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# The Earth Scientist

## First life may have arisen above serpentine rock, say Stanford researchers

by Max McClure, *Stanford Report*

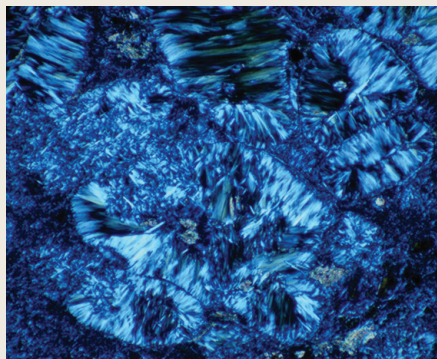
Stanford Earth scientists lend geophysical support to a theory of life's origins – but show that, if it's accurate, the first organisms could only have arisen during one brief stretch of geological time, long ago.

About 3.8 billion years ago, Earth was teeming with unicellular life. A little more than 4.5 billion years ago, the Earth was a ball of vaporous rock. And somewhere in between, the first organisms spontaneously

arose. Pinpointing exactly when and how that shift happened has proven a difficult bit of interdisciplinary detective work.

A team of Stanford geologists hasn't quite solved the problem, but they've come closer. By examining the geology and environment of the early Earth, the researchers demonstrate the plausibility of one theory: that life originated above serpentinite rock on the ocean bottom. Because the necessary conditions only existed for a few

*(continued on page 8)*



*Photomicrograph of a thin section of serpentinite rock.*

PHOTO: EMILY POPE

## Unusual earthquake gave Japan tsunami extra punch, Stanford scientists say

by Louis Bergeron, *Stanford Report*

The earthquake and tsunami that hit Japan on March 11 were generated on a fault that didn't rupture in the usual fashion, according to a study by researchers at Stanford University and the University of Tokyo. The rupture initially shot westward, then slowed markedly in that direction while the fault began rupturing rapidly eastward. The "flip-flop" fault motion first

shook Honshu violently, then deformed seafloor sediments on the fault plane with such force that they triggered the huge tsunami. What researchers don't know is what the odds are that comparable faults could behave in a similar fashion.

The magnitude 9 earthquake and resulting tsunami that struck Japan on March 11 were like a one-two punch – first violently shaking, then

*(continued on page 10)*

*A ferry boat rests inland amidst destroyed houses after a 9.0 earthquake and subsequent tsunami struck Japan March 11.*



PHOTO: LANCE OPL, GARRY WELCH / U.S. MARINE CORPS





**Pamela A. Matson**

*Chester Naramore Dean,  
School of Earth Sciences*

*Richard and Rhoda Goldman  
Professor of Environmental Studies*

## Dean's Message

It is my pleasure to introduce this issue of our alumni newsletter. I hope you will enjoy reading about some of our research efforts and catching up on school news.

An exciting academic year is under way and I hope you will check in periodically to see what's new. If you live near or are visiting campus, I invite you to stop by and visit. And you can always visit [earthsci.stanford.edu](http://earthsci.stanford.edu) to read the latest news, find out about upcoming events, and stay in touch with other alums.

As always, your comments and suggestions are most welcome. My thanks for your continuing interest in our programs and our students.

With warm wishes,

## Amorphous diamond, a new super-hard form of carbon, created under ultrahigh pressure

by Louis Bergeron, *Stanford Report*

A new form of carbon that rivals diamonds in its hardness, but has an amorphous structure similar to glass, has been produced under ultrahigh pressure in laboratory experiments. The research team was led by Stanford mineral physicist Wendy Mao and graduate student Yu Lin.

An amorphous diamond – one that lacks the crystalline structure of diamond, but is every bit as hard – has been created by a Stanford-led team of researchers.

But what good is an amorphous diamond?

“Sometimes amorphous forms of a material can have advantages over crystalline forms,” said Yu Lin, a Stanford graduate student involved in the research.

The biggest drawback with using diamond for purposes other than jewelry is that even though it is the hardest material known, its crystalline structure contains planes of weakness. Those planes are what allow diamond cutters to cleave all the facets that help give a diamond its dazzle – they are actually breaking the gem along weak planes, not cutting it.

“With diamond, the strength depends on the direction a lot. It’s not a bad property, necessarily, but it is limiting,” said Wendy

Mao, the Stanford mineral physicist who led the research. “But if diamond is amorphous, it may have the same strength in all directions.”

That uniform super-hardness, combined with the light weight that is characteristic of all forms of carbon – including diamond – could open up exciting areas of application, such as cutting tools and wear-resistant parts for all kinds of transportation.

Other researchers have tried to create diamond-like amorphous carbon, but have only been able to make extremely thin films that contain impurities such as hydrogen and do not have completely diamond-like atomic bonds. The amorphous diamond created by Mao and Lin can be made in thicker bulk forms, opening up more potential applications.

Lin is the lead author of a paper describing the research that will be published in *Physical Review Letters*. Mao, Lin’s adviser, is a coauthor. Colleagues at the Carnegie Institution of Washington contributed to the research and are also coauthors.

The researchers created the new, super-hard form of carbon using a high-pressure device called a *(continued on page 15)*



*Graduate student Yu Lin loads glassy carbon spheres into a sample chamber where they will be compressed by a pair of diamond anvils. Wendy Mao, assistant professor of Geological and Environmental Sciences, looks on.*

PHOTO: L.A. CICERO

## Extracting natural gas from shale can be done in an environmentally responsible way, says Stanford researcher on government panel

by Louis Bergeron, *Stanford Report*

More and more natural gas is being extracted from underground shale deposits, but environmental concerns have been raised. Stanford geophysicist Mark Zoback, who recently served on a Department of Energy panel of experts, says it can be done safely.

Natural gas currently provides more than a quarter of the energy used in the United States and that fraction is likely to continue growing. New technologies are making it easier and more economical to produce natural gas from where it lies in shale formations deep underground. But as gas plays a bigger role in meeting our energy demands, safety and environmental concerns about the extraction process have mounted.

Earlier this year, President Obama instructed Secretary of Energy Steven Chu to put together a panel to address the safety and environmental aspects of shale gas production. Mark Zoback, a professor of geophysics at Stanford University, was asked to be part of that panel, which recently released its first report; He spoke with *Stanford Report* about shale gas as an energy source and the recommendations in the report.

### Why has natural gas from shale become such a major energy source in the United States?

Fundamentally, it is due to several technological breakthroughs. We have known about these organic-rich shale formations for 100 years, but getting the natural gas out of these extremely impermeable rocks was essentially impossible.

Over the last five to 10 years, however, it has been demonstrated that by carefully controlled hydraulic fracturing in a well drilled horizontally into the shale, you can enhance the permeability of the shale to produce commercial quantities of gas.

According to the Energy Information Agency, natural gas deposits, both in the United States and the world, are absolutely enormous. According to some estimates, at

current consumption rates there is enough gas to last for 100 years.

### Is burning natural gas any better than burning coal or oil when it comes to global warming?

Burning coal currently provides about 50 percent of the electricity used in the United States and it accounts for about 40 percent of all U.S. carbon dioxide emissions, as well as a number of other pollutants. Generating electricity with natural gas reduces carbon emissions by about half. In a new study I've carried out with Prof. Steve Gorelick, we argue there is more than enough gas from shale in the U.S. to completely replace coal for generating electricity in the next 20-30 years. Countries such as China, India and Australia also use large quantities of coal for electrical power generation and switching to natural gas would dramatically reduce their emissions.

Natural gas is also a cleaner fuel for running cars and trucks than gasoline or diesel fuel. Estimates are that switching to natural gas would reduce carbon dioxide emissions from gasoline- and diesel-powered vehicles by about 25 percent. Using domestic natural gas for transportation could significantly lessen our dependence on imported oil.

Natural gas is also an ideal back-up for renewable energy sources such as solar and wind because gas-fired power plants start up quickly and are much more efficient and clean than coal-burning plants.

### Speaking of renewables, wouldn't we be better off directing our efforts toward renewable resources such as solar, wind and water?

Absolutely. I see natural gas as a transition fuel to an energy future that is far less dependent on fossil fuels. But the global energy system is so huge that even if we move as quickly as possible to develop renewable energy sources such as wind, water and solar, we will need to continue using fossil fuels until mid-century.

Remember too that over this same period the demand for energy will continue going up dramatically *(continued on page 12)*

CALWEST/CREATIVE COMMONS



*A gas well in central California with the Sutter Buttes in the distance.*

*“There have been a lot of misconceptions and ill-informed debate regarding shale gas development... The public deserves assurance that the full economic, environmental and energy security benefits of shale gas development will be realized without sacrificing public health, environmental protection, and safety.”*



*“The climate science is still unclear about why summers in the Corn Belt haven’t been warming. But most explanations suggest that warming in the future is just as likely there as elsewhere in the world...farmers in the Corn Belt seem to have been lucky so far.”*

## **U.S. farmers dodge the impacts of global warming – at least for now, Stanford researcher says**

by Louis Bergeron, *Stanford Report*

The United States seems to have been lucky so far in largely escaping the impact of global warming on crop production. But for most major agricultural producing countries, the rising temperatures have already reduced their yields of corn and wheat compared to what they would have produced if there had been no warming, according to a new study led by Stanford researchers.

Global warming is likely already taking a toll on world wheat and corn production, according to a new study led by Stanford University researchers. But the United States, Canada and northern Mexico have largely escaped the trend.

“It appears as if farmers in North America got a pass on the first round of global warming,” said David Lobell, an assistant professor of environmental Earth system science at Stanford University. “That was surprising, given how fast we see weather has been changing in agricultural areas around the world as a whole.”

Lobell and his colleagues examined temperature and precipitation records since 1980 for major crop-growing countries in the places and times of year when crops are grown. They then used crop models to estimate what worldwide crop yields would have been had temperature and precipitation had typical fluctuations around 1980 levels.

The United States, which is the world’s largest producer of soybeans and corn, accounting for roughly 40 percent of global production, experienced a very slight cooling trend and no significant production impacts.

Outside of North America, most major producing countries were found to have experienced some decline in wheat and corn (or maize) yields related to the rise in global temperature. “Yields in most countries are still going up, but not as fast as we estimate they would be without climate trends,” Lobell said.

Lobell is the lead author of a paper about the research published May 5 online in *Science Express*.

The researchers found that global wheat production was 5.5 percent lower than it would have been had the climate remained stable.

Russia, India and France suffered the greatest drops in wheat production relative to what might have been with no global warming. The largest comparative losses in corn production were seen in China and Brazil.

Total worldwide relative losses of the two crops equal the annual production of corn in Mexico and wheat in France. Together, the four crops in the study – wheat, corn, soybeans and rice – constitute approximately 75 percent of the calories that humans worldwide consume, directly or indirectly through livestock, according to research cited in the study.

“Given the relatively small temperature trends in the U.S. Corn Belt, it shouldn’t be surprising if complacency or even skepticism about global warming has set in, but this study suggests that would be misguided,” Lobell said.

Since 1950, the average global temperature has increased at a rate of roughly 0.13 degrees Celsius per decade. But over the next two to three decades average global temperature is expected to rise approximately 50 percent faster than that, according to the report of the Intergovernmental Panel on Climate Change. With that rate of temperature change, it is unlikely that the crop-growing regions of the United States will continue to escape the rising temperatures, Lobell said.

“The climate science is still unclear about why summers in the Corn Belt haven’t been warming. But most explanations suggest that warming in the future is just as likely there as elsewhere in the world,” Lobell said.

“In other words, farmers in the Corn Belt seem to have been lucky so far.”

This is the first study to come up with a global estimate for the past 30 years of what has been happening, Lobell said.

To develop their estimates, the researchers used publicly *(continued on page 13)*







## Seaports need a plan for weathering climate change, say Stanford researchers

by Donna Hesterman, *Stanford Report*

A warming planet means rising oceans, but seaports are not prepared for the expensive construction they will need to protect themselves, according a global survey of ports conducted by Stanford researchers. But the researchers have created a computer model that will help ports with their planning.

The majority of seaports around the world are unprepared for the potentially damaging impacts of climate change in the coming century, according to a new Stanford University study.

In a survey posed to port authorities around the world, the Stanford team found that most officials are unsure how best to protect their facilities from rising sea levels and more frequent Katrina-magnitude storms, which scientists say could be a consequence of global warming. Results from the survey are published in the journal *Climatic Change*.

“Part of the problem is that science says that by 2100, we’ll experience anywhere from 1.5 to 6 feet of sea level rise,” said the study’s lead author, Austin Becker, a graduate student at Stanford. “That’s a huge range.”

Port authorities, like many government agencies and private companies, have to make tough financial decisions when it comes to funding infrastructure, he

said. They need accurate information from scientists about what to expect, so that they can plan accordingly. Building a structure to withstand a 6-foot sea level rise would cost much more than trying to accommodate a 1.5-foot rise, said Becker, a doctoral candidate in the Emmett Interdisciplinary Program in Environment and Resources at Stanford.

In 2009, Becker distributed 160 surveys to members of the International Association of Ports and Harbors and the American Association of Port Authorities – the first worldwide survey of port authorities to address climate change adaptation. A total of 93 agencies representing major seaports on every continent, except Antarctica, responded. The majority of respondents ranked sea level rise and increased storm events associated with climate change high on their list of concerns. However, only 6 percent said that they intend to build hurricane barriers within the next 10 years, and fewer than 18 percent had plans to build dikes or other storm protection structures.

“As we saw with Katrina in 2005, storm and flood damage can devastate a regional economy for years after an event and have national impacts,” said Becker. Katrina, a Category 5 hurricane, caused an estimated \$1.7 billion of damage to Louisiana ports. This month, the region is bracing for flood damage once *(continued on page 14)*

*More than 80 percent of the world’s freight moves by ship. Despite their crucial role in the global economy, few seaports are preparing for the impacts of climate change, including rising sea levels and more frequent storms.*

*“As we saw with Katrina in 2005, storm and flood damage can devastate a regional economy for years after an event and have national impacts.”*

## Climate Change Teacher Workshop

Donna Edwards, Megan Nesland (BS GES '07), and Daisy Yeung were among the high school and middle school teachers who participated this summer in the NASA-funded Climate Change Education Project Workshop. In this collaboration between the School of Earth Sciences and the Stanford Teacher Education Program, teachers spent four days on campus working on a three-week curriculum on climate change they took back to their respective schools. The teachers will return to campus twice during the academic year to continue their learning about climate change and evaluate student response to the new curriculum.



## Stanford Earth Sciences students compete to develop geothermal potential of the Rio Grande Rift

Stanford Earth Sciences graduate students were among those selected to participate in the National Geothermal Student Competition, sponsored by the National Renewable Energy Laboratory in partnership with the U.S. Department of Energy's Geothermal Technologies Program. The first-of-its-kind intercollegiate competition challenged student teams to advance their understanding of geothermal energy's potential as a significant contributor to the nation's energy portfolio in the coming decades. Each team conducted an assessment of the geothermal energy potential in the Rio Grande Rift area of southeastern Colorado and northeastern New Mexico, developing innovative plans for tapping into the geothermal resources of those areas.

The Stanford team was one of eleven participating in the competition. Their project, *Exploration and Development Plan for Eastern San Luis Basin, Rio Grande Rift, Colorado*, provided an assessment of the potential and implications for geothermal energy production in the region, incorporating geologic, engineering, and social constraints on the development of

a large-scale geothermal operation. The other teams represented the Colorado School of Mines, Oregon Institute of Technology, Pennsylvania State University, San Diego State University, Texas A & M, University of California at Davis, University of Idaho, University of North Dakota, University of Utah, and Virginia Polytechnic Institute and State University.

Stanford Earth sciences students Sarah Pistone and John Murphy of the Department of Energy Resources Engineering, and Pablo Garcia Del Real of the Department of Geological and Environmental Sciences were members of the Stanford team, along with Matt Ganser and Lena Perkins from the School of Engineering. Stanford School of Earth Sciences professors Dennis Bird and Roland Horne acted as advisors for the Stanford team. While the Stanford students didn't win the competition (UC Davis took first place), they were invited to present their results at the Geothermal Resources Council Annual Meeting and to submit their work for publication in *Mountain Geologist* magazine.





## Wrigley Field Program in Hawaii

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Stanford Earth Systems' Wrigley Field Program in Hawaii is an interdisciplinary program investigating the Earth sciences, life sciences, and Hawaiian culture to address environmental issues that arise from the interaction between humans and nature. Led by Stanford faculty with extensive research and teaching experience in Hawaii, students spend ten weeks working, studying, and living on the islands of Hawaii and Kauai. Students explore the volcanic processes that formed the Hawaiian Islands, study Hawaii's unique terrestrial and marine ecosystems, and learn how humans have interacted with the natural world throughout history.



*Left: Students taking measurements of the pali to record geologic movement into the ocean; this shelf may have collapsed in the past, causing a massive tsunami.  
Bottom: Calah Hanson (Hum Bio) taking notes underwater.*

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*An outcrop of serpentinite from the Isua Supracrustal sequence of West Greenland, at the western margin of the Greenland Icecap. Under the West Greenland ice fields, the researchers have identified serpentinite among some of the oldest rocks yet found.*

## Serpentinite

*(continued from page 1)*



PHOTO: EMILY POPE

million years, the findings provide a potential timestamp for the appearance of the Earth's first organism.

The paper, authored by geophysics professor Norm Sleep, geological and environmental sciences professor Dennis Bird, and former graduate student Emily Pope, appears in this week's *Philosophical Transactions of the Royal Society B*.

### Serpentinite under the sea

Greenish-colored serpentinite is common enough in California to be the official state rock. But geologists are more interested in deep-sea serpentinite deposits, where the mineral forms "white smoker chimneys" – hydrothermal vents – in which alkaline vent fluids interact with more acidic seawater.

The resulting reaction can form microscopic "pore spaces" in the chimney stone. This honeycombed rock acts as a percolator for white smoker fluid, concentrating dissolved substances inside the tiny spaces. Because the nucleic acids that make up RNA may have occurred naturally in vent fluids, this process increased the probability of spontaneously forming complete RNA strands. The tiny pores could have even allowed the resultant organisms to survive without cell membranes, using the rock itself for structure and protection.

An outcrop of serpentinite from the Isua Supracrustal sequence of West Greenland, at the western margin of the Greenland Icecap. Under the West Greenland ice fields, the researchers have identified serpentinite among some of the oldest rocks yet found.

The pH difference between the vent fluids and the ocean also could have provided an important energy supply for early organisms. When serpentinite is oxidized by seawater, hydrogen is formed. Microbes can react hydrogen with carbon dioxide

to form methane or acetate, both of which serve as sources of chemical energy.

"These same conditions exist wherever water comes out of serpentine in the Bay Area," explained Sleep. "If you look, you can see hydrogen bubbling out of the ground."

But this model of life's origins is only feasible under very specific conditions. Serpentinite, a cool Earth, and an acidic ocean all must have coexisted for a time.

Serpentinite was likely present when life arose. Unfortunately, the geological record only reliably goes back approximately 3.8 billion years, making a definitive statement impossible. Still, under the West Greenland ice fields, Bird and Pope have recently identified serpentinite among some of the oldest rocks yet found.

The temperature of the Earth was also habitable at the time in question. A few hundred million years after its formation, the planet had cooled below 120°C – hot by human standards, but livable for certain microorganisms.

### Acid enough?

The single most time-restricted requirement for early life would have been the acidity of the ocean. In order for early life to make use of a pH gradient between hydrothermal vents and seawater, the oceans must have been 100 times as acidic as they are today – a state of affairs that overlapped with a cool Earth for only a few million years.

The early oceans would have remained acidic as long as the early earth's atmosphere remained high in carbon dioxide. Much of the gas was eventually trapped in the earth's mantle by subducting continental plates.

"This leaves a relatively brief window for the origin of life, at least by this mechanism," said Sleep.

Smoking-gun evidence in support of the origin-of-life theory remains hard to come by. Geologists are currently looking deep in the Earth's crust for ancient white smoker structures. And the search continues for a modern-day version of membrane-less rock-living microbes.

"It's conceivable that a biologist might get lucky," Sleep said. "But I'm not holding my breath."

*...this model of life's origins is only feasible under very specific conditions. Serpentinite, a cool Earth, and an acidic ocean all must have coexisted for a time.*



## Win-Win: A story of research and outreach

by Laura Erban, graduate student,  
Department of Environmental Earth  
System Science

I was in a bind. Datasets for my work in Vietnam were streaming in, but almost exclusively in Vietnamese. Online translation tools were botching the job, as the meaning of many Vietnamese words is context-specific (I later learned that to describe a person's shirt as "blue" one might refer to it as an "ocean shirt"). The result of translating a well log, a literal description of the geologic materials found during a drilling operation, read as if randomly generated. This was not among the daily graduate school challenges I could face by just working harder in the comfort of my cubicle.

Since Vietnamese is among the three most commonly spoken languages on the Peninsula, I abandoned Internet output in pursuit of real people. I saw potential for an opportunity in this obstacle. If I found the right student to work with, the student could gain academic credit or research experience in exchange for making these data intelligible. I searched at Stanford and other colleges on the Peninsula, asking around before hitting it big in my own building: I found more than twenty interested students.

Juniors and seniors at Yerba Buena High School in San Jose, the students were enrolled in the only AP science course offered there, Environmental Science. A tip from Jenny Saltzman, the School of Earth Sciences director of education outreach, led me to meet their teacher, Chung Khong, who holds a teaching fellow position in Professor Jon Payne's paleobiology lab during the summer. Mr. Khong told me that approximately 60 percent of his students were Vietnamese, and many were enrolled in language classes at their school in addition to being home-speakers. He was thrilled with the idea of sharing his class with me.

Once a week throughout the school year I made my way to Yerba Buena. To contextualize the day's work, I gave a brief lecture at the beginning of each meeting on a component of the fundamentals underlying my research on naturally occurring arsenic contamination of groundwater systems in Cambodia and

Vietnam. Afterwards, we broke into smaller groups, with replicates working over different pieces of the datasets I sought to understand. The students bounced phrases off of one another, their handheld e-dictionaries, and their Vietnamese teachers and relatives. When stumped—how could "powder" or the "flour" one cooks with be a geologic

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*"I abandoned Internet output in pursuit of real people. I saw potential for an opportunity in this obstacle..."*

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material?—they tried me: it's silt! They read reports, interpreted maps, drew geologic cross-sections, and translated my letters requesting visits with ministerial officials that (to everyone's great astonishment) got me in the door to crucial meetings in Hanoi and Ho Chi Minh.

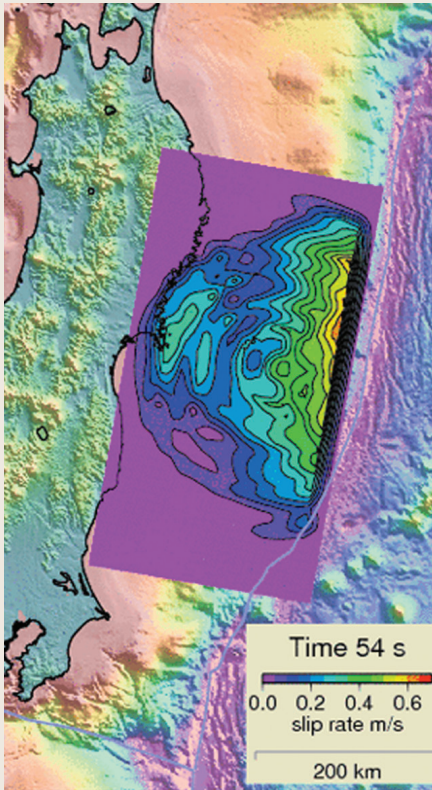
We worked across my goals and interests as well as theirs. Sometimes we digressed into impromptu college counseling or calculus lessons. I tried to infuse the sessions with some feel for what a career in science is really like. Before I went abroad to do field work, I explained the data I needed to obtain and the experiments I would do; when I returned, I shared the photos and stories of how it all happened. At the end of the year, the students had a chance to visit Stanford and to get inside the laboratories and meet more of the people who work in them. Some students who never would have thought to put Stanford on their college list before this experience will be applying next year.

Most of the time I spend doing research, alone or with colleagues, is focused on the problems; breakthroughs are comparatively brief. In that way, I expect I'm in abundant company around here. While we're usually inclined to dig deeper into the trove of resources on campus in search of answers, reaching out can also be immensely rewarding. I encourage others to pursue knowledge in ways that engage our surrounding community, as well.



PHOTO: J. SALTZMAN

*Simulating aquifer contamination and clean-up using a physical model at Stanford.*



View an animation of the Tokohu earthquake, courtesy of Greg Beroza, at <http://news.stanford.edu/news/2011/may/japan-quake-tsunami-052411.html>.

## Tohoku earthquake

(continued from page 1)

swamping the islands – causing tens of thousands of deaths and hundreds of billions of dollars in damage. Now Stanford researchers have discovered the catastrophe was caused by a sequence of unusual geologic events never before seen so clearly.

“It was not appreciated before this earthquake that this size of earthquake was possible on this plate boundary,” said Stanford geophysicist Greg Beroza. “It was thought that typical earthquakes were much smaller.”

The earthquake occurred in a subduction zone, where one great tectonic plate is being forced down under another tectonic plate and into the Earth’s interior along an active fault.

The fault on which the Tohoku-Oki earthquake took place slopes down from the ocean floor toward the west. It first ruptured mainly westward from its epicenter – 32 kilometers (about 20 miles) below the seafloor – toward Japan, shaking the island of Honshu violently for 40 seconds.

Surprisingly, the fault then ruptured

earthquake rupture, but this is the first time we have clearly seen it occur in a real earthquake.

“The depth of the water column there is also greater than elsewhere,” Beroza said. “That, together with the slip being greatest where the fault meets the ocean floor, led to the tsunami being outlandishly big.”

Beroza is one of the authors of a paper detailing the research, published online last week in *Science Express*.

“Now that this slip amplification has been observed in the Tohoku-Oki earthquake, what we need to figure out is whether similar earthquakes – and large tsunamis – could happen in other subduction zones around the world,” he said.

Beroza said the sort of “two-faced” rupture seen in the Tohoku-Oki earthquake has not been seen in other subduction zones, but that could be a function of the limited amount of data available for analyzing other earthquakes.

There is a denser network of seismometers in Japan than any other place in the world, he said. The sensors provided researchers with much more detailed data than is normally available after an earthquake,

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*“Now that this slip amplification has been observed in the Tohoku-Oki earthquake, what we need to figure out is whether similar earthquakes – and large tsunamis – could happen in other subduction zones around the world.”*

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eastward from the epicenter, up toward the ocean floor along the sloping fault plane for about 30 or 35 seconds.

As the rupture neared the seafloor, the movement of the fault grew rapidly, violently deforming the seafloor sediments sitting on top of the fault plane, punching the overlying water upward and triggering the tsunami.

“When the rupture approached the seafloor, it exploded into tremendously large slip,” said Beroza. “It displaced the seafloor dramatically.

“This amplification of slip near the surface was predicted in computer simulations of

enabling them to discern the different phases of the March 11 temblor with much greater resolution than usual.

Prior to the Tohoku-Oki earthquake, Beroza and Shuo Ma, who is now an assistant professor at San Diego State University, had been working on computer simulations of what might happen during an earthquake in just such a setting. Their simulations had generated similar “overshoot” of sediments overlying the upper part of the fault plane.

Following the Japanese earthquake, aftershocks as large as magnitude 6.5 slipped in the

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## Summer Undergraduate Research in Geoscience and Engineering

These 17 undergraduate students (chosen from more than 100 applicants) presented their research projects at the conclusion of the first Summer Research in Geoscience and Engineering (SURGE) program at a final symposium in August. SURGE is the School of Earth Sciences' new summer program, providing scholars from diverse cultural, racial/ethnic, and socioeconomic backgrounds with a research experience in a school laboratory or research group. SURGE also prepares scholars to apply to graduate school, and introduces them to career opportunities in the geosciences.

The longer-term goal of the program is to see under-represented minority scholars enrolled in Stanford and other geoscience institutions in numbers commensurate with their representation in the United States population, reflecting the diversity of our national communities and international partnerships. For more information about SURGE and the other programs of the School of Earth Sciences Office of Multicultural Affairs, please visit [oma.stanford.edu](http://oma.stanford.edu).

### Tohoku earthquake

*(continued from page 10)*

opposite direction to the main shock. This is a symptom of what is called "extreme dynamic overshoot" of the upper fault plane, Beroza said, with the overextended sediments on top of the fault plane slipping during the aftershocks back in the direction they came from.

"We didn't really expect this to happen because we believe there is friction acting on the fault" that would prevent any rebound, he said. "Our interpretation is that it slipped so much that it sort of overdid it. And in adjusting during the aftershock sequence, it went back a bit.

"We don't see these bizarre aftershocks on parts of the fault where the slip is less," he said.

The damage from the March 11 earthquake was so extensive in part simply because the earthquake was so large. But the way it ruptured on the fault plane, in two stages, made the devastation greater than it might have been otherwise, Beroza said.

The deeper part of the fault plane, which sloped downward to the west, was bounded by dense, hard rock on each side. The rock transmitted the seismic waves very efficiently, maximizing the amount of shaking felt on the island of Honshu.

The shallower part of the fault surface, which slopes upward to the east and surfaces at the Japan Trench – where the overlying plate is warped downward by the motion of the descending plate – had massive slip. Unfortunately, this slip was ideally situated to efficiently generate the gigantic tsunami, with devastating consequences.

Other coauthors of the Science Express paper are Annemarie Baltay, a graduate student in geophysics at Stanford, and Satoshi Ide, an associate professor of Earth and planetary science at the University of Tokyo.

Funding for the research was contributed by the Japanese Society for the Promotion of Science.

*"When the rupture approached the seafloor, it exploded into tremendously large slip. It displaced the seafloor dramatically."*

## EXAMPLE OF HYDRAULIC FRACTURING FOR SHALE DEVELOPMENT

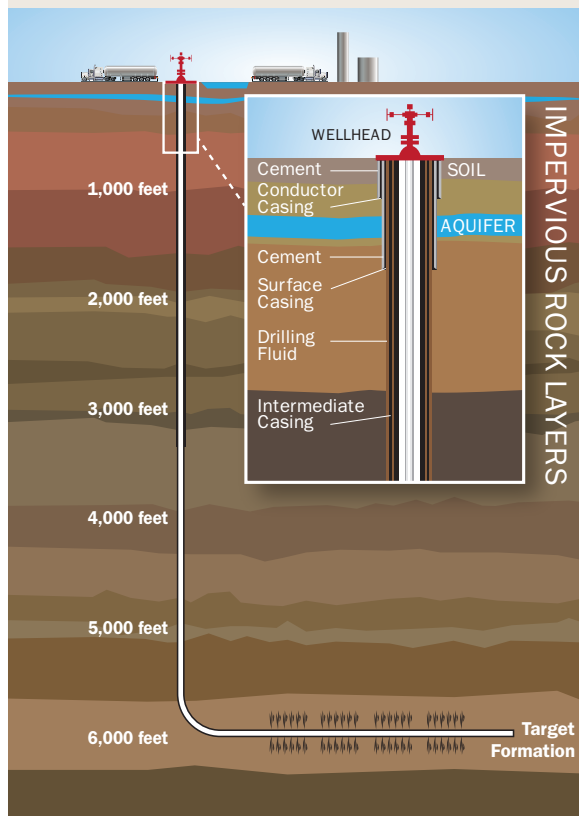


ILLUSTRATION: ENERGYFROMSHALE.ORG

## Shale gas

(continued from page 3)

because of increasing standards of living in China, India and the rest of the developing world. We have to address the many issues associated with energy and the environment on many fronts – we need to save energy through improved efficiency; more fully utilize renewables; and develop new clean energy sources.

To me, enhanced utilization of shale gas resources provides an opportunity to transition to clean and renewable sources over the next few decades while helping to meet current and growing global energy needs. Our study addressed some of the things that could be done to accomplish this while reducing the environmental impact of shale gas production.

**The hydraulic fracturing or “fracking” of gas shale has raised concerns about potential damage to the environment and to human health. How serious are those concerns?**

It is somewhat ironic that nearly all of the reported problems associated with shale gas development have been attributed to hydraulic fracturing, when in fact the exact opposite is the case. Most problems associated with shale gas wells have arisen from poor well construction – it is critically important to drill properly and to line the wells with steel casing that is properly cemented in place. Nonetheless, identifying measures to reduce the environmental impact and improve the safety of shale gas production are precisely the issues the subcommittee was asked to address in our report.

There are three main aspects of hydraulic fracturing that have caused concern: the chemicals in the fracturing fluid; fear of the fracturing fluid interacting with drinking water aquifers; and the disposal of the fracturing fluid coming out of the well after it has been in contact with the shale formations.

**So what about the chemicals in the fracturing fluid?**

Hydraulic fracturing fluid is mainly water, with small amounts of thickening agent added – usually guar, the same thickening agent used in making ice cream. There is also some biocide, to kill bacteria in the water, as well as a little bit of a friction reducer.

Unfortunately, an act of Congress exempted the gas companies from having to reveal the chemicals in the fluid. I say unfortunate because it has led to unnecessary suspicion and paranoia. Our report recommends that the contents of fracturing fluid be fully disclosed.

**Has hydraulic fracturing caused drinking water contamination?**

There have been fears that hydraulic fracturing fluid injected at depth could reach up into drinking water aquifers. But, the injection is typically done at depths of around 6,000 to 7,000 feet and drinking water is usually pumped from shallow aquifers, no more than one or two hundred feet below the surface. Fracturing fluids have not contaminated any water supply and with that much distance to an aquifer, it is very unlikely they could.

This said, there are instances where natural gas has been found in drinking water supplies, which is one of the problems that can be caused by poor well construction. If the steel well casing is not fully cemented, gas can leak up around the outside of the casing and contaminate shallow aquifers. In fact, a related problem is that there are a number of aquifers contaminated with natural gas that can be traced to leaking casings of very old wells that predate recent drilling for natural gas by 40 or 50 years.

**What about disposing of the water that flows out of the well after hydraulic fracturing?**

This can be a serious issue. When that water comes back up the well, it has picked up chemicals present in the shale that aren't good for human health or the environment. The water that comes back can be very saline and can contain chemicals such as selenium, arsenic and iron.

That water has to be disposed of properly, which can mean injecting it into a storage well that has been permitted and licensed by the Environmental Protection Agency to standards that will prevent leakage.

Alternatively, it can be treated and reused, which is the preferable solution. More and more, that is what is being done in the northeastern U.S. So the water goes right back into the shale from which it came.

The subcommittee report made a number of recommendations. (continued on page 13)

*“I think the real take-home message is that climate change is not just about the future, but that it is affecting agriculture now. Accordingly, efforts to adapt agriculture such as by developing more heat- and drought-tolerant crops will have big payoffs, even today.”*



## Shale gas

*(continued from page 12)*

What would you say is the most critical thing for people to bear in mind regarding developing our natural gas resources?

Our most important recommendations were for more transparency and dissemination of information about shale gas operations, including full disclosure of chemicals and additives that are being used during drilling and hydraulic fracturing. We also recommend a number of steps to better protect air and water quality. We call for more and better data collection before,

during and after drilling, so that if problems are encountered, the causes can be established and remedies more easily identified.

There have been a lot of misconceptions and ill-informed debate regarding shale gas development. To quote our report: The public deserves assurance that the full economic, environmental and energy security benefits of shale gas development will be realized without sacrificing public health, environmental protection and safety. We hope to have taken a step in this direction.

## U.S. farmers

*(continued from page 4)*

available global data sets from the United Nations Food and Agriculture Organization and from the University of Delaware, University of Wisconsin, and McGill University.

The researchers also estimated the economic effects of the changes in crop yield using models of commodity markets.

“We found that since 1980, the effects of climate change on crop yields have caused an increase of approximately 20 percent in global market prices,” said Wolfram Schlenker, an economist at Columbia University and a coauthor of the paper in Science.

He said if the beneficial effects of higher carbon dioxide levels on crop growth are factored into the calculation, the increase drops down to 5 percent.

“Five percent sounds small until you realize that at current prices world production of these four crops are together worth nearly \$1 trillion per year,” Schlenker said. “So a price increase of 5 percent implies roughly \$50 billion per year more spent on food.”

Rising commodity prices have so far

benefited American farmers, Lobell and Schlenker said, because they haven’t suffered the relative declines in crop yield that the rest of the world has been experiencing.

“It will be interesting to see what happens over the next decade in North America,” Lobell said. “But to me the key message is not necessarily the specifics of each country. I think the real take-home message is that climate change is not just about the future, but that it is affecting agriculture now. Accordingly, efforts to adapt agriculture such as by developing more heat- and drought-tolerant crops will have big payoffs, even today.”

Justin Costa-Roberts, an undergraduate student at Stanford, is also a coauthor of the Science paper. David Lobell is a researcher in Stanford’s Program on Food Security and the Environment, a joint program of Stanford’s Woods Institute for the Environment and Freeman Spogli Institute for International Studies. Schlenker is an assistant professor at the School of International and Public Affairs and at the Department of Economics at Columbia.

*This work was supported by a grant from the Rockefeller Foundation.*

*“Five percent sounds small until you realize that at current prices world production of these four crops are together worth nearly \$1 trillion per year... So a price increase of 5 percent implies roughly \$50 billion per year more spent on food.”*

## In Memoriam

**Thomas Barrow**, PhD '53 Geo

**Frederick “Rick” Bjorck**, BS '63 PE, ENG '65

**Bob Earlougher**, BS '63 PE, MS '64 PE, PhD '66 PE

**John Lawton**, BS '50 Geo, MS '52 Geo, PhD '56 Geo

**Sullivan Marsden**, BS '44 Chem Eng, PhD '48 Phys Chem; Professor Emeritus, Department of Petroleum Engineering (now Energy Resources Engineering)

**Tjeerd van Andel**, Professor Emeritus, Departments of Geology and Geophysics

## Seaports

(continued from page 5)

again, as the National Weather Service is predicting that the Mississippi River could crest in New Orleans on May 23.

And with scientists forecasting a doubling of Category 4 and 5 hurricanes in the Atlantic Ocean by 2100, it seems all the more imperative to start thinking about adapting port infrastructures now, he said.

### Threat of violent storms

Sea level rise and more frequent violent storms resulting from climate change threaten to take a tremendous toll on all types of infrastructure – especially along the coasts, said study co-author Martin Fischer, professor of civil and environmental engineering and director of the Center for Integrated Facility Engineering at Stanford.

Fischer, Becker and a group of Stanford engineers are developing computer models to help port authorities and other government agencies make more informed decisions about adapting to climate change as they plan for the next generation of infrastructure. The group meets weekly at a seminar that focuses on engineering and policy for a sustainable future.

“Look around at any seaport today and you will see structures that were built 100 years ago,” said Fischer. “And the buildings that we are building today will be around when sea level rise begins to reshape the coast.”

The problem on a global scale, he said, is that ports may start scrambling all at once to adapt their structures to changing environmental conditions. “It could potentially exceed our capacity for construction worldwide,” he added.

Fischer and his colleagues have developed a model that demonstrates how a rapid, simultaneous push to fortify the world’s seaports could drive up demand for construction materials and equipment. The model, called Sebastian, uses a Google Earth platform to simulate the costs and time required for building dikes around 200 of the world’s most active seaports. Sebastian knows the shape of the ocean floor at each location and tailors the structure to each site to produce an estimate of the materials, labor and equipment that would be needed to fortify the port against sea level rise.

“Sebastian allows us to run different scenarios based on different levels of sea

rise, and see how the ports are affected,” said Fischer. Using criteria in the Army Corps of Engineers manual, the model calculates the resources needed for each variation of the structure. It’s a way to calculate big-picture, worldwide demand, Fischer said, but it also gives managers more reliable information about how much survivability they are buying when they invest in different types of protective structures.

### Lack of oversight

Another difficult challenge in preparing for climate change at seaports is that no single agency or individual has sole authority over any given port, according to Becker. Some ports are privately owned, some are public and some are a mixture of both. And a broad range of entities – from transportation companies to insurance companies to the Environmental Protection Agency – have some stake in how they are managed. The arrangement greatly complicates ports’ efforts to budget and plan for the future, according to the study.

But plan they must, said Fischer.

“By the end of the century, quite a few ports will be in trouble, even if you are using the most conservative estimates for sea level rise,” he said. “And if you use the estimates at the top of the range, all of them will be in trouble.”

Other co-authors of the study are Satoshi Inoue of the National Graduate Institute for Policy Studies in Tokyo and Ben Schwegler, a consulting professor of civil and environmental engineering at Stanford and chief scientist at Walt Disney Imagineering.

The research was funded by a planning grant from the Sustainable Built Environment Initiative at the Woods Institute for the Environment at Stanford. Additional funding was provided by a McGee grant from the Stanford School of Earth Sciences.

*Donna Hesterman is a science-writing intern at the Woods Institute for the Environment.*





## Amorphous Diamond

(continued from page 2)

diamond anvil cell. They did a series of experiments with tiny spheres of glassy carbon, an amorphous form of carbon which they compressed between the two diamond anvils. The spheres were a few tens of micrometers (millionths of a meter) in diameter.

They slowly cranked up the pressure on the spheres. When the pressure exceeded 40 gigapascals – 400,000 times atmospheric pressure – the arrangement of the bonds between the carbon atoms in the glassy spheres had completely shifted to a form that endowed the spheres with diamond-like strength.

The researchers detected the shift in internal bonding by probing the spheres with X-rays.

They also did experiments in which a glassy sphere was simultaneously subjected to different pressures from different directions, to further assess the strength of the new form of carbon. While the diamonds in the anvil pressed in on the sides of the sphere with a pressure of 60 gigapascals – about 600,000 times atmospheric pressure – the pressure on the tip of the sphere reached 130 gigapascals.

“The amorphous diamond survived a pressure difference of 70 gigapascals – 700,000 atmospheres – which only diamond has been able to do,” Mao said. “Nothing else can withstand that sort of stress difference.”

Although the bonds between atoms in the glassy spheres were altered by the extreme pressure, the amorphous, or disordered, structure of the spheres was unchanged.

“The material doesn’t get any more ordered as we compress it. It maintains its disorder,” Mao said. The outer form of the original material was also retained – if the researchers started with a sphere, then even at the highest pressures, the sphere was still a sphere. The only change was in the type of bonds between the carbon atoms.

One characteristic of the new amorphous diamond is that it is not always hard or always soft. The hardness of the amorphous carbon is tunable; it is soft at low pressure, but the greater the pressure, the harder it gets. Once the pressure of the anvil was released, it returned to its original form

as simple glassy carbon, with strength no greater than it had to begin with.

For the amorphous diamond to find widespread application, Mao said, someone will have to find a way to either make the material at low pressure or figure out how to preserve it once the super-hard form is created under high pressure.

Even though the amorphous diamond returned to plain old glassy carbon when the pressure was released, there are still potential applications. The material could be used as a gasket in high-pressure devices where having a gasket that hardens with pressure would be beneficial. Or it could be used in further high-pressure experiments.

“We use a diamond anvil cell to compress samples for high-pressure research, but because this amorphous diamond phase hardens with pressure, it could be a second stage anvil inside the diamond anvil,” Lin said.

“Having another anvil in sequence would let us create even higher pressures at the very tip.”

Since the focus of Mao’s research group is to answer questions about the extreme environments in the deep Earth and other planetary interiors, a “double diamond” anvil could prove extremely useful. One can only speculate as to what exotic materials might be discovered with such an amped-up anvil.

*Wendy Mao is an assistant professor with a joint appointment in the Department of Geological and Environmental Sciences at the School of Earth Sciences, and in Photon Science at the Department of Energy’s SLAC National Accelerator Laboratory. Yu Lin is a graduate student in the Department of Geological and Environmental Sciences.*

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## Save the Date

**DECEMBER 5, 2011**  
**American Geophysical Union  
(AGU) Alumni Reception**

5:30 - 7:00 p.m.  
Chevy's  
201 3rd Street  
San Francisco, CA

**FEBRUARY 23, 2012**  
**North American Prospect Expo  
(NAPE) Alumni Reception**

5:00 – 6:30 p.m.  
Hilton Americas-Houston  
Meeting Room 230  
1600 Lamar  
Houston, TX

**APRIL**  
**American Association of Petroleum  
Geologists (AAPG) Alumni Reception**

Long Beach, CA  
(date and location TBD)

## Departures and Arrivals

Mona Tekchandani, who for four years managed the Earth Sciences Fund and the school's alumni relations and stewardship programs, left Stanford at the end of August to move to Dubai. Since then, two new colleagues have joined the school's external relations team: Astrid Thompson, who is working with Associate Dean for External Relations David Voss as a major gifts fundraiser and director of the school's alumni relations program, and Candace Ayers, who is director of the Earth Sciences Fund and responsible for the school's stewardship program. Both Astrid and Candace look forward to hearing from SES alumni and friends--please keep handy their contact information below.



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