PROFILE

Profile of Michael Manga

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Geology is about more than just rocks and other hard objects. Fluids play a major role in shaping the surface of not just Earth but other planets and moons as well. In fact, according to Michael Manga, a geologist at the University of California, Berkeley, just about everything in Earth can be viewed as a fluid. "The atmosphere and the oceans are fluids," he explains. "Volcanoes erupt magma, which is a fluid. Water flowing through the Earth's crust—groundwater—is a fluid. Earth's mantle can be viewed as a fluid on geological timescales, even though it's a solid material." Throughout his career, Manga, who was elected to the National Academy of Sciences in 2018, has applied principles of fluid dynamics to help answer a wide range of questions in earth science: What makes volcanoes erupt explosively, how can earthquakes trigger distant volcanic eruptions, how do groundwater flows and earthquakes interact, and what goes on beneath the icy surface of moons in the outer Solar System.

Finding Geophysics

Achievement runs in Manga's family. His father grew up in South Africa, the son of fruit sellers, and after immigrating to Canada and working in a steel mill, he eventually became a professor of health economics at the University of Ottawa. Manga's mother took care of the family while Manga and his brothers were growing up, but later went back to school and earned a doctorate in linguistics. Growing up in Ottawa, Ontario, Manga developed an interest in science in elementary school, when he joined the Macoun Field Naturalist Club. This club for children and teenagers meets on weekends at what is now the Canadian Museum of Nature, where adult volunteers introduce facets of nature and natural history. The club also organizes camping trips where members can study various species in the field and become comfortable in the outdoors. Manga participated in the club through high school.

Perhaps due to the influence of the Macoun Club, Manga intended to study entomology when he entered McGill University in Montreal. Those plans changed following his exposure to introductory courses in his first year. Manga chose to major in the subject that he least understood: physics.

Michael Manga. Image credit: Margaret Gennaro (photographer).

Manga might not have been introduced to geophysics, the field that would ultimately become his career, had it not been for an offhand remark by a physics laboratory instructor the following year. In teaching the students how to use a pendulum to measure Earth's gravitational pull, the instructor mentioned that gravity could be measured to six or seven significant figures. Manga initially found this hard to believe and said so. The instructor replied that there was someone in the geophysics department who did just that. Manga met with the geophysicist in question, David Crossley, and learned about Crossley's research looking for oscillations of Earth's inner core, using superconducting gravimeters that were sensitive enough to measure snowfall. Part of what attracted Manga to the field was the way the program integrated coursework from multiple classic disciplines: math, physics, and earth science.

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Manga became one of only three geophysics majors at McGill at the time. He conducted research, under the mentorship of Jafar Arkani-Hamed, on the formation of the dark spots on the moon. "Those are big impact craters filled with lava," Manga explains. "And the question was, where did those lavas come from? And why did it take hundreds of millions of years for the impact basins to fill up with lava?" Manga spent 2 years working with Arkani-Hamed, learning to write computer code to simulate the internal evolution of the moon in an attempt to answer some of these questions. The results were published in 1991 (1).

Fluid Mechanics and Earth Science

After receiving his bachelor's degree in geophysics from McGill in 1990, Manga went on to graduate school at Harvard University. At Harvard, he studied with Richard O'Connell, a geophysicist, and Howard Stone, a chemical engineer who specialized in fluid mechanics and who got Manga interested in studying the fluid mechanics of bubbles. Manga was attracted to certain parallels between earth science and fluid mechanics: Both are concerned with explaining everyday phenomena, and both involve a combination of laboratory experiments and computer simulations. Manga wrote his dissertation on the behavior of bubbles in viscous fluids, such as lava and magma (2). "Volcanoes erupt because they're full of bubbles," Manga explains, "lava flows are full of bubbles, and by understanding the behavior of bubbles, we can learn something about how those processes work."

Manga received a Master's degree in engineering sciences in 1992 and a doctorate in earth and planetary sciences in 1994. He was then chosen for a Miller Research Fellowship with the Miller Institute for Basic Research in Science at the University of California, Berkeley. These postdoctoral fellowships are earmarked for research at the University of California, Berkeley in any area of basic science. As a Miller Fellow, Manga worked with Raymond Jeanloz, a high-pressure mineral physicist, on the thermal properties of materials at high temperature and pressure and how those properties influence convection in Earth's mantle (3). Manga would later return to the Miller Institute as a professor in 2008 and would serve as the Institute's executive director from 2010 to 2016.

Volcanoes

In 1996, Manga became an assistant professor at the University of Oregon. Manga had developed an interest in hydrology while at the Miller Institute and continued to do research in that field at Oregon. He also met volcanologists at Oregon who got him interested in volcanoes. Although Manga enjoyed his work in Oregon, the natural environment there did not suit him. "I have terrible grass allergies," he explains, "and the Willamette Valley's big agricultural product is grass seed." So, after 5 years in Oregon, he returned to Berkeley in 2001 as a faculty member, where he remains today.

Manga's research has touched on a wide range of topics in earth and planetary sciences, but a common thread has been the role of fluids in planetary processes. Manga has done extensive research on the fluid dynamics of volcanoes. In one article, of which he is particularly proud, Manga and then-graduate student Helge Gonnermann showed how feedback between the formation of gas bubbles that drive magma to the surface, escape of those bubbles, and the breakage of magma determine whether a volcano will erupt explosively or not (4).

A recent project studying underwater volcanic eruptions illustrates the diversity of methods Manga uses in his research. In 2012, one of the largest underwater volcanic eruptions in history occurred in the Kermadec Islands of New Zealand (5). Much of the erupted material consists of pumice, a rock containing trapped gas bubbles that enable it to float on water. To understand the nature of such underwater eruptions, Manga and his colleagues investigated the process by which the pumice forms and why some of the pumice fragments float while others do not (6). The team went into the field to collect samples of floating and sunken pumice from the eruption. Back in the laboratory, they heated the pumice fragments and measured the extent to which they took up water using X-ray imaging techniques. The team also measured the extent to which the pores in the rock were interconnected. Finally, they combined these results with model simulations of magma ascent during eruption to produce a picture of what happened during the eruption. The results suggest that magma emerged from the volcano vent as a largely continuous stream, which then fragmented as it cooled and hardened in the water. Small fragments quickly filled with water and sank to the bottom, while larger fragments retained enough trapped gas to float to the surface. Some of these floating fragments gradually filled with water and ultimately sank as well, while the rest remained afloat until they washed up on beaches.

Groundwater, Earthquakes, and Ice Worlds

Another intersection of geology and fluid dynamics where Manga has done significant work involves the relationship between groundwater and seismic activity. For example, oil and gas extraction produces large amounts of wastewater contaminated with hydrocarbons. This wastewater is reinjected into the ground, and the resulting pressure changes can increase the likelihood of earthquakes (7). Thus, more frequent earthquakes can be a hazard of increased oil and gas production. With another earth scientist at Berkeley, Chi-Yuen Wang, Manga coauthored a book on earthquakes and water (8) and explored how earthquakes affect fluid flows. "We've known for thousands of years that when earthquakes happen, we see all kinds of responses in other Earth systems," Manga says. "Volcanoes will erupt, mud volcanoes erupt, we see more water flowing in rivers and streams, the water level in wells will change, the chemistry of the water in wells will change. And these changes will happen up to thousands of kilometers away from the earthquake."

One way that earthquakes can cause such responses is via changes in fluid pressure and fluid flows.

In one instance, Manga showed how earthquakes can remove temporary barriers to groundwater flow, increasing permeability and leading to significant drops in well water levels (9). In another instance, Manga and Wang found that earthquakes can breach the low-permeability rock layers, called aquitards, that surround aquifers, causing water to leak from one aquifer into another (10). In this way, wastewater stored underground could find its way into aquifers used for drinking water.

Manga also uses fluid dynamics to understand the geology of other planets and moons. Some moons in the outer Solar System are covered in ice, which may conceal liquid oceans. The icy surface of Europa, one of Jupiter's moons, features various pits and domes, ~10 km across. Manga and a colleague, Chloé Michaut, now at the École Normale Supérieure de Lyon, showed how these features could be formed by the injection of liquid water beneath the ice surface, supporting the existence of liquid water on Europa (11). In a recent article, Manga and colleagues attempted to explain a series of parallel, regularly spaced, volcanically active fissures near the south pole of Saturn's moon, Enceladus, another ice-covered world (12).

Geysers

In his Inaugural Article (13), Manga turned to geysers. Geysers are fascinating to many people, as evidenced by the millions of visitors each year who travel to Yellowstone National Park to watch geysers erupt. However, they are also a phenomenon that Manga considers underappreciated even among fellow earth scientists. "I really struggle sometimes to convince people that geysers are worth studying," he says. "For every [National Science Foundation] proposal I write, there'll be one reviewer who says geysers are not worth studying." Manga is convinced of the scientific value in studying geysers. "In a way, geysers are simpler versions of volcanoes. I would argue, if we cannot explain how geysers work, our prospects for understanding magmatic volcanoes are much lower. They're also a window into geothermal systems, the systems that transport heat and fluids inside the Earth. Some people speculate that geysers may be the best place for life to originate because they're episodically hot, warm, and cool, and they have nutrients. And so they provide some of the gradients that may enable life to get started."

Steamboat Geyser in Yellowstone National Park is the world's tallest active geyser. In 2018, it began erupting after a 3.5-year dormancy. Manga's Inaugural Article (13) addresses three questions: Why Steamboat began erupting when it did, what determines the intervals between eruptions, and what makes Steamboat's eruptions taller than those of other geysers.

Manga says: "My hope with the article was to partly make the case that geysers are interesting and worth studying, and that we should be able to answer these basic questions, and if we can't, there are fundamental things about the Earth we don't understand." Manga and his coauthors ruled out external factors, such as earthquakes and precipitation changes, as causes of Steamboat's reactivation, but the true cause remains ambiguous. They also presented evidence that the interval between eruptions varies seasonally, with shorter intervals in the summer and longer intervals in winter. As to why Steamboat's eruptions are tall, Manga proposed that it might be because the underground cavity, where the water that erupts from the geyser is stored, is buried deeper at Steamboat than at other geysers. The deeper the cavity, the greater the ambient pressure and, thus, the water reaches a higher temperature before it begins to boil and trigger an eruption. "And the warmer the water is, the more energy it has to sustain an eruption," Manga explains. "And so, the deeper you store the water, the more energy you have to drive the eruption column."

Manga has earned numerous honors for his research. In 2003, he received the Young Scientist Award from the Geological Society of America and was chosen as one of *Popular Science* magazine's Brilliant 10. In 2005, he was named a MacArthur Fellow. Also in 2005, likely as a result of publicity from the MacArthur fellowship, *People* magazine profiled him in its 2005 "Sexiest Man Alive" issue. Of this unusual honor, Manga says, "It's ridiculous. I'm sure my wife thinks it's ridiculous, too, and my kids thought it was ridiculous." Nevertheless, he sees the value in using the publicity to further the cause of science and agreed to be included as a way of introducing science into the magazine, where it might reach an unaccustomed audience. However, the honor Manga is most proud of is the Distinguished Teaching Award he received from the University of California, Berkeley in 2017. "I think that we can sometimes have a greater impact on the world through our teaching and through the students we get to work with, than through the papers that we write."

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