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Anatomy of a volcanic eruption undersea

Submarine flows from the Hunga Tonga–Hunga Haʻapai eruption decimated seafloor cables

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In December 2021, an undersea volcano in the southern Pacific Ocean, the Hunga Tonga–Hunga Haʻapai (hereafter called the Hunga volcano) began erupting. In January 2022 the eruption reached a powerful climax, triggering atmospheric waves that traveled around the globe and a tsunami that swept across the Pacific Ocean (1, 2). An estimated 75% of Earth's volcanoes are underwater, and 20% of all fatalities caused by volcanic eruptions since 1600 CE have been associated with underwater volcanism (3). Yet, explosive underwater eruptions are poorly understood. On page X of this issue, Clare et al. (4) report that volcanic debris from the Hunga eruption traveled under the sea at an unprecedented distance and at record-breaking speed—more than 100 km, at velocities reaching 122 km/hour —and destroyed a vast network of seafloor telecommunication cables. Given that 95% of global communications are carried by seafloor cables, the findings highlight system vulnerabilities to underwater volcanism (5). Clare et al. show that the particulate debris ejected from the Hunga volcano (the eruption column) collapsed vertically and directly into the ocean. This debris, consisting of rock and ash, then traveled as volcaniclastic submarine density currents on the submerged slopes of the volcano.

These were the fastest submarine density currents to have been recorded. The currents then traveled along the seafloor, destroying almost 200 km of cable that lay more than 15 km away from the volcano. Additionally, one of the cables was moved over 5 km by the currents. Bathymetric surveys, which map the shape and depth of underwater terrain, revealed 2-km-wide scours of the seabed where the currents eroded close to 100-m thickness of sea floor. The authors used the timing and extent of cable breaks, repeated bathymetric surveys, eruption observations, and rock core sampling to document the column collapse and resulting volcaniclastic submarine density currents. They calculated the velocity of the currents, determined the likely flow paths, and mapped where the currents eroded the seabed and deposited large volumes of volcanic debris on the seafloor.

Pyroclastic density currents typically form from eruption column collapse, which drives rapidly moving mixtures of volcanic ash and gas down the volcano's slopes. Clare *et al.* made the unexpected observation that Hunga's volcaniclastic submarine density currents transitioned between two types of flow behaviors, or rheologies. The morphology of the deposit from the currents and the occurrence of deposition on high-angle slopes of the volcano suggest that the currents must have initially been dense, granular, particle-laden, and carried by gas, similar to pyroclastic density currents on land. Characteristics of the deposits suggest that the currents then transitioned to water-carried, particle-laden submarine density currents, so-called turbidity currents. Understanding the internal dynamics of pyroclastic density currents is hampered by their destructiveness and opacity, which means not much can be revealed about them by long-distance observation. Much more is known about turbidity currents through direct monitoring, owing to new sensors and methods that provide measurements of, for example, flow velocity profiles (*6*).

Conceptual models of pyroclastic density currents have assumed that they are analogous to turbidity currents with respect to fluid mechanics. Moreover, theoretical work has suggested that pyroclastic density currents can propagate for substantial distances underwater without mixing with water (*7*). However, until now, evidence for this in the deep sea has been lacking (*8*). The switch from pyroclastic to turbidity current rheology, as observed by Clare *et al*., indicates nuanced differences between having gas or water as the carrier fluid. This transition makes the Hunga eruption an ideal case study to further explore how analogous turbidity currents are to pyroclastic density currents. If the differences prove substantial, then some of the underlying assumptions of various frameworks used to model and understand pyroclastic density currents are up for challenge. This has implications for how volcanologists interpret the volcanic rock record, conduct hazard assessments at volcanoes, and use numerical models to calculate potential flow paths for future eruptions.

Recent studies have documented giant scours on the seafloor surrounding submarine volcanoes across the world, for example, at Macauley and Raoul Islands in the southwest Pacific (*9, 10*). Little is known about the eruptions that formed these scours, which likely occurred thousands of years ago. Conceptual modelling proposed that the scours formed during highly explosive eruptions, but this has not been tested. The seafloor erosion and scours reported by Clare *et al.* are comparable in size to those observed around other submarine volcanoes, which suggests that these morphological features of the seafloor are the result of powerful volcanic flows from submarine or near-shore volcanic eruptions. Thus, events with the magnitude of the Hunga eruption may not be uncommon. This highlights that large submarine volcanic eruptions are an underappreciated global risk. Effort must be invested in quantifying the dangers associated with these eruptions and exploring the engineering requirements for remediating them.

The findings presented by Clare *et. al*. contribute an important dataset that should inform new models that can guide the engineering and repair of submarine infrastructure. The Hunga eruption also raises questions about the largely unexplored hazard of submerged calderas and the direct collapse of the eruption column into water. This will spark research for many years to come, using the Hunga volcano as a natural laboratory to generate and test new hypotheses on explosive volcanism. Some of the areas to explore in the future include the seawater's role in driving or suppressing explosive eruptions and the effect of volcaniclastic submarine density currents on marine ecology. Some planetary scientists are even drawing analogies between the Hunga eruption and volcanoes on Mars (*11*). Ultimately, the Hunga volcano will be a vital case study for better understanding the risk that undersea and shallow-water volcanoes pose to the submarine environment and critical seafloor infrastructure.

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