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Detecting Underwater Eruptions Through Satellite Sleuthing

By Philipp A. Brandl

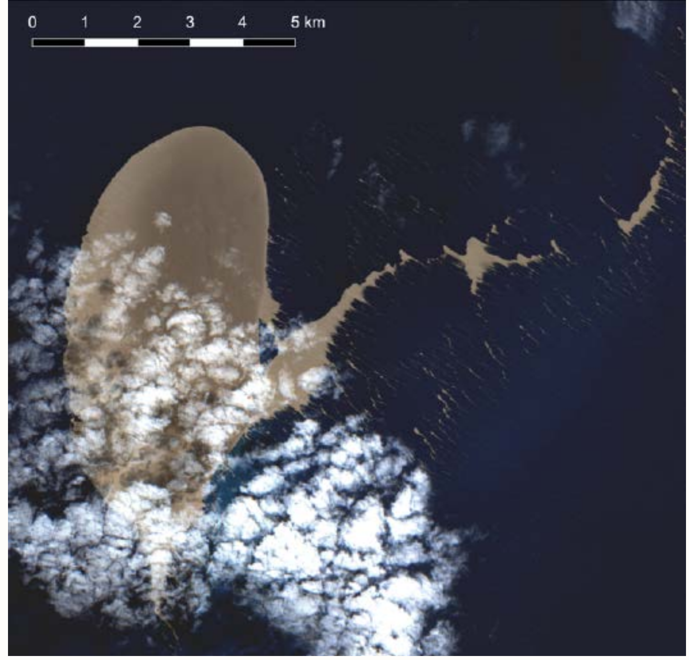
Scientists located the volcanic source of a pumice raft floating in the South Pacific Ocean using data from low Earth orbit, illustrating their promise of finding and monitoring undersea eruptions.

In August 2019, news media reported a new pumice raft floating in the territorial waters of the South Pacific island kingdom of Tonga. This visible evidence of an underwater volcanic eruption was borne out by seismic measurements, but conditions were less than ideal for using seismic sensors to precisely locate the source of the eruption. My colleagues and I eventually traced the source of the pumice raft to a submarine volcano referred to as Volcano F using a combination of satellite and seismic data (Figure 1), demonstrating remote sensing's potential for locating and monitoring underwater volcanoes [*Brandl et al.*, 2020].

A pumice raft made of buoyant volcanic rock floats in the Pacific Ocean in 2006. Last year, another pumice raft was spotted in the South Pacific, its origin traced to an underwater volcano with the help of satellite observations. Credit: Fredrik Fransson/Science Photo Library

Volcanoes that breach the sea surface often provide clues to impending eruptions, and the events during and after eruptions demonstrate the hazards that marine volcanoes can pose to communities nearby. For example, after several months of growth, a large sector of the south flank of Anak Krakatau, a volcanic island situated in the Sunda Strait of Indonesia, suddenly collapsed into the sea on 22 December 2018. The resulting tsunami killed more than 430 people in nearby coastal areas of Java and Sumatra; it also injured 14,000 people and displaced 33,000. This cascade of events was not totally unexpected because the part of the island above water was clearly visible and was being monitored [*Walter et al.*, 2019].

Unlike events above the sea surface, landslides, earthquakes, volcanic eruptions, and other geological events below the surface are seldom observed as they are happening, but they can also wreak havoc on vulnerable coastal communities. Despite the hazards they pose, assessing the natural hazard risk and mitigating the aftereffects of submarine events remain major challenges. In many cases, the events themselves are hidden beneath the water, and only their direct aftermaths are visible. Recent advances, especially in remote sensing techniques, may enable scientists to identify potential underwater hazards and areas at risk in the near future.



On 21 August 2019, this pumice raft close to the Exclusive Economic Zone border between Fiji and Tonga was visible from space. Satellite data, combined with seismic readings, helped locate the undersea volcano that was the source of the pumice. Credit: European Space Agency, Copernicus Sentinel-2, CC BY-SA 3.0 IGO (bit .ly/ccbysaigo3-0)

The Challenge of Underwater Eruptions

Landslides and earthquakes are particularly hazardous when they occur not as isolated events but as parts of cascading natural disasters. When these events occur underwater, the disaster might not be evident until it is well under way. Landslides can be directly located only if they are associated with seismicity or are not exclusively submarine. And although global seismic networks can precisely locate earthquakes, determining the details of fault motion, which can influence whether quakes trigger subsequent hazards like tsunamis, requires knowledge of the local seafloor geology and tectonic structure.

Mapping the seafloor for potential hazards will remain challenging because water rapidly absorbs the electromagnetic waves that are key to the satellite remote sensing methods used to map land surfaces. In most cases, submarine volcanic activity thus stays obscured. This is especially true if an eruption is effusive rather than explosive or if an eruption does not breach the sea surface to produce a detectable volcanic gas plume in the atmosphere.

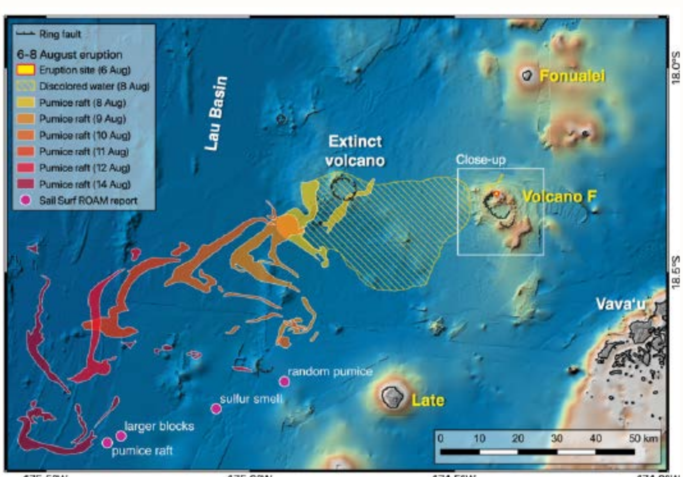


Fig. 1. The drift of the pumice raft between 8 and 14 August 2019 following the 6–8 August eruption at Volcano F. Dots represent locations of pumice on the sea surface and other observations reported by the ROAM catamaran.

Visible eruptions from submerged volcanoes are the exceptions. These include silicic eruptions at island arcs, which are often explosive and eventually eject matter into the air. They also include eruptions of pumice, a highly porous, low-density abrasive volcanic rock that can float on the sea surface [*Carey et al.*, 2018]. Large volumes of pumice can aggregate into rafts that drift with the wind, waves, and currents and present hazards for ships. But these rafts also provide clues to recent submarine eruptions.

Scientists currently rely on in situ methods to track floating pumice rafts, but improved Earth observations from space, coupled with automated image analysis and artificial intelligence, could further enable tracking, ultimately allowing us to trace them back to their volcanic sources if weather permits.

Sourcing the Tonga Pumice Raft

During the August 2019 eruption that produced the pumice raft near Tonga, two stations of the global seismic network located far out in the Pacific Ocean on the islands of Niue and Rarotonga recorded T phases, low-frequency sound waves related to submarine volcanic eruptions. Under ideal conditions, such seismoacoustic signals can be transmitted over very long distances because they couple into a specific layer of the ocean water column, the sound fixing and ranging (SOFAR) channel, which acts as a guide for sound waves. Sound waves reach their minimum speed within the SOFAR channel, and these low-frequency sound waves may travel thousands of kilometers before dissipating. T phases from the 2011 submarine eruption of the Monowai volcanic system, for example, were transmitted in the SOFAR channel over more than 15,000 kilometers.

However, under less favorable conditions, seismoacoustic signal transmission may be more limited. The Tonga Ridge is one example of where such unfavorable conditions prevail because the ridge sits in shallow water and breaches the surface in some places, thus blocking seismoacoustic signal transmissions in some directions. During the

August 2019 eruption, it was not possible to use triangulation to define the precise location of the source, because only two stations recorded the relevant T phases. This difficulty clearly emphasizes the need for increased sensitivity of the global seismic network in this part of the world, which is particularly important with respect to submarine natural hazards.

Seismoacoustic signals may be directly linked to an active submarine eruption, but seismic precursor events may also hint at increasing activity within a volcanic system. In the case of the 6–8 August eruption of Volcano F, eight earthquakes of magnitude 3.9–4.7 were detected in the vicinity of the volcano in the days and hours prior to the eruption. However, given the tremendous amount of seismic activity in this area and the related mass of data under normal conditions, events of this scale usually trigger interest only when followed by a larger and more significant geohazard.

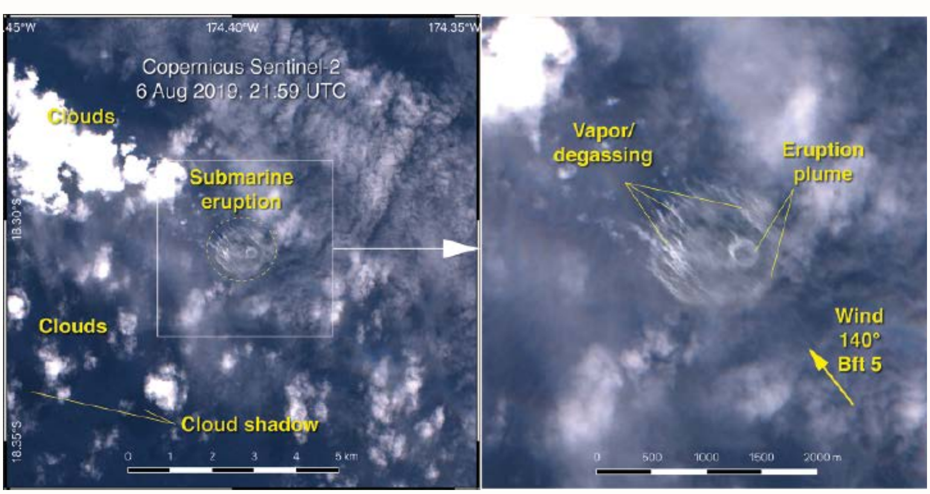
Thus, submarine volcanic eruptions may go unnoticed unless boats and ships report encountering pumice rafts or surveillance flights report visual observations of eruption plumes. In this respect, recent advances in the quality, quantity (e.g., daily coverage), and availability (e.g., the open-source data of the European Union's Copernicus program) of satellite observations have greatly improved our ability to visually detect ongoing volcanic eruptions and their immediate aftermaths, thus representing an important addition to monitoring capabilities. Satellite data may include, among other things, visual observation of the sea surface and spectral detection of volcanic gases or temperature variations in the atmosphere.

The European Space Agency's (ESA) Sentinel-2 satellite, for example, captured a plume of discolored convecting water, volcanic gas, and vapor about 1.2 kilometers wide coming from the shallow submarine eruption of Volcano F. By combining data from Sentinel-2, available through Copernicus, and from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) system, we tracked the daily dispersal and drift of the related pumice raft.

Ship-based multibeam mapping of submarine volcanoes can help constrain eruption dynamics and volume and help monitor morphological changes of volcanic edifices during or after an eruption.

Gathering Data from Many Sources

Because these satellite techniques are restricted to studying the sea surface, we may still miss many volcanic eruptions in the deep sea. Only hydroacoustic techniques deployed from ships or autonomous underwater vehicles (AUVs) are capable of surveying the ocean floor at needed resolutions, so increased marine research focused on rapid response to submarine eruptions and landslides could strengthen our ability to predict potential natural hazards in the deep sea.



This satellite imagery shows the sea surface on 6 August 2019 following the eruption of Volcano F. Abbreviations are UTC, coordinated universal time; Bft 5, Beaufort scale category 5 winds, corresponding to 29–38 kilometers per hour. Credit: European Space Agency, Copernicus Sentinel-2, modified by Philipp Brandl

Ship-based multibeam mapping (which can achieve resolutions down to about 15 meters) of submarine volcanoes can help constrain eruption dynamics and volume and help monitor morphological changes of volcanic edifices during or after an eruption. And developments in robotic technology for seafloor mapping, such as autonomous surface vehicles and improved AUVs, which could extend resolution to less than 1 meter, may soon lead to significant advancements in our marine remote sensing capabilities. But currently, the limited coverage of these techniques (less than about 30% of the ocean floor has been mapped by ship-based multibeam sonar) means that only a few areas exist where repeated multibeam surveys allow us to analyze changes in bathymetry over time.

Several segments of the East Pacific Rise, the Galápagos Spreading Center, and the Juan de Fuca Rise are examples of areas where detailed bathymetric maps have been used to monitor volcanic activity. In the southwestern Pacific, well-mapped areas include arc volcanoes such as those in the Tofua-Kermadec Arc, the Monowai Volcanic Center, the Havre and Brothers volcanoes, and West Mata. Repeated phases of growth and partial collapse of the edifice of the Monowai arc volcano have been well monitored [*Watts et al.*, 2012]. However, this level of monitoring has been possible only through repeated bathymetric surveys (1978, 1986, 1998, 2004, 2007, and 2011) that together integrate to an important time series.

During a cruise in 2018, my colleagues and I "accidentally" mapped the flanks of Volcano F (it was not the focus of our cruise). By combining our data with preexisting data from an Australian cruise, we created a combined bathymetric map (Figure 2) that could serve as a basis for identifying future changes in bathymetry due to volcanic activity [*Brandl et al.*, 2020].

At present, the risk potential of cascading events in the submarine realm is poorly understood, mainly because of the lack of data and monitoring. Studies like those described above would be of great value in assessing the risks of cascading natural disasters elsewhere—for example, at the many arc volcanoes whose edifices are composed of poorly consolidated volcaniclastic material rather than solid masses of rock. Volcanic growth can lead to a buildup of material that if followed by partial sector collapse, can trigger a tsunami—this was the case at Anak Krakatau in 2018.

Emerging technologies such as artificial intelligence and machine learning could fill an important gap. Proactive automated processing of data from global seismic networks could help to identify clusters of increased seismicity that could be precursors to volcanic eruptions. The locations and timing of these clusters could then be used to pick out features in hydrophone data from the same times and places that correlate with submarine eruptions. Earth and computer scientists are currently developing techniques for automated image analysis and data processing as well as the use of artificial intelligence for pattern recognition and the proper identification of submarine volcanic eruptions.

Compiling existing data and collecting new data related to submarine volcanic activity in a dedicated open-access database should help researchers estimate risk potentials as the first step toward forecasting natural hazards.

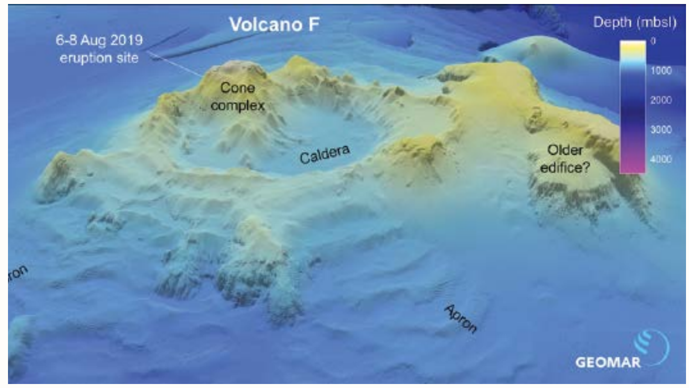


Fig. 2. Composite bathymetry of Volcano F from ship-based multibeam data collected by R/V Sonne *cruise SO267 and R/V* Southern Surveyor *cruise SS2004/11.*

Moving Beyond Accidental Discovery

Currently, submarine eruptions from island arc volcanoes and mid-ocean ridges are observed mainly by accident or when their eruption products breach the sea surface. Thus, we likely never see a significant proportion of submarine volcanic eruptions. And we lack the ability to monitor submarine volcanic activity on a global scale, which limits our ability to assess risks related to underwater volcanic eruptions, sector collapses, and cascading events.

Remote sensing techniques that collect data from space and at sea may provide us with more powerful tools to detect and monitor this volcanic activity and to project associated risks in remote areas. Recent advances in data processing may also greatly improve capabilities in this field. And compiling existing data and collecting new data related to submarine volcanic activity in a dedicated open-access database should help researchers estimate risk potentials as the first step toward forecasting natural hazards.

The experience with the 2019 eruption of Volcano F shows how important the integration of open-source and interdisciplinary remote sensing data is for the monitoring and management of natural hazards.

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