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Exploration for Volcanogenic Massive Sulfide Mineralization along the Kermadec Arc—Havre Trough, New Zealand

INTRODUCTION

The discovery of hydrothermal venting on the Galapagos Spreading Center in 1977 resulted in considerable interest in mid-ocean ridge hydrothermal systems as analogues to ancient volcanogenic massive sulfide (VMS) deposits (Hannington *et al.* 1995; Herzig & Hannington 1995; Herzig 1999). Considerably less attention has been given to submarine arcs (de Ronde *et al.* 2001), despite evidence for significant mineralization related to geothermal systems on subaerial arc volcanoes, e.g. White Island, New Zealand (Hedenquist *et al.* 1993; Giggenbach *et al.* 2003) and Lihir, Papua New Guinea (Petersen *et al.* 2002; Kamenov *et al.* 2005). However, over the last decade, submarine arcs have started to receive greater attention, with the result that many have been found to be hydrothermally active (de Ronde *et al.* 2003; de Ronde *et al.* 2005; Stoffers *et al.* 2006; de Ronde *et al.* 2007).

Although useful as analogs of ancient VMS ore forming processes, mid-ocean ridge settings are difficult targets in terms of exploitation owing to their depth (typically $\geq 2,500$ m). Furthermore, ridge settings are dominated by basaltic lava flows, whereas many large ancient VMS deposits are associated with intermediate to felsic pyroclastic rocks. Arc-associated systems are typically at shallower water depths compared to mid-ocean ridges, and the association with arc-volcanoes means that they may be longer-lived and more focused in terms of magma supply and heat production, potentially producing much larger deposits than are typical along mid-ocean ridges. Compared to mid-ocean ridge hydrothermal deposits, those on arcs also tend to have higher f_{O_2} , lower Fe and higher Au concentrations (Wright *et al.* 1998; de Ronde *et al.* 2005). Elevated Au contents makes such deposits more attractive for exploration and potential exploitation (Herzig 1999).

The Kermadec intra-oceanic arc is a 1,220 km long system formed by the subduction of the Pacific Plate beneath the Australian Plate (Fig. 1). The Kermadec arc is the most systematically explored submarine arc in the world for hydrothermal activity. Exploration over the last nine years has shown that the majority of the volcanoes and calderas along the arc are hydrothermally active, ranging from diffuse low-temperature venting

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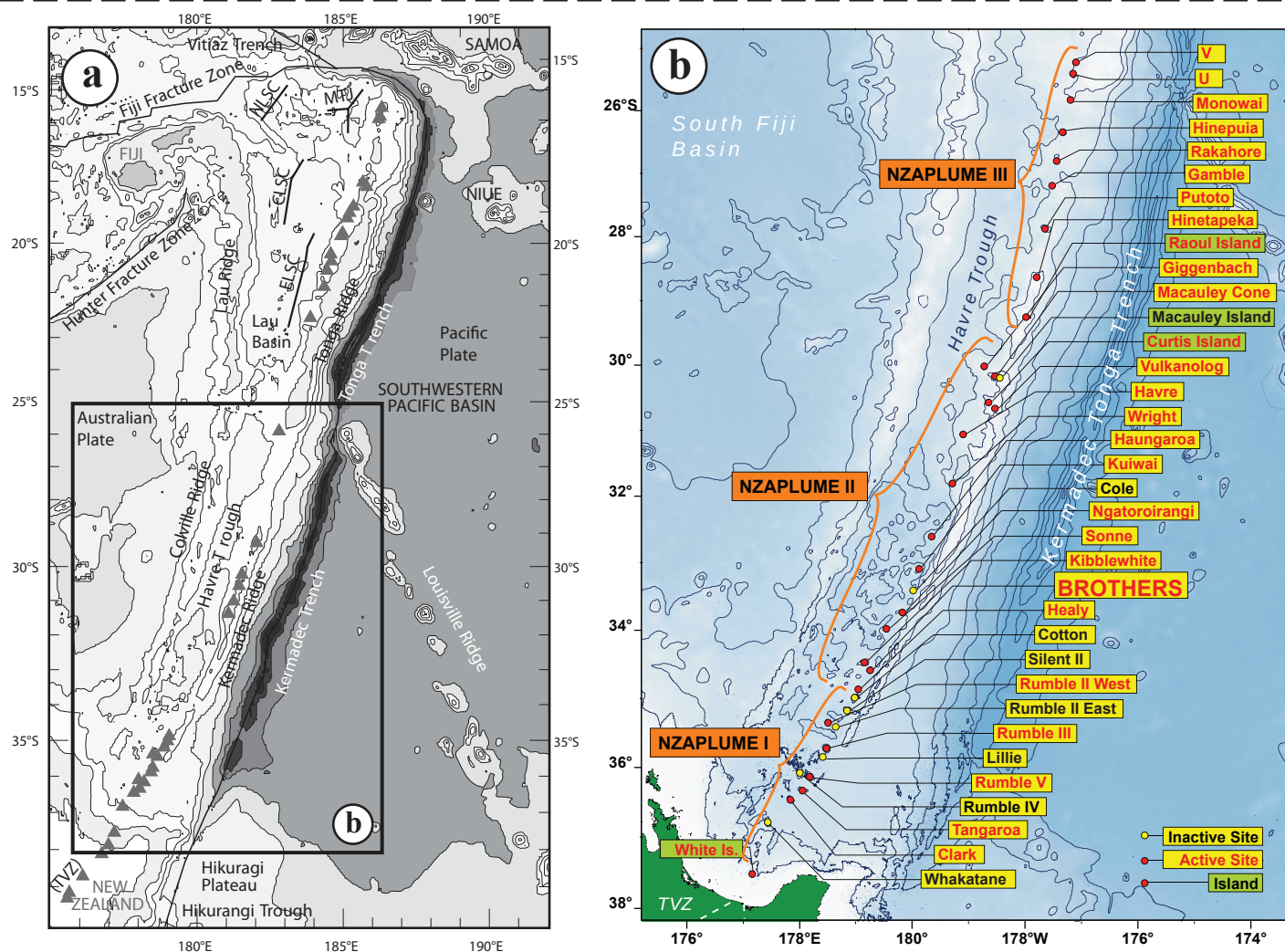


Figure 1. The Tonga-Kermadec subduction system; the Pacific Plate is being subducted westward underneath the Australian Plate. A) The active arc is denoted by triangles. B) Expanded view of the southern portion of the Kermadec arc, showing the location of important hydrothermally active submarine volcanoes and calderas. After Massoth and de Ronde (2006).

to robust black-smoker style venting with associated VMS mineralization. The primary exploration tool has been mapping of hydrothermal plumes in the water column above submarine volcanoes, utilizing a number of sensors to detect both physical (e.g., light-scattering) and chemical (e.g., ^3He) anomalies. Subsequent tracing of these plumes back to their sources has revealed significant mineralization on several of the volcanoes along the Kermadec arc. Significantly, these systems are Cu- and Au-rich, with concentrations considerably elevated compared to ridge settings. For example, the Solwara 1 deposit in the Bismarck Sea, near Papua New Guinea, has indicated reserves of 870 kt @ 6.8% Cu, 4.8 g/t Au, 23 g/t Ag and 0.4% Zn (at a 4% Cu cut off; www.nautilusminerals.com). In contrast, mineralized samples from Brothers volcano are much more Zn- and Pb-rich, with up to 1850 ppm Au, 38% Zn, 8% Pb and 2.7% Cu (de Ronde *et al.* 2005).

GEOLOGICAL SETTING

The Kermadec arc represents the southern half of the ~2,500 km long Kermadec-Tonga arc (Fig. 1),

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formed by the subduction of the Pacific Plate westwards underneath the Australia Plate. Although there are about 57 submarine volcanic centers along the entire arc, most (33) occur along the 1,220 km-long Kermadec arc (de Ronde *et al.* 2005). The Kermadec arc represents the northeastward extension of the Taupo Volcanic Zone of the North Island of New Zealand, and varies from continental crust just offshore to oceanic crust in the north. The southern portion of the Kermadec arc front (south of $\sim 32^\circ\text{S}$) is represented by submarine stratovolcanoes that occur west of the high-standing Kermadec Ridge (Fig. 1) (Wright *et al.* 1996). The southward transition from oceanic to continental crust, combined with subduction of continentally-derived sediments and overthickened oceanic crust of the Hikurangi Plateau, results in a variety of magma source compositions that are reflected in the elemental and isotopic composition of erupted products along the arc, and likely the variability in the hydrothermal fluids and mineralization (de Ronde *et al.* 2001; Massoth *et al.* 2003; de Ronde *et al.* 2005; de Ronde *et al.* 2007).

The backarc to the Kermadec-Tonga comprises the Lau-Havre-Taupo backarc complex (Fig. 1), which is southward propagating and undergoing active extension. This backarc complex evolves from north to south from oceanic spreading in the central and northern Lau Basin, through rifting of arc crust along the southernmost Lau Basin and the Havre Trough to continental rifting within New Zealand (Wright *et al.* 1996). West of the Lau Basin and Havre Trough is the Colville Ridge, a remnant arc, which became isolated from active arc volcanism at ~ 5.5 Ma. The Lau Basin is undergoing more rapid extension compared to the Havre Trough, with rates as high as 159 mm yr^{-1} in the northern Lau Basin, whereas extension is $15\text{--}20 \text{ mm yr}^{-1}$ in the Havre Trough. The transition from more rapid extension and oceanic spreading in the Lau Basin to rifting-dominated extension in the Havre Trough occurs where the trench-oblique Louisville Seamount Chain is subducted; subduction of this chain has progressively migrated southwards over the last 4 Ma (Wright *et al.* 1996).

METHODOLOGY

Prior to 1996, active hydrothermal activity along the submarine portion of the Kermadec was unknown (Wright *et al.* 1998). A series of research cruises using New Zealand, German, Japanese and American research vessels were undertaken to systematically explore the arc for hydrothermal activity and subsequently to undertake more detailed studies on volcanic centers shown to be hydrothermally active (Wright *et al.* 1998; de Ronde *et al.* 2001; Massoth *et al.* 2003; de Ronde *et al.* 2005; de Ronde *et al.* 2007). A variety of sophisticated technologies is utilized in order to carry out these studies. These methods involve the following: 1) conductivity-temperature-depth-optical (CTDO) sensor surveys, 2) remotely operated vehicles (ROVs), 3) manned submersibles, 4) autonomous underwater vehicles (AUVs), and 5) ship-based and shore-

based geochemistry (elemental and isotopic).

The principle method of detecting and locating sites of hydrothermal venting is by mapping plumes that are formed in the water column above actively venting hydrothermal systems (Figs. 2A, 3); these provide a broad and widely dispersed exploration target. Hydrothermal plumes occur in both dissolved and particulate forms. Thus, exploration for plumes has relied on a number of chemical and physical parameters to determine the different styles of venting. Hydrothermal plumes along the Kermadec arc have been most successfully mapped in real-time using light-scattering detection (measured in ΔNTU), based on the presence of venting-associated particulates (primarily Fe- and Mn-oxyhydroxides), Eh, and CH_4 (de Ronde *et al.* 2001).

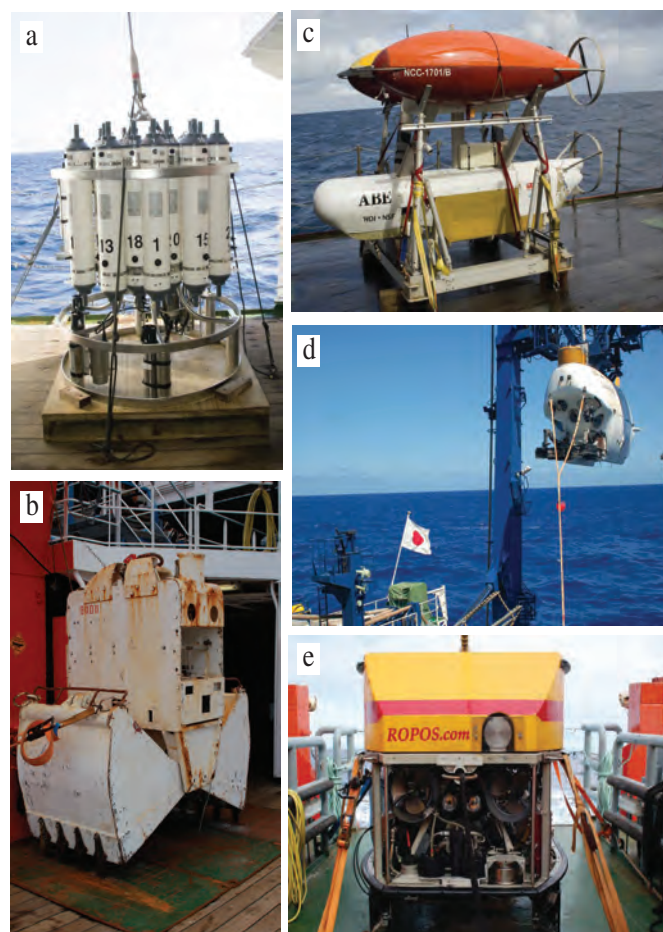
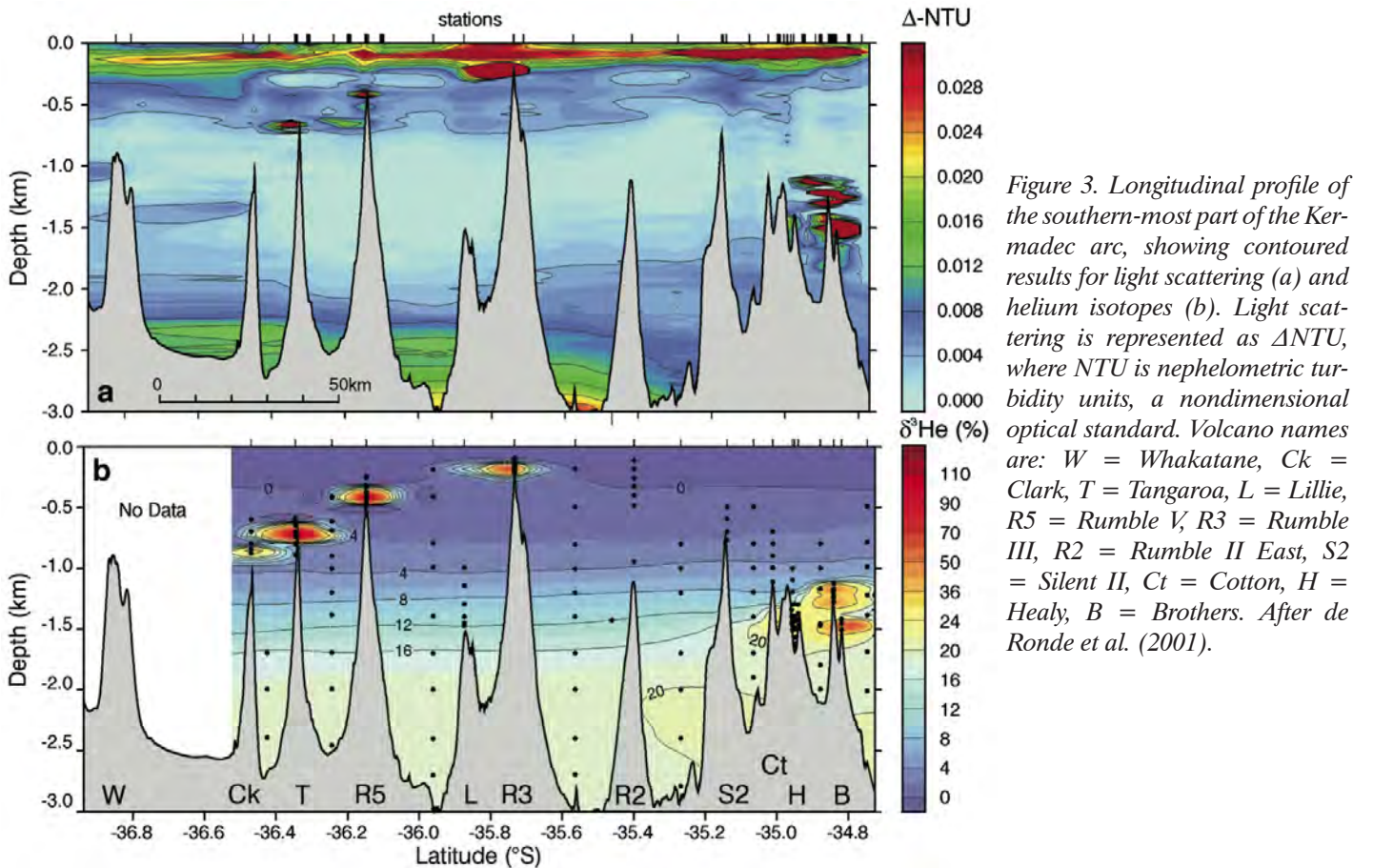


Figure 2. Since 2001, GNS Science has mounted six research expeditions to the Kermadec arc (NZAPLUME I, II, and III, ROVARK, and two legs of NZASRoF), as well as participating in nine cruises led by groups from Japan, Canada and Germany. These cruises have involved the use of plume mapping (CTDO), manned (Shinkai, Pisces) and unmanned (ROPOS, QUEST) submersibles and autonomous underwater vehicles (AUVs e.g., ABE): a) CTDO rosette, R/V Sonne, July 2007, b) TV-grab, R/V Sonne, April 2007, c) ABE after a mapping mission on Brothers Caldera, R/V Sonne, July 2007, d) JAMSTEC submersible Shinkai 6500, being deployed in the Havre Trough, October 2006, e) ROV ROPOS on the R/V Sonne, April 2007.

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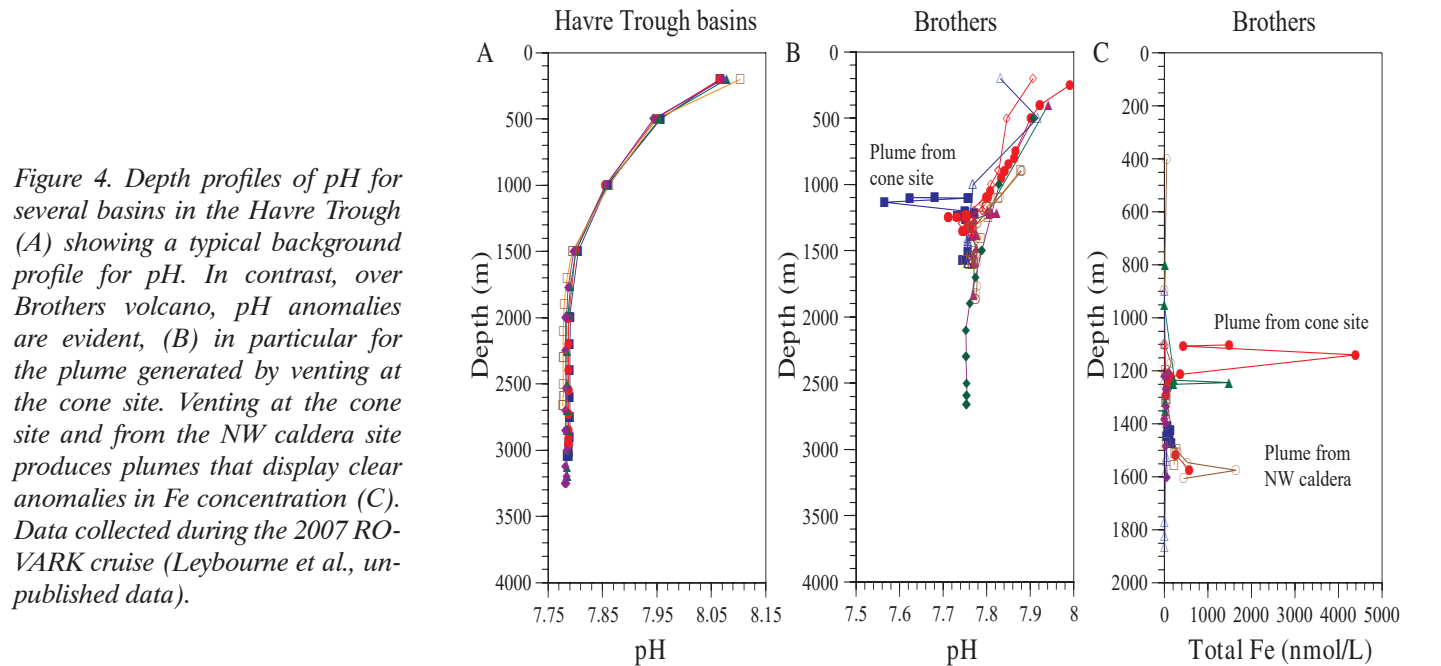
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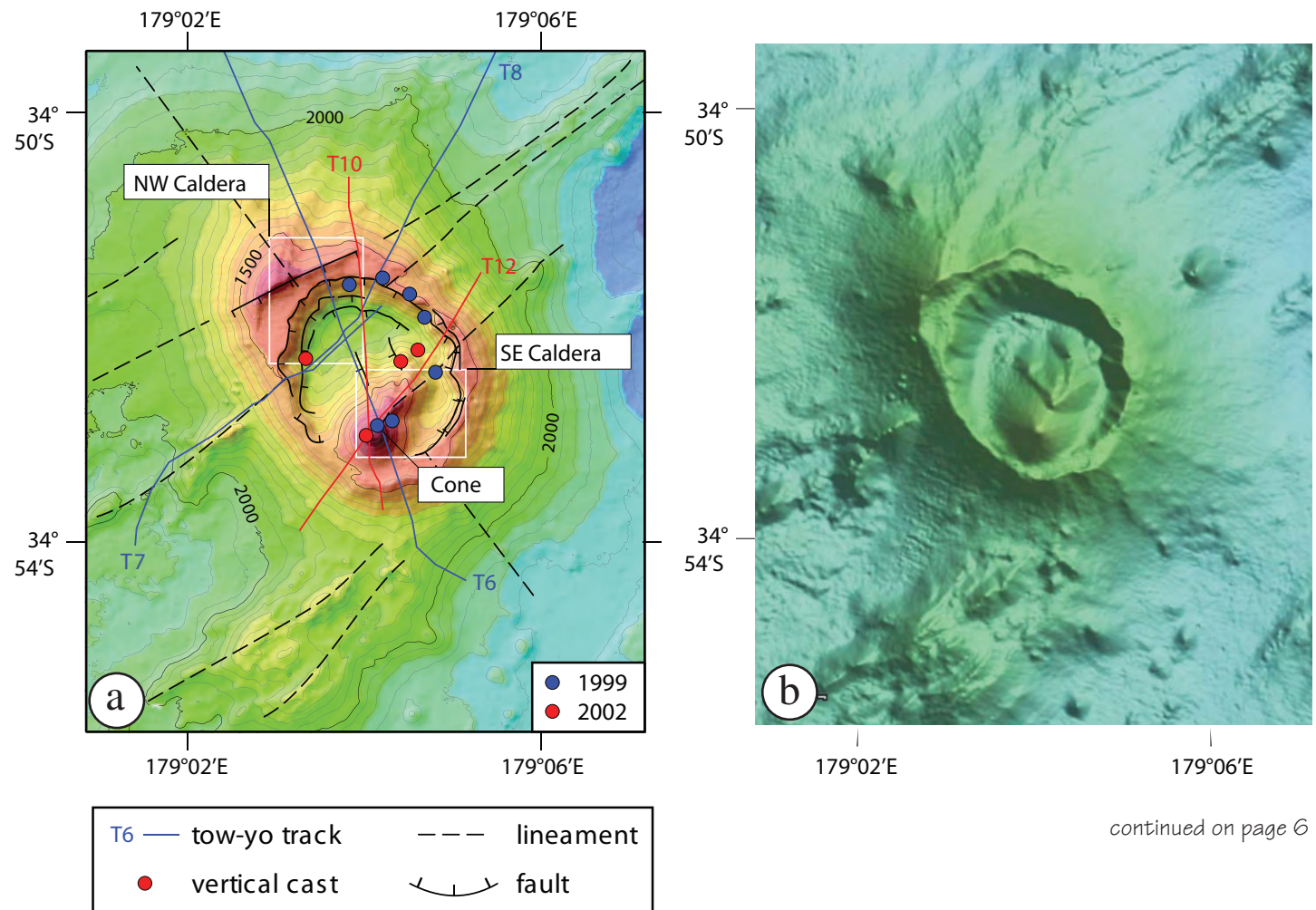
During plume mapping exercises using the CTDO (Fig. 2A), discrete water samples are also collected, permitting more detailed ship- and shore-based geochemical and isotopic characterization, including total dissolvable Fe and Mn, CH₄, H₂S, and He isotopes (Fig. 4). Results from the Kermadec arc show that hydrothermal

plumes originate from focused high temperature and diffuse low temperature venting at discrete volcanic cones in addition to more complex caldera systems (de Ronde et al. 2001). For example, venting occurs from both the cone site and the NW caldera wall at Brothers caldera (Figs. 5, 6). Given that submarine arc volcanoes have

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Figure 5. Brothers volcano is 1,850 m deep caldera, ~11-13 km long by 7-8 km across, with a basal diameter of 3-3.5 km, surrounded by 290-530 m high walls. A volcanic cone rises 350 m from the caldera floor. A) Color bathymetry of Brothers volcano. Also shown are fractures, faults and volcanic structures that are generally aligned to the inferred regional basement fabric. The dots represent vertical casts using the CTDO for 1999 and 2002 studies, although additional vertical casts and tow-yo surveys were undertaken in 2007. Lines labeled "T" are tow-yo tracks (see text for details). Boxes outlined in white encompass the northwest caldera, southeast caldera, and cone sites, as indicated. B) Digital elevation model of Brothers caldera volcano based on gridded EM300 multibeam echosounding data at a cell size of 25 m (sunlight from the north). Figure from de Ronde et al. (2005).

depths to their summits ranging between > 1800 m and ~ 100 m, plumes occur predominantly in shallow and mid-water depths (Figs. 3, 5). The chemical composition of hydrothermal plumes along the Kermadec arc are different to those at mid-ocean ridges and commonly have elevated concentrations of Fe, H₂S and CO₂; Fe/Mn values range from 0.2 to 18, at the high end significantly greater than those typically found at mid-ocean ridges (Massoth & de Ronde 2006). In addition, because the depth of venting on arc volcanoes is typically shallower than occurs on the ridge crests, maximum venting temperatures are generally lower along arcs, constrained by the pressure-dependent boiling point of hydrothermal fluids. Although the frontal Kermadec arc has been systematically surveyed (critically, CTDO casts are performed between volcanic centers to properly define background values), only recently has exploration been extended into the Havre Trough with the 2007 ROVARK (NZASRoF`07) cruise.

Manned and unmanned submersibles have been

deployed during a number of cruises to the Kermadec arc-Havre Trough over the last four years, including dives using *Shinkai 6500* in 2004 and 2006, 23 *Piscis V* dives in 2005, and *ROPOS* in 2007. More recently, the AUV ABE (Autonomous Benthic Explorer) has been deployed at

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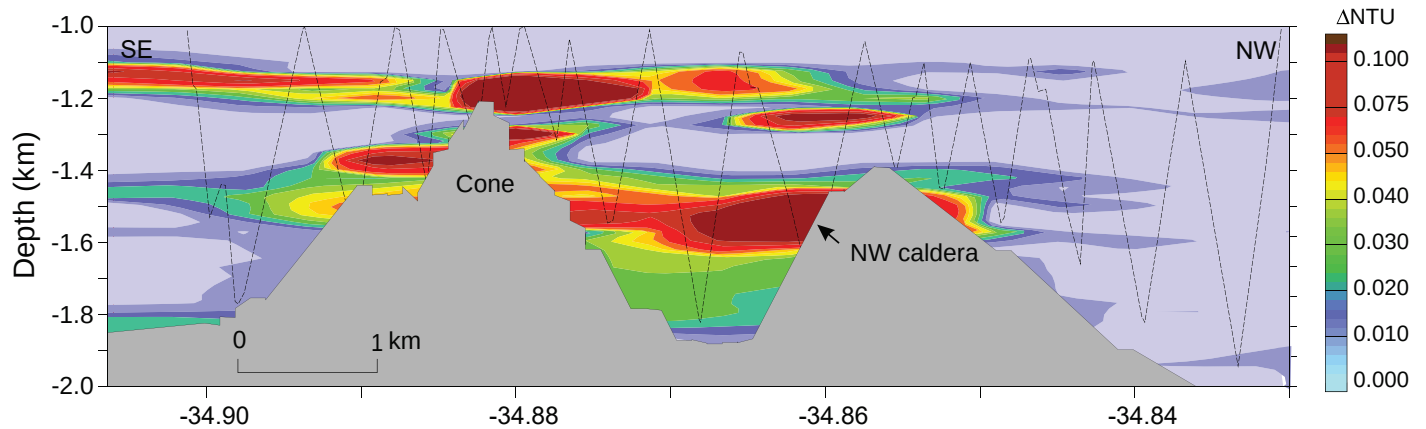


Figure 6. Light scattering measurements (ΔNTU) based on CTDO profiling of Brothers volcano in 1999. Note the presence of plumes that originate from distinct sites on Brothers Cone and the NW caldera wall. The thin sawtooth line indicates the tow-yo path of the CTDO array as it was towed across the volcano.

Brothers volcano during the 2007 ROVARK cruise where it was used to map the caldera floor at a resolution (< 2 m) not previously undertaken for a submarine volcano (initial results of this work are available at: <http://www.oceanexplorer.noaa.gov/explorations/07fire/welcome.html>). ABE was also equipped with a magnetometer and Miniature Autonomous Plume Recorders (MAPRs) to map in high resolution the magnetic signature associated with hydrothermal activity and the precise location of vent fields.

DETAILED STUDIES OF MINERALIZATION

Following initial dredging of sulfide samples from Brothers and Rumble II West calderas in 1996 (Wright *et al.* 1998), samples of vent fluids and sulfide chimneys have been recovered from a number of vents sites along the Kermadec arc. The most extensive exploration to date has been carried out at Brothers caldera volcano (de Ronde *et al.* 2005). Brothers is host to two distinct styles of active venting: 1) gas-rich, low-temperature (typically $< 70^{\circ}\text{C}$) emanations from the young cone in the southern

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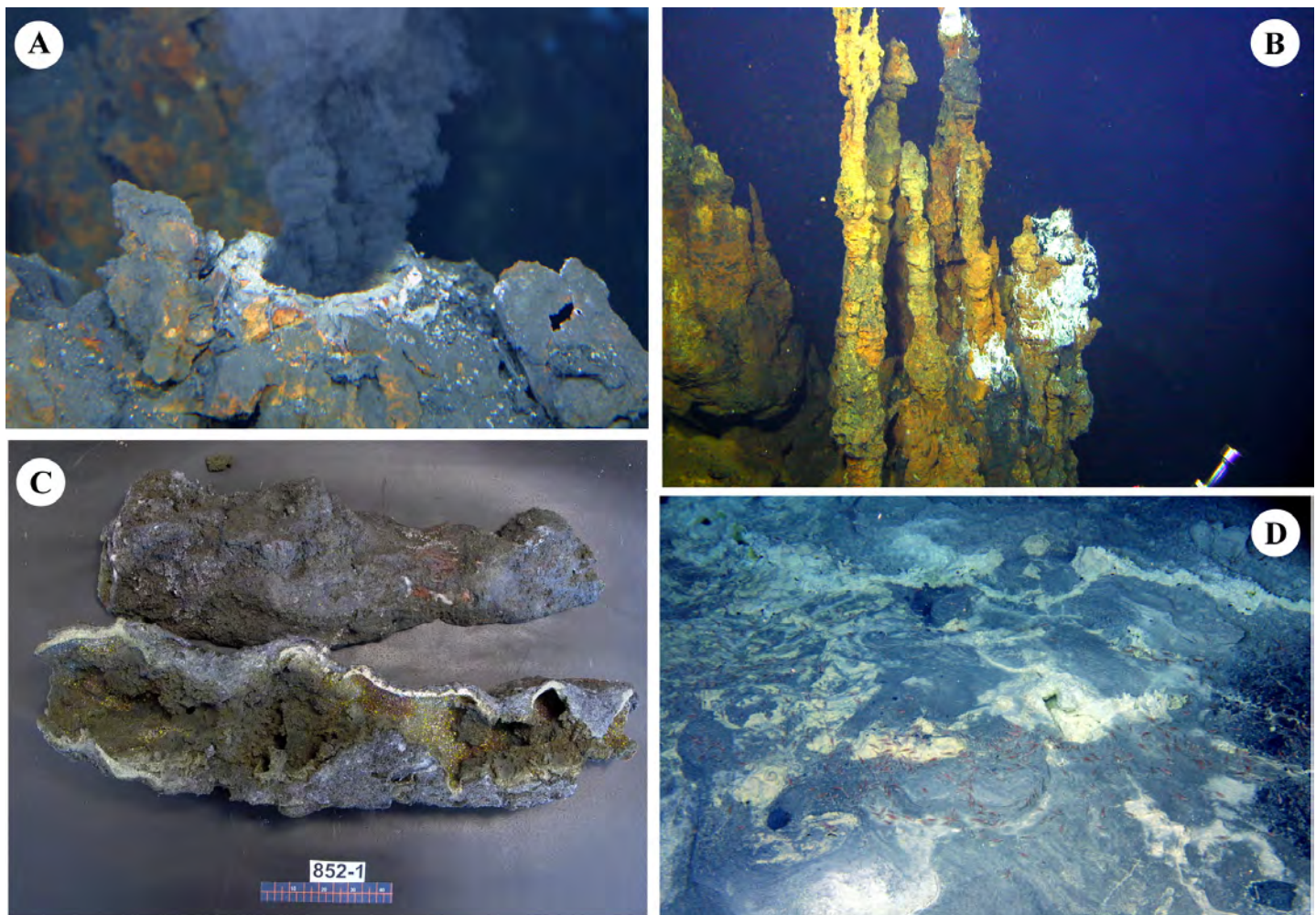


Figure 7. A) Black smoker at the NW caldera site, Brothers, venting at 274°C. Horizontal field of view ~ 0.5 m. B) Inactive chimneys at Brothers. Vertical field of view ~ 3 m (chimneys are ~ 5 m tall). C) Interior of massive sulfide chimney from Brothers, dominated by pyrite, chalcopyrite, sphalerite and barite. D) Diffuse venting (68°C) at the cone site, Brothers. The pale yellow/white material is dominantly elemental sulfur forming a crust over sediment. Horizontal field of view ~ 5 m.

part of the caldera, and 2) high-temperature (max 302°C) metal-rich emanations from the NW caldera site (Fig. 7). At the NW caldera site, sulfides crop out over an area ~200 x 600 m, with numerous 1-5 m tall sulfide chimneys (Fig. 7) (de Ronde *et al.* 2005). Numerous active chimneys occur around a depth centered at ~1,650 m. The walls of the NW caldera site are steep, with the active chimneys commonly perched on intervening benches and typically aligned orthogonal to the slope of the walls.

Microscopy and X-ray diffraction studies of sulfide samples recovered from Brothers indicate that mineralization is dominated by pyrite, marcasite, chalcopyrite, and sphalerite, hematite, goethite, and barite (de Ronde *et al.* 2005). Less abundant minerals include epidote, titanite, albite, quartz, cristobalite, anhydrite, natroalunite, pyrrhotite, arsenopyrite, enargite, bornite, intermediate solid solution, chalcocite, covellite, galena, rutile, birnessite, and native sulfur (Reyes *et al.* 2004; de Ronde *et al.* 2005).

Mineralization at Brothers is characterized by two dominant types: Cu-Fe-rich and Zn-Ba ± Pb-rich. In addition, mineralization at Brothers is relatively enriched

in Au (especially with the Cu-rich mineralization), Ag, Tl, Ga, As, Sb, and Cd (de Ronde *et al.* 2005). Recent analytical developments have produced new techniques for age dating seafloor massive sulfide samples, based on $^{210}\text{Pb}/^{226}\text{Ra}$ and $^{226}\text{Ra}/\text{Ba}$ (Ditchburn *et al.* 2004; de Ronde *et al.* 2005). Results from Brothers and Rumble II volcanoes indicate sulfide chimney ages on the order of months to 1,200 years (Ditchburn *et al.* 2004; de Ronde *et al.* 2005).

CHALLENGES AND FUTURE DIRECTIONS

More recently, other submarine volcanic arcs have been investigated for hydrothermal activity, in particular the Mariana arc (e.g., Embley *et al.* 2006), but none have been explored as systematically as the Kermadec arc has. GNS Science, along with scientists from NOAA and the Italian Istituto Ambiente Marino Costiero (IAMC-CNR), in late 2007 explored using CTDO and swath mapping for the first time the entire Aeolian arc in the Mediterranean Sea.

There are currently three exploration companies

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dedicated to exploring for seafloor massive sulfides: 1) Nautilus Minerals, which has greater than 370,000 km² of tenements off-shore of Papua New Guinea, Fiji, Tonga, the Solomon Islands and, as of 2008, in the Havre Trough in New Zealand waters; 2) Neptune Minerals, which has exploration licenses of greater than 278,000 km² along the Kermadec arc in New Zealand waters as well as in the waters of Papua New Guinea, the Federated States of Micronesia and Vanuatu; and 3) Blue Water Minerals, Inc. Challenges include difficulties of mining in an active submarine arc setting, in particular the environmental impact on vent-associated communities. Nautilus Minerals is in the mine planning stages to exploit Cu-Au mineralization (Solwara 1) in 1500 m water depth in the Bismarck Sea, near Papua New Guinea. Solwara 1 is a relatively small deposit by the standards of Cu-Au deposits mined on land, with indicated reserves of 870 kt @ 6.8% Cu, 4.8 g/t Au, 23 g/t Ag and 0.4% Zn and inferred resources of 1,300 kt @ 7.5% Cu, 7.2 g/t Au, 37 g/t Ag and 0.8% Zn (at a 4% Cu cut off; www.nautilusminerals.com). Future exploration will likely involve development of geochemical and geophysical techniques to explore in older, inactive portions of arc systems (e.g., Colville Ridge; Fig. 1).

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