What lies under a volcano – and how do we know?

By Professor Kathy Cashman, Bristol University

Professor Cashman based her talk on the dramatic change in the understanding of subvolcanic systems and what it means for us.

In volcanoes around the World the common feature is a magma chamber. Magma is a melt, consisting of molten silica with or without bubbles. Whilst on the surface lava or tuff deposits are the result of the cooled magma.

The magma chamber has been the dominant paradigm for 100 years, since 1911 and the phrase was coined by 'Daly'. More recently there has been a major shift in thinking. Systems are now seen as vertically extensive, formed mostly of crystals, either as a solid or a "mush", not a melt.

Why has this shift in thinking occurred?

Geophysics (in real time) and **petrology** (reverse engineering) are now used to study subvolcanic systems.

Geophysics.

Earthquake waves allude to rock composition. The P wave arrives first at a receiver, the S wave is next and the last is the surface wave which can be the most disruptive.

The P wave travels at a velocity that can be controlled by rock composition, temperature and melt fraction. The S waves cannot travel through liquids.

Earthquake waves are used to image the subsurface, P wave tomography, which is in turn used to look for a melt. The passive experiment is to use the records from seismometers dotted about. The active experiment is to set off explosives to induce waves.

Where to look for a magma chamber?

A good example for study is the Yellowstone super volcano, which had large eruptions 1.2Ma and 0.6Ma, and still has an active hydrothermal system heat source. Tomographic imaging of Yellowstone shows no large accumulation of melt, instead a mushy magma below the surface. The melt that is apparent using the scale of seismic wavelengths, is a small percentage. No large magma chamber has been found worldwide. What has been found was mush – mostly crystals with some melt, for an eruption there has to be 50-60% melt. Yellowstone does not have a large mass of magma chamber, but there is a large volume of magma stored there.

How is melt this organised?

There are two possibilities. The melt might be along the grain boundaries, or because the melt is more buoyant, the melt could segregate. The S wave anisotropy suggests that melt is organised in horizontal layers. The presence of a melt is confirmed by M-T survey which gives conductivity evidence.

Examples:

Toba in Indonesia has a melt which is segregated into sills.

TCMS: magma storage in the mid-crust Altiplano-Puna magma body in Peru has 15-25% melt about 15km below the surface.

Mid-crustal magma storage is a common feature of volcanic arcs.

How is magma transported to the upper crust?

Melt is transported in localised dykes. Connections to the surface form just before an eruption. Earthquakes are shallow until an eruption, they then spread over a large vertical column/extent.

Summary of geophysical evidence:

1. Underneath volcanoes geophysical evidence suggests the systems are dominated by crystals.
2. Some evidence of melt segregating into lenses or layers that could feed an eruption.
3. Evidence for magma chambers in the upper crust suggests they are transient.

Petrology.

Volcanoes erupt in diverse styles and produce a wide range of magma composition.

What can magma tell us?

'Reverse' engineering. During the eruption of Sci de Fuego volcano a pyroclastic flow devastated a community. The petrological evidence suggests a vertically distributed system which picked up crystals / material from several kilometres during the eruption.

By using phase diagrams and water as an example, with two or more components in a cooling liquid the composition can be shown to be variable.

Classical views of magma evolution.

Melt changes composition by:

1. Separating crystals from the melt – fractional crystallisation.
2. Melting can interact with and assimilate the surrounding crust.
3. Mixing with other melts.

How well does this model work?

Example: Mount St. Helens 1980-86.

Mount St. Helens is the result of the subduction of the Juan de Fuca plate under North America. This volcano has a 40.000 year history, and has been active in the last 4000 years, most recently between 2004 and 2006. A magnitude 4.5 earthquake took place below the volcano in March 1980. On 18th May there was a big eruption that was the worst case scenario that had been predicted. The north flank moved north by 50m in the two months before the eruption. The over steepened flank collapsed, causing a landslide, then a blast which was directed to the north, followed by a vertical column.

In 1986 eruptions continued, adding sticky, composite lava domes in the magma chamber. The bulk compositions shows a wide diversity, typical of volcanoes worldwide with a large array of crystal composition.

The mineral phase diagram was used to pinpoint the place from where the magma was stored, in the case of Mount St. Helens the eruptive magma came from about 6 km below the surface, at a temperature of 880°C. The crystals have a complex and varied histories. The observed diversity posed a conundrum which is not well explained by the presence of a single magma chamber.

From where and when did the crystals come?

By looking at melt inclusions, which are known to absorb more CO_2 and H_2O at high pressure, these pressures are consistent with earthquake depths accompanying explosive eruptions. The track of magma ascent is deduced using crystal compositions. The crystals act as clocks, with magnesium being used to determine how long the boundary was in existence. By using crystals of a known age, relative time can be converted to absolute time and compared with the earthquake sequence to image magma chamber processes.

However, the crystal cores are very old. Many of the crystals in volcanic rocks don't "belong" with the melt that transports them to the surface, and are commonly "assembled" only years to decades before they are erupted.

Summary of petrological evidence translated to trans-crustal magmatic systems.

1. Crystals are assembled from different parts of the magmatic system before being transported to the surface.
2. Crystals even next to each other within the same sample may have different histories, except for the last stages of growth.
3. Crystals have a common history at the rim, they are all in the same magma.

How to create a volcanic eruption?

The creation of a magma chamber with:

A: incremental inputs into the country rock, creating a space in the crust. This is a classical view, and requires a mafic trigger coming from below.

B: catastrophic pre-eruptive reorganization of melt lenses within the mush.

C: syn-eruptive tapping of melt lenses within mush.

Magmatic systems should be viewed as reservoirs, rather than chambers.

A reservoir configuration provides stability to accumulate a lot of melt in individual pockets, particularly if maintained at the eutectic.

A collapsing melt-mush system, or the rearrangement of melt, is not necessarily seen on the surface.

RT instabilities, (Rayleigh-Taylor instability, is an instability of an interface between two fluids of different densities which occur when the lighter fluid is pushing the heavier fluid), of thin buoyant layers under a denser layer will destabilize in mush. By looking at the changing density ratio in different tank sizes, a confined melt destabilizes on a shorter time scale, whereas an infinite system takes much longer to destabilize.

Examples:

Santorini, Greece. During the Minoan eruption of 1600BCE 60 km^3 was ejected. Eg. Druitt et al (2012) suggested the crystals had been assembled in the magma chamber 100 years before the eruption. There appear to be multiple timescale constraints for a high flux magma chamber assembly.

A variant on the above occurs when there is a collapsing melt and fluid layer and mush system. Gases are dissolved in the magma under pressure, but CO_2 is hard to dissolve. Magma is fairly incompressible. The volatiles expand which gives a hint to an eruption.

Soufriere Hills, Montserrat 1995-2010. During the eruption there were earthquakes and the release of gases. Inflation was apparent when not erupting, and deflation during an eruption. The gases released with the eruption were more than can be accounted for in the amount of magma erupted. These gases decoupled from the eruption of magma, which suggests a volatile accumulation at depth.

Stromboli – syn-eruptive tapping of vertically distributed melts. Big eruptions are preceded by lava flows. The lava flow drainage causes a magmastatic head change, the consequence of which is the influx of volatile-rich magma and paroxysmal eruption.

“Recharge” maybe syn-eruptive, with the deep and shallow reservoirs only connecting during an eruption.

Examples:

Eyjafjalljokull, 2010. Explosions were followed by lava flows, which were in turn followed by more explosions. Why were there more explosions? During the eruption at the surface, the decompressive earthquake waves propagated downwards, intersecting and tapping the deeper melt lenses. The earthquakes waves went down and stalled.

In regions of tectonic extension, melt lenses may also be tapped horizontally. Laki in Iceland produced 15 km^3 of lava. The H_2S oxidised (stimulated by sunlight) to H_2SO_4 and formed sulphuric acid. In 1814 this caused acid rain to fall and created problems with crop failure in Europe. Where the Mid Oceanic Ridge was pulling apart, vent migration meant there were isolated, laterally distributed melt pockets.

The Taupo volcanic zone in New Zealand is also pulling apart, with several large associated rhyolitic eruptions. Different magma types evidence suggests are being tapped from horizontally aligned melt lenses, as in Iceland.

Studies of super volcano eruptions are also starting to provide evidence of multiple melt lenses.

Examples:

Cerra Galan in the Andes.

Yellowstone there are nine different melt pockets. In an earlier stage there were up to eighteen melt pockets.

Super volcano eruptions: areas for exploration.

1. When do isolated lenses combine to produce a very large eruption?
2. Are multiple magma storage regions required to make a really big eruption?

Summary:

1. Volcanoes are underlain by extensive heterogeneous magma/mush systems. These systems are vertically extensive.
2. The magmatic systems are quite variable in their crystal to melt ratio.
3. The big challenge is to try to figure out when, how and where these systems can produce large eruptions.

The most recent advancement in the study of volcanic provinces is the use of drones to photograph and collect data.

March, 2019.