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Physicists Invading Geologists' Turf

Forum

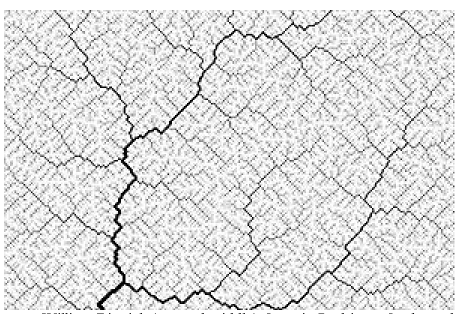
- Join a Discussion on The Environment

By JAMES GLANZ

Dr. William Dietrich has walked, driven and flown over more natural landscapes than he can remember. As a veteran geomorphologist, he has studied how everything from the plop of a raindrop to mighty landslides and geologic uplift have shaped the face of the planet.

So when he admits to the growing influence on his field of an insurgent group of physicists, mathematicians and engineers with all-encompassing mathematical theories but hardly any field experience, the earth almost begins to rumble.

Geology, a field that has always gloried in descriptive detail but has had less luck deriving mathematical generalizations, is changing. Invigorated by satellite maps, supercomputers and fresh ideas from physics, researchers are deriving sweeping theories without ever having put hammer to rock.



William Dietrich (top and middle); Ignacio Rodriguez Iturbe and Andrea Rinaldo

Though geologists typically investigate the landscape up close, hammer in hand, scientists are now applying the theories of physics to draw more abstract conclusions. The photograph above shows a network of folds within folds in clear-cut mountains in the Oregon Coast Range. A computer, programmed to analyze elevation data, pictures a similar landscape in a different way, producing an image of a watershed in northern California, right. Without reference to any specific landscape, a computer calculated this schematic river network by assuming that a river will flow in the ways that require the least expenditure of energy.

The trend is unsettling to some old-school geologists, but even they concede that the work has prompted new research in traditional academic circles. While the new researchers have not yet proved that the shape of every hill and dale can be predicted by simple equations, they have at least raised the question of whether landscapes are sculptured by something other than a reductionistic accumulation of forces.

"In some ways, they irritate us," said Dr. Dietrich, a professor at the University of California in Berkeley, speaking for university and government geologists.

But Dr. Dietrich added that the new, physics-inspired theories of landscape formation, which have found success by ignoring the detail-oriented approach of traditional geology and focusing instead on the earth's overall patterns, are "a way of discussing some sense of regularity in what otherwise is a very messy world."

"I've come to appreciate the perspective," he said.

Inspired by ideas long familiar in physics, and fueled by the recent availability of high-quality satellite maps of much of the planet's surface, the new approach turns the earth sciences on their head, asserting that the most prominent structures on the surface of the planet are shaped not by just local factors, as had been thought, but by the most general properties of physics and mathematics.

The goal of the new research, said Dr. Andrea Rinaldo, a mathematician and engineer at the University of Padua, is to uncover "a fundamental, hidden order that manifests itself across a wide range of scales," seeking universal laws amid the welter of processes, as physicists do with their theories.

By contrast, the traditional view concentrates on how river basins, mountain slopes and badland canyons emerge as specific forces like weathering, erosion and sedimentation do their work throughout the eons at every point of the terrain.

But the grand patterns that seem so consistent from one range of hills or network of rivers to the next, such as the precise ways in which tributaries snake around and multiply in number in the upstream direction to drain an area of a certain size, have always been a bit mysterious from the vantage of traditional geology. It is as if voters in every democracy in the world opted to divide their countries into the same number of provinces or states, even though there was no international campaign to do so.

Enter the theorists.

They find strikingly similar patterns emerge from simple approaches like assuming that the paths that tributaries cut are those that minimize the energy expended by all the water running down the basin. The principle that nature often takes the path of least resistance has helped physicists cut through other complex phenomena.

"We've taken the point of view that there are certain generic processes, and therefore equations" that describe them, said Dr. Daniel H. Rothman, a professor in the department of earth, atmospheric and planetary sciences at the Massachusetts Institute of Technology.

For example, Dr. Ignacio Rodriguez-Iturbe, a professor in the department of civil and environmental engineering at Princeton University, said that "regardless of the infinite variety that you find in river basins, there are some scaling laws that hold amazingly well for the different ones." He cites the structure of tributaries as a prime example of that kind of scaling.

And behind laws like those, said Dr. Donald L. Turcotte, a geophysicist at Cornell University, could lie manifestly practical insights on subjects like land use, helping planners predict the frequency of large landslides and inland floods or estimate long-term erosion -- all questions that are extremely difficult to answer with straightforward geology.

"There's a lot of pretty useful material that comes out of all that," Dr. Turcotte said. "I think it's one of the frontiers of science."

The scientists also say that geology gives them an exciting new field of play for mathematical techniques that were developed in more mature areas of research -- like the theory of how solids melt or metals become magnetized -- where rapid advances are now hard to come by.

But the incursion of high-flown physics ideas into geology has been driven by more than just the creative powers of the new theorists. What has largely freed them to think about landscapes without tramping over them is the recent availability of high-resolution maps of elevations along the earth's surface made by satellites and distributed by the United States Geological Survey and other government agencies.

Digital maps made with point-by-point elevation measurements obtained by satellite are available for most of the world with a resolution, or smallest discernable detail along the surface, of about three-fifths of a mile, said Peter Dodds, a graduate student in the mathematics department at M.I.T. who is working with Dr. Rothman. But large parts of the United States have been mapped to a resolution of about 100 feet, Dodds said, and better techniques, some of them relying on range-finding lasers for determining elevations are just coming into play.

"Traditionally, they've come from maps people have put together, partly on foot, partly on airplanes," Dodds said. "Now they're getting it straight from above."

Mathematicians like Dodds thirst for exactly the sort of data that those maps provide. He and other theorists pour the digital elevations into computers that compile statistics on the number of hills and mountains of every size in some landscapes -- from bumps to snowy peaks -- or all of the almost countless paths that water could take down a basin during a storm.

By comparing those statistics from landscape to landscape, the scientists try to find general rules governing the patterns that cover the earth's surface, and then explain why the rules should hold true.

It was a close examination of many river basin maps by Dr. Rinaldo, Dr. Rodriguez-Iturbe and others several years ago that ignited the current burst of research, said Dr. Jayanth R. Banavar, a physicist at Pennsylvania State University.

Given the elevation data, computers could trace the downhill paths that water should take from any point on the terrain of the basins, Dr. Banavar said. Not surprisingly, those paths drew out a dendritic pattern that branches ever more finely in moving up the basin from a central river past its tributaries, the tributaries' tributaries, and so on; and more finely still among the small channels in the hillsides that flow with water only when it rains.

That pattern is generally called a river network, but "one that has been derived just by looking at the rugged terrain," rather than the flowing water itself, Dr. Banavar said. But how can this be analyzed statistically?

Decades ago, geologists and hydraulic engineers used maps of ordinary rivers and streams to show that if a patch containing some of the smaller tributaries was expanded, as though with a zoom lens, it would look approximately like a patch of larger tributaries in the same basin.

Geologists had filed away that odd fact, but the physics-minded researchers showed, by analyzing the derived river networks on computers, that similar relations held to good accuracy for virtually every fold of the landscapes. The analysis showed that smaller sub-basins looked like larger basins, as long as the zoom was done properly.

"There are basins within basins within basins," Dr. Banavar said.

To make the correspondence precise, the basins had to be stretched slightly more in one direction, along the main basin, than across. And the difference in those stretch factors, expressed quantitatively as exponents in a set of power laws, gave the researchers a target to aim for when coming up with a theory to explain why the network patterns should be so reliable and widespread around the world.

Dr. Rinaldo and Dr. Rodriguez-Iturbe took as a hint the way that electrical current flows through a complicated set of wires and resistors. In that case, the current always distributes itself so that the amount of energy being dissipated as heat in the resistors is as low as possible. Perhaps, the researchers theorized, the channels etched in the landscape over the centuries formed patterns that allowed water to dissipate the least possible gravitational energy on its way downhill.

With the help of a simple but powerful erosion equation developed in part by Dr. Banavar and Dr. Amos Maritan of the International School for Advanced Studies in Trieste, Italy, the researchers could match the exponents if they made one further assumption: the landscape never quite etched its way to the minimum energy state, but got hung up in certain stable configurations it encountered on the way.

"The resulting network was in magnificent agreement with the observations," Dr. Maritan said.

The story does not end there, since Dr. Rothman and others are using ever sharper satellite data to search for deviations from the power laws, or to find whether some other overriding principle can explain the patterns.

But the practical implications of the work could already be substantial, since the stability of certain aspects of the patterns could yield clues into how an eroding landscape will and will not change in the future, helping planners estimate the impact of development or farming. The frequency of large floods and landslides could be closely related to the same patterns; large cataclysms of that kind are among the natural forces that rearrange landscapes.

A close understanding of how water shapes the terrestrial surface would also allow scientists to compare its statistical properties with the landscapes of Mars and determine whether they, too, were once shaped by water or something else.

For all the insights of the new research, geologists are far from abandoning their worldview. In fact, they too are using satellite data -- to perform detailed computer calculations of how rain and wind erode one particular landscape into another over time. But even there, Dr. Dietrich said, the physics-oriented researchers have inspired discoveries of order amid the reductionistic detail.

"The places where they accomplish that," Dr. Dietrich said, "will, I think, have a lasting effect on how we think about the planet."
