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When Anak Krakatau in Indonesia erupted on 22 December 2018, part of the island collapsed into the ocean, causing a deadly tsunami.

THE VOLCANOLOGY REVOLUTION

Forty years after the Mount St Helens eruption galvanized volcano science, researchers are harnessing powerful new tools to forecast and understand eruptions. **By Jane Palmer**

Early in 2018, the volcano Anak Krakatau in Indonesia started falling apart. It was a subtle transformation — one that nobody noticed at the time. The southern and southwestern flanks of the volcano were slipping towards the ocean at a rate of about 4 millimetres per month, a shift so small that researchers only saw it after the fact as they combed through satellite radar data. By June, though, the mountain began showing obvious signs of unrest. It spewed fiery ash and rocks into the sky in a series of small eruptions. And it was heating up. Another satellite instrument recorded thermal emissions from Anak Krakatau that reached 146 megawatts — more than 100 times the normal value. With the increased activity, the slippage jumped to 10 millimetres per month.

Then, on 22 December, the southern flank crashed into the sea, triggering a tsunami that killed at least 430 people along the nearby coasts of Java and Sumatra. Although nobody foresaw that disaster, a 2019 study found that satellite and ground-based instruments had picked up a suite of precursory signals that could help forecast similar events in the future at Anak Krakatau and other peaks.

The unexpected collapse at Anak Krakatau shows some of the challenges facing researchers as they try to monitor thousands of potentially dangerous volcanoes around the world — each one unique. But it also highlights several advances in the field that promise to give scientists a much better chance of forecasting disasters.

Volcanologists are making substantial headway, thanks to a torrent of data from satellites that can detect subtle movements of mountains, ground-based sensors that track molten rock moving deep underground, and gas-sniffing devices that drones can carry over seething mountains. And the theoretical understanding of volcanoes has grown markedly as researchers have learnt to combine all these data into models of what is happening within volcanic systems. Researchers are now experimenting with machine learning to sift through the flood of data to identify subtle patterns, such as the early movement of Anak Krakatau months before it showed signs of waking.

The field has made huge strides since the greatest volcanic crisis in US history exactly 40 years ago — the eruption of Mount St Helens on 18 May 1980 in Washington state. That event — which started with the largest landslide in recorded history — killed 57 people and blanketed much of Washington and nearby states with ash, shutting down the region for days. But it was also a turning point for volcanic science, sparking a huge influx of money and people into the field and setting the stage for rapid improvements in understanding.

Scientists had flocked to the mountain in the months before the blast and had carefully tracked its behaviour, including frequent earthquakes, gases fuming from its crater and an ominous bulge that swelled from its northern flank. "It was the first really significant eruption that was captured by modern-day scientific instrumentation," says Seth Moran, scientist-in-charge at the US Geological Survey (USGS) Cascades Volcano Observatory in Vancouver, Washington. "And so, in a lot of ways, it's become a benchmark for the ways that people go about looking at volcanoes around the world."

The proliferation of ground- and space-based monitoring data since then, coupled with increases in computing power, has revolutionized scientists' understanding of volcanic systems. Ultimately, researchers are hoping that new tools and techniques will nudge them closer to being able to assign probabilities to the chances of a volcano erupting in a given time frame, much as meteorologists dole out the chances of rain or snow on any specific day.

"I think that when people look back on this period, they will imagine this is the golden era of physical volcanology," says volcanologist Christopher Kilburn at University College London.

Historic blast

The first hints of trouble at Mount St Helens came on 16 March 1980, with a series of small earthquakes. Then, a week later, steam explosions burst through the ice on top of the volcano, carving out a crater that grew to 400 metres across within days. Teams of researchers arrived from the USGS and other institutions to keep vigil over the mountain. Planes flew over the smoking crater to measure the gases escaping from the volcano, and seismometers registered the tremors from magma — molten rock — moving beneath the surface. Volcanologists climbed the mountain's slopes to measure the bulging northern flank using tape measures and laser-surveying equipment.

"Tall volcanoes collapse. They are not just growing, they're collapsing."

Magma was clearly rising high in the volcano and pushing against the slope, and researchers warned that a major eruption could happen soon. But what happened next caught scientists by surprise.

At 8:32 a.m. on 18 May, a massive landslide crashed down the mountainside, taking the summit and snow and ice with it. The release in pressure uncorked the volcano, triggering a powerful explosion. A blast of rocks, ash, gas and steam was propelled upwards and outwards at supersonic speeds, and travelled as far as 25 kilometres northwards.

"We learnt from the May 18th eruption how unstable steep-sided volcanoes are, and how they can fail and generate a big surge or lateral blast," says Don Swanson, a research geologist at the USGS Hawaiian Volcano Observatory, who was involved in monitoring the 1980 eruption. "What seems so obvious now, wasn't obvious before that time."

After the eruption, scientists analysed the landscape and found it littered with hummocks — large hills and mounds that had been transported downslope in intact blocks. These features matched those found near many volcanoes around the world. And from the historical record, volcanologists recognized that around 1,000 similar landslides had taken place on more than 550 volcanoes. "Tall volcanoes collapse, they're not just growing, they're collapsing," says volcanologist Thomas Walter at the German Research Centre for Geosciences in Potsdam.

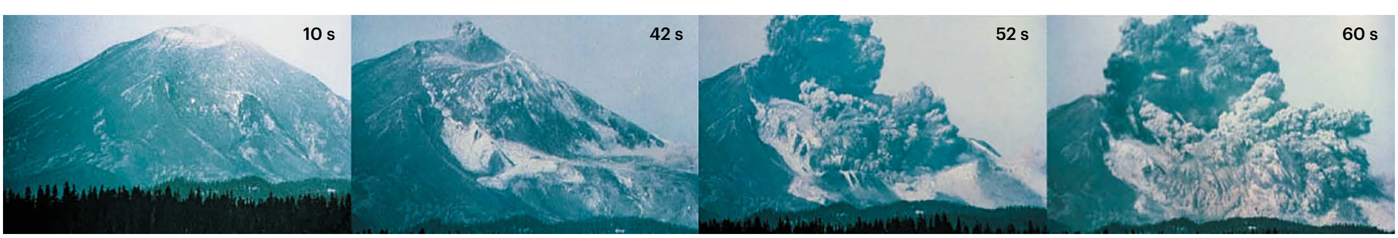
The eruption of Mount St Helens taught other lessons, such as the deadly impact of super-heated volcanic ash and gas racing down the mountain at hurricane speeds, and the power of mudslides that destroyed everything in their path. The eruption also spurred a huge growth in volcanology. In the decade after the blast, the USGS established volcano observatories in the Pacific Northwest, Hawaii and Alaska.

Funding for the USGS's volcanic hazards programme today is nearly ten times what it was before the Mount St Helens blast. And after a volcanic mudslide in Colombia killed 23,000 people in 1985, the USGS established the Volcano Disaster Assistance Program to help other countries prepare for volcanic crises — a project that soon proved its worth when USGS researchers worked with scientists in the Philippines in 1991 to assess the risk from Mount Pinatubo. Tens of thousands of people were evacuated from the region before the volcano's cataclysmic eruption.

Researchers today rely on many of the lessons learnt at St Helens, Pinatubo and dozens of other volcanoes. Typically, seismic shaking is the first sign that a volcano is stirring. Eruptions occur when magma pushes to the surface, but even as magma begins to rise from Earth's mantle, it can trigger quakes. Today, seismic networks are monitoring dozens of some of the most dangerous volcanoes around the world.

That same magma movement can cause volcanoes to inflate, as Mount St Helens did before its blast. Researchers can now record movements safely and continuously, using GPS receivers and, more recently, satellite-borne radar — which detected the movement at Anak Krakatau.

Even before warning signs can be seen or felt, rising levels of carbon dioxide from a volcano's crater or vents can hint at trouble ahead. Magma contains dissolved gases and as this molten material rises and the pressure



USGS

On 18 May 1980, a giant landslide — the largest in recorded history — carried away the north flank of Mount St Helens, triggering an eruption.

decreases, gases separate off and travel upwards. Carbon dioxide, one of the least soluble of the volcanic gases, escapes first, while the magma is still deep in the volcano. "In principle, you should get a gas signal long before the magma reaches the surface in an eruption," says volcanic-gas geochemist Alessandro Aiuppa at the University of Palermo in Sicily, Italy.

Historically, scientists had to collect gas samples from near the crater or vents – a dangerous task that yielded only episodic bites of information. Then, in 2005, Italian researchers designed an instrument – a multicomponent gas analyser system (Multi-GAS) – that is not much bigger than a shoebox. Volcanologists install these sensors near vents, and also mount them on drones that fly over active craters to measure the levels of five key gases emitted by volcanoes. "This has been a real revolution for volcanic-gas science because it means you can have a measurement of volcanic-gas composition every second, in real time, on your computer," Aiuppa says.

Blast forecast

The Multi-GAS instruments had their trial by fire on Stromboli, a volcano off the north coast of Sicily. Italian scientists installed these sensors, along with cameras and spectrometers, on the volcano in 2005 and have collected gas data ever since. In February 2007, lava began to ooze out of the volcano in an effusive eruption. The researchers saw that carbon dioxide levels rose tenfold over the two weeks before the volcano erupted explosively on 15 March[1].

The findings allowed volcanologists to build a conceptual model of this complex volcano, in which explosions emanate from a deep magma chamber 7–10 kilometres below the summit. The researchers determined that the chances of an explosive eruption increase when carbon dioxide emissions top 2,000 tonnes per day.

In August 2019, Stromboli oozed lava again, and for the next two weeks the Italians tracked a slow, progressive increase in carbon dioxide. "So, we knew that something was going to happen," Aiuppa says. The team increased its vigilance and also closely monitored ground-level changes using tiltmeters that measure subtle changes in ground angle. Eventually, what they saw made them certain that an explosion was coming soon, and they alerted the local authorities minutes before a blast on 28 August.

At Mount Etna on the Sicilian mainland, Italian researchers are tracking low-frequency sound waves – infrasound waves – that some volcanoes emit before they erupt. Scientists installed the system on Etna in 2008 and analysed its performance for 59 eruptions in the following 8 years. It successfully predicted 57 of the events, and sent messages to the researchers about an hour before each eruption[2]. Given this success, in 2015 the team programmed the system to send automatic e-mail and text-message alerts to the civil-protection department in Rome and to the city of Catania close to the volcano.

The researchers' original motivation for developing the system was to find a way to detect eruptions at unmonitored volcanoes, because even remote blasts can have far-reaching impacts. The eruption of Eyjafjallajökull in Iceland in 2010 created an ash plume that disrupted air traffic across Europe for weeks. "Volcanic risk has no borders," says Maurizio Ripepe, a geophysicist at the University of Florence, Italy, who helped to create the automated early-warning system on Etna.

Currently, fewer than half of the world's active volcanoes on land have any sort of ground instrumentation, and in many cases this consists of just a few seismometers. But in the past decade, researchers have gained new ways to monitor all volcanoes using instruments mounted on satellites.

Data deluge

On 10 April 2020, Indonesia's Anak Krakatau spewed a column of ash 500 metres into the sky and the Center for Volcanology and Geological Hazard Mitigation in Indonesia issued a level-2 alert, which signifies that the volcano has the potential to erupt but poses limited hazards.

After the deadly tsunami in 2018, German volcanologists had found a striking pattern at Anak Krakatau that was apparent in data recorded by the moderate-resolution imaging spectroradiometer (MODIS) on a NASA satellite. Infrared channels revealed that thermal emissions jumped in June 2018 (ref. 3). "The whole volcano was hot, the most intense activity ever recorded," says Walter. "So, this was clearly anomalous behaviour."

The researchers also used satellite radar observations, which can detect small changes in vertical and horizontal motion, to find that the volcano's flank was already slipping at a rate of 10 millimetres per month before it collapsed (see 'Island on the move').

The research demonstrated how, even when ground instrumentation is limited, scientists can learn about the lead-up to an eruption or volcanic landslide from satellites. "As volcanologists, we always used to say that we were data poor," says Michael Poland, scientist-in-charge at the USGS Yellowstone Volcano Observatory in Vancouver, Washington. "But now the satellite data really expand our ability to see what volcanoes are doing."

Volcanology got a huge boost in 2014 and 2016 with the launch of the European Space Agency's Sentinel 1A and 1B radar satellites. Using the technique of interferometric synthetic-aperture radar, they can track movements of volcanoes at unprecedented resolution levels and at frequent time intervals (see 'Inflation watch'). "These satellites can detect subcentimetre deformation of ground surfaces, meaning that we can see when the volcano is swelling," says volcanologist Charles Mandeville, programme coordinator of the USGS Volcano Hazards Program. "There is a whole fire hose of such data being collected now."

Researchers have combined radar data with satellite observations that record temperature and sulfur dioxide emissions to capture a multidimensional picture of what happens at volcanoes before and during eruptions. A

ISLAND ON THE MOVE

Satellite radar data reveal how the ground surface of Anak Krakatau, a volcanic island, shifted in the 12 months before an eruption on 22 December 2018. The southwestern region collapsed during the eruption, triggering a deadly tsunami. Such observations could help to forecast when a volcano will erupt.

Vertical movement (mm yr^{-1})
100
0
–100
–200
–300

Movement East or West (mm yr^{-1})
100

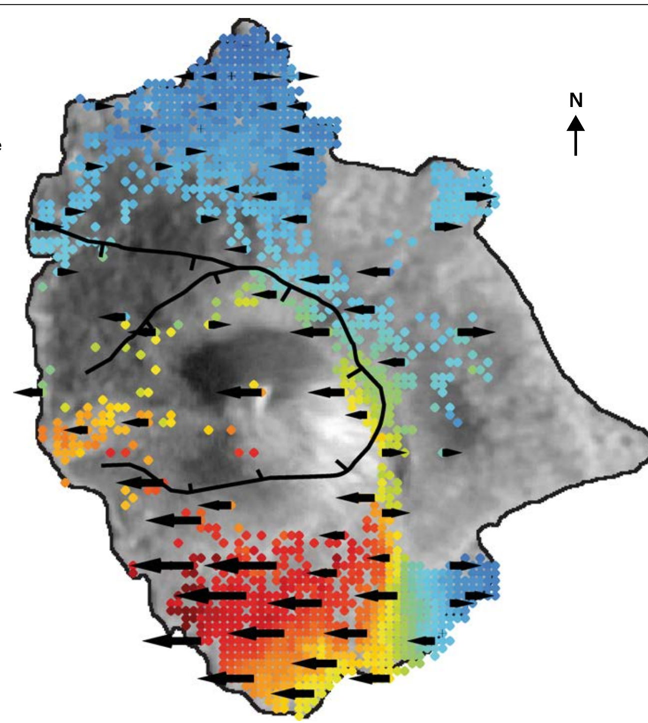
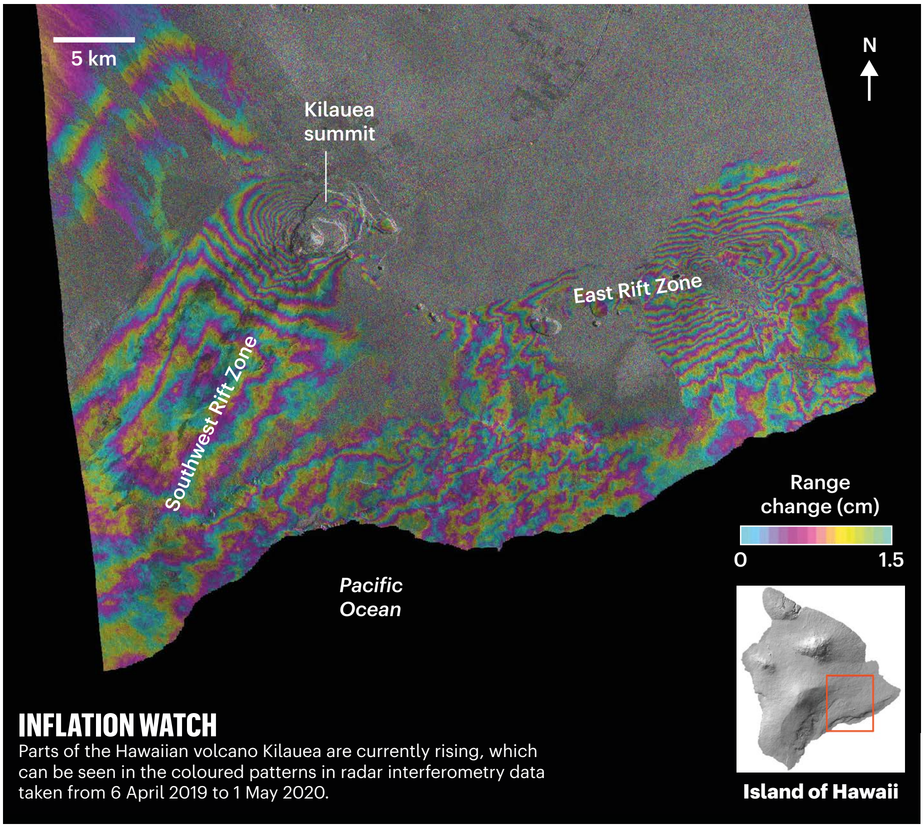


FIG. 3B WALTER, T. R *ET AL. NATURE COMMUN.* **10**, 4339 (2019)



INFLATION WATCH
Parts of the Hawaiian volcano Kilauea are currently rising, which can be seen in the coloured patterns in radar interferometry data taken from 6 April 2019 to 1 May 2020.

MICHAEL POLAND, USGS

study of the 47 most active volcanoes in South America, which used 17 years of satellite data, showed that changes in at least one of these variables, and sometimes in all three, precede an eruption, sometimes years in advance[4].

To exploit these data, many of which are freely available, Walter and colleagues have created a volcano-monitoring platform called MOUNTS (monitoring unrest from space). The platform uses data from the current suite of Sentinel satellites and ground-based earthquake information, and currently monitors 17 volcanoes, including Anak Krakatau.

As they started on the project, however, the researchers faced a new and unusual problem — too much data. The satellites provide torrents of readings, more than researchers can analyse using conventional methods. "There are so many volcanoes and so much data that we needed smarter ways of dealing with the data set," Walter says.

In response to this challenge, researchers have turned to machine-learning techniques, a form of artificial intelligence in which computer algorithms such as neural networks can be trained to pick out patterns in data. Juliet Biggs, a volcanologist at the University of Bristol, UK, and her colleagues have created a neural network that has churned through some 30,000 Sentinel-1 images of more than 900 volcanoes and flagged about 100 images as needing more attention. Of those images, 39 showed real ground distortions[5], meaning that the AI system had reduced the workload for the volcanologists by a factor of nearly 10. Now, they are testing their system on some half a million images from more than 1,000 volcanoes.

"You just can't look at every image," Poland says. "I see machine learning as having a real impact in filtering through these massive volumes of data."

For the MOUNTS platform, scientists have also developed a neural network to search for large shape changes. Other groups are trying to develop algorithms that can sift through temperature or gas-emission data from satellites.

When Anak Krakatau sprang back into action on 10 April this year, Walter was quick to monitor the situation remotely by analysing the satellite data. Because visibility was low, he had to rely on the radar data, which can penetrate thick clouds. The information will help scientists understand the behaviour of Anak Krakatau and in the future it might be used to help create a tsunami early-warning system for landslides from the Indonesian volcano, Walter says.

Biggs says that the combination of satellite data and AI is a useful tool for drawing attention to possible risks and prioritizing the installation of ground-based instruments. Such remote-monitoring techniques provide valuable information and are safer for scientists, but she thinks they are never going to completely replace having instruments close to the volcano itself.

In the United States, researchers will soon gain a large new source of ground-based data. In March 2019, US legislators passed a bill to fund the National Volcano Early Warning System (NVEWS). When implemented, NVEWS will lead to the installation of digital broadband seismometers on 104 of the country's volcanoes and new digital-telemetry networks with sufficient bandwidth to carry data from a number of different ground sensors.

Future shocks

In the past 40 years, scientists have successfully forecast the timing of many eruptions, from smaller blasts at Mount St Helens in the early 1980s to the ash-rich lava fountains at Mount Etna. "A lot of progress has been made on the timing aspect," Poland says. "Perhaps in a very large part because of the amount of instrumentation, the advent of space-based monitoring and the increase in observations that we have."

Nevertheless, volcanic eruptions still take people fatally by surprise. A small explosive eruption at Mount Ontake in Japan in 2014 killed 63 people, and a violent eruption of the Fuego volcano in Guatemala in June 2018 killed hundreds. A minor eruption at White Island in New Zealand in 2019 claimed 21 lives.

One challenge facing volcanologists is that they are trying to infer what's happening deep underground by looking at data such as gas emissions and shape changes on the surface. And each volcano has its own personality — its own unique set of materials and structure.

The individualistic nature of volcanoes highlights the limitations of using patterns from past eruptions to forecast future ones. When volcanologists see the first warning signs, they often think they've seen this before and know what happens, Poland says. "But the volcanoes haven't watched that movie," he says. "They've evolved in ways that are incredibly complex, and our understanding of the complexities are very cursory at this point."

With more data and better understanding of volcanic systems, researchers hope to develop dynamic models that can capture the physics and chemistry of what happens below ground. In this way, the development of volcanology could parallel that of meteorology, which uses dynamic models of the atmosphere to forecast weather many days in advance.

But volcanic systems are so complex and so hidden that volcanic forecasts will never be as good as meteorological ones, says Poland. "It is a fun exercise to think that one day you will open the newspaper and see the volcano forecast next to the weather forecast," he says. "But we are still a long way from that."

Jane Palmer is a freelance writer based in Colorado.

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