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Peering into the Crystal Fabric of Rocks

When you get right down to it, earthquakes and volcanoes have atomic-scale causes

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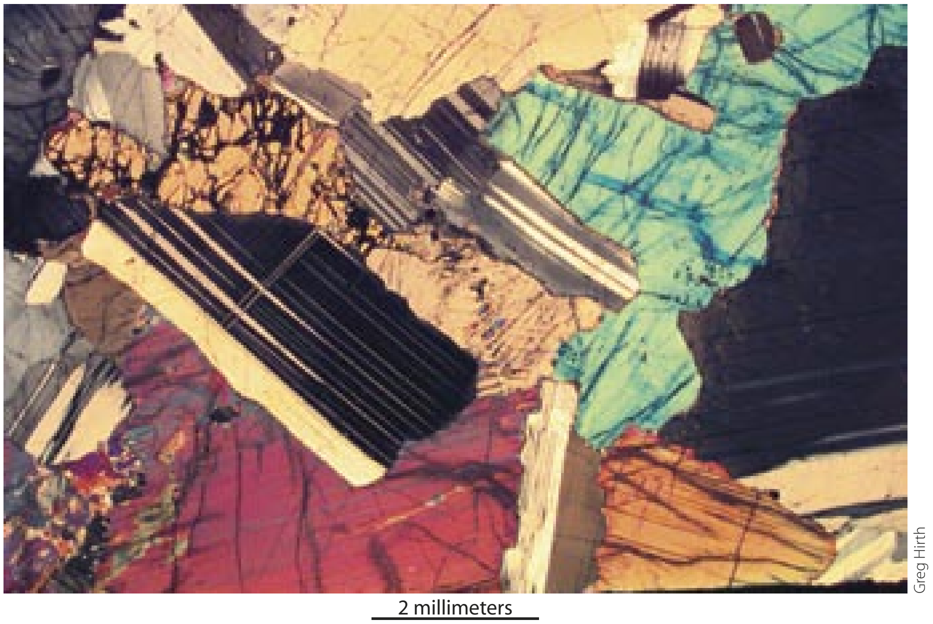
"Rock solid" is an oxymoron, to my way of thinking. Oh, the expression does have some truth in that minuscule, superficial portion of our planet where humans dwell. But the majority of rocks nearly everywhere else in the earth are continually changing their physical characteristics. Just below Earth's surface, rocks are constantly subjected to heat that causes them to flow like syrup, and to intense stress that causes them to crack like glass.

On a planetary scale, the flowing and breaking of rocks causes volcanism and earthquakes, which pose hazards to people. But on an even more fundamental scale, the face of the earth is continually shaped and reshaped because rocks *aren't* rock solid. They slide, crack, flow, and melt. These abilities underlie larger processes by which mountains and volcanoes are made, continents are rifted, new seafloor is created, and the great tectonic plates comprising Earth's surface are set in motion to collide or slide against each other.

It turns out that the same forces that affect rock formations across continents and ocean basins—heat and pressure—also affect the deformation of rocks on the microscopic scale. Rocks are composed of a fabric of crystals. Just the way a solid metal paper clip—when heat or force is applied—can bend, break, or stretch, so, too, can the crystal fabric within rocks.

The core of my research is to investigate the microstructures and micromechanics of crystals within rocks. My field of science, called rheology (from the



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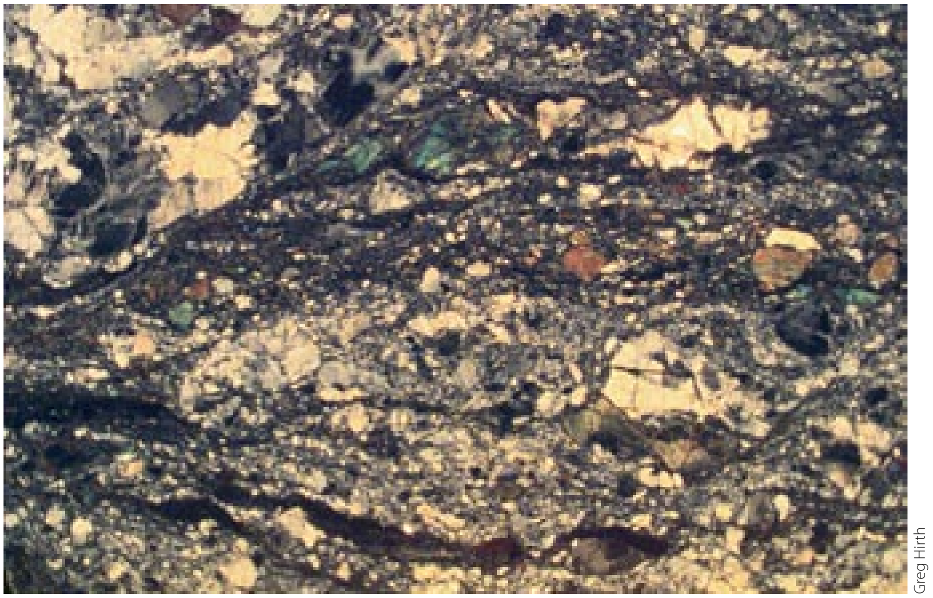
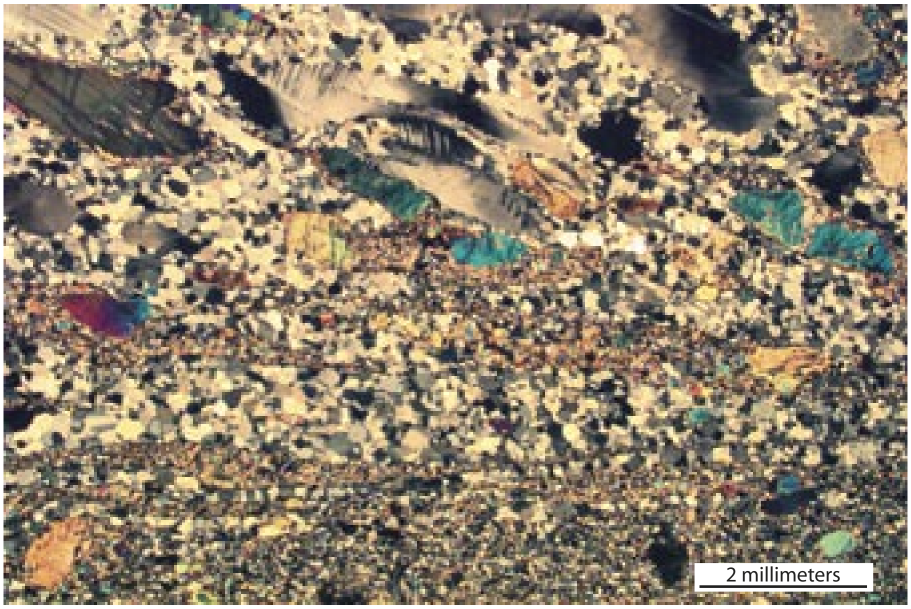


Greg Hirth

Using optical and electron microscopes, scientists can detect how crystals within rocks change their sizes, shapes, and orientations when the rocks are subjected to heat and stress. These atomic-scale changes can ultimately lead to earthquakes and volcanoes. Large crystals are evident in a photo of "undeformed" rock from the Indian Ocean seafloor (top). But (bottom), the crystals are broken and ground up in similar rock subjected to stress.



Greg Hirth

In this rock sample, heat has caused crystals to change shape and "flow" within the rock, which accommodates strain without causing the crystals to break.

Greek word *rheos*, meaning current), is the study of the flow of matter. Amazingly, understanding what happens on an atomic scale provides insights into what happens on a planetary scale.

From crystals to earthquakes

My work is similar to that of material scientists, who might examine the microscopic textures of bricks or steel to determine loads in house walls or fatigue thresholds in airplane wings. My friends jokingly call me a "rock psychologist," because I study the properties of rocks under stress and strain.

Heat and stress causes chemical and physical alterations and defects in the crystal structure of rocks. Under stress, atoms are pushed against other atoms, sending further ripples of changes down the line, like people crowding in subway cars. Chemical bonds break. The rocks' well-ordered lattice of atoms breaks down and rearranges itself.

In short, crystals change their size, shape, and orientation within rocks. Using optical and electron microscopes, we can detect these changes in rocks' crystalline structure. The changes we identify provide telltale information on threshold temperatures or stress levels at which the rocks' interior structure began to crack, flow, or melt. Thus, rheology holds the key to answering a fundamental question like "How deep into the crust will earthquakes occur?"

Flowing rocks

Near the surface, rocks are unconsolidated and porous. There's sufficient room to accommodate any force applied. It's like pushing a pile of sand. As a consequence, large earthquakes are infrequent.

But deeper down in the earth, there's less excess room to accommodate strain. The stress in rocks builds up. At a threshold point, the stress surmounts the strength of the rocks' crystal structure. Bonds between atoms break suddenly. The rocks crack and slide, releasing pent-up energy. The result is an earthquake.

Deeper in the earth, however, temperatures rise. The heat encourages some—but not all—of the atomic bonds within the rocks' crystal lattice to break, freeing atoms from their rigid atomic scaffolding to move momentarily. The atoms reorient themselves in relation to neighboring atoms, bonding with them in new alignments that actually change the shape of the crystal.

This movement of atoms within rock crystals (and the crystal shape-changing it causes) accommodates the strain on the rock, so that the stress never builds high enough to cause the rock to break. At lower temperatures, the same stress would shatter all the atomic bonds at once. At higher temperatures, the rocks "flow." At still higher temperatures the rocks liquefy, or melt.

This phenomenon of flowing rocks explains why earthquakes diminish deeper in the earth. Along plate boundaries, such as the San Andreas Fault in California, earthquakes are restricted to depths between 3 and 15 kilometers.

In the lab and in the ocean

To test these theories, we conduct experiments that subject various rock samples to temperatures and pressures they experience within the earth. By studying the microstructure of the rocks samples—before and after—we can map the changes in crystal structure that accommodate different experimental strains, and we can reveal much about the processes that determine the rocks' strength and vulnerabilities.

But these experiments use samples on the scale of one's pinkie finger and take place over the course of a day. Do similar microstructural changes occur in the "real" Earth, over distances of tens of kilometers and time spans of millions of years?

To confirm our laboratory experiments, we investigated rocks collected by the Ocean Drilling Program from the Indian Ocean. With support from the National Science Foundation (NSF), we examined both undeformed rocks and the same type of rock from deeper beneath the surface, where it had been deformed by heat and pressure.

These oceanic rocks are good models for validating experimental analyses of rocks because they are freshly made, with no previous history of deformation, and then they have been rapidly exposed to cold seawater, which effectively quenches them with their microstructure preserved.

Continental rocks, in contrast, are old and have been subjected to repeated shifts and traumas and exposed to high temperatures over their long histories. All these factors modify their microstructure, often blurring and overprinting records of their deformation.

We see similar microstructural changes in oceanic rocks and in our experimental samples. That gives us confidence that the microscopic rock behavior and mechanics observed in laboratory samples can sharpen our understanding of rock dynamics on a planetary scale.

Going against the crystal grain

With this confidence (and NSF support), we have applied a rheological approach to elucidate details of many other intriguing questions about the earth. For example, how is new ocean crust created at mid-ocean ridges? This process, which continually paves and repaves Earth's surface and creates new oceans and continents, starts on an atomic level when crystals within rocks in the mantle begin to melt.

How and when do rocks with different types of crystals melt? How does this melt dissolve the edges of other rock crystals to create pore space in which it flows? How do these microscopic rivers of molten rock coalesce, grow larger, and rise to the surface to form new oceanic crust? All these processes are ultimately controlled by basic, atomic-scale physical and chemical properties of rocks, which I have been investigating in collaboration with WHOI colleagues Wenlu Zhu, Peter Kelemen, and others ("Unraveling the Tapestry of Ocean Crust").

I have also been examining another intriguing and important microscopic phenomenon of flowing rock. When rocks' symmetrical crystal lattice breaks down, crystals begin to deform and flow in a particular direction. The rocks' crystal lattice eventually realigns—not symmetrically, but oriented in the particular direction that the crystals flowed in.

The phenomenon (called anisotropy) has important implications for scientists trying to learn more about Earth's interior using a primary tool: seismic waves. Earth scientists deduce a great deal about the characteristics of rocks within the earth by analyzing the speed of seismic waves traveling through them. But seismic waves will travel more slowly when they go against the crystal alignment, and faster when they travel in alignment with the crystal structure.

A new generation of ocean-bottom seismometers promises to lead to new discoveries about the shrouded inner workings of the inaccessible mantle ("Listening Closely to See into the Earth"). But a more detailed understanding of mantle rheology will be critical to interpret the new seismic data most precisely.

Life thrives between the cracks

More recently, we have also been applying rheological techniques to illuminate how hydrothermal vent systems evolve. These systems occur on mid-ocean ridges, where magma from Earth's mantle rises toward the surface and heats rocks below the seafloor ("The Remarkable Diversity of Vents").

Cold seawater percolates downward through cracks in the ocean crust and is heated up. The seawater reacts chemically with the rocks to create hot, mineral-rich hydrothermal fluids that rise and are vented at the seafloor, where they provide nutrients that sustain thriving communities of deep-sea life.

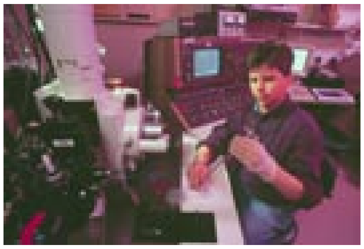
Once again, this entire biogeochemical cascade of events has a rheological foundation—the cracks and conduits within ocean crust that set the stage for the process. We have been investigating the micromechanics of cracking of peridotite in the face of the hot and cold temperature contrasts it experiences.

When peridotite cracks, it creates permeable pathways for seawater to percolate downward. The water chemically reacts with peridotite to create another type of rock, called serpentinite.

Serpentinite is a more slippery substance than peridotite, which may be an important factor in causing fewer earthquakes along faults in the ocean. With my WHOI colleagues Jian Lin and Jeff McGuire, we are exploring how we can use our knowledge of earthquakes in the oceans to increase our understanding of earthquakes on land, too. ("Earthshaking Events).

In addition, the chemical reactions that form the serpentinite from seawater may provide critical conditions for the development of some hydrothermal vents. Thus, the micromechanics of fractures in rocks and the evolution of permeability in oceanic crust will also play a key role in exploring a new frontier: the potential for a deep biosphere of microbial life beneath the seafloor. Microcracking continually creates new mineral surfaces that are exposed to fluids and microbes—creating the sites and conditions for the biogeochemical reactions that may sustain large communities of microbes ("Is Life Thriving Beneath the Seafloor?").

In the earth sciences, microscopic cracks can open entirely new vistas, and how matter flows turns out to matter quite a lot.



Greg Hirth spent much of his youth enthusiastically running around the woods of Ohio and the mountains of Colorado. He went to Indiana University to study political science with an idealistic goal of changing the role of politics in environmental affairs. But he quickly changed his major to geology, motivated partly by opportunities to work in the field. In his geology textbooks, Hirth read about the research of his father John, a material scientist. That spurred his pursuit of a Ph.D. degree in rock deformation at Brown University, where he met his wife, Ann Mulligan (now an Assistant Scientist in the Marine Policy Center at WHOI). Hirth came to WHOI in 1993, where he has pursued a myriad of research opportunities in the lab (particularly with colleagues at MIT), ocean, and field. He is particularly grateful for his colleagues' encouragement to go back to his roots and study geology in the field. Ann and Greg now enjoy gardening, following the fortunes of the Patriots and Red Sox, and the wilds of Cape Cod, through which Hirth also leads trips for the Cape Cod Bird Club.