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COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES // CIRES

The Quake that Shook the Planet

CIRES scientist probes the Japanese Earthquake

Satellites detect looming water shortages

Sniffing out earthquake potential in Colorado and New Mexico

Virtual rock collection sheds light on America's past

This issue

Background: Rocks stacked along the coast of the Southern Island of New Zealand. Credit Anne Sheehan

On the cover: The wave from a tsunami crashes over a street in Miyako City, Iwate Prefecture in northeastern Japan after the magnitude 8.9 earthquake struck the area March 11, 2011. Picture taken March 11, 2011. REUTERS/Mainichi Shimbun

1.8 microseconds

How much was shaved off the length of the 24-hour day by the Japanese Earthquake. The intense tremblor accelerated the earth's spin. To learn more about the earthquake and its accompanying tsunami see **Page 2**.

Seat of Wisdom

The ultimate throne for geologists to sit on and ponder their latest rock riddle. The chair, which CIRES Fellow and former CIRES Director Robert Sievers is sculpting, will reside in the main CIRES building. The starting block of Queen Anne Lace Marble—black marble with white marbling spread throughout—comes from Morocco and weighs more than one ton. The design is inspired by the Lincoln Memorial chair, and Sievers hopes it will inspire all CIRES staff and students who sit on it with "a notion of judgment, wisdom and knowledge," or failing those lofty goals, to just "think great thoughts."

"GRACE can measure changes in total water to about 1-centimeter accuracy over the scale of the Missisippi River Basin. No other method for monitoring groundwater gives such an accurate, big-picture view for a whole region."

—CIRES Fellow John Wahr on using Gravity Recovery and Climate Experiment (GRACE) satellites to measure groundwater, **Page 4**.

3,960 miles

The approximate distance from the surface of Earth to its center. Seven miles is the deepest humans have drilled into the planet.

Fellowship Focus:

Dr. Delores Robinson

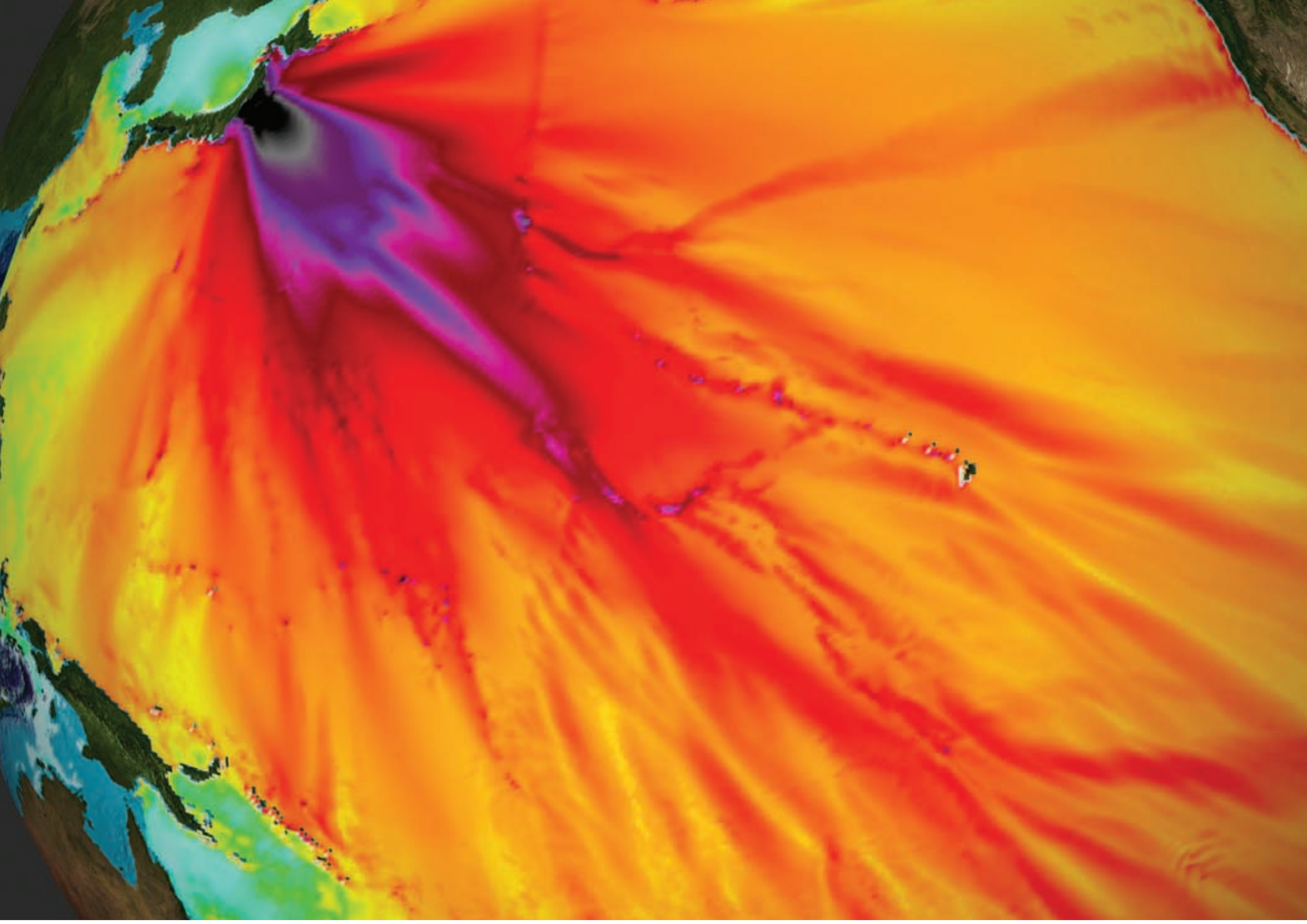
By Kristin Bjornsen

When CIRES Visiting Fellow Delores Robinson does fieldwork in Nepal, one of the first questions locals ask her is "Are you a doctor?" Knowing they mean MD, not PhD, Robinson, who speaks Nepali, usually answers, "No, we're here to study dhungaa," Nepali for rocks. "They often then ask, 'Is there gold or diamonds in them?'" Robinson said. "It's hard for people to understand why we'd be looking at rocks just for science."

But rocks contain more than precious metals—they also hold a wealth of information on a mountain belt's age, history and seismic risks of a mountain belt. Robinson, an associate professor at the University of Alabama, studies how mountain belts form, evolving from colliding tectonic plates into mature peaks and plateaus. While conducting her visiting fellowship at CIRES, she is investigating the role erosion plays in that process. "As rain, ice and rivers erode away the rock, they change the surface shape," Robinson said. "This drives formation and movement of the mountain belt because the underlying plates want to maintain a particular, energetically favorable shape." The moving plates, in turn, create faults, fractures in the earth's crust that trigger earthquakes when they shift.

Since 1967, CIRES has awarded more than 265 Visiting Fellowships. Go to cires.colorado.edu/collaboration/fellowships for more info.

"If you know where the faults are, you know where the earthquakes will be," Robinson said. "By identifying fault location and activity, we can help with earthquake preparedness. Government leaders can know the key places to concentrate resources and educate people about what to do during an earthquake."



By Jane Palmer

A mere three days after an earthquake so powerful it knocked the planet off its axis—the March 11 Honshu quake—CIRES Fellow Roger Bilham gazed from the safety of a helicopter at the flattened towns and flooded coastline of the Japanese island below.

Bilham, the first geologist outside Japan to conduct an aerial survey of the damage, had arrived in Japan to learn about the nature and impact of the earthquake and its accompanying tsunami. "The extent of the damage was truly amazing," said Bilham, the scientific member of the NOVA team making the documentary *Japan's Killer Quake*. "The tsunami picked up everything in its path—cars, houses, warehouses—and just tumbled them relentlessly inland on and on and on."

Although power, fuel and food shortages made immediate access to the epicentral region difficult, seismometers had diligently recorded every ripple of the quake. GPS receivers also had pinpointed the island's location as it shook, shuddered and ultimately shifted permanently by as much as 5 meters toward the east in response to the earth's tremors. "Never before have we had such a surplus of data," Bilham said. "There are no mysteries in this earthquake."

Piecing together the cause of the quake didn't prove difficult for scientists. Earth's crust is made up of several colossal slabs of rock—known as tectonic plates (see p. 13)—and Japan lies on a boundary between two plates. Each year the Pacific plate had driven farther underneath the edge of the North America plate that Japan sits on, compressing the edge and dragging downward the North America plate thereby causing immense stresses to build up. "The energy that drove this earthquake had been building up for many hundreds of years," Bilham said. "Think of it as a giant elastic band that has been wound up for a thousand years."

"The tsunami picked up everything—cars, houses, warehouses—and just tumbled them relentlessly inland on and on and on."

At 2:45 a.m. March 11, 2011, the tension reached a breaking point. At a location 100 kilometers off the coast of Japan, the edge of the compressed plate finally sprung eastward tens of meters, initiating a magnitude 9.0 earthquake.

Matthew Bradley

The Day the Earth Moved

Probing the Japanese earthquake

Japanese tsunami wave height as it propagated across the Pacific.
Credit: NOAA

Shock waves radiated outwards through Earth, and Japan's detection systems picked them up instantly. The billions Japan had invested in early-warning systems and earthquake engineering paid off as a combination of old and new technologies—including sirens and email messages—alerted the citizens and kept most of the cities' structures standing, Bilham said. "My first reaction on arrival in Tokyo was of admiration for the seismologists and earthquake-engineering community of Japan," he said. "It was a success story given the enormity of the earthquake."

And then the tsunami struck.

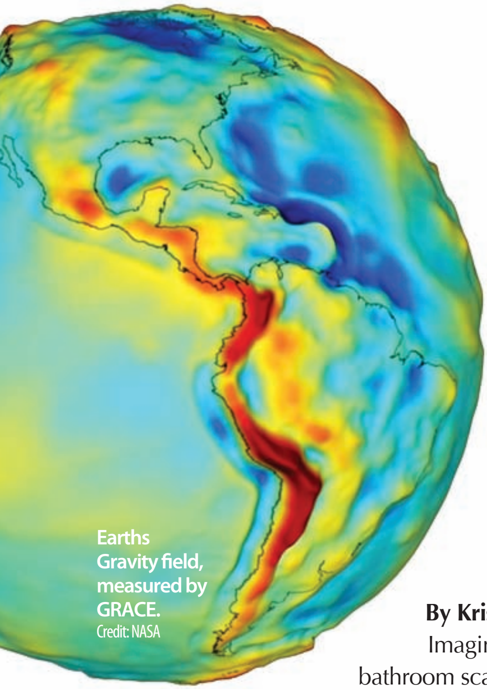
The sudden upper flip of the compressed rock lifted a six-kilometer mass of water upward to the surface of the sea. As this same rock collapsed back, it propelled immense waves across the ocean.

One side of the wave raced toward the coast of Japan. As the speed of an ocean wave depends on the water depth (a wave will travel slower in shallow water), in the deep ocean the tsunami travelled at more than 800 kilometers per hour—as fast as a jet aircraft. It took just minutes to reach the coast, and it raced ashore with heights of 13 meters in places. "Probably a cubic kilometer of water just sploshed landward and kept going until it ran out of steam," Bilham said.

"Probably a cubic kilometer of water just sploshed landward and kept going until it ran out of steam."

Despite a death toll in the tens of thousands and a recovery cost estimated to exceed $300 billion, worse may still be to come. For decades, Japanese scientists have anticipated a large earthquake to hit from the south, caused by a slip of the Philippine plate relative to the Eurasian plate. And sometimes a great earthquake, like the Honshu quake, can cause the next patch of the plate boundary to slip, Bilham said. Consequently, all eyes are on how the Honshu earthquake has impacted the neighboring part of the plate boundary, he said.

"This whole region is in a very high state of stress, and seismologists have been expecting it to go any minute—so this recent earthquake is going to have brought that closer in time," Bilham said. "The question is: how much closer?"



Earths Gravity field, measured by GRACE.
Credit: NASA

Until the Well Runs Dry

Satellites reveal global groundwater depletion

By Kristin Bjornsen

Imagine having a bathroom scale that not only told you how many pounds you've gained or lost, but also told you exactly where on your body that weight change occurred—a few ounces shed from your arms, two pounds added to your midsection, one pound packed into the saddlebags. Now imagine the scale did this with incredible sensitivity—a couple milligrams lost from pared fingernails, an eyelash that fluttered away.

While it's debatable whether anyone would want such precise measurements of their love handles, that's what the GRACE (Gravity Recovery and Climate Experiment) satellites do for Earth—measuring changes in mass at any region on the planet. The data from GRACE have proven invaluable for monitoring such phenomenon as the melting of the polar ice caps, rise in sea level and even changes in groundwater.

Until now, monitoring groundwater has been notoriously tricky. The traditional method—point readings of individual wells—is laborious and unreliable, since a single well may not be representative of the entire aquifer. Using GRACE, however, CIRES Fellow John Wahr and his colleagues are studying groundwater in ways never before possible and are revolutionizing the field of hydrology in the process. For the first time, scientists can reliably measure total changes in a region's groundwater.

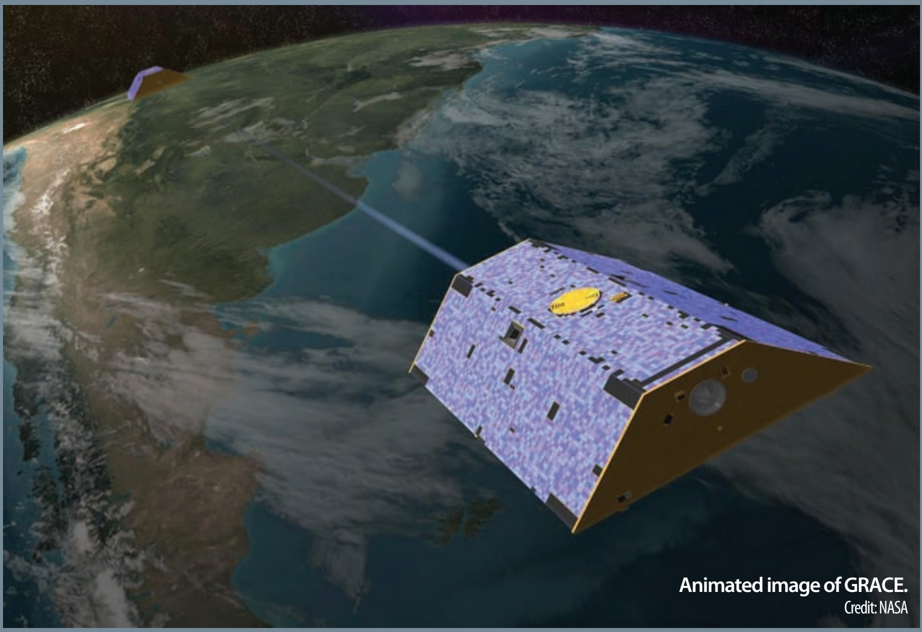
The results have been eye-opening. Wahr and colleagues, along with researchers at the University of California, Goddard Space Flight Center and other institutions, have discovered that in places like northern India, North Africa and California's Central Valley, humans are drawing out groundwater faster than it's being replenished. The disparity could have disastrous results for the more than 1.5 billion people who depend on it for drinking water.

Launched in 2002, GRACE consists of two twin satellites, each about the size of a car, that travel in identical orbits. As they circle the planet, they measure subtle changes in Earth's gravity field (see "How Grace Works"). This allows scientists to map regions of greater and smaller mass—for example, the Himalayas versus the Mariana Trench, respectively. By comparing the data month to month, they can determine how that mass migrates with time.

Since 2002, the biggest mass changes recorded by GRACE have been ice melt in Greenland, Antarctica and Alaska. "But another dramatic long-term mass change we've seen is in northern India, Pakistan and Bangladesh," Wahr says. "It's a huge mass loss, and it's due to farmers pumping water from the ground for their fields." This area is the most heavily irrigated region on Earth, with more than 75 percent of it irrigated. According to Wahr and his colleagues' calculations, from 2002 to 2008 the region lost 44 million acre-feet of water annually—enough to submerge the entire state of Oklahoma in a foot of water each year.

Researchers at the University of California have also observed dramatic drawdown in California's Sacramento-San Joaquin Valley, where from 2003 to 2010, aquifers lost 25 million acre-feet of water. GRACE has detected groundwater depletions in North Africa and northeastern China as well. "It's a serious problem," Wahr said. "In India, the wells are drying up, and some people are having trouble getting enough to drink." Wahr's results have garnered attention from policy makers, with Indian leaders even discussing the findings on the Parliament floor.

Nevertheless, many traditional hydrologists and water managers have been skeptical of the satellite-based findings. "It's a radical idea to think you can measure 1-centimeter changes in groundwater from space—that somehow the satellites up there can see water beneath the soil," Wahr said. "Even though I've been involved with GRACE from the beginning, it's still staggering to think about what you can accomplish. But once you understand how GRACE works, you understand how fantastic the methodology is."



Animated image of GRACE.
Credit: NASA

How GRACE Works

»» Twin satellites—spaced 220 kilometers (137 miles) apart—circle Earth in identical orbits, 483 kilometers (300 miles) above the surface.

»» Global Positioning System (GPS) receivers on the satellites track their exact location above the planet down to within 1 centimeter (.39 inches) or less.

»» By beaming microwaves between each other, the two satellites measure the distance between one another to less than 1 percent of the width of a human hair.

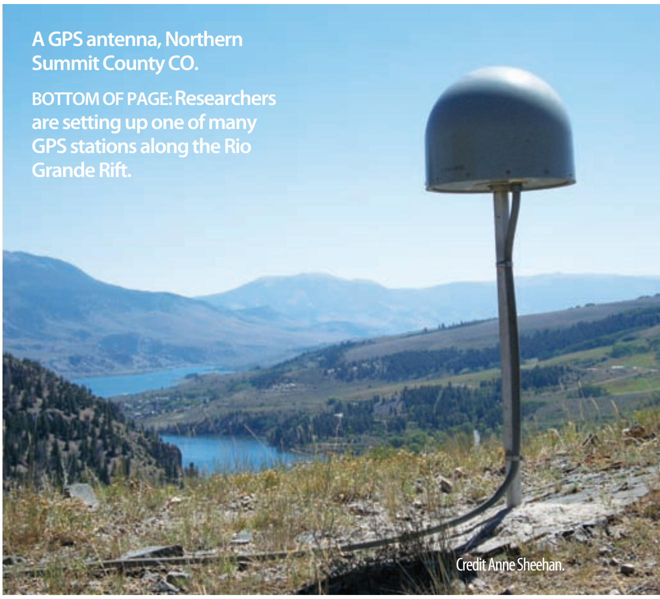
»» As the leading satellite passes over a region with greater mass—the Andes in South America or the Rocky Mountains in North America, for example—the stronger gravity field pulls on the first satellite with greater force, causing the satellite to speed up and move farther ahead of the trailing satellite. As the second satellite moves over the more-massive region, it, too, accelerates and catches up with the first satellite.

»» The crafts' instruments use these small changes in distance to calculate the mass anomalies that caused them. To isolate the contribution from groundwater, scientists subtract out other factors, such as soil moisture and surface water, using models and observations.

»» By comparing data month to month, scientists can determine how Earth's mass relocates over time—for example by ice sheet melting, groundwater depletion, or an earthquake heaving up chunks of rock.

How Risky is the Rift?

Estimating earthquake potential of the Rio Grande Rift



A GPS antenna, Northern Summit County CO.

BOTTOM OF PAGE: Researchers are setting up one of many GPS stations along the Rio Grande Rift.

Credit Anne Sheehan.

By Jane Palmer

While the impacts of the August 23, 2011, Colorado earthquake at magnitude 5.3 paled in comparison with those of the magnitude 5.8 earthquake that hit the East Coast the same day, it showed the Rio Grande Rift—the north-trending continental rift zone that extends from Colorado's central Rocky Mountains to Mexico—is by no means dead but seismically alive and kicking.

"We don't expect to see a lot of earthquakes in that region, or big ones, but we will have some earthquakes," said Anne Sheehan, CIRES Fellow and Associate Director of CIRES Solid Earth Sciences Division. Sheehan, her team and colleagues from the University of New Mexico, have studied the rift zone—the chasm where Earth's crust is being pulled apart—for the last five years to assess the risk of earthquakes.

Colorado and New Mexico, with their mix of mountains and plains, sit mainly on the seismically stable part of the nation where earthquakes are a rarity. The Rio Grand Rift region; however, presents an exception to this relative calm. Along the rift, spreading motion in the crust has led to the rise of magma, the molten rock material under Earth's crust, to the surface, and the creation of long, fault-bounded basins that are susceptible to earthquakes.

Previously, geologists have estimated the rift is not spreading at all, or has spread apart by up to 5 millimeters each year, but accurate measurements have proved problematic, Sheehan said. The slow rates of motion in the region mean that any instruments must be able to measure mere fractions of millimeters of movement, she said. "Low-strain-rate regions have been notoriously difficult to get a real number for," Sheehan said. "The margins of error in previous estimates can be nearly as much as the estimates themselves."

To address this problem, the scientists installed semi-permanent Global Positioning System (GPS) instruments at 25 sites in Colorado and New Mexico to track the rift's miniscule movements from 2006 to 2011. "The GPS has reduced the uncertainty dramatically," she said. "We can actually resolve those tiny, tiny motions—I think it is amazing that it works."

The primary goal of the researchers was to assess the potential earthquake hazards posed by the rift and to better understand how the interiors of continents deform. The high-precision instrumentation has provided unprecedented data about the volcanic activity in the region—information that will help give probabilities for the likelihood of earthquakes, Sheehan said. "The big questions we wanted to get at were 'Is the rift active? How is it deforming? Is it alive or dead? Is it opening or not?'" she said.

The researchers also hope that the data will shed light on the mystery of how continents deform away from plate boundaries, Sheehan said. At plate boundaries scientists can observe what is going on pretty clearly, she said. "Things move past each other and crash into each other—at active plate boundaries the rates of motion detected by GPS can be centimeters per year," she said. "Compare that with the fraction of a millimeter per year that we have measured for the Rio Grande Rift."

The scientists will publish the study's results in the scientific journal *Geology* in early 2012. Until then, Sheehan cannot talk about the details of their findings; however, she will say what the recent earthquake has shown so conclusively: "The rift is definitely still active."

Credit Anne Sheehan.

TheScience

"The big questions we wanted to get at were 'Is the rift active? How is it deforming? Is it alive or dead? Is it opening or not?'"

Eavesdropping on Tsunamis

Underwater instruments assist early-warning systems

By Jane Palmer

When Anne Sheehan retrieved her group's ocean bottom seismometers (OBSs) offshore of New Zealand in 2010, it wasn't only the recorded heaves and shudders of five major earthquakes that caught her attention. It was the relatively faint ripples chronicled on the accompanying seafloor pressure gauges—which measured half-centimeter changes in wave height on the ocean surface nearly 4,000 meters above—that astounded her.

The seafloor pressure gauges had picked up a tsunami in the seas above.

Like land-based seismometers, OBSs record ground motions, including the seismic waves of earthquakes, but seafloor pressure gauges capture seismic waves and also changes in the height of the water column above. "It was a big surprise," said CIRES Fellow Anne Sheehan and Associate Director of CIRES Solid Earth Sciences Division. "We are used to getting seismic waves but the water waves? To be able to see those as they go over the sensor was pretty amazing."

The potential use of these deft instruments struck Sheehan immediately. "When I saw the results, I thought, 'Wow, we should see if we can use these to inform tsunami estimates and warning systems,'" she said.

CIRES at sea

Sheehan, CIRES Fellow Peter Molnar and their colleagues at Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology had originally launched the OBSs and differential pressure gauges (DPGs)—instruments designed to measure the differences in pressure—into the ocean in 2009 with the goal of learning more about the structure under New Zealand's Alpine Fault. "It was a 'drop and pray' approach," Sheehan said. "Sometimes the instruments don't come back."

The scientists had surveyed the sea floor with sonar before choosing the "sinking sites," Sheehan said. No steep slopes the instruments might tumble down, no submarine canyons, nor regions of heavy currents where the ocean noises might interfere with the signals. "We try to put them in places where there is some sediment, some goopy stuff or some mud so they will sink into it," she said.

The scientists' precautions paid off. One year later, the team successfully collected 29 of the 30 instruments. It was then they saw not just the roars of the seismic data, but the relative whispers of the tsunami activity. "To get that as a by-product of a seismic experiment was very interesting," Sheehan said. "I had never seen that done with ocean-bottom seismometers before."

Predicting the unpredictable

While earthquakes still cannot be predicted with certainty, in the last decade scientists have made strides in issuing warnings, watches and evacuations for the tsunamis that accompany them. NOAA launched its DART (Deep-ocean Assessment and Reporting of Tsunamis) recording buoys in 2008 to help provide real-time tsunami detection as the waves travel across the deep-ocean. These instruments also use seafloor pressure gauges, but they are sparsely spaced in the deep ocean, Sheehan said, limiting their forecasting power. Following the 2010 Chilean earthquake, for example, scientists overestimated the tsunami threat to Hawaii and the western Pacific because it took three hours for the tsunami to hit the closest DART buoy, delaying the time the scientists could use real information to refine their models.

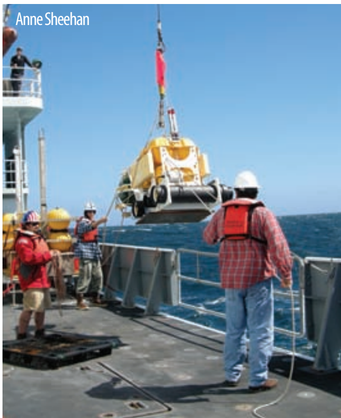
The data from seafloor pressure gauges collected as a byproduct of OBS experiments offer an exciting opportunity to measure tsunami waves, Sheehan said. The information gathered can help scientists reconstruct the entire process of tsunami propagation and transformation from the open ocean through the continental shelf, and also help them refine their forecasting models. In addition, the project has sparked and strengthened international collaborations with other research institutes, she said. "People are pretty much lining up to work with the data."

Funding for this research was provided in part by a CIRES Innovative Research Program (IRP) award, which is designed to stimulate a collaborative research environment. **Learn more at http://cires.colorado.edu/science/pro/irp/.**

TheScience

Seafloor instrumentation can pick up half-centimeter changes in wave height on the ocean surface 4,000 meters above.

Anne Sheehan

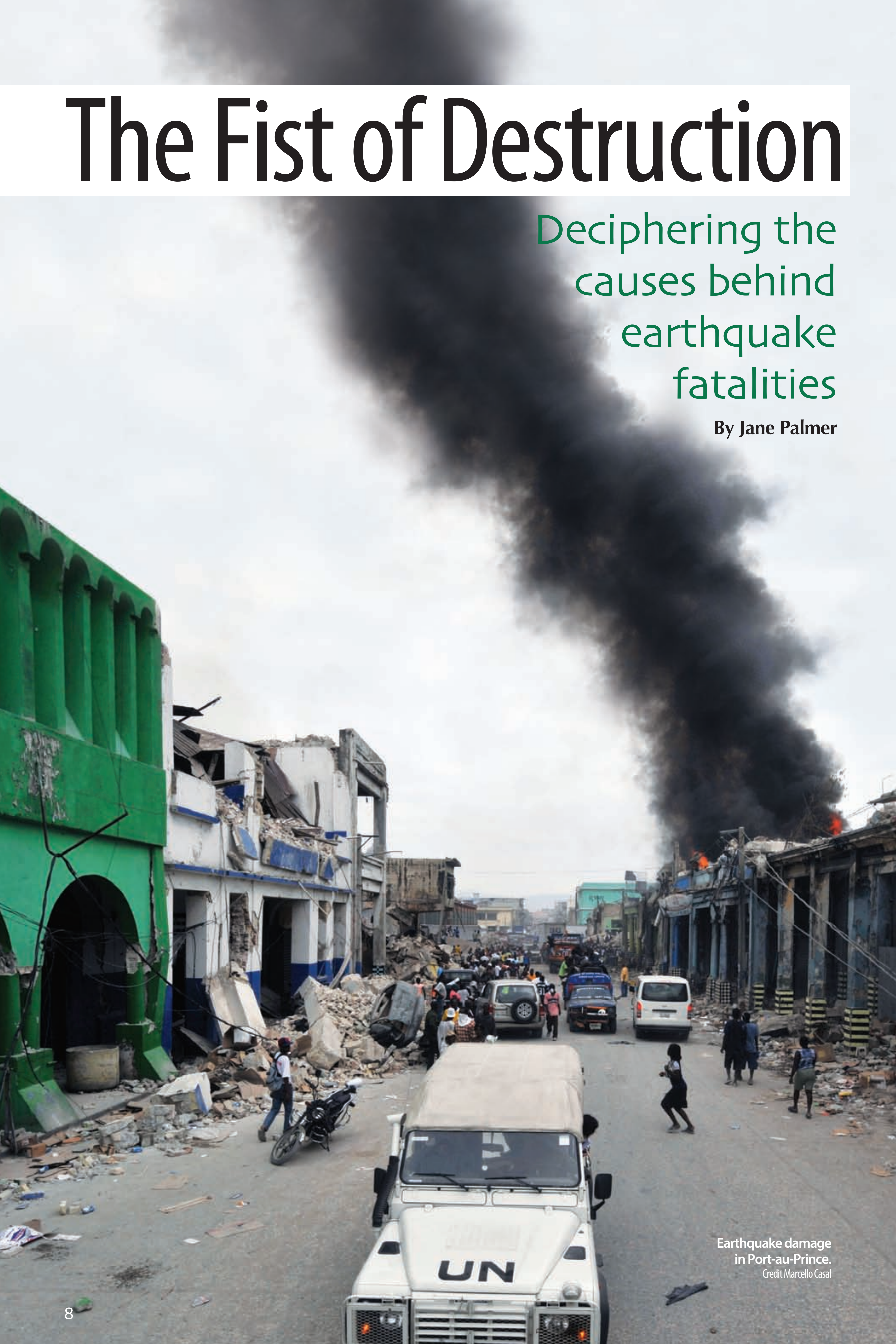


Anne Sheehan

The Fist of Destruction

Deciphering the causes behind earthquake fatalities

By Jane Palmer



Earthquake damage in Port-au-Prince.
Credit Marcello Casal

Haiti, 2010:
Magnitude 7 earthquake,
death toll – 230,000

New Zealand 2010:
Magnitude 7 earthquake,
death toll – 0

Can this staggering difference in death tolls be attributed solely to the relative poverty in Haiti, where poorly-constructed structures collapsed killing thousands, and insufficient resources hampered the disaster response, killing legions more?

"Not true," says CIRES Fellow Roger Bilham. Poverty is only one of five factors—the "five fingers in the fist of destruction," Bilham calls them—that affect the number of casualties suffered in a major earthquake. While poverty and its evil twin ignorance —meaning inhabitants and even governments often don't know how to prepare for potential earthquakes—play their part, in 2010 Bilham and Nicholas Ambraseys of Imperial College in London uncovered one previously unidentified culprit in earthquake fatalities: corruption in the building industry.

Corruption in this sector frequently takes the form of corner-cutting on materials, poor building practices as well as bribes to subvert inspection, Bilham said. "The question is: how to prove it?"

While the impacts of poverty and corruption are highly similar, the scientists attempted to tease apart the influence of both "fingers" on earthquake death tolls. The first stage of their analysis compared the data on a country's relative wealth with a Corruption Perceptions Index (CPI)—a measure of the frequency and extent of bribes paid within various countries compiled by Transparency International—a global civic society based in Berlin. The scientists found a direct correlation between the two variables. "What this says is that if a country is rich, it is not generally corrupt; if it is poor, it is very corrupt," Bilham said.

Some anomalies did exist to this simple relationship, however. Italy, Turkey and Haiti were more corrupt than they "should" be on the basis of their wealth, whereas India, New Zealand and China were less corrupt than expected.

To determine how many earthquake deaths due to building collapses happened in the anomalously corrupt countries, the researchers then analyzed all the compiled earthquake fatality data for the last 30 years. Their finding was staggering: 83 percent of the earthquake deaths occurred in the "more corrupt than expected" nations. "That is not exactly proving anything, but it is a solid result," Bilham said.

While corruption primarily impacts those living in cities, the fourth "finger of destruction" impacts those living in rural communities, Bilham said. In most nations, engineers build structures in the civic centers with full knowledge of earthquake preparedness, Bilham said. But the villages don't hear anything about it. "We know how to build for earthquakes but we don't get the message to the people who need it—the guy who is going to die in the earthquake," he said.

"We know how to build for earthquakes but we don't get the message to the people who need it—the guy who is going to die in the earthquake."

For the fifth finger—the opposing thumb in the problem of global earthquake fatalities—Bilham points at seismologists themselves.

Certain limitations in data and accepted practices can make assessing the potential for earthquakes in a region difficult. Researchers, for example, cannot determine the history of earthquakes in regions where there is no historical record, and since some earthquakes happen well below the earth's surface, "traditional methods of estimating seismic activity are inadequate," Bilham said,"and geodetic methods for assessing the strain rates in earthquakes zones can be misleading".

Before the 8.0 Chengdu earthquake, for instance, which killed 68,000 people in 2008, the stresses measured in the earth's crust—the strain rate—were only three times more than those currently measured in Colorado.

Could this mean a magnitude 8.0 earthquake could happen in Colorado?

It is not implausible, Bilham said. "If an earthquake happened tomorrow, people would do these calculations and say, 'We should have seen this coming.'"

"In this fist of destruction, there are all these factors," Bilham said. "But the biggest one is the danger of seismologists being too conservative in a region where they don't have sufficient information to say, 'You cannot have an earthquake.'"

Mountains to Molehills

How different climates sculpt mountain ranges

By Jane Palmer

A harsh climate can wear anyone down, and mountains are no exception. But when it comes to certain mountain ranges, bad weather has done more than erode the surface slopes—it's changed the shape of the mountains altogether, said CIRES Fellow Greg Tucker.

"It is amazing," Tucker, a geologist in CIRES Solid Earth Sciences Division, said. "The power of climate shows up in the shape of a hillslope."

Photos taken of the Apennines in Italy.
Credit Greg Tucker

Tucker's fascination with the topic started with his first visit to the Italian Central Apennines ten years ago. There, the gentle, rubble-covered mountaintops perched on incongruously steep, intact bases caught his attention. The change in slope dated from the last ice age, Tucker learned, but why would the change in climate cause such a radical shift in mountain topography?

How did those mountains get there?

This notable change in mountain slope exists in locations where Earth's crust is being stretched, Tucker said. Large blocks slide relative to one another under the crust and mountains form when one block slides up and out of the ground, he said. Mountains are a little like escalators, he said. "Each earthquake is like one step on the escalator because it raises the mountain up and shifts it to one side."

"The power of climate shows up in the shape of a hillslope."

Once a mountain section or "step" emerges from the ground, winds, rain, sun and snow set to work, wearing down the surface slopes. The higher older slopes, or steps, have seen more of this weathering than the lower slopes, Tucker said. "But unlike steps on an escalator, rocks break down and erode."

If weather erosion is not high in comparison the rate of the mountain uplift the mountain slope remains similar to the angle of the fault plain, Tucker said. But if the erosion is relatively substantial it wears down the slope, he said. "So the slope of a mountain depends on the relative power of tectonics versus erosion," he said.

Tucker and his team hypothesized that the changes in the slope of the mountain front might have a really simple explanation. If the slope has changed in older and younger parts of the slope, it suggests the speed of erosion has changed, Tucker said. So the older, upper parts of the mountain may have seen a different climate than the recent one, he said.

Probing the mountain morphology mystery

To estimate how long-term weather patterns might sculpt mountain ranges, the scientists designed an innovative geometric model using the Apennines as a test case. Although they expected colder, harsher conditions to cause slightly more erosion, using this methodology they found that the freezing temperatures in near-glacial climates—periglacial climates—can erode mountain ranges 10 times faster than temperate ones and result in radical shape changes to the mountains.

In the Apennines, for instance, "it really looks like the upper parts of the slopes got almost blasted away," Tucker said.

The explanation for this result lies in the fact that different climates can vary greatly in their power to erode, Tucker said. "At the height of the last ice age, the upper ground level lay in a temperature regime called the 'frost-cracking window'," Tucker said. At temperatures of about –5° degrees Celsius, ice crystals form in the rock; these crystals then grow as thin films of liquid water migrate toward them, he said.


Greg Tucker

TheScience

The slope of an Apennine mountain is decided by opposing forces: weather erosion and how fast the hillside is emerging from the ground.

The burgeoning crystals pressurize the rocks from within eventually creating holes and cracks. In the last ice age, this internal freezing effect broke up the rocks and crumbled the hillsides to form gentle mounds of rubble, Tucker said. The current, warmer climate has no such effect, however. "As the rocks slide up from underground, they hardly get touched by erosion at all," he said. "So they are almost a mirror image of the fault plane." The result of the different climatic conditions is broken-up, potholed rocks up high and sheer, intact rock below.

Another unforeseen application for the scientists' novel new model also exists. Using information about the shape of the hill slope and the speed at which the fault is moving, researchers can now determine how fast the current climatic conditions are eroding the rock in certain types of mountain ranges, Tucker said, "which is really cool because until now scientists haven't had many numbers for how fast the rock is weathering."

X-ray Through the Earth

The earth consists of several distinct layers, each with their own properties.

THE CRUST

The crust comprises the continents and the ocean basins. It has variable thickness, being 35-70km thick in the continents and 5-10km thick in the ocean basins.

THE MANTLE

The mantle is separated into the lower and upper mantle and totals about 2900km thick. This is where most of the internal heat of the earth is located.

The crust and the solid portion of the upper mantle make up the lithosphere. The lithosphere is divided into the many tectonic plates that move around in relation to each other (see opposite page).

THE CORE

This layer is separated into the liquid outer core and the solid inner core. The outer core is 2300km thick and composed of a nickel-iron alloy and the inner core is 1200km thick and composed almost entirely of iron.

Earth's Crust 5-70km CRUST

Upper Mantle

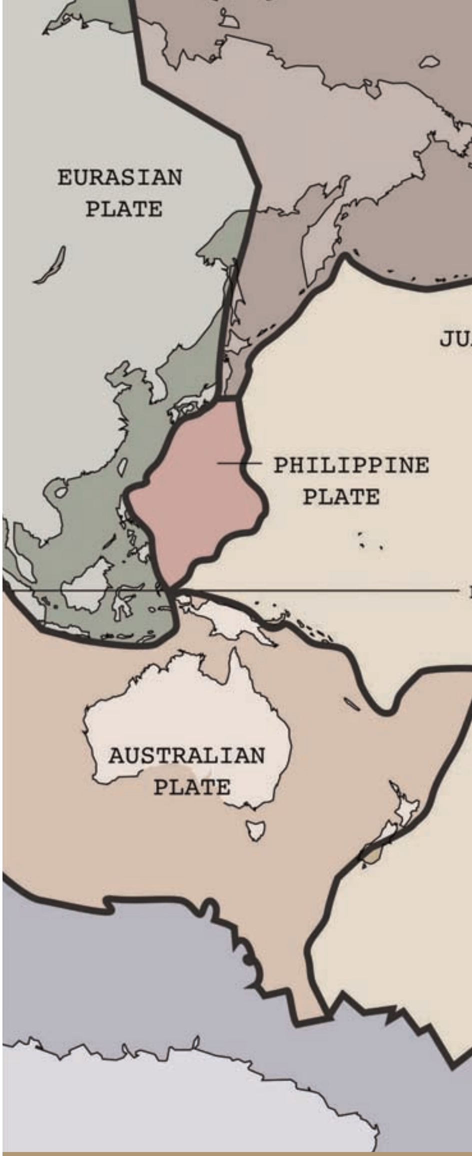
Lower Mantle

MANTLE 2900km

Outer Core 2300km

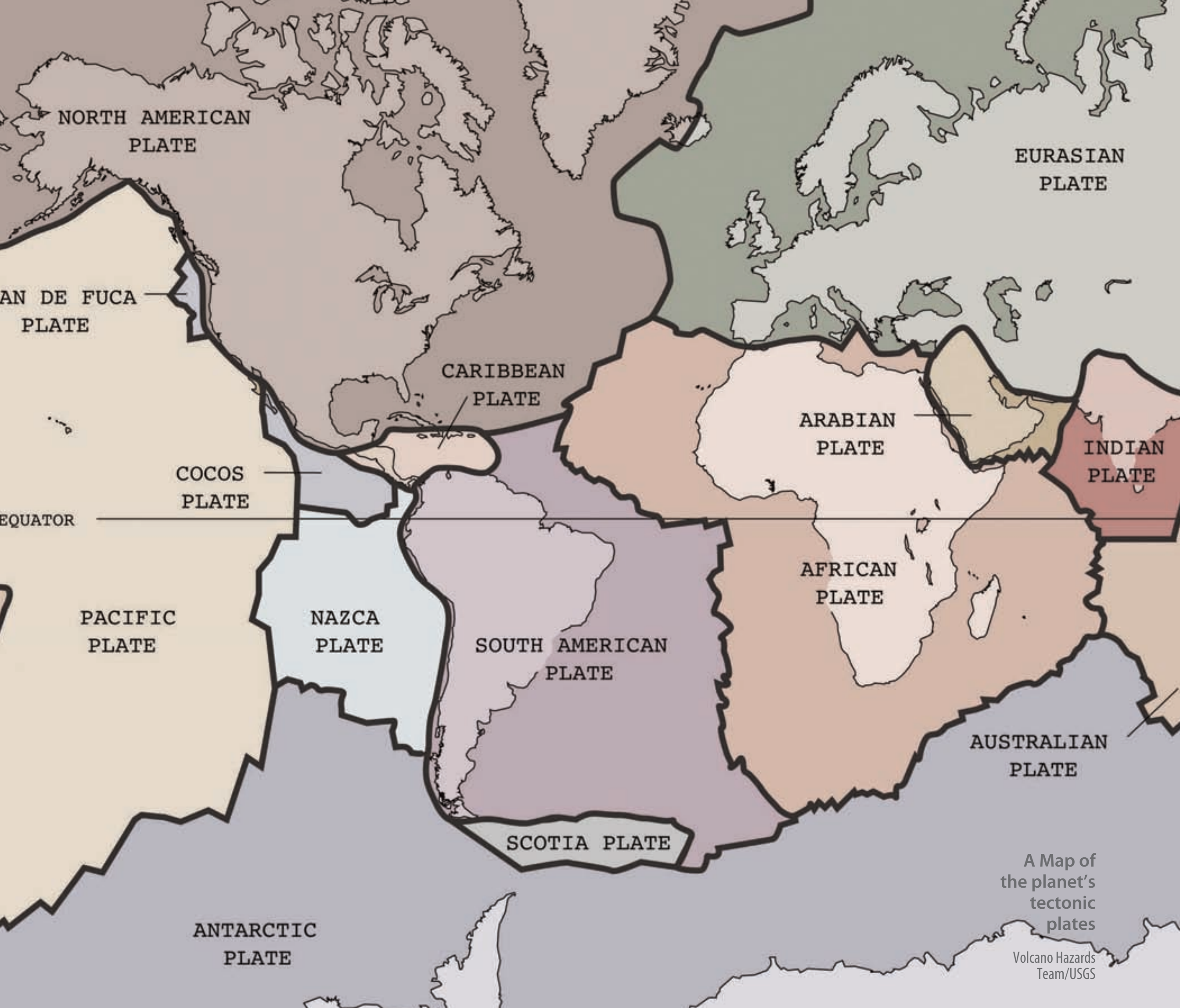
Inner Core 1200km

CORE 3500km



earthquake fact:

There is about one magnitude 7 earthquake per month, which is the size of the earthquake that devastated Haiti in 2010. However, most magnitude 7 earthquakes go unnoticed by the media because they happen in unpopulated regions and cause little to no destruction to human settlements.



A Map of the planet's tectonic plates

Volcano Hazards Team/USGS

Earthquake Essentials

By Celia Schiffman, CIRES graduate student in the Geological Sciences Department at CU Boulder

What is an earthquake?

An earthquake is what happens when two blocks of the earth suddenly slip past one another causing ground shaking and seismic waves.

The surface where they slip is called the fault or fault plane. This fault movement can be everything from a rapid, massive shaking that results in a great earthquake, to a slow creep that is undetectable to humans and can only be recorded by sensitive instruments.

Where do most earthquakes occur?

The biggest earthquakes generally occur on the largest faults, which are found where tectonic plates meet. These tectonic plates are large plates of rock that make up the surface of Earth. If the planet were an egg, the cracked shell would be the tectonic plates.

Earthquakes by the numbers: a common occurrence

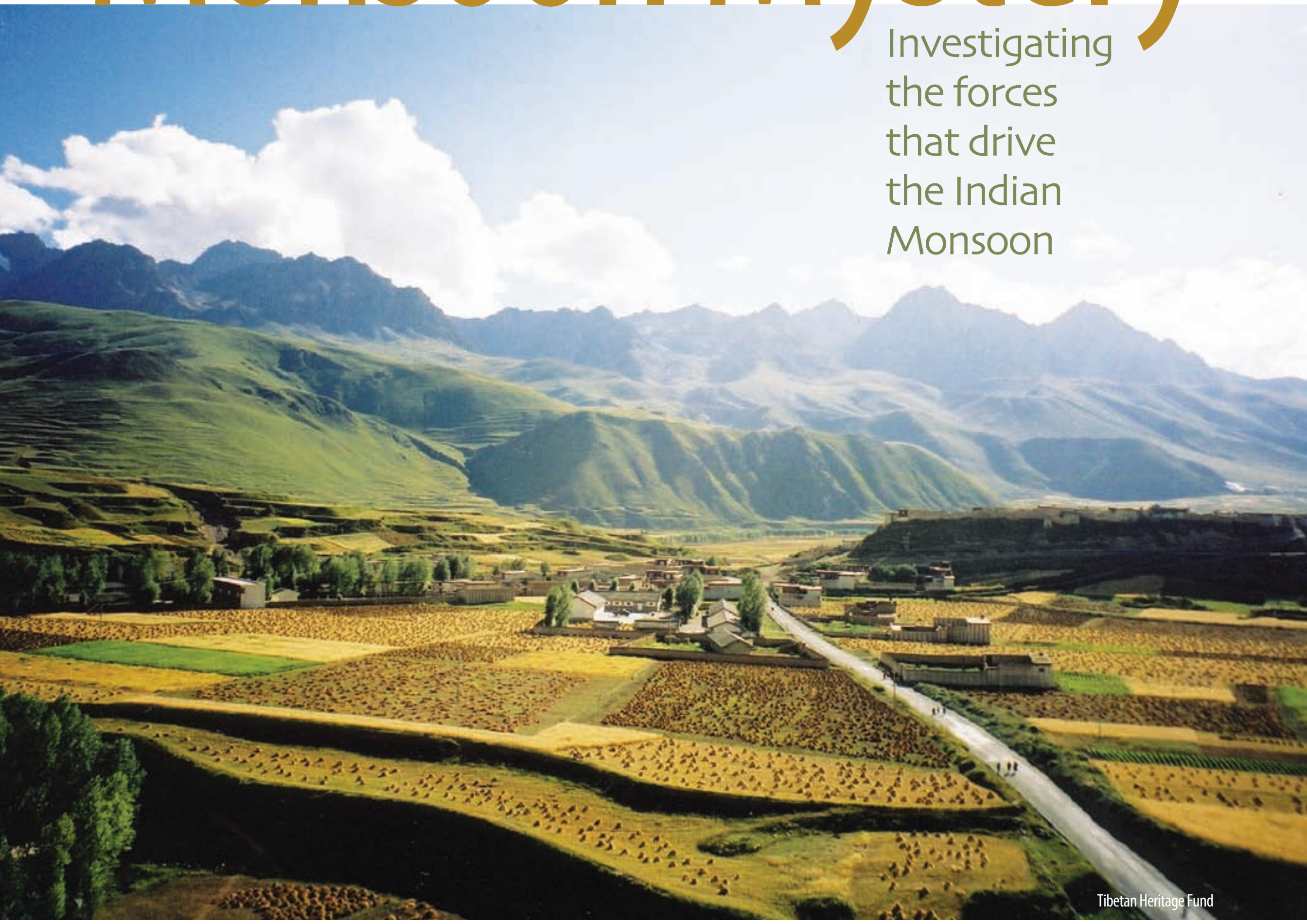
Earthquakes are very common, and chances are one has happened while you have been reading this — there are more than one million of them per year throughout the world.

Average earthquakes per year

Magnitude 8+: 1
Magnitude 7-7.9: 15
Magnitude 6-6.9: 134
Magnitude 5-5.9: 1,319
Magnitude 4-4.9: 13,000
Magnitude 3-3.9: 130,000
Magnitude 2-2.9: 1,300,000

Monsoon Mystery

Investigating the forces that drive the Indian Monsoon



Tibetan Heritage Fund

By Kristin Bjornsen

Getting demoted from Batman to the Boy Wonder, Robin, isn't fun, but that may be the ignoble fate that awaits the Tibetan Plateau. For decades, meteorologists and geologists have thought the 5,000-meter-high plateau—the world's highest and largest—played a crucial role in the South Asian Monsoon (aka Indian Monsoon), but new research might relegate it to side-kick status.

"There's a big controversy about whether the Tibetan Plateau is important or not in driving the Indian Monsoon."

"There's a big controversy about whether the Tibetan Plateau is important or not in driving the Indian Monsoon," CIRES Fellow Peter Molnar said. The classic view is that the plateau has a large part in strengthening the monsoon, while the new view gives it a smaller, mostly mechanical role. "We're trying to figure out what its role is," he said.

It's not an academic question since millions of people depend on the Indian monsoon, which can deliver more than 400 inches of rain to regions, for drinking water, hydropower and agriculture. Understanding the mechanisms behind it is key to predicting its intensity and fluctuations year to year.

From the Arabic word mausim for "seasons," monsoons are marked by seasonally reversing wind systems. From about June to September, the sun bakes the land in India; air heats up and rises, creating a low-pressure area. Wind rushes in from the southwest, carrying water from the Indian Ocean. In October, the land cools and the winds reverse, blowing back toward the ocean to the southwest.

The Tibetan Plateau, the "roof of the world," was thought to help fuel this process by further heating the air and driving atmospheric convection (rapid ascent of warm, moist air). "The sun warms the plateau's surface, making air at that altitude hotter than it would be without the plateau," Molnar said. Consequently—under the traditional theory—the high, hot plateau acts sort of like an air pump, creating a low-pressure zone that sucks in moist, rain-bearing air from the Bay of Bengal.

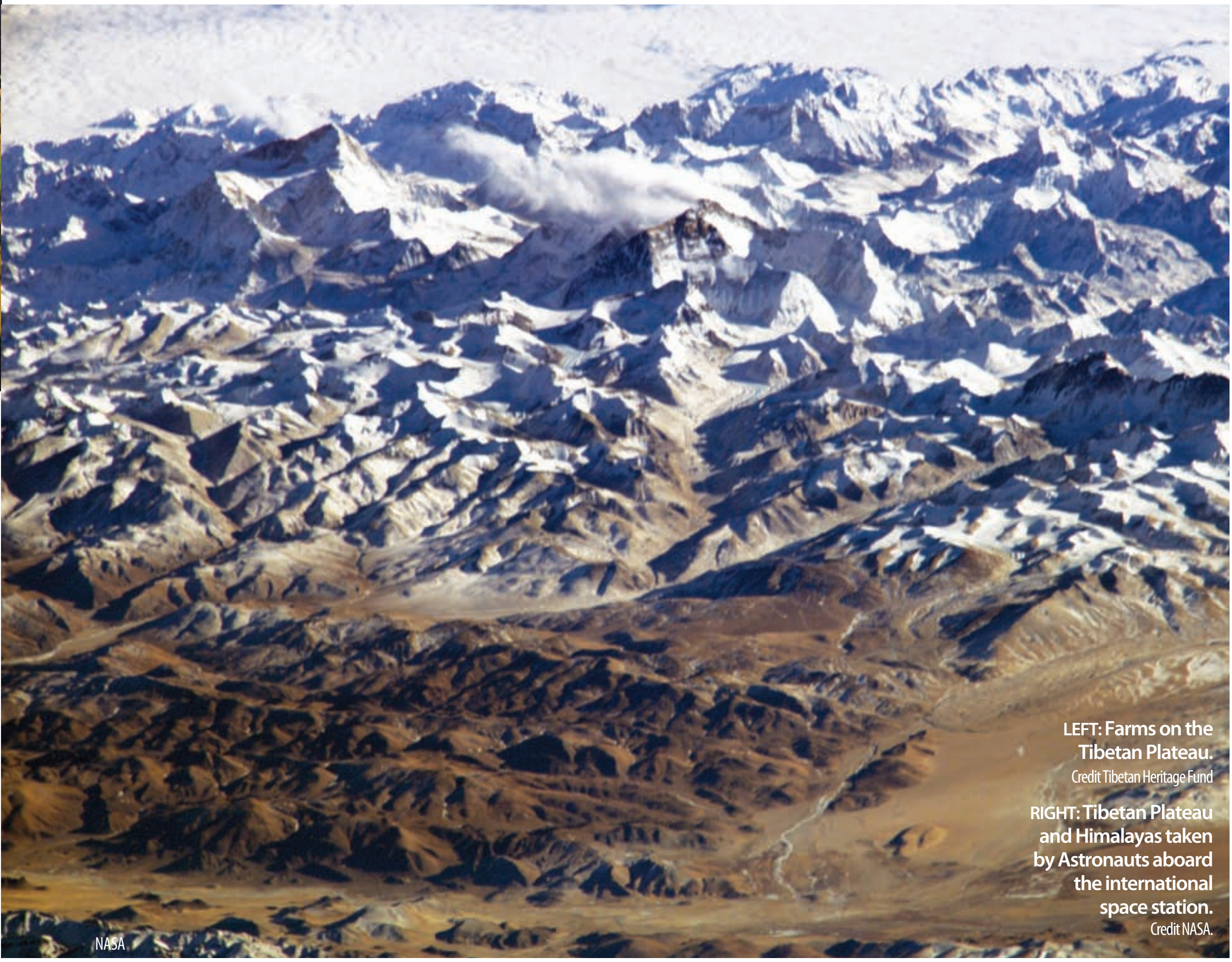
But some of Molnar's colleagues noticed something strange. The hottest summer temperatures in the upper troposphere (about 10 kilometer high) weren't over the entire Tibetan Plateau, as you'd expect, but over its southern edge and the northern Himalaya. Most of the Tibetan Plateau wasn't playing much of a part.

"What this means is that the high temperature was due more to latent heating [heat released when water condenses]," Molnar said. Essentially, the Himalaya forces up moist air from the ocean, he said. As the air rises, it cools and water condenses, releasing rain and latent heat. The latent heat makes the air hotter, which makes it rise higher to the top of the troposphere (bottom of the stratosphere). This cycle continues, leading to the high temperature seen aloft over the southern edge. "So the monsoon rains are being driven not so much by the plateau, but simply because you have a wall of mountains mechanically forcing the air up," Molnar said.

The Himalaya strengthens the monsoon in another way: They prevent India's warm, moist air from mixing with the cold, dry air from China and Europe. "Without that barrier, everything would dissipate away, and you'd get rain but not a strong monsoon. So even with no Tibetan Plateau, you should still get monsoons."

Nevertheless, even if the Himalayan/southern edge barrier is the dominant player—mechanically strengthening the monsoon—that doesn't mean the plateau has no effect. It could still act as a "thermal pump," intensifying the monsoon to some degree, which is what Molnar is investigating. "I'd like to know whether Tibet's thermal effect matters or if it's purely mechanical." To answer that, he's looking at the plateau's geologic history (when and how it became high) and the area's climate history (when the monsoon was strong and weak), to see whether one affects the other.

But don't write off the Tibetan Plateau yet. Even if it turns out to have a minor role, that could spell the difference between a strong and weak monsoon. A strong monsoon is defined as 10 percent more rain than average and a weak monsoon as 10 percent less. "That's a small range, but as far as Indian civilization is concerned, if you dropped its rainfall by 10 percent, it would be a different world," Molnar said. "So the Tibetan Plateau doesn't have to make a big contribution to have a big effect."


NASA

LEFT: Farms on the Tibetan Plateau.
Credit Tibetan Heritage Fund

RIGHT: Tibetan Plateau and Himalayas taken by Astronauts aboard the international space station.
Credit NASA.

Rocks, Rocks and Yet More Rocks

Credit Anne Sheehan

Virtual rock collection furthers insights into North America evolution

By Jane Palmer

In a geologist's universe, CIRES Fellow Lang Farmer justifiably earns the lauded title as "The Great Dane of all rockhounds."

For the last eight years, Farmer who is also Chair of Geological Sciences Department, along with colleagues from the University of Kansas and the University of North Carolina, have amassed the mother of all rock collections, currently totaling 64,985 rock samples but growing by the day. Even though the collection is a virtual one—each rock is "stored" in an online database—each entry represents a real individual rock, dug or retrieved from the ground, cleaned off, inspected and written about.

The database, called the North American Volcanic and Intrusive Rock Database (NAVDAT) provides a web-accessible repository for the age and chemical compositions of western North America volcanic rocks. It supplies an unprecedented resource for researchers, educators and even the general public, Farmer said. Most notably, researchers can "mine" the database to learn more about the geological history of North America. "We are using it to look at the geological evolution of an entire continent over a hundred million years," he said.

Credit Anne Sheehan

Volcanic rocks are gems of historical information, Farmer said. These rocks derive from magmas—bodies of molten rock located below Earth's surface—and, if geologists can find them on the surface, they can reconstruct how the continent has evolved through time, he said. "People have been using volcanic rock data—whether it is age or composition or petrology—to reconstruct the history of continents for 50 years."

Over the past thirty years, new geological techniques that yield geochemical, geochronological, and geospatial analyses of these volcanic rocks have produced unprecedented amounts of data, Farmer said. The construction of an online database therefore saves the research community countless hours of searching through the literature and collating previous results, he said.

To this end, the inter-university team created the NAVDAT database culling the information from previously published literature, doctoral theses and records from the United States Geological Survey. The researchers also add new information as it is discovered. "It is a living database," Farmer said.

Powerful map interfaces allow users to quickly plot sample locations on satellite images, and hyperlinked geochemical plots allow users to rapidly investigate space-time patterns in the compositions of rocks. These tools allow users of the database to address a wide variety of issues concerning the geologic evolution and present volcanic state of western North America. The database is also a tool for lecturers and students across the USA, Farmer said. "It has real educational value," he said.

Farmer has used the database to look at the evolution of Colorado over the last 80 million years. Specifically, he searched the database to investigate why the southern Rocky Mountain area has seen so much volcanic action when it lies so far inland from a continental margin. He has shown that much of this activity, known as magmatism, stems from an episode some 60 million years ago when the oceanic lithosphere moved under western North America.

He credits this surprising discovery to the large quantities of data at his disposal in the database. "When you consider 10,000 analyses all at the same time, much of the sampling bias goes away," Farmer said. "A discovery is not based on a couple of analyses—it is based on everything."

TheScience

Scientists use volcanic rocks to understand the evolution of America. More rocks equals more knowledge.

The Trickle-Down Effect

How earthquakes impact rivers

By Jane Palmer

Falling buildings, landslides and tsunamis jump to mind as the most immediate consequences of an earthquake. But waterfalls? To investigate how earthquakes affect river systems and subsequently how they shape the landscape decades after the event, CIRES Fellow Greg Tucker and former CIRES graduate student Brian Yanites travelled to Taiwan, which experienced a major earthquake in 1999.

What was the immediate impact of the 1999 earthquake?

There was a series of rivers crossing the Chelungpu fault, which when it ruptured pushed up one side of the fault over another creating sharp drops. Instantly, in a matter of seconds to minutes, the earthquake created a set of brand-new waterfalls, some of which were up to six meters high.

When the water plunges over like that, it will carve out the rock beneath. In Taiwan, the rivers are powerful because they are fed by typhoons. Also, the rocks are relatively soft and so the erosion at the base of the waterfall is phenomenal. As the base erodes, the waterfall essentially moves back. So today, 10 years later, the waterfalls have moved upstream as much as a mile or so.

Researchers expected the formation of waterfalls, but were there any surprises in this study?

When Brian looked far upstream of the fault, he noticed that many of the segments of the rivers were absolutely choked in sand and gravel with no bedrock in sight. What we think is happening here is the earthquake essentially shook loose a lot of sediment on the hill slopes. The earthquake was accompanied by thousands and thousands of landslides.

So it looks like the big earthquake of 1999 had a dual role. Where the rivers were sitting just upstream of the fault, it created a waterfall that turned the river on high speed, it just sliced like a buzz saw. But further upstream the river was just cloaked with dirt that had been shaken loose on the hillsides. The dirt basically shields the channel bedrock from erosion, and will continue to do so until it is washed away again. Brian Yanites' calculation suggests that this could take up to hundreds of years in some places.

CIRES FELLOW
Greg Tucker

Why is it important to understand this?

There are issues of preparedness in seismically active areas. The levels of erosion in places like Taiwan are so fast that they can have a very real effect on communities and infrastructure. For example, in Taiwan there was a hydrodam not far upstream from one of the fault structures. When that waterfall started retreating it posed a threat to that dam.

It is imperative as a community that we develop the tools to at least estimate, if not to forecast, what might happen in response to any kind of management action. What is going to happen to something complicated like a river system if you build a dam, if you cut down the trees, if you change the hydrology? That is why we need to be able to understand the physics of landscape processes, and to understand the physics we need to find natural experiments like Taiwan and use them to refine our models.

Credit Brian Yanites

Feeling the Heat

Investigating supraglacial lakes role in glacier melt

By Jane Palmer

Dangling in thin air above a Himalayan glacier, Ulyana Horodyskyj drills holes into a vertical cliff to mount one of her three round-the-clock spies: solar-powered cameras poised to capture the hourly rises and sometimes-spectacular falls of the lakes below.

"On one occasion the first camera showed a drainage of 3 meters," said Horodyskyj, a CIRES graduate student advised by CIRES Fellow Roger Bilham and a recipient of a CIRES Graduate Student Research Fellowship. "Overnight! I could see the water line—it was incredible."

Horodyskyj studies how supraglacial lakes—which sit atop the surfaces of glaciers—form and evolve in the Himalaya. She hopes her research will unveil new insights into the demise of glaciers in the area and help forecast hazards like flooding. "When people think about glaciers, they think in terms of advances and retreats, but glaciers are also shrinking vertically," Horodyskyj said. "We aim to understand the physics behind this process."

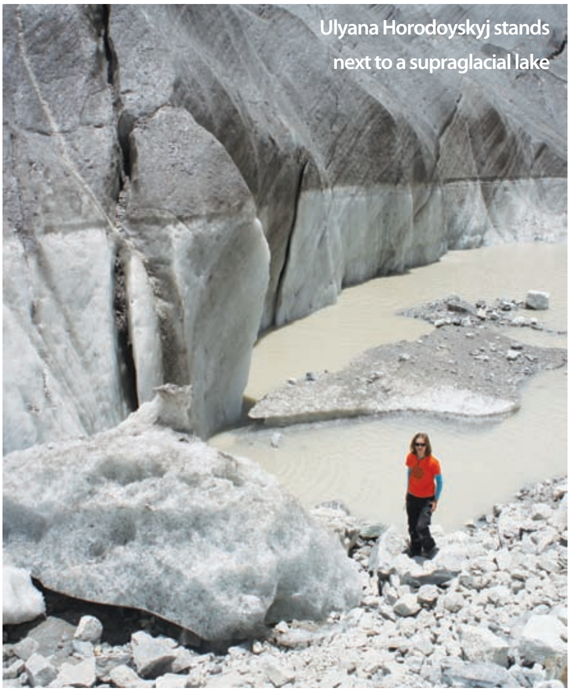
The supraglacial lakes most likely act as catalysts for this vertical ice loss, Horodyskyj said. To investigate this hypothesis she spent a month on Ngozumpa, Nepal's largest glacier, with a local Sherpa, Ang Phula, to set up her experiment.

Once there, Horodyskyj rappelled down the glacier's lateral moraine to set up the three cameras, each one focused on a different region. The cameras took hourly snapshots of three supraglacial lakes, and Horodyskyj recorded the water-level changes in one particular lake during the month of her field trip. She also measured the rate of melting on the north- and south-facing ice walls of the lake, using a laser rangefinder, as well as the incoming and outgoing solar irradiation. "This is a way to really quantify what is happening," she said.

During her stay, Horodyskyj watched the water rise by a total of 28 centimeters, which is 9 meters deep at its center. Two major icefalls, only a week apart, contributed 6 and 8 centimeters respectively to this overall water rise. "It was like being in a shooting gallery when you are near these lakes—things are collapsing everywhere," Horodyskyj said. "It doesn't matter whether your wall is facing east, west, north or south—they are all collapsing."

"It was like being in a shooting gallery when you are near these lakes—things are collapsing everywhere,"

Credit Ulyana Horodyskyj



Ulyana Horodoyskyj stands next to a supraglacial lake

One camera also captured the 3 centimeters overnight drainage in a larger lake, further upglacier, Horodyskyj said. The theory is that as the glacier moves, crevasses open up, she said. Once there is a conduit between the lake and the base of the glacier, the water drains through it. “You can just hear the water flushing,” she said.

The third camera, focused on the smallest lake near the end of the glacier, showed that lake to have changed from milky blue to brown during the field season and also to have doubled in size due to the monsoon rains. These initial results reveal that these lakes can undergo substantial changes in a very short amount of time, said Horodyskyj. “The big-picture question is figuring out just how fast these changes happen,” she said, “and what that means to the overall health of the glacier and how much time it has left.”

Insights from the study might also help with planning for natural disasters, Horodyskyj said. Flooding from glaciers will become a big problem for local villages if melt and drainage of these lakes continues on the “fast-track”, as the initial results show. Being able to predict when, and how large, any water surges would be, is invaluable, she said. “So there is basically a big human impact story to the science.”

TheScience

Lakes perched atop glaciers may play a major part in vertical glacial ice loss.

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A Mw9 earthquake in Kashmir?

Investigating temples in Kashmir gives insights into previous earthquake events
Credit Roger Bilham

New data reveal megaquake is possible in western Himalayan kingdom

By Jane Palmer and Kristin Bjornsen

While the 2005 7.6 Kashmir earthquake caused 75,000 deaths and immeasurable damage to the lives of survivors, its devastating impacts could be a pale shadow of what is to come, cautions CIRES Fellow Roger Bilham.

"A magnitude 9.0 earthquake, though unexpected, is possible in Kashmir," said Bilham, whose team of CIRES scientists, along with researchers from India and Pakistan, have studied rates of crustal deformation—telltale measurements of earthquake susceptibility—in the region for the past eight years.

The study's results constitute the first comprehensive predictions of seismic activity in the area based on GPS measurements, and the collected data identify an area between the Kashmir Valley and the Pir Panjal Range where accumulating strain could potentially generate a megaquake.

This region, which is in the western end of the Himalaya in northern India and eastern Pakistan, lies along a collisional tectonic boundary, where the Indian continental plate is smashing into the Eurasian plate, thrusting up the Himalaya. By measuring how fast points in the mountain ranges to the northeast and southeast of the Kashmir Valley are converging, the researchers identified the "locked" region of the Kashmir Himalaya, north of which the rocks are being compressed. As the strain builds, the rocks will eventually reach a breaking point and allow the Himalaya to slide over the Indian plate.

"We are NOT forecasting a Mw=9 earthquake in Kashmir. We have merely determined that earthquakes of this severity are possible."

In the past several hundred years small patches of the locked region have slipped in damaging but less extreme earthquakes than the maximum possible event now identified by geodetic data, Bilham said. If a 9.0 earthquake were to occur in Kashmir, he estimates the rupture would extend from the 2005 earthquake zone near Muzafferabad, Pakistan, to the Kangra 1905 earthquake zone in northern India—a distance of about 480 kilometers (300 miles)—and from the Zanskar Range to south of the Pir Panjal range—a distance of about 190 kilometers (120 miles).

Above and near this zone, structural damage would be severe, Bilham said. Moreover, landslides may block various rivers, resulting in temporary lakes and subsequent catastrophic floods downstream outside the Kashmir Valley in the Punjab region of India, he cautions. The worst-case scenario would be a repeat of the 883 AD flood, which blocked the Jhelum River Gorge, resulting in the creation of a 15-meter-deep lake that flooded most of the Kashmir Valley. The flood alone would displace more than a million people and result in catastrophic interruption to food production, he said.

The death toll, both directly from the earthquake casualties and indirectly through flooding and food shortages, could be unprecedented, Bilham said. About 6 million people would be affected due to the collapse of buildings and civic structures, he estimated.

Despite highlighting these dire consequences, however, Bilham asserts, "We are NOT forecasting a Mw=9 earthquake in Kashmir. We have merely determined that earthquakes of this severity are possible."

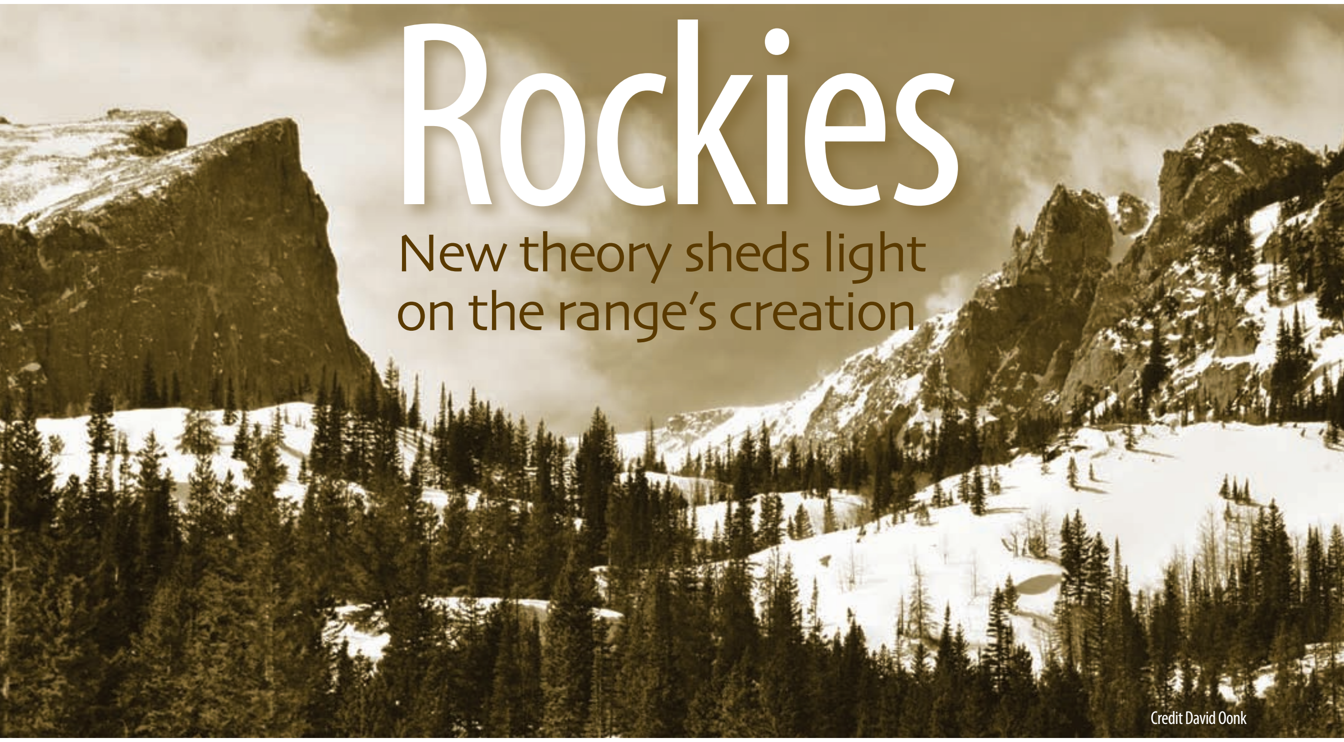
So why draw attention to the potential for earthquakes in this region?

Bilham believes that although currently India's building codes are adequate to protect its population, they are unevenly implemented. Advising civic leaders about the possibility of a major earthquake and enforcing building codes more strictly—especially for villages and affordable housing in cities—would mitigate more severe consequences.

Science has a duty to alert the region's inhabitants of what may occur, Bilham said. "That these megaquakes seldom occur does not mean we should ignore them," he said.

Fields of Flowers that grow in the Kashmir Valley.
Credit Majeed Wani.

The Birth of the Rockies



New theory sheds light on the range's creation

By Jane Palmer

Just how the Rocky Mountains formed in Colorado has always puzzled scientists. Some 1,000 kilometers (600 miles) inland and far removed from the nearest tectonic plate, the only comparable inland mountain range is the Himalaya, which scientists deduced were formed by the collision of the Indian plate with the Eurasian plate.

"But there really was no India slamming into North America," said CIRES Fellow Craig Jones. "So how the central Rockies have formed is an enigma."

Geologists have some understanding of how the southern and northern portions of the Rocky Mountain Range, one of the longest mountain chains on Earth, have formed, but have previous explanations of the creation of the mountain range in Colorado and New Mexico have proved problematic, Jones said.

Jones and his team; however, have proposed a new model that may give valuable insights into the long-standing riddle. Not only could their research explain the origin of the Rockies, it could also elucidate other geological phenomena: why a swath of gold, silver and other precious metal deposits stretches across Colorado, and why a marine basin deepened in the states of Colorado and Wyoming just before the Rockies rose. The sediments of this marine basin are the Pierre Shale, a layer of shale lying along the Front Range of Colorado. "Pierre Shale has nasty tendencies to bow up people's basements," Jones said. "Why more than a mile of this stuff was dumped into this area has been puzzling."

Previously scientists believed that the oceanic plate subducting, or moving under, North America rose from the mantle to rub against the continent's bottom all the way from the ocean to Colorado. The theory was this action as it moved eastwards pushed the landmass into mountains much like a rug piles up underfoot, said Jones. But the hypothesis just doesn't explain the facts, he said. "That model predicted removal of material that is still found to lie underneath California and Arizona," he said. "That in and of itself was unsatisfying."

The new model hinges on an unusually thick lithosphere—the stiff part of the earth's surface that make up the tectonic plates—under Wyoming. As the oceanic slab slipped underneath the Wyoming section, called the Wyoming craton, friction between the underlying slab and craton sucked part of the Southern Wyoming and Colorado downwards to form a basin, Jones said.

This basin in which Pierre Shale built up, amplified mountain-building forces far inland and forced the formation of the Rockies, he said. "A huge basin develops and all of a sudden these mountains come rocketing out of it," Jones said. "We end up with the counter-intuitive visage of mountains rising up out of a hole."

The hypothesis, if confirmed, could not only unravel the geological origin of the Rockies, but could also illuminate the mechanisms that have led to mountain ranges worldwide. "We are adding a new collection of processes that can control how mountain belts develop that previously haven't really been appreciated," Jones said. "Considering these processes might explain other puzzling mountain belts."

Earth Girth

Melting ice is expanding the planet's waistline

By Jane Palmer

Like many of its denizens, Earth is getting thicker around its middle. But it is not cookies and donuts that pose a problem for the podgy planet, but an age-old slimming elixir: water.

Ice loss from the Greenland and Antarctica icesheets that injects the oceans with more fresh water drives the phenomenon, says CIRES Fellow and aerospace engineer Steve Nerem.

"If you imagine Earth is like a soccer ball and you push down on the North Pole it would bulge out at its 'equator'," he said. "So Earth ends up looking like a slightly squished ball."

The change in Earth's shape reflects the redistribution of mass on the planet and, as gravity depends on mass, Earth's gravity field changes also, Nerem said. Scientists can measure this variable from satellites. Data from the Gravity Recovery and Climate Experiment (GRACE)—twin satellites launched in 2002 that make detailed measurements of Earth's gravity field to monitor changes in ice mass, the amount of water in the ocean and losses in continental water—enabled the researchers to test a theory that the ice loss was changing the planet's shape.

TheScience

Ice loss from Greenland and Antarctica sends more water into the oceans leading to a "fatter" Earth.

Using the GRACE values for ice loss in Greenland and Antarctica, Nerem and CIRES Fellow and physicist John Wahr, predicted how that ice loss has changed Earth's shape since 2002, and their calculations agreed with the changes recorded by laser-ranging measurements from a variety of different satellites.

"We found that Greenland and Antarctica cause most of this change," Nerem said.

The two regions are losing a combined 382 billion tons of ice a year, which means Earth's waistline is growing at about 0.7 centimeters per decade, Nerem said.

From the time scientists first began measuring Earth's shape, they've noted it's not a perfect sphere, Nerem said. The spinning of the planet means, just like any non-rigid spinning object, material tends to move out to the equator. "So there is more mass along the equator than there is at the poles," he said.

Most of the time the scientists have been taking measurements of its shape, Earth has been changing from this elliptical, or oblate shape, to a rounder one as it readjusts to the end of the ice age 20,000 years ago, Nerem said. Since the downward pressure of land-based ice has reduced as the ice melted, the land underneath has "rebounded" causing Earth to become more spherical, he said. "It is a bit like a sponge, it takes a while to come back to its original shape."

In the mid-1990s that trend changed; however, as the planet appeared to start flattening out again, Nerem said. Puzzled by this observation, the scientific community came up with theories as to why this might be the case. "But a lot of it was speculation, albeit informed speculation," he said.

That was until the launching of the GRACE satellite mission. Using the high-resolution GRACE dataset, Nerem and Wahr were able to conduct their experiment confirming the relationship between ice mass loss and the shape of Earth. But this Nerem says is only a starting point. "People have started to suggest that the melting in Greenland and Antarctica has started to affect Earth's rotation," Nerem said. "That is another thing to think about."

The Greenland Ice Sheet.
Credit Konrad Steffen

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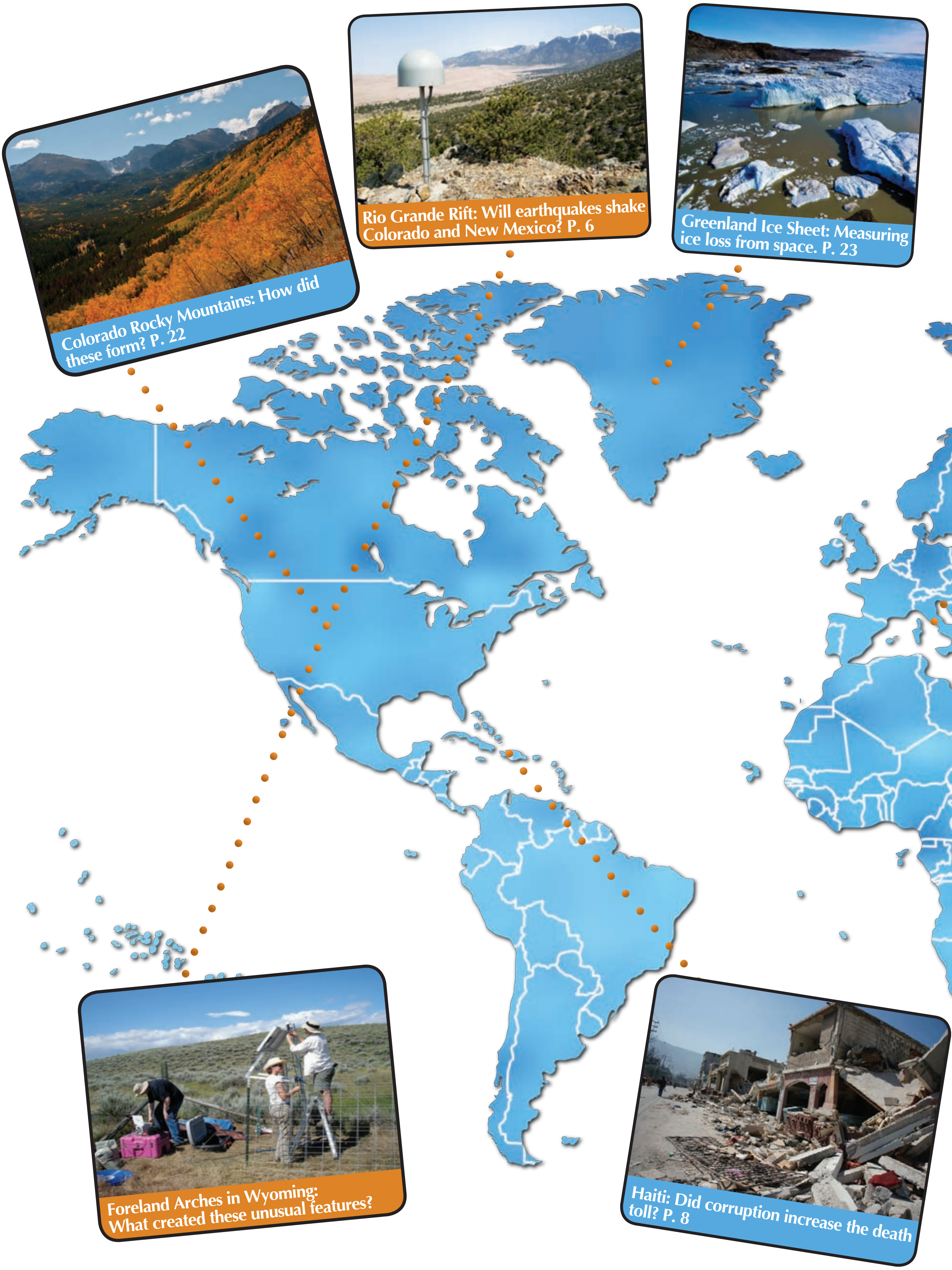
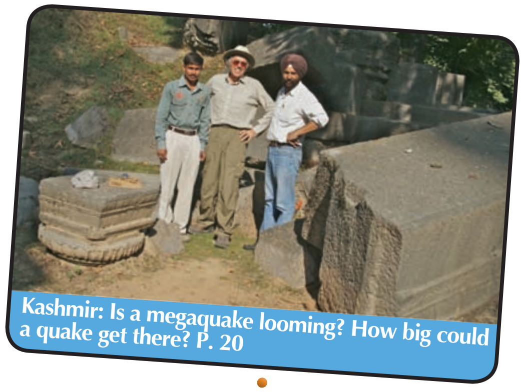


Italian Appenines: What makes them that shape? P. 10



Kashmir: Is a megaquake looming? How big could a quake get there? P. 20

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Himalayas: Do lakes atop glaciers accelerate ice loss? P. 18

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