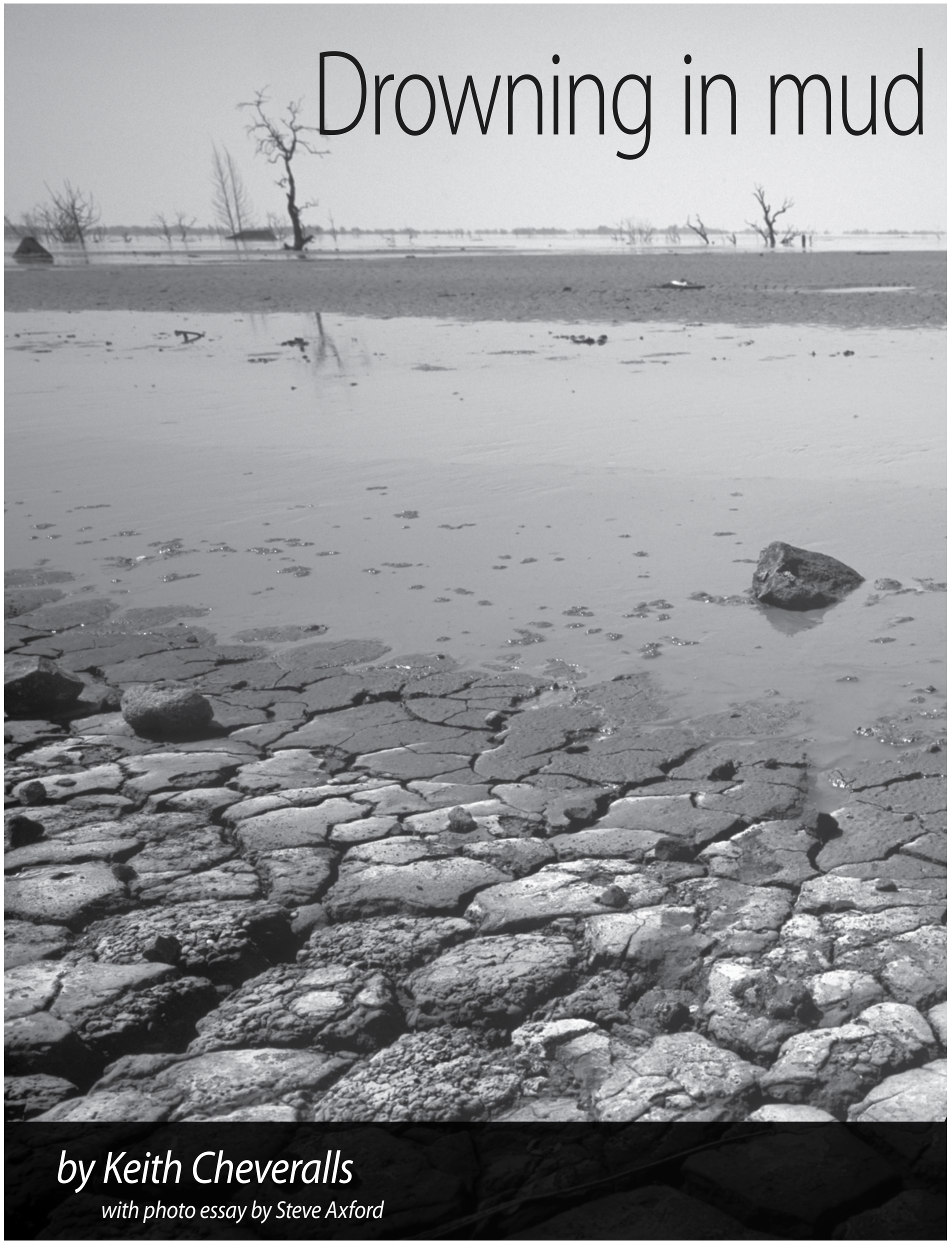


Drowning in mud

by Keith Cheveralls

with photo essay by Steve Axford

Scientists confront an ongoing eruption

The Lusi mud volcano *devastates the landscape in Sidoarjo, Indonesia. In the distance, steam rises from the volcano's vent.*

Photograph by Craig Cooper

At 5:00am on May 29, 2006, residents of the Indonesian city of Sidoarjo awoke to explosive eruptions of gas, water, and so much mud that within days the entire village was buried up to its rooftops. Although devastating, the eruption would have been manageable—were it not for the fact that it has never stopped. Nearly five years later, the eruption has a name, Lusi, and has set a record as the largest mud volcano in the world. Since that May morning in 2006, Lusi has ejected an average of 50,000 cubic meters of mud—enough to flood a football field to a depth of ten meters—every day.

FEATURES Mud volcanoes

After flowing for nearly five years, the mud now covers over six square kilometers and has buried a dozen villages. Tens of thousands of Indonesians, most of whom were already poor, have seen their homes and land destroyed, and thousands more are threatened by the flow of mud, which, while currently contained by a series of levees, shows no sign of stopping.

Two competing explanations for Lusi's sudden eruption have emerged. Measurements indicate that the mud is coming from a vast, pressurized reservoir about one and a half kilometers below the surface. Geologists posit that a series of pressure spikes in an exploratory natural gas well 140 meters away from the volcano perturbed the reservoir and triggered the eruption. Another theory, championed by the drilling company that owns the well, focuses on an earthquake that occurred two days prior to the eruption and 150 miles away from it. This theory suggests that the earthquake reactivated a dormant fault beneath the reservoir, destabilizing it and triggering the eruption.

The severity of the eruption itself, combined with the dramatic debate between geologists, who mostly favor the drilling hypothesis, and the drilling company, with its obvious interest in blaming the eruption on a natural cause, has led to extensive media coverage. Meanwhile, the eruption continues, the mud advances, and other questions haunt geologists and displaced residents alike. Why is Lusi ejecting so much more mud for so much longer than any other mud volcano? Will the surface near the volcano eventually collapse under its own weight, forming a crater-like depression that could destroy even more of the surrounding communities? And—perhaps the most urgent question of all—when will the eruption stop?

The Berkeley connection

Michael Manga speaks with a striking precision and calm for someone who studies some of the most brutal and elemental forces on earth. He began his career by modeling how bubbles in magma can drive volcanic eruptions and now, ten years after coming to UC Berkeley's earth and planetary science department, studies fluid processes in many geological systems—everything from how planets evolve over millions of years, to how volcanoes work, to how water flows through porous rocks. In 2006, he published a paper on hydrological responses to earthquakes—including mud volcano eruptions.

EUROPEAN PRESSPHOTO AGENCY

Steam rises from Lusi's eruption site, surrounded by sandbags and earth-moving equipment. Unlike a magma volcano, Lusi does not have a prominent, mountain-like cone. Instead, Lusi consists of a vent surrounded by a vast plain of mud, formerly farmland.

Before (top) and after (bottom) images from NASA's Terra satellite show the size of Lusi's eruption. In these false-color images, red indicates areas of dense vegetation. Before Lusi erupted, in August 2004, the area is occupied by villages and farmland. In November 2008, approximately six square kilometers of mud and levees mar the landscape. The white spot in the center of the mud is steam rising from the volcano's vent.

NASA

Then, a few months later, Lusi erupted. Manga was drawn into the debate about the cause of the eruption when engineers at the drilling company cited his study to support their theory that the distant earthquake triggered the eruption. Manga disagreed with their interpretation of his results, and felt obligated to formally respond. "Because of the consequences and the relevance to who's responsible," he explains, "and because we thought there were certain things being misrepresented, we had a moral obligation to respond in writing."

Four years later, Manga's group has not only issued two written responses rebutting the drilling company's theory, with which he disagrees, but has run experiments on mud from Lusi, studied mud volcanoes in California, and developed a physical model of Lusi's eruption—the results of which provide the first concrete predictions of the eruption's duration.

Mud volcanoes around the globe

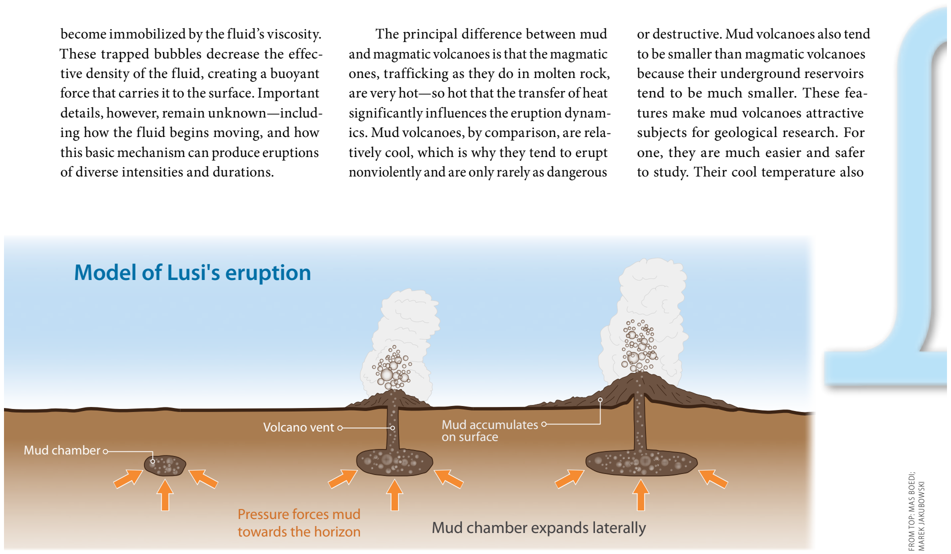
Mud volcanoes are not rare; thousands of them dot geologically active areas around the world. The archetypical mud volcano is simply a vent from which varying quantities of mud and gas bubble to the surface. Indeed, mud volcanoes look much like their better-known cousins, magmatic volcanoes, except that they erupt mud instead of magma. This resemblance holds beneath the surface, too; both mud and magmatic volcanoes typically discharge fluid (be it mud or magma) through channels and fractures that are connected to pressurized reservoirs deep underground.

The mechanism that drives eruptions is also, on a basic level, the same. Because mud and magma are both very dense, pressure in an underground reservoir alone cannot drive the fluid to the surface. Instead, the fluid rises when dissolved gases form bubbles that

Lusi's enormous size dwarfs excavation equipment. Rising steam hovers over the volcano's vent, obscuring piles of dirt that are part of the levee system built to contain the mud.

become immobilized by the fluid's viscosity. These trapped bubbles decrease the effective density of the fluid, creating a buoyant force that carries it to the surface. Important details, however, remain unknown—including how the fluid begins moving, and how this basic mechanism can produce eruptions of diverse intensities and durations.

The principal difference between mud and magmatic volcanoes is that the magmatic ones, trafficking as they do in molten rock, are very hot—so hot that the transfer of heat significantly influences the eruption dynamics. Mud volcanoes, by comparison, are relatively cool, which is why they tend to erupt nonviolently and are only rarely as dangerous or destructive. Mud volcanoes also tend to be smaller than magmatic volcanoes because their underground reservoirs tend to be much smaller. These features make mud volcanoes attractive subjects for geological research. For one, they are much easier and safer to study. Their cool temperature also



FROM TOP: MAS BOEDI; MAREK JAKUBOWSKI

means that the complicating effects of heat are absent. "The most compelling reason to study them is that they're low temperature versions of magmatic volcanoes," says Manga.

Although Lusi is no ordinary mud volcano—the eruption began violently, and has been longer, and bigger, than that of any other documented mud volcano—Lusi is scientifically promising, Manga says, because the proximity of the gas well provides unprecedented information about what the earth looked like at the eruption site before the eruption. "At best, an eruption happens, and then you can drill into it," Manga explains. "But you never know what things were like before the eruption. And we'll never have that information again, I suspect."

By exploiting this information to construct a model of Lusi, Manga has made predictions about the future of the eruption and has also learned something about how volcanoes erupt generally. But first, back in 2006, Manga felt obligated to help settle the debate about the triggering mechanism: was it the drilling, or was it an earthquake?

> "If I'm wrong about this, then I don't deserve to keep my job."
> -Professor Michael Manga

The earthquake hypothesis

When an earthquake occurs, it disturbs the earth in two ways. The movement of tectonic plates during an earthquake permanently redistributes stresses on the Earth's crust, while the propagation of seismic waves causes transient fluctuations in stress. It is well known that these transient fluctuations, which can travel hundreds of miles from an earthquake's epicenter, could alter fluid flows deep underground, resulting in a variety of phenomena at the surface, including geyser activity, changes in water well levels, and mud volcano eruptions.

In his 2006 paper, Manga and his colleague Emily Brodsky at UC Santa Cruz collected data on earthquakes that triggered a hydrological response. They then plotted the distance between each earthquake and the event it triggered against the magnitude of the earthquake, creating a scatter plot that revealed a roughly linear correlation between earthquake magnitude and distance to the triggered event. When Manga added the Indonesian earthquake, it landed well outside of the scattered points—indicating that the earthquake was much weaker and farther away from Lusi than any earthquake known to have triggered hydrological activity.

This analysis alone, Manga argued in a one-page paper he published in 2007, was strong evidence against the earthquake-triggering hypothesis. His paper contradicted, rather than supported, the drilling company's theory. But the results were statistical in nature, and it was possible that Lusi was an extreme outlier. To test the hypothesis further, Manga and graduate student Max Rudolph analyzed samples of erupted mud from Lusi. Their results provided direct experimental evidence against the earthquake-triggering hypothesis.

Let it flow

Rudolph and Manga's analysis rested on the complex fluid behavior of mud. Some fluids, like water, have the important property that their viscosity is a constant; they will always flow at a rate proportional to the force acting on them. Most fluids, however, exhibit a more complex response to force. Toothpaste is one example. "You could leave the cap off your toothpaste tube and put it upside down, and the toothpaste would stay in the tube," Rudolph explains, "but when you squeeze the tube it flows out."

In other words, toothpaste has a yield strength; it won't flow at all until a force above a certain threshold acts on it. Mud also has a yield strength, but with a twist: that strength will decrease if it is subjected to oscillating shear stress—that is, it will flow more easily when shaken.

Rudolph and Manga set out to test whether shaking from the earthquake's seismic waves reduced the strength of the mud in the underground reservoir, freeing it to flow to the surface. They obtained samples of erupted mud from the volcano and measured how it responds to shear forces of varying frequencies. They compared these

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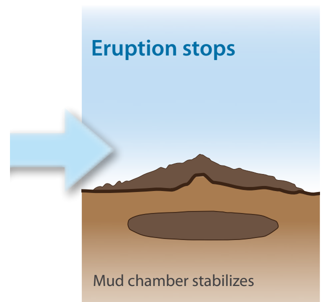
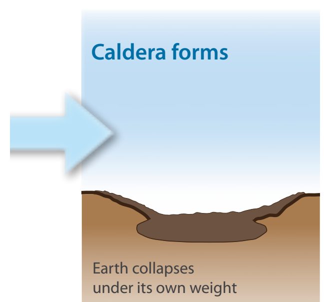
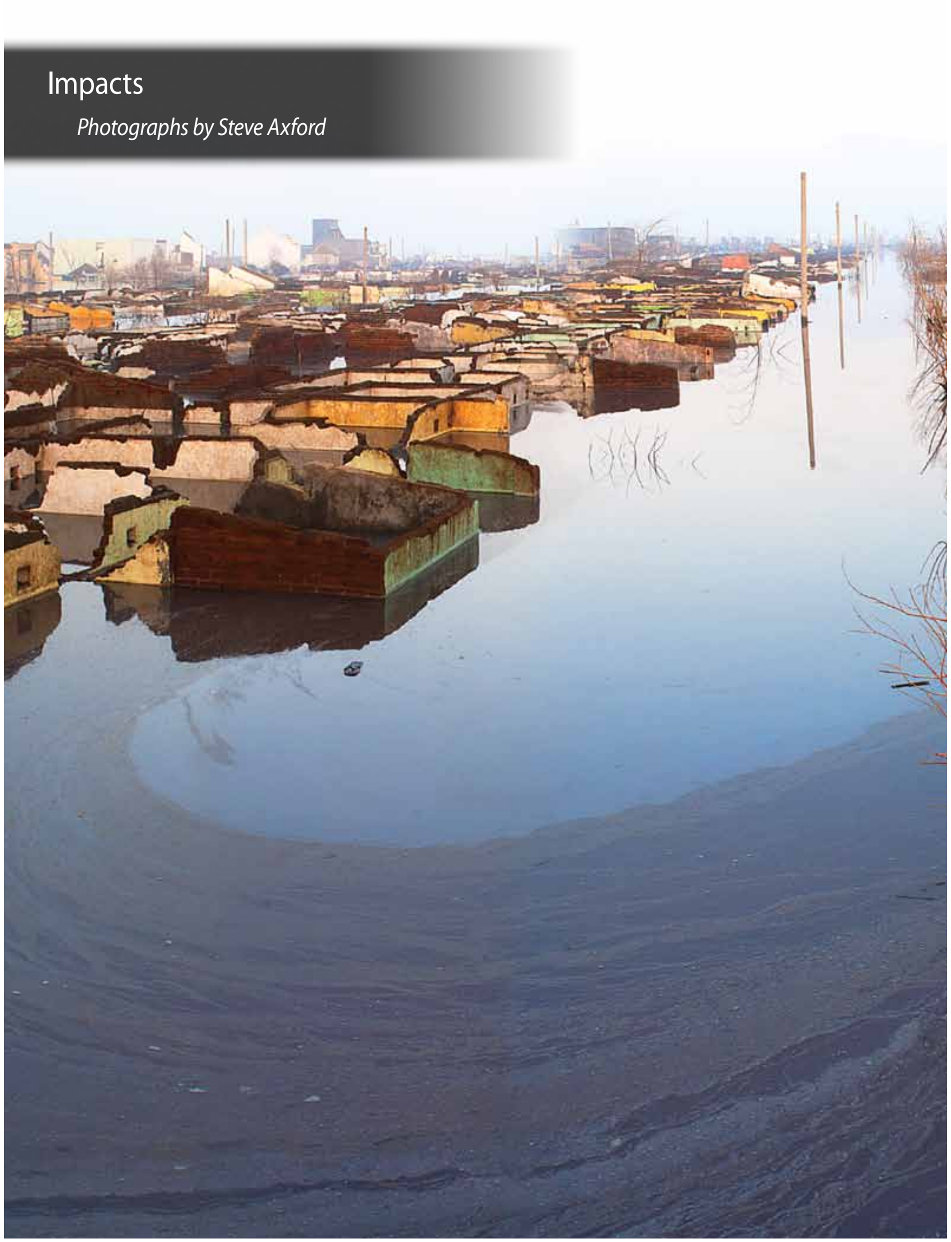


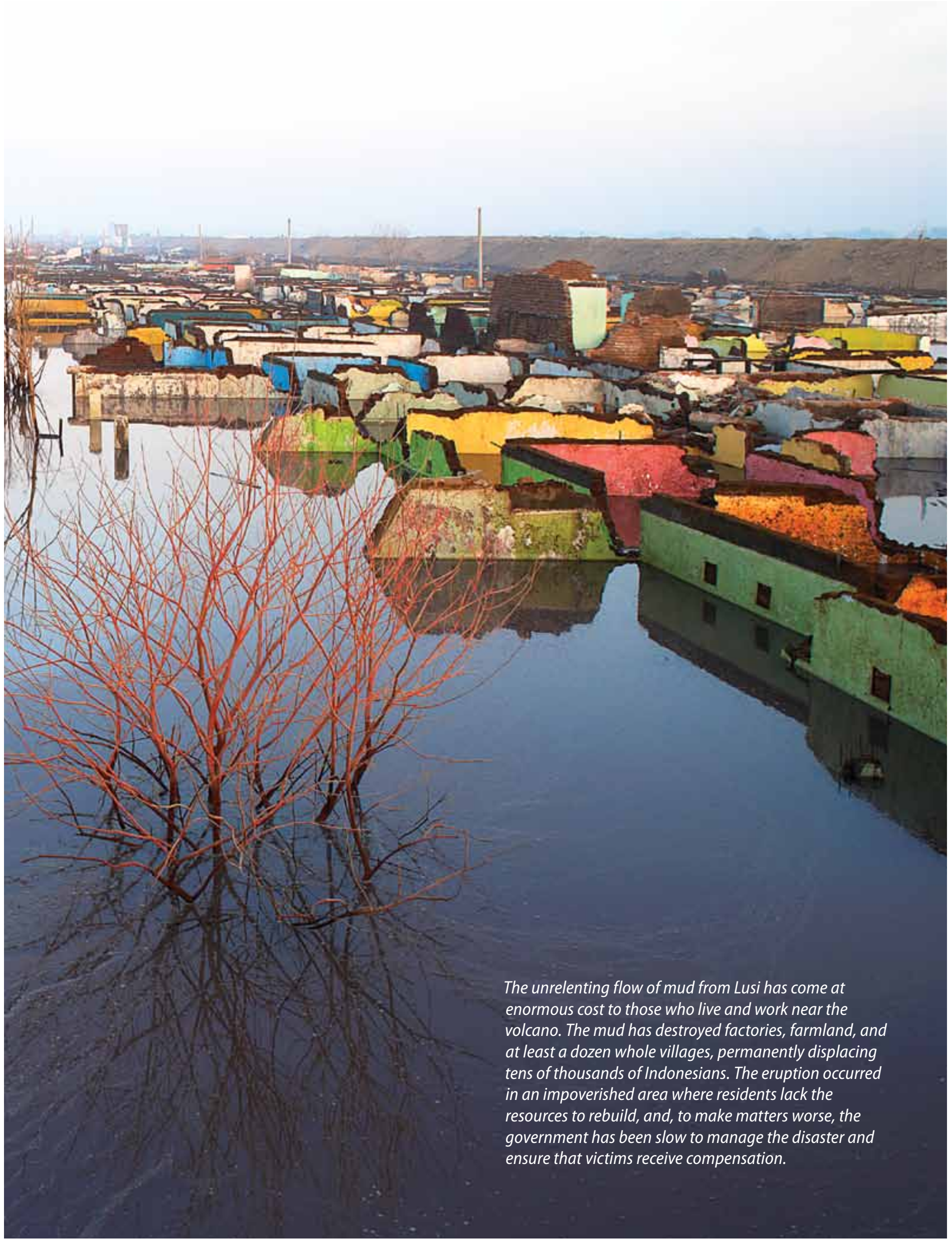


Before the eruption begins (far left), the pressurized mud chamber is dormant. Then, a conduit to the surface forms, pressure drives mud to the surface, and the mud chamber expands laterally as more of the surrounding material is drawn into the chamber. Given this eruption course, two outcomes are possible. Eventually, the eruption may cease (top right), or the chamber may collapse under the weight of erupted mud, forming a depression called a caldera (bottom right).

Impacts

Photographs by Steve Axford



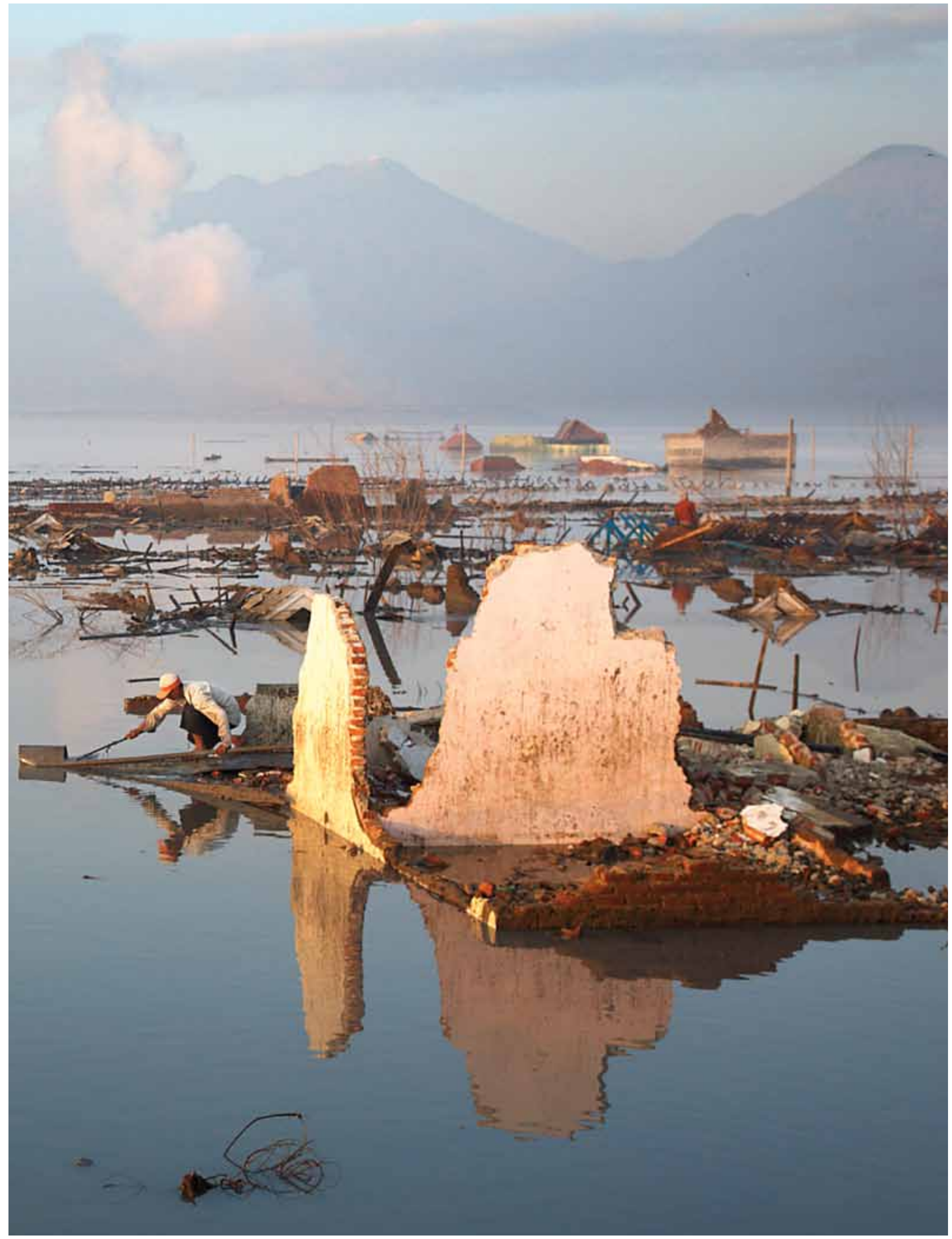


The unrelenting flow of mud from Lusi has come at enormous cost to those who live and work near the volcano. The mud has destroyed factories, farmland, and at least a dozen whole villages, permanently displacing tens of thousands of Indonesians. The eruption occurred in an impoverished area where residents lack the resources to rebuild, and, to make matters worse, the government has been slow to manage the disaster and ensure that victims receive compensation.

In 2006, the government ordered Lapindo Brantas, the company responsible for the drilling that probably triggered Lusi, to pay $400 million to displaced Indonesians. Five years later, only 20 percent of the promised sum has reached residents. The company says it will distribute the full amount by 2012—six years after the eruption began. Meanwhile, the Indonesian House of Representatives voted last year to declare the eruption a natural disaster and to discourage holding Lapindo Brantas responsible for further costs. Lawsuits from environmental groups against Lapindo Brantas are stalled in the Indonesian legal system.

Many believe the government's response is compromised by the complex relationship between the drilling company and government officials. The billionaire Aburizal Bakrie indirectly controls Lapindo Brantas. At the time of the eruption, he was also the minister of social welfare in the Indonesian cabinet. Currently, Bakrie remains one of Indonesia's wealthiest men, is the chairman of one of Indonesia's most powerful political parties, and is a major financial supporter of Indonesian President Susilo Yudhoyono. Bakrie denies accusations that his control of the drilling company constitutes a conflict of interest between his political and business activities.

The mud continues to flow; occasionally, it overtops the levees the government built to contain it, flooding adjacent communities. Whether those residents will ever be compensated for damage caused by ongoing flooding is uncertain.



In California, mud volcanoes are several meters in height. Top: Fresh mud flows from a mud volcano near the Salton Sea in southern California. A yellow research book shows the size of the volcano. Bottom: Graduate student Max Rudolph stands next to the mud volcanoes he studies.

FROM TOP: MAX RUDOLPH; MAX RUDOLPH; MAREK JAKUBOWSKI

measurements to the magnitude of the shear forces induced by the earthquake in 2006, and found that those forces were one hundred times smaller than the smallest forces that caused Lusi's mud to lose yield strength in the lab.

This result allowed Rudolph and Manga to conclude that the mud would not have lost yield strength during the earthquake, adding to the evidence against an earthquake-triggered eruption of Lusi. But this result revealed little about the mechanisms by which earthquakes might trigger other volcanic eruptions—a subject Rudolph and Manga decided to pursue last spring by studying smaller and more accessible mud volcanoes. Careful experiments on these mud volcanoes, they hoped, would extend their general understanding of the responses volcanoes exhibit to the ground motions that occur during earthquakes.

Mud volcanoes closer to home

Rudolph and Manga chose to study a collection of small, harmless, and easily observed mud volcanoes located near the Salton Sea in southern California. They began making detailed observations of the volcanoes—recording their temperature, estimating how much mud and gas they ejected, and analyzing samples of the mud—in order to correlate these measurements with the area's frequent minor seismic activity. Instead, a few months into the study, a remarkable thing happened: a major earthquake occurred just 60 miles south of the volcanoes. Instruments nearby revealed that the seismic

Non-Newtonian fluids

To quantify the differences between a fluid like water and a more complicated fluid like mud, scientists use theories from a branch of physics called fluid mechanics. "Newtonian" fluids, like water and oil, are a class of fluids that have a linear relationship between how much they flow and how much force is applied to them: the harder they're pushed on, the faster they flow. The ratio between the intensity of the applied force and the flow rate defines the fluid's viscosity. A Newtonian fluid always flows in response to a force, no matter how small, and always with the same viscosity (provided that thermal fluctuations and quantum effects are negligible).

The vast majority of fluids we encounter are non-Newtonian. The reason is that the Newtonian model of fluids only works when the fluid's constituent particles are identical, weakly interacting, and very small. Because most fluids are a mixture of interacting molecules and larger particles, the Newtonian model often fails. What makes fluid mechanics so complicated is that there are many ways the model can fail—that is, there are many different kinds of non-Newtonian fluids. Some, like molasses, paint, and blood, simply have a nonlinear force-flow relationship, which means that their viscosity depends upon the applied force. Push harder and harder on molasses, for example, and its apparent viscosity will decrease. Other fluids have a time-dependent viscosity: the longer a force is applied, the faster (or slower) they flow.

Some fluids, like toothpaste and mud, have a non-linear force-flow relationship that fails below a certain threshold force; that is, they do not flow in response to an applied force unless it is sufficiently strong. The threshold force at which these fluids begin to flow is called the yield strength. In something like mud, the yield strength is a consequence of interactions between small (micron-sized) particles of soil and silt. Mud, at its most basic, is nothing but a dense suspension of such particles in water. When unperturbed, these particles tend to pack together such that the application of a small force is not sufficient to dislodge them. Larger forces, however, easily disrupt the packing and allow the mud to flow.

waves at the site induced shear forces strong enough to alter the mud's properties, and, tellingly, they observed fresh mud flows and a 70 percent increase in the flow of gas two days after the earthquake. How likely was such a large earthquake to occur during their observations? "We got very lucky," says Rudolph.

It was a rare chance to test two competing theories that they had developed to explain how an earthquake could trigger a volcanic eruption. One model hypothesized that an earthquake, by reducing the mud's yield strength, could allow bubbles of gas immobilized in the mud to begin rising to the surface. Under the right conditions, the rising bubbles could entrain the mud and bring it to the surface, much as the gas bubbles released by opening a can of shaken soda carry along with them much of the soda.

To test this model, Rudolph and Manga used fluid dynamics to calculate how quickly the bubbles rose through the mud from measurements of their size at the surface. They found that the time required for the bubbles to rise to the surface was much greater than the time that elapsed between the earthquake and the appearance of new mud flows. This result indicated that bubbles mobilized by the earthquake's shaking couldn't have dragged mud or gas to the surface fast enough to explain the observed increase in volcanic activity.

They turned to a second model, in which seismic waves transiently increase the permeability of the earth, allowing more gas and mud to escape. Rudolph and Manga aren't exactly sure how this might happen; one idea is that an earthquake could unblock the many small cracks and channels through which mud and gas can travel deep underground, leading to an increase in flow until the channels became blocked again. By a series of estimations, they demonstrated the plausibility of this mechanism and now believe it is the correct model for the California mud volcanoes.

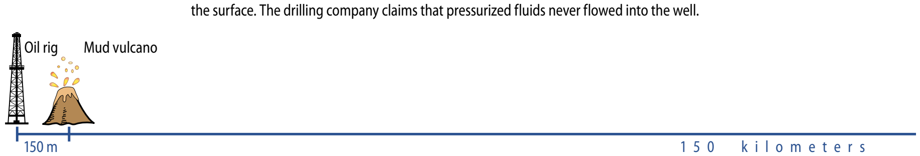
Back to Lusi

Could this mechanism explain the eruption of Lusi? No, asserts Rudolph, because their estimates indicate that it requires that the mud volcano be very close to the earthquake. Indeed, all the evidence—the historical data,

Theory vs Theory

The drilling theory: Most geologists believe that drilling activity at the natural gas well triggered the eruption of Lusi when pressurized water and mud from deep underground flowed into the well, creating fractures that allowed the mud to reach the surface. The drilling company claims that pressurized fluids never flowed into the well.

The earthquake theory: The chief proponent of this theory is the drilling company that owns the natural gas well near Lusi. It claims that an earthquake triggered the eruption by shaking the mud and enabling it to flow more easily, but geologists counter that the earthquake was too far away to affect the mud's properties.



their measurements of the mud's properties, and their results in California—argue against the triggering of Lusi's eruption by an earthquake.

Consequently, Manga is confident that an earthquake did not trigger Lusi's eruption. "If I'm wrong about this," he says, "then I don't deserve to keep my job. That's how comfortable I should feel. Because we apply all the best science we've done, we calculate things, and there's absolutely no reason to think that it could have been caused by the earthquake." Over the years, most geologists familiar with the eruption have come to agree. And, while establishing that drilling operations at the natural gas well did cause the eruption is more difficult, the present consensus is that they probably did.

The volcano has a 1 in 3 chance of erupting for at least **80 more years**.

According to Manga, the eruption was probably caused by mistakes made by engineers working on the gas well. Exactly how these mistakes led to the eruption will probably never be known. But what is clear is that engineers did not install steel casing inside the well, allowing fluid to flow into and out of the well at varying depths. This flow likely unleashed such high pressures that new fractures appeared in rock near the well—a process called hydrofracturing—which eventually formed a conduit from the mud reservoir to the surface.

With the debate surrounding the cause of the eruption of Lusi largely settled—an important development, because it helps determine who will bear the cost of compensating those displaced by the mud—Manga and his students have started looking to the future. They began thinking about how to predict when the eruption would end. "I think that's a more forward looking perspective, instead of just dwelling on the eruption that happened in 2006," Rudolph says.

Predictions, predictions

Many parameters determine how long a volcano eruption will last. The properties of the erupting fluid, the quantity of fluid that lies beneath the ground, and the nature of the conduit between the reservoir and the surface all influence eruption dynamics. Generally, however, there are only two ways an eruption can end: either the fluid simply stops flowing or the weight of the erupted fluid—essentially, the weight of the volcano's cone—causes the volcano to collapse on itself and into the emptying reservoir, forming a depression on the surface called a caldera. The formation of calderas by both mud and magmatic volcanoes is well documented, and the formation of one by Lusi could devastate the area surrounding the eruption.

But how is it possible to predict which of these outcomes will occur, or when, given the complexity of an erupting volcano? Such predictions are normally very difficult to make, because so many properties of volcanoes are simply unmeasurable. Manga, with Rudolph and graduate student Leif Karlstrom, overcame this difficulty by exploiting data collected from the natural gas well to constrain many unknown parameters, like the depth of the reservoir and the forces driving the mud to the surface. This allowed them to build a simple model of Lusi in which a pressurized reservoir of mud drives the eruption.

Crucially, their model included the counter-intuitive fact that the effective size of the mud reservoir increases as the eruption progresses. As mud erupts and more fluid flows into the reservoir, the solid mud at the boundary of the reservoir undergoes a transition from a solid-like to a fluid-like state. As the amount of fluid mud increases, the reservoir, in effect, grows larger. This, Manga thinks, explains why the eruption rate has been constant for the last five years—the pressure in the reservoir is buffered by the addition of more mud.

With their model constructed, and many of its parameters constrained by the drilling data, they used a clever trick to generate predictions despite uncertainty in some remaining parameters. They used their model to perform computer simulations of the eruption for many plausible values of these parameters, generating a distribution of different eruption types and durations. Using this distribution, they calculated the probability of each outcome. The results which emerged are, consequently, probabilistic, but place important and surprising constraints on the future of the eruption.

Their most important result is that the volcano has about a 1 in 3 chance of erupting for at least 80 more years. This result is, obviously, bad news for those affected by the volcano, but should inform the Indonesian government's long-term response to the disaster. A second result tempers the bad news: the longer the volcano erupts, the less likely it is to collapse and form a caldera—which would likely impact an even greater area near the eruption. In another twist, however, the probable size of a caldera, if one forms, increases the longer the eruption continues.

These results present a complex picture of Lusi's future and pose difficult questions for officials overseeing the response to the disaster. They clearly establish, however, that the eruption will likely continue impacting its local environment for many years. And while there remains significant uncertainty in their predictions, Manga's model establishes which of the unknown parameters are most likely to influence eruption dynamics, and which are unimportant. "I think the prediction is the most important thing we've done," Manga says. "Hopefully it will inspire people to either send us information that's relevant or collect information, and then we can update and revise the model."

Geologists' understanding of Lusi has grown enormously since its violent birth in 2006. While Manga and his students' model of the eruption advances that understanding even further, much remains to be discovered, including the detailed structure of the mud reservoir and how the future of the eruption depends upon the properties of the earth surrounding the eruption site.

The elucidation of these details will inevitably require the work of many geologists. For his part, Manga intends to continue his work on Lusi. With the model that he and his students developed, Manga now has a solid basis on which to build more detailed theories of how Lusi works. "A model," he concludes, "is just a starting point."

Keith Cheveralls *is a graduate student in biophysics.*

JON SHEER

An enormous plume of steam rises from Lusi. The small shape below the steam cloud is an excavator.