

Rapid submarine caldera collapse during the 2022 climactic eruption of Hunga volcano (Tonga)

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Caldera-forming eruptions are among the most hazardous volcanic processes, particularly submarine ones. Yet, the dynamics of submarine caldera-forming eruptions and, thus, the hazards they pose are not well understood, owing to the relative inaccessibility of the resulting calderas and eruption products. Here we show the changes in geomorphology of Hunga volcano (Tonga) after the 15 January 2022 eruption. From repeat high-resolution seafloor mapping we find that the caldera deepened from ~150 m to ~850 m, with its structural caldera floor ~150 m below infill, and marginally widened from ~4.5 to 4.8 km in diameter. The total displaced volume is $8.9 \pm 0.1 \text{ km}^3$. Of this, $6.85 \pm 0.05 \text{ km}^3$ is attributed to caldera collapse, with the remainder due to surface erosion by eruption-fed density currents. Our post-eruption bathymetry also revealed landslide deposits intercalated with pyroclastic infill, implying syn-eruptive caldera collapse, and inward-stepping terraces, which we interpret as surface normal fault splays over piston subsidence. The caldera and magmatic system geometry suggests that ~8 km³ of Dense Rock Equivalent magma erupted to initiate collapse, less than 30% of the magma reservoir. The magnitude of the resulting tsunami was probably enhanced by the speed and style of caldera formation, highlighting the capacity for relatively small but steep calderas collapses at submarine volcanoes to generate hazardous tsunamis.

Submerged and volcanic-island calderas are associated with some of the largest and deadliest eruptions on Earth^{1,2}. For example, the 1883 eruption of Krakatau, Indonesia, took >30,000 lives, causing widespread devastation due to resultant pyroclastic density currents and tsunami³. The 15 January 2022 Hunga volcano (Tonga) eruption produced a larger tsunami, and despite local devastation, fortunately few lives were lost⁴. Despite these violent events, the submarine setting limits the ability to resolve the morphological evolution and dynamics of caldera

collapse. Here, we compare the pre- and post-2022 climactic eruption bathymetry at Hunga volcano to understand the relationship of caldera formation to the eruption sequence and the resulting hazards.

Detailed insights into eruption-induced geomorphic changes exist at subaerial volcanoes^{5–7}; however, most submarine caldera systems remain poorly characterized because they are either unmapped or surveyed only at coarse spatial resolution. Repeat high-resolution bathymetric observations before and after submarine caldera

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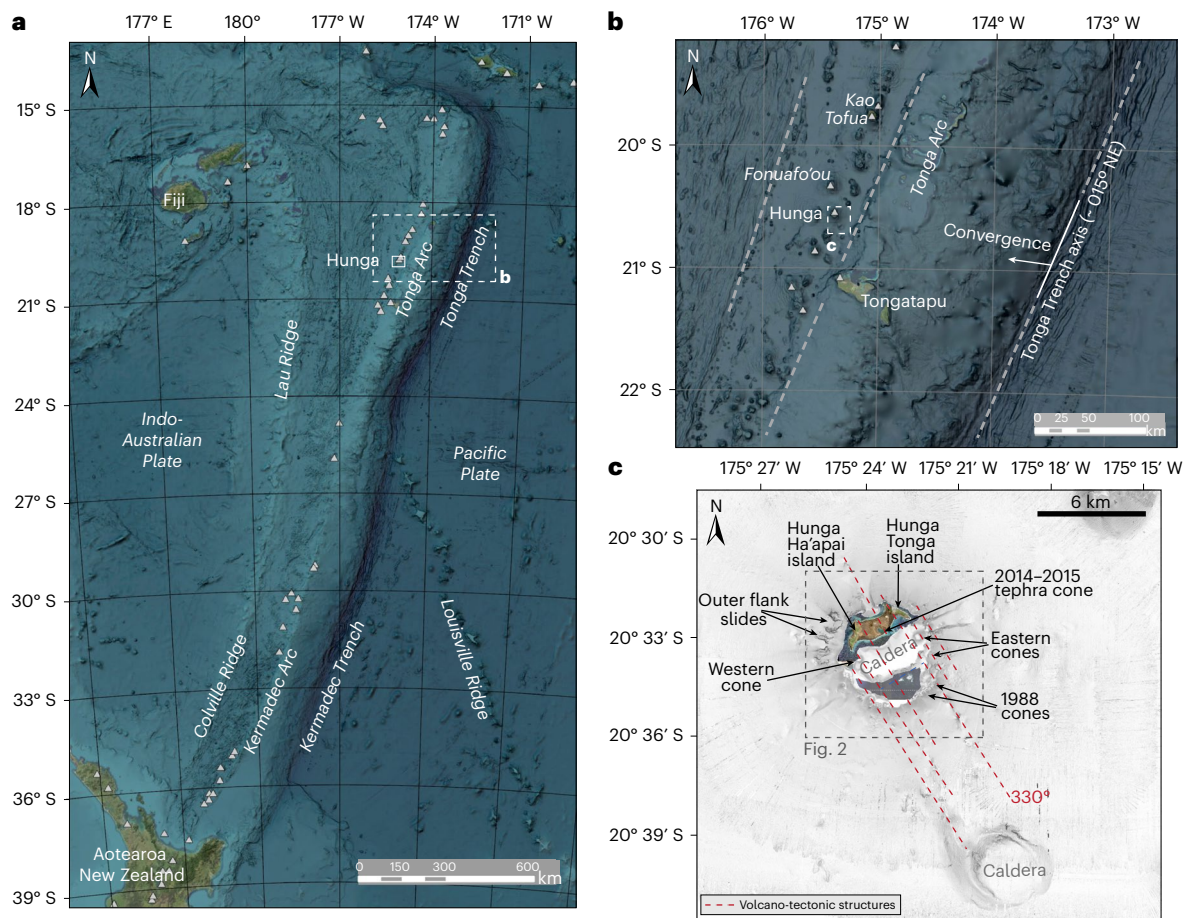


Fig. 1 | Regional bathymetric map of the Tonga–Kermadec Arc showing the detail of the local tectonics and caldera structures. a, Location map of the Tonga–Kermadec Arc. Light-grey triangles indicate major submarine volcanoes. The dashed white box indicates the area of **b**. **b**, Location map of Hunga volcano, 65 km north of the main population centre on Tongatapu island. The Tonga Trench

trends $\sim 15^\circ$ NE, and convergence vector in this area $\sim 5\text{--}15^\circ$ from trench-normal. The dashed white box indicates the location of **c**. **c**, Pre-2022 bathymetric map of the area of Hunga volcano, with interpreted local volcano-tectonic structures (dashed red lines). The dashed black box indicates the area shown in Fig. 2.

eruptions, essential for capturing eruption-driven seafloor changes, are rare and typically limited to minor events^{8–10}. As a result, the processes governing submarine caldera formation, caldera collapse dynamics and associated hazards such as tsunamis¹¹ remain poorly understood. The shallow submarine eruption of Hunga volcano in 2022 provides a unique opportunity to address these questions. This was one of the most explosive eruptions of the last Century^{12–14}, which generated deadly volcanic tsunamis^{4,13}, global atmospheric pressure waves¹⁴ and a $>55\text{-km}$ -high plume that injected volatilized seawater into the stratosphere^{15–18}. The eruption involved ~ 11 h of intense explosive magma–seawater interaction¹⁷, and produced widespread seafloor disturbance, including $>100\text{-m}$ -deep scours on the volcano’s flanks formed by volcanoclastic density currents deposits, which disrupted seafloor ecosystems and damaged >190 km of critical seafloor telecommunication cables^{19,20}. Here, we analyse the formation and evolution of Hunga volcano caldera using a time series of high-resolution bathymetric surveys and water column observations, supported by subsurface geophysical data. Comparing bathymetric datasets from 2015 and 2016 with those from April, May, July and October 2022, we quantify geomorphologic changes to interpret the structural geometry of the caldera, the associated caldera collapse mechanisms and magma volume erupted. These observations reveal previously unrecognized dynamics of submarine caldera formation and highlight the need to reassess hazard assessment associated with small caldera systems worldwide.

Structural setting

Submarine and island caldera volcanoes are common globally^{21–25}. At least 74 submarine volcanoes occur along the Tonga–Kermadec Arc (Fig. 1a), with 20 caldera complexes, including Hunga, Fonuafo’ou and Tofua within the central arc (Fig. 1b). The Tonga–Kermadec volcanic arc is oriented parallel to the subduction zone, where plate convergence is slightly to moderate oblique ($\sim 10^\circ$), and is the fastest on Earth ($\sim 200\text{ mm yr}^{-1}$)^{26–28}. Hunga volcano lies within a zone of weak extension ~ 190 km west of the Tonga Trench axis, and ~ 30 km west of the uplifted arc front (Fig. 1a). The pre-2022 bathymetry near Hunga volcano reveals structural ridges connecting the Hunga caldera to another caldera ~ 10 km to the SE (Fig. 1c). These ridges are orientated 45° offset from the Tonga Trench and appear to represent local extensional adjustment associated with the slightly oblique subduction (Fig. 1b).

Hunga volcano is a $\sim 1,800\text{-m}$ -high mainly submarine basaltic andesitic stratovolcano. Before the 2022 eruption, two $\sim 2\text{-km}$ -long and $<140\text{-m}$ -high islands were present on the NW (Hunga Ha’apai island) and NE (Hunga Tonga island) caldera margin (Fig. 2 and Extended Data Fig. 1).

The islands expose a succession of outward-dipping pyroclastic sequences and lavas². Radiocarbon dating of a pyroclastic deposit sequences and geochemically correlated downwind tephra indicate at least one previous caldera-forming eruption $\sim \text{AD } 1100$, with older distal fall deposits suggesting cyclical repetition of this activity². Shallow explosive (Surtseyan) submarine and surface eruptions occurred

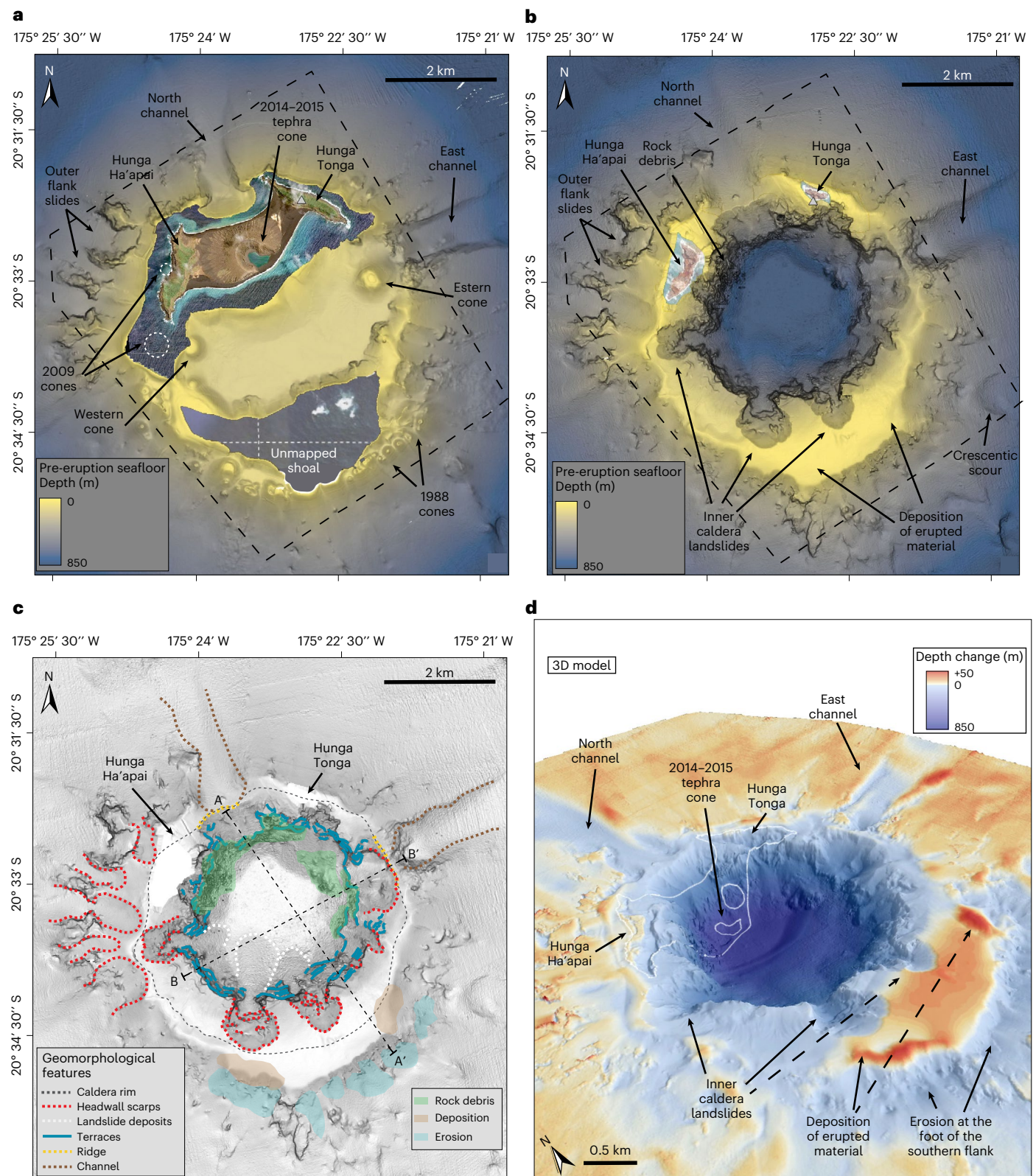


Fig. 2 | Time series of Hunga volcano caldera before and after the 2022 eruption, revealing geomorphological and volumetric changes. **a, b**, Bathymetric maps showing the Hunga caldera morphological evolution pre-eruption (**a**) and post-eruption (**b**). The dashed black line indicates post-eruption survey coverage. White circles in **a** indicate the 2009 cones³². **c, d**, Geomorphological classification of the Hunga caldera and surroundings. A–A' and B–B' dashed lines indicate the location of the Sparker seismic profiles,

SPK-03 and SPK-05, respectively (**c**); and 3D volume change model (**d**) (that is, integrating all emerged and submerged elevation models; see the Methods for details). Note: colour scale is nonlinear, with blue colours indicating erosion and red colours indicating deposition. The white line in **d** indicates the outline of the 2014–2015 tephra cone, connecting Hunga Ha'apai and Hunga Tonga islands, visible in **a**.

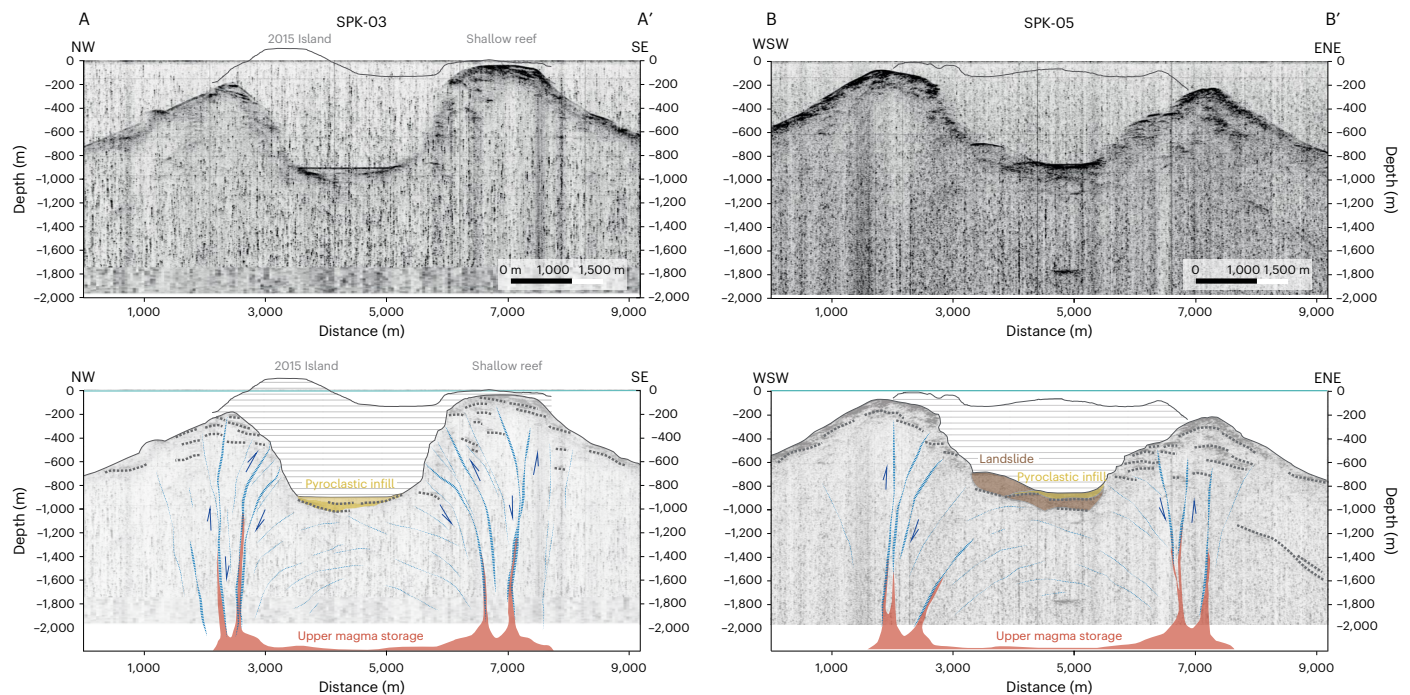


Fig. 3 | Seismic reflection profiles and interpretation of the internal structure of Hunga caldera. Sub-bottom sparker seismic profiles (top) collected by RV Araon in April 2022 (see location in Fig. 2c), and interpretation (bottom) of the sub-seafloor structure. Dashed grey lines indicate the reflectors

identified in the profiles. The yellow area delimits the pyroclastic caldera infill. The brown area indicates landslide deposits. Note: seismic penetration depth limited due to the high-frequency range of the signal encountering dense and/or coarse volcanic material.

from marginal vents surrounding the Hunga caldera in 1912, 1937²⁹, 1988^{30,31}, 2009^{32,33} and 2014–2015³⁴. The 2014–2015 eruption built a 2-km-diameter tephra cone and this general vent area was also where the 2021–2022 eruption sequence started^{34,35}. Nearby island volcanoes (Tofua³⁶) and shallow submarine volcanoes (Fonuafo’ou) show similar overall form, structural/vent orientation, composition and caldera size to Hunga volcano. These and other nearby emergent basaltic-andesitic cones (for example, Kao, 1,030 m above sea level) may be potential precursors to calderas.

Caldera morphological and structural changes

The 5.6-km-diameter summit area of Hunga remained largely similar (~27 km²) after the 2022 eruption. The pre-eruption bathymetry (Fig. 2a) revealed ~22 cones around the outer circumference of the caldera. Cone diameters are mainly between ~100 m and 160 m, with some larger cones in the west (~200 m) and east (700 m) (Fig. 2a). The central Hunga caldera contained a ~2 × 4 km WSW–ENE oriented basin with water depths between 150 m and 200 m (Fig. 2a). Immediately SSW of Hunga Ha’apai, a shallow platform was formed by wave erosion of a tephra cone produced by the 2009 eruption³² (Fig. 2a). The southern caldera rim was a broad shallow shoal (<10 m) with reefs of emergent lava at low tide. Cones associated with the 1988 eruption lie along the south caldera edge (Fig. 2a).

The 15 January 2022 eruption widened and deepened the caldera, caused channel erosion, sheet erosion on the southern volcano flank, and intra-caldera wall landslides, with ~0.5–1 km wide headwall scarps, and run-out deposit extending ~1.6–2 km into the caldera centre (Fig. 2b,c). The total net volume of material displaced from the eruption was 8.9 ± 0.1 km³, made up of 7.7 ± 0.1 km³ lost from within the broader caldera rim, and 1.2 ± 0.1 km³ on the rim and upper southern volcano flanks (Fig. 2d). The 7.7 km³ difference in the central caldera includes the caldera basin of 6.85 ± 0.05 km³ (estimated using a cylindrical harmonic model; Methods), with the additional ~0.9 km³ representing material eroded from the rim and the northern and eastern erosive channels (Fig. 2c).

Caldera structure and fluid vents

The Hunga volcano post-eruption caldera has a diameter of ~4.2–4.6 km, and the structural diameter (d_s)²¹, estimated from the inflection point of steepest inner slopes, is 4 ± 0.4 km (based on the caldera geomorphology; Fig. 2c). The deepest portion, ~850 m below sea level (bsl), occurs in the northwest of the caldera (Fig. 2b,d). The caldera walls vary from near vertical (~70° slope) on the NW margin to a series of inward-steepening concentric terraces in the east and south (Fig. 2c), separated by steep ~100–150-m-high escarpments, at water depths between 150 m and 780 m (Extended Data Fig. 2). These terraces are not tilted on listric failure planes; instead, they appear to be formed by surface normal faulting (Figs. 2 and 3), accommodating caldera failure^{21,37}. The landslide deposits, with a total volume of ~0.4–0.5 km³ (interpreted from bathymetric data), occur below, intercalated with and above flat-lying pyroclastic infill in the caldera floor (Fig. 3). The caldera infill reaches up to 150 m, and we estimate the structural floor lies at ~1,000 m bsl (clearly distinguished by a strong reflector; Fig. 3). The total vertical subsidence between pre- and post-2022 eruption surveys is 1,100 to 800 m (average ~1,000 m), with the greatest collapse occurring in the NW below the initial vent area (Fig. 2d).

Active fluid plumes were observed in acoustic water column data from the May 2022 survey (Fig. 4a). The largest plume was ~450–500 m high ($>6.9 \times 10^7$ m³ vent) at ~700–650 m bsl within the NW caldera margin (Fig. 4c,d). A second large plume ($\sim 3.8 \times 10^7$ m³ vent) occurred at ~650 m bsl near the SE edge of the caldera floor (Fig. 4c,e,f). Other smaller vents occurred above escarpments on the NW caldera wall at ~50–130 m bsl (Fig. 4a,b).

Caldera water column structure

Repeated vertical profiles of conductivity, temperature and depth–pressure (CTD) across the Hunga caldera, collected 3 and 9 months post-eruption (April and October 2022), revealed a two-layer water structure with a strongly marked thermocline (Extended Data Fig. 3). A distinct surface layer of warm and low-salinity waters extends down to ~150–200 m bsl, and sits above a homogeneous colder and denser

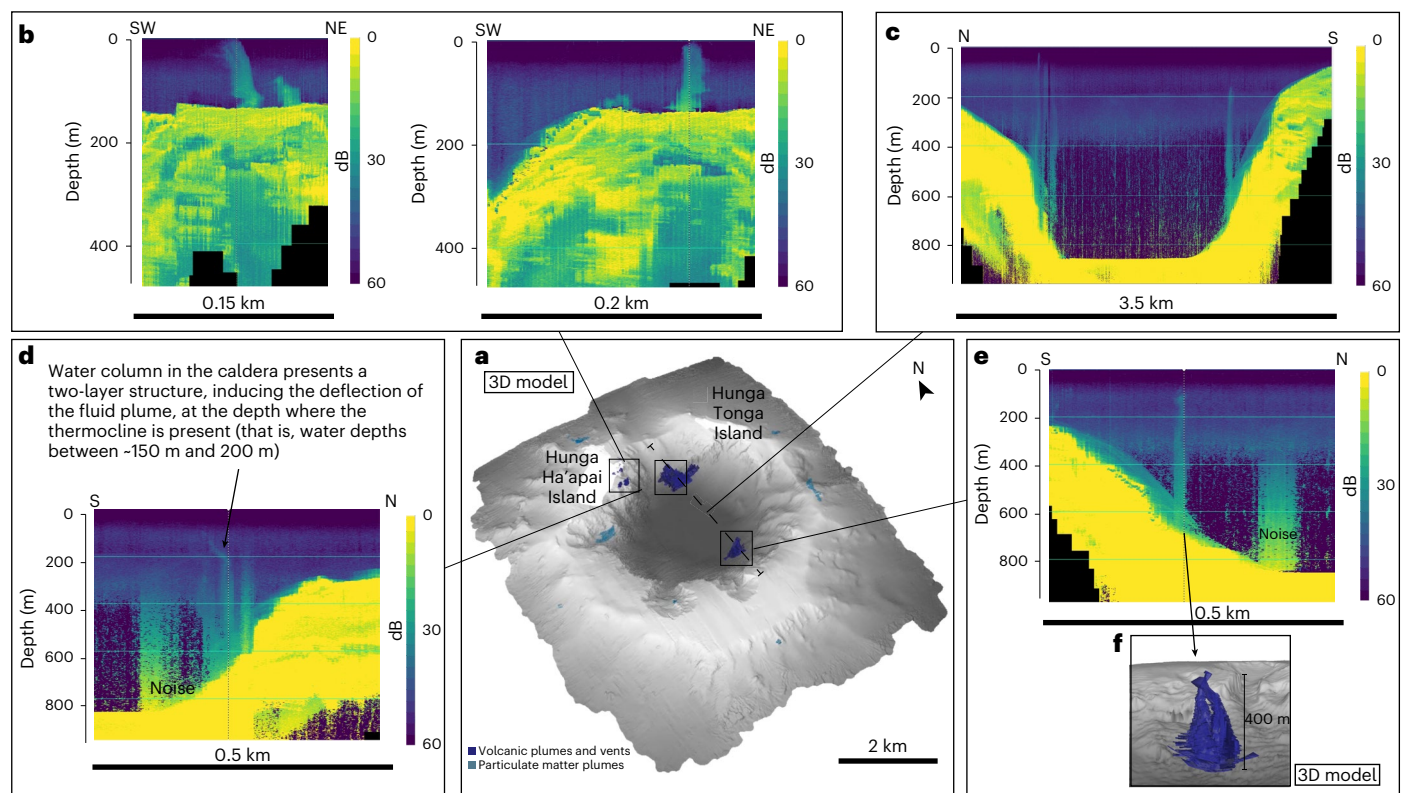


Fig. 4 | Water column imagery showing active volcanic vents identified in Hunga volcano in May 2022. a, A 3D model of Hunga volcano showing the distribution of active vents observed during the survey in May 2022. **b**, Shallow fluid plumes observed at 30–150 m bsl, on the NW of the caldera. **c**, Cross-section

showing the major vents aligned on a N–S direction across the caldera. **d**, Deep vents, located at 350–600 m bsl, in the NW. **e**, Second major vent in the SE, also shown in a 3D model. **f**, A 3D model and MBES water column images extracted using Echoview software.

water layer down to the caldera floor. Comparison between the two hydrographic datasets shows slight decrease in salinity of the bottom layer between April and October 2022, with the latter being more homogeneous (Extended Data Fig. 3). This water structure suggests little vertical mixing within the caldera, and potential oceanographic differences between the inner caldera and the surrounding waters, similar to the stratification seen in a terrestrial crater lake³⁸.

Collapse of Hunga caldera

Calderas are major volcanic-tectonic features associated with surface subsidence above a magma reservoir and are distinct from explosion-excavated craters^{39–42}. The most common case is gravitational failure due to underpressure within a shallow reservoir^{1,43}. In simple cases, deep reverse faults develop around the failed block above the magma reservoir and these propagate up the surface, to be expressed as a series of arcuate ring faults around the caldera margins⁴⁴. Ring faults are rarely visible in small steep and fresh calderas, such as Hunga volcano, but their position can be inferred from the interpretation of caldera wall terraces (Figs. 2c and 3). Ring faults are also conduits for magma rise and thus control the distribution of caldera-rim cones (Fig. 2a) and fluid vents^{45,46} (Fig. 4). Distinct steps on caldera walls such as at Hunga volcano (Extended Data Fig. 2) typically indicate normal faults that splay from the main zone of collapse^{21,47,48}.

The generally simple geometry of the Hunga caldera indicates a piston-style collapse of the caldera floor⁴⁸, although there is a slight asymmetry with a deeper NW portion, which may reflect greater material loss at the major vent zone (Figs. 2d and 4). The timing and high-rate of collapse is indicated by the intra-caldera landslide deposits intercalated with and below flat-laying pyroclastic caldera infill (Figs. 2c and 3). These relationships suggest that the caldera collapse occurred during the eruption, and landsliding synchronous with caldera collapse. This is

consistent with mechanical models of caldera ring-fault failures initially exceeding equilibrium limits, causing landslides to reduce wall slopes⁴⁷.

The greatest subsidence and steepest slopes within the occurred on the northwestern side of Hunga caldera (Fig. 2d), coincident with the vents from the 2014–2015 and 2021–2022 eruptions⁴⁴ (Fig. 2a). Together with the observed post-eruptive vents (Fig. 4a,d) this suggests the NW vent was the primary eruption site for the first part of the eruption. The presence of submarine chilled bombs consistent with compositions of the final eruption stages¹⁷ near the southern deep gas plume (Fig. 4a,e,f) suggests that this vent was active after caldera collapse. The positions of the volcanic vents around Hunga caldera before the 2022 eruption (Fig. 2a) fit the caldera classification of type-Ms of Geyer et al.⁴⁹. However, the positions of the vents post-eruption (Fig. 4a) suggest a type-Rs structure (defined as vents occurring along an arcuate line parallel to the caldera margin⁴⁹), with Hunga vents located at opposite sides of the caldera, along the trend of regional structural lineations identified in the Hunga area (Fig. 1b,c).

Magmatic underpressures driving caldera collapse

The morphology of calderas is controlled by the geodynamic context of their formation, eruption volume, magma composition and depth, as well as crustal lithology and regional tectonic stress regimes⁵⁰. Caldera morphology can therefore provide valuable insights into the deep volcano structure, such as the amount of magma underpressure needed to trigger the collapse⁵¹. Hunga caldera has a structural diameter (d_s)/subsidence (s) ratio of ~4, following the 2022 eruption, which places it within the stage 4 fully mature calderas, following the Acocella (2007) classification²¹. Moreover, this caldera shows evidence for upper an outer surface normal faults that branch from an inner reverse ring fault structure, consistent with underpressure-driven collapse (Fig. 3). The pre-eruption caldera infill is unknown, but using a conservative

estimate of 350 m of subsidence, the maximum d_s/s of $4/350 = 11.4$ places Hunga volcano also within the stage 4 category²¹. The aspect ratio (r) (that is, depth to magma divided by magma diameter^{49,51}) of the final caldera, estimated from the depth to the top of the magma reservoir (2 km)^{17,44} and the magma reservoir width (4–5 km)⁴⁴, is 0.4–0.5, which places it firmly in the category of weak calderas ($r < 0.7$), defined by Geshi et al.⁵¹. Using friction model relationships presented by these authors⁵¹, we calculate that a relatively low underpressure of ~30 MPa was needed to trigger collapse of Hunga caldera.

Hunga erupted andesitic pyroclastics¹⁷, and the uppermost reservoir 2–10 km below the volcano^{17,44} was estimated to contain ~27 km³ of magma⁴⁴. Based on caldera dimensions and underpressure estimates, only ~26% of magma withdrawal was required to initiate collapse, that is, 7–8 km³ Dense Rock Equivalent (DRE). This places a lower estimate on eruption volume, because it does not account for recharge during the eruption as was inferred by gravitational changes in the magmatic system⁴⁴. This is a similar value to the caldera geomorphic volume estimate of 6.85 ± 0.05 km³. A further 100–150 m of caldera infill (Fig. 3) adds ~0.3–0.4 km³, suggesting a 7.2 ± 0.05 km³ volume loss. The edifice density is expected to be higher than magma density (estimated at $2.4\text{--}2.6$ g cm⁻³)⁴⁴ so that DRE magma loss could be higher. This effect is probably countered by parts of the edifice dispersed (<5 vol.% lithics)¹⁷ and gas expansion of the magma reservoir (<5 vol.%)¹⁷. A total geomorphic loss estimate is thus probably 7 ± 0.7 km³. Combining the geomorphic and magma underpressure estimates suggests that the Hunga 2022 eruption involved at least 8 km³ DRE magma.

Ongoing volcanic activity at Hunga

Repeat bathymetric datasets from 4 months (May 2022) and 9 months (October 2022) post-eruption show no substantial morphological changes, excluding large-scale intra-caldera volcanism or landslides (Extended Data Fig. 3). The best evidence for ongoing volcanism at Hunga volcano is active fluid vents identified in the NW and SE caldera margins in May 2022 (Fig. 4). However, the absence of these deep vents 5 months after the eruption (October 2022) suggests that either degassing from the eruptive vents had ceased as magma withdrew, or the system became sealed by hydrothermal mineralization. Earthquakes following the 2022 eruption show a progressive withdrawal of magma after the 2022 event⁵². Despite this, an ongoing presence of magma is indicated by shallow fluid plumes remaining on the NW caldera margin near Hunga Ha'apai, at <150 m bsl (Fig. 4a,b), and observed also in the October 2022 survey (data not shown). This suggests that magmatic fluid is migrating up the caldera ring fault system. The ongoing hydrothermal fluid output might also be responsible for the slight decrease in salinity within the caldera and the two-layered water structure remaining stable for at least 9 months after the 2022 eruption.

Global context

The ~4-km-diameter caldera of Hunga volcano lies within the lower ~12% of a global calderas database including 177 calderas^{21,22,49} and subsequently published literature. Hunga caldera collapse (~1 km) is similar to the average of the range estimated in the global dataset. The ratio of subsidence to diameter (0.25) at Hunga volcano is higher than most calderas, with calderas <10 km in diameter, and very similar to Newberry, Somma-Vesuvius, Nisyros, Fantale and Miakejima (Extended Data Fig. 4a). The modest lateral dimension is consistent with the generally smaller footprint of intermediate and mafic magmatic systems, compared with rhyolitic ones. Meanwhile, the relatively deep collapse at Hunga may reflect a weak submarine edifice, dominated by tuffs and volcanoclastic sediments with isolated pillow lavas and shallow intrusions.

The DRE eruption volume of the 2022 Hunga event in relation to the caldera diameter sits well within the broad global trend. With an aspect ratio (r) of 0.5, Hunga caldera is on the global average, within a subset of 32 calderas of <10-km diameter, with the collapse

probably being initiated with an underpressure as low as 30 MPa (Extended Data Fig. 4b). This suggests a similar sub-caldera structure and dynamic to calderas such as Askja, Somma-Vesuvius and Tambora.

The Indo-Australian plate oceanic crust under the Tonga Arc is ~20 km thick with a bulk basaltic composition and seismic properties similar to other island arcs⁵³. The greater crustal thickness supports the formation of mid-crustal magma storage, which promotes caldera formation. Supporting this, Contreras-Reyes et al.⁵³ noted common shallow intrusions below the volcanic arc representing ongoing high rates of shallow intrusion and ponding of magma.

Implications for submarine caldera-forming eruptions

Our time-series bathymetric mapping reveals geomorphological changes on Hunga volcano caldera due to the syn-eruptive caldera collapse on 15 January 2022, and exposes a critical gap in global preparedness for submarine volcanic hazards.

Our results imply that rapid caldera collapse during major submarine eruptions may radically transform ocean structure, processes and composition, as well as eruption hazards, such as generating extreme density mass flows and tsunami hazards. The eruption triggered the largest and highest tsunami ever recorded from an underwater volcanic eruption, exceeding other well-documented cases in recent history (for example, Krakatau⁵⁴), with tsunamic waves heights reaching ~40 m at distances up to 100 km from the source. These observations highlight the capacity for submarine caldera collapse to generate exceptional tsunami magnitude, even in relatively small volcanic systems⁵⁵. In addition, fracturing and ring-fault development associated with caldera subsidence may lead to sudden and deep ingress of seawater into shallow magma reservoirs, radically transforming eruption explosivity, and promotes the generation of powerful volcanoclastic density currents.

Our study underscores the urgent need for high-resolution repeat seafloor mapping to capture the dynamics of submarine caldera formation and collapse. These time-series datasets are essential for improving submarine volcano hazard monitoring, strengthening tsunami early-warning systems and protecting critical seafloor infrastructure, particularly in poorly surveyed regions such as the southwest Pacific.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41561-026-02099-7>.

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Methods

Pre-eruption bathymetry datasets were acquired in November 2015 using a WASSP DRX-46 multibeam echosounder (MBES) (160 kHz) mounted on MV Pacific Rose, and in May 2016 onboard R/V Falkor (FK160407) using a Kongsberg Maritime EM302 (30 kHz) MBES echosounder. The repeat post-eruption swath bathymetry of Hunga and surroundings is a mosaic of different datasets acquired during several surveys, including: (1) April 2022, by R/V Araon, using a Kongsberg EM120 (12 kHz) MBES (summit and surrounding flanks); (2) May 2022, on M/V Pacific Horizon, using a WASSP DRX-46 (80 kHz) MBES (summit plateau and upper flanks); (3) April–May 2022, by R/V Tangaroa, using a Kongsberg EM302 (30 kHz) MBES (surrounding flanks)⁵⁶; (4) July–September 2022, using the SEA-KIT International's Uncrewed Surface Vessel (USV) *Maxlimer*, with a Kongsberg EM710 (70–100 kHz) MBES (summit area)⁵⁷; and (5) October 2022, on M/V Pacific Dawn, using a WASSP DRX-46 (80 kHz) MBES (summit area).

All bathymetric datasets were corrected for heading, depth, pitch, heave and roll. Postprocessing was conducted using QPS Qimera software (V 2.3.5), and all processed MBES datasets were gridded at a 10-m horizontal resolution. Corrections for sound velocity were made using direct measurements during survey and from sound velocity profiles calculated from CTD vertical profiles.

CTD profiles collected in the October 2022 survey were acquired using a *Ruskin RBR* logger with a sampling rate of 2 Hz. Conductivity data were used to calculate salinity, and depth was calculated from the data recorded by the pressure sensor. Data recorded were exported directly to OceanDataView software, used to represent the water column structure and hydrographic parameters along the two transects of CTD profiles collected in the caldera.

Water column anomalies were systematically detected from the MBES data from the surveys conducted in May and October 2022, and Echoview software was used for MBES water column analysis to identify and map seafloor vents emitting gas fluids and/or particles. Seafloor vent locations were estimated by their relative detection in vertical and laterally angled beams of each multibeam track and triangulated between parallel survey lines. Disturbance height and vent size were estimated by the strongest beam response (closest to the vent). Errors in position are estimated to be ~20 m in *X* and *Y*, while vent height uncertainties are ~30 m depending on the position of the vent in relation to the sensor and the observed margin of water disturbance.

Sub-bottom profiles were collected in April 2022 by R/V Araon using Seismic Sparker system with a 5,000 J electrode power (ELP100 model) and a sampling frequency of 4,000 Hz. During the seismic survey, the ship moved along the survey track lines at ~4–4.5 knots. The acquired data were immediately processed onboard by applying band-pass filtering (that is, 30–60–600–650 Hz and automatic gain control) and deconvolution (that is, removal of effects masking the primary reflected structures detected).

The subaerial (emergent) topography of the Hunga volcano has been documented since 2015, with increased focus from late 2021 to present, using Maxar WorldView (WV-2, WV-3 stereo imaging at 0.5 m per pixel resolution). Digital elevation models (DEMs) generated at 1-m ground sample distance were calibrated and validated by National Aeronautics and Space Administration (NASA) ICESat-2 lidar altimetry tracks, based on footprints with absolute ranging precision (and hence centre of mass (COM) referenced) at <20 cm. The DEM were complemented by field differential GPS surveys in 2018 and 2019 on visits to the 2014–2015 tephra cone by SSV Seamans and students from the Sea Education Association programme assisted by NASA colleagues. Integrated CSA Radarsat Constellation Mission (RCM) spotlight SAR images every 2–3 days were acquired from December 2021 through April 2022 using multiple beam geometries at ~1-m spatial sampling, courtesy of the RCM-vetted user programme. These satellite data were further used to track volumetric changes at Hunga Ha'apai and Hunga Tonga islands from late January 2015 to present, with subaerial topography

(including a drone-based, real-time kinematic-global positioning system (RTK-GPS) controlled survey carried out in November 2015 by the University of Auckland), merged with the various bathymetric datasets.

Integrated three-dimensional (3D) topographic models combining the pre- and post-eruption bathymetry were used to construct a 10-m DEM of the entire Hunga volcano edifice. This was used as a baseline to measure differential volumes after careful co-registration and leveling against the regional seafloor 'ground plane' as a stable reference over this time of period. A cylindrical harmonic model approach was applied to model a set of best-fitting cylindrical harmonic coefficients and a power spectrum that rendered ~95% of the 3D shape of the Hunga caldera. This produced between 10 and 12 values, which were integrated to produce volume estimates to compare with those measured from the differential sonar/satellite DEM datasets with agreement to a few per cent. The cylindrical harmonic model approach provides validation and calibration of the displaced volume. A similar approach was carried out to evaluate the volume of the 2014–2015 Hunga tephra cone³⁵. Drone-based (DJI Phantom 4) aerial photogrammetry of Hunga Ha'apai and Hunga Tonga islands was collected during surveys conducted in May and October 2022, and used to estimate changes in the subaerial expression of the system via structure-from-motion computations (that is, developed at NASA for planetary spaceflight).

Data availability

Source data are provided with this paper. These data are also available via Marine Geoscience Data System (MGDS) at <https://www.marine-geo.org/doi/10.26022/IEDA/330859>, via Zenodo at <https://doi.org/10.5281/zenodo.7456324> (ref. 58) and via Tuwhera Open Access at <https://open-repository.aut.ac.nz/workspaceitems/131143/view>.

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and Canada's Radarsat Constellation Mission (RCM) programme for satellite observations, plus timely observations from NASA's ICESat-2 and ISS/GEDI laser altimeter capabilities in Earth's orbit.

Author contributions

Conceptualization of the work: M.R., S.J.C. and S.-H.P. Data collection: S.-H.P., S.J.C., M.R., K.M., S.J.W., M.S.M., F.L., N.H., P.T. and T.K. Formal analyses: M.R., S.J.C., S.-H.P., J.G., D.A.S., Y.C., J.J., J.Y., B.H., S.S., S.-G.K., G.S. and J.D.L.W. Global caldera database: S.J.C. and M.R. Funding acquisition: S.J.C., S.-H.P., M.R., M.B., M.A.C., I.A.Y. and J.H. Main draft writing: M.R. and S.J.C. Discussion, review and editing of manuscript: all authors.

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Competing interests

The authors declare no competing interests.

Additional information

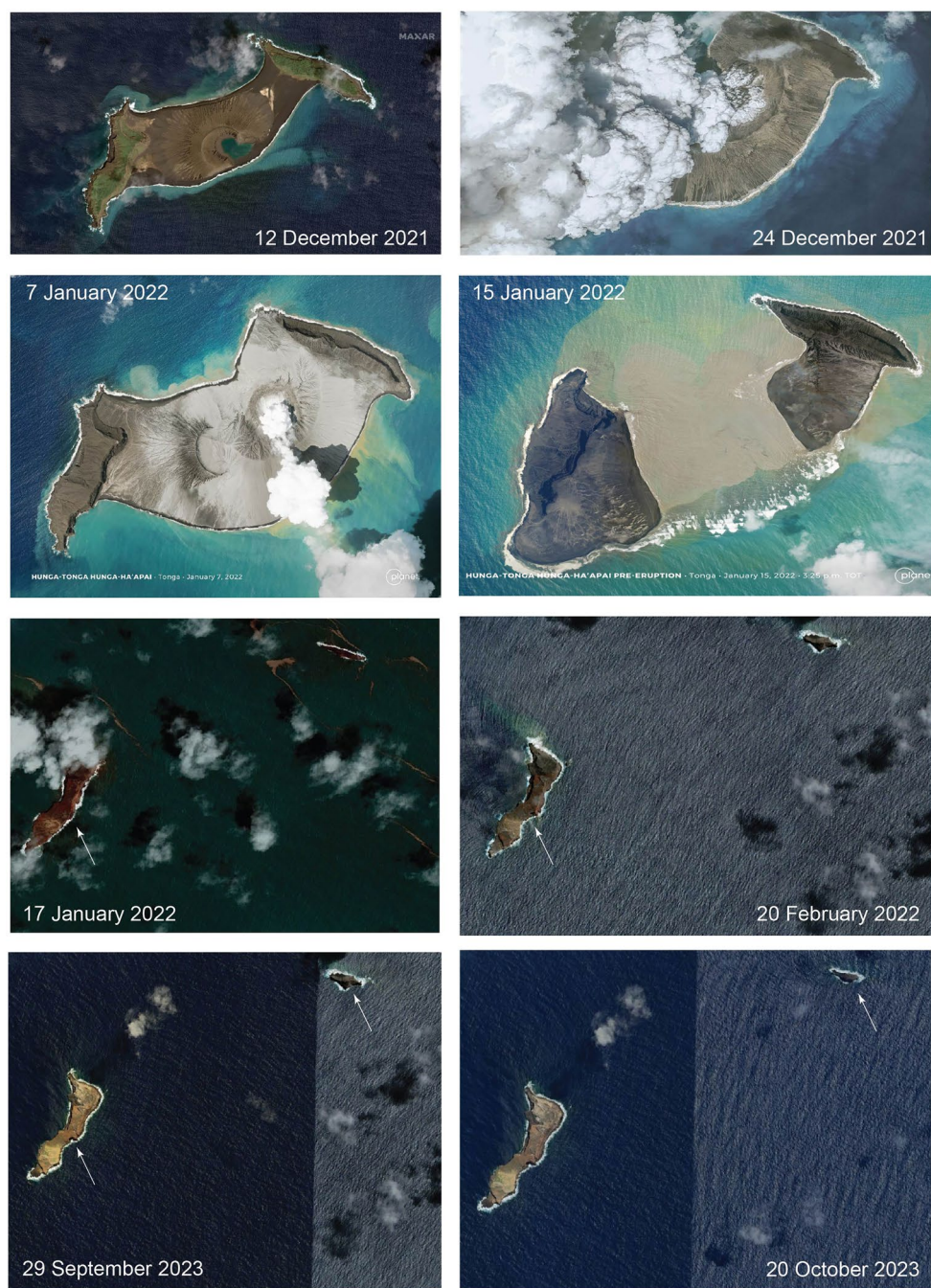
Extended data is available for this paper at <https://doi.org/10.1038/s41561-026-02099-7>.

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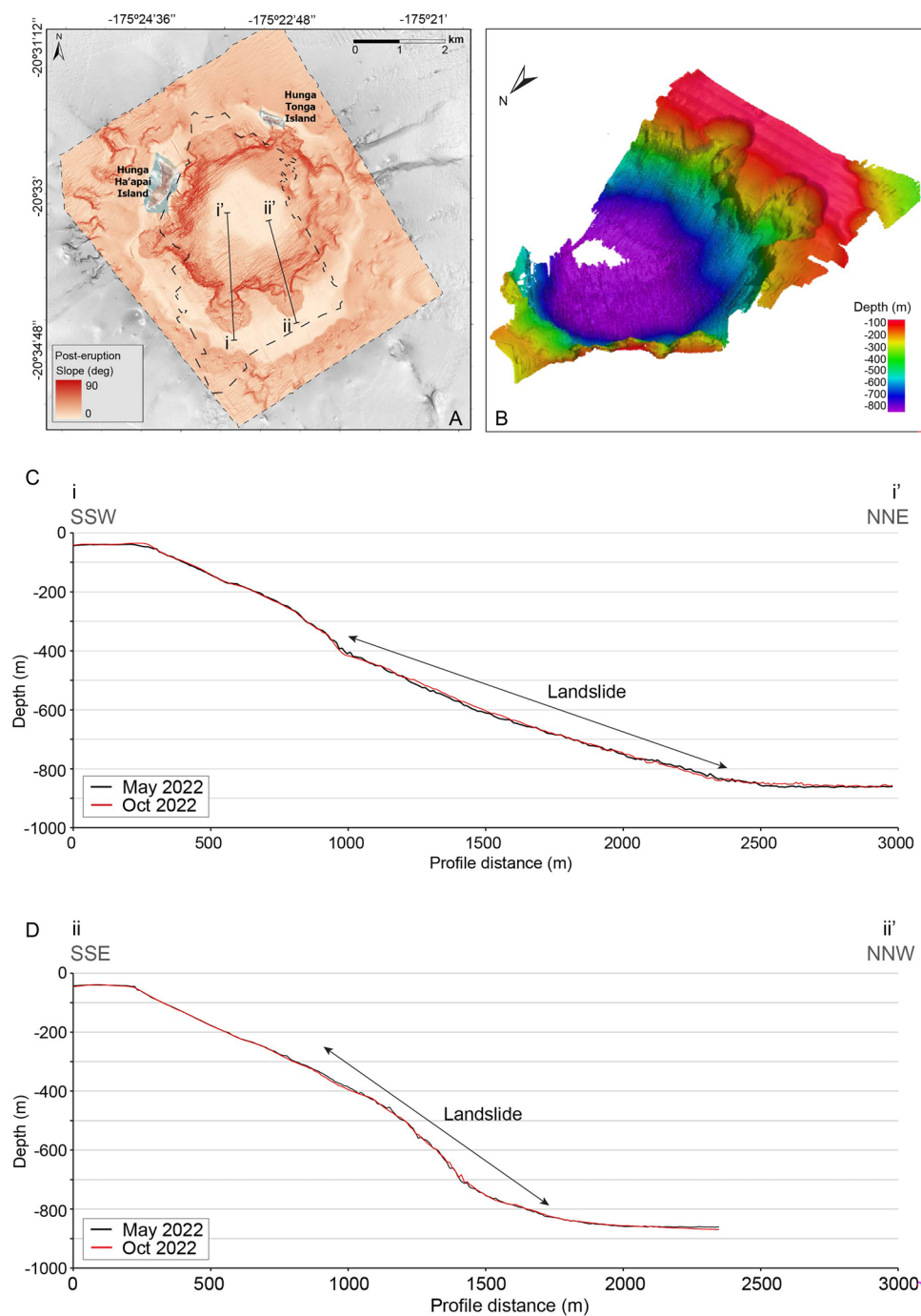
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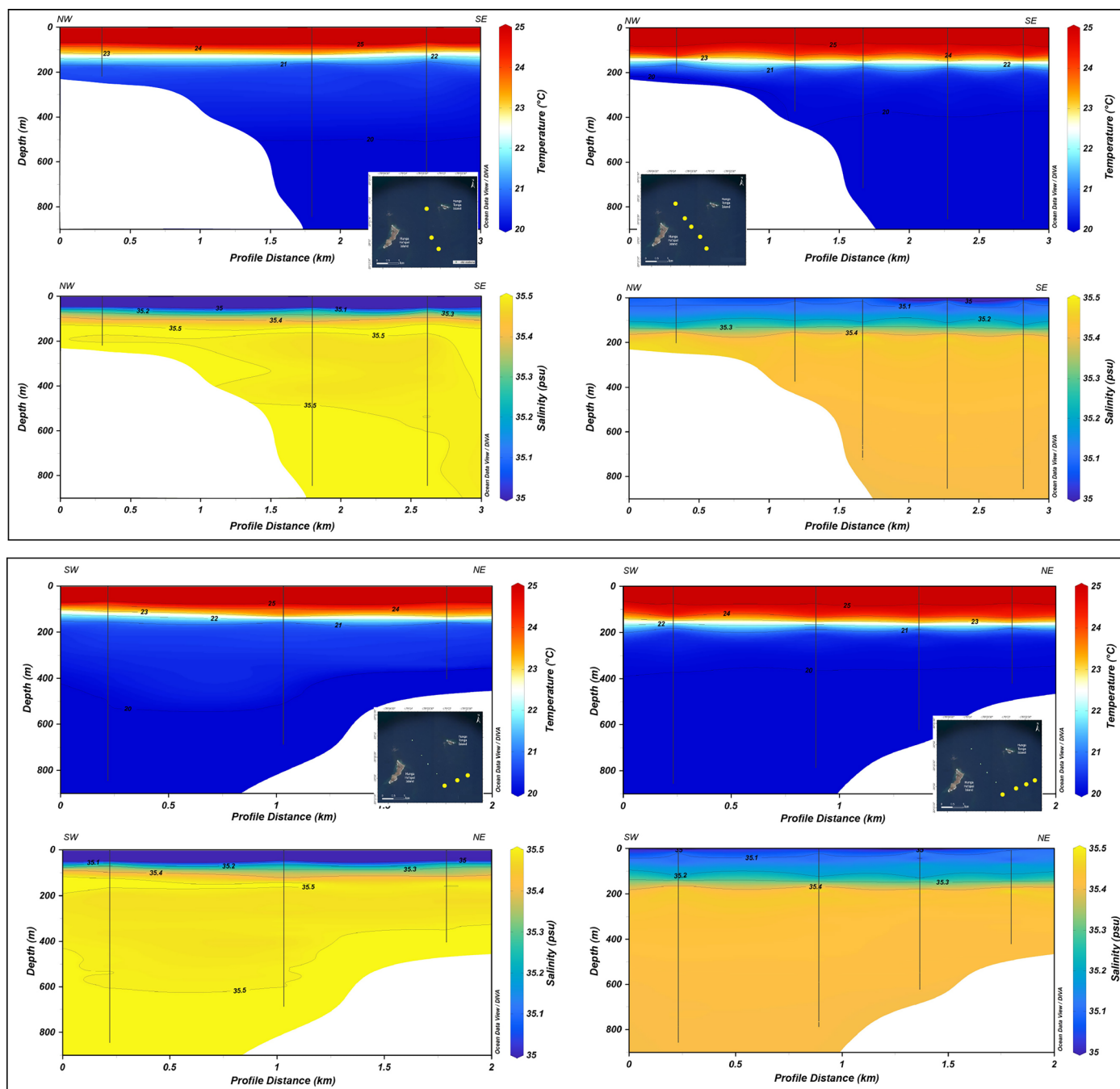
Extended Data Fig. 1 | Satellite imagery revealing the evolution of submerged parts of Hunga volcano. Satellite images showing the emergent parts of Hunga caldera, Hunga Ha'apai and Hunga Tonga islands undergoing continuous changes

since December 2021 (upper panels) to October 2023 (lower right panel). White arrows in the lower panels indicate the erosion of Hunga Ha'apai and Hunga Tonga. Satellite imagery sources: Maxar Technologies and Google Earth.



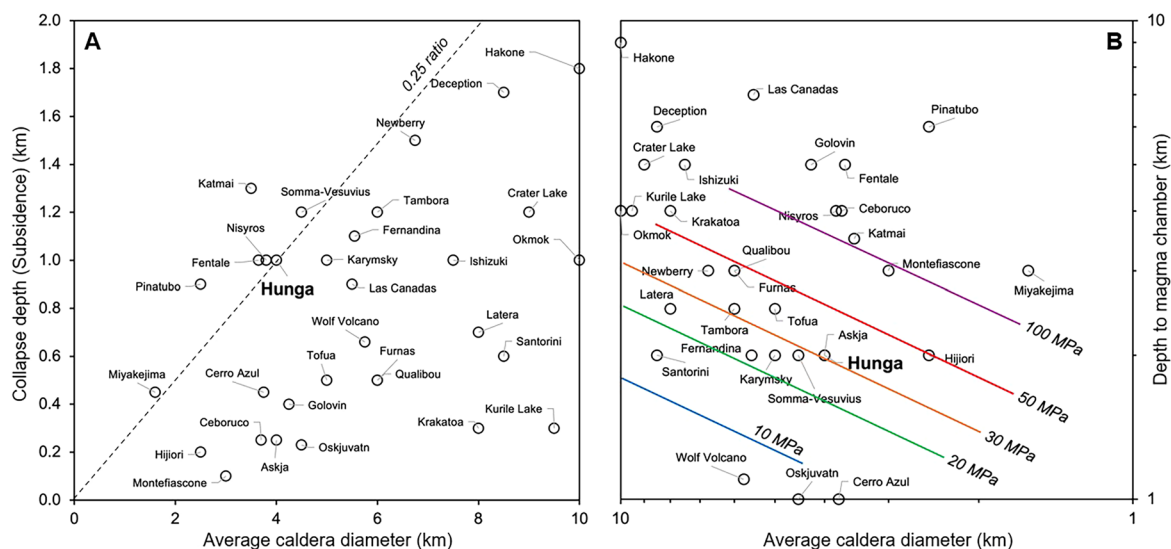
Extended Data Fig. 2 | Slope map of Hunga caldera and comparison of bathymetric profiles over submarine landslides, four and nine months post-eruption. (a) Slope map of Hunga caldera, calculated from the post-eruption bathymetric dataset. Black dashed line indicates the coverage of the repeated seafloor mapping survey conducted in October 2022. (b) 3D image

of the repeated bathymetric dataset, showing the detail of the two submarine landslides of the southern rim of the Hunga caldera. (c) and (d) Comparison of the bathymetric profiles of the submarine landslides, 4-month (May 2022, black line) and 9-month (October 2022, red line) post-eruption, indicating the location of the landslide Mass Transport Deposits (MTD).



Extended Data Fig. 3 | Inner caldera water column hydrographic vertical profiles, four and nine months post-eruption. NW-SE (upper panels) and SW-NE (lower panels) transects showing the Temperature (°C) and Salinity (psu) in April 2022 (left panels) and October 2022 (right panels). Yellow dots in insets

indicate the location of the CTD vertical profiles, shown as black lines in the transects. Hydrographic transects build using OceanDataView® software⁵⁹. Note: Data available in Source Data.



Extended Data Fig. 4 | Global comparison between calderas worldwide. (a) Collapse depth (subsidence) (km) vs average caldera diameter (km), with dashed line indicating the 0.25 ratio; and (b) Depth to magma chamber (km) vs average caldera diameter (km), with coloured lines indicating the critical

underpressure in magma chamber for caldera collapse, based on the calculations made by Geshi et al (2023)⁵¹ Note: Data for these plots is available in Extended data Table 3.