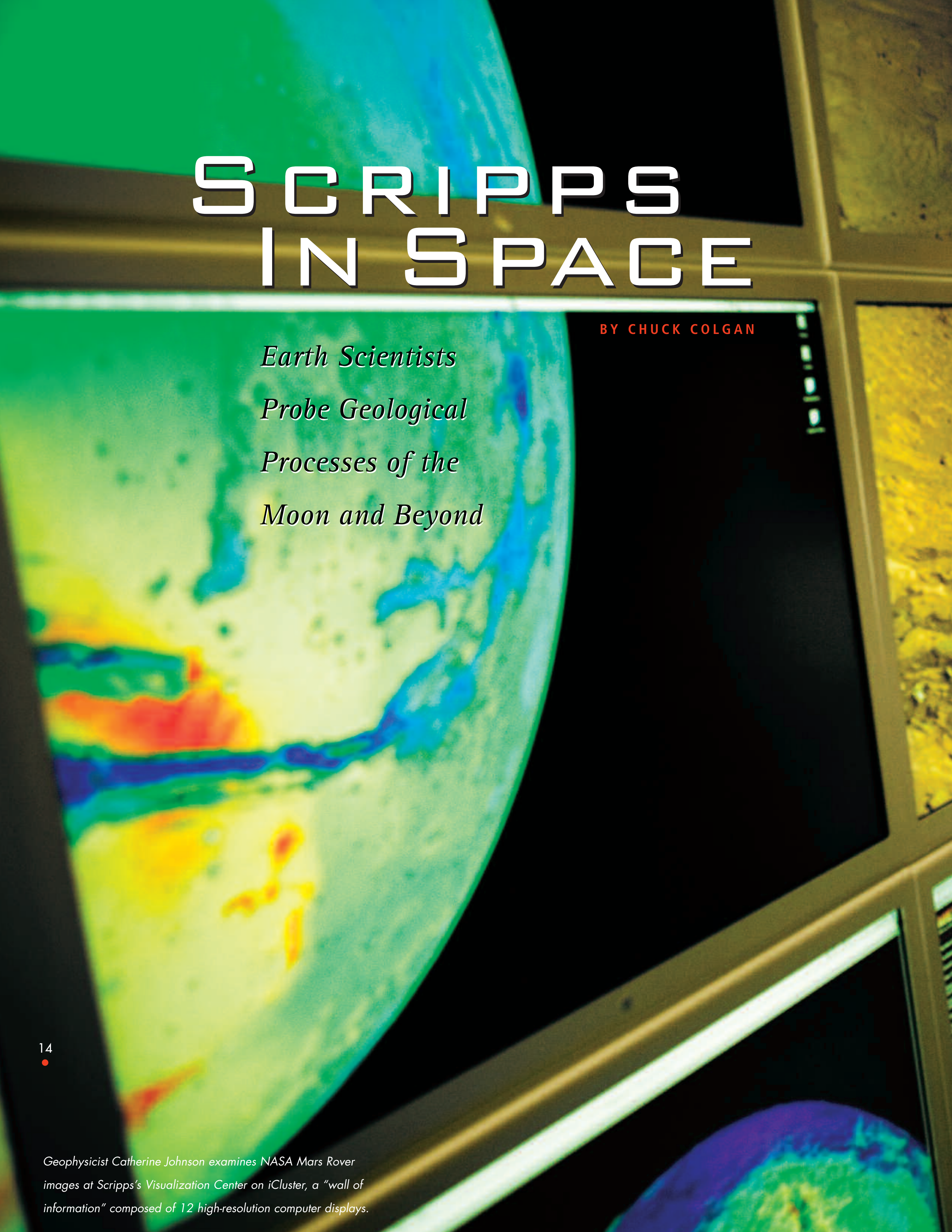


Scripps In Space

BY CHUCK COLGAN

Earth Scientists Probe Geological Processes of the Moon and Beyond

Geophysicist Catherine Johnson examines NASA Mars Rover images at Scripps's Visualization Center on iCluster, a "wall of information" composed of 12 high-resolution computer displays.

FOR SOME EARTH SCIENTISTS AT Scripps Institution of Oceanography, investigating one world isn't enough. They turn their attention to the sky and wonder about the geological processes taking place on planets and moons throughout the solar system.

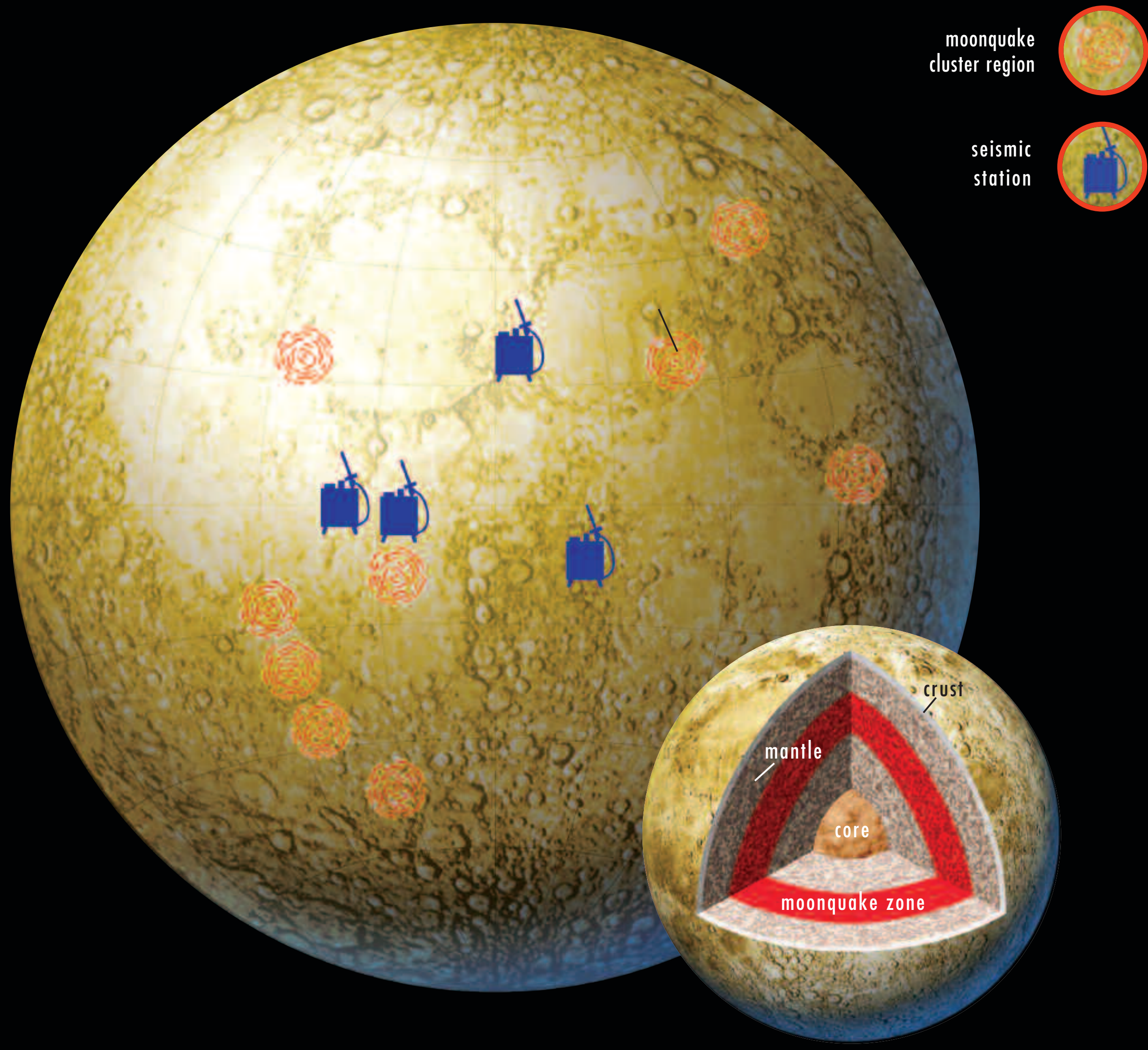
Using scientific techniques developed for understanding Earth's internal configuration, these planetary geoscientists are discovering that some other nearby heavenly bodies have histories and structures similar to those at home. Their efforts also are helping to advance design of sophisticated instruments for remotely sensing geological data with applications for monitoring conditions on Earth.

They're finding that Earth's geological processes are not entirely unique within the solar system. So far, evidence of volcanism, seismic activity, gravitational tides, magnetic fields, tectonic deformation, and other geophysical forces are variously found on the three other inner planets—Mercury, Venus, and Mars; our Moon, and the four largest moons of Jupiter.

But why would an oceanographic institution be interested in extraterrestrial geology?

EARTHQUAKES ON THE MOON

NASA astronauts deployed seismic instruments on the nearside of the Moon during four Apollo Missions between 1969 and 1972. The network supplied moonquake data until 1978, providing insight into the Moon's internal structure and composition. One discovery was seismic activity clustered in regions deep within the Moon believed to be the result of the buildup and release of strain generated by Earth-Moon gravitational forces. This moonquake zone is 700-1200 kilometers (435-745 miles) below the moon surface.

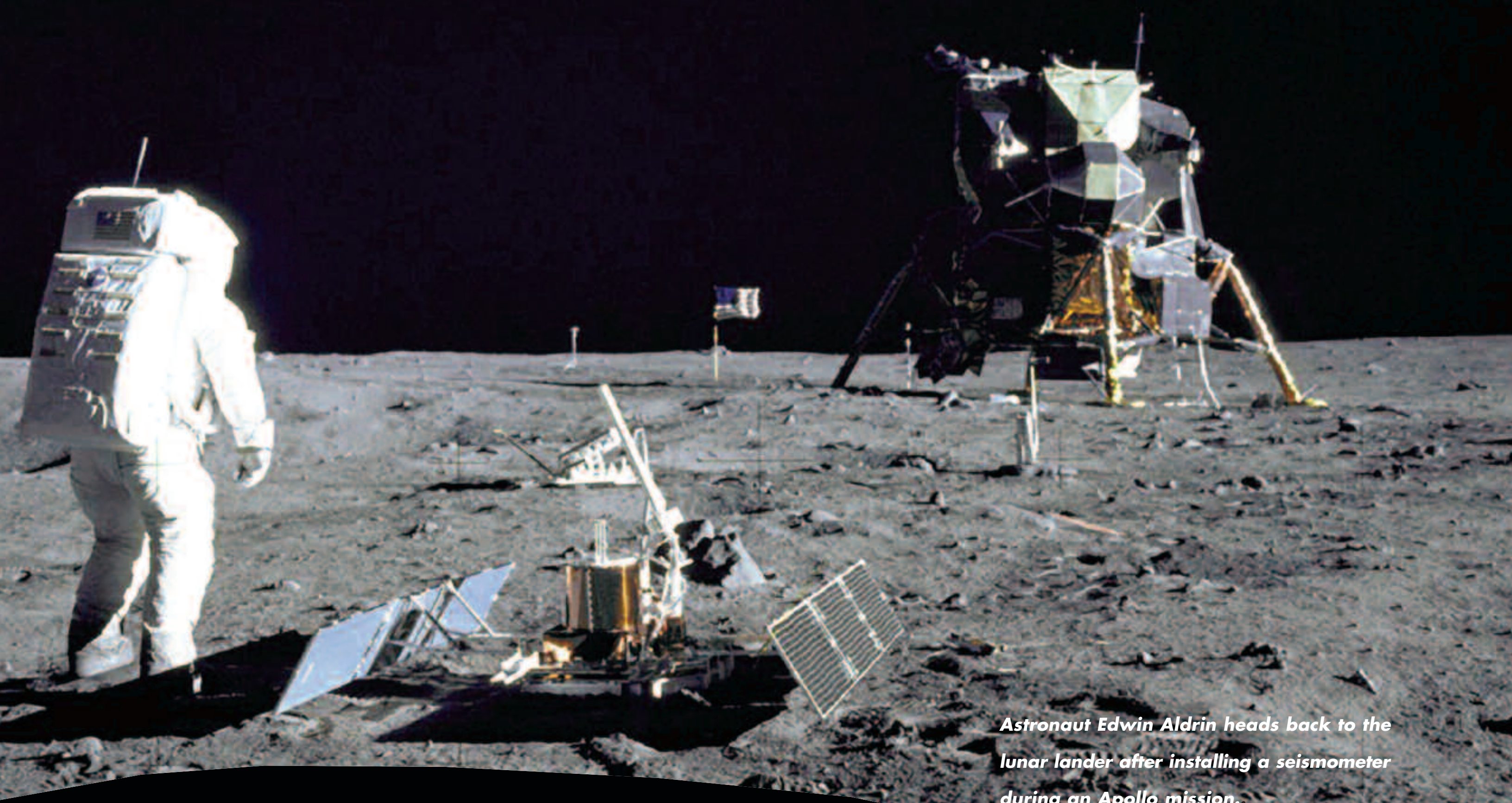


Below, *Graduate student Renee Bulow found new moonquake information in 30-year-old NASA data.*

According to geophysicist Catherine Johnson, studying other parts of the solar system helps us decipher our own planet's evolution. Put more simply, she said, "Exploration is what we do at Scripps, and it's not just here on Earth."

FROM EARTH TO SPACE

Planetary geoscience is by its nature a highly cross-disciplinary field. In order to interpret the various types of remote sensing and other data from space instruments and surface lander missions, the planetary geoscientist must have a solid background in such diverse subjects as astronomy, mineralogy, geochemistry, atmospheric sci-



Astronaut Edwin Aldrin heads back to the lunar lander after installing a seismometer during an Apollo mission.

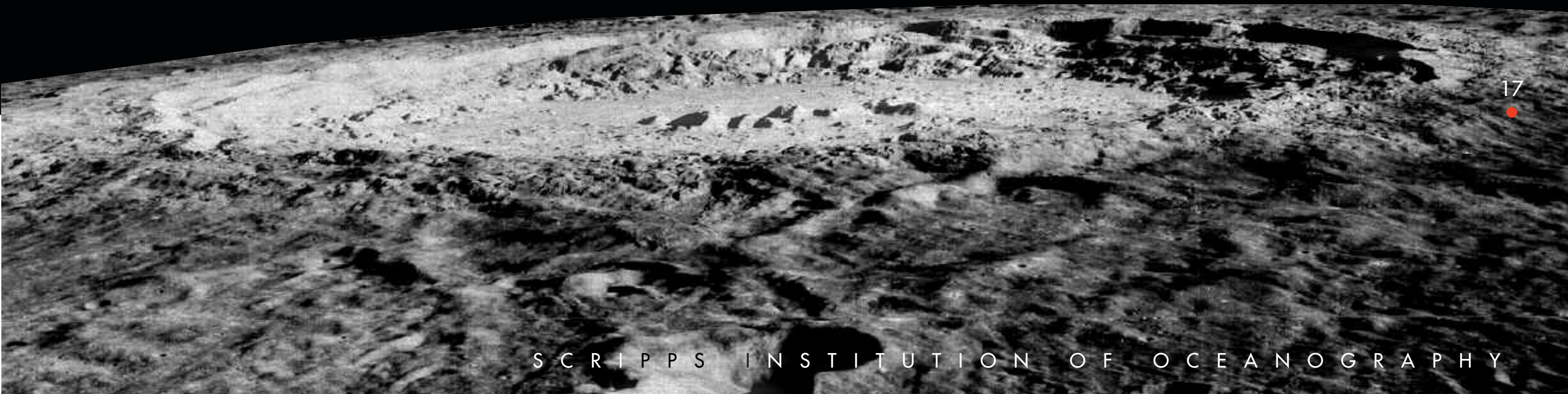
ences, and computer programming. Supplying that foundation is the role of academic programs such as those of the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP), where students train in terrestrial earth sciences and can apply similar concepts to planetary studies. There is considerable expertise at IGPP in collecting, processing, and modeling large sets of geophysical data for understanding Earth's interior that can be translated and utilized for studying other planets and moons.

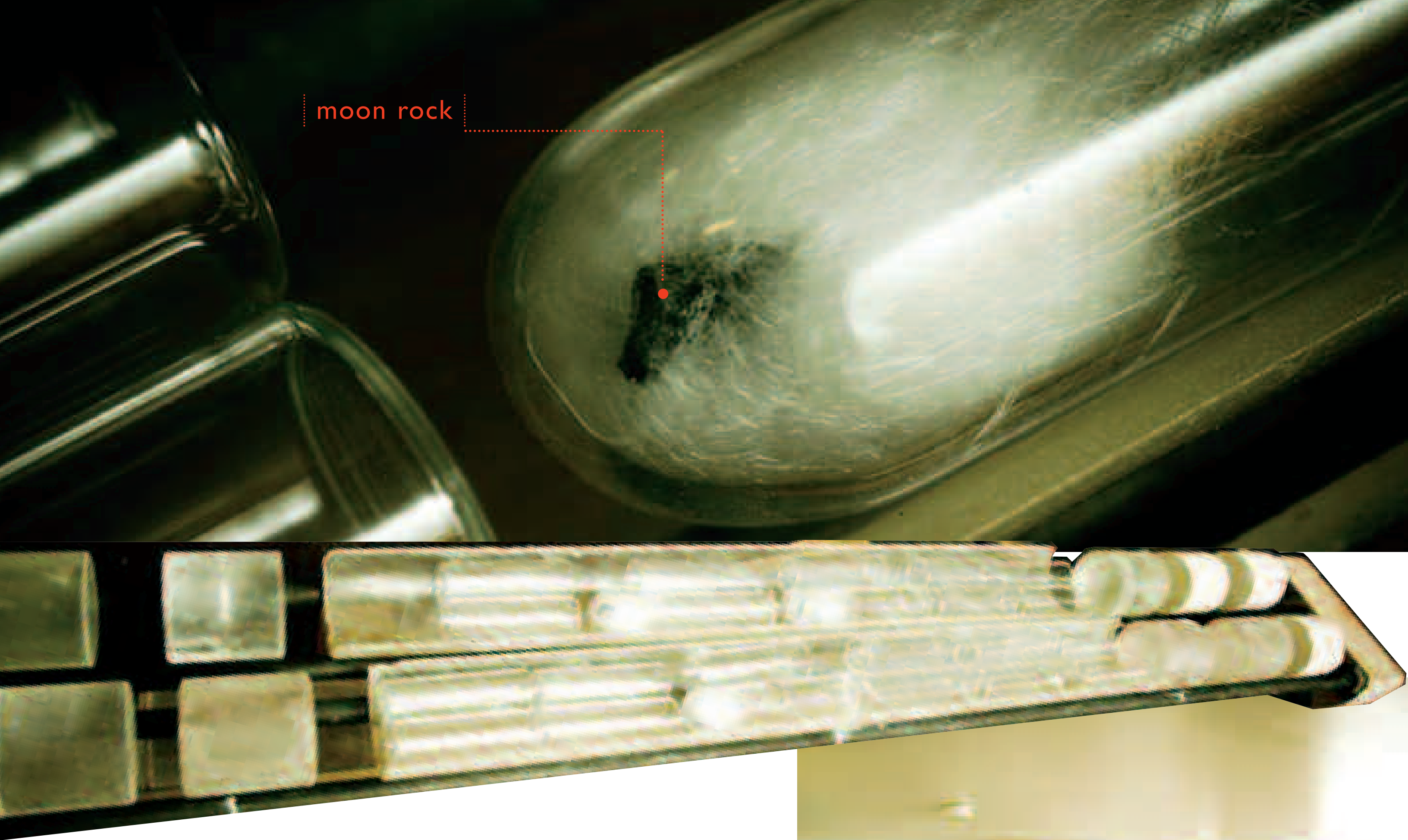
Johnson's Earth-based research interest is geomagnetism, specifically the behavior of Earth's magnetic field over the past 5 million years. Her space interests have varied from the topography of Venus to magnetic fields on Mars and lunar seismology. A 1994 Scripps graduate, she cites a similarity between today's planetary studies and the advancements made in earth sciences in the 1960s when the first measurements of deep-earth seismology and gravity confirmed continental drift and plate tectonics. Space geophysics, she said, allows researchers to "go back to asking fundamental questions about how planetary bodies develop and evolve."

THE EARTH-MOON SYSTEM

From the beginnings of IGPP at Scripps in 1959, the focus of planetary research has been the Earth-Moon system. IGPP founder and oceanographer Walter Munk conducted pioneering studies of the gravitational torque between the two bodies and the Moon's effects on tides and Earth's rotation. Many others followed, leading investigations into the origin of the Moon, its composition, and internal structure.

Today, two of Johnson's students are continuing to ask basic questions about Earth's Moon. One has found that even 30-year-old digital data can yield new information, and another is the first to apply a modern laboratory technique to lunar rock samples to help





resolve the Moon's geological history.

Renee Bulow, a fifth-year student, decided to analyze lunar seismic data from the Apollo missions to look for information that possibly escaped the attention of scientists who did the analysis in the 1970s. Her advantage was that the original moonquake data couldn't be adequately processed without present-day computers.

During Apollo missions from 1969 to 1972, astronauts installed four seismometers at locations on the Moon. They were the first space instruments to collect data in a digital format and telemeter it back to Earth. The network operated until 1978 when NASA permanently shut down the instruments because of budget issues and the overwhelming amount of data. No computer at that time could handle 13 gigabytes of data. That's a quantity small by today's standards when as much information can be processed from a single earthquake in a matter of hours. In the 1970s, scientists converted a subset of the digital data from more than 10,000, nine-track magnetic tapes to paper printouts that were reviewed visually on light tables. Some 12,500 seismic events were cataloged. The data set, however, contained many sections of "noisy" data with no way to distinguish internally generated moonquakes from meteor impacts and surface thermal expansion and contraction.

Unlike the Earth, the Moon does not have active plate tectonics, so in contrast to the hundreds of earthquakes recorded each day, fewer than 10 moonquakes occur daily. The Apollo-era scientists identified shallow quakes ranging 20 to 30 kilometers (12.4-18.6 miles) below the surface and deep quakes at depths of about 700 to 1,200 kilometers (435 to 745 miles), about halfway to the Moon's center. The shallow quakes were relatively rare; there were fewer than 30 over eight years, but some of them were intense, measuring up to magnitude 5.5 and lasting more than 10 minutes. More significantly, researchers distinguished 6,500 smaller and deeper quakes that appeared to be clustered at some 75 locations and that happened at somewhat regular intervals.

Using modern seismological data processing techniques and contemporary computers, Bulow filtered and cleaned up the noisy data from the most active of the deep moonquake clusters. So far, data from five regions have been analyzed, with the result of about 30 percent more moonquakes being found. She identified a peak period of activity at 27.2 days, the time it takes the Moon to orbit Earth, which indicates that gravitational forces from Earth generate moonquakes. She also was able to better pinpoint moonquake centers and correlate recordings from the seismometer stations.

"It's still not understood how moonquakes occur at such great depths, where temperatures are believed to be 1,000° C (1,832° F)", Johnson said. "That's typically at much higher temperatures and deeper than earthquakes, which gives us even more to wonder about the interior of the Moon."

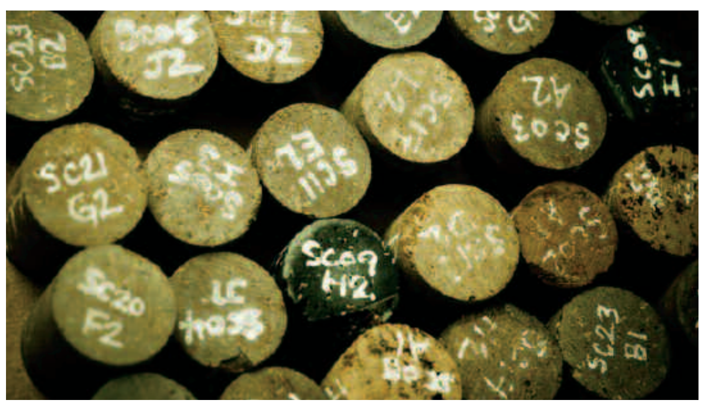
THE MOON ROCKS

Third-year student Kristin Lawrence studies moon rocks from the Apollo missions to better understand their origin and development. Working with Johnson and geophysicist Lisa Tauxe, an expert on geomagnetic fields, Lawrence is the first to apply modern lab methods to determine the history of lunar samples based on their magnetic properties, or paleomagnetism. By measuring the orientation and intensity of magnetic minerals in rocks, it is possible to establish the magnetic fields that existed when the rock formed and gain insight about ancient geological conditions.

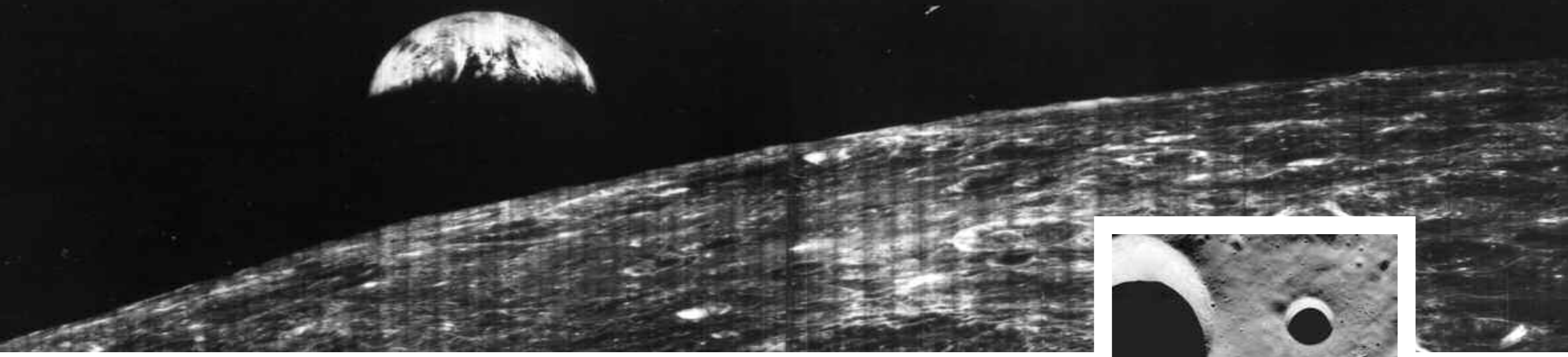
Planetary scientists generally agree that the Moon was formed some 4.6 billion years ago when a massive asteroid or other object collided with a very young Earth, knocking free the material that later condensed into the Moon. This explains the similar mineral structure and composition of the Earth and Moon.

Data from Apollo missions have supplied a basic understanding of the geological history of the Moon. Initially the Moon was molten rock, or magma. As it cooled, the first pieces of crust formed, which we still see today as the lighter areas on the Moon's surface. Meteoroids and other objects bombarded the early Moon, resulting in a surface riddled with craters. The Moon also had what is estimated to be a billion-year period of volcanism that formed basalt rocks that we can see as dark areas.

One aspect of the lunar geology that still puzzles planetary scientists is the Moon's core. Most likely the



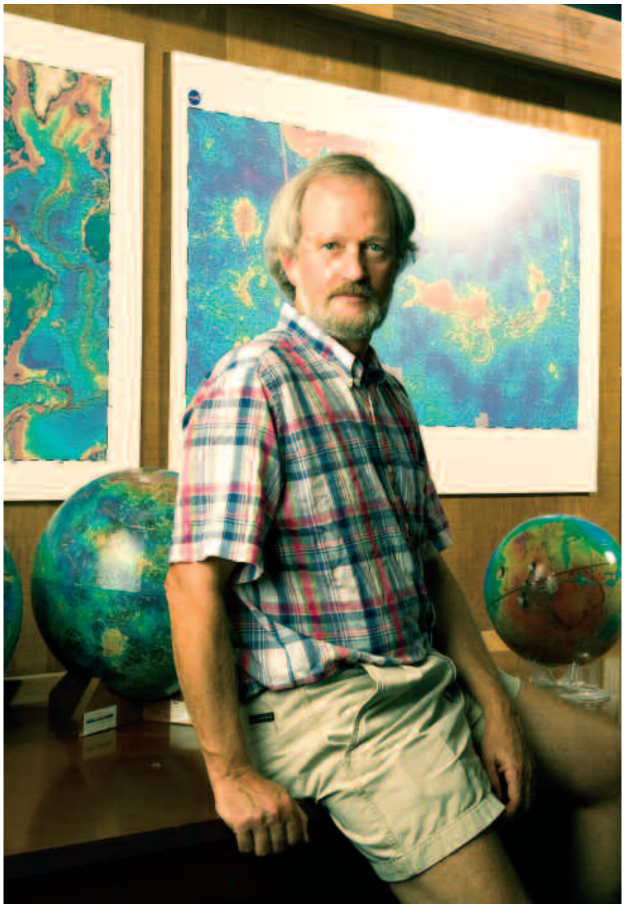
Graduate student Kristin Lawrence (opposite page bottom and above) puts minute samples of moon rock (opposite page top) through laboratory processes that allow their original magnetism to be measured. The samples are heated to 800° C (1,472° F), cooled, and measured in a magnetometer at -263° C (-442° F). Small Earth rock sample cores (above) are similarly examined.



lunar core is made primarily of iron and nickel like the Earth, but is it solid or molten? It's the Earth's dynamic, liquid outer core that generates the strong magnetic fields on our planet that extend tens of thousands of kilometers into space as the magnetosphere, shielding us from destructive effects of charged particles from the solar wind. Measurements show the Moon has no internally generated magnetic field today; however, regions of the lunar surface are magnetic. Were these areas magnetized by external sources or did the Moon once have an internal magnetic field, and if so, how intense was it?

Some 382 kilograms (842 pounds) of lunar material were brought back to Earth during six Apollo surface missions. More than three-quarters of the samples remain in pristine condition in a vault at the Johnson Space Center in Houston, Texas, and on occasion small amounts are given out for research. In the 1970s, several scientists measured remnant magnetic fields in Moon rocks and said that their magnetization was of lunar origin and billions of years old. Unfortunately, later improvements in test methodologies showed the results for paleomagnetic intensities to be inconclusive.

Lawrence received 6.5 grams of moon fragments, about the size of a small sugar cube, because she and Johnson proposed to examine them with newer techniques. She is using instruments in Tauxe's paleomagnetics laboratory, sort of a time machine for rocks housed in a metal-shielded room where the walls cancel out Earth's magnetic fields. Over the past five years, Tauxe and Scripps colleagues Peter Selkin and Jeff Gee have established an elaborate system of checks that are performed during various stages of paleomagnetic analysis to assure reliability. This method has become the standard for terrestrial rock analysis.



During processing, Lawrence seals tiny amounts of lunar samples in evacuated quartz tubes, heats them to 800° C (1,472° F), cools them to room temperature in the magnetic field-free room, and then measures them in a magnetometer at temperatures of 10° Kelvin or -263° C (-442° F). The procedure removes unwanted secondary magnetism and allows the original magnetization of the rocks to be measured.

Lawrence is still in the early stages of processing the lunar samples and is months away from publishing results; however, she is accomplishing her major objective in coming to Scripps by studying planetary geophysics while participating in hands-on fieldwork. She has also collected samples from ancient lava flows in Mexico and analyzed rocks from Antarctica.

"Earth materials are easier to analyze for their paleomagnetic properties because you know exactly where they came from and have lots of samples to com-

Left, *NASA scientist Bruce Bills is on loan to Scripps as a liaison between the space agency and the UC San Diego science community.*

Left, *Geophysicist David Sandwell uses space instruments in earth studies and teaches an undergraduate course called Physics of Surfing.* **Below**, *NASA's ICESat spacecraft*

pare their histories," Lawrence said. "What's exciting about the moon rocks is that they are sufficiently old that they provide clues to formation of the solar system and processes that created the inner planets."

FROM SPACE BACK TO EARTH

Some two dozen Scripps researchers have NASA-funded projects ranging from using satellite instruments to observe coastal water quality to searching for traces of life in Earth's oldest rocks. NASA spends about $5.5 billion on science programs annually, but has announced it is limiting growth to 1.5 percent next year and 1 percent each year through the end of the decade. The agency also recently declared a preference for funding space missions rather than Earth missions. The scientific challenge then becomes, according to visiting research geophysicist Bruce Bills, to "look for ideas for scientific techniques and instruments that can be developed both for sending to other planets and for monitoring Earth."

Bills is on quasi-permanent loan to Scripps from the Goddard Space Flight Center in Greenbelt, Md., as a liaison between NASA and the UC San Diego science community. He cites many examples of space instruments that have proven beneficial for terrestrial purposes. The Magellan spacecraft launched in 1989 carried the first synthetic-aperture radar to view details of the surface of Venus. Today, such instruments are used for a wide variety of environmental applications, such as monitoring crops, deforestation, ice flows, and oil spills. The Mars Global Surveyor launched in 1996 carried the first laser altimeter to precisely map surface topography, yielding a technology for mapping on Earth today.

Geophysicist David Sandwell's experience offers insight into how even secret military satellite programs occasionally result in space instruments coming into general scientific use.

In 1985, the Navy launched Geosat, a satellite carrying a radar altimeter to measure the bumps and dips in the ocean surface caused by subtle variations in the pull of gravity. By combining this information with the 40-year record of soundings from research vessels, it is possible to map the topography of the seafloor kilometers below the surface. The Geosat data were classified and unavailable for public use until 1995, when the European Space Agency launched a radar altimeter satellite and began releasing ocean-surface data.

Soon after the Geosat data were available Sandwell and Walter Smith of the National Oceanic and Atmospheric Agency produced the most complete, high-resolution map of the world seafloor available that has become a standard reference tool for marine science and education. An interactive version can be viewed by selecting "global topography" at http://topex.ucsd.edu/. This global model is also used for the ocean component of Google Earth.

Johnson lamented that the costs of planetary satellite missions are large and the logistics complex, but is optimistic that many opportunities will continue in the future. "When dealing with scientific projects in space," she said, "you have to not only secure funding, but you have to be flexible when things at NASA change."