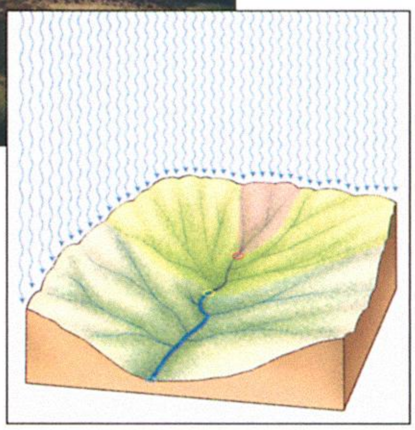
Quartz grains altered by cosmic rays are forcing geologists to reevaluate which forces shape landscapes and how fast they operate

Subtleties of Sand Reveal How Mountains Crumble

Crowding the windowsill in Jim Kirchner's office is a heap of cotton sacks bulging with tiny pebbles, dirt, and sand scooped from a clear mountain stream in Idaho. Hidden in each of these sediment samples are a few rare atoms called cosmogenic nuclides. Kirchner intends to find and count these atoms, and when he does, he'll be able to figure out how fast the rugged landscape of central Idaho has been wearing down over the past 10,000 years.

Kirchner, an earth scientist at the University of California (UC), Berkeley, is one of a couple dozen researchers worldwide who are using cosmogenic nuclides to study long-term erosion rates, a tool that has enabled them to paint a portrait of landscape formation with previously unparalleled resolution. Barely out of its infancy, this technology has already spawned a slew of applications, from examining the sustainability of agricultural practices to decoding signals of global climate change.



Cosmic cues. Sediment in Idaho rivers (*above*) revealed history of surrounding watersheds (*right*), thanks to changes wrought by cosmic rays.

"The work is revolutionizing our quantitative understanding of the Earth's surface," says Paul Bierman, a geomorphologist at the University of Vermont in Burlington. A pioneer in the emerging field, Bierman has helped develop the technique in areas ranging from the deserts of Namibia to the mountains of Tennessee. "This field is fascinating because it's still in its youth and it can still be used to tackle problems that people have never made a measurement on," he says.

The budding research is based on cosmogenic nuclide dating, a procedure that scientists have used for about 15 years to determine how long a chunk of matter such as a boulder or an outcrop has rested on or near Earth's surface. Such "exposure ages" have helped them pin dates on items as diverse as antarctic meteorites, ancient earthquakes in Montana, and glacial advances in Tibet.

In theory, cosmogenic dating is simple. Cosmic rays—which are constantly bombarding the planet—occasionally collide with nuclei in the atoms of certain minerals, producing rare isotopes, or nuclides. Although the rays can penetrate a meter or two through rock or soil, most nuclide production occurs within a half-meter of the surface, decreasing exponentially with depth. The longer a rock is exposed, the more nuclides it accumulates.

The theoretical leap from exposure ages to erosion rates came early. In 1985, two scientists at UC San Diego, Devendra Lal and James Arnold, proposed that cosmogenic nuclide concentrations in sediments should correspond to the erosion rate of the material that shed them. The team reasoned that as rock and soil erode from Earth's surface, deeper lying materials that were once shielded from cosmic rays become increasingly exposed. The slower the erosion rate, the greater the accumulation of nuclides.

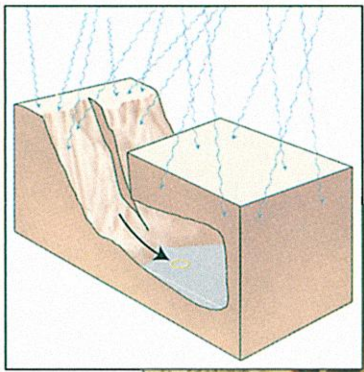
In 1995 and 1996, three studies reported by independent teams launched the cosmogenic erosion rate bonanza. The teams tested the notion that they could estimate the average long-term erosion rate of an entire catchment or watershed from concentrations of cosmogenic nuclides in quartz-rich sediment plucked out of the watercourse draining the catchment.

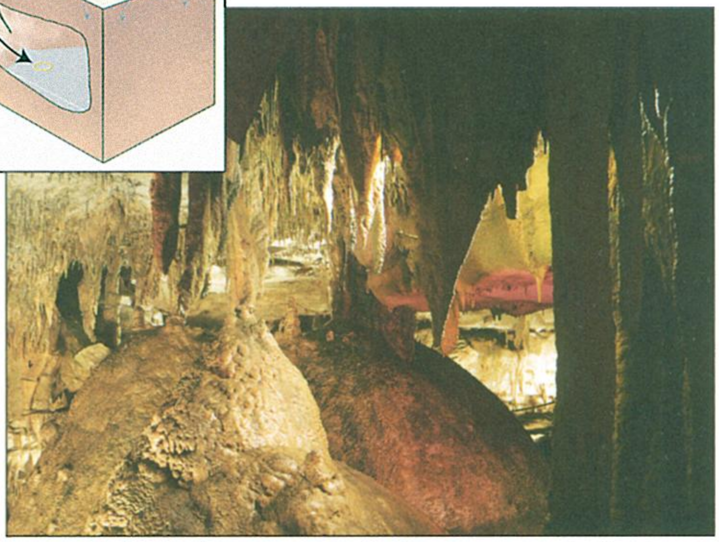
Quartz is a near-perfect material for erosion rate analysis. A hard and stable crystal made of silica (SiO_2), it's one of the most common minerals in the world and is abundant in rock and sand. Cosmic rays that strike quartz can transform its oxygen atoms into ^{10}Be and silicon atoms into ^{26}Al, unstable isotopes (radionuclides) of beryllium and aluminum. The new sampling technique regards hillsides as conveyor belts that funnel quartz and other eroded materials into streams and the waiting hands of geologists. "By picking up a handful of sand, you've collected a half-million grains that come from all over a catchment," says Douglas Burbank, a tectonic geomorphologist at UC Santa Barbara. "It's a very potent integrator of the information and obviously far more efficient than sampling hundreds of outcrops."

Sediments usually flush quickly through a watershed, so the sprinkling of new cosmogenic nuclides this eroded material acquires while tumbling downhill and downstream is generally insignificant when compared with the nuclides accumulated during the much longer time span the material lies on or near Earth's surface. It's this time span that the concentration of nuclides in a sediment sample measures, and it varies from sample to sample, ranging from about 1000 to 100,000 years.

Scientists who study the evolution of

CREDITS: (LEFT TO RIGHT) JIM KIRCHNER; ILLUSTRATION: C. SLAYDEN the landscape are bubbling with enthusiasm for their new tool. A key reason is that this 100,000-year range spans the era during which the forces of erosion shaped much of the modern landscape. "We've known for years how to measure how old rocks are," says UC Berkeley's Kirchner. "What cosmogenics now allows us to do is to tell how old the hills are, how old the valleys are, how fast the Earth's surface is evolving. This is a whole class of questions we can answer much better now than we ever could before."





Gimme shelter. Sediment swept under the cosmic-ray umbrella of Mammoth Cave rewrote a key sequence of Ice Age events.

Before long Kirchner will take the sediment samples piled in his window downstairs to his laboratory, where they will be separated, crushed, boiled in phosphoric acid and then in hydrofluoric acid, and finally reduced to small, powdery flecks. Kirchner will drive these precious powders 65 kilometers south to Lawrence Livermore National Laboratory, home to one of only two accelerator mass spectrometers in the country powerful enough to extract the information Kirchner needs. The other spectrometer resides at the PRIME Lab at Purdue University in West Lafayette, Indiana.

What happens next is testimony to extraordinary recent advances in spectrometers and the skill of the scientists who operate them. To tally ^{10}Be atoms in each of the Idaho samples offered by Kirchner, the Livermore spectrometer hurls them down its long tunnels at speeds of up to 80 million kilometers per hour. If they had to, scientists at Livermore say, they could tune this machine to pick out as few as five atoms of ^{26}Al or ^{10}Be in backgrounds of 10,000 trillion (10^{16}) atoms, although typical concentrations are 1 to 10 parts per trillion.

Working with such infinitesimal numbers can be tricky, however. Burbank warns that researchers must carefully choose study areas to avoid garbling the message of nuclide concentrations. Data analysis assumes that quartz is evenly distributed in the landscape, yet this is not always the case. Streambed samples ignore boulders and gravel, important products of erosion where landslides have occurred. In some catchments, a complex history of sediment burial, exposure, and reburial simply defies interpretation. Finally, Burbank cautions, cosmogenic analysis is so time-consuming and expensive that researchers may not be able to afford enough data to draw rock-solid conclusions. (It costs about $1000 to transform a sediment sample into a point on a graph, Kirchner estimates.) "You don't have the luxury of trying to test alternative interpretations rigorously," Burbank says. "That's a tough restriction."

With those caveats in mind, however, researchers now have a good tool for determining how fast erosion happens. The early results contain some surprises. Kirchner was startled when the nuclide concentrations in the sediments he drew out of streams in 37 different catchments in Idaho's mountains revealed erosion rates over the past 5000 to 27,000 years that averaged a whopping 17 times higher than modern-day rates, a finding he reported in the July 2001 issue of *Geology*. After ruling out climate change and other factors, Kirchner concluded that the huge discrepancy must be due to catastrophic erosion events (triggered, for example, by devastating wildfires followed by massive flooding) so rare that decades of regular observations are unlikely to spot them. "What you see when you look at erosion in those mountains from day to day bears no resemblance to the long-term average," Kirchner says. One lesson to be drawn from this study, Kirchner suggests, is that in young, dynamic mountain ranges, engineers may be greatly overestimating the time it will take reservoirs to fill with debris should one of these catastrophic events occur during the reservoir's lifetime.

Cosmogenics can also reveal notes from underground, as in Darryl Granger's "burial dating" of gravel and sand that washed into caves thousands of years ago. Burial dating assumes that when sediments enter a cave that's deep enough to shield them from cosmic rays, they quit accumulating cosmogenic nuclides. By analyzing the slow decay of ^{26}Al and ^{10}Be in buried sediments from Mammoth Cave in Kentucky, Granger—a geomorphologist at Purdue University—has traced a 3.5-million-year history of the cave and the Green River. Earlier studies had unraveled the sequence of Mammoth Cave's formation, but not the timing. Granger's work tied the cave's history to the geological history of the Green River and the regional climate record. One of his several surprising discoveries was that the finger of the Laurentide ice sheet that dipped into Kentucky to form the Ohio River arrived 1.5 million years ago, 700,000 years earlier than previously thought. Granger's study was reported in the July 2001 *Geological Society of America Bulletin*.

A number of researchers are using cosmogenics to tackle questions with more immediate environmental and economic consequences. In Sri Lanka, where 200 years of intensive farming have stripped much of the native rainforest from the island's highlands, a group led by Friedhelm von Blanckenburg—a geochemist then at the University of Bern, Switzerland—used the technique to measure long-term erosion rates in remnant forest patches. When the team compared these natural long-term rates with modern-day rates generated by agricultural practices, they found that cultivation had increased erosion a staggering 20- to 100-fold. The group presented its results last month at a meeting of the American Geophysical Union.*

Meanwhile, Arjun Heimsath, a geomorphologist at Dartmouth College in Hanover, New Hampshire, is looking at the other side of the coin. By analyzing cosmogenic nuclides in sediments and bedrock, he is studying how quickly new soil is produced from the bedrock that underlies soil on hillsides. Heimsath hopes to use his work to create models that will predict how climate change and management practices affect soil production and erosion.

By clocking and measuring long-term erosion rates, scientists can now begin to understand the forces that drive them. Some

* AGU 2001 Fall Meeting, San Francisco, 10 to 14 December.

studies have produced unexpected results. Only a decade ago, for example, many geologists assumed that as the climate grows warmer and wetter, erosion and chemical weathering (the chemical breakdown of soil and rocks) accelerate. But this notion has itself been slowly eroding. Clifford Riebe, a geomorphologist at UC Berkeley, has used cosmogenics to produce some of the first quantitative evidence that challenges the old assumption. When he compared weathering rates with long-term erosion rates at seven sites that span wide climate ranges in California's Sierra Nevada mountains, Riebe found that erosion and weathering did indeed go hand in hand but that climate had little effect on either. "Given that chemical weathering gets its name from weather," Riebe says, his results "came as a surprise."

Instead, Riebe discovered, erosion was swiftest on steep slopes near geologic faults or river canyons—evidence that tectonic activity eclipsed climate in driving erosion and weathering. Extrapolated to a global scale, that conclusion bolsters a 13-year-old theory that the uplift and erosion of the Himalayas—and the ensuing consumption of atmospheric CO_2 by chemical weathering reactions—triggered a global cooling that began about 40 million years ago. Riebe is now roaming from the rainforests of New Zealand to the deserts of Mexico to see whether tectonics dominates weathering rates even in those extreme climates.

As cosmogenic studies of erosion move out of the hands of specialists and into more widespread usage, new applications are blossoming. Researchers like Vermont's Bierman readily rattle off long lists of their plans and predictions for future research. "Overall, what keeps this exciting for me is [applying the techniques to] problems that we otherwise haven't been able to solve," Bierman says. "It's not an incremental learning experience. It's a major learning experience."

–LIESE GREENSFELDER

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BIOENGINEERING

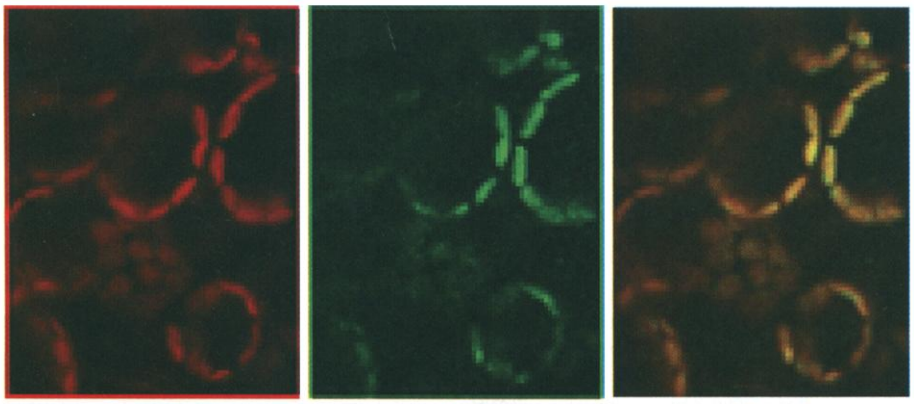
Plant Scientists See Big Potential in Tiny Plastids

Tinkering with plant cells' second genome could boost photosynthesis or turn plants into drug factories

When it comes to genetic engineering, the genes inside the nucleus get all the attention. But plants have an unassuming second genome inside tiny organelles called plastids. And although this small, circular genome carries far fewer genes than its nuclear counterpart, researchers say its potential for genetic engineering far outstrips its size.

The plastid genome arose some 1.5 billion years ago, when the ancient ancestors of modern plants are thought to have engulfed photosynthetic bacteria and put them to work manufacturing food. Over time, many of the original plastid genes slipped into the nucleus, but a small genome with about 100 genes remains. Plants now contain undifferentiated organelles that can diversify into a number of specialized plastids, each of which carries this secondary genome. The most famous member of the plastid family is the chloroplast, the photosynthesis factory. Others include the amyloplasts, which store starch, and the oil-producing elaioplasts.

Because plastids present an easy way to produce proteins in high concentrations and offer unique access to the photosynthetic machinery, some plant scientists believe they offer some of the best opportunities to make transgenic crops that grow more efficiently, for instance, or that manufacture medicines. "You get high yields" of proteins produced by plastids, says emeritus Harvard molecular biologist Lawrence Bogorad. And when it comes to boosting photosynthesis, "you can probably do things in the chloroplast compartment that you can't do in the nuclear compartment," Bogorad says. But transforming plastids is technically tricky, and the field, although growing, remains small.



Neon plastids. When inserted into the plastid genome, a gene for a fluorescent marker protein (GFP) signals a successful transformation.

CREDIT: P. MALIGA/RUTGERS UNIVERSITY

The promise of plastids

For years, researchers have dreamed of tinkering with the genes in plants to turn them into living, photosynthesizing drug factories. If plants could be engineered to pump out lots of therapeutic proteins, these could be isolated and made into medicines. But, although creating transgenic plants by altering their nuclear DNA has become routine, it remains extremely difficult to get these plants to produce the desired protein—say, antibodies against herpesviruses or enzymes for diagnostic kits—in large quantities. In most such plants, the new protein accounts for a paltry 1% of the plant's total protein output, although levels as high as 25% have been reported in a few exceptional cases.

Transgenic plants made with altered plastids are much more productive than nuclear-engineered plants. Last year, geneticist Henry Daniell of the University of Central Florida in Orlando inserted a gene cluster for an insecticidal *Bacillus thuringiensis* toxin into the chloroplasts of tobacco plants; the chloroplasts churned out vast amounts of the crystallized protein—45% of the cell's total protein output. Levels routinely reach 5% to 15% in the latest studies, says geneticist Pal Maliga of Rutgers University, New Brunswick, New Jersey.

Engineering the plastid genome has additional advantages over nuclear transformation. For example, the risk that foreign genes introduced into plastids will spread to other plants is much lower than the risk that nuclear genes will make such a leap. This is because plastid DNA in most crop species is transmitted only from generation to generation through the ovules, the plant "egg," not through pollen, the plant "sperm"—just as animals' mitochondrial DNA is passed down only through the egg. Plants produce