Splitting continents

Why do some pairs of continents trigger lots of volcanoes when they break apart, while others don’t? Jenny Collier describes how her team’s work is providing answers, suggesting the truth is a lot more complex than traditional theories have assumed.

According to Plate Tectonic Theory, the Earth’s outer rigid shell (or lithosphere) consists of a dozen or so ‘plates’, which float on a viscous mantle like slabs of ice on a pond. These plates move constantly, driven by the release of energy from the Earth’s molten interior. This motion has characterised our planet for the past 4.5 billion years, and will probably continue for another 4.5 billion years until, finally, the heat supply runs out. Then the Earth will be geologically dead like the Moon or Mars, and no new oceans or mountain chains will be created.

Because of plate tectonics, in the past the continents have undergone cycles of collision and amalgamation followed by splitting and separation. These major reorganisations of the landmasses have dictated many climatic and evolutionary developments. The last phase of this cycle started around 167 million years ago, with the break-up of Pangaea to form today’s familiar world map.

Continental break-up is a fundamental part of Earth history. We know that when it happens, it can do so either with a bang – a period of explosive volcanism – or with a whimper, with hardly a volcano in sight.

The consensus among scientists before our work was that these very different styles of break-up are controlled by the temperature of the mantle beneath the separating continents. According to this theory, if hot mantle is present, for example due to an underlying plume rising from deeper in the Earth, then a volcanic margin will form. This has been the cornerstone of our understanding for 20 years.

The emphasis on mantle temperature as the main control on what happens when you stretch and break the lithosphere was mostly based on observations made along the borders of the Atlantic Ocean. These areas were the best studied as they are in easy reach for most European and North American research vessels. However, the mantle temperature model was so simple and elegant that it was applied globally, even where there was no direct data to support it.

Stretching the theories

As scientists went out and studied other areas, the idea started to be questioned. Some researchers suggested, for example, that the rate at which the stretching occurred before break-up had been overlooked. If it happened faster, would it lead to more volcanism? We decided to test this in an area that stretched much more quickly than the Atlantic examples, yet was also thought to sit over hot mantle: we went to the Indian Ocean to study the separation of India from the Seychelles.

This break-up occurred shortly after the extrusion of the Deccan Traps – a vast pile of basaltic rocks that covers about a third of India to a depth of about 2km. We wanted to look for the offshore extension of these volcanic rocks that, according to the prevailing theory, should have formed when the two continents separated.

Our project was ambitious, so we compiled a team of researchers from three institutions – Imperial College, London, the National Oceanography Centre in Southampton, and Leeds University – and arranged for geophysical instruments from four different organisations to be delivered in three 30ft containers. Planning for the cruise in 2002 and 2003 was tense, with the build-up to the Iraq war resulting in several changes to our port and start date. It was a huge relief when we finally set sail with all the equipment on board!

Our goal was to collect the data needed to produce a seismic image from which we could identify any volcanic material that had been erupted as the continents split apart. We needed to determine the seismic velocity – the speed at which a seismic wave travels through rock – below the seabed by letting off bursts of compressed air and recording the signal with seismometers placed on the seafloor.

We wanted to record signals that had travelled 20-30km into the Earth, so we assembled one of the loudest airgun arrays ever fired from a NERC vessel and a total of 32 receivers. All this equipment covered the decks of the RRS Charles Darwin completely. First we surveyed the Indian side of the divide then sailed across the equator to survey the Seychelles side. One highlight for the novice sailors on board was an extensive and educational survey along the equator to survey the Seychelles side. Once our computer model we simulate the

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Existing theories simply couldn’t explain the near-complete absence of volcanism along the India-Seychelles margin. Was it possible that despite the presence of the Deccan Traps there had been no mantle plume? What about the stretching rate? We set out to test our understanding of how the Earth works using state-of-the-art modelling.

In our computer model we simulate the initial stretching and break-up of a piece of lithosphere and use it to calculate how much volcanicism erupts to the surface. At any time we can vary the temperature of the mantle (for example, to simulate the arrival of a hot plume), stop, then restart the stretching and alter the stretching rate. To make sure that the model was working correctly we also compared its predictions to the well-studied case of the North Atlantic.

The results showed that the difference between bang and whimper break-up is not down to anything as simple as ‘hot or not’. Instead, the geological history of the region is critical. It is not simply the stretching rate that matters, but rather the relative timings of the phases of extension and arrival of hot mantle beneath the thinning lithosphere. In the North Atlantic, we found that earlier extension focused the hot upwelling mantle, allowing it to reach shallow depths quickly and leading to melting and volcanicism when break-up occurred.

In the Indian Ocean, there was also an earlier episode of extension but it caused more stretching and happened closer in time to the break-up, so it tapped and exhausted the hot mantle. Therefore despite similar hot mantle temperatures below the thinning lithosphere in both cases, in the Atlantic the pre-break-up events enhanced volcanic eruptions, whereas in the Indian Ocean they turned them off.

Our research shows the need for a major review of the traditional hot-mantle volcanic margin hypothesis. We have found that rift history can either suppress or enhance the production of magma and is just as important as mantle temperature in controlling what happens. This underlines how much we still have to learn about how our planet works – and that the only way to do this is to get out there and make new observations.

MORE INFORMATION
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