Finding **faults**

Volcano experts **Hugh Tuffen** and colleagues had been using a ten-metre-high thumb in the Icelandic landscape as a landmark to guide them to more interesting rocks. But then they realised the landmark could reveal the secret of volcanic earthquakes.

Top: The crater of Mt St Helens, July 2007, showing the active dome (back of crater) belching steam and volcanic gases. The crater walls were formed in the famous eruption on 18 May, 1980.
Above left: Faults in brightly-coloured flow-banded obsidian lava from Iceland.
Above right: The US Geological Survey collected samples from the growing dome with a lawnmower box dangling from a helicopter. USGS.

We have long known that faults in the Earth's crust cause tectonic earthquakes – so-called because they are directly linked to tectonic plate movements. This is clearly seen when large earthquakes strike, rupturing the surface and exposing the top of the fault plane. These visible faults record a vast amount of information about how earthquakes are triggered.

But some of the most earthquake-prone places on Earth are actually far from tectonic faults – they are volcanoes with growing lava domes. The epicentre of these earthquakes is just below the lava dome, and many thousands of small, shallow earthquakes may occur each year. These often immediately precede sudden dome collapses or explosions, making them vital monitoring tools. But exactly how they are triggered has been highly controversial.

Scientists have speculated that gas escaping from magma a few hundred metres beneath the surface belches through existing cracks in the volcano, triggering an earthquake. This theory falls down because the size of cracks required can be unreasonably large.

An alternative idea is that oozing magma solidifies, creating a solid plug of lava that somehow chugs upwards to the surface, creating many small earthquakes.

Exactly how these processes work – and so what earthquake patterns actually mean – has remained a mystery, partly because we can't find any distinctive sign of them in volcanic rocks from the geological record.

By chance, while I was an Open University PhD student studying lava erupted beneath Icelandic glaciers, my supervisor, Harry Pinkerton, and I stumbled across a beautifully dissected shallow vent that had fed viscous lava to the surface. For weeks we had been using the ten-metre-high thumb-shaped feature as a landmark to guide us to more interesting rocks. We realised that something strange had been going on. The obsidian lava (obsidian is a type of black glass produced by volcanoes) clearly showed all the hallmarks of the kind of fault slippage which you can find on a grand scale in earthquake zones, but in miniature. The faults were tiny – only centimetres or at most a few metres in length. The oddest thing about it was that, unlike large-scale slips, these faults in the rocks had subsequently completely healed – or melted – back together again. Were we

We used a lawnmower grassbox dangling from a helicopter.

really looking at miniature faults that had formed in hot magma – and might they have generated earthquakes?

I took a fellowship in Munich and worked with Don Dingwell, the expert in how magma flows and breaks. Some simple calculations soon suggested that the size of the faults in Iceland and the size of recorded volcanic earthquakes matched each other perfectly.

We wrote two papers controversially proposing that faulting of hot magma may trigger volcanic earthquakes, and that we had discovered the tiny, hot, hyperactive cousins of tectonic faults. While this paper was in review in 2004 the Mt St Helens volcano in Washington State erupted again. I was very happy to read that hot solidified lava was chugging out of the vent, accompanied by swarms of shallow volcanic earthquakes: this perfectly supported our theory.

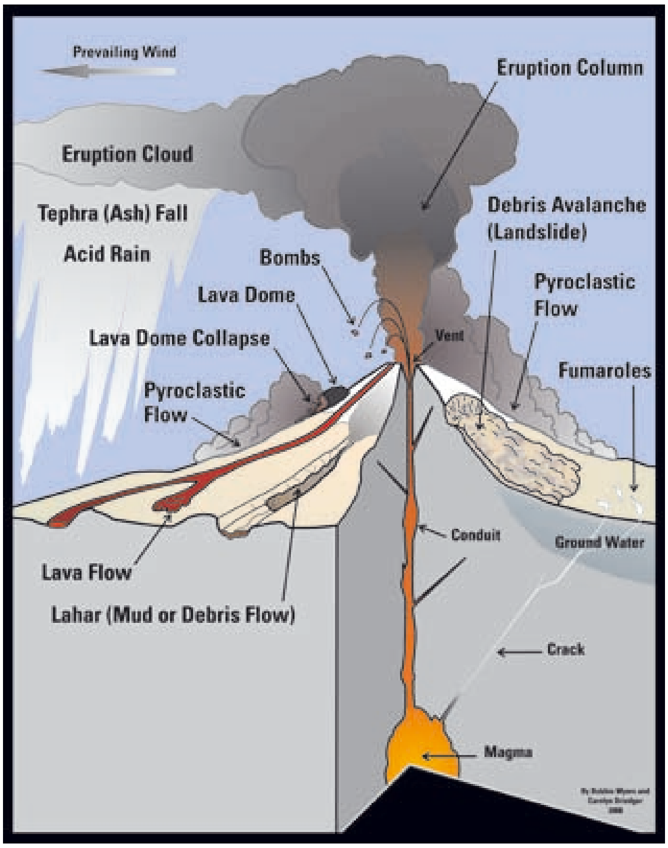
Meanwhile, Don put me in touch with Juergen Neuberg's volcano seismology research group at Leeds. His group had shown how solidifying magma goes from being ductile to brittle as it rises in a conduit, building on work by Steve Sparks and others at Bristol. We used this to predict the depth magma would fracture and found that it matched the depth of measured earthquakes pretty well.

At a conference in Japan I met Peter Sammonds, a rock physicist from University College London, and wrote a proposal to work in his experimental lab in London. Although Mt St Helens had won over some sceptics, it would be great to prove once and for all that breaking hot magma really could trigger measurable earthquakes.

Peter and colleagues have developed a unique facility for breaking rocks at high temperatures and measuring the tiny earthquakes caused by fracturing on a millimetre scale. This was exactly what we needed to test our theory. After a steep learning curve I managed to crack enough obsidian to get the results we needed. PhD student Rosie Smith was already looking at high-temperature fracture of a different kind of lava. Together with Rosie's work, we showed unambiguously that cracking of lava can indeed create measurable earthquakes, even at temperatures as high as 900°C, at which lava can flow if it is deformed more slowly. Moreover, the earthquakes in the lab looked pretty similar to those recorded at lava domes worldwide.

We published our work in *Nature* in 2008. In our paper we argued that crack growth in magma may govern movement of highly-viscous magma and earthquake triggering. In fact this process could be very similar to tectonic faulting.

So earthquakes related to crack growth may tell us something about the state of the lava dome. This is very exciting, especially if we can determine experimentally how the cracking-related earthquakes relate to the state of the magma, such as whether it is highly crystalline, riddled with cracks, or close to failure.



USGS/Bobbie Myers & Carolyn Driedger

Don's research group published a complementary paper in the same issue of *Nature* that suggests lava may indeed emit a distinctive burst of cracking immediately prior to breaking.

Back in 2006 we received more NERC funding for a project to investigate earthquakes during the recent 2004-2008 Mt St Helens' eruption. What was special about this eruption is that, together with great seismic data, the US Geological Survey (USGS) collected a large number of samples from the growing dome in the volcanic crater. This is dangerous work. They used 'Jaws' – a lawnmower grassbox dangled from a helicopter by a chain.

It looks like those damned gases may play an important role after all!

These samples allow us to measure the fracturing behaviour of a variety of dome samples from different stages of the eruption, and to compare lab results with the seismicity recorded at the volcano. This means we can explore whether changes in the nature of the lava, such as its temperature or the amount of bubbles, may affect its strength and the type of earthquakes produced before it breaks. The first results are coming out as this article goes to press. We think we can build a dataset that will allow others to understand more clearly how lava domes grow and collapse.

Regarding the seismicity, things are, however, not so simple – it looks like those damned gases may play an important role after all! Bernard Chouet from USGS and colleagues have recently proposed that some of the shallow earthquakes at Mt St Helens have nothing to do with fracture of lava but are instead triggered by slugs of gas entering a crack just beneath the dome. This is something we can also test in the lab during our NERC project, as we can introduce water into the samples to recreate the type of fluid movement into cracks that may trigger earthquakes.

It is an exciting time in volcano research, as new crossovers with other disciplines such as fracture mechanics and seismology are leading to new ways of tackling some of the most important problems. We can learn so much from bringing together geophysical observations from active volcanoes with experimentation and modelling. But there is also still a huge amount to be learned from basic field studies of volcanic rocks, an approach on which much of our understanding of volcanoes is based, but which has been increasingly unfashionable in recent years. ❖

MORE INFORMATION

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