Rock 'n' roll. Gray concrete "smart rocks" and colorful radio-tagged "tracer rocks" await a bumpy ride.

GEOMORPHOLOGY

How to Build a Smarter Rock

Predicting when and where rivers will move gigatons of rock and sediment has proved a murky problem; a new generation of electronic smart rocks could clarify matters

In April 2011, one of the largest and longest floods on record coursed down Reynolds Creek, a steep mountain stream that runs through sagebrush meadows and aspen groves in southern Idaho. Fed by snowmelt from the Owyhee Mountains, the floodwaters tore down river banks and sent a jumble of rocks tumbling downstream.

Some of them were no ordinary pebbles. More than 200 were brightly painted natural rocks that contained radio tags inserted into specially drilled holes. Four others were "smart rocks" made of sleek brushed aluminum. Researchers had crafted each metal rock to mimic a natural stone's shape and density, and then inserted custom-made electronics that could measure and record movements 512 times per second. It was the smart rocks' first trip down a real river; previously, they'd been coddled in a carefully controlled laboratory river called a flume. Their mission: to help researchers better understand how waterways move tons of rock and other sediment downstream.

It is no small issue. Worldwide, rivers transport an estimated 13 gigatons of sediment each year, more than any other force on Earth besides humans. But predicting where that material will end up has proved difficult. Current models for predicting the movement of coarse sediment in a river—some based on equations developed by Albert Einstein's son Hans in the 1950s—are frequently off by at least an order of magnitude, says Joel Johnson, a geomorphologist at the University of Texas (UT), Austin. That's a problem for engineers trying to protect bridges, dams, and levees from shifting flows, and ecologists trying to plan expensive river restoration projects. Researchers, meanwhile, have struggled with the difficult and dangerous task of finding out what's really going on during floods, when rivers do most of their heavy lifting. That's why Johnson and other researchers are pioneering a new approach: building increasingly sophisticated smart rocks that are intelligent enough to take measurements on their own. The devices, Johnson says, are "a killer app" that gives scientists a unique glimpse of river dynamics "from the point of view of the rocks."

Chasing marbles

Deploying objects to track shifting river sediments is not a new idea. In the 1960s, the influential late geomorphologist Gordon "Reds" Wolman of Johns Hopkins University in Baltimore, Maryland, dropped marked marbles into a nearby stream, then noted how far they moved. He continued to find the marbles into the 1980s; he even offered students six beers for every marble recovered, recalls fluvial geomorphologist Peter Wilcock of Johns Hopkins. Decades later, he says, one student found a stash, but "I don't believe they ever received the payout. … The link to immortality was presumably sufficient compensation."

Not your average rock. Custom-made aluminum rocks hold sophisticated electronics that help researchers pinpoint forces that send them tumbling.

Since then, researchers have tried to make it easier to find such tracers by using rocks embedded with iron magnets or even radio-frequency identification tags similar to those used to identify lost pets and track merchandise. Those tracers, however, can reveal only how far an object travels, not fine-scale information about the forces that set rocks tumbling or what happens along the way. "We know the rocks go downstream—we're not idiots," says Joanna Curran, a hydrologist at the University of Virginia in Charlottesville. But because sediment transport is a nonlinear physical process, small mistakes in input measurements can result in disproportionately large output errors in mathematical model predictions. Improving the models means getting down to nitty-gritty details, including better measurements of dozens of variables ranging from large-scale channel slopes and water velocities to minute interactions between a single grain of sand, the water flowing around it, and the river bed. Sediment scientists, Curran says, want to measure forces down to the level of a rock's "skin."

Now, advances in materials and electronics are making that possible. In one project, Curran is helping undergraduate students use a three-dimensional printer to make plastic smart rocks about 7.5 cm across. Each has

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sensors on six sides and a gyroscope that measures the rock's orientation. The gear is helping Curran gain insight into a key river variable: shear stress, the same side-slipping force that tectonic plates produce as they slide past one another, or if you run your hand along a brick wall. Rocks of different sizes and shapes respond differently to the shear stress created by flowing water, Curran says. It takes more shear stress to move an angular rock than a rounded one, for example. To quantify such differences, Curran has been dropping her fake stones into a flume in her lab. They transmit data to a computer through plastic tubes attached to the rocks. Eventually, she'd love to untether her rocks and release them into a real river—to better understand, for example, the best way to take down a dam and restore natural sediment flows. But she's worried about the cost: At roughly $250 apiece, "these are expensive little things" and she's afraid to lose them.

A rocky start

Such fears, however, didn't stop UT's Johnson from leaving his four aluminum rocks—which cost roughly $800 apiece—at the mercy of a raging Reynolds Creek early last year. After putting his creations in the remote stream, he and doctoral student Lindsay Olinde waited for the floodwaters to rise and then fall as the snowpack petered out. Then, in July 2011, Olinde hiked back in with a field assistant and began searching for both the hundreds of radio-tagged stones—which cost only about $5 apiece, not counting labor—and Johnson's four metal mimics. A previous study had suggested that most faux-rocks wouldn't move more than 100 meters downstream. After a week of searching with an antenna that chirped in response to the painted, radio-tagged rocks, Olinde had found only one within the 100-meter reach. "I thought my equipment was broken," she says.

That was just the beginning. Over the next 5 months, she took four more rock-hunting trips, sometimes scrambling through the steep canyons. By November, her gloves were freezing to the icy boulders, and she was hearing the chirp of the radio tags in her sleep. Ultimately, she located roughly 150 of the radio-tagged stones. One-half had moved more than 2500 meters downstream, and a few had tumbled more than 6440 meters. "We had fist-sized particles move almost 7 kilometers," Johnson says, in awe.

Olinde had a similar struggle finding the four aluminum rocks. The chirping radio tags do not work in close proximity to aluminum, so Olinde had to use a metal detector instead. But the creek turned out to be full of metal objects such as old ranching equipment, making the detector all but useless. Finally, a rancher's dog found the first smart rock in September, more than 2000 meters downstream from where it had been deposited. Olinde spotted a second by accident in November, where it lay in an icy pool 900 meters downstream, glinting in the sun. The other two are still missing in action.

Back at the laboratory, the researchers were relieved to find that the two survivors had collected data despite their rough rides. But relief turned to disappointment when they discovered that the batteries—supposedly strong enough to survive at least a month—had died after just 40 hours. During that brief period, the smart rocks very accurately recorded no movements whatsoever, Johnson says. "We are certain that those rocks stayed still," he says ruefully. "In hindsight, we should have done a lot more testing. … I was banging my head against a wall."

All was not lost. By combining data on the radio-tagged, natural tracer rocks' unusual distribution with geographic information system data on local topography, Olinde and Johnson are studying how variables such as the steepness and width of the creek channel influenced where the tracers ended up.

Brains vs. brawn

Inspired by last year's experiment, Olinde has been testing a new kind of smart rock along Reynolds Creek. It is somewhat cruder than Johnson's aluminum models, but cheaper and sturdier. She makes them by filling rubber molds of natural rocks with wet concrete, and then inserting a $100 accelerometer about the size of a matchbox. Its penny-sized battery lasts for months, allowing the accelerometer to record the rock's spatial orientation along three axes every 15 minutes. At that rate, Olinde can't see how moment-to-moment forces influence movement, but she can see how the rocks shift in concert with changing water levels. After inserting radio tags into the rocks, she spray-paints them with neon colors. (The results, she jokes, look like artworks created by a cross between British landscape artist Andy Goldsworthy and the American pop-surrealist Andy Warhol.)

Earlier this year, Olinde released 73 of her new "not-so-smart" rocks into Reynolds Creek, along with 1200 simpler, radio-tagged versions. When the spring floods came, antennae she had installed along the river tracked the rocks as they rolled by. Later, she and a team of assistants searched a 10 km stretch of creek and recovered 33 of the 73 more sophisticated sensors. Unlike Johnson's aluminum rocks, however, the majority of Olinde's concrete versions had continued to collect data throughout their journey. "Joel's rocks are the fine Renaissance gentlemen," she jokes. "My rocks are the burly mountain men."

Olinde is still analyzing the data, but one thing is clear: Current sediment transport models don't do a good job of predicting the rocks' rests and motions. Other researchers agree. The Reynolds Creek work "is a very well done study," Curran says, and "it should add to the body of knowledge on when and why a large cobble moves in a mountain stream." But it also highlights the potential value of scaling up the use of smart rocks to study waterways of all shapes and sizes, from small mountain streams like Reynolds Creek to continent-spanning rivers like the Nile. And it demonstrates the need for even more sophisticated sensors that can reveal the role played by variables like bottom roughness or water depth. "This is the challenge that remains, … moving from smart to genius rocks," Curran says.

That's a goal Johnson says he'll continue to try to reach. He's working on more robust models of his aluminum rocks and is considering a change in strategy to take into account the rocks' limited battery power: waiting until a flood rises and then tossing the rocks in to record the tumult, even if only for a few hours.

In the meantime, Olinde hopes to help other smart rock researchers avoid problems by writing a methods paper that details the obstacles she encountered and how she overcame them. And she is getting ready to mix another batch of concrete for her sturdy, if less talented, rocks. **–EMILY UNDERWOOD**

Before the flood. Geomorphologist Lindsay Olinde plunks her faux rocks into Reynolds Creek in Idaho.

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