

VOLCANOLOGY

Throwing mud

The causes of the catastrophic eruption of the Lusi mud volcano in Indonesia are hotly debated. Data from a nearby exploration well and a new look at the stress regime suggest that drilling operations, and not an earthquake set the eruption off.

Debi Kilb

Scripps Institution of Oceanography,
IGPP/SIO/UCSD, MS 0225, La Jolla,
California 92093-0225, USA.

e-mail: dkilb@ucsd.edu

Earthquakes have been considered to play a potentially important role in causing mud volcano eruptions, but a quantitative understanding has proven elusive. One line of investigation explored the framework of a triggering threshold, dependant on earthquake magnitude and the inverse of the distance from its epicentre¹. However, it has been suggested that mud volcano eruptions are typically not linked to earthquakes^{2,3,4}, and many mud volcanoes have erupted in the absence of seismic activity. The inception of the 'Lusi' mud volcano in 2006, which buried the region near the eastern Javan city of Sidoarjo in a hot torrent of mud, has once again fuelled this debate^{1,5,6}. A new study⁷ uses regional data on historical earthquakes along with a detailed log of drilling operations to rule out an earthquake-only trigger and suggests that the eruption most likely resulted from increased pressure at depth due to the drilling.

The Lusi mud volcano started erupting on 29 May 2006. Mudflows emanating from it have since covered well over 6 km² of the surrounding land and led to the displacement of tens of thousands of people⁸. Two candidate causes have been suggested: stress changes induced by nearby drilling for gas exploration⁵, and the Yogyakarta earthquake of magnitude 6.3, which occurred just two days before the eruption¹. With an epicentre 280 km away from the eruption site, the earthquake's magnitude and distance parameters do not exceed most published triggering thresholds, but some studies claim we should not be so quick to rule it out as the agent¹. So was the earthquake indeed the trigger? The question is not only academic: because of the large damage that the Lusi mud volcano has caused, an attribution of the cause to



KATIE ROBERTS

Figure 1 Example of a mud volcano. Photo of the Dashgil Mud Volcano, which is 9 km south of Gobustan, Azerbaijan.

human action could produce claims for compensation.

For a mud-volcano to erupt, the material constituting the volcanic system first needs to be liquefied — for example, through static or dynamic stress changes. A trip to the beach can illustrate the point: if the sand at the shoreline is wet enough, you will start to sink down, creating a permanent set of footprints embedded in the sand. And a little dance to keep from sinking into what feels like quicksand only causes your dance-floor to become even mushier. Typically the movement will create what looks like water escaping up around your feet and between your toes. The increase in pressure from the body weight causes the water surrounding the grains of sand in the compressed area under your feet to escape into uncompressed regions around the feet. This process whereby the sand becomes mushier, or fluidized, owing to the application of pressure is called liquefaction, and can be caused not only by the amplitude of the stress changes — that is, the body weight in this

example — but also by the duration of the stress variations.

The beach experiment illustrates how static and dynamic stress changes can induce liquefaction. A static stress change is a single permanent force that is constant, like the first footstep at the sea-shore, whereas dynamic stress changes result from an evolution of repetitive stress increase and decrease cycles — in this case analogous to the fancy footwork near the water's edge. At relatively short distances, static and dynamic stress changes can be equally large, but at greater distances, static stress changes are negligible and dynamic stresses can be orders of magnitude larger.

Davies and colleagues⁷ investigate stresses caused by earthquakes (including the Yogyakarta earthquake) as well as the drilling work at the site of the Lusi eruption. They test the possibility that the volcanic system of Lusi was teetering on the edge of stability, like a house of cards almost ready to topple, so that only a small perturbation of stress was needed to activate the eruption. But then why did

earlier earthquakes, such as a magnitude 6.6 earthquake in September 1998 that struck about 100 km closer to the Lusi volcano, not do the deed? This earlier earthquake could, of course, have primed the Lusi system for eruption, leaving the 6.3 Yogyakarta earthquake to finally kick the system into failure. But Davies and colleagues suggest that the probability of such a scenario is quite low.

Davies and colleagues estimate the static and dynamic stress changes that the 6.3 Yogyakarta earthquake generated at the site of the Lusi eruption. They find that the dynamic stresses are similar to what can be generated from the force of an adult footstep, whereas the static stress changes are about 500 times smaller than that. The nearby drilling, on the other hand, generated drill-pipe pressures capable of causing stress changes similar to the pressure generated by about 10 to 20 elephants, all balancing on a single

stool. Intuitively, these larger stress changes would be the more probable trigger of the eruption, which is what Davies and colleagues conclude. But there is no way to be absolutely certain because we are restricted to using primarily surface measurements to infer what is going on in a complex system at depth.

It is likely that there is a temporal and spatial aspect to setting a mud volcano off that induces variability in the potential triggering threshold, rendering it difficult to quantify. High-tech monitoring of the daily discharges of multiple mud volcano systems might be the best way to provide site-specific constraints and improve our understanding. Such monitoring would help establish what the recharge rates are, and whether there are connections between nearby systems. Large eruptions could require a healing period — during

which recharge occurs — before another eruption can occur, thus raising the triggering threshold.

Davies and colleagues provide the best guess of Lusi's causes, under the current constraints of data availability. Better technological tools will hopefully provide a clearer picture when the next eruption occurs.

References

1. Mazzini, A. *et al. Earth Planet. Sci. Lett.* **261**, 375–388 (2007).
2. Manga, M. & Brodsky, E. E. *Ann. Rev. Earth Planet. Sci.* **34**, 263–291 (2006).
3. Mellors, R., Kilb, D., Aliyev, A., Gasanov, A. & Yetirmishli, G. *J. Geophys. Res.* **112**, doi:10.1029/2006JB004489 (2007).
4. Wang, C.-Y., Wong, A., Dreger, D. S. & Manga, M. *Bull. Seis. Soc. Am.* **96**, 355–363 (2006).
5. Davies, R. J., Swarbrick, R. E., Evans, R. J. & Huuse, M. *GSA Today* **17**, 4–9 (2007).
6. Tingay, M., Heidbach, O., Davies, R. & Swarbrick, R. *Geology* **36**, 639–642 (2008).
7. Davies, R. J. *et al. Earth Planet. Sci. Lett.* doi: 10.1016/j.epsl.2008.05.029 (2008).
8. Cyranoski, D. *Nature* **445**, 812–815 (2007).

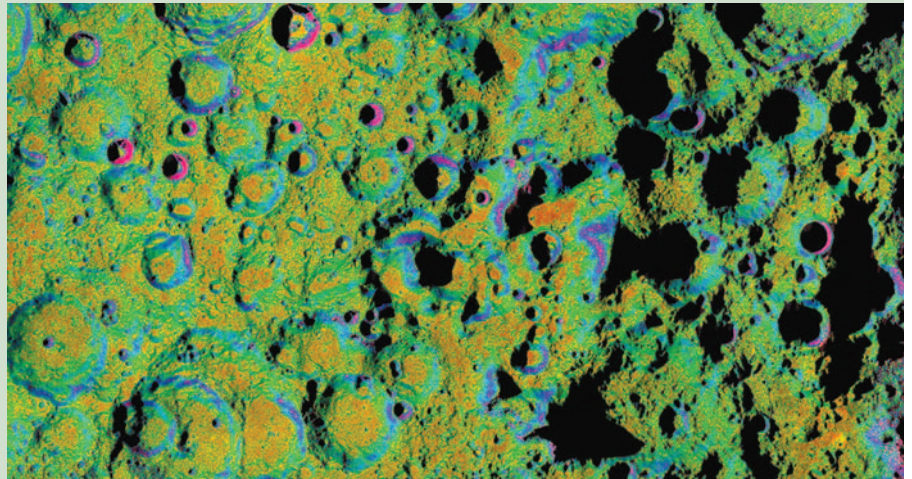
PLANETARY SCIENCE

Shackleton grows older

With the regular dispatch of new probes and spacecraft to exotic far-away planets and moons, Earth's own Moon isn't the locus of our fascination that it once was. Yet, as a recent report of substantial water in the Moon's mantle suggests, Earth's nearest neighbour hasn't revealed all its secrets. It is, after all, a body that perpetually hides one of its halves from our view.

Because of the way the Moon is tilted on its axis, its south polar region receives sunlight at a low angle, which makes it difficult to obtain information about this heavily cratered terrain. However, data returned by the recent SMART-1 mission as well as radar data from Earth-based antennae offer a fresh perspective. Paul Spudis from the Lunar and Planetary Institute, Houston, and colleagues used these data to re-evaluate the geology and age of the Shackleton Crater (*Geophys. Res. Lett.*, **35**, L14201; 2008).

The 20-km-wide crater straddles the lunar south pole, and as a result it has received a fair bit of attention. Because it is almost always in the shadows, it is also likely to be much cooler than other regions on the Moon's surface. It may therefore act as a potential trap for volatiles, such as water carried by meteorites. But a key to the crater's potential for gathering water is its



age — a relatively young crater would not be expected to trap a significant quantity of volatiles.

Previous work on the morphological attributes of Shackleton Crater suggested that it formed ~1 billion years ago and is thus a young feature (in the eyes of planetary scientists). Using their high-resolution data, Spudis and colleagues tested this assessment by making a fresh estimate of the crater's age: they looked at the density of secondary craters that had been dug into material ejected when Shackleton Crater formed. The higher the number of these craters, the older the Shackleton Crater must be.

Comparing the density of secondary craters around Shackleton Crater with that on the Moon's surface where the absolute ages are known, they came up with a crater formation date a little more than 3.5 billion years ago, much older than previously thought. The relatively fresh appearance of Shackleton Crater may have more to do with the low angle at which sunlight illuminates it rather than its age.

Shackleton Crater appears to have been around for long enough to accumulate volatiles, which might prove to be an asset if long-term human settlement on the Moon is ever planned.

Ninad Bondre