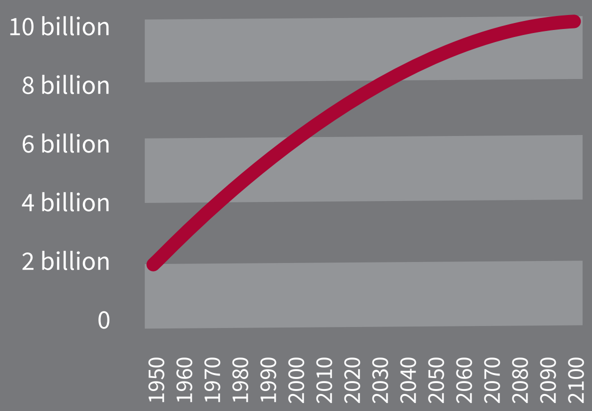
Stanford EARTH

STANFORD UNIVERSITY SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES

WORLD POPULATION PROJECTION



From United Nations Department of Economic and Social Affairs 2010

Population growth and increased per capita consumption of limited natural resources make the work of the Stanford School of Earth, Energy & Environmental Sciences increasingly urgent.

EARTH'S POPULATION NOW EXCEEDS 7 BILLION, AND IT IS EXPECTED TO REACH BETWEEN 9 AND 10 BILLION BY 2050. With per capita consumption also on the rise, we face a daunting array of high-stakes challenges. We must find and develop sustainable sources of energy, water, food and mineral resources. We must reduce the risks of and increase our resilience to climate and environmental change and natural hazards. We must sustain the planet's long-term life support systems.

At Stanford University's SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES, these urgent issues drive our mission and our expanding scope of work. We are an interdisciplinary community of faculty and students who are knowledge seekers and problem solvers. We develop and employ an array of leading-edge analytical and computational tools to explore and understand the nature of a changing planet. We advance fundamental research that provides the essential foundations for problem solving in the Earth sciences. We conduct innovative, use-inspired research that we translate into breakthrough solutions.

THE SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES is part of the historic bedrock of Stanford. The first professor hired by the university, geologist John Casper Branner, also served as Stanford's second president, and the first PhD awarded by Stanford was in geology. Over the decades, we have continued to evolve to include a growing range of disci-plines that address Earth's natural processes, resources and environment, as well as the ways human beings affect and are affected by our planet. Stanford faculty and students have already made important progress in key areas — from plate tectonics and earthquakes to food security and the search for water and sustainable energy — but there is much more to be done.

EARTH CHALLENGES. STANFORD SOLUTIONS.

THE QUEST FOR ENERGY

This page: Worldwide, booming urban centers with dense populations and busy transportation and industrial hubs require vast energy resources. (above) Stanford Earth scientists and engineers study energy alternatives, including geothermal sources. The world's largest complex of geothermal power plants is located at The Geysers, 100 miles north of the Stanford campus . (below)

Next page: Stanford Earth faculty provide expertise to policy makers. (left) Ongoing laboratory and field studies focus on storing carbon dioxide securely underground. (right)

THE TRAJECTORY IS CLEAR: ENERGY IS A KEY INGREDIENT IN ALMOST EVERYTHING WE DO, and as nations move from developing to developed, demand for energy is growing dramatically. Meeting that demand while limiting unintended negative consequences is one of our major challenges.

At Stanford Earth, we are advancing scientific disciplines that are critical to achieving that goal. Our work is both fundamental and translational. Our research informs efforts to discover and produce oil and gas with a smaller environmental footprint and to make those resources cleaner. We also conduct research to improve oil and gas recovery, reducing the pressure to develop new resources. And we explore alternative renewable sources and seek ways to produce and use them more efficiently.

Engineering and the physical sciences underlie this work. Our research mobilizes leading-edge knowledge, tools and approaches to address the energy issues confronting the planet, now and into the future. For example, we apply our understanding of geological formations and use 3-D seismic imaging to identify resources. We pioneer and employ advanced computational techniques to improve performance and reduce uncertainty. We develop assessment tools to understand and reduce greenhouse gas and other pollutant emissions from fossil fuels.

CHALLENGE: Utilize global shale gas resources as a transition fuel to a fully decarbonized energy future.

SOLUTION: Although approximately 150,000 shale gas wells have been drilled in North America, many fundamental scientific questions must be answered to assure that these resources are developed in an optimal way. Stanford scientists are researching more efficient, effective and environmentally responsible approaches to developing shale gas resources.

WHAT'S NEXT: Continue to improve the efficiency of shale gas development and reduce its environmental impact. Work with colleagues in China to responsibly develop shale gas resources as an alternative to burning coal for electricity production. China's electrical power sector currently emits three times as much carbon dioxide as the United States, with emissions in China likely to double in less than 25 years.

CHALLENGE: Find ways to make fossil fuels cleaner.

SOLUTION: Stanford scientists and engineers have developed a way to capture carbon dioxide from fossil fuel burning power plants and inject it deep underground for long-term sequestration, preventing the release of greenhouse gases into the atmosphere.

WHAT'S NEXT: Build on these methods of geological storage by accelerating the conversion of carbon dioxide into stable minerals that can be stored permanently.

CHALLENGE: Develop geothermal as a low-carbon energy alternative.

SOLUTION: Stanford faculty and students are developing technologies to access enhanced geothermal systems (EGS) — unconventional sources of geothermal energy found in regions of the world not normally associated with geothermal development. EGS — fractured rocks, found or created in geothermal reservoirs — are complex systems that require advanced scientific investigation. Stanford's work explores methods to efficiently and safely access these systems.

WHAT'S NEXT: Stimulate rock fractures to increase energy extraction while reducing seismic and water resource impacts, and develop field methods to determine properties of the fracture network.

FRESHWATER AND FOOD FOR THE PLANET

This page: To advance sustainable land use practices, Stanford scientists study the economic, ecosystem and social impacts of various agricultural processes, including eco-certification among coffee growers in Colombia. (above) In Southern Asia, where pathogens compromise surface water and arsenic contaminates groundwater, Stanford researchers decipher the roots of the problems and explore ways to bring safe water for human consumption and irrigation. (below left) Stanford scientists develop economic, climatic and agricultural data and computational models to identify factors that affect price volatility in major crops, including rice. (below right)

Next page: A theoretical computer simulation shows higher (red) and lower (blue) concentrations of groundwater contamination.

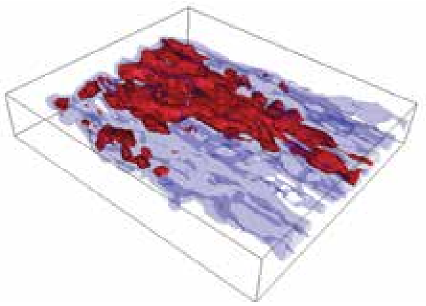
CLEAN WATER AND SUSTAINABLE FOOD SOURCES ARE CRUCIAL TO HUMAN SURVIVAL. Water is essential to sustaining a healthy planet, from direct human consumption to use in agriculture, industry and ecosystems. Yet around the world, more than a billion people currently do not have safe water supplies. In many areas, freshwater is depleted, and human needs override those of natural ecosystems and their species. Nearly a billion people go to bed hungry at least part of the time, and growth in population and consumption will make the food challenge even greater. Meanwhile, land degradation, the use of land for biofuels and a changing climate further threaten our ability to feed Earth's population.

Stanford Earth faculty are addressing these challenges by creating new knowledge, preparing tomorrow's scientists and decision makers and translating discoveries into solutions that help ensure access to safe freshwater and food. In the lab and in the field, we are evaluating climate impacts on water supplies and agriculture. We are cre-ating new technologies to evaluate and manage groundwater and surface water, and to increase water use efficiency. We are working to improve aquaculture, livestock production and fertilizer use, and are creating water delivery systems for communities in the developing world. Our faculty are also generating new perspectives about food price volatility, food policy and food security around the world.

CHALLENGE: Predict the spatial and temporal distribution of freshwater contamination.

SOLUTION: In South and Southeast Asia, where surface sources of drinking water are almost universally contaminated with microbial pathogens, individuals and communities have turned to groundwater as a source of "safe" drinking water. Unfortunately, groundwater is commonly laced with arsenic, native to Himalayan rocks and sediments. Stanford scientists have worked to determine the processes responsible for arsenic release from sediments to groundwater. They are developing models to predict low-arsenic zones and identify land use practices that may threaten arsenic-free groundwater.

WHAT'S NEXT: Determine the extent of arsenic-contaminated groundwater across Asia; identify regional- to village-based optimal water sources or treatment options; examine means to limit arsenic uptake in rice.



CHALLENGE: Ensure the sustainability of freshwater resources.

SOLUTION: Stanford scientists formed the Global Freshwater Initiative, which studies the vulnerability and of water sources around the world. Using field and remote sensing data, a team of biophysicists and social scientists has developed quantitative simulation-based planning tools to analyze water allocation and management policies, such as taxes, water markets and water rights structures. Successful studies have been conducted in the United States, Mexico and India.

WHAT'S NEXT: Advance water security in Jordan; analyze water supply vulnerability in urban areas throughout the world.

CHALLENGE: Harmonize food production with social and environmental benefits.

SOLUTION: Working at the interface of humans and the environment, Stanford researchers have studied the effectiveness of eco-certification programs that seek to connect consumers with sustainably grown commodities. Combining farm surveys and remote sensing data, the team demonstrated that certification programs in Colombia lead to higher farm incomes as well as other social benefits. In addition, tree cover on certified farms increased much more than on non-certified farms.

WHAT'S NEXT: Replicate studies for other commodities, including cacao and soybean, and other forms of private regulation of land use; study synergies between private and public land regulation.

THE CHANGING EARTH, DEEP TIME TO PRESENT DAY

This page: In the Arctic, Stanford researchers collect ice cores and measure light under the ice to understand how Earth's oceans respond to a changing climate. (above) Stanford scientists gather and analyze deep-sea corals from Palau and other locations to understand their ecology and study the record they contain of ocean acidification events over time. Stanford's coral samples span thousands of years. (below)

Next page: Stanford scientists collect water samples at multiple depths to determine the chemistry and biology of the Chukchi Sea. (left) Seen through a microscope, shells in Lower Triassic limestone provide a window onto deep time. (center) Stanford's state-of-the-art facility for the analysis of isotopes and trace elements utilizes mass spectrometry to study Earth's mantle, the movement of uranium in the environment and other issues. (right)

WHY DOES OUR WORLD LOOK THE WAY IT DOES? HOW DID LIFE EVOLVE HERE? WHAT CAN EARTH'S PAST TELL US ABOUT ITS FUTURE? The Earth sciences provide tools to help us find answers to such questions.

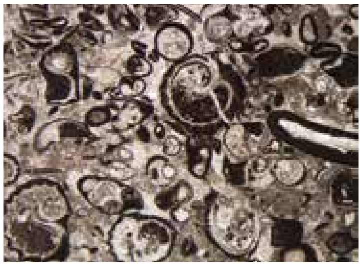
Exploring across deep time to the present day, Stanford Earth is working to uncover the complex nature of a planet that is 4.54 billion years old and ever-changing. The quest for deeper understanding drives our field and laboratory-based studies of the planet and its oceans, atmosphere and land in locations all around the globe, using sophisticated chemical analyses, remotely sensed data and simulation models. Through this work, we develop insight into Earth's past that enables us to project its ongoing evolution.

Often our research explores the impacts of human activity on the planet. Stanford faculty and students are investigating the dynamics and impacts of climate variability and change, including the role of humans as a component of the climate system. Other projects explore the dynamics of the carbon cycle, track global-scale vegetation-climate patterns or interpret the fossil record to provide context for Earth changes in the past and those unfolding today.

CHALLENGE: Understand the pace of change in the ocean.

SOLUTION: In the field and through sophisticated computer modeling and satellite imaging, Stanford scientists are tracking marine uptake of atmospheric carbon dioxide and its impact on phytoplankton growth in Arctic and Antarctic oceans. Their work will provide a greater understanding of the impact of warming on ecosystems.

WHAT'S NEXT: Intensify our studies of algal blooms recently discovered by Stanford under polar ice, and deepen our understanding of the impacts of melting sea ice.



CHALLENGE: Explore the relationship between planetary change and biological evolution.

SOLUTION: Combining field geology with geochemical analyses, Stanford scientists are examining carbonate sediments in China, Italy and Turkey deposited before, during and after mass extinctions of the late Permian and Triassic periods. By discovering which species died off and how environments changed, we can better understand how biodiversity responds to processes such as ocean acidification and climate change.

WHAT'S NEXT: Build a comprehensive database of animal body sizes spanning the past 550 million years to better understand how animal evolution has been shaped by long-term environmental change during long intervals between mass extinction events.

CHALLENGE: Track climate change patterns across time.

SOLUTION: Combining field studies of strata in North America, Asia and Europe, stable isotope measurements and numerical modeling, Stanford scientists seek improved understanding of the terrestrial paleoclimate of Earth, from billions of years ago to the past few thousand years. These studies explore the links and feedbacks between the ancient biosphere, atmosphere and lithosphere to infer how future climate may change as atmospheric greenhouse gases increase.

WHAT'S NEXT: Compile Earth's climate history and share results with climate modelers and decision makers to improve climate change forecasting and inform policy.

HAZARDS, RISKS, VULNERABILITIES, RESILIENCE

This page: Stanford geophysicists are studying the massive earthquake and ensuing tsunami that devastated Japan in 2011 to understand and predict these phenomena and protect life and property. (above) To investigate our living, changing planet, Stanford students explore an active pahoehoe lava flow in the eastern rift of Hawaii's Kilauea volcano. (below left) Stanford faculty and students create physics-based computational simulations to understand earthquakes, tsunamis and volcanoes. (below right)

Next page: Simulations indicate that rapid uplift of the seafloor during earthquakes generates sound waves that could provide early warning of tsunamis. (left) One of the world's most important crops, corn is sensitive to global warming. (right)

VOLCANOES, TSUNAMIS, EARTHQUAKES, LANDSLIDES, RISING SEA LEVELS, STORMS, HEAT WAVES, HEAVY RAINFALLS — for millennia, all have shaped and reshaped the planet, sometimes with devastating results for Earth's human inhabitants. Today, some of these threats are intensifying, and our risks are greater than ever.

At Stanford Earth, expanding our knowledge of hazards and of human vulnerability to them is key to reducing risk and building resilience in our communities. We seek to understand Earth's structure and dynamics, predict and monitor disasters as they occur, explore the impacts on human activity and develop approaches to help inform people and reduce vulnerability.

For example, we are merging insights from physics, mathematics and geology to measure, model and simulate deformations of Earth's crust that cause and are affected by earthquakes, volcanoes and hydrothermal activity. We also are exploring the hazards posed by large, slow-moving landslides in urbanized areas. How can we determine, in advance, where such events are likely to occur? How can we predict the severity of their impacts? How can we plan to prevent loss of life, damage to our communities and environmental destruction? These are just a few questions on our agenda.

CHALLENGE: Predict the intensity of earthquake shaking.

SOLUTION: Stanford scientists have developed a new approach that uses the ambient seismic field — seismic waves present in Earth at all times — to construct "virtual earthquakes" that can be used to predict variations in the intensity of shaking during real earthquakes. The technique has proved successful in reproducing variations in ground motion for moderate (magnitude ~5) earthquakes. It has also been extended to predict the shaking expected from larger (magnitude ~7) earthquakes on the San Andreas Fault in Southern California.

WHAT'S NEXT: Apply the approach to predict shaking in cities where earthquakes are likely to strike in the future.

CHALLENGE: Provide early warning of tsunamis.

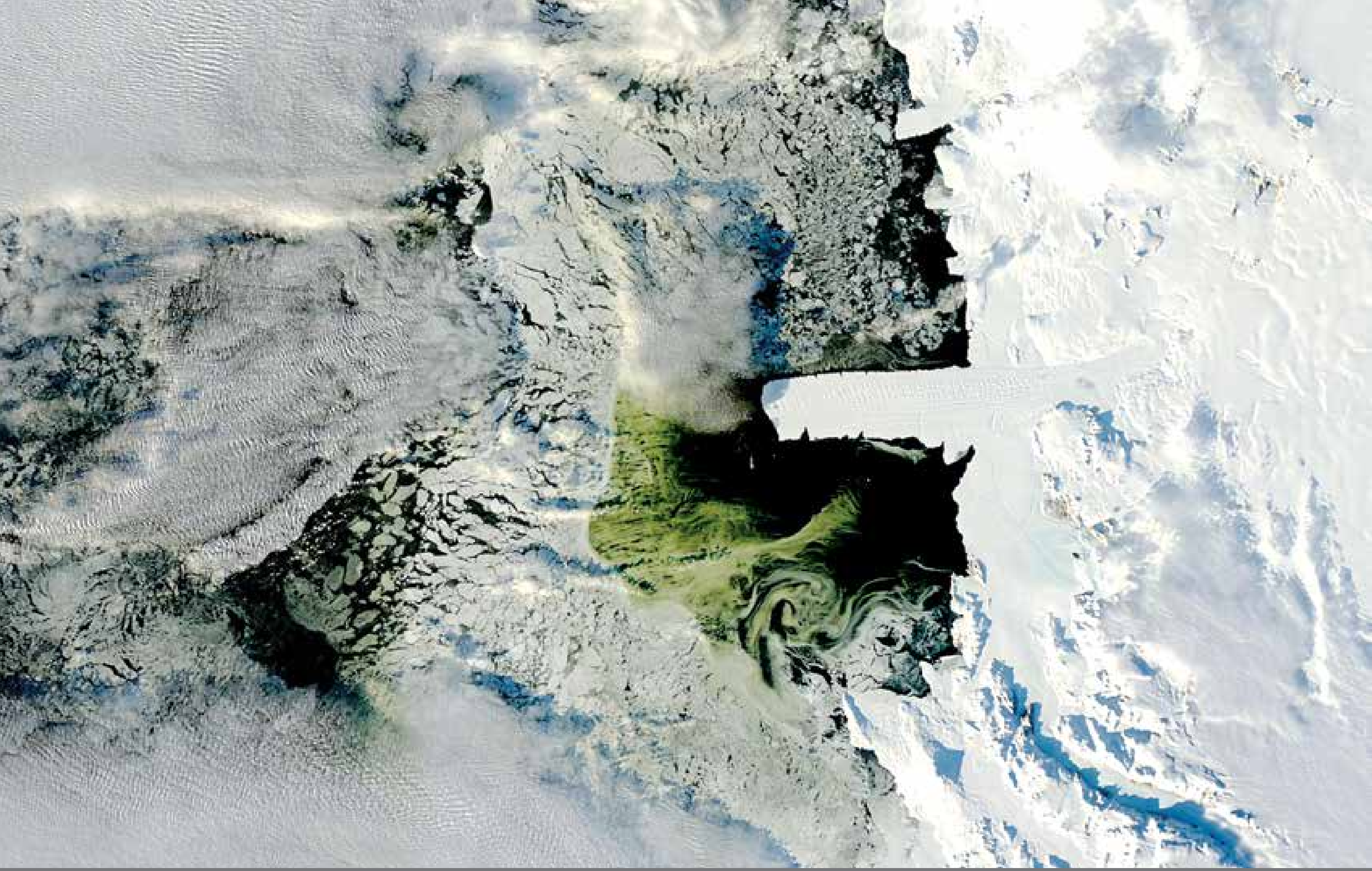
SOLUTION: Studying the devastating events in Tohoku, Japan, in 2011, Stanford scientists are developing computer simulations of subduction-zone earthquakes, which excite seismic waves in solid earth and sound waves in the ocean, and uplift the seafloor to create tsunamis. Since tsunamis travel much more slowly than seismic or acoustic waves, a 10- to 30-minute early-warning window exists for coastal communities and critical facilities. Preliminary simulations show that long-period sound wave amplitudes, recorded by cabled ocean-bottom pressure sensors, correlate well with tsunami wave heights.

WHAT'S NEXT: Validate simulations against seafloor pressure and wave height data recorded during the Tohoku event, and extend models to other subduction zones worldwide.

CHALLENGE: Reduce the vulnerability of agriculture worldwide.

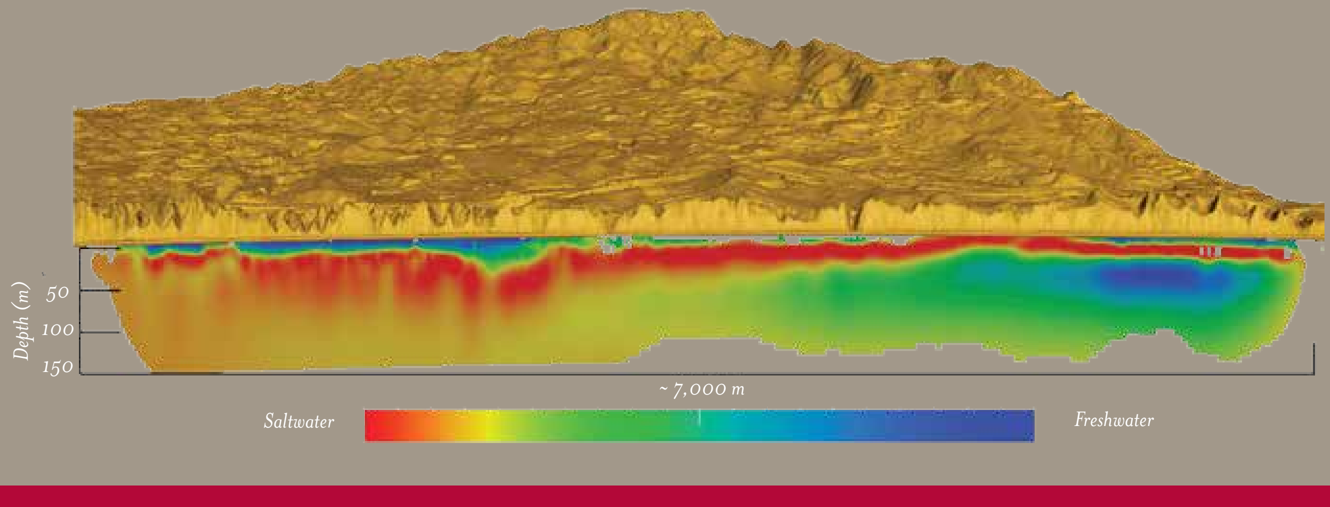
SOLUTION: Stanford scientists have created databases and conducted studies that identify crops and regions most vulnerable to climate change and can help crop breeders focus on traits needed to adapt to climate change. These data can also inform the investments of major foundations and agencies with an interest in global food productivity and security.

WHAT'S NEXT: Communicate why adapting crops matters to people concerned about food security, climate change and other Earth issues, and work with breeders to improve traits most relevant to climate adaptation.



UNDERSTANDING EARTH THROUGH ADVANCED TECHNOLOGY AND COMPUTATION

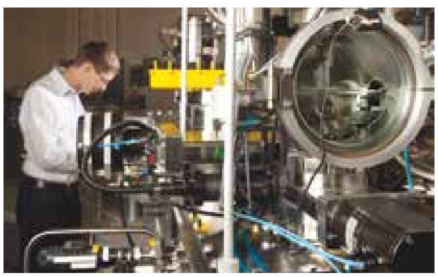
This page: In their ongoing field research in Antarctica's Terra Nova Bay, Stanford oceanographers utilize satellite images to study what happens to the carbon-rich base of the food chain when seasonal ice forms. (above) Electrical resistivity measurements taken by Stanford scientists along the coast of California's Monterey Bay track the intrusion of saltwater into the underlying freshwater aquifer, an impact of groundwater withdrawal. (below)



IN THE FIELD, THROUGH REMOTE SENSING, WITH HIGH-PERFORMANCE COMPUTING AND STATE-OF-THE-ART ANALYTICAL LABORATORIES, Stanford Earth scientists employ powerful and inventive research methods and technologies to explore and understand the planet. We establish and share cutting-edge computational and analytical facilities with Stanford partners and others, providing access to resources that advance research and contribute to a collaborative culture on campus. Key facilities — including our plasma lab, our nanocharacterization lab and the Stanford USGS Microanalytical Center — employ sophisticated technologies and equipment to analyze Earth materials on the smallest scales possible. Our scientists also utilize synchrotron radiation sources and free electron x-ray lasers — the most intense x-ray sources in the world — at the nearby SLAC National Accelerator Laboratory. These unique resources yield insights critical to advancing solutions.

In recent years, the acquisition of data from satellites, aircraft-based sensors, ground-based arrays and new surface and subsurface instrumentation has exploded, generating the potential for a vast increase in Earth sciences discoveries. Advanced computational capabilities are essential to both processing this information and simulating processes involving the extraordinarily complex Earth system, and are critical to leadership in Earth, energy and environmental sciences. Integrating Earth and computer science, the Stanford Center for Computational Earth and Environmental Sciences uses state-of-the-art hardware and computational methods to expand the frontiers of computational geosciences. This approach engages computer scientists and architects in the design of software and hardware that address increasingly complex challenges.

a.



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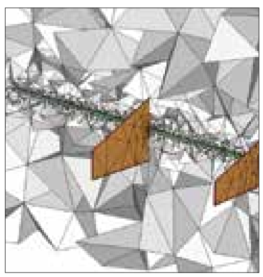

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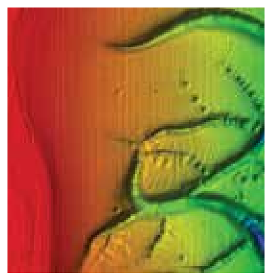

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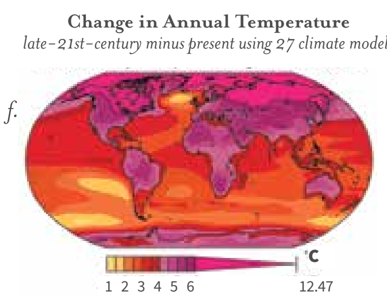

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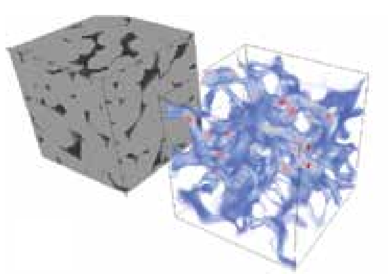


(a.) A partnership between Stanford Earth Sciences and the U.S. Geological Survey, the Sensitive High-Resolution Ion Microprobe with Reverse-Geometry (SHRIMP-RG) lab measures elemental abundances and isotopic ratios from minute volumes of minerals, volcanic glass or biological materials to answer questions in Earth sciences.

(b.) Reservoir engineers employ advanced simulation models to understand the flow of oil and gas in subsurface formations. This figure shows an unstructured grid, which allows the accurate representation of fractures along a horizontal well. The models can be used to predict and optimize shale gas production.

(c.) Three-dimensional seismic reflection images of the seafloor are essential to oil and gas exploration. Captured from offshore, this image shows the surface of the seafloor off the coast of West Africa.

(d.) In the Extreme Environments Laboratory, scientists study materials at very high pressures and very low to very high temperatures, simulating the conditions in the interiors of Earth and other planetary bodies and guiding the development of new materials for hydrogen fuel storage, advanced batteries and other applications.

(e.) A pioneering research method funded by the Carnegie Institution for Science uses satellite and airborne instruments to measure Earth's chemistry, structure, biomass and biodiversity in unprecedented detail over massive areas. This color-coded map shows individual tree species in a section of Kruger National Park in South Africa.

(f.) Stanford models show climate change is now occurring 10 times faster than at any time in the past 65 million years.

(g.) Theoretical rock physics modeling and computer simulations at Stanford reveal the geological properties and processes of different types of rock.

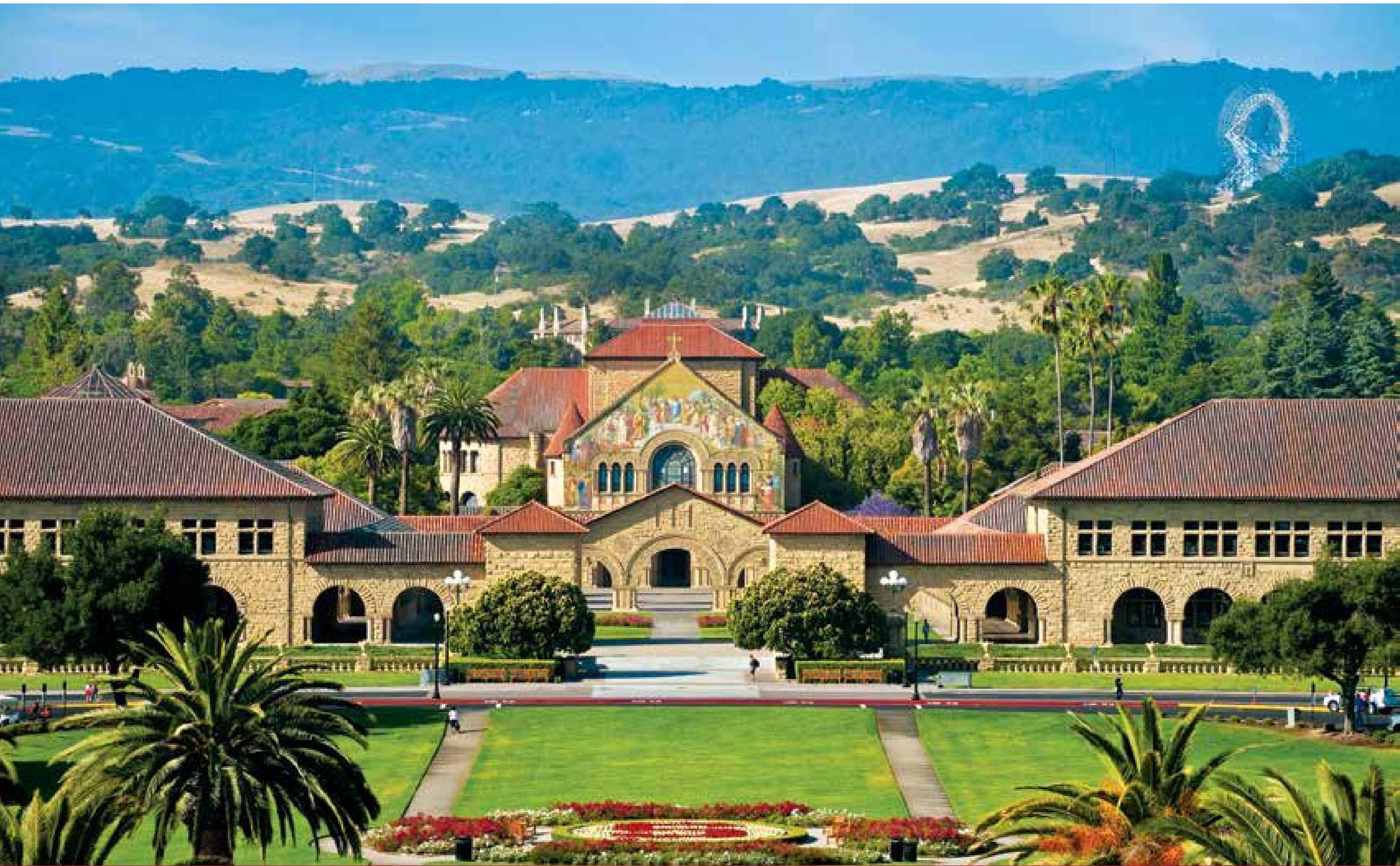
EDUCATING A NEW GENERATION OF EARTH SCIENTISTS

Field research is an important component of learning for Stanford students in the Earth and environmental sciences, shown in Chile's Torres del Paine National Park. (above)

THIS GENERATION OF EARTH AND ENVIRONMENTAL SCIENTISTS HAS A CRITICAL ROLE TO PLAY in a rapidly changing world. Stanford Earth is preparing men and women to explore and discover the workings of the planet and its resources and environment. Students also gain the communication and leadership skills they will need to share Earth sciences knowledge with numerous stakeholders.

Following are just a few areas in which our students are contributing knowledge and solutions: exploring the evolution of the seafloor and the continents; studying the relationship among global warming, land use and extreme weather events in developing countries; using advanced technologies to evaluate and manage groundwater resources; researching the impact of higher temperatures on crop yields; discovering and efficiently producing oil and gas; understanding, measuring and reducing greenhouse gas emissions from fossil energy sources; and assessing earthquake risks in the Himalayas and the American Pacific Northwest. Our graduates go on to careers that reflect the many ways the Earth and environmental sciences make a difference, in academia, industry, government and non-governmental organizations.

The School of Earth, Energy & Environmental Sciences offers both disciplinary and interdisciplinary degree programs: geology, geophysics, Earth systems, energy resources engineering and petroleum engineering, and environment and resources. Demand is high, and our student populations have increased by more than 40 percent in the last five years. Both undergraduate and graduate students bring diverse strengths, perspectives and ambitions to their shared mission to address the planet's challenges. At Stanford, they join a close-knit community of faculty mentors and students engaged in collaborative research and its translation into sustainable solutions. Faculty members employ innovative approaches in the classroom, field and laboratory, and emphasize systems thinking, creativity and teamwork.



STANFORD SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES AT A GLANCE

DEAN

Pamela A. Matson
Chester Naramore Dean,
School of Earth Sciences
Richard and Rhoda Goldman
Professor of Environmental Studies

FACULTY

61
13 members of the U.S. National Academies (Science and Engineering), including emeritus

BUILDINGS

Geology Corner/Braun Hall (1904)
Mitchell Earth Sciences (1968)
Green Earth Sciences (1991)
Yang and Yamazaki Environment and Energy (2008)

LIBRARY

Branner Library: 125,000 volumes and 270,000 sheet maps

WEBSITE

earth.stanford.edu

DEGREE PROGRAMS

Undergraduate: Approximately 200 students

- Earth Systems Program (also coterminal MS)
- Energy Resources Engineering
- Geological Sciences
- Geophysics

For information, contact Richard Nevle (rnevle@stanford.edu)

Graduate: Approximately 400 students

- Energy Resources Engineering
- Earth System Science
- Geological Sciences
- Geophysics
- Emmett Interdisciplinary Program in Environment and Resources
- Computational Geoscience (MS)

For information, contact Roni Holeton (roni@stanford.edu)

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PLANET EARTH
IS *EVERYONE'S* BUSINESS

Earth's challenges are comprehensive and complex — far beyond the scope of a single scientific discipline. Addressing these challenges requires sophisticated and ever-evolving tools, inventive cross-disciplinary collaboration and people who believe in studying and understanding our changing planet and in using their knowledge to help solve problems.

At Stanford Earth, our research is about both discovery and problem solving. We generate new knowledge and advance practical solutions that matter to humans and the other species with which we share the planet. We bring a spirit of innovation to everything we do — whether we're studying Earth's origins or advancing solutions to ensure its future.

Planet Earth is everyone's business. At the Stanford School of Earth, Environmental Sciences, the planet is our unique focus and our mission.

Stanford