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What are mud volcanoes, how do they form and what secrets do they hold about the planet?

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Rice farmers in Sidoarjo Regency, Indonesia, woke up to a strange sight on May 29, 2006. The ground had ruptured overnight and was spewing steam.

Over the next few weeks, water, boiling mud and natural gas were added to the mix. As the eruption intensified, the mud began to spread across the fields. Alarmed residents evacuated, hoping to wait out the eruption.

Except it didn't stop. Weeks passed and the spreading mud enveloped entire villages. In a frantic race against time, the Indonesian government began building dams to contain the mud and stop the spread.

When the mud overtopped these dams, they built new ones behind the first. The government finally succeeded in stopping its advance, but not before the flows wiped out a dozen villages and forced 60,000 people to relocate.

Why did the Earth suddenly start spewing large amounts of mud like this?

Explosive combinationThe Lusi structure, a contraction of Lumpur Sidoarjo, meaning "Sidoarjo mud," is an example of a geological feature known as a mud volcano.

They form when a combination of mud, fluids and gases erupt on the Earth's surface. The term "volcano" is borrowed from the much better known world of igneous volcanoes, where molten rock comes to the surface.

I have been studying these fascinating structures in subsurface seismic data for the past five years, but nothing compares to seeing an active eruption.

In the case of mud volcanoes, in many cases the mud bubbles to the surface fairly quietly. But sometimes the eruptions are quite violent. In addition, most of the gas that comes out of a mud volcano is methane, which is highly flammable.

This gas can ignite, creating spectacular fiery eruptions.

Mud volcanoes are little known in North America, but much more common in other parts of the world, including not only Indonesia but also Azerbaijan, Trinidad, Italy and Japan.

They form when fluids and gases that have built up under pressure inside the Earth find an escape route to the surface through a network of fractures.

The fluids rise through these cracks, dragging mud with them, creating the mud volcano as they escape.

The idea is similar to that of an automobile tire containing compressed air. As long as the tire is intact, the air remains safely inside. However, once the air has an exit path, it begins to escape. Sometimes, the air escapes as a slow leak; in other cases, an explosion occurs.

Excessive pressure

Excessive pressure within the Earth builds up when subsurface fluids cannot escape below the weight of overlying sediments. Some of this fluid was trapped within the sediment when it was deposited.

Other fluids may migrate from deeper sediments, while others may be generated in place by chemical reactions in the sediments. One important type of chemical reaction generates oil and natural gas.

Finally, fluids can become overpressured if they are compressed by tectonic forces during mountain formation.

Overpressures are commonly encountered during oil and gas drilling and are usually planned for. A primary way to deal with overpressures is to fill the well with dense drilling mud, which has sufficient weight to contain the overpressures.

If the well is drilled with insufficient mud density, the overpressured fluids can rapidly rise up the wellbore and explode at the surface, causing a spectacular blowout. Famous examples of blowouts include the 1901 Spindletop blowout in Texas and the more recent Deepwater Horizon disaster in 2010 in the Gulf of Mexico.

In those cases it was oil, not mud, that came out of the wells.

Deep EarthIn addition to being fascinating in their own right, mud volcanoes are also useful to scientists as windows into conditions deep in the Earth.

Mud volcanoes can involve materials up to 10 kilometers below the Earth's surface, so their chemistry and temperature can provide useful information about deep Earth processes that cannot otherwise be obtained.

For example, analysis of the Lusi mud eruption has revealed that the water was heated by a subsurface magma chamber associated with the nearby Arjuno-Welirang volcanic complex.

Each mud volcano reveals details about what is happening underground, allowing scientists to build a more complete 3D picture of what is happening inside the planet.

Continuous eruptionToday, more than 16 years after the eruption began, the Lusi structure in Indonesia continues to erupt, but at a much slower rate. Its mud covers a total area of approximately 7 square kilometers, more than 1,300 soccer fields, and is contained behind a series of dikes that have been built up to a height of 30 meters.

Almost as interesting as the efforts to stop the mud have been the legal battles aimed at assigning blame for the disaster. The initial rupture occurred about 200 meters from a gas exploration well that was actively being drilled, prompting widely publicized accusations that the oil company responsible for the well was to blame.

The operator of the well, Lapindo Brantas, responded that the eruption was natural, triggered by an earthquake several days earlier.

Those who believe that the gas well triggered the eruption argue that the well experienced a blowout due to insufficient mud density, but that the blowout did not reach the surface of the well. Instead, fluids reached only halfway down the well before injecting laterally into fractures and erupting at the surface several hundred meters away.

As evidence, these proponents point to measurements made in the well during drilling. In addition, they suggest that the earthquake was too far from the well to have had any effect.

In contrast, proponents that the trigger was an earthquake believe that the Lusi eruption was caused by an active hydrothermal system in the subsurface, something similar to Old Faithful the Old Faithful in Yellowstone National Park. They argue that such systems have a long history of being affected by very distant earthquakes, so the argument that Lusi was too far away from the earthquake is not valid.

They further suggest that a pressure test on the well performed after the eruption began showed that the well was intact, with no fractures or fluid leaks. According to this interpretation, there is no evidence that any of the drilling mud ever came out of the Lusi eruptions.

In 2009, Indonesia's highest court dismissed a lawsuit accusing the company of negligence. The same year, police dropped criminal investigations against Lapindo Brantas and several of its employees, citing lack of evidence. Although the lawsuits have been settled, the debate continues, with international investigative groups lining up on both sides of the dispute.

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