# Department of Earth, Atmospheric, and Planetary Sciences

The Department of Earth, Atmospheric, and Planetary Sciences (EAPS) has broad intellectual horizons encompassing the solid Earth, its fluid envelopes, and its diverse neighbors throughout the solar system and beyond. The Department seeks to understand fundamental processes that define the origin, evolution, and current state of these systems and to use this understanding to predict future states. The Department comprises 39 faculty (including one with a primary appointment in Civil and Environmental Engineering and one with a primary appointment in Biology) and more than 170 research staff, postdoctoral appointments, and visiting scholars. We note the loss of our distinguished colleague and friend, Edward N. Lorenz, who passed away in April.

EAPS is notable for its emphasis on interdisciplinary problems. The Earth Resources Laboratory and Kuwait Center at MIT bring together faculty, staff, and students in intensive and multidisciplinary efforts to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science (CGCS) builds on the programs in meteorology, oceanography, hydrology, chemistry, and satellite remote sensing in the Schools of Science and Engineering. To facilitate growth, CGCS became an independent Center in the School of Science but retains close interaction with EAPS.

## Educational Activities

### Graduate Program

EAPS has vigorous graduate educational programs in geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. During the past academic year, 168 graduate students were registered in the Department, including 72 students in the MIT/Woods Hole Oceanographic Institution Joint Program. Women constitute 46 percent of the graduate student population.

The excellence of the EAPS graduate program is built not only on the strength of teaching and supervision by the faculty but also on involvement of EAPS graduate students in departmental activities. Students develop formal and informal ways to improve educational experience as well as student life. The departmental Graduate Student Mentoring Program continues as a well-received approach to provide peer support for new students. Many graduate students are involved in Graduate Student Council activities, and they use their experiences in EAPS to make positive changes for the entire graduate student population. EAPS awards a prize for excellence in teaching to recognize the superior work of teaching assistants in many of our classes. Prizes were awarded to Martha Buckley, Lindsay Hays, Noah McLean, and Cristina Thomas for service during the 2008 academic year.

### Undergraduate Program

EAPS continues to make increasing the number of undergraduate majors in the department a priority. In AY2004, we had a 95 percent increase in the number of

undergraduate majors. In AY2006, we again increased our undergraduate major population to the highest level in more than 20 years. EAPS enters AY2009 with 31 undergraduate majors. We look forward to using the strengths and enthusiasm of our new faculty as we review the curricula for our four tracks within the major and revise and expand our degree requirements. We believe one of the greatest challenges for EAPS and MIT is to find a pathway to expose every undergraduate at MIT to the earth sciences. With the rise of energy, environmental, and climate change issues as central foci of policy debate, it is critical that our graduates have a knowledge base for discussion and decision making in their role as citizens.

The Department's commitment to fostering undergraduate research is illustrated by our annual award of the Goetze Prize for Undergraduate Research, presented for research conducted within the Undergraduate Research Opportunities Program (UROP) or for a senior thesis. At the 2008 Student Awards and Recognition Dinner, the Goetze Prize was awarded to graduating seniors Jessica Stanley (first prize) and Scott Berdahl (honorable mention). Andrew Wickert received the W.O. Crosby Award for Sustained Excellence in recognition of his achievements, academically and intellectually, and participation in Department activities. It is a new award that EAPS has established as we strive to improve our recognition of the accomplishments of our majors. This past year, Mr. Paul Hoffman was the first UROP student to benefit from Dr. David P. Bacon's (1977) establishment of a fund supporting UROP research in EAPS. Dr. Bacon was motivated by the desire to encourage exceptional undergraduate research and to honor the career achievements of Professor Kerry Emanuel.

EAPS presents the undergraduate student body with opportunities to become acquainted with the world from an earth sciences perspective. The Department acts on its belief that EAPS should have a strong presence in the undergraduate program at MIT beyond our population of majors. The Department remains committed to Terrascope and its problem-based approach to education during the first year at MIT. We continue to provide many UROP projects supervised by EAPS faculty, participate in freshman advising seminars, and sponsor a weekly undergraduate seminar. The overwhelming majority of students in these programs have not been EAPS majors.

## Faculty

Professor Samuel Bowring was appointed as the Robert R. Shrock Professor in Earth, Atmospheric and Planetary Sciences for a 5-year renewable term beginning July 1, 2007. He was also elected a fellow of the American Geophysical Union.

Professor Tanja Bosak received the 2007 Subaru Outstanding Woman in Science Award at the annual meeting of the Geological Society of America. The award is presented to a woman who has influenced the field of geosciences in a major way based on her Ph.D. research. She was also appointed to the Cecil and Ida Green Career Development Professorship in Earth and Planetary Sciences for the period July 1, 2007, through June 30, 2010.

Professor Edward Boyle was elected to the National Academy of Sciences.

Professor Linda Elkins-Tanton was awarded the Matsui Career Development Professorship.

Professor Brian Evans was awarded the Louis Néel Medal by the European Geosciences Union for his "internationally acclaimed path-breaking research on the rheology of rocks, his elegant experiments based on physics and materials science, and his discoveries in the relationship between deformation and fluid transport in a variety of geophysical environments."

Professor Raffaele Ferrari was appointed as the Cecil and Ida Green Professor of Oceanography for a 5-year renewable term beginning July 1, 2007.

Professor Timothy Grove was elected a fellow of the American Academy of Arts and Sciences, and he begins his 2-year term as president of the American Geophysical Union on July 1, 2008.

Professor Alison Malcolm received an early career travel award from the Society for Industrial and Applied Mathematics (SIAM) to attend the SIAM imaging science meeting.

Professor John Marshall was elected a fellow of the Royal Society (national academy of science of the UK).

Professor Dianne Newman (primary appointment in the Department of Biology) was elected a fellow of the American Academy of Microbiology. She also received an Eli Lilly and Company Research Award and was named a Howard Hughes Medical Institute investigator.

Professor Stéphane Rondenay was promoted to associate professor without tenure.

Professor Sara Seager received the 2007 Helen B. Warner Prize, awarded annually by the American Astronomical Society for significant contributions to observational or theoretical astronomy.

Professor Sang-Heon (Dan) Shim was promoted to associate professor without tenure.

Professor Roger Summons was elected a fellow of the Royal Society (national academy of science of the UK).

Professor Jack Wisdom was elected to the National Academy of Sciences.

Professor Carl Wunsch received the 2007 Prince Albert I of Monaco Medal. This medal is named in honor of the late Prince Albert I of Monaco who, in 1919, organized the Oceanography Section of the International Union of Geodesy and Geophysics.

Professor Maria Zuber was named a fellow of the American Association for the Advancement of Science for "outstanding research contributions and scientific leadership in the geophysical studies of Earth and the solid planets." She also was awarded an honorary degree from Brown University.

## Research and Administrative Staff

Dr. Michael J. "Mick" Follows was promoted to the rank of senior research scientist.

Dr. Nilanjan Chatterjee was promoted to the rank of principal research scientist.

Dr. Patrick Heimbach was promoted to the rank of principal research scientist.

Dr. Mark E. Willis was promoted to the rank of principal research scientist.

## Current Research

Professor Tanja Bosak's laboratory for geomicrobiology and microbial sedimentology is studying morphological and molecular microbial fossils to understand the parallel evolution of life and our planet. Her group is using modern microbes and methods of microbial physiology, molecular microbiology, and geochemistry to understand how microbes shape sedimentary rocks and why microbes produce polycyclic lipids that can persist in sediments for billions of years.

Professor Sam Bowring's lab continues to push the limits of high-precision geochronology as applied to understanding Earth history. They determined the eruption age of the Bishop Tuff, a major pyroclastic eruption in California, to 767.1 ± 0.9 thousand years ago. This demonstrates the potential for millennial-scale resolution of events in the past million years allowing magma chamber dynamics and a geomagnetic timescale to be calibrated with unprecedented precision. The last year has also seen publication of a major new paper on the geochronology of Neoproterozoic rocks in Oman.

Professor Edward Boyle has obtained the first water column profile of dissolved iron in the Southwest Pacific Ocean and finds that iron is highly correlated with the helium-3 concentration; this result demonstrates that hydrothermal vents are the major source of iron to the deep South Pacific Ocean. His group has also found the unusual lead isotope signature of Upper Mississippi Valley lead (emitted during the mid-19th century) in a coral from Bermuda.

Professor Clark Burchfiel's main research effort continues from 28 years of work in China and focuses on the tectonic evolution of the eastern part of the Tibetan Plateau and regions to the southeast into Indochina. A second area of research is in the Balkan region of southern Europe where the Cenozoic history of extensional tectonism has yielded a complex evolution.

Professor Linda Elkins-Tanton is working on processes of chemistry and physics that control planetary evolution in the first tens of millions of years after accretion, when planets are cooling and developing their silicate mantle structure and compositions, their earliest crusts, and atmospheres formed by degassing the planetary interiors. Her group is also working on processes of melting in the asthenosphere and the effects of melt on the lithosphere, including creating gravitational instabilities, lithospheric underplating, and compositional fertilization.

Professor James Elliot, Research Scientist Dr. Michael Person, and their colleagues observed Pluto occult a star under special circumstances and discovered high-altitude waves in Pluto's atmosphere. They have modeled these waves both as Rossby waves and as gravity waves but so far have been unable to discern which model is the correct explanation.

Professor Kerry Emanuel's research this year focused on several projects related to tropical cyclones. With colleagues in Australia, he showed that tropical cyclones might intensify over land if the soil in advance of the storm is sufficiently hot and whose properties allow for large thermal conductivity when the soil is wet. They have also been able to infer how tropical cyclone activity might respond to global warming by applying a new "downscaling" method to some of the global models run in support of the recent Intergovernmental Panel on Climate Change (IPCC) report. With graduate student William Boos, they were able to provide a physically consistent explanation for the sudden onset of the Indian monsoon, based on theory, observations, and numerical models.

Professor Brian Evans and graduate students Nick Austin and Lili Xu are collaborating with scientists at Berne University in Switzerland to examine the microstructure of naturally deformed rocks along the Morcles nappe. This team has interpreted the microstructures by using a new method that correlates the grain structure of the rocks with the mechanical power dissipated during emplacement of the nappe. The technique is successful in resolving several discrepancies in understanding the mechanical history of that mountain-building event.

Professor Raffaele Ferrari is the leader of a National Science Foundation/National Oceanic and Atmospheric Administration climate process team, involving 10 institutions and 15 principal investigators, whose goal is to improve the representation of upper ocean physics in ocean models used for climate studies. The prevailing dynamical paradigm had previously been that the dominant subgridscale process in the surface mixed layer of the oceans is vertical mixing of density and momentum driven by atmospheric surface fluxes and stresses. The team changed this perspective and showed that lateral transport by geostrophic eddies and vertical transport by submesoscale frontal circulations are crucial elements of upper ocean dynamics and must be parameterized in climate models.

Professor Frederick Frey, Research Staff Scientist Malcolm Pringle, and associated students have focused their research efforts on basalts recovered from the 5,000-km north-south linear trend of submarine volcanoes forming the Ninetyeast Ridge in the Indian Ocean. They are using the MIT EAPS Ar-Ar mass spectrometer facility to date the eruption ages of basalt recovered at 23 dredge sites extending over 3,000 km along the ridge.

Professor Tim Grove and Eva Holbig have used experimental petrology and trace element geochemistry to infer possible melting processes beneath the Tibetan Plateau. A long-standing controversy has been the nature of mantle flow beneath Tibet. They found that Tibetan lavas preserve a trend of increasing extent of melting with increasing depth. This "upside-down melting" is one of the expected modes of melt generation beneath Tibet and the lavas contain evidence for it.

Professor Thomas Herring is using Global Positioning System (GPS) and very long baseline interferometry data to develop geophysically based models of changes in the rotation of the Earth and Earth deformations on global, regional, and local scales. He is also using interferometric synthetic aperture radar to study fine-scale surface deformations. His group is studying tectonic deformations over much of the southern Eurasian plate boundary, southern New Zealand, and the western United States. The group is also involved in monitoring and modeling human-induced deformations in oil fields. To support these activities and to improve even further the accuracy of GPS measurements, MIT is a data analysis center for the International GNSS (Global Navigation Satellite System) Service and acts as the GPS Analysis Center Coordinator of the National Science Foundation Plate Boundary Observatory, which is part of the EarthScope program.

Professor Oliver Jagoutz, who joined the Department in January 2008, is studying the origin and evolution of oceanic and continental crust. Recent studies focus on the origin of magmatic upper continental crust in subduction zones and the importance of dry and wet magmas for formation of the continental crust. His current studies focus on the processes in the deep sub-arc mantle and mechanism leading to rift-to-drift transition and the formation of oceanic crust in slow-spreading ridges.

Professor Alison Malcolm, who joined the Department in January 2008, is working on problems in nonlinear imaging, imaging with multiply scattered waves for oil exploration, wavefront healing, and numerical methods for wave propagation.

Professor Paola Malanotte-Rizzoli started a new 5-year research project in the Singapore–MIT Alliance for Research and Technology. The research will focus on hydrodynamic modeling of the three-dimensional circulation and water mass properties in three domains: the local Singapore Strait, the regional basin comprising the Singapore Strait, and the entire South China Sea, all in fully realistic configuration with real coastlines and bottom topography.

Professor John Marshall was on sabbatical at the Courant Institute (New York University) in Manhattan for most of 2008, where he continued his collaborations with Professor Shafer Smith on the more theoretical fringes of oceanography. He continues his work on aqua-planet climates—worlds where there is an atmosphere and ocean and the possibility of ice, but no land. This has turned out to be a fascinating and extremely rich area of research, focusing on hitherto unexplored and rather fundamental aspects of coupled climate dynamics.

Professor Dianne Newman's laboratory is studying the coevolution of life and Earth. Specifically, they are taking an interdisciplinary approach to studying the molecular mechanisms that underlie putatively ancient forms of metabolism. By understanding the way extant organisms function at the molecular level, they hope to gain insights into the evolution of ancient metabolic and biomineralization pathways, interpret the chemical signatures of early life found in the geologic record, and understand how multicellular bacterial communities survive in the context of anaerobic infection.

Professor Shuhei Ono and his research group developed a new state-of-the-art instrumentation for high-precision isotope ratio analysis of all four stable isotopes of sulfur. His group will use the instrument to study the origin of mass-independent isotope fractionation and its application in the research of deep biosphere, Archean geochemistry, and global sulfur cycles.

Professor Ronald Prinn, Dr. Matthew Rigby, Dr. Jin Huang, and their colleagues report that AGAGE network measurements of atmospheric methane showed renewed growth in 2006–2007 after almost a decade of little change. Using an inverse methodology, they conclude that the near-simultaneous increases at all latitudes are consistent with a drop in the major methane sink (OH free radicals) accompanied by an increase in northern hemisphere emissions.

In the past year, Professor Stéphane Rondenay and his group used a seismic imaging approach developed in their group to introduce important new constraints on the character of dehydration reactions that take place in subduction zones and influence seismicity and volcanism in these regions. They also pursued our collaboration with researchers at Royal Dutch Shell on the development of new passive seismic imaging approaches to characterize hydrocarbon reservoirs.

Professor Daniel Rothman and his group have shown how to reconstruct the growth of channel networks incised by groundwater flow. Their work links network growth dynamics to geometric form and provides a means of identifying the origin of enigmatic amphitheater-headed channels such as those found on Mars. To see movies of the reconstruction, go to http://segovia.mit.edu/movies.php; password: bristol.

Professor Sara Seager is part of a research group based at Goddard Space Flight Center that studied a planet about 904 trillion miles from Earth, known as HD 209458b. The researchers used NASA's Spitzer Space Telescope to capture the most detailed information yet about an extrasolar planet.

Professor Sang-Heon (Dan) Shim and his research group study the physical properties of the recently discovered phase, which is the dominant constituent at the lowermost mantle, using laser spectroscopy in his lab and x-ray techniques at synchrotron facilities. The group has shown that the mineral phase change provides explanations for the seismic observations origin, which has not been well understood.

Professor Peter Stone and his group have carried out new projections of global warming during the 21st century as part of MIT's Joint Program on the Science and Policy of Global Change. Unlike the projections of the IPCC, the MIT projections were constrained to be consistent with observed 20th century observations. Correspondingly, the new projections give more warming than those made by the IPPC's multimodel ensemble because the IPCC ensemble mixes heat into the deep ocean too efficiently. For example, for the IPCC's A2 (business as usual) scenario the multimodel ensemble gives a 5 percent probability that the mean warming will exceed 4.1°C by 2100, while the MIT analysis gives a 46 percent probability.

Professor Roger Summons's main research findings comprise a variety of new evidence for a superanoxic event at the end of the Permian period. Their data support the hypothesis that euxinic conditions were pervasive leading up to the end-Permian mass extinction and that sulfide generated in the ocean and evading to the atmosphere was a prime toxic agent. They collaborated on fundamental studies of biosynthesis and isotopic fractionation that underpin interpretations of molecular and isotopic fossils in the geological record.

Professor Robert van der Hilst and his coworkers developed new methods for imaging the physical boundary and estimating the temperature contrast between Earth's mantle and core, near 2,900 km depth, using methods adapted from the exploration for hydrocarbon resources. With colleagues in the Geology Program, van der Hilst reviewed the geological history of the Tibetan Plateau and investigated the tectonics and present-day deformation near the May 18, 2008, earthquake that devastated large regions in southwest China. Under van der Hilst's leadership, the EAPS Earth Resources Laboratory has increased its role within the MIT Energy Initiative and has started major research collaborations with, for instance, Schlumberger and ENI.

Professor Carl Wunsch and his collaborators continue to focus on understanding the global ocean circulation and its contribution to climate change, both past and present. Major efforts continue in combining a state-of-the-art general circulation model with global ocean observations over the last 15 years and interpreting the result. A major conclusion is that many decades will be required for apparent trends in the circulation to become statistically significant. In parallel, they are studying the ocean circulation of the last glacial maximum and, in particular, are attempting to obtain quantitative bounds on it.

Professor Maria Zuber and colleagues at Harvard University developed a model of the sulfur cycle of Mars that can explain many aspects of the planet's geology and chemistry. Her group also identified climatic oscillation patterns within the north polar cap of Mars, identified the largest known impact basin in the solar system beneath the northern plains of Mars, and performed the first laser ranging to the planet Mercury from a spacecraft. Her proposal for a dual spacecraft mission to map the gravity field of the Moon in unprecedented detail was selected and is the first MIT-led NASA mission.

**Maria T. Zuber**
**Department Head**

*More information about the Department of Earth, Atmospheric, and Planetary Sciences can be found at http://eapsweb.mit.edu/.*