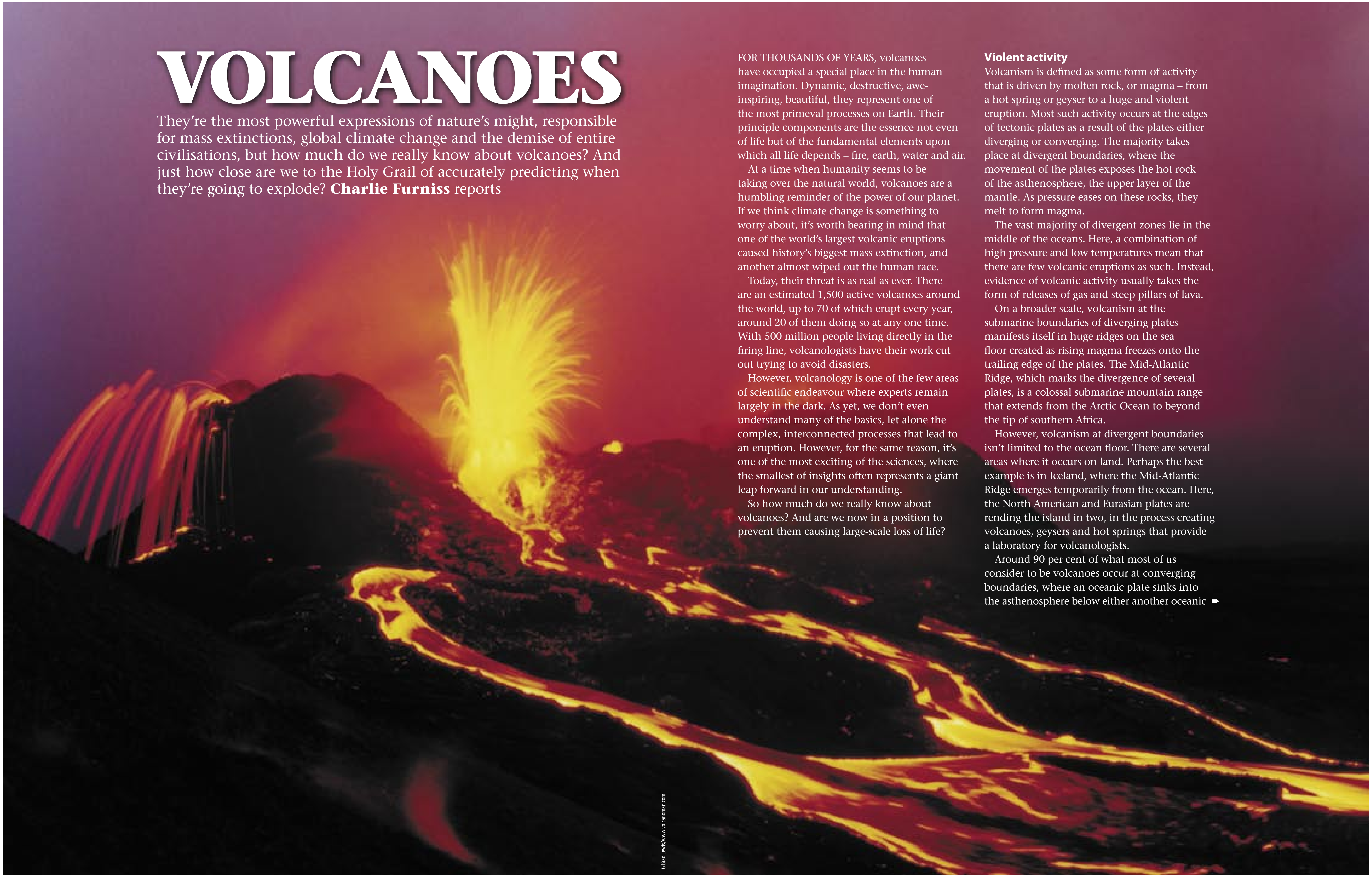

G Brad Lewis/www.volcanoman.com

VOLCANOES

They're the most powerful expressions of nature's might, responsible for mass extinctions, global climate change and the demise of entire civilisations, but how much do we really know about volcanoes? And just how close are we to the Holy Grail of accurately predicting when they're going to explode? **Charlie Furniss** reports

FOR THOUSANDS OF YEARS, volcanoes have occupied a special place in the human imagination. Dynamic, destructive, awe-inspiring, beautiful, they represent one of the most primeval processes on Earth. Their principle components are the essence not even of life but of the fundamental elements upon which all life depends – fire, earth, water and air.

At a time when humanity seems to be taking over the natural world, volcanoes are a humbling reminder of the power of our planet. If we think climate change is something to worry about, it's worth bearing in mind that one of the world's largest volcanic eruptions caused history's biggest mass extinction, and another almost wiped out the human race.

Today, their threat is as real as ever. There are an estimated 1,500 active volcanoes around the world, up to 70 of which erupt every year, around 20 of them doing so at any one time. With 500 million people living directly in the firing line, volcanologists have their work cut out trying to avoid disasters.

However, volcanology is one of the few areas of scientific endeavour where experts remain largely in the dark. As yet, we don't even understand many of the basics, let alone the complex, interconnected processes that lead to an eruption. However, for the same reason, it's one of the most exciting of the sciences, where the smallest of insights often represents a giant leap forward in our understanding.

So how much do we really know about volcanoes? And are we now in a position to prevent them causing large-scale loss of life?

Violent activity

Volcanism is defined as some form of activity that is driven by molten rock, or magma – from a hot spring or geyser to a huge and violent eruption. Most such activity occurs at the edges of tectonic plates as a result of the plates either diverging or converging. The majority takes place at divergent boundaries, where the movement of the plates exposes the hot rock of the asthenosphere, the upper layer of the mantle. As pressure eases on these rocks, they melt to form magma.

The vast majority of divergent zones lie in the middle of the oceans. Here, a combination of high pressure and low temperatures mean that there are few volcanic eruptions as such. Instead, evidence of volcanic activity usually takes the form of releases of gas and steep pillars of lava.

On a broader scale, volcanism at the submarine boundaries of diverging plates manifests itself in huge ridges on the sea floor created as rising magma freezes onto the trailing edge of the plates. The Mid-Atlantic Ridge, which marks the divergence of several plates, is a colossal submarine mountain range that extends from the Arctic Ocean to beyond the tip of southern Africa.

However, volcanism at divergent boundaries isn't limited to the ocean floor. There are several areas where it occurs on land. Perhaps the best example is in Iceland, where the Mid-Atlantic Ridge emerges temporarily from the ocean. Here, the North American and Eurasian plates are rending the island in two, in the process creating volcanoes, geysers and hot springs that provide a laboratory for volcanologists.

Around 90 per cent of what most of us consider to be volcanoes occur at converging boundaries, where an oceanic plate sinks into the asthenosphere below either another oceanic ➨

> “A volcano could start rumbling tomorrow and have a massive explosion in two weeks’ time, and we wouldn’t have any more notice than that”

plate or a continental plate – a process known as subduction. (Continental plates are too buoyant to subduct, so there is no volcanism associated with their convergence.)

At all subduction zones, the same processes lead to the production of magma. As the oceanic plate descends into the hot asthenosphere, heat and pressure melt the minerals of the plate itself, as well as sediments such as quartz and clay minerals that were present on the top. These processes release water vapour and carbon dioxide, and more magma is produced when these gases reduce the melting point of the hot, soft rock in the asthenosphere.

As magma is less dense than the surrounding rocks, it finds its way up through the upper plate to shallow levels, where it often resides in so-called magma chambers. “Depending on how these are recharged and what is happening above them,” says Dork Sahagian, professor of earth and environmental sciences at Lehigh University, Pennsylvania, “these can supply magma for an eruption.”

At subduction zones, volcanism is often expressed as a broad arc of volcanoes on the surface of the upper plate. (The arc arises because of the curvature of the Earth – think about the shape that’s made by cutting into the peel of an orange.) These arcs are most evident as chains of islands formed where oceanic plates converge. The islands are formed as erupted lava and volcanic debris pile up on the ocean floor over millions of years, eventually reaching the surface. The Marianas and Aleutian islands, where the Pacific and Philippine, and Pacific and North American plates meet respectively, are perhaps the best examples.

On land, the arc formation is less apparent. Nevertheless, volcanism resulting from oceanic–continental plate convergence is evident among long mountain ranges that run parallel to a coastline – the Cascade Mountains in the western USA or the Andes in South America, for example.

However, not all volcanoes are associated with divergent and convergent plates. Those in Hawaii, for example, lie in the middle of the Pacific plate, thousands of kilometres from its boundaries.

In 1963, Canadian geophysicist Tuzo Wilson of the University of Toronto noticed that the Hawaiian islands lay in a chain that became progressively older towards the northwest. Noticing the same pattern in other Pacific island groups, Wilson hypothesised that they were formed where the plates moved over what became known as volcanic ‘hotspots.

During the early 1970s, US physicist Jason Morgan subsequently suggested that the sources of hotspot volcanism were mantle plumes – fountains of magma that bubbled up from the edge of the Earth’s core. “The plume theory suggests that the heat of the core creates thermals in the asthenosphere – just like those in the atmosphere – which cause volumes of magma to rise to the surface,” says Gillian Foulger, professor of earth sciences at Durham University.

Today, scientists believe that there may be as many as 50 hotspots around the world, with Hawaii, Reunion, Yellowstone and Iceland overlying the most active. However, during the past ten years, the mantle plume explanation has been the source of vigorous debate (see *Hotspot theory feels the heat*).

Top: the lake inside the caldera of Mount Pinatubo in the Philippines was created by magma loss when it erupted in 1991; **Above:** the Galapagos Islands formed over a volcanic hotspot

Jim Sugar/Corbis

Roger Ressmeyer/Corbis; Corbis

Sticky magma

The 1883 eruption of Krakatau, an Indonesian volcanic island in the Sunda Strait, is perhaps the most famous in recent history. Its magnitude is legendary. The explosion was 13,000 times as powerful as that of the atomic bomb that destroyed Hiroshima. The sound was heard more than 4,000 kilometres away in Mauritius. The subsequent tsunamis rocked ships off the coast of South Africa and were detected as far away as the English Channel. More than 36,000 people died.

But not all volcanoes are so violent. Indeed, volcanologists recognise two types of volcanic eruption: explosive and effusive. The composition of magma is the key. “Sticky magmas prevent gas from escaping,” says Bill McGuire, director of the Benfield Hazard Research Centre at University College London, “so pressure builds up and leads to a violent eruption. Where magmas are of relatively low viscosity, the gases can escape very easily, so you don’t get the same build up of pressure.”

Sticky magmas tend to occur at subduction zones, while the more fluid magmas are more commonly associated with divergent plates and hotspots. “At subduction zones, the magma is more viscous because it contains a high proportion of silica-rich sediments and partially melted sub-crustal rock,” says Sahagian. “The basaltic magmas that occur most frequently at divergent boundaries are more fluid because their silica content is lower and the rock is more completely melted.”

Basaltic lava from effusive volcanoes certainly has the ability to inundate and destroy property, says McGuire, but it tends to flow so slowly that it’s rarely a threat to human life. “It’s the explosive volcanoes, particularly those around ➨

The birth of an eruption

Above: Kilauea, on Hawaii’s Big Island, is one of the world’s most active volcanoes, but its eruptions tend to be relatively sedate

The processes that cause eruptions are occupying the minds of many volcanologists today. Understanding what causes magma to break through to the Earth’s surface provides the key to predicting the timing, nature and magnitude of an eruption, and can help prevent the loss of lives.

Dork Sahagian of Lehigh Univeristy, Pennsylvania, and Alex Proussevitch of the University of New Hampshire have produced some of the most groundbreaking work. During the past 15 years, they’ve shown how an explosive eruption is caused by the growth of bubbles of water vapour and carbon dioxide within magma once it has collected close to the Earth’s surface. Sahagian explains: “The basic idea is that as magma rises, the pressure in the system decreases, so the gases become less soluble and nucleate [form bubbles]. It’s the same principle that causes bubbles to appear as if from nowhere when you unscrew the cap of a fizzy-drink bottle.”

This growth of bubbles contributes to a process of positive feedback. As they grow, the magma rises, the pressure reduces and the bubbles grow further.

However, this feedback process requires a trigger. “A magma chamber might be quite stable until something alters the equilibrium,” says Sahagian. “This might be new magma coming from below, introducing more gas into the system. Or it might be a landslide or another form of surface deformation that unplugs the system and releases the pressure.” The latter often results in cataclysmic events and was the trigger for the eruption of Mount St Helens in 1980.

Whatever the trigger, the effect is the same: to cause bubbles to grow and the system to expand. Eventually, the bubbles can grow so large and so abundant that the magma turns to foam. In basaltic eruptions, this foam dissipates relatively harmlessly. “There tends to be less water in the system, so there is less gas to start with,” Sahagian explains. “And the low level of silica means the magma is less viscous and any gas can escape from the bubbles more easily.”

However, at subduction zones and some hotspots, higher silica levels mean the magma is very viscous, so the gas can’t escape so easily. “The bubbles grow so large and so quickly that the foam eventually disrupts and basically explodes.”

Hotspot theory feels the heat

When Jason Morgan proposed his mantle plume theory to explain the origin of volcanic hotspots during the early 1970s, it was quickly accepted by the geological establishment. His beautifully simple hypothesis suggested that they were the result of columns of magma rising from the edge of the Earth's core. Chains of volcanic islands such as Hawaii and the Canaries were thus formed over millions of years as tectonic plates passed over the stationary plumes.

Not only did Morgan's proposition fit perfectly with plate tectonics theory – at the time the trendiest idea in earth sciences – but it also offered a tantalising glimpse into the chemistry and dynamics of the planet's interior.

Over the past decade, however, some scientists have begun to doubt the theory's validity. One of the first was Gillian Foulger, professor of earth sciences at Durham University. In 1996, she took a team of researchers to Iceland to search for mantle plumes using state-of-the-art seismic equipment. But instead of finding a narrow column extending 3,000 kilometres down to the core–mantle boundary, she found only a shallow, slab-shaped body that lay no deeper than 500 kilometres.

Soon after, another group from the California Institute of Technology announced that they had found the same results in a global study.

Since then, other inconsistencies have emerged. The ages of some of the island chains supposedly formed by plumes vary almost randomly, rather than progressing in an orderly manner in a particular direction. And analysis of rocks from the Icelandic crust shows that they weren't created at a temperature hot enough to form a plume. Many scientists now also believe that the pressure at the Earth's core is too high to allow narrow plumes to form at all.

Foulger believes that hotspots are caused by geological processes that take place at shallow depths, but admits that understanding them fully will require more work. However, one hypothesis suggests that the formation of island chains is caused by cracks in the crust that form as plates stretch.

the Pacific plate – the so-called Ring of Fire – that we have to be most concerned about," he says.

The principal dangers associated with explosive volcanoes are what's known as pyroclastic flows and lahars. "Pyroclastic flows are clouds of ash and gas that become more dense than air," says Sahagian. "So instead of rising up into the sky, they run down the side of the volcano." A basal flow of more coarse volcanic material often moves along the ground underneath this cloud.

Nothing is safe from a pyroclastic flow. If the extreme temperatures – up to 700°C – don't incinerate everything in its path, then rocks and boulders, often travelling at velocities in excess of 100 kilometres per hour, will destroy whatever remains. The flows that accompanied the eruption of Krakatau were so violent that they not only killed 1,000 people some 40 kilometres across the Sunda Strait in Sumatra, they also created huge tsunamis – some more than 30 metres high – that killed more than 35,000 others on Sumatra, Java and other islands in the region.

Lahars, or mudflows, occur mostly commonly after an eruption, when intense rainfall erodes loose volcanic rock and soil. However, they can also form during an eruption when snow and ice melt rapidly or the wall of a crater lake gives way. The debris can vary in size, from small pebbles to boulders ten metres in diameter. Like those of pyroclastic flows, the effects of lahars racing down mountainsides and into river valleys can be devastating: around 23,000 people were killed by lahars following the eruption of Nevado del Ruiz in Colombia in 1985.

Averting disaster

The historical record is littered with evidence of the destructive capabilities of volcanoes. The eruptions of Santorini in 1628 BC and Vesuvius in 79 AD are among the most famous. Today, the threat is as real as ever – one in 12 people lives within a volcanic danger zone.

But according to McGuire, it's impossible to know precisely which volcanoes present the biggest danger. "Twelve of the biggest eruptions in the past 200 years were the first time that volcano had erupted in historical times," he says. "None of these would have been considered a particular threat until they showed signs of activity. A volcano could start rumbling tomorrow and have a massive explosion in two weeks' time, and we wouldn't have any more notice than that."

Although we can't stop volcanic eruptions, volcanologists can help to avert disasters by monitoring volcanic activity and attempting to predict the timing and nature of eruptions. Seismometers record movements that occur within the volcano – earthquakes, rifting,

➨

Michele Falzone/JAI/Corbis

Alberto Garcia/Corbis

Opposite: Gunung Bromo in eastern Java, Indonesia – grey ash that fills the caldera gives the area a moonscape-like appearance; **Above:** volcanologists had successfully predicted the timing of Mount Pinatubo 1991 eruption and organised an evacuation

Opposite: survivors of the 2002 eruption of Mount Nyiragongo in the Democratic Republic of Congo flee across a lava bridge in the devastated town of Goma on their way to safety in neighbouring Rwanda. One in 12 people live within a volcanic danger zone

landslides, mudflows and so on – caused by magma rising to the surface. Each of these mechanisms has a characteristic waveform by which they can be identified.

Deformation of the ground and the volcano itself – known as the edifice – generally indicates an intrusion of magma beneath, says Jeff Johnson, professor of geophysics and volcanology at the University of New Hampshire. "So if we see the edifice expanding it's a sign that we have something to worry about." Sophisticated GPS technology, tiltometers and satellite-mounted radar instruments capture such movements to the millimetre level.

Gas emissions indicate whether or not the conduit is open, and so whether or not pressure is building up within the system. "Gas escaping is a good thing," says Johnson. "However, if we have a system displaying deformation and a lot of seismicity, but which is releasing no gas, we start to worry that it's building up to a huge pop."

Measuring gas emissions would once have meant taking readings inside the crater. Today, however, volcanologists can monitor levels of sulphur dioxide using an ultraviolet spectrometer. "Because sulphur dioxide absorbs UV light," says Johnson, "you can measure how much UV isn't reaching your instruments and convert that into a concentration of gas."

Similarly, remote infrared technology measures the radiative temperature of surfaces around a volcano. Scientists from the Philippine Institute of Volcanology (PIV) and the US Geological Survey (USGS) used a range of monitoring techniques to avert disaster in the Philippines in 1991, when Mount Pinatubo began rumbling in March that year. Over the following months, signs of activity increased. And when a large explosion on 7 June sent a column of ash seven kilometres high, the volcanologists warned of an eruption within the next two weeks. In the week that followed, the authorities organised an evacuation of the area, and by 14 June, 60,000 people had left a 30-kilometre zone around the mountain.

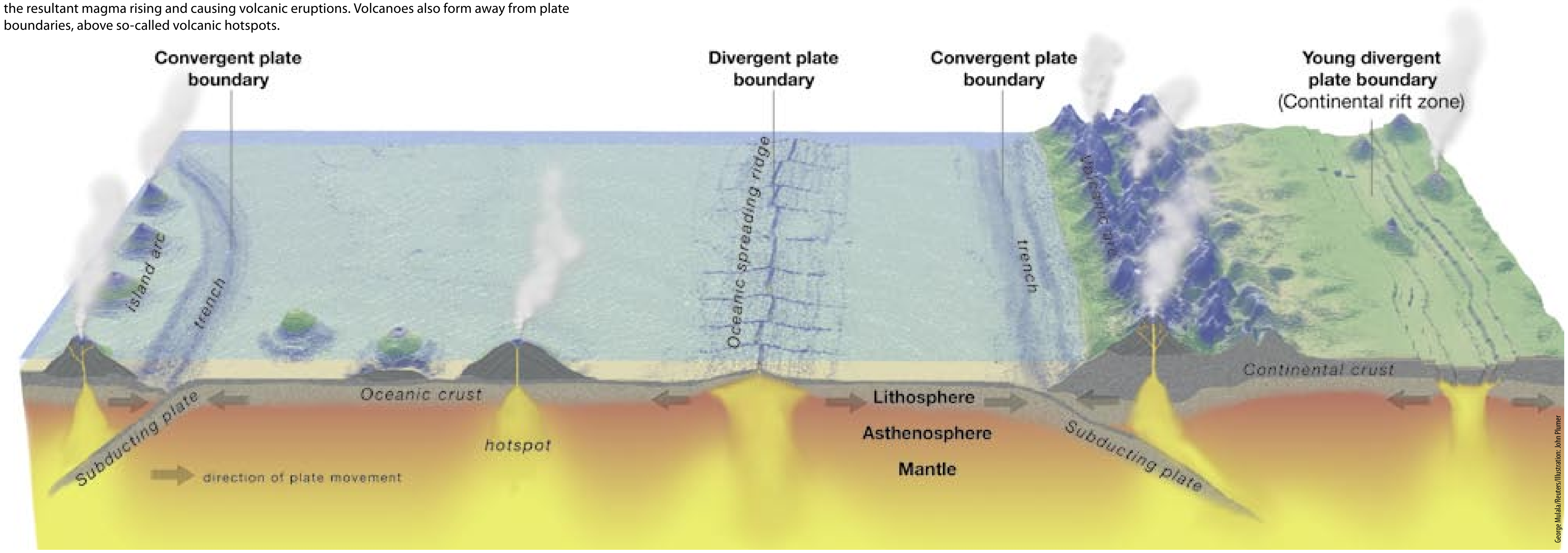
They were just in time. On 12 June, Pinatubo entered a violent eruptive phase that saw four large explosions generate columns of ash up to 24-kilometres high and pyroclastic flows that extended four kilometres from the mountain. The largest came on 15 June. A colossal eruption ejected a cloud of ash 34 kilometres into the atmosphere. Pyroclastic flows extended 16 kilometres from the mountain and ash deposits ➨

How big a bang?

In 1982, volcanologists Christopher Newhall and Steve Self devised the Volcanic Explosivity Index (VEI) as a way of describing the scale of an eruption. Several factors are used to assign eruptions a score, including the volume of erupted material, the height of the eruption column and the duration. The index ranges between zero and eight, with each increase in score representing a ten-fold increase in the various factors. The highest score on the list, VEI8, is reserved for eruptions that emit more than 1,000 cubic kilometres of material.

Subduction in action

The vast majority of volcanoes are found along the boundaries of tectonic plates. Convergent boundaries, where the plates are crashing into each other, host around 90 per cent of what we generally think of as volcanoes. Here, as one plate is pushed below another – a process known as subduction – it melts, the resultant magma rising and causing volcanic eruptions. Volcanoes also form away from plate boundaries, above so-called volcanic hotspots.



George Mulala/Reuters/Illustration: John Plumer

> “Volcanology is one of the most exciting fields of scientific endeavour. It’s one of the few sciences where new insights often represent real breakthroughs in our understanding”

mixed with rains from Typhoon Yunga, causing huge lahars to race down the mountain’s side.

Pinatubo turned out to be one of the largest volcanic eruptions in history. With a Volcanic Explosivity Index of six, it sent out an estimated 25 square kilometres of erupted material. As such, it ranks alongside Krakatau and the famous eruption of Santorini, which some scholars believe brought about the downfall of the Minoan civilisation. But thanks to the efforts of the PIV and the USGS, only 300 people died. However, predicting the timing of an eruption isn’t always so straightforward.

The problem with predictions

Mount Tungurahua in central Ecuador has erupted every 80–100 years during the past millennium, and geological evidence suggests that if a similar eruption took place today, thousands of people would be in grave danger. So one would assume that when seismometers detected a change in activity last May, the area would have been evacuated immediately. However, scientists at Tungurahua Observatory were in a difficult position.

In October 1999, the authorities evacuated 30,000 people from the area on the advice of volcanologists. But when the predicted eruption didn’t materialise, the evacuees grew restless. Many had already lost their livelihoods. Stuck in sub-standard living arrangements, they began to demand repatriation. When a group of protestors marched on a military blockade outside the town of Baños, a scuffle ensued and the army shot and killed a member of the public. Fearing further unrest, the government relented and allowed the people to return to their homes.

In the years that followed, Tungurahua continued to bubble away: there were regular explosions, tremors, ash plumes and gas emissions. Incandescent material flew from the crater, and occasionally lahars cascaded down the slopes. Although the area remained on alert, local residents had become somewhat blasé about the threat, and the authorities were reluctant to disrupt their lives once more.

But when the number of explosions began to drop off, the volcanologists grew nervous. “We could interpret these readings in one of two ways,” says Johnson. “Either the majority of the gas in the system had escaped, and any eruption would be non-explosive and effusive. Or the system had plugged itself up and was building up to a huge explosive eruption.”

In the event, they took a gamble and advised the government to order another evacuation. And, as unpopular as it was at the time, it soon proved to be the right decision.

On 16 August, Tungurahua produced the largest eruption in the sequence that began in 1999. Although it was only classified as VEI2, it was potentially devastating. It sent an ash plume eight kilometres into the atmosphere; large incandescent rocks rained down over nearby villages and farmland; pyroclastic flows raced down the western and northwestern slopes; entire villages were engulfed and livestock and crops devastated. However, thanks to the volcanologists’ nerve, only five people died.

The dilemma faced by the scientists at Tungurahua is shared by all volcanologists engaged in predicting the timing and nature of eruptions. “It’s an incredibly difficult task,” says Johnson. “And because of the stakes involved – peoples’ livelihoods or their lives – it’s an incredibly stressful one, too.”

Because there are several mechanisms involved and still a lot of unknowns, he says, it’s impossible to be 100 per cent sure. “If the crater is getting hotter, that could mean magma is approaching the surface or it could mean that a crack has opened – perhaps during an earthquake – from which hot water is escaping.”

The only way to predict patterns more accurately is to study the mechanisms of volcanic eruptions as they happen. “Volcanology is a very young science,” Johnson explains, “and we only have a few examples of big eruptions on which to base our knowledge. At the moment, we’re building up our understanding of the precursary signals of different types of eruption. In 50 years’ time, we’ll have another half dozen examples, and hopefully we’ll be in a better position to make more accurate predictions.”

Scientists such as Dork Sahagian and Alex Proussevitch hope that models will eventually help improve the prediction of eruptions. Based on their groundbreaking studies into the growth of bubbles in magma (see *The birth of an eruption*) they have built a computerised model that replicates accurately the eruption process. “We’ve drawn data from experiments on the behaviour of gasses in a variety of liquids, including molten natural rock, artificial silicate melts and even syrup,” says Sahagian.

However, he too says that they need more information to make reliable predictions. “Our model can reproduce a generic volcanic eruption, but we need data about a specific volcano – its shape, geometry, stress fields, strength of the edifice and so on – before we can accurately replicate its behaviour.”

Most of these things are relatively easy to measure, but one crucial factor is still missing, he says. “The plumbing system that delivers magma to the surface – the conduit geometry – is perhaps the most important factor of all.” The popular image of a single pipe rising to the top of a volcano is fallacy, he says. “These are incredibly complex systems made up of a collection of little conduits and pipes, the geometry of which is very important and very difficult to determine.”

To date, no-one has attempted to map a volcano’s conduit geometry. Although it may be technically possible, says Sahagian, the associated practicalities, cost and risk mean it’s impossible to find funding. “Mapping the conduit geometry is the Holy Grail. If we could do that, it would be a major step forward.”

Despite the size of the challenge and the responsibility that accompanies monitoring and modelling work, Sahagian remains enthusiastic about the task ahead. “Volcanology is one of the most exciting fields of scientific endeavour. It’s one of the few sciences where new insights often represent real breakthroughs in our understanding.”

In many ways it’s more similar to astrophysics than it is to other earth sciences, he says, because volcanologists can neither observe the processes directly nor conduct full-scale experiments. “It’s one of those things where the more you know, the more you realise how much you don’t know. I’m not even sure that we know enough yet to know how much we don’t know. But we’re learning all the time, and although there’s still a long way to go, we’re beginning to understand some of the basics.”

George Mulala/Reuters

Jim Nieland/USGS; Lyn Topinka/USGS

Opposite: a rebel soldier supervises the clearing of lava in Goma after the eruption of Nyiragongo; **Top:** prior to the May 1980 eruption, the area around Mount St Helens in the Cascade Range, Washington, USA, was popular with tourists; **Above:** the eruption reduced the mountain’s height by about 400 metres