STANFORD UNIVERSITY
SCHOOL OF EARTH SCIENCES
EARTH · ENERGY · ENVIRONMENT

Fall 2012

The Earth Scientist

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Addressing the environmental impacts of hydraulic fracturing

by Louis K. Bergeron

Vigorous debates about the ongoing boom in natural gas production have grabbed a lot of headlines over the last year.

Energy companies are extracting 20 percent more natural gas than they were just five years ago and moving into areas of the country that have not seen drilling operations before. This rapid expansion, coupled with uncertainties about environmental impacts of the extraction process, has triggered considerable concern.

Natural gas is far cleaner than coal when used for electrical power generation and is also a flexible fuel, useful for heating, transportation, and providing a back up for wind and solar energy. Nonetheless, the public is right to be concerned about the development of shale gas resources, says Mark Zoback, professor of geophysics in the Stanford School of Earth Sciences.

Much of the debate has centered on the practice of hydraulic fracturing, often referred to as "fracking", the process of injecting fluid into a gas well and raising the pressure enough to fracture the rock the gas is trapped in, making extraction possible.

But that process—and unidentified, but potentially hazardous chemicals in the fluid—is what has prompted some to fear that hydraulic fracturing operations could extend far beyond the well, opening up conduits for the hydraulic fluid and its "mystery" chemicals to percolate into groundwater reservoirs, contaminating water used for drinking or irrigation.

"There are a number of potentially detrimental environmental impacts of shale gas development that need to be addressed," says Professor Zoback, "but, ironically, hydraulic fracturing isn't one of them."

Zoback points to the fact that whenever leakage appears to have contaminated subsurface water supplies the reason has been shown to be poor well construction. Proper well construction, along with proper disposal of wastewater from drilling and hydraulic fracturing, are critical concerns in natural gas extraction, he says.

Zoback's area of expertise is geo-mechanics—the study of how rocks and other Earth materials behave mechanically on scales from the microscopic to the massive tectonic plates that cover the surface of the Earth. He began studying hydraulic fracturing over 30 years ago as a technique for measuring the forces in the Earth. For the past four years, much of his research has been focused on shale gas development. Twice in the past year he has testified before Congressional committees on development issues.

Last year, Zoback was asked to join a panel put together by Secretary of Energy Steven Chu at the request of President Obama to provide advice on the environmental risks associated with shale gas production. In August 2011, the Shale Gas Production Subcommittee filed a report setting forth 20 recommendations for reducing the environmental impact of shale gas production, including a call for complete "disclosure of all chemicals used in hydraulic fracturing fluids on both public and private lands," to help allay public concern over the composition of fracking fluids.

Another concern about shale gas development is the potential for the process to trigger earthquakes.

(click to jump to page 12)

Dean's Message

The fall season brought the start of a new school year and the excitement of welcoming new students to the School of Earth Sciences. Our graduate population has grown substantially, as have majors in our undergraduate programs. I believe this increasing demand reflects student concerns about the Earth, resource, and environmental challenges facing our human population of 7 billion and growing. The students are being taught by world-class faculty who are seeking through their own research to learn more about our planet and its resources and, at the same time, to use that knowledge to help solve critical problems. Together, our faculty, students and alumni around the world are tackling high stakes challenges related to energy and other natural resource demands and depletion, food and water needs, natural-disaster risks and preparedness, and climate change and other environmental changes, among others. It's not surprising that we're a growing enterprise!

This edition of *The Earth Scientist* provides an update on current faculty research, teaching, and student activities. We feature a few of our faculty on subjects ranging from hydraulic fracturing and carbon capture to climate change impacts in the Arctic. Also in this issue, we introduce you to two interdisciplinary graduate student communications initiatives as well as a rigorous summer undergraduate research program that brings to Stanford students from diverse backgrounds.

I am delighted that so many of you accepted our invitation to submit updates on your professional and personal lives. The names of those who sent updates are listed in **Class Notes** and their news, collected on our website, promises to be enjoyable reading. Of course I always enjoy seeing you in person, and hope you can attend one of our upcoming events either here on campus or in your community.

Until then, I extend warm wishes to you from The Farm.

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

Save the Date

AGU FALL MEETING
San Francisco | 3–7 December 2012

AMERICAN GEOPHYSICAL UNION (AGU)
Monday, Dec. 3, 2012
San Francisco, CA

NAPE EXPO

NORTH AMERICAN PROSPECT EXPO (NAPE)
Thursday, Feb. 7, 2013
Houston, TX

AAPG ANNUAL CONVENTION & EXHIBITION

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS (AAPG)
Conference runs May 19-22, 2013
Pittsburgh, PA (reception date TBD)

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Stanford Earth Sciences by the numbers*

GRADUATE PROGRAMS

114 MS Students	294 PhD students
59%-41% Men-Women	8% Underrepresented minorities
63%-37% US-International	64% Increase in total applicants since 2005-06

UNDERGRADUATE MAJORS

203 Students	41% Increase since 2005-06
61%-39% Women - Men	25% Underrepresented minorities
93%-7% US – International	1,100 Undergrads we touch with our classes and programs

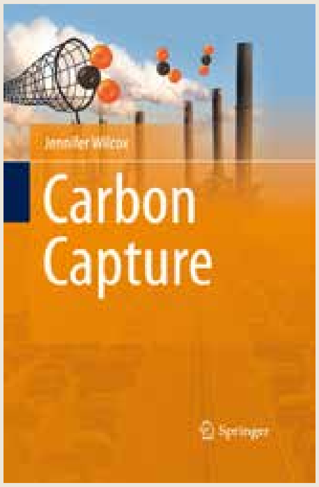
BY DEPARTMENT

56 Total faculty	12 Geophysics
12 Energy Resources Engineering	>25% Precourt Institute for Energy faculty who are from SES
16 Environmental Earth System Science	37% Woods Institute for the Environment senior fellows who are SES facult
16 Geological and Environmental Sciences	14 Members of the national academies

*2011-12 academic year

The number of applicants to our graduate program is up 64%.

The number of students in our undergraduate program is up 41%.



Jennifer Wilcox, assistant professor of energy resources engineering

Capturing the gigaton problem of CO_2 emissions

by Heather Rock Woods

Jennifer Wilcox drives a Volt and charges it with electricity generated from PV at her home. She often commutes on her bike 30 miles from Half Moon Bay to campus.

Her efforts don't stop there.

With 300 million people in India not yet hooked up to electricity, and coal and natural gas the most-used energy sources on the planet, Wilcox investigates carbon capture, or how to separate CO_2 from power plant emissions and other sources to mitigate climate change.

Wilcox is also the author of *Carbon Capture*, published in April.

The textbook focuses on mechanical and chemical engineering methods for "above ground" capture of CO_2. Storage methods, on the other hand, are mostly below ground, the domain of geologists and geophysicists.

"This comprehensive textbook…has arrived at a pivotal moment," Robert Socolow of Princeton University said in a review. "Wilcox's book will usher a new generation of students into this critical field."
The following is a Q&A with Assistant Professor Wilcox.

What prompted the book?

When I arrived here four years ago, I created a course on carbon capture and storage with Sally Benson (professor of energy resources engineering and director of the Global Climate and Energy Project). I realized then that the massive scale of carbon dioxide emissions— ~30 gigatons (30 billion tons) annually worldwide—is a bigger problem than we can really fathom.

Carbon capture has the potential to play a big role in the move to a more sustainable energy future. Because it involves chemical engineering, which is my expertise, this is an area where I can contribute.

The textbook provides a skill set for the next generation of chemists and chemical engineers. Although primarily aimed at this audience, the textbook takes an interdisciplinary approach and may be used by students in many disciplines. Finding solutions to global warming and energy challenges will require social scientists, physicists, Earth scientists, chemists, mathematicians, engineers and behavior change specialists. It will take a different kind of thinking.

Is carbon capture currently in use?

Carbon capture and storage is a somewhat new field, but carbon capture has been used since the early 1900s to purify CO_2 for use as a chemical feedstock and for carbonated beverages like soda.

"Amine scrubbing" is the current state-of-the-art technology. This involves pumping the chemical amine solvent down through a tall tower directly at the power plant site, while simultaneously blowing the flue gas containing CO_2 in the opposite direction, up the tower. The CO_2 forms a chemical bond with amine. Then, the solution is pumped through a second tower where heat is added to break the chemical bonds. This results in a pure stream of CO_2 that is captured and may be used for carbonated beverages or other uses.

As for capturing carbon dioxide for the purpose of keeping it out of the atmosphere, there are only pilot projects at the moment.

I'm not convinced that at the scale of gigatons of carbon dioxide amine scrubbing is the best solution. It's an energy inefficient process, and the amine-based solvent is volatile, hazardous, and corrosive.

What will move the field forward?

The textbook includes fundamental concepts and equations, and discusses the most advanced carbon capture technologies, including absorption, adsorption, and membrane separation technologies. I encourage students to take the next steps through end-of-chapter challenges that explore current limitations. Maybe a student will have a passion for improving the efficiency of one of the chemical processes and spend his or her career making it happen.

One-step carbon capture and storage might be possible in the future, and I examine some scenarios for that in the book. Here's an example: to generate energy, we oxidize fossil sources like coal or natural gas, releasing heat plus CO_2 and H_2O. What if we reversed this combustion process using wind or solar as the energy source and turned the CO_2 and water back into a hydrocarbon *(continued on page 5)*

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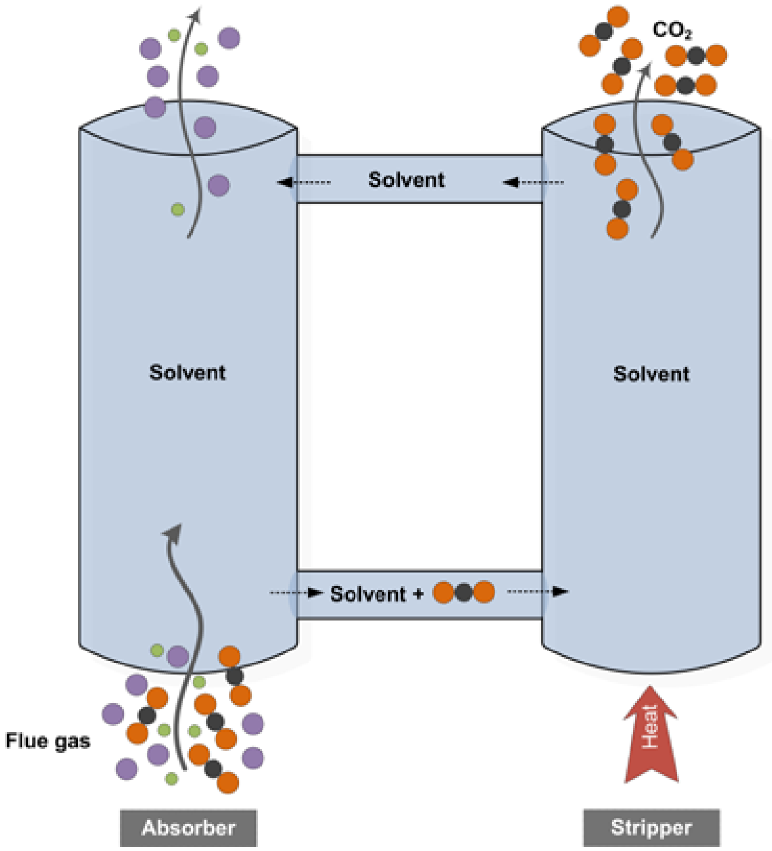

Image courtesy of Panithita Rochana, PhD student, Clean Energy Conversions Group

that could be stored as a fuel? This could be a game-changing approach. Fuel is a market that could match the gigatons of CO_2 we generate on an annual basis. The problem is that water and CO_2 are very stable molecules, from which we've already harnessed the energy from oxidation of hydrocarbons. Logically, the wind and solar energy would be used directly, but when these resources are stranded far from the grid, this fuel conversion process might be an interesting approach to consider.

How did you approach writing your first textbook?

It was pretty intense. There was a tremendous amount of material I had to learn in just a few years. I wanted the book to come out soon enough for use in the classroom while the topic was of global interest.

I kind of treated the effort like a marathon by breaking it up into small steps and accomplishing achievable goals one at a time. As a marathon runner you have moments in a race where you feel like you can't or won't continue, but then you find the strength within yourself and you push through. It can be very rewarding. Also, throughout the writing process I received a lot of support from the scientific community. Many folks from Stanford, faculty and postdocs, reviewed several chapters. My students helped with the images and tables for the book also.

Did your research focus change based on what you learned in writing the book?

The research that I carry out related to carbon capture is primarily focused on adsorption and membrane technologies. This text is based largely on the fundamentals behind separation processes and the materials and their properties used for carbon capture. When I update the textbook, I plan to funnel in more of my own research efforts and ideas.

Carbon Capture is available at amazon.com and at the Stanford Bookstore in the textbook section.

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Adam Brandt, assistant professor of energy resources engineering

From well to wheel — the full lifecycle of carbon-based fuels

California oil field with steam injection into the subsurface. Photo by Adam Brandt.

by Heather Rock Woods

In most ways, Adam Brandt's work life has stayed the same despite happy upheavals last July: first baby, moving offices, and being promoted to tenure-track assistant professor of energy resources engineering in the School of Earth Sciences.

He's still teaching classes, writing papers, and meeting with students and postdocs. And he's still absorbed in measuring and mitigating carbon-intensive sources of fuel.

Carbon-dioxide-emitting fossil fuels are an inescapable source of energy for the next few decades, even as solar and wind power grow. Furthermore, oil rarely bubbles out of the ground anymore without extensive intervention.

"A massive economic force is pushing us toward fossil energy sources that are harder to get: the oil sands in Canada, one-mile-deep offshore oil drilling in the Gulf of Mexico, exploration in Arctic waters," said Brandt.

These methods often let loose more carbon dioxide than conventional oil drilling because they require more energy to obtain the fuels.

To determine the full effect, Brandt factors in the entire lifecycle—from "well to wheel"—including the energy put into extracting, refining, and transporting the fuel to a gas station near you. His calculations show that oil from the oil sands mines, for example, releases on average 20 percent more carbon dioxide than conventional oil.

Those averages are important, but carbon-intensity can vary from well to well, and mine to mine. For instance, many California oil fields use steam injection to get heavy oil out; the energy to boil water into steam adds to total carbon emissions for each gallon of oil produced.

"Flaring, steam injection, and intense methods to remove scarce oil are three conditions that can push you into the 20 percent range," Brandt said.

To account for individual differences, Brandt and postdoctoral researcher Hassan El-Houjeri have spent the last year developing a tool that allows direct comparison of carbon intensity for different oil field production practices. It's ready for use with California's Low Carbon Fuel Standard, which calls for a 10 percent reduction in carbon dioxide per unit of fuel over 10 years. *(click to jump to page 12)*

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Left: The NASA-sponsored ICESCAPE expedition that discovered the bloom was led by environmental Earth system science professor Kevin Arrigo (pictured below). Photo by Gert Van Duken.

NASA mission finds massive algal blooms under Arctic sea ice

by Max McClure, *Stanford Report*

The "impossible" discovery, spearheaded by Stanford Professor Kevin Arrigo, is a harbinger of major changes in Arctic ecosystems as the planet warms.

A massive phytoplankton bloom has been found underneath the Arctic pack ice in the Chukchi Sea. The under-ice bloom, previously thought impossible, will require a complete rethinking of Arctic ecosystems – and is a potent indicator of global warming's effects on the far north.

The 2011 NASA-sponsored ICESCAPE expedition that discovered the bloom was led by environmental Earth system science Professor Kevin Arrigo. The paper announcing the find appeared in *Science*.

Under-ice discovery

Unlike most Arctic research teams, ICESCAPE headed deep into the Chukchi Sea ice pack, north of the Bering Strait. The research cruise, consisting of prominent scientists in the fields of oceanography, biology, chemistry and optics, was intended to improve NASA's remote monitoring of the Arctic's changing conditions.

"Suddenly, the fluorometer" – the fluorescence-measuring device used to estimate the algal content of water – "went nuts," Arrigo said. "We thought there was something wrong with the instrument."

Most models of biological production in the Arctic Ocean assume a value of zero below pack ice. Sea ice and snow cover have historically reflected incoming solar radiation, leaving no sunlight for plankton in the water below.

"Not only was the value not zero," said Arrigo, "production was higher there than it was in open water."

Based on samples from surrounding water and on the species of algae in the bloom, the scientists confirmed that the phytoplankton had not drifted under the ice from elsewhere.

Instead, changing ice conditions now allow light to penetrate large swaths of Arctic sea ice. Thick "multi-year" ice, which requires several seasons to accumulate, is on the decline, while warming temperatures favor thinner "first-year ice." Additionally, the melt pools that now commonly form on top of Arctic sea ice decrease the ice pack's ability to reflect light.

The resulting under-ice environment is ideal for Arctic phytoplankton. The thin ice lets in light while protecting the algae from ultraviolet radiation.

"Grow rates under the ice are higher than I thought was possible for Arctic phytoplankton," Arrigo said. Algal cells that would normally take three days to divide were doubling more than once a day.

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Julie Sweetkind-Singer, head librarian, Branner Earth Sciences Library & Map Collections, with some of the maps depicting California as an island. Photo by L.A. Cicero.

Largest private map collection of 'California as Island' comes to Stanford

by Cynthia Haven, *Stanford Report*

The 800 maps will be going digital in the coming months.

California is an island. Always has been. Always will be.

A new Stanford Libraries acquisition of 800 maps from one of the nation's top map collectors, Glen McLaughlin, bolsters the claim: California was portrayed as an island on maps for well over a century.

"To my knowledge, it is the largest collection featuring California as an island in private hands in the world," said McLaughlin. "The collection was built over a 40-year time period, from 1971 to last year."

Cartographers call it the greatest snafu ever, persisting on a few Asian maps even into the 1860s. But perhaps those mapmakers sensed a deeper truth.

"California is surrounded by deserts and mountains, so much so that it might as well be an island," said Rebecca Solnit, author of Infinite City: A San Francisco Atlas. "It has 2,000 species of plants found nowhere else on the Earth, as well as a lot of endemic butterflies, reptiles, and other critters."

For the early European explorers, "It was a place where everything was inverted, everything was different," she said. "The stupendous scale of a lot of things and the fertility of the land made it an otherworldly wonderland – with trees 30 feet across and waterfalls 1,000 feet high, and tribes that collectively spoke more than 100 languages. It was the second richest linguistic area on the Earth after Papua New Guinea."

Enough was enough in 1747, when King Ferdinand VI of Spain issued a royal decree proclaiming: "California is not an island."

Stanford's Bill Lane Center for the American West, in conjunction with Stanford Libraries, has just awarded Solnit a six-month Maynard Parker Fellowship so that she can study and write a book about the California-as-Island maps.

The San Francisco writer is the author of more than a dozen books about art, landscape, public and collective life, ecology, and politics. She has received a Guggenheim Fellowship and a Lannan Literary Award, and is a contributing editor to *Harper's*. Stanford Libraries acquired Solnit's research files, notebooks, drafts, correspondence, hard drives, and related material last year.

Her most recent book, *Infinite City*, coordinated 30 cartographers, artists, writers, and researchers to "reinvent" the atlas. "I've loved maps all my life," she said. With that book, "I found out I'm not the only one."

The early European cartographers had reason for their confusion about California. The state has been in the public sunlight for so long, it's hard to remember that to Europeans it was once one of the most mysterious and unreachable places on Earth.

According to McLaughlin, "California and the Northwest coast of America was one of the unexplored places on Earth, along with Antarctica and Australia."

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To sail northward from Baja meant going directly into the prevailing swells. Ships had to steer out toward Hawaii, then aim far north of their California target and sail southward along the coast. So the in-between coastline remained a mystery.

Seeking a trade route, sailors sought the fabled "Northwest Passage" that would connect the Pacific and the Atlantic.

That was the beginning of the error, but hardly its end. "Some of these maps continued to be produced after it was widely known that California was not an island," said Jon Christensen, formerly executive director of the Bill Lane Center for the American West.

The earliest Spanish maps from the 16th century show a continuous coastline, but a Carmelite friar, Antonio de la Ascensíon, accompanied Sebastian Vizcaíno on his West Coast expedition of 1602-03 and apparently drew a map depicting California as an island around 1620.

Plunder was commonplace, and Spanish maps were a hot commodity. They were also a state secret. It's generally accepted that the Dutch captured a ship en route, and the charts were waylaid to Amsterdam. What we know for sure is that the maps were widely copied.

Perhaps it's just what the Spanish wanted, suggested Solnit. "I've been told that Spain knew it wasn't an island, but it was politically expedient for others to think it was. They weren't going to share what they knew with everybody else."

Enough was enough in 1747, when King Ferdinand VI of Spain issued a royal decree proclaiming, "California is not an island."

But the mystique for map collectors had just begun.

McLaughlin's collection started when he was on assignment in London in 1971. "We were just poking around in shops in the Knightsbridge area, and I discovered a 'California as Island' map. I had no idea. I was the director for Memorex Corporation then, and we entertained visitors from other countries. So I bought a map and put it in the entryway. It was a real icebreaker.

"I used to say, 'This is the way you guys used to portray us!'" His guests would reply, "Yes, we still think of you that way, too. Floating off the mainland."

According to Christensen, "Californians often think of themselves as an island. Bio-geographically, it's still very much an island," with its unique Mediterranean climate at the edge of a continent.

Isolated by the Sierra Nevada on one side and the Pacific on the other, California uniquely borders Mexico and faces Asia. It is "distinct economically, politically, socially. We often go our own way," Solnit added.

Something else that makes California unique: It's home to Silicon Valley – and Stanford was a natural locale to digitize the maps. The project began in 2008 under the guidance of Julie Sweetkind-Singer, head librarian of Stanford's Branner Earth Sciences Library and Map Collections, and formerly a private maps librarian for McLaughlin.

The 800 maps will be posted online in coming months.

"That was an integral part of the vision for bringing the maps to Stanford," said McLaughlin. "They will be part of a great digital map library that we're building here. Anyone will be able to see them and study them. They'll be available 24/7. I don't know of any library that would keep its maps room open for those hours. It's terrific."

Cynthia Haven is the associate director for communications at the Stanford University Libraries.

Top, left: Planisphere representant toute l'etendue du Monde, by Louis Renard, 1715 (detail).
Top, right : This map, created in 1626/1627, depicts California with a flat northern coast. Map top border depicts plans of towns; side borders show figures of the inhabitants of different countries.
Center, right: This map was created in Amsterdam in 1666 and reissued in 1668, 1669, 1670, 1672, 1675 and 1676. It was issued in an English edition in 1668 and a Spanish edition in 1669.
Bottom, right:This map, created in 1640, depicts California as an island with indented northern coast; points, capes and nearby islands are labeled. Vignette along the map bottom depicts explorers talking with natives.

SURGE, Class of 2012.

"Before this program I didn't know much about grad school," said Tara Larrue. "Now I have a better chance anywhere."

Summer research program fosters graduate school aspirations

by Heather Rock Woods

Sixteen undergraduate students with family roots in Trinidad and Tobago, Mexico, Thailand, Chicago, and elsewhere now have their sights set on graduate school after seizing opportunities to work with principal investigators in the School of Earth Sciences last summer.

In mid-August, a few days before presenting their summer's research, the students reflected on their eight-week tenure with the Summer Undergraduate Research in Geoscience and Engineering (SURGE) program.

"This was my first research experience. It's very interesting to focus all your efforts on one question and build your own methods to explore it," said Tara Larrue, now a fourth-year environmental science major (with a concentration in geology) and computer science minor at Northeastern University in Boston.

SURGE is run by the school's Office of Multicultural Affairs (OMA) to encourage talented and motivated students from diverse backgrounds to become geoscience graduate students—especially at Stanford, whose reputation can deter candidates from even considering it.

"We're trying to invest in their future and the diversity of geoscience as a whole," said OMA Assistant Dean Tenea Nelson. "With diversity in individuals, you increase the diversity of thought and research and perspectives. Out of that come new discoveries."

Only in its second year, the program provided a supportive environment to the recent group. They shared a dorm, attended faculty talks together, learned about applying to grad school and taking GRE exams, went on school field trips and social outings, and created a sense of community and a network that could help them through their grad school years and beyond.

"It's a great program," said Keiron Durant, a junior in chemical engineering at the University of Arkansas. "I met great people, networked with professors, and gained experience related to the side of the industry I want to get into."

Durant, a native of Trinidad and Tobago, arrived at Stanford knowing he wants a career in petroleum exploration. His mother encouraged him and his sister from a young age to go into science or engineering. His sister is now a geologist at Shell in Houston.

With direction and mentoring from Anthony Kovscek, professor of energy resources engineering, and postdoctoral researcher Christophe Duchateau, Durant analyzed and visualized how heptane (a simple substitution for carbon dioxide) flows through a micro-scale model of an aquifer. Studies like these shed light on how carbon dioxide can be used for enhanced oil recovery.

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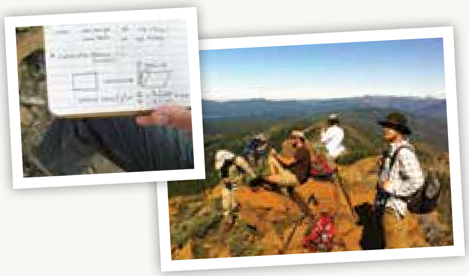
Blogging from the field

Visit earthsci.stanford.edu/blogs to read the blogs described below.

Lauren E. Oakes, a PhD candidate in the Emmett Interdisciplinary Program in Environment and Resources (E-IPER), studied and wrote about the ecological repercussions of the dieback of yellow-cedar forests in the Alexander Archipelago in southeastern Alaska.

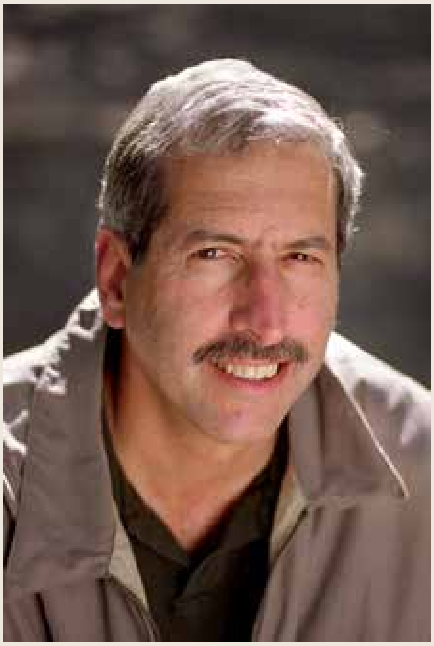


Undergraduate students in GES 190, Research in the Field, blogged about their team-based experience collecting data to answer research questions. Taught from tent camps, the students spent a week at the Trinity Ophiolite in northern California, near Mt. Shasta, and another at the Josephine Peridotite, located in southwest Oregon near the coastal town of Brookings.

Anne Egger (PhD ’10), former SES undergraduate program director, now assistant professor of geological sciences and science education at Central Washington University, is part of a team of scientists and engineers working to collect magnetic data using ground surveys and an aircraft that can fly without a pilot or crew on board, called an unmanned aerial system, or UAS. Their goal is to map the geophysics below the surface of Surprise Valley, a small rural community in the northeastern corner of California.

Hari Mix and Jeremy Caves, graduate students in the Department of Environmental Earth System Science, shared some of their adventures and photos from their field season in Mongolia working on an NSF project.

Kimberly Lau, graduate student in the Department of Geological and Environmental Sciences, blogged about her field work this summer in south China.



Mark Zoback, Benjamin M. Page Professor, geophysics.

A short video about Professor Zoback and his work can be viewed at http://energyinnovation.stanford.edu/individual/courses/shale-gas.php.

"Now that the promise of natural gas for reducing greenhouse gas emissions is being realized, it makes the need for environmental protection during shale gas development even more important," said Zoback.

Hydraulic fracturing

(continued from page 1)

A typical hydraulic fracturing operation involves pressurizing a relatively small volume of rock for a short period of time, typically about two hours, which generates extremely small micro-seismic events. "The energy released by one of these tiny micro-seismic events is equivalent to the energy of a gallon of milk hitting the floor after falling off a kitchen counter," Zoback says. "Needless to say, these events pose no danger to the public."

In several cases, however, larger, but still very small earthquakes have been associated with hydraulic fracturing operations. Out of the hundreds of thousands of hydraulic fracturing operations carried out over the past few years, there have been only a few reports of triggered earthquakes that might have been large enough to be felt by people living in the region and none were reported to have caused significant damage. Of greater concern are earthquakes triggered by the injection of wastewater from the drilling and fracturing process.

Drilling and hydrofracturing a natural gas well typically takes several million gallons of water. That water is mixed with a number of relatively benign additives, Zoback says. However, when the water is injected into shale during hydraulic fracturing, it picks up a number of naturally occurring chemicals from the shale including arsenic, selenium, iron, and sometimes, radioactive particles. When the hydraulic fracturing water is flowed back to the surface prior to gas production, the highly saline "flowback" water must be properly handled.

Most commonly, the flowback water is injected into disposal wells, licensed by the U.S. Environmental Protection Agency. With proper construction, these disposal wells prevent the injected water from leaking into the environment. But the volumes of water and the pressures involved in wastewater injection sometimes exceed the capacity of the geologic formations being used to store them, and trigger small-to-moderate earthquakes, the largest confirmed one being a magnitude-4.7 event in February in Arkansas.

In an article that appeared in the April 2012 issue of *Earth* magazine, Zoback pointed out that roughly 150,000 wastewater injection wells have been safely operating in the U.S. for many decades with no earthquakes being triggered. He laid out five simple steps that regulators and energy companies could take to reduce the low risk of triggering earthquakes by wastewater injection even further.

Zoback points out that "the preferable solution is not to inject the flowback water at all, but to reuse it in subsequent drilling and hydraulic fracturing operations." Increasingly, gas companies in the northeastern U.S. have been taking this approach.

It has long been known that burning natural gas for electricity instead of coal has the potential to significantly reduce greenhouse gas emissions. With the development of hydrofracturing, Zoback says that potential reduction is fast becoming a reality, noting that, "the rapid switch to natural gas from coal in just the past four years has dropped U.S. CO_2 emissions to levels not seen for 20 years."

Shale gas resources are found in many countries around the world, including China, which generates three times as much CO_2 as the U.S. by burning coal for electricity.

"Now that the promise of natural gas for reducing greenhouse gas emissions is being realized, it makes the need for environmental protection during shale gas development even more important", he said.

Zoback is currently serving on a committee advising the Canadian government about shale gas development and environmental protection. Previously he served on the National Academy of Engineering committee established at the request of Interior Secretary Ken Salazar to investigate the Deepwater Horizon disaster in the Gulf of Mexico.

Well to wheel

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"We're finalizing the tool for regulatory use. It's open source and very transparent, so people can understand the calculations." Brandt said. "To meet the 10 percent reduction target, California companies will be able to look at the numbers when choosing components of their energy portfolio."

NASA mission

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A shifting Arctic

While the discovery marks the first direct observation of an under-ice bloom, the conditions that allow for it in the Chukchi Sea exist over a large area of the Arctic.

"We suspect that this is a lot more widespread than we realize," said Arrigo.

The appearance of under-ice blooms may presage wholesale shifts in the ecosystem of the Arctic. Colder-water phytoplankton production, as with under-ice algae, may cause organic matter to drop to the ocean floor sooner. The effect would benefit bottom-feeding species, to the detriment of species that feed in the water column.

And, as algal blooms are able to occur earlier in the year, animals that depend on timing their behavior to "pulses" in algal productivity may be left out in the cold.

One piece of seemingly good news is an increase in the Arctic's ability to sequester carbon. As the Arctic Ocean's productivity increases, so should its carbon capture rate. But, Arrigo says, the effect is unlikely to make much difference.

"Even if the amount of CO_2 going into the Arctic Ocean doubled, it's a blip on a global scale," he said.

SURGE

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New Vistas

Many SURGE students have drawn on a reservoir of imagination and passion to pursue their college majors.

Growing up, "I never even thought about studying science or going to grad school. My family is all farmers and factory workers," said senior Diana Flores, a geoscience major minoring in geographic information systems at Montclair State University in New Jersey. Her parents lived 40 miles from a volcano in Mexico before moving to the U.S., which inspired her academic focus. "I'm interested in geohazards and how they impact people — that's what I want to do for a career if it's possible."

Over the summer, Flores tackled two online databases and learned to use Matlab software to investigate possible connections between climate change and past changes in the Earth's geomagnetic field. With advice from Kristin Portle Lawrence, a lecturer in the Earth Systems Program, she sifted through oxygen-18 data from caves to understand past rainfall and temperature conditions.

Flores is one of the SURGE students who submitted their abstracts to national conferences to share their findings, and she has now added Stanford to her list of graduate schools to consider.

Larrue, the research rookie from Northeastern, also expanded her list. "Before this program I didn't know much about grad school. Now I have a better chance anywhere," she said.

Her parents are both in business, but the people Larrue knew from childhood weren't in science, and many didn't go to college.

Her project for Greg Beroza, professor and department chair of geophysics, took advantage of her computer science minor—"Although it's different taking classes on programming than actually using it for a research question," she noted.

Geophysics graduate student Marine Denolle mentored Larrue as she ran simulations of what ground motion to expect from surface seismic waves, depending on ground densities, speed of the waves and other factors. The resulting knowledge helps improve building codes to protect people during earthquakes.

"Everyone we worked with is awesome," Larrue said. "It's been a very good summer."

Keiron Durant, a junior in chemical engineering from the University of Arkansas, working in Tony Kovscek's lab; Kovscek is professor and chair of energy resources engineering.

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Class Notes

In response to our summer survey, we heard from nearly 170 alums, from the classes of 1951 to 2011, from as far away as Malaysia, Anchorage, and Rome and as close to campus as Menlo Park and San Francisco. Visit **earthsci.stanford.edu/classnotes** to read what these alums are up to, and please keep sharing your news with us by contacting Astrid Thompson at astrid.thompson@stanford.edu.

Azhar Abdullah, BS ’97 PE

John W. Alden, Esq., BS ’55, MS ’56 PE; JD ’59

Richard Atwater, BS ’74 Geo

Bob Avakian, MS ’70 Geophysics

Kristen Averyt, PhD ’04 GES

Steve Bacharach, MS ’94 Geophysics

Raphaele C. Bally, MS ’85 Geophysics

Maurizio Battaglia, PhD ’02 Geophysics

Rachel Beane, PhD ’97

John D. Beaulieu, PhD ’71 Geo

Rolf Beier, MS ’51 Min Sci

Anne L Berry, MS ’73 Geo

Jennifer Blank, BS ’83 Geo

Alan Bol, BS ’81 Geo

Art Bookstrom, PhD ’75 Geo

Tom Brannon, BS ’81 Geo

Laurie Brooks (formerly Noddings, Langer), MS ’79 PE

Cindy Buchner, BS ’97 ESys

Anna Lee Burchard, BAS ’85 AES & Classical Studies

Shaughn Burnison, MS ’89 Geophysics

John W. Burrows, BS ’60 Geo

Bob Bush, MS ’81 Geo

Butch Butler, MS ’77 Geophysics

Bruce Buxton, PhD ’86, AES

Tony Campbell, BS ’84 Geo

Elizabeth J. Cassel, PhD ’12 GES

Claudia Chern, BS ’12 ESys

Stephen R. Clark, MS ’77 PE

Guy Clum, BS ’53 Geo

John Cogan, PhD ’75 Eng Geo

Marc Coladon, MS ’73 AES

Bernard H. Coyle, Jr, MS ’75, Eng ’76 AES

Bob Daniel, PhD ’79 Geophysics

Richard G. Darling, PhD ’68 Geo

Steve Davis, PhD ’04 GES

Brian Dent, PhD ’73 Geophysics

Ross Denton, BS ’74 Geo

Katherine Dickinson, BS ’02, MS ’03 ESys

John H Dilles, PhD ’84 Geo

Walter L. Dowdle, MS ’70 PE

Ted Driscoll, PhD ’85

Darcy Dugan, BS ’04 ESys

Andrew L. Evans, PhD ’89 AES

Phillip Farrell, BS ’73 Geophysics

Dan Feltham, BS ’56

Dr. Christian C. Finch, BS/MS ’73 Geo

Juan-Mauricio Florez, PhD ’05 Geophysics

David Forbes, BS ’49, MS ’50 Min Sci

Chuck Fox, MS ’86 PE

Chris Friedel, BS ’01 ESys

Chris Friedemann, BS ’86 PE; MBA ’92

Rachel Friedman, BS ’08, MS ’09 ESys

George Frye, ENG ’73 PE

Tom Goodlin, BS ’82 Geo

Leslie C. Gordon, ’78 Geo

Ellen Gray, BS ’06, MS ’07 GES

Gordon Greve, BS ’56 EE; MS ’58, PhD ’62 Geophysics

Mohinder S Gulati, PhD ’73 PE

Steve Haas, MS ’83 Geophysics

Peter Hahn, BS ’57, MS ’59 Geo

Andrew Hanson, PhD ’99 GES

Will Harte, BS/MS ’11 ESys

Carey Haughy (previously Huggins and van Tamelen), BS/MS ’87 Geo

Peter Hay, PhD ’65 Geo

Paul O. Hayne, BS ’03, MS ’05

Edward L. Heffern, BS/MS ’73 Geo

Donald Heinrichs, BS ’60, PhD ’66 Geophysics

Beverly L. Herzog, MS ’78 AES

Robert G. Hickman, BS ’68 Geo & Geophysics

Carroll Ann Hodges, PhD ’66 Geo

Sally Barrow Hurlbert, BS ’80 Geo

Richard Iverson, MS ’80 AES; MS ’81 Hydro; PhD ’84 AES

Alison Iwerks Martin, BS/MS ’01 ESys

Nan Jackson, BS ’74 Geo

Louis-Marie Jacquelin, MS ’09 ERE

Stephen E. Johnson, BS/MS ’83, PE

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Jonathan Godard Kuespert, MS ’84 AES

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Kathanne Lynch, BS ’80 Geophysics
Paul Martin Mai, PhD ’01 Geophysics
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Robert K Mark, MS ’69, Physics; PhD ’72 Geo
José Kanan Marques, MS ’75 PE
Diogenes Fernandes Marra, MS ’96 PE
Cecelia McCloy, MS ’84 Geo
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Karen McLaughlin, PhD ’06 GES
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Lawrence D. Porter, BS ’54 Physics
Jared M. Potter, PhD ’82 Geo
Francisco Querol, PhD ’74 Geo
Julien Robert Ransone, BA ’63 Econ
John L. Redmond, MS ’62 Geo
Travis Riddell, BS ’98 ESys
J. E. (Rick) Riseden, MS ’68 PE
Gary Robinson, BS ’78 Geo
Brian Romans, PhD ’08 GES
Richard E. Rowland, BS ’56 Geo
Matthew Sabisky, BS ’83 Geo
Rafe Sagarin, BS ’94 ESys
Phil Salvador, MS ’75 Geo
Lucy Harding Schumer, BS ’75 Geo
Kerry Sieh, PhD ’77 Geo
Heather Simon, BS ’01 ESys
Charles H. Simonds, BS ’67 Geo
Samuel J. Sims, PhD ’61, Geo
Aaron Slowey, PhD ’06 GES
Judy Terry Smith, MS ’64, PhD 68 Geo
Alejandro E. Soto,MS ’75 Eng Geo
Nick Speyer, MS ’07 ERE
Bruce A. Sramek, ’69 Geo
Peter H. Stauffer, BS ’57, MS ’59, PhD ’65 Geo
Timothy D. Steele, MS ’65, PhD ’68 Hydrology
Don Steeples, PhD ’75 Geophysics
George Steinmetz, BS 79 Geophysics
Huai Su, MS ’64 AES
James Super, BS ’11 GES; MS ’11 ESys
Vernon Taylor III, BS ’70 Geo
Erminia Townsend (Mallia-Zarb), MS ’00 Geophysics
Kevin Townsend, BS ’11 ESys
Allan H. Treiman, MS ’77 Geo
Sarah Truebe, BS ’06, MS ’07 ESys
Bob Tyson, BS ’69 Geo
Amy Arends Vesela, BS ’92 AES
Nicholas Vidargas, BS ’02, MS ’03 ESys
Neth Walker, MS ’11 CEE
Halbert S. Washburn, BS ’82 PE
Laura Wasylenki, BS ’92 Geo & Symbolic Systems
John P. Wiedmann, BS/MS ’61; MBA ’71
Curtis Wilbur, BS ’74 Geo

AES=Applied Earth Sciences
ESys=Earth Systems
E-IPER=Emmett Interdisciplinary Program in Environment and Resources
Geo=Geology
GES=Geological and Environmental Sciences
Min Sci=Mineral Sciences
PE=Petroleum Engineering

Stanford University
School of Earth Sciences

397 Panama Mall
Mitchell Building, Suite 101
Stanford, CA 94305

Presorted First Class
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Palo Alto, CA
Permit #28

About *The Earth Scientist*

Editor: Cynthia Gori

Graphic Designer: Jami Butler

Printed on: New Leaf Reincarnation Matte (FSC), 100% recycled fiber, 60% post-consumer waste, processed chlorine free

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Student communications initiatives

Generation Anthropocene

Generation Anthropocene compiles interviews conducted by students in an Earth Systems Program class called Podcasting the Anthropocene. As part of their experiment in interdisciplinary science communication, students talk with geologists, engineers, ecologists, doctors, project managers, oceanographers, and historians on the theme of life in the Anthropocene age.

Listen at http://www.stanford.edu/group/anthropocene/cgi-bin/wordpress/.

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