research into processes that can speed up the subsurface mineralization of carbon dioxide, allowing power plants to lock away the planet-warming greenhouse gas permanently. Their breakthroughs in long-term carbon storage started with fundamental observations about the geology, petrology, and geophysical structure of our planet.

Many of the environments we work in are less than hospitable, and collecting data there for research requires innovation and engineering savvy. We have a long tradition at Lamont of finding new and better ways of doing science. In this report, you will read about Chris Zappa, who is designing multi-sensor drone payloads that are turning unmanned aerial systems into a research air force for studying Arctic sea ice. You will also read about Spahr Webb, who designs sea-floor pressure gauges and seismometers that are helping scientists understand earthquake behavior and earthquake and tsunami risk along major submarine plate boundaries, including the Pacific ring of fire.

The scientific and technical achievements taking place across Lamont are made possible, in part, by the many friends, supporters, and alumni who provide continued support for our research and educational endeavors. Your contributions enable us to deepen our understanding of our planetary home and to enhance our collective ability to address the most complex environmental challenges ahead. We deeply appreciate the generosity of our donors and all that your gifts make possible.

Thank you for your support.

Sean C. Solomon
Director



Earth has limits to the amount of carbon dioxide in its atmosphere before the environment as we know it starts to change. Too much CO_2 absorbed by the oceans makes the water more acidic. Too much in the atmosphere warms the planet. With emissions from our carbon-based economies rising, Lamont scientists are developing ways to prevent CO_2 from entering the atmosphere by turning it to stone.

***Above:** Peter Kelemen and his team examine carbonate veins in mantle rock that was thrust to the surface in Oman. (Lamont-Doherty Earth Observatory)*

Turning CO_2 to Stone

There are places in the world where carbon dioxide reacts naturally with the local rock, turning the planet-warming gas to stone. It's a slow process in nature, but scientists at Columbia University's Lamont-Doherty Earth Observatory have found a way to harness that reaction and speed it up so they can take CO_2 from power plants and lock it away quickly and permanently.

In a ground-breaking study that holds new potential for combating climate change, Lamont scientists announced this spring that, for the first time, CO_2 that had been captured from a power plant in Iceland and pumped underground had mineralized into a white, chalky substance for permanent storage, and that this conversion had happened far faster than anyone expected.

Lamont scientists are now exploring similar possibilities with vastly greater storage potential beneath the oceans off the U.S. coasts, and they are experimenting with a type of rock that makes up much of Earth's mantle that could go the next step: to take CO_2 directly out of the environment.

"It's clear that, no matter what we may wish, we will not put the brakes on the carbon economy fast enough to avoid overshooting safe CO_2 limits in the air," said geologist Peter Kelemen, who is leading studies on mantle rocks and their potential for CO_2 removal. "On the bright side, our research into Earth processes is showing that there are things we can do that emulate natural systems to address the carbon problem."

"Our research into Earth processes is showing that there are things we can do that emulate natural systems to address the carbon problem."

-Peter Kelemen

The Iceland Project

> *"We knew that under natural conditions this was happening, but we did not know on what time scale. The energy company was so impressed by the success, they decided to adopt it."*
>
> *- Martin Stute*

Scaled up, the process of capturing CO_2 from power plants and factories and turning it into a solid could buy time as countries worldwide shift away from fossil fuel use and toward cleaner energy sources. The Intergovernmental Panel on Climate Change (IPCC) has described carbon capture and storage (CCS) as a critical technology for keeping climate change in check. There are challenges, though. In most of the 15 large-scale CCS operations functioning today, CO_2 is stored as either a gas or a supercritical fluid in natural subsurface repositories, typically sandstone, or reused to force oil or gas out of played-out wells. The process has been used for over 20 years for storage, and longer for oil recovery, but there has been a lingering question: could stored CO_2 leak out?

At Iceland's Hellisheidi Power Plant, Lamont hydrologist Martin Stute, Adjunct Senior Research Scientist Juerg Matter, and colleagues tried something different. They took CO_2 captured at the power plant and mixed it with water and hydrogen sulfide, creating soda-like carbonation, then injected the mixture into porous basalt rocks 400 to 800 meters underground. Basalt, which is created as lava cools, contains calcium, iron, and magnesium, which react naturally with CO_2 to form solid carbonate minerals. Within two years, 95 percent of the injected CO_2 had turned to mineral – far faster than the 8 to 12 years originally expected.

Reykjavik Energy plans to inject 10,000 tons of CO_2 per year starting in 2016 and increase that level. The continuing experiment will also test some remaining questions, such as whether the pore spaces in the rocks could clog over time. The researchers have found that the pressure from the process itself creates tiny fractures, expanding the area where newly injected CO_2 can flow in and mineralize, which they expect will minimize clogging.

Top: When CO_2 mineralizes, it forms a white chalky substance in the pore spaces of the rock. (Annette K. Mortensen) Bottom: Lamont's Martin Stute discusses the piping system for emissions at Hellisheidi with project leader Edda Sif Arradotir of Reykjavik Energy. (Lamont-Doherty Earth Observatory) Opposite Page: Námafjall, Iceland. (Galyna Andrushko)

Exploring Off Shore

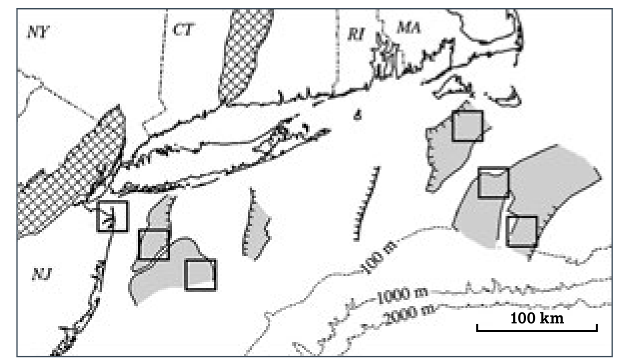
Basalt, which made Iceland the ideal location for testing CO_2 mineralization, is also abundant beneath the oceans, including just off shore from coastal power plants.

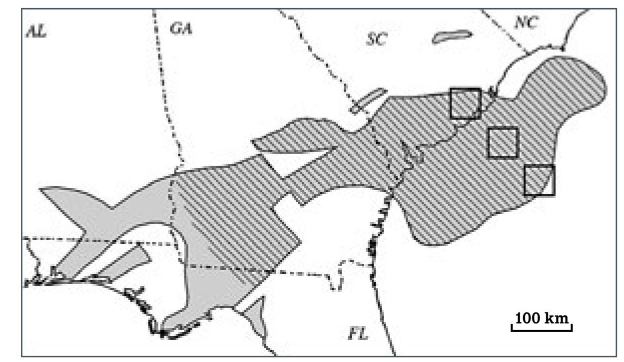
David Goldberg, a geophysicist at Lamont, has been leading off-shore studies to map basalt reservoirs with the potential to store carbon.

> *"Iceland was a key demonstration. The holy grail is off-shore."*
>
> *- David Goldberg*

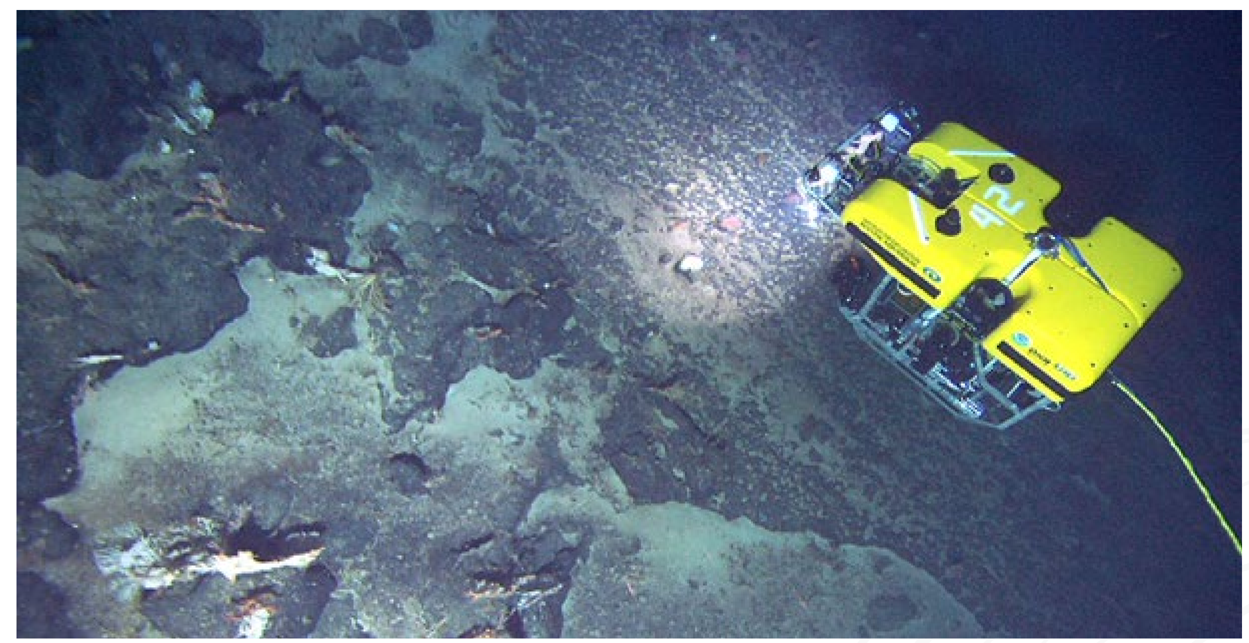
Goldberg has proposed burying CO_2 off the U.S. East Coast about a mile below the seafloor and is working on one of five Department of Energy projects using seismic data to determine how much could be stored in those and other off-shore reservoirs. Goldberg's team is also proposing the first test of off-shore basalt storage, a project that would pump 1 million tons of CO_2 into basalt off the Pacific Northwest.

"Iceland was a key demonstration. The holy grail is off-shore," Goldberg said. The storage potential in the oceans is immense, and it moves the process away from communities. It also avoids the need for water resources. Where the Iceland project added fresh water to the captured CO_2, off-shore projects could mix seawater with purified CO_2 to speed up the reaction time.

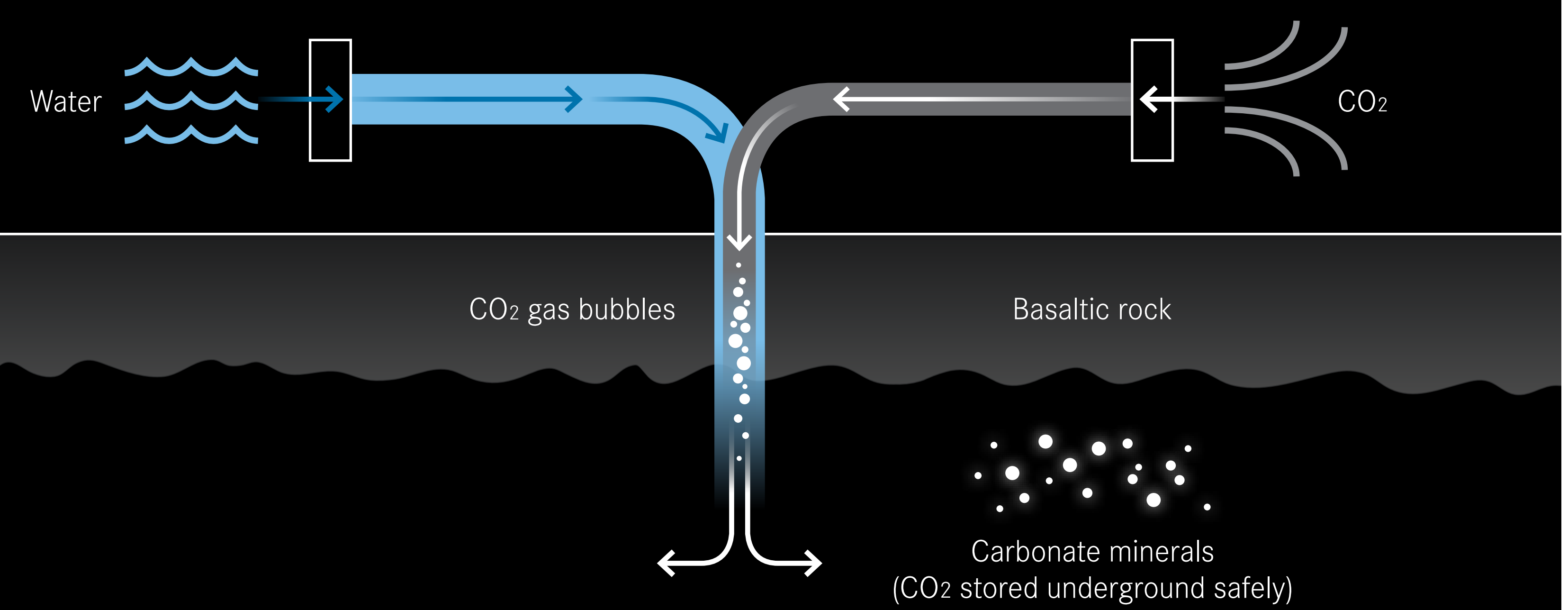




Opposite page: *Lamont operates the R/V Marcus G. Langseth, the nation's premier seismic research ship. Its technology can develop 3D maps of Earth's interior several miles beneath the seafloor. (APS for Lamont-Doherty Earth Observatory)* ***Left:*** *Off-shore and on-shore basalt regions mapped by Goldberg's team. (David Goldberg)* ***Bottom:*** *A remote vessel examines seafloor basalt.. (NOAA)*



Locking away CO_2 quickly and permanently



Pulling CO_2 from the Environment

It is increasingly apparent, however, that we will need to do more than just capture CO_2 from power plants to keep temperatures from rising beyond 2° Celsius. We will also need to start taking CO_2 out of the environment, as reports from the IPCC and the National Research Council (NRC) and National Academy of Sciences have warned.

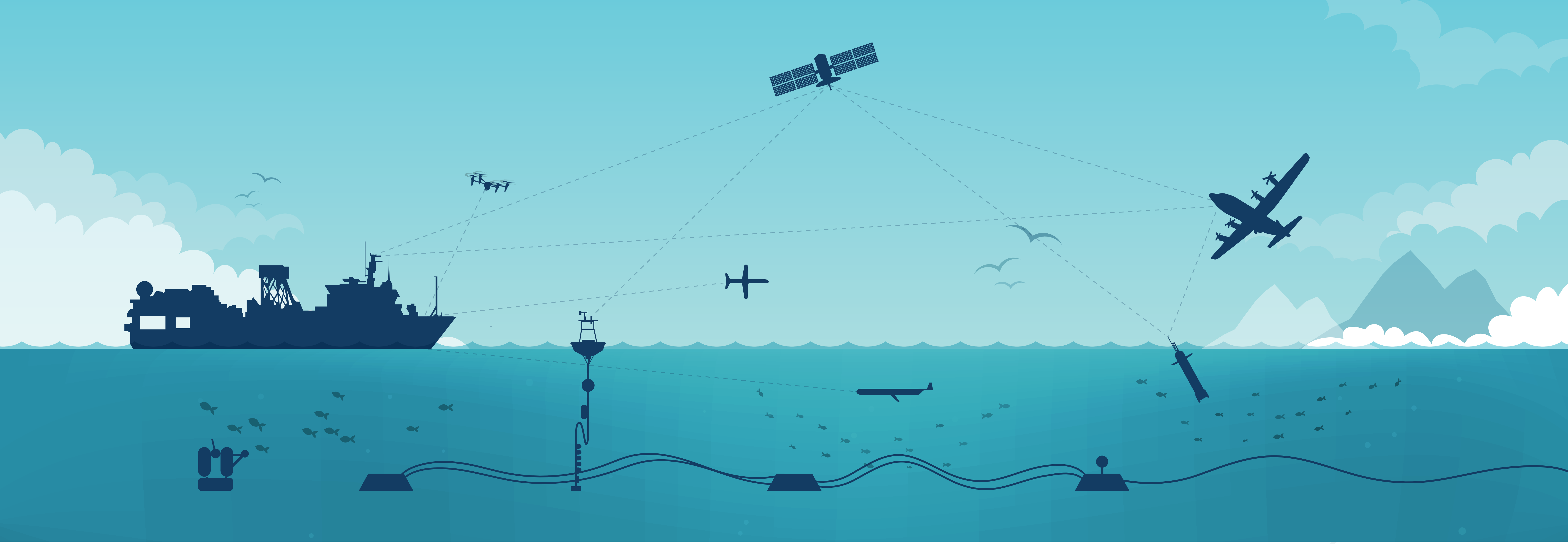
In addition to basalt, Kelemen has been working with peridotite, a fast-reacting rock that comprises much of the Earth's upper mantle and can be found near the surface on all continents and beneath the sea floor. This winter, he will be leading an international drilling project in Oman, where a large block of mantle has been pushed to the surface by plate tectonic forces and is exposed to weathering. The Oman formation naturally sequesters 10,000 to 100,000 tons of CO_2 every year, leaving magnesium and calcium carbonate veins in the rock. Kelemen estimates that by speeding up the process, peridotite could be used to store 1 billion tons of CO_2 per cubic kilometer of rock per year.

Fossil energy industries recognize the challenges that lie ahead as the planet warms and the international community begins to take action. "They know they're going to have to protect their investment by getting involved in carbon management," Kelemen said. ▪

"They know they're going to have to protect their investment by getting involved in carbon management."

-Peter Kelemen

Opposite page: *Smoke stack. (DJ Mattaar)* ***Left:*** *When olivine in peridotite reacts with carbon dioxide and water, it forms a carbonate. (Lamont-Doherty Earth Observatory)* ***Right:*** *Peter Kelemen examines carbonate veins in a rock formation in Oman. (Lamont-Doherty Earth Observatory)*



Exploring Our Changing Earth, in Real Time

Right now, scientists at Lamont-Doherty Earth Observatory are exploring undersea volcanoes, monitoring coastal erosion along hard-to-reach shorelines, and studying the movement of sea ice, all in real time. By loading drones with high-tech instruments and using satellites and undersea cables interacting with sensors in some of the most remote locations on Earth, they are uncovering the secrets of our planet.

"Real-time Earth observation is going to change the way science is done over the next 10 to 20 years," said Tim Crone, a marine geophysicist who is co-leading a Lamont-Doherty Earth Observatory initiative to push the frontier of real-time data about the planet. "We're on the precipice of a new kind of science, and technology is giving us an opportunity to do amazing things."

Lamont is one of the few research facilities in the world where scientists are putting all types of scientific platforms, from seafloor to space, to use for real-time data analysis. Data is coming in from cabled arrays crossing the sea floor, underwater vehicles, and aerial labs as large as airplanes and a small as drones. Satellites are beaming back data from seagoing sensors that are monitoring ocean chemistry and currents around the world.

Those real-time measurements are fueling breakthroughs across the sciences as they verify computer models and reveal unexpected changes.

> *"We're on the precipice of a new kind of science, and technology is giving us an opportunity to do amazing things."*
>
> *-Tim Crone*

Drone lab opens new landscapes to science

***Above left:** Elise Rumpf launches a small drone with a camera over Chile's Quizapu volcano. (Lamont-Doherty Earth Observatory) **Top right:** Christopher Zappa's team prepares a fixed-wing drone for a flight to study Arctic sea ice off Svalbard, Norway. (Christopher Zappa) **Bottom right:** Drone payload, (Christopher Zappa) **Opposite page:** A drone's-eye view of corals in Moorea, French Polynesia, where Alessio Rovere and colleagues are monitoring the health of a reef that underwent dramatic bleaching in 2015. (Alessio Rovere and Elisa Casella/ MARUM,Uni Bremen & Leibniz ZMT / Lamont-Doherty Earth Observatory)*

In the Arctic, oceanographer Christopher Zappa has been redesigning instruments typically found aboard research ships or aircraft and fitting them into drones that he flies low over the sea ice. The drones' range allows him to expand his study area and avoid interference from a ship's heat and movement, while also significantly cutting costs. The result is unmatched data on sea ice topography and movement and new insights into how sea ice breaks up and how the atmosphere and ocean affect one another.

"UAS's (unmanned aerial systems) are where autonomous and remotely operated underwater vehicles were 20 years ago. You had these great platforms, but scientists were just beginning to understand how to use them," Zappa said. "Today, there are underwater vehicles everywhere in the world's oceans. What's been lacking for UAS is the ability to put scientific-quality instrumentation into the payload. To do something really scientific grade requires significant engineering."

> *"UAS's are where autonomous and remotely operated underwater vehicles were 20 years ago. You had these great platforms, but scientists were just beginning to understand how to use them."*
>
> *-Christopher Zappa*

Zappa, a co-leader of the Real-Time Earth initiative with Crone and physical oceanographer Ryan Abernathey, is expanding that engineering capacity at Lamont through his UAS lab, which designs high-tech payloads with hyper-spectral imaging, lidar, thermal infrared cameras, and other sensors for scientific missions.

Scientific drones come in all sizes, from light helicopters you can launch from your hand to fixed-wing drones the size of small airplanes. Small quadcopters can't carry much more than a camera, but they are giving volcanologists Einat Lev and Elise Rumpf the ability to map lava flows and peer inside calderas. Alessio Rovere puts small drones to work monitoring coastal erosion and coral bleaching. While satellites can provide close-ups, their fly-by frequency, coverage, and data collection are limited, and clouds often obstruct the view. With drones, Rovere, a geologist, can get close to hard-to-reach stretches of shoreline without disturbing the land.

Zappa, whose sea ice work relies on more sophisticated instruments, uses larger fixed-wing drones with auto-piloted GPS navigation and 10-20 hours of flight time. With payloads the size of a soccer ball, Zappa can fly hyperspectral imaging systems that use light waves to infer what an object is made out of or how energy flows. He can examine algae in the water and how it affects surface heat budget, for example. Another payload drops buoys that profile the atmosphere and measure ocean temperature and salinity.

"UAS's allow scientists to get right up next to a glacier, something you would not normally do with a ship. If you want to look at a coastal region, you can routinely fly transects across the surf zone," Zappa said.

As costs come down, drones could even be flown into hurricanes to collect real-time data about wave height, momentum, and heat, he said.

Real-time data from the deep

In the oceans, Lamont scientists are using remote and autonomous underwater vehicles to explore the seafloor and measure the marine environment.

Zappa is partial to solar-powered drifters that connect to sensors on the seafloor or in the water column and can telemeter data to satellites for real-time monitoring. Robin Bell's Polar Geophysics Group, which built the IcePod to map Antarctica's Ross Ice Shelf from the air, deploys buoys for real-time monitoring of water temperature, salinity, and currents around the edges of the ice shelves.

Crone has spent much of his career developing instrumentation for a different kind of remote sensing system: a seafloor observatory with a fiber-optic cable running 300 miles from the coast of Oregon to an array of sensors. The sensors are now sending back real-time observations from Axial Seamount, a submarine volcano at a mid-ocean ridge where new ocean floor is being created. Marine geophysicist Maya Tolstoy used the real-time data to study a 2015 eruption there, starting with an uptick in earthquakes ahead of the eruption and monitoring how energy from the eruption moved through the water.

Processing rivers of data

"Everyone's science will get better from this."

-Tim Crone

All of this incoming data raises the demand for computer power and for smart ways to process and archive it.

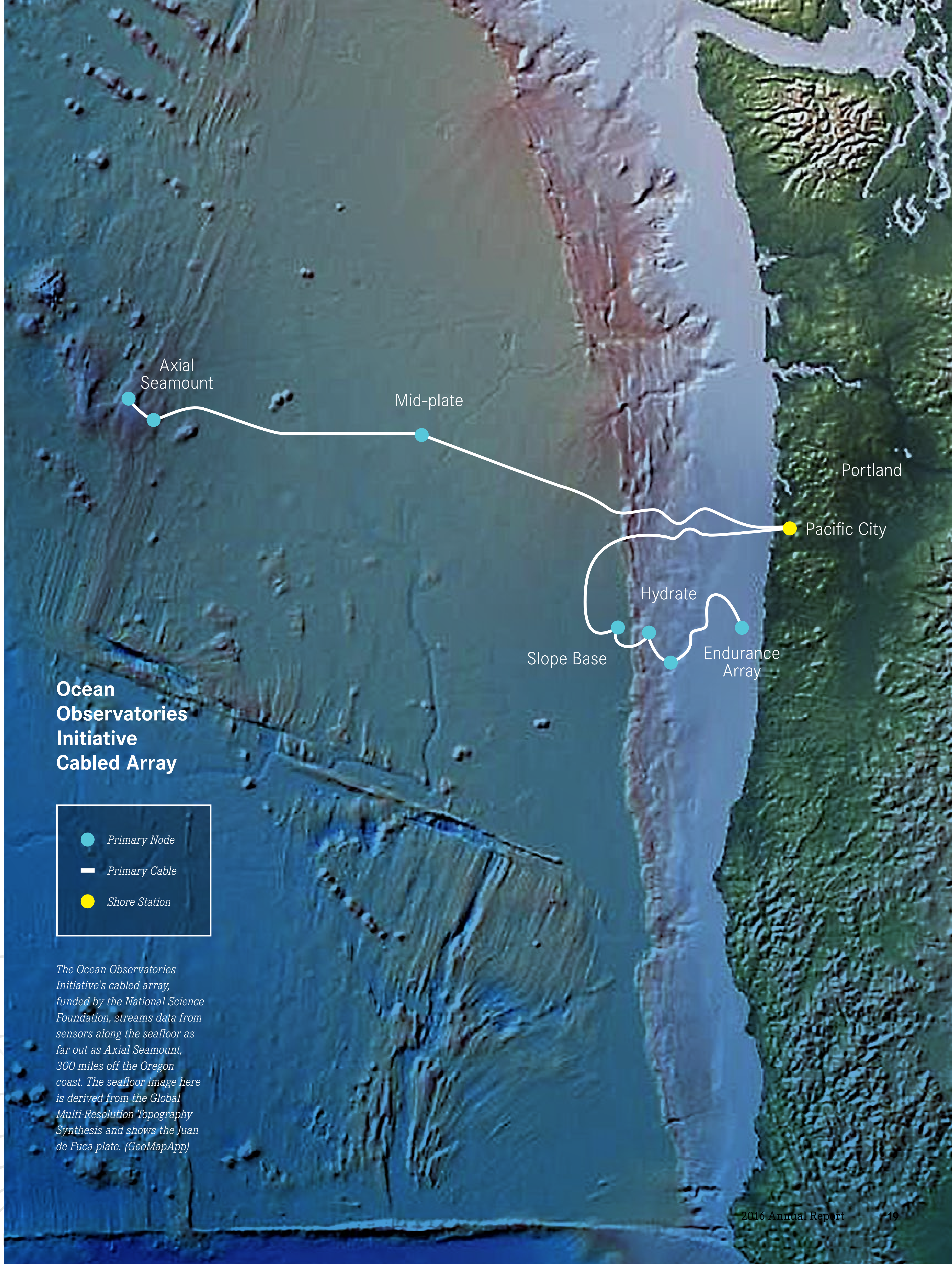
The Interdisciplinary Earth Data Alliance (IEDA), led by Kerstin Lehnert and Suzanne Carbotte at Lamont, plays a crucial role by storing scientific data from scientists around the world and making the data widely available along with tools for analysis. Abernathey, meanwhile, is working on ways to improve data system architecture and establish high-performance-computing capabilities tailored to Lamont's data needs.

"These platforms will be used for experiments in the coming years that we can't imagine today," Crone said. "The same thing goes for the internet and satellites that can connect us. It's about having a problem to solve, building the sensor or device, connecting it to a platform or a network, and bringing in data to start solving that problem."

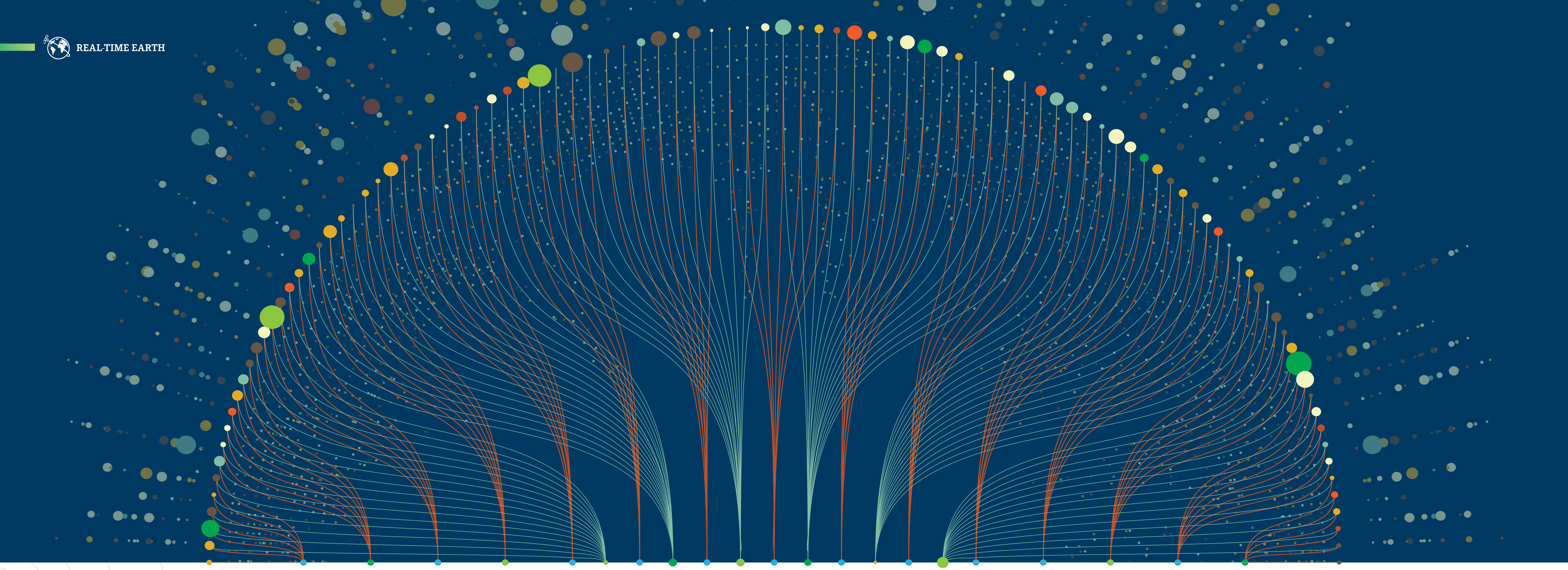
"This is the future," Crone said.

This is also Lamont's heritage. Lamont was built on founder Maurice "Doc" Ewing's vision of constant data collection and open data sharing to empower global research and discoveries. If Ewing's scientists didn't have the technology they needed, they built it themselves.

As Lamont's scientist-engineers continue to push the frontiers of science, the Real-Time Earth Initiative is taking data access to new levels. "Everyone's science will get better from this," Crone said, "because everyone will be able to tap into building new systems to observe the Earth." ▪



The Ocean Observatories Initiative's cabled array, funded by the National Science Foundation, streams data from sensors along the seafloor as far out as Axial Seamount, 300 miles off the Oregon coast. The seafloor image here is derived from the Global Multi-Resolution Topography Synthesis and shows the Juan de Fuca plate. (GeoMapApp)



IEDA:
Revolutionizing Big Data

Most research databases are narrowly focused. They might contain only seismic data from earthquakes, for example, or chemical data from volcanic rocks. The Interdisciplinary Earth Data Alliance (IEDA) set out to create a different kind of research experience, and the result is fueling groundbreaking multi-disciplinary discoveries worldwide.

Created and managed by scientists at Lamont-Doherty Earth Observatory, IEDA brings together diverse datasets from across geochemistry and marine geoscience into one system. Importantly, it provides the tools that allow scientists from a wide range of fields to easily search for and explore relationships among many different kinds of data.

"This is a new era of data mining," said IEDA Director Kerstin Lehnert, a geochemist and Doherty Senior Research Scientist at Lamont.

"Through IEDA, scientists can find the natural samples, the composition, the geochemistry of the samples. If you need to know the structure of the crust underneath those samples, you can get to the seismic data. You can check if there are experimental results for chemical composition from close to these rocks that can tell you where they come from. Are there any dated rocks? Where is geochronology in this particular area? The data starts to be networked, and it comes together in IEDA," Lehnert said.

Before IEDA, these kinds of data were largely inaccessible, often stored on scientists' local computers, in their lab notebooks, or fragmented throughout the scientific journals. By bringing the data together in an easily searchable format, IEDA has created a way for researchers to quickly access thousands of values for analysis and comparison. Two scientists were recently able to document a link between deep Earth geochemistry and a rise in oxygen in Earth's atmosphere by downloading 70,000 samples of continental igneous rock geochemistry from IEDA. Finding all the data would have taken years before IEDA was created.

"Integrating different kinds of observations and observations made from many different regions in order to gain a global perspective is a powerful way to gain new insights into science problems," said IEDA Associate Director Suzanne Carbotte, a marine geophysicist and Bruce C. Heezen Lamont Research Professor.

"This is a new era of data mining."
-Kerstin Lehnert

Understanding the data needs of scientists

IEDA combines EarthChem, the world's largest geochemistry database, with the Marine Geoscience Data System, which serves data for studies of seafloor and deeper crust and mantle processes.

EarthChem started as the petrology database PetDB at Lamont in 1996, when relational databases were just beginning to be developed. Today it includes several partner databases and some 400,000 samples and 20 million analytical values from across geochemistry, along with the tools to mine the collections. The EarthChem Portal also connects with other large databases, including Germany's GeoRock, a database in Japan, and the U.S. Geological Survey's national geochemical database, allowing IEDA users to search across all these major databases at once.

The Marine Geoscience Data System traces its origins to the early 1990s, when Lamont oceanographer Bill Ryan launched a first-of-its-kind web-accessible database of seafloor bathymetry data. Building upon this early resource, the Marine Geoscience Data System serves a wide range of marine geoscience data collected by research ships and other platforms, including data back to 1954. It includes global bathymetry data, seafloor imagery, seismic data that provide cross-sectional views beneath the seafloor, as well as other multidisciplinary data from a series of national research programs.

The IEDA system is also uniquely equipped to incorporate smaller, niche data sets, which it then makes open and accessible through interactive, map-based interfaces and other tools.

One focus is compiling what are known as "long-tail" data: what scientists do with observational data in their labs and how they analyze it.

"A lot of what people do with different data sets in their labs can be very innovative and unique and new," said Vicki Ferrini, an oceanographer who works with IEDA's marine geophysics data. "It all gets out through scientific publications, interpretations of it get out, but actually making the data that supports those publications accessible and reusable and into something that can be built upon is what we're really aspiring to do."

Part of IEDA's success stems from its team's close connections to science. Lehnert, Carbotte, and many of the IEDA team members are scientists who are intimately familiar with scientific workflows and how scientists search for and analyze data. They know what scientists need and how to customize solutions and incorporate different types of results.

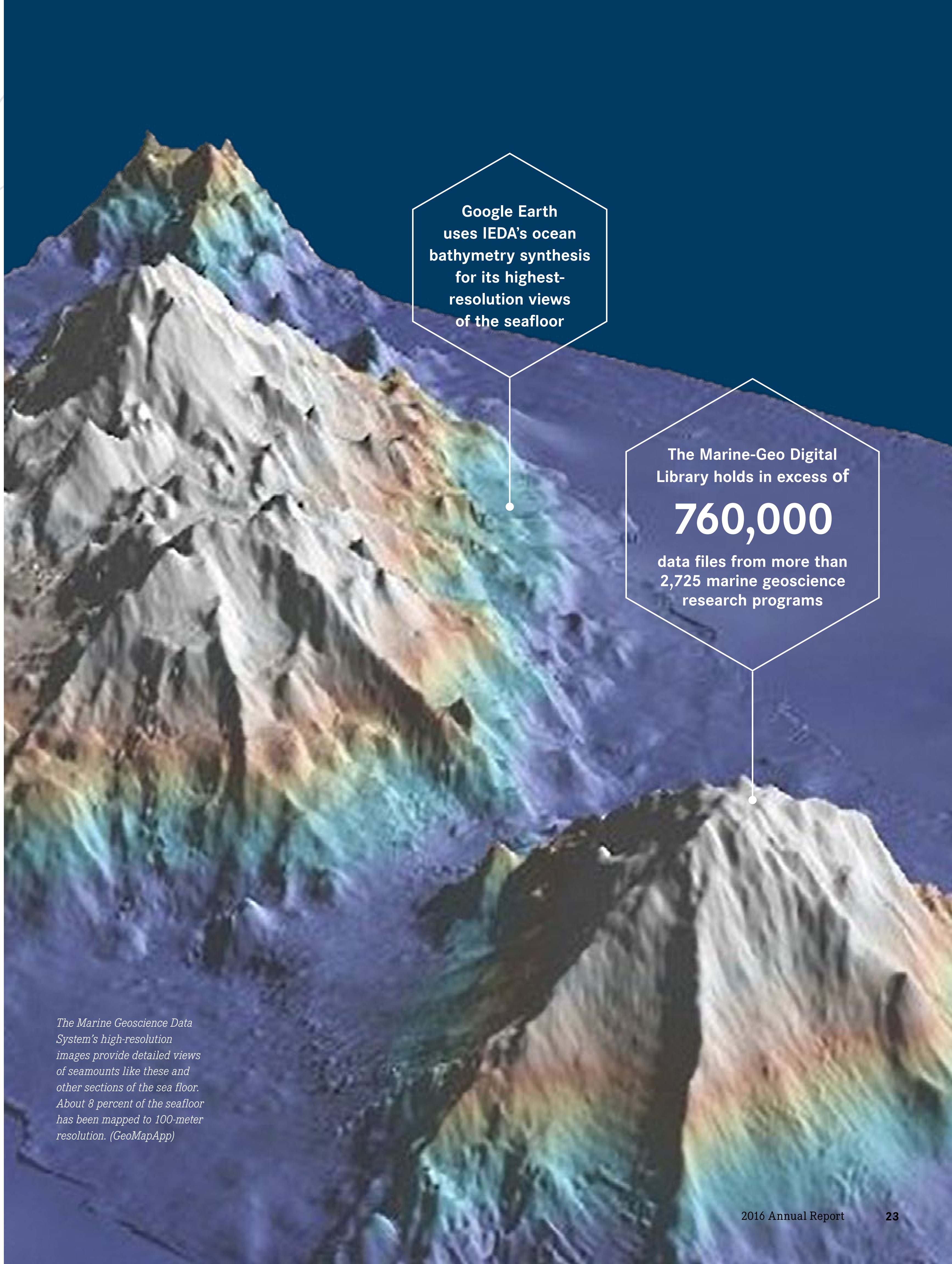
In addition to the repositories and analysis tools, IEDA has identification systems that link published papers to their original data and samples. Openness of data is critical to scientists' ability to test theories and reproduce results, and data management plans are now required by the National Science Foundation, which supports IEDA. IEDA also makes data and samples available for reuse so scientists don't have to collect the same kinds of data from the same location again, saving time and money.

"IEDA builds upon Lamont's rich legacy of acquiring diverse multidisciplinary data to address science questions that dates back to the earliest days of Doc Ewing and the globally ranging expeditions of Lamont ships."

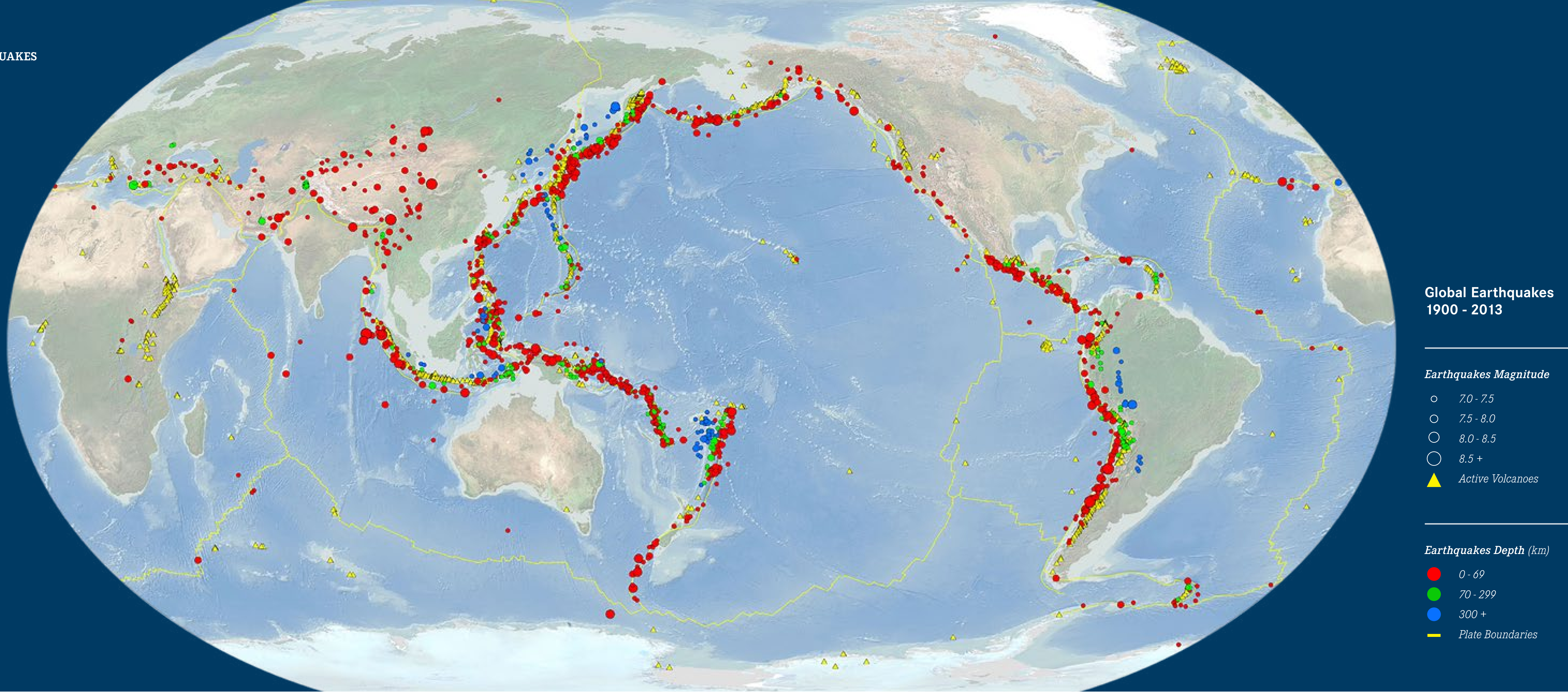
-Suzanne Carbotte

"IEDA builds upon Lamont's rich legacy of acquiring diverse multidisciplinary data to address science questions that dates back to the earliest days of Doc Ewing and the globally ranging expeditions of Lamont ships," Carbotte said. Maurice "Doc" Ewing, Lamont's founding director, ordered all ocean expeditions to routinely collect diverse sets of geoscience and oceanographic data. When new scientific questions arose, data and samples were often there for analysis.

"We're making the data available, and people can take the data for whatever they need," Lehnert said. ▪



The Marine Geoscience Data System's high-resolution images provide detailed views of seamounts like these and other sections of the sea floor. About 8 percent of the seafloor has been mapped to 100-meter resolution. (GeoMapApp)



Learning from Slow Slip Earthquakes

Off the coast of New Zealand, there is an area where earthquakes happen in slow-motion as two tectonic plates grind past one another. The Pacific plate is moving under New Zealand at about 5 centimeters per year there, pulling down the northern end of the island as it moves. Every 14 months or so, the interface slowly slips, releasing the stress, and the land comes back up.

Unlike typical earthquakes that rupture over seconds, these slow-slip events take more than a week, creating an ideal lab for studying fault behavior along the shallow portion of a subduction zone.

In 2015, Spahr Webb, the Jerome M. Paros Lamont Research Professor of Observational Physics at Lamont-Doherty Earth Observatory, and an international team of colleagues became the first to capture these slow-slip earthquakes in progress using instruments deployed under the sea. The data they collected from the New Zealand site will help scientists better understand earthquake risks, particularly at trenches, the seismically active interfaces between tectonic plates where one plate dives under another.

"We don't yet understand the stickiness of the interface between the two plates, and that is partly what determines how big an earthquake you can have," Webb said. "In particular, we care about the stickiness near the trench, because when you have a lot of motion near a trench, you can generate big tsunamis."

Previously, scientists thought that the soft sediments piled up near trenches were usually not strong enough to support an earthquake and that they would dampen the slip, Webb said. "We're recently seen a lot of big tsunamis where there has been large slip right close to the trench," he said.

One reason the 2011 Tōhoku earthquake in Japan was so devastating was that part of the interface very close to the trench moved a large distance, around 50 meters, pushing the water with it, Webb said. While the main part of the Tōhoku earthquake involved uplift of only a few meters, the part near the trench doubled the size of the tsunami, leading to waves almost 40 meters high at some points along the coast.

To be able to anticipate tsunami-producing earthquakes and more accurately assess regional risks, scientists are studying why some areas of trenches have these slow-slip events, why others continuously creep, and others lock up and build strain that eventually erupts as a tsunami-generating earthquake.

Above: A map of major earthquakes from 1900 to 2013 shows the connection between tectonic plate boundaries and large earthquakes. The yellow lines mark plate boundaries; the dots are earthquakes greater than magnitude 7. (USGS)

The Alaska Risk

Webb has his sights next on the Aleutian Trench, just off Kodiak Island, Alaska. It is one of the most seismically active parts of the world. A large tsunami-generating earthquake there could wreak havoc not only in Alaska but along the west coast of North America and as far as Hawaii and Japan, as the Good Friday earthquake did in 1964.

Lamont scientists, including Donna Shillington and Geoffrey Abers, have spent years studying the structure of the Aleutian Trench and what happens as the Pacific plate dives beneath the North American plate. Webb and a large group of collaborators now want to find out where sections of the trench are sliding and where sections are locking to help understand what determines where it locks. Finding slow-slip earthquakes could help reveal some of those secrets.

To study the New Zealand slow-slip event, Webb and his colleagues installed an array of 24 absolute pressure gauges and 15 ocean-bottom seismometers directly above the Hikurangi Trough, where two plates converge. Absolute pressure gauges deployed on the seafloor continuously record changes in the pressure of the water above. If the seafloor rises, pressure decreases; if the seafloor moves downward, pressure increases due to the increasing water depth. When the slow-slip event began, the instruments recorded how the seafloor moved.

The scientists found that parts of the Hikurangi interface slipped and others didn't during the slow-slip event. "It may be that much of the interface slips in these events but you have a few places that are locked, and those finally break and create earthquakes and tsunamis that cause damage," Webb said.

Most of the instruments used in the New Zealand study were built at Lamont in the OBS (ocean-bottom seismometer) lab started by Webb.

In Alaska, Webb and his collaborators have proposed an experiment that would again use a large numbers of Lamont-built ocean-bottom seismometers and pressure gauges, this time to collect data near Kodiak Island. Alaska is a special challenge for seafloor measurements. The ocean is quite shallow south of Alaska before deepening near the Aleutian Trench, and seismic instruments on the seafloor can be moved by strong currents or damaged by bottom trawling. Webb and the team in the OBS lab at Lamont developed a solution: they built heavy metal shields that sink to the sea floor with the seismometers to protect them.

Once data from the instruments are collected, they will be made publicly available so seismologists across the country can begin to analyze the records in search of clues to the area's earthquake behavior.

By detecting patterns of earthquakes, scientists can help regional engineers plan construction to better withstand worst-case earthquake scenarios, but predicting earthquake remains elusive.

"If we start seeing precursors based on the off-shore data, then maybe we'll also get some predictive ability," Webb said. "The hope is if you have better off-shore measurements, you'll start to understand things better, and maybe there is some sign of motion happening before the earthquake that will provide some warning." ▪

Bottom left: *A Lamont ocean-bottom seismometer. (Lamont-Doherty Earth Observatory)* ***Bottom right:*** *The OBS lab at Lamont builds ocean-bottom seismometers. (Lamont-Doherty Earth Observatory)* ***Opposite page:*** *An ocean-bottom seismometer is deployed with a Lamont-built shield to protect it from damage. (Lamont-Doherty Earth Observatory)*

How Far Did Sea Level Rise?

It's No Walk-on-the-Beach Calculation

Figuring out how far sea level rose during past warm periods in Earth's history starts with a walk on the beach, a keen eye for evidence of ancient shorelines, and a highly accurate GPS system. The math isn't as simple as subtracting the distance from the old shoreline to the water's edge, though. As massive ice sheets retreated during past ice ages, their weight on the land below lifted and the land rebounded. On longer time scales, circulation within the Earth's mantle has changed the shape and height of the crust, as well.

Lamont-Doherty Earth Observatory marine geologist Maureen Raymo has been at the forefront of the discovery of these forces and of efforts to account for them. Her goal – working in collaboration with Robin Bell's Polar Geophysics Group through their joint Changing Ice, Changing Coastlines Initiative – is to answer two critical questions: how far will sea level rise as the planet warms now, and how fast?

The answers require knowledge of how the ice sheets are changing now and how sea level rose long ago when global temperatures were warmer than today.

While Bell's team focuses on the ice sheets, Raymo and her colleagues and graduate students have been mapping old shorelines and collecting samples around the world, from Australia's Cape Range to Argentina's rocky coast.

Above: *An eroded shoreline. (Filip Fuxa)*

From beaches to clean labs

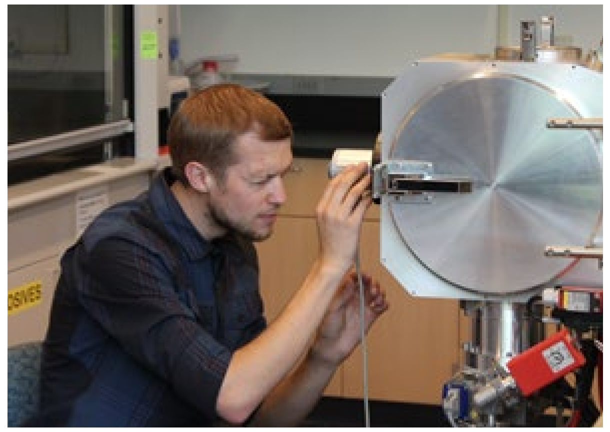
Scientists can spot changes in the fossil structures along the shoreline by using drones and planes equipped with lidar. But to figure out the age of ancient stranded reefs, they need to hike in with rock hammers and GPS.

In Western Australia, Lamont graduate student Michael Sandstrom, with colleagues from both Columbia University and the University of Western Australia, spent weeks walking the coast with heavy packs this summer, documenting the height and location of old shorelines and chipping off samples to take back to the lab.

__Above:__ Waves have eroded this old coral reef, now well above modern sea level. (Michael Sandstrom) __Above right:__ Michael Sandstrom uses a thermal ionization mass spectrometer to help narrow down the ages of ancient shoreline samples. (Lamont-Doherty Earth Observatory) __Opposite page:__ Michael Sandstrom collects samples from corals embedded in an ancient reef in the Cape Range region of Australia. He will use isotopes from the samples to determine the age of the reef to help determine how sea level rose in the past. (Dan Marone)

"In a modern beach environment there are a lot of indicators of where current-day sea level is – tidal notches, subtidal bedding, articulated bivalves (unopened shells can be indicators of intertidal zones). Once we get an idea of what the modern environment looks like, we hike inland looking for the same assemblages and indicators, and we can say that when this past shoreline formed, sea level was at this point," Sandstrom said.

Back at Lamont, home to one of the most advanced clean labs in geochemistry, Sandstrom uses a thermal ionization mass spectrometer to narrow down the ages of old shoreline samples. One test separates



out the isotopes strontium-86 and strontium-87. The isotopes' relative levels in seawater have changed over millions of years, creating something of a time-stamp that scientists can use to determine when the shells were alive. Sandstrom also uses cosmogenic dating techniques with beryllium-10 to determine how long ancient reefs have been above the water level where they would be exposed to cosmic rays. The test provides a minimum age for checking against the strontium results. With younger corals, Sandstrom can also use uranium-thorium dating, by which he compares levels of uranium-234 to thorium-230 to determine how long the uranium-234 has been decaying.

The GPS data paired with the dates allow the scientists to track the rise and fall of old shorelines and calculate the influence of other forces.

"All of these shorelines were deposited basically horizontally when they were formed. Any sort of local deformation is an indication of either tectonics or dynamic topography," Sandstrom said. "If we're able to get really accurate ages, we can tell the relative uplift rates and can calculate roughly what elevation local sea level was. Then we can start to look at other climate records and figure out how sea level relates to things like atmospheric CO2 concentration, what climate was like, what the ocean currents were doing."

Rebounding land and mantle movement

Raymo, a Bruce C. Heezen Lamont Research Professor at Lamont, was drawn to sea level research by a paradox. Fossil evidence from the mid-Pliocene warm period, about 3 million years ago, indicates that temperatures were 1 to 2 degrees Celsius warmer than today. However, sea level estimates from that time varied widely, ranging from 10 meters to about 40 meters above the present level, implying very different polar ice sheet responses for a small amount of warming. Why did different studies come to such different conclusions about the height of past sea levels?

"It turns out, the answer was twofold: no one had corrected their field observations for isostasy, or the deformation of the crust in response to the addition or removal and ice and ocean water – we figured out how to do that; and no one had recognized the really strong influence of dynamic topography, which also deformed ancient shorelines," Raymo said.

"No one had corrected their field observations for isostasy, or the deformation of the crust in response to the addition or removal of ice and ocean water – we figured out how to do that."

-Maureen Raymo

***Above:** Marine geologist and paleoceanographer Maureen Raymo, Bruce C. Heezen Lamont Research Professor, is one of the world's leading sea-level researchers. (Lamont-Doherty Earth Observatory)*

***Opposite page top:** These rocky outcroppings in Australia's Cape Range coast are remnants of ancient wave-cut shorelines. Three old shorelines sampled by the scientists are visible in the photo. (Michael Sandstrom)*
***Opposite page bottom:** The colored lines on the satellite image of Australia's southern Cape Range mark ancient shorelines from four periods when the ocean was higher than today. (Michael Sandstrom)*

While working along the U.S. East Coast a few years ago, Raymo and Alessio Rovere, then a postdoctoral research scientist at Lamont, noticed that the calculations of mid-Pliocene sea levels 3 million years ago were still too varied, even when they accounted for isostasy. They realized then that dynamic topography – the patterns of uplift and subsidence of the crust induced by movement in Earth's mantle over time scales of hundreds of thousands of years – was playing an important role.

Raymo's team is now working on isolating the influence of dynamic topography on ancient shorelines around the world.

Today, sea level is rising at about 3 millimeters per year as rising temperatures cause the oceans to expand and glaciers to melt. At the end of the last glacial period, about 15,000 years ago, it rose much faster, reaching about 40 mm per year. Understanding what happened then and in other periods past is allowing scientists to make better estimates of the risk ahead. ▪

Tropical Cyclones on Track to Grow Fiercer

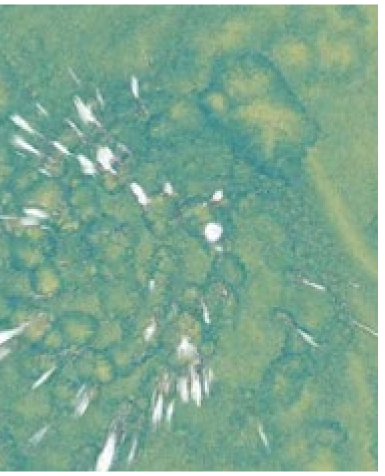
Powerful tropical cyclones are expected to become even stronger as the planet warms. That trend hasn't become evident yet, but it will, scientists say.

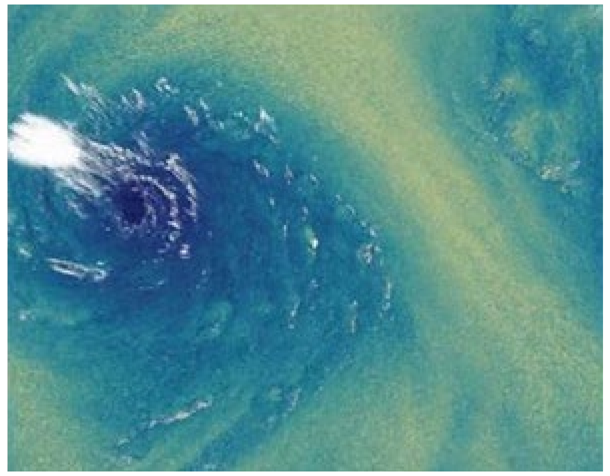
So far, the warming effects of greenhouse gases on tropical cyclones have been masked, in part by air pollution, according to new research led by Adam Sobel, a professor at Columbia University's Lamont-Doherty Earth Observatory and School of Engineering, along with Lamont physicist Suzana Camargo and post-doctoral research scientists Allison Wing and Chia-Ying Lee.

Over the past century, tiny airborne particles called aerosols largely canceled out the effects of planet-warming greenhouse gas emissions when it came to tropical storm intensity, the scientists found. Aerosols cool the climate by absorbing and reflecting sunlight. That might sound like a good thing, but many of those particles come from the burning of fossil fuels and wood, and they contribute to acid rain, smog, and lung damage.

That compensating effect won't continue if greenhouse gas warming continues to increase, Sobel said. The levels of man-made aerosols in the atmosphere have declined as vehicles and power plants have added filters and scrubbers to reduce their impact on human health, but greenhouse gas concentrations continue to rise.

Image: Typhoon Nepartak lashed Taiwan with 150-mile-per-hour winds and flooded parts of China in 2016. (NASA)





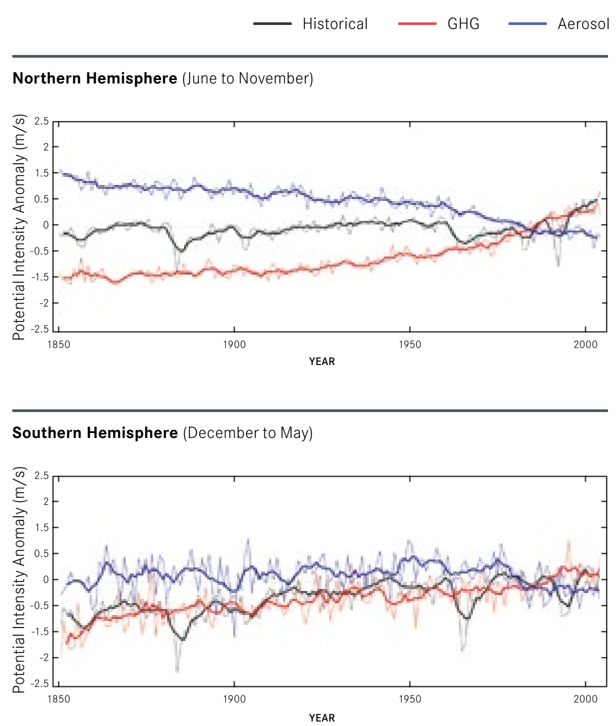
Extreme weather research is data-intense

Above: *Using computers, Allison Wing simulates how clouds can self-aggregate into tropical cyclones. Watch the animation on Lamont's Vimeo channel at vimeo.com/LDEO. (Allison Wing)* ***Opposite page:*** *NASA's Terra satellite captured this image of Typhoon Nepartak approaching Taiwan on July 7, 2016. (NASA Goddard MODIS Rapid Response/Jeff Schmaltz)*

Sobel, Camargo, and their colleagues working on extreme weather research at Lamont are at the forefront of improving our understanding of how tropical cyclones, known regionally as typhoons or hurricanes, behave and how climate change will affect them.

The work is data-intense. The scientists pull from many types of weather, ocean, and atmospheric data, including output from sophisticated computer models, to expand understanding of how tropical cyclones have changed and the physical mechanisms by which climate affects extreme weather. Lamont's open-access Climate Data Library provides some of that data. It supports analysis and visualization of a large array of observational and model data, including over 320 terabytes of CMIP5 climate model data, and hosts other large datasets used by international collaborations such as the Hurricane Working Group and Drought Task Force, said Research Scientist Naomi Henderson.

The Lamont scientists' research is leading to many practical applications, particularly for urban planning, such as their development of a new tropical cyclone risk model that incorporates climate factors in determining the probability that a tropical cyclone will make landfall at a given location. Through the Initiative on Extreme Weather and Climate, Sobel and Camargo are also reaching out to business and policy leaders who have the power to use that information to take action.



Above*: The charts show potential intensity anomaly over time using the CMIP5 climate model project. The black line is historical potential intensity, blue is the influence of aerosols only, red is the influence of greenhouse gases only. ©Suzana Camargo*

Detecting the influence of climate change

To understand the effects that greenhouse gases and aerosols have on tropical cyclones worldwide, the scientists used existing climate model simulations to analyze changes in potential intensity, which predicts the maximum intensity that tropical cyclones could reach in a given environment.

Many factors contribute to a tropical cyclone's intensity. At the most basic, the storm's convective strength – the motion of air rising from the ocean surface to the atmosphere – depends on the temperature difference between the surface ocean and the upper atmosphere. Computer models that simulate the physics of tropical cyclones suggest that this difference should increase as the climate warms, and that tropical storm strength should increase with it.

Through their analyses, the scientists found that the largest future increases in tropical cyclone potential intensity are expected to be at the margins of the tropics, particularly in the Atlantic and Pacific, but these increases are only beginning to become visible in observations, and their attribution to human influence is still debatable due to the complicating effects of natural variations.

Model calculations indicate that aerosols have about twice the effect of greenhouse gases on a tropical cyclone's potential intensity. So while greenhouse gas levels have been higher than aerosol levels for many decades (which is why the planet has warmed by about 1.5°F since the Industrial Revolution) they only recently surpassed the cooling effect of aerosols in terms of their influence on tropical cyclone intensity.

"The fact that global warming's fingerprints don't yet jump out at us when we look at hurricanes isn't surprising – it's what current science tells us we should expect. The same science tells us those fingerprints will show up eventually in more ultra-powerful storms."

-Adam Sobel

We have seen harbingers of that change in recent years: Typhoon Haiyan, also known as Yolanda, killed more than 6,300 people as it devastated parts of the Philippines as a Category 5 storm in 2013. Last year, Hurricane Patricia became the second most intense tropical cyclone on record when its sustained winds reached 215 mph before weakening to hit Mexico with winds still powerful at 150 mph. ▪

Students isolated microbes to create a battery while participating in the Secondary School Field Research Program at Lamont. (John Bjornton)

Education

Education of diverse audiences is a core component of Lamont's mission, from the graduate students who learn by working alongside our scientists, to high school students and teachers who participate in summer fieldwork programs and workshops, to community members who attend our scientists' public talks and participate in science events.

During fiscal year 2016, we focused on expanding our education programs, helping our scientists incorporate education and outreach activities into their federal research proposals, and inaugurating new internship programs with secondary schools in the metropolitan region. These efforts have strengthened the connections between Lamont's world-leading research in Earth and environmental sciences and STEM (science, technology, engineering, and math) education initiatives.

Lamont also received National Science Foundation funding approval for two new proposals this fiscal year: one will support a project cultivating ethical practices for young STEM learners, and the other will develop broader participation of under-represented groups in STEM.

Education of diverse audiences is a core component of Lamont's mission.

STEM Partnerships

Above top: *Students in the Secondary School Field Research Program work in Lamont labs as they conduct summer research. (John Bjornton)* ***Above bottom:*** *The new Climate and Life internship program is expanding the number of high school and undergraduate students learning on campus each summer. (Einat Lev)*

The Observatory has focused on establishing structured programs with schools and school districts for students to participate in educational research experiences with Lamont scientists in their laboratories. In fiscal year 2017, Lamont will have formal partnerships with three schools: the Lycée Français de New York in Manhattan, Cresskill High School in New Jersey, and Uncommon Charter High School in Brooklyn. The programs will allow students to learn key scientific skills, attend lectures, network with scientists, and gain a greater understanding of careers in science. The students will produce a scientific poster and have an opportunity to present their experiences and research to their school communities.

The support of foundations and federal agencies helped to bring nearly 80 future scientists to campus during the summer. The Lamont Summer Intern Program immersed 34 undergraduates in intensive 10-week research projects. The Secondary School Field Research Program brought 30 high school students, 13 undergraduates, and nine high school teachers for six weeks of field and laboratory research. Lamont also has ongoing partnerships with the Manhattan Center for Science and Mathematics and the network of Outward Bound Schools in New York.

Field trips and professional development workshops on the Lamont campus drew more schools and groups to campus. Since January 2016, nine school groups have visited the campus for field trips, and more scientists are participating in these opportunities to increase their outreach activities and engage with new groups.

Community Outreach

Lamont has always taken an active role in outreach events in the New York area. In 2016, Lamont scientists participated in events at the American Museum of Natural History; the Intrepid Sea, Air, and Space Museum; St. Thomas Aquinas College; the SUBMERGE Marine Science Festival; and the World Science Festival. These events drew more than 250,000 people, and numerous labs at Lamont shared their science with the public. In the coming year, additional career events featuring Lamont campus scientists will be organized.

Lamont has also started to offer workshops and programs to organizations that are engaged and involved in STEM education. Locally, we have started to work with Outward Bound, which operates 11 public schools in New York City using a model rooted in Expeditionary Learning Education and grounded in the idea that adventure, community service, and other forms of engaging experience can be used to teach and motivate young people. We also established a partnership with the STEM education office at the New York City Department of Education, and in the coming year we will be offering a series of professional development workshops to STEM teachers in New York.

Department of Earth and Environmental Sciences

Left: *Margie Turrin gets local schools involved in the health of the Hudson River through the Day in the Life of the Hudson River Estuary event. (Lamont-Doherty Earth Observatory)* ***Right:*** *Graduate student Kyle Frischkorn works with phytoplankton in the Dyhrman Lab. (Lamont-Doherty Earth Observatory)*

Much of our formal education is taught through the Department of Earth and Environmental Sciences, which the National Research Council named the best Earth and environmental science Ph.D. program in the country, a ranking that reflects Lamont's exceptional people, resources, and affiliated programs. The graduate students bring enthusiasm and innovative ideas, lending new energy to our investigations and inspiring future research.

In Fall 2016, the department welcomed 17 new graduate students. Many of our new and continuing graduate students were recipients of prestigious fellowships this past year. Among them:

- Six were recipients of National Science Foundation Graduate Research Fellowships: Alexandra Boghosian, Megan Frieberger, Sean Kinney, Tierney Larson, Kira Olsen, and Rebecca Trinh.
- Joshua Maurer received a NASA Earth and Space Science Fellowship, designed to ensure continued training in disciplines that contribute to NASA's scientific goals.
- Alejandra Borunda received a Ford Foundation Dissertation Fellowship, created to increase the diversity of college and university faculties.

Awards and Honors

Lamont-Doherty Earth Observatory is home to 11 members of the National Academy of Sciences, two National Medal of Science recipients, and a McArthur "Genius Grant" winner. Scientists on campus receive a wide variety of honors and awards for their work. Here are a few highlights from the past year.

Maureen Raymo was elected to the National Academy of Sciences, one of the highest honors awarded to scientists in the United States. Raymo is a marine geologist and paleoceanographer whose name is connected with key theories about sea-level rise and how ice ages wax and wane.

Christopher Scholz received the Seismological Society of America's Harry Fielding Reid Medal, the society's top honor, for his pioneering work in rock mechanics. The SSA cited Scholz's skill at communicating earthquake science and his wide range of contributions over a nearly 50-year career.

Ryan Abernathey was named a Sloan Research Fellow and received a CAREER grant from the National Science Foundation. Abernathey is an oceanographer whose work focuses on mesoscale turbulence, which contributes strongly to the mixing of heat and water from different parts of the oceans.

Nicolás Young received the Blavatnik Award for post-doctoral scientists for his development and application of novel geochemical techniques to measure changes in ice sheets in response to shifting climate and their contributions to sea level rise. Young is now a Lamont Assistant Research Professor.

Chris Small was honored by the Association of American Universities and members of Congress with the Golden Goose Award for his work on hypsographic demography, the study of population by altitude. The research has had far-reaching applications by companies including Intel and Procter & Gamble.

Terry Plank was elected to the American Academy of Arts and Sciences, a prestigious honorary society that dates back to 1780. Plank, a geochemist, probes Earth's interior to study magmas generated by plate tectonic processes, the recycling of Earth's crust, and how volcanoes erupt.

Peter Schlosser was elected to the German National Academy of Sciences, the Deutsche Akademie der Naturforscher Leopoldina. Schlosser, a geophysicist, was honored for his contributions to understanding water movement in natural systems using trace substances such as radiocarbon.

Suzanne Carbotte was named a fellow of the American Geophysical Union. Carbotte is a marine geophysicist whose work focuses on the formation of oceanic crust at mid-ocean ridges. She also is a leader in geoinformatics and serves as Associate Director of the Interdisciplinary Earth Data Alliance (IEDA).

Development

Lamont-Doherty's research and education initiatives are funded through a combination of public and private support. It is through the extraordinary generosity of friends, alumni, and staff that we are able to advance Lamont's contribution to the scientific knowledge needed to understand the changes affecting our planet and to make wise choices for a more sustainable future. Every gift helps, and every donor becomes a partner with a crucial role in helping us to uncover the complexities of the Earth system and develop approaches that can lead to a better quality of life for future generations.

We received several remarkable gifts during the past year. Among them, the Gordon and Betty Moore Foundation donated $2.6 million, including $2.2 million for Lamont's Changing Ice, Changing Coastlines initiative to support instrumentation for high-resolution mapping of the sea floor beneath the Ross Ice Shelf in Antarctica. The World Surf League, through its philanthropic arm WSL PURE, donated $1.5 million to support Lamont-Doherty's Center for Climate and Life and our scientists as they lead research in ocean health and ecosystems, ocean acidification, sea level rise, and the role the oceans play in climate change.

We are deeply appreciative of the continued generosity of the G. Unger Vetlesen Foundation, which provided $761,000 during fiscal year 2016. The Foundation's decades of support have enabled the Observatory to recruit and retain key members of our staff who lead pioneering research programs and increase our understanding of the processes that govern the workings of our planet, particularly in the broad field of climate science.

We also acknowledge with gratitude the generosity of The Alfred P. Sloan Foundation, The Brinson Foundation, the Comer Science and Education Foundation, the University of Hawaii Foundation, and Riverkeeper, Inc., for their continued support, and we extend our thanks for the funding received from the American Chemical Society, the Robert and Catherine Murray Foundation, and the Schlumberger Foundation.

Advisory Board

The Lamont Advisory Board is comprised of 17 community leaders, donors, loyal friends, and alumni who are committed to our mission to generate fundamental, actionable knowledge about the origin, evolution, and future of the natural world. The Board meets quarterly and provides advice and support to the Observatory. Sarah E. Johnson, a film producer and philanthropist, continued her leadership as chair of the Advisory Board in 2016.

Alumni Board

Lamont's Alumni Board, led by Greg Mountain ('81), is made up of former graduate students, researchers, and staff who strive to promote the welfare of Lamont by acting as advocates and supporters of the Observatory's mission. Members play an important role in fostering communication and interaction among Lamont alumni.

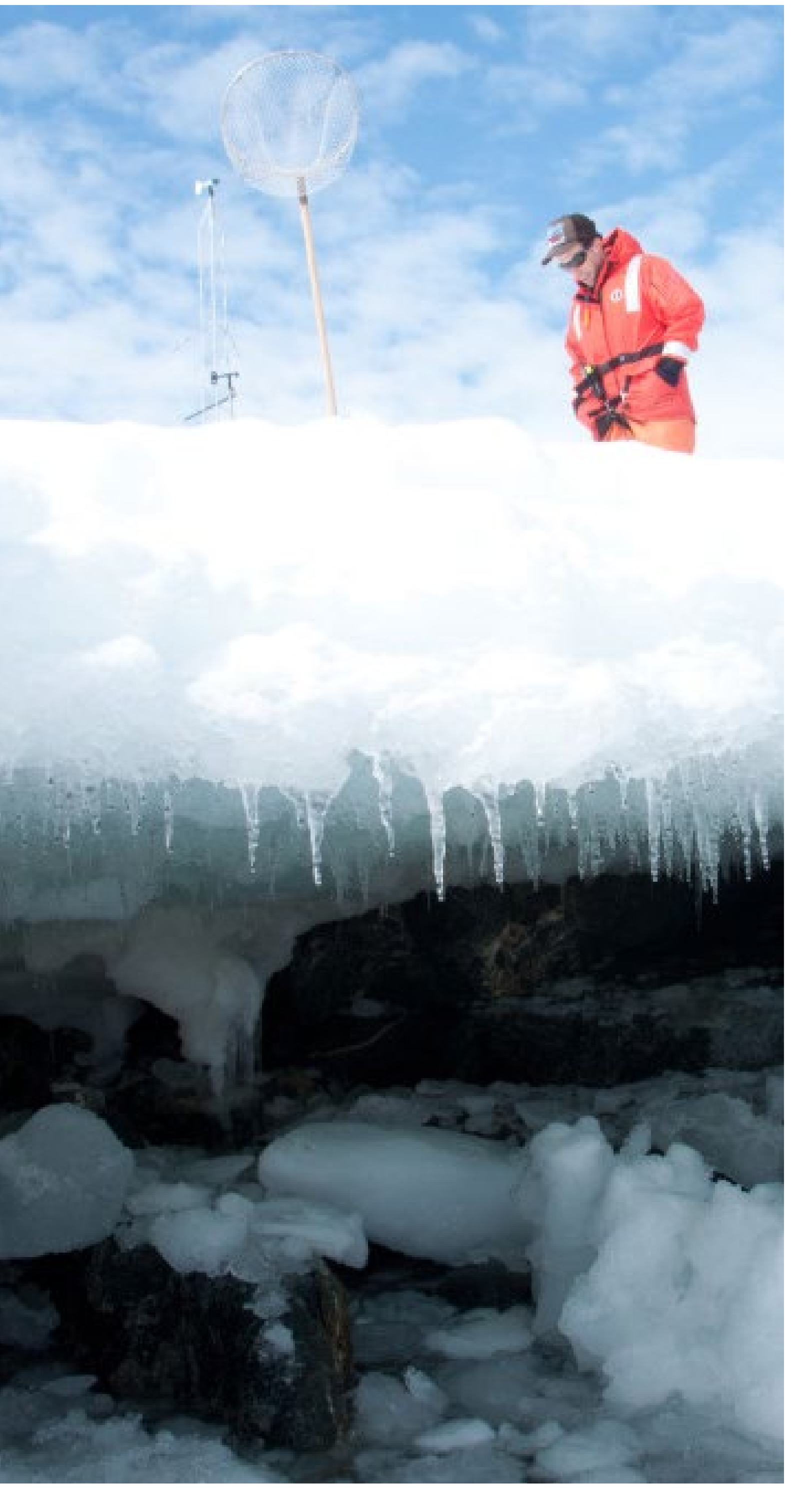
We encourage alumni to connect with us and experience the value of maintaining ties across miles and years, whether at our annual Alumni Reception at the American Geophysical Union Fall Meeting each December or on visits to our campus.

Please sign up for our e-newsletter to receive updates about our research and educational activities. You may reach us at development@ldeo.columbia.edu

For a list of all of our generous supporters this past year, please see page 48.

Financials

Statement of Activities



Sources of revenue

(in $1,000s)

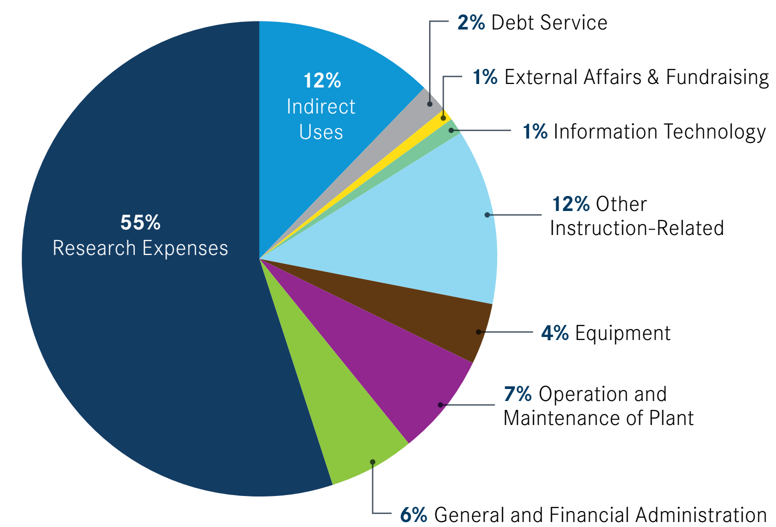
Sources of revenue	FY15	FY16
National Science Foundation	39,588	42,360
National Oceanic and Atmospheric Administration	1,588	2,036
National Aeronautics and Space Administration	4,543	3,971
National Institute of Environmental Health and Safety	1,589	1,733
U.S. Geological Survey	4,308	658
Office of Naval Research	1,687	1,146
New York State	99	55
Department of Energy	709	1,169
Miscellaneous Federal Funds	845	857
Environmental Protection Agency	253	257
New York City Department of Environmental Protection		20
Total Government Grants - Direct & Indirect	**55,208**	**54,128**
Private Grants	2,669	3,548
Gifts	1,829	1,932
Endowment Income	6,824	7,357
Miscellaneous	593	515
Indirect Sources	10,163	8,291
Total Non-Governmental Sources	**22,077**	**21,643**
Total Sources	**77,285**	**75,771**

Uses of Revenue

(in $1,000s)

Uses of Revenue	FY15	FY16
Research Expenses	44,228	42,247
General and Financial Administration	4,221	4,485
Operation and Maintenance of Plant	5,321	5,216
Equipment	1,380	3,369
Other Instruction-Related	7,444	8,807
Information Technology	776	783
External Affairs and Fundraising	1,139	660
Debt Service	1,239	1,401
Indirect Uses	10,919	9,334
Total Uses of Revenue	**76,668**	**76,302**
Net Operating Gain/(Loss)	**618**	**(531)**
Capital Expenses	(724)	(607)
Subtotal Non-Operating Expenses	**(724)**	**(607)**
Beginning Fund Balance	**8,702**	**8,007**
Ending Fund Balance	**8,007**	**8,396**

Breakdown of Revenue Uses



Our Donors

We are grateful to the many friends and alumni who sustain our research and educational endeavors through their financial contributions. Annual giving is critical to the advancement of our mission, the stability and ongoing operations of the Observatory, and the maintenance and stewardship of our campus.

The following gifts were made to Lamont between July 1, 2015, and June 30, 2016.
With appreciation, we acknowledge the generosity of the following.

$500,000 +

Gordon and Betty Moore Foundation
The G. Unger Vetlesen Foundation
WSL PURE

$100,000 to $499,000

Comer Science and Education Foundation
University of Hawaii Foundation

$50,000 to $99,000

Alfred P. Sloan Foundation
American Chemical Society
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This page: *Vatnajökull Glacier, Iceland. (Ollie Taylor)*
Back Cover: *Ice on a black volcanic beach in Iceland. (Zinaida Sopina)*

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