LETTERS

Long-term eruptive activity at a submarine arc volcano

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Three-quarters of the Earth's volcanic activity is submarine, located mostly along the mid-ocean ridges, with the remainder along intraoceanic arcs and hotspots at depths varying from greater than 4,000 m to near the sea surface. Most observations and sampling of submarine eruptions have been indirect, made from surface vessels or made after the fact[1–6]. We describe here direct observations and sampling of an eruption at a submarine arc volcano named NW Rota-1, located 60 km northwest of the island of Rota (Commonwealth of the Northern Mariana Islands). We observed a pulsating plume permeated with droplets of molten sulphur disgorging volcanic ash and lapilli from a 15-m diameter pit in March 2004 and again in October 2005 near the summit of the volcano at a water depth of 555 m (depth in 2004). A turbid layer found on the flanks of the volcano (in 2004) at depths from 700 m to more than 1,400 m was probably formed by mass-wasting events related to the eruption. Long-term eruptive activity has produced an unusual chemical environment and a very unstable benthic habitat exploited by only a few mobile decapod species. Such conditions are perhaps distinctive of active arc and hotspot volcanoes.

Direct observations of submarine volcanic eruptions have only been made when their vents or products reach the ocean surface, as happened during eruptions of Myojinsho[7], Surtsey[8], Macdonald seamount[2] and Kavachi[9]. Such shallow eruptions are usually too violent to study with existing technology, although some samples of fluids, microbes and volcanic products were obtained from the eruption of Macdonald seamount in the late 1980s[1,2,10]. Conversely, the more effusive deep-ocean basalt eruptions along the mid-ocean ridge have eluded direct observation. However, seafloor observations of fresh lavas, and sampling of fluids and microbes have been made within days to weeks following at least four deep submarine eruptions[11]. These eruptions have been relatively small ($\leq 55 \times 10^6\,m^3$)[12] and short-lived (hours to days)[13,14]. Phenomena associated with these mid-ocean ridge eruptions include: (1) large increases in volatiles produced by magma degassing and subsurface phase separation of the hydrothermal fluids[6,15], (2) blooms in microbial productivity driven by the increased volatile flux[4,16,17], and (3) in some cases, extinction and subsequent rapid renewal of the macrofaunal vent communities[18,19].

Submarine volcanism associated with intraoceanic island arcs is quite different in character from mid-ocean ridge volcanism. Volatiles released during the subduction of an oceanic plate causes partial melting of the overlying mantle wedge, yielding lavas that are, on average, more siliceous and gas-rich than mid-ocean ridge basalt[20]. These volcanoes are fixed with respect to their magma source for longer periods than their mid-ocean ridge counterparts, allowing their growth into shallow water or emergence as islands. The shallower depth range and the more explosive nature of submarine arc volcanism results in the generation of a much larger proportion of volcaniclastic material than at the mid-ocean ridge. These volatile-rich habitats on shallow isolated peaks may support fauna capable of surviving on intermittent hydrothermal production[21].

A survey of more than 50 submarine volcanoes along the Mariana arc in February and March 2003 identified 12 sites with hydrothermal plumes[22]. The plume overlying the summit of NW Rota-1 (Fig. 1a) was distinguished by high rise height, elevated δ^3He values and low pH (ref. 22). Dives with the remotely operated vehicles (ROV) ROPOS and Hyper-Dolphin investigated NW Rota-1 in March/April 2004 and October 2005. NW Rota-1 is conical and about 16 km in diameter at its base at 2,700 m. The summit at 517 m lies along a ridge between a pair of southwest–northeast trending, inward-facing fault scarps that cut across the volcano. Rock samples collected during the dives at NW Rota-1 are vesicular, moderately fractionated, medium-K basalt and basalt andesites (51.8 ± 0.5% SiO_2, 0.62 ± % K_2O, 6.4 ± 1.1% MgO)[23].

The south flank of the volcano between 700 and 884 m (Figs 1 and 2) is dominated by volcaniclastic debris and talus. Large-scale mass wasting is ubiquitous, with narrow spurs of lava forming headwalls of massive rock slides. The northwest–southeast trending summit ridge is composed primarily of volcaniclastic sand with some rock outcrop. Its western end has a sharp crest with a steep, unstable southern slope and a gentler northern slope (Fig. 3a). Deposits of black ash and lapilli (defined as volcanic particles <2 mm and 2–64 mm in diameter, respectively) intermixed with milllimetre-sized sulphur globules were observed on flat surfaces or within small depressions on the outcrops along the summit ridge (Fig. 3b).

ROPOS surveys discovered an active crater ~15 m in diameter and >20 m deep at a depth of 540 m on the south side of the summit. 'Brimstone Pit' (Fig. 2) was discharging a pulsating, opaque, yellowish smoky plume with characteristics unlike any known hydrothermal

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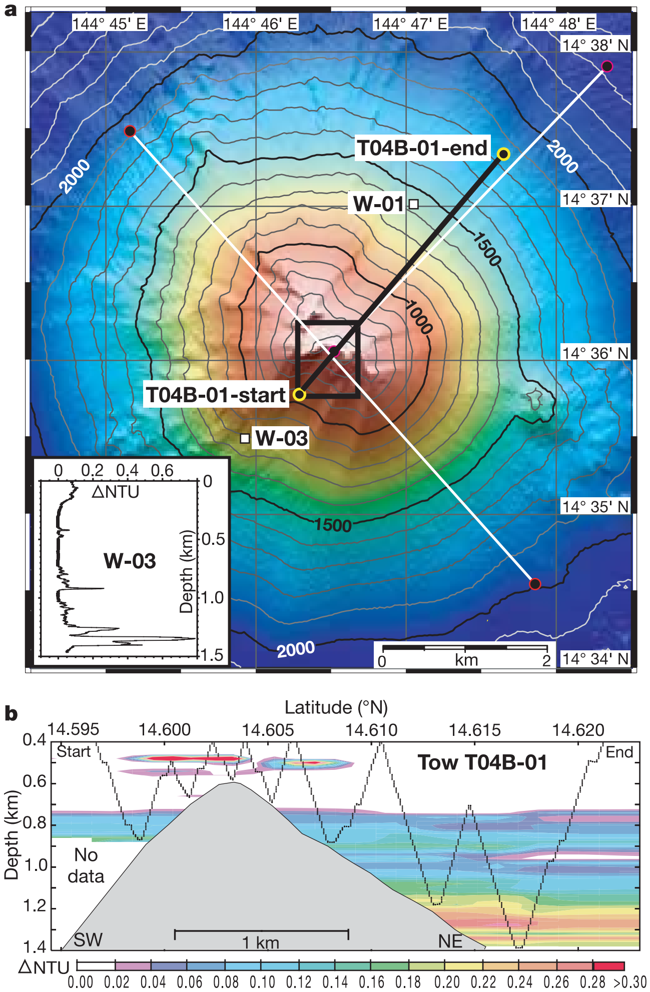

Figure 1 | Bathymetry of NW Rota-1 volcano and hydrothermal plumes. **a**, EM300 multibeam bathymetry of upper portion of NW Rota-1 volcano, southern Mariana arc (grid-cell size is 30 m; contour interval is 100 m). The base of the volcano is approximately 2,770 m, beyond the map boundary. The area shown in Fig. 2 is indicated by the black box. CTD tows that encountered the deep turbidity plume are shown by straight lines and RV *Wecoma* vertical casts (W-01, W-03), taken six weeks after tows, are indicated by square symbols. The inset is the turbidity profile for W-03. Units are in nondimensional nephelometric turbidity units above the local ambient water (ΔNTU). **b**, Southwest to northeast turbidity profile (TO4B-01) over NW Rota-1. The scale bar at the bottom of the image is colour-coded in ΔNTU.

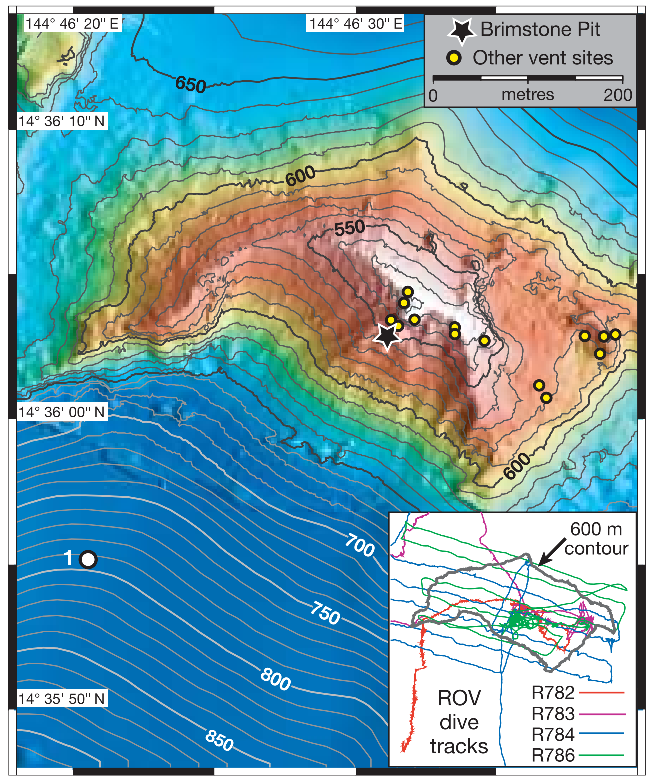

Figure 2 | Bathymetry and location map of the summit ridge of NW Rota-1 volcano with locations of features discussed in text. Contours are 10 m. High-resolution Imagenex sonar data over the ridge crest (2-m grid cell spacing) are overlaid on lower-resolution EM300 multibeam data. The white circle (point 1) is where extremely turbid layer was observed at the beginning of Dive R782. The lower-right inset shows the locations of dive tracks for R782–R784 and R786. Imagenex survey lines are the straighter northwest–southeast trending tracks.

plumes (Fig. 3c). First, it exhibited extreme fluctuations in volume and intensity. Over a period of minutes explosive surges enveloped ROPOS before receding. Second, the plume had a distinct yellow hue that resembled sulphurous plumes emitted during volcanic bursts from subaerial volcanoes (for example, the White Island volcano offshore of New Zealand). Upon recovery, ROPOS was coated with thousands of solidified globules of sulphur (Fig. 3d). Their teardrop shape indicated a semi-molten state upon contact with the vehicle (the melting point of amorphous sulphur is 119 °C). Third, during the most intense discharges, lapilli and ash were ejected up and away from the pit. Radiometric dating using the ^{210}Po–^{210}Pb method[24] of one of these fresh lava fragments that landed on ROPOS yielded a maximum eruption age of 3 March 2004, just 27 ± 12 days before sample collection on 30 Mar (see Methods). During a return visit to the site in October 2005 volcanic 'bombs' (at least 15 cm in diameter) were observed explosively degassing near the rim of a pit, showering the vehicle with volcanic debris (Fig. 3e). Some of these dark particles were observed in the plume about 25 m above the summit of the volcano and 50 m above the rim of Brimstone Pit. This chronic fallout of volcaniclastic ejecta and sulphur globules is the origin of the deposits mantling the summit outcrops and the unstable slopes of the upper flank of the volcano.

Water sampled by ROPOS from ~5 m below the crater rim within Brimstone Pit during a lull in the activity in 2004 was thick with particulate sulphur, had dissolved sulphate concentration at least 15% above ambient background sea water, had low concentrations of H_2S ($<$100 μmol litre^{-1}) and was extremely acidic with a pH (measured at 25 °C) of around 2.0. The overall chemical composition of the sampled water and the sulphur isotope ratios[25] of hydrogen sulphide, elemental sulphur, and sulphate from Brimstone Pit are consistent with magmatic degassing of SO_2 and its disproportionation into sulphuric acid and elemental sulphur:

$$3SO_2 + 2H_2O \rightarrow S(0) + 4H^+ + 2SO_4^{2-}$$

The water sampled from Brimstone Pit had a temperature as high as 30 °C in a zone of vigorous mixing. However, because this water was in contact with molten sulphur at a minimum of 119 °C, hotter water probably existed at the bottom of the pit.

A deeper dive (R782) encountered a highly turbid layer beginning at 700 m and continuing to the sea floor at a depth of 890 m (point 1, Fig. 2). A nephelometer on the CTD (a conductivity, temperature and depth measuring instrument) towed over the volcano during the 2004 expedition detected a zone of turbid layers surrounding the volcano from a depth of 700 m to over 1400 m (Fig. 1b). The scanning electron microscope imagery of particulate samples from the plume show that its suspended fraction consisted primarily of volcanic glass fragments[26]. The deep turbid layer was uniquely

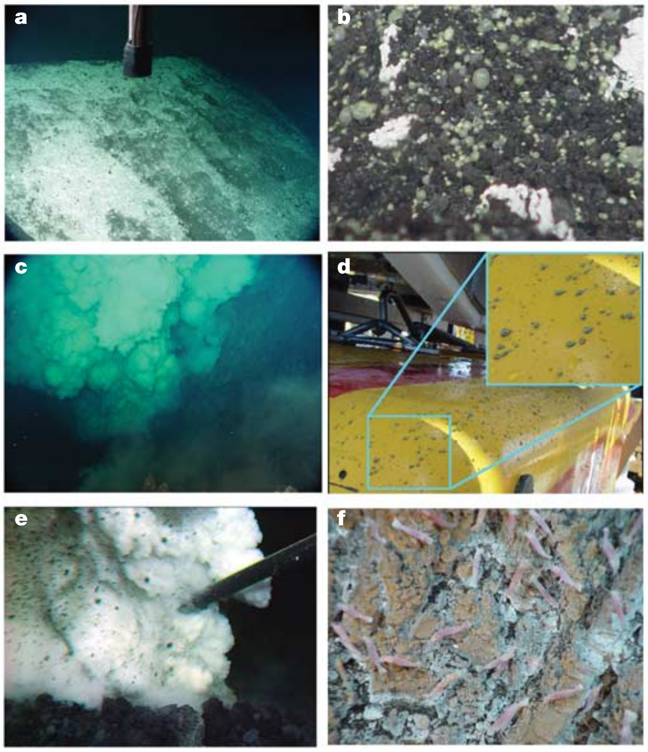

Figure 3 | Images of the sea floor at NW-Rota-1. a, The summit ridge showing the unstable south flank of volcaniclastic sand. The image is ~5 m across. **b**, Close-up of sea floor near Brimstone Pit composed of sulphur globules (pale spheres ~2–3 mm across), black lapilli and ash and unknown white material. **c**, A cloud of sulphur-rich fluid erupting from Brimstone Pit in March 2004. The image is ~5 m across. Video clips of the 2004/2005 activity in Brimstone Pit can be viewed at: http://www.oceanexplorer.noaa.gov/explorations/04fire/logs/brimstone/brimstone.html. **d**, Sulphur droplets coat ROPOS after dive R784 to Brimstone Pit. **e**, Showers of particles from explosive degassing of volcanic bombs at pit, October 2005. Frame-grab of high-definition video on Hyper-Dolphin remotely operated vehicle. **f**, Shrimp (~2–3 cm long) swarming on an outcrop near Brimstone Pit.

associated with NW Rota-1; a CTD cast made at 14° 32.13′ N, 144° 51.78′ (~12 km southeast of NW Rota-1) encountered no significant turbidity anomaly. Two CTD casts (W-01, W-03) made by the research vessel RV *Wecoma* six weeks after the RV *T. G. Thompson* measurements found a somewhat diminished deep turbidity layer on the northeast and southwest flanks of the volcano (Fig. 1a, inset). The deep turbid layer was not present on full water depth CTD profiles taken in 2003 (ref. 22), nor was the high turbidity visually apparent on the video imagery in 2005 even though the summit eruptive activity was more intense. The origin of the deep turbid layer is uncertain, although periodic collapse of loose volcaniclastic material built up from chronic eruptive activity (for example, an apparent shoaling of the eruption site by 20 m occurred between April 2004 and October 2005) is a likely mechanism.

Vent-associated animals coexisted with microbial mats at diffusely venting sites above Brimstone Pit across to the eastern ridge (Fig. 2). The abundance of crabs was low (*Austinograea* cf *yunohan*a) but two species of alvinocaridid shrimp (*Opaepele loihi* and an undescribed species (under description by R. Webber) reached localized densities of over 200 individuals per m^2 (Fig. 3f). Exposed sessile animals that occur on the inactive peak a few hundred metres to the northwest and elsewhere at Mariana and Izu-Bonin arc vents (observations made during the 2004 RV *T. G. Thompson* Submarine 'Ring of Fire' expedition by V.T. and S.K.J. in 2004) were absent; a few limpets occurred below overhangs. This assemblage was probably persistent despite the chronic eruptive disruptions: complete size ranges of juveniles and adults of both shrimp species were present, indicating continuous recruitment, and the same assemblage was observed twice, more than a year apart. Sustained eruptive activity with chronic fallout of volcanic ejecta, congealing sulphur and unstable surfaces probably exclude extensive colonization of the hydrothermal outlets by sessile fauna.

The unusual physical and chemical character of the Brimstone Pit and environs, the unstable volcaniclastic slopes, the juvenile ejecta, the mobile biologic community and the turbid plume around the lower flank of the volcano observed in 2004 indicate that we were observing chronic eruptive activity at NW Rota-1. Submarine eruption plumes have been classified by the ratio of mass transport of water to the mass flux of magma[27,28]. The Brimstone Pit plume at NW Rota-1, at least during the periods of our observations, was characterized by relatively high concentrations of magmatic gas, low magma throughput and high seawater entrainment. This results in the production and fallout of sulphur precipitates and volcanic material near the vent and occasional volcaniclastic density flows at an arc volcano. This study provides the first observations of a deep submarine eruption of an arc volcano, but this case is just one example of a wide range of phenomena that needs to be observed and sampled to understand the behaviour of submarine arc volcanoes better. The persistence of eruptive activity for at least 18 months at NW Rota-1 also implies that it will be possible to learn much about the evolution of submarine arc volcanoes and the nature of their chemical, geological and biologic systems by *in situ* monitoring.

METHODS

^{210}Po–^{210}Pb dating. Very fresh glass was handpicked under a binocular microscope for ^{210}Po–^{210}Pb dating of the lava fragment collected at NW Rota-1 in 2004. The sample was dissolved and ^{210}Po (half life = 138.4 day) was repeatedly determined by α-spectrometry in aliquots over one year (ref. 24). The eruption age was determined by best-fit regression to a radioactive ingrowth curve[24]. Polonium volatilization from erupting magmas creates an initial ^{210}Po deficit relative to grand parental ^{210}Pb in freshly erupted magmas, which is subsequently erased with time via radioactive ingrowth towards secular equilibrium. Incomplete Po degassing would cause reported ages to be overestimates, and so the reported age is nominally a maximum. A sample from shallow submarine Macdonald seamount[1] was 100% degassed on the date of sample collection (presumed eruption), yet degassing at greater depth (~3 km) is presently constrained to just 75–100% (ref. 24). The lapilli fragment dated here contained 13% of its pre-eruptive ^{210}Po on the date of sample collection, indicating that at least 87% of the Po was lost upon eruption. The shallow depth and copious production of S aerosols implies that the maximum age (100% degassing) is a realistic estimate. Error in maximum age is a worst-case scenario determined by regression through the data at the limits of their analytical error ranges.

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