THE CAUSE OF VOLCANIC ERUPTIONS

BY ANDREW ROBINSON

Volcanoes have been a major force in shaping the planet we live on – yet until quite recently, we knew surprisingly little about them

THE WORLD'S MOST recent major volcanic eruption — that of Mount Ontake in Japan, 200km west of Tokyo, in September 2014 — took hikers and scientists by surprise. More than 60 people were killed by ash, stones and poisonous fumes, yet scientific instruments located around the volcano had given no signal of the coming explosion.

Tiltmeters and sensors connected to the GPS satellites — designed to measure the angle and elevation of the slopes — showed no change during the run-up to the eruption, or even while it was in progress. This indicated that there was no rise in molten rock, or magma, within the mountain. Seismometers showed a spike in activity about two weeks before the eruption, but this settled down at a rate of 10-20 small earthquakes per day: a level much lower than that of many Japanese volcanoes, such as the iconic Mount Fuji (which last erupted in 1707). A mere 11 minutes before Ontake's blast, seismometers detected a volcanic tremor: a type of seismic activity untypical of the earthquakes that frequently accompany eruptions.

The earliest human reference to volcanism is probably an enigmatic wall painting from the settlement of Çatalhöyük in Anatolia, western Turkey, which may show a volcano erupting over tightly packed houses – perhaps a depiction of neighbouring Mount Hasan's eruption in 6200BC. However, the first reliable references to volcanism date from ancient Greece and Rome. Plato accurately described the formation of lava or obsidian (volcanic glass): "Sometimes when the earth has melted because of the fire, and then cooled again, a black-coloured stone is formed," he wrote.

Aristotle, who coined the word 'crater' (Greek for 'cup') to describe the shape of volcanic summits, less accurately said that the fire beneath the earth was the result of "the air being broken into particles which burst into flames from the effects of the shocks and friction of the wind when it plunges into narrow passages".

This ancient wall painting from Çatalhöyük, Turkey, seems to depict a volcano erupting close to a human settlement

Famously, Pliny the Younger gave an eyewitness account, in AD 79, of the eruption of Mount Vesuvius that buried Pompeii and Herculaneum. The disaster killed his uncle, naturalist Pliny the Elder, when he went on a rescue mission to help Pompeii. Today, 'Plinian' is the term used to describe a Vesuvian type of eruption.

DIGGING FOR KNOWLEDGE

It is ironic that Pliny the Elder died as a result of an eruption. Although he compiled in his *Naturalis Historia* the earliest coherent list of active volcanoes, Vesuvius went unmentioned, presumably because it was not known to have erupted. In the following years, its danger was forgotten, along with Pompeii and Herculaneum. Only after another major eruption in 1631 (following six centuries of repose) were the towns rediscovered when wells were sunk during the rebuilding of modern Portici, which turned out to

Sicily's Mount Etna, pictured here in April 2013, is one of the world's most active volcanoes

> IN A NUTSHELL

Plato gave us the first description of lava, but it wasn't until the late 18th Century with the work of William Hamilton and others that the study of volcanoes began in earnest. This led to our modern-day understanding of their role in shaping the planet.

lie on top of Herculaneum. Pompeii and Herculaneum were excavated from the 1730s onwards, and prompted the first stirrings of our understanding of volcanoes.

In the 1750s, French botanist Jean-Étienne Guettard recognised that the black stone used for construction in France's Auvergne region was similar to Italian rocks from Vesuvius and Mount Etna. He discovered that the stone in the French buildings was quarried at Volvic, a village south of Vichy. He guessed that 'Volvic' came from the Latin *volcani vicus*, 'volcanic village' – so it seemed that the Romans were aware of the connection, too.

Guettard visited the Volvic quarry and climbed the hill behind it. To his delight, a series of old volcanic cones stretched before him, now smooth and vegetated. In 1752, he delivered a paper to the French Academy of Sciences entitled *Memoir On Certain Mountains In France That Have Once Been Volcanoes*. Over the next few decades he and others, notably Nicolas Desmarest, studied and mapped a chain of 50 volcanoes in the Auvergne, the most famous being Puy de Dôme. We now know that the last eruption there occurred about 6,000 years ago.

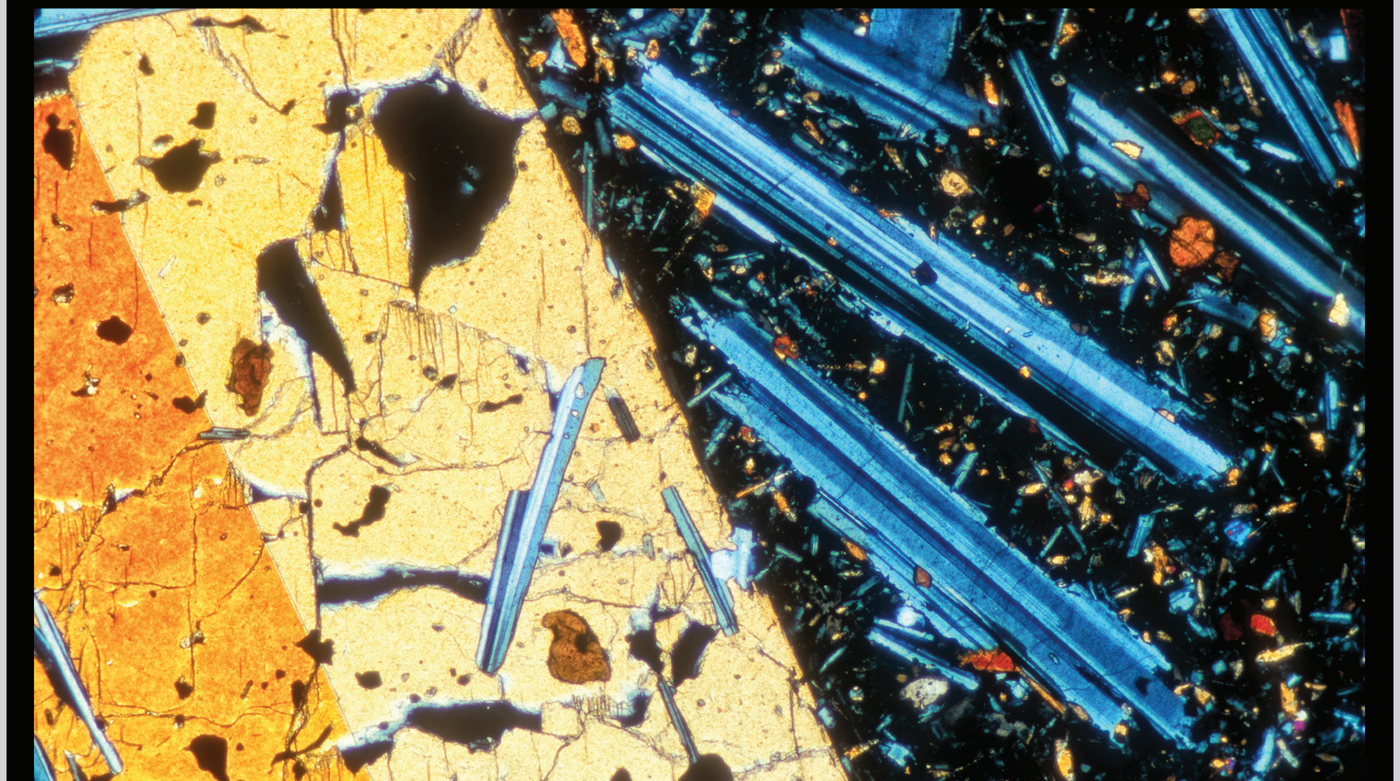
Among those attracted to Vesuvius was William Hamilton, Britain's ambassador to Naples from 1764 to 1800 (and husband of Emma, the mistress of Admiral Nelson). Vesuvius erupted violently nine times during Hamilton's stay; he made more than 200 sorties up its flanks, and became one of the pioneers of volcanology. He began to compile a list of eruptions, by collecting the dates on which the priests in Naples and the villages and towns around the volcano had displayed sacred images to ward off destruction. Hamilton was intrigued by the stolid philosophy of the locals: "Each peasant flatters himself that an eruption will not happen in his time, or, if it should, that his tutelar saint will turn away the destructive lava from his ground; and, indeed, the great fertility of soil in the neighbourhoods of volcanoes tempts people to inhabit them," he wrote. Hamilton's letters to the president of the Royal Society in London, published in 1772, became the first modern work of volcanology.

THE KEY EXPERIMENT

Debate raged for a long time about how rocks are formed. It wasn't until the 1790s that simply melting and cooling rocks in a laboratory settled the argument for good

IN THE LATE 18th Century, there were two competing theories regarding the formation of terrestrial rocks. Neptunists, believers in the story of the Flood, maintained that most rock had been laid down as layers of sediment by the action of water. Vulcanists (or plutonists), after observing the material ejected by erupting volcanoes, proposed that some rocks had been melted by heat inside the Earth. But if they were right, and so-called volcanic rocks such as basalt and granite had once been molten, why did these rocks show crystal structure rather than looking like glass, like the mineral obsidian?

Experiments by James Hall in the 1790s suggested the reason. Hall took samples of whinstone – the name given to basalt in his area near Edinburgh – and melted them in an iron foundry. He called the molten substance 'magma'. When cooled quickly, magma turned to glass. Cooled over several hours, however, it reverted to crystalline rock very similar to whinstone. By varying the time of cooling, Hall could vary the size of crystals. He repeated the experiments with six lava samples from Mount Etna, Mount Vesuvius and Iceland. Whinstone and lava, Hall noted in 1800, "agree so exactly in all their properties... as to lead to a belief of their absolute identity".



This micrograph of a basalt rock sample clearly shows the crystalline structure, which obscured the rock's volcanic origins until Hall's experiments shed new light on the matter

SOLID THEORIES

Neither Guettard nor Hamilton proposed a theory of volcanism, however. At this time, the dominant idea was that rocks were of sedimentary origin and had been laid down in layers by the biblical Flood. Volcanic activity was therefore a recent and superficial phenomenon – merely the result of veins of coal catching fire underground and burning their way to the surface. Indeed, the word 'volcanic' only entered the English language in 1774.

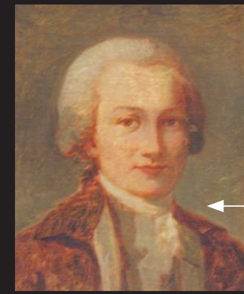
In the 1780s, James Hutton – the so-called father of modern geology – carried out field observations in Scotland. His work, along with rock experiments by his friend James Hall in the 1790s, made it clear that many rocks were of igneous origin. They were formed not by water, but by being melted within the Earth and extruded at the surface through volcanoes (see 'The Key Experiment').

Hutton's idea of a dynamic Earth with a molten interior was elaborated by Charles Lyell in his *Principles Of Geology*, published in 1830-33. This strongly influenced Charles Darwin's interpretation of active volcanoes in South America as the agent of mountain building, and of extinct underwater volcanoes in the Pacific as the foundation of coral islands. The idea was firmly established by 1883, when the Indonesian island of Krakatoa erupted for 100 days, ending with a titanic blast that destroyed the volcano and sounded like gunfire nearly 5,000km away. It generated both a tsunami that annihilated 36,000 people, and an ash cloud that caused global atmospheric effects for years.

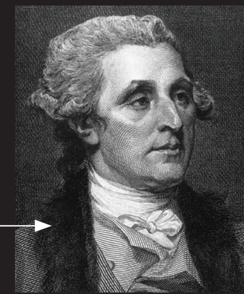
A scientific expedition from Europe landed on the remains of the island less than two months later. The ejecta thrown out by the eruption, when analysed in a laboratory, turned out not to belong to the rock of the old volcanic cone, but to be newly solidified magma from deep down. The expedition's Dutch leader, RM Verbeek, decided that Krakatoa

CAST OF CHARACTERS

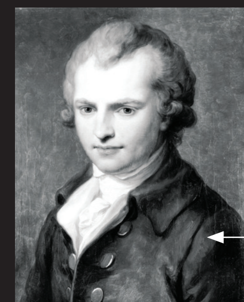
Some of the key players in the birth and evolution of the science of volcanology



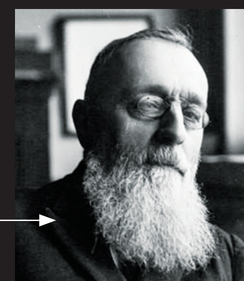
Jean-Étienne Guettard (1715-86) was a French geologist and mineralogist, who began his career as a botanist. He created the world's earliest geological map, based on his survey of France. In the 1750s, he was the first to recognise the volcanic origin of the mountains in the Auvergne region of central France.



William Hamilton (1731-1803), a Scottish diplomat, served as the British ambassador to the Kingdom of Naples from 1764 to 1800, a period that coincided with frequent eruptions of Vesuvius, which Hamilton observed and reported at close quarters. In effect the first volcanologist, he received the Royal Society's Copley Medal of Britain in 1770.



James Hall (1761-1832), as the son of a wealthy Scottish landowner, was free to pursue his interests in geology and chemistry. Touring Europe in 1783-86, he climbed Vesuvius five times. Back in Scotland he became a friend of James Hutton, whose geological observations Hall later confirmed by laboratory experiments.



Alfred Lacroix (1863-1948) was professor of mineralogy at the National Museum of Natural History in Paris. Co-author of a pioneering work on the optical properties of rock-forming minerals, he is best known in volcanology for his detailed investigation of the 1902 eruption of Mount Pelée in Martinique, which was published in 1904.

John Tuzo Wilson (1908-93), a Canadian geophysicist and geologist who reached the rank of colonel during World War II, was a key contributor in the 1960s to the theory of plate tectonics, which transformed volcanology. He also proposed the hot-spot theory to explain the volcanic origin and continuing volcanism of the Hawaiian Islands.

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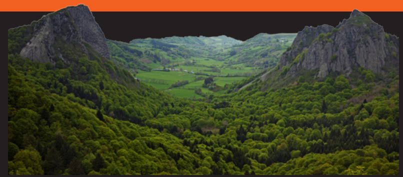
TIMELINE

How our understanding of the nature of volcanoes has developed over the past 250 years



1752

Evidence for Europe's volcanic origin is submitted to the French Academy of Sciences, based on a survey of mountains in the Auvergne by Jean-Etienne Guettard.

1772

William Hamilton, inspired by Pompeii's excavation and the activity of Vesuvius, publishes *Observations On Mount Vesuvius, Mount Etna And Other Volcanos*, the first scientific report on volcanic eruptions.

1790s

The concept of magma is introduced by James Hall, as a result of laboratory experiments on the melting of igneous rocks, including basalt (or 'whinstone') from Scotland and lava from active volcanoes in Europe.

1883

Krakatoa's explosive eruption in Indonesia creates an ash cloud with global atmospheric effects, including brilliant sunsets in London. A scientific investigation of the eruption is published by Britain's Royal Society.

1902

The eruption of Mount Pelée in Martinique incinerates neighbouring St Pierre. The French scientific report that follows introduces the concept of a *nuée ardente* ('burning cloud'), later renamed as a pyroclastic flow.

1963

The hotspot theory proposed by John Tuzo Wilson explains the volcanic history of the Hawaiian Islands in terms of a moving tectonic plate and a stationary hot spot created by a mantle plume.

PHOTO: THINKSTOCK, PRESS ASSOCIATION, NASA, ALAMY X2, SCIENCE PHOTO LIBRARY

had ejected its magma chamber into the air, and the space had then been filled by the cone's collapse, creating a caldera or giant crater. He further suggested that seawater penetrating the magma chamber had provoked the mega-blast.

Today, Verbeek's first idea is generally accepted, but not the second. The mixing of magma and seawater usually gives rise to a distinctive deposit of very fine-grained, widely dispersed ash. No such deposits have been found at Krakatoa. Rather, the current view is that the main blast was caused by the violent mixing of two magmas: a basaltic magma injected beneath a denser, dacitic magma. The first magma, being less dense, rose buoyantly and abruptly, and an explosion resulted. The presence in the ejecta of both types of magma, in different proportions at different times during the eruption, supports this view.

FATAL FLOW

The cause of Krakatoa's tsunami is less clear. Some scientists have suggested an underwater explosion. Verbeek favoured either the slumping of the cone into the caldera, or the sudden displacement of water by hot gases and rocks 'falling' into the sea: in other words, what is now termed a pyroclastic flow. Such flows are a common and deadly feature of certain volcanoes. Pyroclastic flows probably smothered Pompeii and Herculaneum; they certainly occurred as a result of the lethal 1902 eruption of Mount Pelée in Martinique, where they were observed for the first time by scientists cruising past the ruins of the port of St Pierre in a sailboat.

"The cloud was globular, with a bulging surface covered with rounded protuberant masses which swelled and multiplied with terrible energy," the scientists wrote. "It rushed forward over the waters, directly towards us, boiling and changing its form every instant. It did not spread out laterally; neither did it rise into the air but swept on over the sea in surging masses, coruscating with lightning." The original term for the phenomenon, *nuée ardente* ('burning cloud'), was given by Alfred Lacroix in his scientific report on Pelée's eruption.

With the introduction of plate tectonic theory in the 1960s, it at last became clear why volcanoes and earthquakes occur in certain areas.

NEED TO KNOW

A quick glossary of some key terms used in volcanology

1 MAGMA
Magma is a Latin term for molten rock, first used in chemistry to mean a pasty substance. Magma is formed at high temperatures inside the Earth, either within the upper mantle or at tectonic plate boundaries. It rises buoyantly into the crust to form pools, sometimes called magma chambers, which feed volcanoes.

2 IGNEOUS ROCKS
Igneous (from the Latin for 'fire') refers to rock formed either by the cooling and solidification of magma inside the Earth, such as granite, or by extrusion of lava on the surface through volcanic action, such as basalt. The most common volcanic rocks are basalt, andesite and rhyolite, in increasing order of silica content and viscosity.

3 PYROCLASTIC FLOW
Whereas a lava flow consists of molten rock, a pyroclastic flow (from the Greek for 'fire' and 'broken into pieces') is a fast-moving current of hot gas and rock, both solid and molten. Hugging a volcano's slopes and then spreading under gravity, pyroclastic flows can reach temperatures of as much as 1,000°C and speeds of up to 700km/h.

The September 2014 eruption of Mount Ontake in Japan claimed over 60 lives, and occurred without any warning

Where tectonic plates touch, the less dense plate is elevated and the more dense plate is subducted, for example beneath Japan. However, at volcanic rifts – such as the Mid-Atlantic Ridge – plates grow and begin moving as new rock is created by the extrusion of magma from the upper mantle.

However, plate tectonics did not give a coherent explanation of intraplate volcanoes, such as those in the Hawaiian Islands. So John Tuzo Wilson came up with his hotspot theory in 1963. According to this idea, the Hawaiian Islands were formed by a stationary, plume-shaped mass of magma rising from deep in the mantle and punching a hole in the Pacific plate as the plate moved in a northwesterly direction. If this is correct, the Hawaiian hotspot should have created a string of volcanoes trending to the northwest – each active for a while, then becoming extinct as it moved away from the hotspot. Its rocks should get older the further away the extinct volcano is from the hotspot's present site beneath Hawaii's Big Island. This is indeed the case. The rocks of the Hawaiian Islands do age towards the northwest, and there is a series of sunken, extinct volcanoes beneath the Pacific – the Hawaiian Ridge and the Emperor Seamounts – that trails off over 5,600km of seafloor towards the Aleutian Islands.

The rocks of extinct Kauai, the northernmost Hawaiian island, are five million years older than those of the Big Island, according to radioactive dating of ancient lava flows. This age agrees with the age predicted by the speed at which the Pacific plate is believed to be moving. The Hawaiian hotspot has generated some 200 volcanoes over 75 million years.

Vital though our understanding of volcanic eruptions is, it cannot forecast the behaviour of the world's 1,300 potentially active, landlocked volcanoes. Only constant monitoring of each volcano may provide this information. It saved thousands of lives in 1991, during the eruption of Mount Pinatubo in the Philippines. But it failed at Mount Ontake in 2014. Ontake erupted in 1979, 1991 and 2007, also without prior magmatic activity, although insufficient instrumentation was in place in 1979 and 1991 to rule this out.

Now, volcanologists charged with monitoring Japan's 110 active volcanoes are wondering if Ontake could be getting ready for a magmatic eruption. The problem is that this volcano does not have an easily predictable cycle. "It's a very quiet mountain," Toshikazu Tanada cautiously noted after the 2014 eruption. "Each active volcano has its own characteristics." ■

ANDREW ROBINSON is the author of *Earthshock* and *Earthquake: Nature And Culture*

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