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Discovery of the Largest Historic Silicic Submarine Eruption

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It was likely twice the size of the renowned Mount St. Helens eruption of 1980 and perhaps more than 10 times bigger than the more recent 2010 Eyjafjallajökull eruption in Iceland. However, unlike those two events, which dominated world news headlines, in 2012 the daylong submarine silicic eruption at Havre volcano in the Kermadec Arc, New Zealand (Figure 1a; ~800 kilometers north of Auckland, New Zealand), passed without fanfare. In fact, for a while no one even knew it had occurred.

The first clue to this eruption was revealed when a passenger of a commercial airliner spotted large rafts of pumice floating on the surface of the ocean. An examination of satellite imagery revealed the likely location of the volcanic source of the pumice raft as Havre volcano and captured images of a plume in the atmosphere generated by the eruption. Pre-eruption and post-eruption bathymetry of the edifice reveals multiple vents with depths up to 1400 meters below sea level.

This discovery is believed to be the largest and deepest silicic submarine eruption of its type ever recorded—a once-in-a-century event. There is no historical precedent for the production of a subaerial eruption column likely from 900 and potentially 1400 meters below sea level, which is also a testament to the magnitude of the eruption. Both the size and depth of this eruption make this event an important end-member on the spectrum of submarine explosive volcanic activity.

A Chance Discovery Spurs a Hunt for More Information

On 31 July 2012, Maggie de Grauw, a passenger on a Virgin Pacific flight from Apia, Samoa, to Auckland, New Zealand, noticed a "peculiar large mass floating on the ocean between Tonga and Auckland." Believing it to be a pumice raft, she emailed the photos to Scott Bryan, a volcanologist and expert on the characteristics and dispersal of pumice rafts.

Through Bryan, de Grauw's photos and descriptions alerted geoscientists around the world to the possibility that something extraordinary had happened in the Kermadec Arc (Figure 1a) [*Global Volcanism Program*, 2012]. The reports of the pumice rafts gave the experts a good idea that an eruption of some kind had occurred somewhere along the volcanic arc, and the hunt was on to find the location, nature, and full extent of the event.

Clues From Satellite and Seismic Data

In search of further support for the observations, researchers examined images from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites. These images revealed the early development of the pumice raft, which within 1 day spread to the size of 400 square kilometers and was scattered over an area of about 20,000 square kilometers just a few days following the eruption [*Jutzeler et al.*, 2014] (Figure 2a).

In addition, images acquired between 18 and 21 July show an obvious atmospheric plume on 19 July but only the pumice raft on 20 and 21 July, suggesting that the eruption lasted less than 2 days and likely just 1 day. Nighttime imagery from MODIS reveals a thermal hot spot from the eruption at 1050 UTC on 18 July. Research by the Laboratoire de Geophysique (Tahiti) using data from the Polynesian Seismic network revealed that there had been frequent magnitude 3 to 5 earthquakes at Havre volcano between 17 and 21 July 2012.

An Eruption at Havre?

The raft, the plume, and the thermal hot spot all appeared at the sea surface above the location of Havre volcano. These observations, combined with seismic data, made the volcano the likely source of the eruption. Identifying Havre volcano as the source has important implications for the eruption depth. Previous mapping of the edifice of Havre volcano and the bathymetry surrounding it indicates that the eruptive vents initially must have been located at depths more than 720 meters below sea level (the shallowest

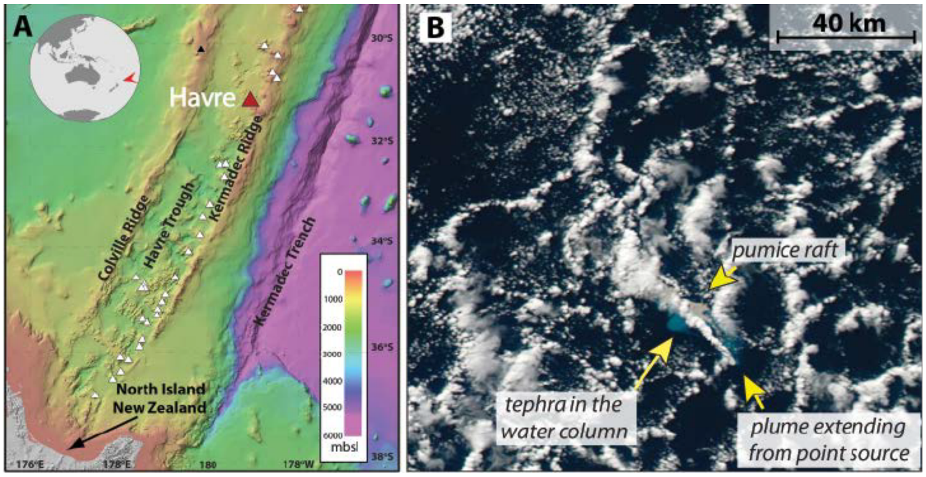

*Fig. 1. (a) Bathymetric map of the southern Kermadec Arc, north of New Zealand, showing the location of Havre volcano (red triangle), a silicic caldera volcano [*Wright et al., *2006]. White triangles show the locations of other volcanoes in the Kermadec Arc. Colors represent meters below sea level (mbsl). (b) NASA Moderate Resolution Imaging Spectroradiometer (MODIS) image from 18 July 2012 showing the atmospheric plume extending from a point source in contrast to the pumice raft (in brown/gray color). Note the light aqua blue water, which is submerged volcanic material in the water column. North is up.*

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point on the volcano), which would make it the deepest submarine silicic eruption ever documented.

Likely Source Found, but New Mysteries Emerge

The eruption of magma in deep submarine settings is poorly understood—many of the world's submarine volcanic arcs remain largely unexplored, submarine silicic eruptions are rare events, and the precise role of hydrostatic pressure in modulating eruptive dynamics is unknown. In fact, had this explosive eruption not occurred, it would likely not have been predicted because of the prevailing idea that hydrostatic pressure at the eruption depth (which exceeds 9 megapascals) can significantly suppress explosivity.

The depth to which explosive silicic volcanic eruptions can occur is controversial, but few observational data exist to inform that debate, making studies at Havre invaluable for exploring thresholds. Further, the eruption yields another obvious question: What processes promoted the development of a subaerial eruption plume from seafloor depths of up to 1400 meters below sea level?

This eruption provides a rare opportunity to further the understanding of deep submarine volcanic eruption processes and is enhanced by unprecedented constraints such as hydrostatic pressure at vents, timing, ejecta volume, and its dispersal.

Post-Eruption Response

To confirm the source of the eruption as Havre volcano and determine the exact locations of vents on the edifice, the National Institute of Water and Atmospheric Research (NIWA), in New Zealand, conducted a post-eruption research voyage to the Kermadec Arc later in October 2012, which included multibeam mapping and dredge sampling of Havre volcano. The new bathymetry was compared to the previous multibeam bathymetry survey of the volcano acquired in 2002 [*Wright et al.,* 2006], permitting detection of, and precise constraints on, new seafloor volcanic features and calculations of their volumes.

Through this comparison, several new features were found, including a previously uncharted bulge on Havre's western caldera wall and several volcanic cones (Figure 2b). Furthermore, the caldera floor was, in places, more than 50 meters shallower. Seafloor sampling at 10 sites yielded a large quantity of pumice, ranging from dark, dense material to light-colored, lower-density dacite and rhyolite pumice.

New Volcanic Features in Detail

A comparison of pre-eruption and post-eruption bathymetry of the edifice using multibeam echo sounders (a 30-kilohertz Kongsberg EM300 and 30-kilohertz Kongsberg EM302, respectively) on board the R/V *Tangaroa* shows a number of new features:

- A new volcanic cone formed at a water depth between 640 and 900 meters below sea level (250 meters high), is 1.2 kilometers across, and has a summit crater 120 meters in diameter. For comparison, its basal diameter is slightly less than Sunset Crater's, a cinder cone in Arizona, in the United States. Mapping revealed that four tongues of ejecta, each up to 50 meters thick, extend from the cone's summit to about 1.5 kilometers to the northwest, north, southeast, and east-southeast. These tongues are hypothesized to be associated with primary or resedimented gravity currents of tephra.
- A small cone field also formed that consists of about eight new cones, each up to 300 meters in diameter. These features have bases at 940 meters below sea level and deeper and range from 60 to 115 meters in height.
- A bulged area between approximately 1080 and 1400 meters below sea level (with a maximum gain in height of 150 meters) has been recognized on the wall and floor of the caldera in the west. The origin of this feature is unknown, but possibilities include the accumulation of proximal suspension-settled or resedimented volcanic ejecta, extrusion of a dome, or intrusion of a cryptodome.

Magnitude of the 2012 Eruption

The magnitude of the Havre eruption in 2012 is based on preliminary volume estimations of the products transported into the raft and those deposited on the seafloor calculated by comparing pre-eruption and post-eruption bathymetry maps. These calculations suggest a bulk erupted deposit volume of about 1.5 cubic kilometers, which is equivalent to 1.5 times the volume of the Mount St. Helens eruption on 18 May 1980 [*Sarna-Wojcicki et al.,* 1981], or about 10 times the volume of the 2010 Eyjafjallajökull eruption in Iceland [*Gudmundsson et al.,* 2012].

Although these are preliminary estimates, they place the 2012 Havre eruption as magnitude 5 on the volcanic explosivity index [*Newhall and Self,* 1982]—making it probably the largest (in addition to being the deepest) historical submarine explosive eruption ever documented. Equivalent-sized subaerial eruptions are dramatic once- or twice-a-century events [*Deligne et al.,* 2010].

Future Research at Havre Volcano

This latest eruption at Havre volcano opens up opportunities to build on past discoveries. A U.S. National Science Foundation (NSF)–funded research expedition is planned for 2015, with the aim to address fundamental questions associated with submarine volcanism. This project is an international collaborative effort between NIWA, the University of Hawaii, the University of Tasmania, Woods Hole Oceanographic Institute, the University of Otago, and the University of California, Berkeley. Researchers will deploy a remotely operated vehicle (ROV) and an autonomous underwater vehicle in tandem to conduct detailed mapping of eruption vents and products and to collect samples in situ.

By combining information and observations from the eruption plume and raft with pre-eruption and post-eruption bathymetry, an accurate measure of vent pressures and ejecta volumes can be produced, and transport

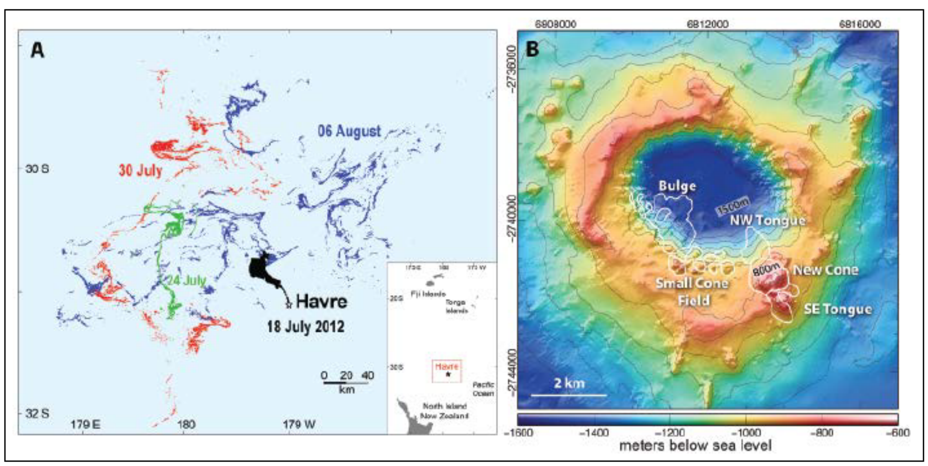

Fig. 2. (a) Dispersal map of the pumice raft during the first 19 days after the eruption. The inset shows the location of Havre relative to the North Island of New Zealand. The red box is the area of raft dispersal shown (18 July to 6 August). The volume of the pumice raft was estimated on the basis of its thickness when intercepted in August and the raft extent on 18 July prior to its attenuation and dispersal by wind and ocean currents. The estimation is 0.2 cubic kilometer; however, it could be as high as 1 cubic kilometer. (b) Post-eruption bathymetry map of Havre volcano, using the World Geodetic System (WGS84). This volcano has a basal diameter of 25 kilometers and a 3-kilometer-wide caldera with a floor at a depth of 1500 meters. A comparison of pre-eruption and post-eruption bathymetry shows new features on the volcano. The main features are outlined by white lines and include new cones, elongated "tongues" of tephra accumulation, and an unidentified bulge in the caldera floor. The color scale shows meters below sea level. The 1500- and 800-meter contours are shown.

styles can be evaluated. Scientists from Australia, New Zealand, and the United States plan to use these data sets to address questions associated with magma ascent, degassing and its fragmentation, and subsequent tephra transport and deposition in deep marine environments.

The research expedition represents an investment in research that will integrate field, experimental, numerical, geochemical, and remote sensing approaches. The project goals are derived from, and will build upon, past research on submarine volcanism and will advance the state of knowledge in the field of submarine volcanology.

The fact that this explosive eruption would likely not have been predicted makes the eruption an important event to consider when contemplating the ongoing debate about how deep explosive silicic eruptions can occur. The event raises questions regarding what processes promoted the development of a subaerial eruption plume from seafloor depths of up to 1400 meters below sea level. Further intriguing questions include the following: How efficient is fragmentation in deep submarine settings? What is the partitioning of primary dispersed ejecta and that which entered the raft?

Submarine Eruptions in Perspective

This year marks the tenth anniversary of the first visual observations (via ROV) of a submarine explosive eruption, which occurred at Northwest Rota-1, a volcano near Guam, in 2004 [e.g., *Embley et al.,* 2006]. Throughout the last decade, more submarine explosive eruptions have been documented in detail than ever before—a testament not only to increasing scientific technologies for the detection of eruptions but also heightening interest in submarine volcanology. In particular, volcanic eruptions from Axial (2006; Juan de Fuca ridge), El Hierro (2011–2012; Canary Islands), and South Sarigan (2010; Marianas Arc) volcanoes are accompanied by detailed multidisciplinary volcanological, geophysical, and remote sensing data [*Chadwick,* 2006; *Carracedo et al.,* 2012; *Green et al.,* 2010].

Across all examples, however, the main limitation in the interpretation of some data sets has been the lack of physical understanding of submarine eruption processes. Studies of Havre volcano may be the key to unlocking this knowledge.

Acknowledgments

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Author Information

Rebecca J. Carey, School of Physical Science and Centre for Excellence in Ore Deposits (CODES), University of Tasmania, Sandy Bay, Tasmania, Australia; email: rebecca.carey@utas.edu.au; Richard Wysoczanski, National Institute of Water and Atmospheric Research, Wellington, New Zealand; Richard Wunderman, Global Volcanism Program, National Museum of Natural History, Smithsonian Institution, Washington, D. C.; and Martin Jutzeler, National Oceanography Centre, Southampton, UK