Fixing One Muddy Mess

Indonesia's mud volcano has been erupting for four years straight. Can anything be done to stop it?

Erin Wayman

Handoko Teguh Wibowo, Surabaya Mud Management Board

On May 27, 2006, a magnitude-6.3 earthquake rumbled across south-central Java.

One day later, an Indonesian oil and gas company, Lapindo Brantas, experienced a "kick," or influx of fluids from the surrounding rock, in a borehole as it drilled its Banjar Panji-1 natural gas exploration well in East Java.

The next day, a mud volcano started erupting 200 meters away, in Sidoarjo, East Java. And it hasn't stopped.

Four years later, scientists are still debating how these three events are related. Some scientists maintain that the earthquake reactivated a fault in East Java, and movement of the fault unleashed a budding mud volcano that was already slowly ascending to the surface, like a blob rising to the top of a lava lamp. Other scientists (some say a majority) suggest Lapindo Brantas hit a highly pressurized layer of limestone, fracturing the rock and allowing pressurized water and gas within the formation to escape to the surface, creating a powerful eruption (see sidebar).

Regardless of what initiated it, the eruption, known locally as LUSI (LUmpur, or mud, SIdoarjo), has already submerged a 7-square-kilometer chunk of Sidoarjo under a lake of mud and water. Sidoarjo, a Chicago-sized district that borders the Madura Strait, is home to approximately 1.5 million people. The mud has already drowned several villages in the district and displaced more than 50,000 people. Sidoarjo, located a couple dozen kilometers south of Indonesia's second-largest city, Surabaya, is an agricultural center for Java, home to rice fields, sugar cane plantations and aquaculture — some of which are now covered in mud. A dozen factories and portions of a major highway, a railway, and oil, gas and water pipelines have all been affected by the eruption. And in November 2006, 13 people died after a gas pipeline exploded after collapsing under the weight of the mud.

The muddy lake is not the only hazard. In addition to LUSI's main vent, other fractures have formed in the area, allowing more water and natural gas to seep to the surface. Some of these gas bubbles are like geysers, shooting water and flammable gas a couple meters into the air and occasionally igniting into a fire burst, says Richard Davies, a geologist at the University of Durham in England. Other gas bubbles do not spurt water into the sky, but instead emit pockets of gas or bubbling pools of water. Some of these gas bubbles have invaded people's homes as well as the streets of Porong, a town in the Sidoarjo district, says Van Williams, a retired U.S. Geological Survey (USGS) geologist currently living in Jakarta, who has worked with the Sidoarjo Mudflow

One year after the eruption began, mud had already covered villages, factories and farms. The mud also drowned a portion of a major highway (top left).

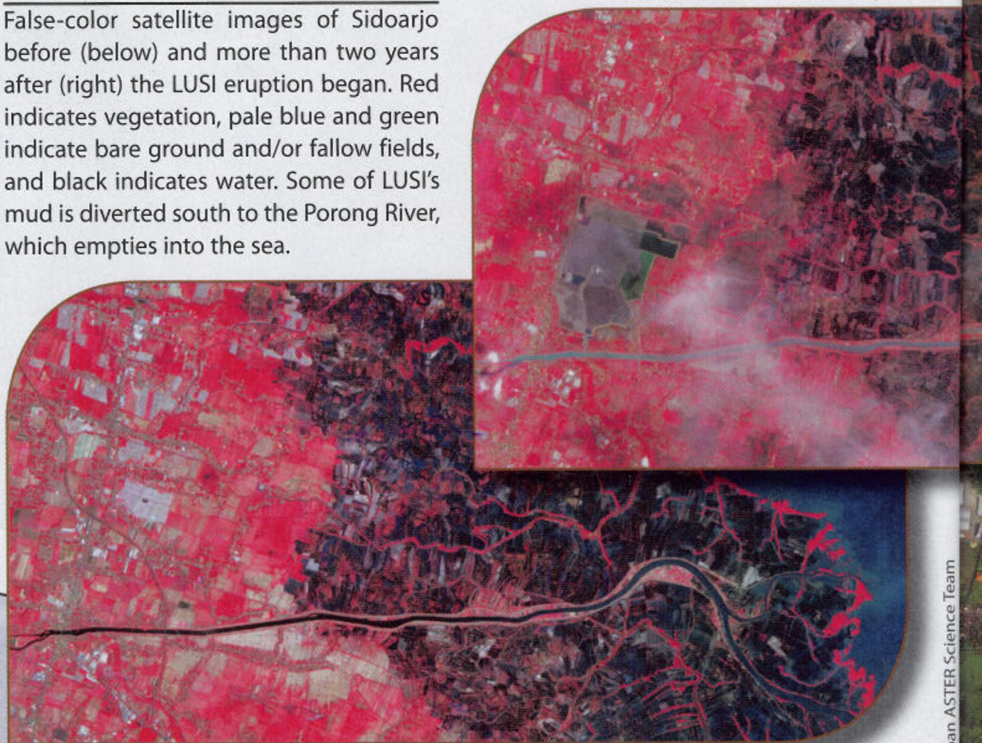
Mitigation Agency, a new agency formed by the Indonesian government to oversee the LUSI disaster.

For many residents of Sidoarjo, the question of the eruption's origins is secondary to the question of what the mud volcano has in store for the future. Since 2006, the mud volcano has spewed more than 100 million cubic meters of watery mud. Since 2007, daily eruption rates have remained steady, with approximately 100,000 cubic meters of 70- to 80-degree-Celsius mud and water reaching the surface each day, enough sludge to fill a 30-story apartment building, Williams says.

In the last few months, however, LUSI's rate of flow has reportedly slowed, Williams says. But whether this is a permanent decline or a temporary shutdown, as has happened before, is unclear because it's difficult to measure the rate of flow. Thus, geoscientists are assessing the long-term behavior of the mud volcano and helping Indonesian officials determine how to minimize the potential economic, environmental and health impacts of the disaster.

NO STOPPING LUSI

In the months after the eruption, some people thought it might be possible to halt the eruption. Although Lapindo Brantas claimed no responsibility in triggering the mud volcano, Indonesian President Susilo Bambang Yudhoyono required that the company pay for many of the attempts to end the eruption. One of the first options they tried was drilling relief wells. The plan was to drill a borehole that would intersect the Banjar Panji-1 well at an angle. Then, workers would pour concrete down the hole to stem the flow of pressurized fluid and gas that powers the mud volcano. Just months after the eruption started, work on two relief wells began, one southwest of the original well and one northwest of the well, with the help of international contractors, including Houston, Texas-based Coots & Boots International Well Control. The wells reportedly failed, in part because subsidence kept warping the wells' casings — and Lapindo Brantas was running out of money. Plans for a third relief well were scrapped because of funding problems.



False-color satellite images of Sidoarjo before (below) and more than two years after (right) the LUSI eruption began. Red indicates vegetation, pale blue and green indicate bare ground and/or fallow fields, and black indicates water. Some of LUSI's mud is diverted south to the Porong River, which empties into the sea.

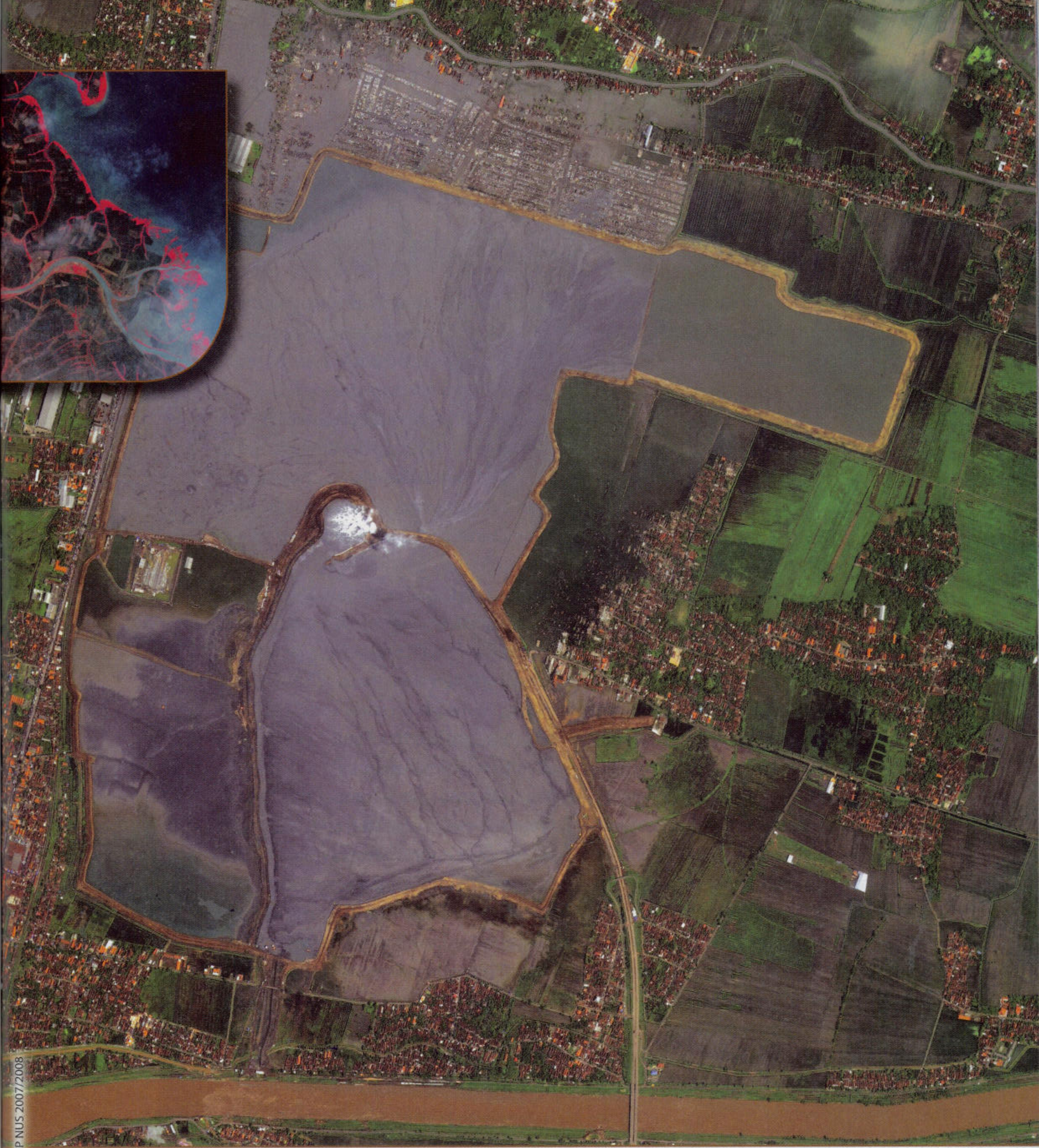
In March 2007, workers began dropping chained concrete balls, each weighing up to 40 kilograms, into the LUSI eruption to stem the flow of mud. The plan did not work.

Bottom: Dimas Ardian/Getty Images; top set: NASA image created by Jesse Allen, using data from NASA/GSFC/METI/ERSDAC/JAROS and the U.S./Japan ASTER Science Team

A group of geophysicists from Indonesia's Bandung Institute of Technology designed another plan. With a budget of $440,000 from Lapindo Brantas, the scientists thought dumping basketball-sized concrete balls chained together into LUSI's main vent would narrow the mud's tunnel to the surface and thus slow down the flow of mud. Workers began dropping the balls in February 2007. By April, close to 400 concrete balls had made the plunge. Initially, the scientists claimed success — yet LUSI continued to spew high volumes of water and mud.

Today, relief wells and other methods of stopping the eruption are no longer practical because the plumbing beneath LUSI has grown more complex as the mud volcano has aged, says Thomas Casadevall, a retired USGS geologist based in Denver, Colo. Since LUSI's birth, there have always been several vents burping mud and water to the surface, says Adriano Mazzini, a geologist at the University of Oslo in Norway. But the lake of mud has obscured several of the original vents, while subsidence has fractured the ground, providing new escape routes for the pressurized water and gas to reach the surface.

Now, Indonesian officials view containment as the best way to deal with the incessant flow. But containment has also become more complicated as the volcano evolves: Soon after the eruption began, Lapindo Brantas funded the construction of a series of earthen dams and levees around LUSI's main vent. However, mud has already swallowed some of the innermost levees, including a levee



In 2008, mud from LUSI had drowned several villages. The white plume in the center of the image is steam from the eruption's main vent. Some of the innermost dams are now covered in mud.

that provided scientists with access to the main vent to sample the watery mixture erupting from LUSI. Now, Williams says, it's impossible to get near that conduit.

In addition to containing the mud, Lapindo Brantas started diverting some of the mud into the Porong River, which empties into the Madura Strait. The mud does not naturally flow south toward the river because there is more subsidence on the north side than the south side of the mud volcano, Williams says. Therefore, Lapindo Brantas installed pumps that force the mud along the two-kilometer journey to the river.

Continued on page 42

The Debatable Birth of LUSI

Earthquake or drilling? That's the most controversial question scientists have asked about the LUSI mud volcano. Four years later, they have yet to reach full agreement on the answer.

Adriano Mazzini, a geologist at the University of Oslo in Norway, thinks LUSI is a natural mud volcano that was triggered by an earthquake. For one thing, Java has a long history of mud volcanism, he says, so LUSI isn't an aberration.

Seismic data of the region's subsurface collected in the 1980s also support this conclusion, he says. Seismic profiles — images of the subsurface that scientists create using data from how sound waves travel through rocks — show there was a "bump" deep beneath the surface, also called "a piercement structure" because it intrudes into overlying rocks. Like a diapir, a relatively buoyant mass of rock that slowly pushes up into denser rock layers above, a piercement structure is a dome saturated with gas and fluids that travels slowly to the surface. One way or another, that bump was destined to become a mud volcano once it reached the surface, Mazzini and his colleagues reported in Marine and Petroleum Geology in 2009. They ran mathematical and numerical models as well as conducted laboratory simulations to support these observations.

Although the mud volcano would have reached the surface at some point, Mazzini says, the magnitude-6.3 earthquake that struck 250 kilometers southwest of LUSI, two days before the eruption started, helped trigger the current eruption. He notes that LUSI began with several eruption points that all align along a northeast-southwest orientation. It's not coincidental, he says: This is the same direction as the area's Watukosek Fault Zone. Mazzini contends that the earthquake reactivated this strike-slip fault zone, and the shearing movement helped the growing "bump" beneath the ground penetrate the surface, erupting into LUSI.

But Richard Davies, a geologist at the University of Durham in England, sees things differently. "The earthquake was too far away and too small to have caused this volcano," he says. Instead, the drilling of Lapindo Brantas' Banjar Panji-1 exploration well initiated the eruption.

The company was targeting the Kujung Formation, carbonates dated to the Oligocene-Miocene epochs (roughly 34 million to 5 million years ago). Drilling companies usually line their boreholes with steel casing in areas known to have highly pressurized sediments; the casing strengthens the borehole and prevents those sediments from entering the well, says Tom Casadevall, a retired U.S. Geological Survey geologist based in Denver, Colo. But Lapindo Brantas left the bottom 1,743 meters of their borehole uncased. The original drilling plans called for casing,

©iStockphoto.com/Andreas Bauer

The plume of steam rising from LUSI's crater two years after the eruption began.

Handoko Teguh Wibowo, Surabaya Mud Management Board

so it's not clear why part of the borehole was left exposed, Casadevall says.

The lack of casing on its own didn't cause the eruption, Davies says. The problem came when the drillers decided to remove the drill bit from the hole. While pulling the drill bit up, the well experienced a "kick," an influx of fluids into the well. "That created pressure in the well," Davies says. "Because they had so much hole without any protection, the rocks weren't particularly strong, and rocks fractured." This allowed water and gas in the formation to rush toward the surface, carrying sediments on the way up. LUSI's eruption began the next day, 200 meters away from the well (no mud has ever actually come up the well itself).

Both sides find fault with each other's arguments. For example, Mazzini notes that at the same time LUSI first erupted, other wells in the area all lost pressure, suggesting fluids within those wells traveled elsewhere. Additionally, the activity at mud volcanoes more than 30 to 40 kilometers away from LUSI increased. This is all due to the reactivation of the fault zone, he says. The lateral movement on the fault acted like a vacuum, sucking up subsurface fluids into the fault plane — which explains the loss of well pressure. "We have to either believe in coincidences or believe the earthquake reactivated this fault — which is the most likely geological scenario — or believe drilling reactivated a 50-kilometer-long fault, which is unrealistic," he says.

Davies and his colleagues, however, provided new evidence for their argument earlier this year. In February, they announced Lapindo Brantas' own drilling records point to the drilling as the cause of LUSI. "We found that one of the on-site daily drilling reports states that Lapindo Brantas pumped heavy drilling mud into the well to try to stop the mud volcano," Davies said in the announcement. "This was partially successful and the eruption of the mud volcano slowed down. The fact that the eruption slowed provides the first conclusive evidence that the borehole was connected to the volcano at the time of eruption."

Despite all of the evidence, scientists may never reach a complete consensus on what caused LUSI — but they all agree it's an important phenomenon to study.

EW

"Muddy Mess" continued from page 39

The system can expel as much as 45,000 cubic meters of sludge each day. But this solution has also been problematic: Some scientists and residents voiced concerns about how the mud might affect aquatic ecosystems and alter the Sidoarjo coastline. At the moment, the pumps are not running at full capacity — not because of environmental concerns but because Lapindo Brantas claimed it did not have the money to maintain the effort, Williams says. Now, the Sidoarjo Mudflow Mitigation Agency is in charge of the pumping, but "it takes time to ramp up the effort," he says.

Whether the current containment structure and the pumping is enough to keep LUSI in check in the long run is still a question mark. To answer that question, researchers need to figure out how long the eruption will last.

HOW LONG WILL IT LAST?

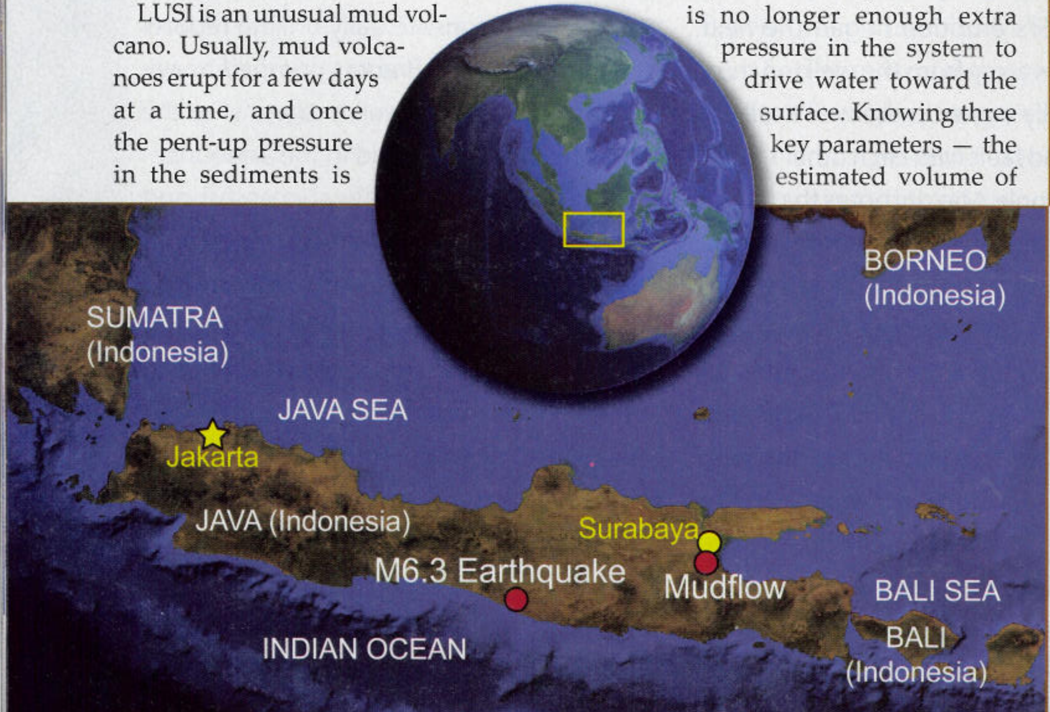
Mud volcanoes exist all over the world. The mechanics of mud volcanoes are not well-known, but they typically occur in sedimentary basins, when sediments become highly pressurized — often due to tectonic activity or the accumulation of fluid or gas (frequently methane, which explains why hydrocarbon-rich Azerbaijan is home to roughly half of the world's mud volcanoes). If any cracks in the rock layer form, the highly pressurized sediments may shoot to the surface, erupting into a mud volcano.

LUSI is an unusual mud volcano. Usually, mud volcanoes erupt for a few days at a time, and once the pent-up pressure in the sediments is released, they stop. They might sputter and bubble a bit, but they essentially remain dormant until enough pressure builds up to set off another eruption. LUSI, however, has maintained a four-year-long eruption with a near-constant volume. LUSI is also much "wetter" than other known mud volcanoes, with water constituting 70 percent of LUSI's eruptive material.

LUSI's oddities make it hard to look to other mud volcanoes for guidance on how long LUSI will continue to erupt. Nonetheless, a team of geologists has pieced together the available evidence to make some estimates. First, they determined that the water erupting from LUSI originates 2.8 kilometers belowground in a limestone aquifer (on the way up, the water pulls up sediments from other rock layers, creating the muddy mix that reaches the surface). Next, they used data from other wells drilled into the same limestone to estimate the volume of water the aquifer contains: between 6 and 225 cubic kilometers, says team member Richard Swarbrick, a geologist affiliated with the University of Durham and GeoPressure Technology in England, who presented the findings at the American Geophysical Union's (AGU) annual meeting in San Francisco, Calif., last December.

Whatever the correct volume is, not all of that water will erupt to the surface, Swarbrick says. As water drains from the aquifer, pressure is relieved; the eruption will stop when there is no longer enough extra pressure in the system to drive water toward the surface. Knowing three key parameters — the estimated volume of water in the aquifer, the amount of material that erupts each day and the subsurface pressure (measured from a well near LUSI) — allowed Swarbrick and his colleagues to calculate how long it might take to drain away the pressure. The team estimated LUSI's eruption may last anywhere from 10 to more than 100 years, but Swarbrick thinks 30 to 35 years is most likely.

But it's also possible LUSI might erupt again. "It might stop in 30 years time, but if you can recharge the pressure in the limestone, then you would potentially kick the whole system off again," says Davies, another team member. For example, if part of the aquifer is exposed at the surface, water will replenish the system and the pressure, he says. "This would be really bad news because it could carry on … indefinitely."



Maps: AGI/NASA; photo: ©Nick Taylor, Creative Commons Attribution 2.0 Generic

In August 2006, residents near LUSI were forced to evacuate their homes after erupting mud and water caused dams surrounding the mud volcano to breach.

LUSI's four-year-long eruption is unusual for a mud volcano, which some scientists say is evidence that LUSI is a human-made accident. Most mud volcanoes, like these in Azerbaijan, only erupt for a few days at a time.

HOW LOW CAN IT GO?

Estimating LUSI's longevity is only one question on researchers' minds. Another problem is subsidence: The weight of LUSI's mud on the surface combined with the removal of the mud from belowground are causing Sidoarjo to sink.

GPS measurements and satellite data show that an egg-shaped region around the mud volcano is subsiding, with rates varying between 0.1 and 4.5 centimeters per day, Davies and his colleagues reported in Environmental Geology in April 2009. "The [maximum] subsidence rates are near the central part of the mud volcano, particularly northwest of the main vent," he says.

Those rates of subsidence could submerge part of Sidoarjo, Williams says. Before LUSI emerged, Sidoarjo was only a few meters above sea level. Now, parts of the district — such as areas northwest of the main vent that lie outside of the containment structures — have already subsided up to two meters and could end up below sea level. Constant flooding could then lead to the formation of a lake, one that would require constant pumping to drain, he says. In addition, subsidence could disrupt already-existing bodies of water, Davies says, by altering drainage patterns and redirecting the flow of rivers.

How much damage LUSI will inflict from subsidence over time is tied to how long the mud volcano will continue to erupt. "If you know that, you can estimate how much total subsidence [will occur] in the region," Davies says. "If it goes on for 10, 20 years, there's going to be tens of meters of subsidence."

Eventually, the whole area around LUSI may collapse: As the mud volcano excavates more and more underground material,

A school destroyed by LUSI's flow of mud.

The main vent of the LUSI eruption.

it is creating a large subterranean void — and one day, the ground may become too weak to withstand the weight of all that mud, Swarbrick says.

The sinking of Sidoarjo may even help LUSI grow bigger. The force of the subsidence "may cause shallow rock layers that were never initially involved in the disaster to rupture and break," Davies says, "and the fluids in those [aquifers] could come up."

IS LUSI A HEALTH RISK?

Many of LUSI's impacts are obvious, but others are more indirect. After the mud began flowing, officials were concerned that heavy metals and other contaminants might be lurking in LUSI's flow. The Indonesian president asked the United States for assistance with several aspects of the disaster, which included analyzing the mud's potential health and environmental effects. The U.S. State Department asked USGS to help out. In September 2007, Casadevall traveled to Sidoarjo, and while he was there, collected a sample of the mud. He returned the following fall and collected additional samples.

Back in the United States, a team of geologists who had studied the health effects of other disasters, such as Hurricane Katrina in 2005 and the World Trade Centers attack in 2001, got to work studying the mud and water.

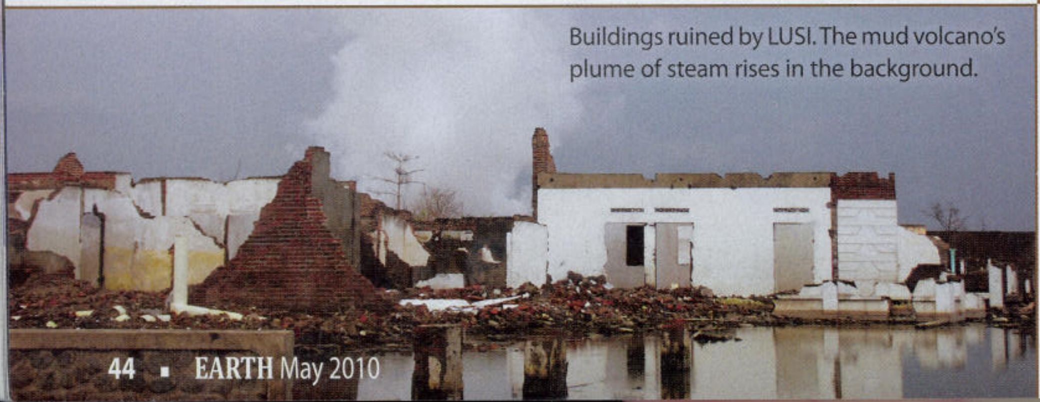
In many ways, their findings are encouraging. "In general, the muds are quite low in a variety of heavy metals that are potentially toxic," says Geoff Plumlee, a USGS geologist based in Denver, Colo., who presented the results at AGU's annual meeting in San Francisco last December.

One component of the mud that might pose a concern is its organic composition, which includes oil. "Any time you're dealing with oil you have to be careful of its constituents, like PAHs [polycyclic aromatic hydrocarbons]," says Bob Rosenbauer, a USGS geologist based in Menlo Park, Calif. Some PAHs are carcinogenic and can cause birth defects.

The concentration of some of the PAHs in LUSI's mud exceeds the U.S. Environmental Protection Agency's (EPA) recommendations for PAH levels in sediments; these are the PAHs with a low molecular weight, which tend to be less toxic, Rosenbauer says. But there are a lot of unknowns regarding the safety of these compounds, he says, such as the cumulative effect of the buildup of these compounds in the environment over time. More work is also needed on what happens when these PAHs dissolve in water or degrade.

The mud that has already dried may also require some additional examination. If dried mud were disturbed, generating dust, a little more than 80 percent of the dust's particles would be small enough to be inhaled into the upper respiratory tract, according to the USGS findings. Both workers who are still constructing and maintaining levees and people who are rummaging through village ruins are possible sources of disturbance that could kick up dust. But only scientists on the scene would be able to determine if these activities are generating enough dust that it might be dangerous, Plumlee says.

After LUSI's mud and water flooded buildings in Sidoarjo, the government demolished the structures.



Buildings ruined by LUSI. The mud volcano's plume of steam rises in the background.

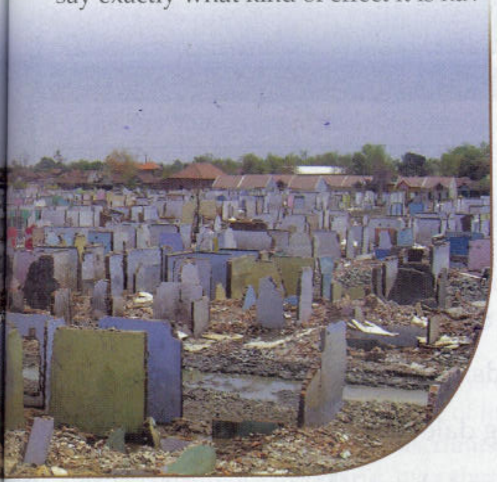
The water that separates from the mud may be more of a worry than the mud itself: It contains levels of nitrate and fluoride that are in excess of EPA drinking water standards. "You certainly wouldn't want to drink it," Casadevall says. Unfortunately, this water is contaminating some water supplies. And the high salinity level

Bottom to top: Adriano Mazzini; ©Hughe82, Creative Commons Attribution ShareAlike 3.0 Unported; Adriano Mazzini

of LUSI's water is a problem for farmers growing rice, Williams adds.

The nitrate might be an environmental problem as well, Plumlee says. If some of the mud is pumped to the sea, the nutrients could set off algal blooms, which can lead to areas of low oxygen levels (sometimes called dead zones). This would not only affect coastal ecosystems but would also harm the shrimp farms that line the Madura Strait. It's something that needs further study, he says.

Overall, however, LUSI's mud doesn't appear to pose a serious threat to human health, Plumlee says. But it's hard to say exactly what kind of effect it is hav-



ing, or will have, because few data are available on the baseline environmental and health conditions prior to LUSI. Sidoarjo is a densely populated, industrial area. "It would be very useful to understand just how polluted the area might have been," he says. "Our data show that there are some things that may be of potential concern, but until it's looked at in a broader perspective … we really won't have a good understanding of what this actually might be doing."

MANAGING LUSI

Given the current understanding of LUSI, the scientists who have studied the unrelenting mud volcano offer some advice on how to deal with the problem — but, they caution, there are no easy solutions.

Containment is probably the best way to manage LUSI, Davies says. "Estimate how long it's going to carry on, and then build dams around it and cordon off the area." But there are some problems with this form of mitigation. Indonesia is a seismically active country, and a large earthquake could provide a fatal blow to the containment structures, Casadevall says. Another issue, Williams says, is that the levees are all built at the same elevation around the mud volcano, but the mud is not distributed evenly because the slope of LUSI's vent is not level. So levee failure on the west side, where the mud is highest, is likely, he says.

In addition to containment, Williams says pumping the mud out to sea is necessary. Although the nutrients in the mud might trigger algal blooms, he is "convinced it could be done with minimal environmental impact." But pumping enough mud to make a difference is an expensive venture. Williams heard "hearsay" that Lapindo Brantas spent about $1 million per month on pumping when they were responsible for the effort, but he estimates they were only doing about one-quarter of the pumping that was needed to keep up with LUSI. The Sidoarjo Mudflow Mitigation Agency has not yet resumed pumping, but the Indonesian government has given them money to run the pumps.

One variable is harder to plan for than the mud: the gas bubbles. So far, the gas bubbles carry only water and natural gas, Williams says, but one day they might also transport mud — and that's a "worst case scenario" because many of these gas bubbles are outside the confines of the levees. Planning for the future is difficult because these bubbles sprout up without any warning and there's no way to predict where one will form. Studying the distribution of gas bubbles at natural mud volcanoes, Davies says, might help scientists determine if gas bubble formation adheres to any kind of pattern.

With all of these uncertainties, the most prudent thing to do is to evacuate the areas at most risk, mainly the region northwest of the main vent, Williams says. "This is a huge can of worms," he says, because Indonesia does not have well-defined laws of eminent domain, so it will be hard to force people to relocate. "It's not going to work unless people pay them to leave," he says.

Despite some of these ongoing problems, "the urgency of the situation has declined," Casadevall says. Although the cost of the mud's damage has risen to $4.9 billion (the Jakarta Globe reported last September), the eruption is not killing people and its behavior remains consistent. "Mud continues to come out. The Indonesians continue to manage it," Casadevall says. And the science suggests they will have to continue to manage it for many years to come.

Wayman is a reporter and associate editor at EARTH.