From the earliest Polynesian voyagers, to whalers and pioneers, sailors and conservationists, the Kermadec region has attracted those who are keen to push the boundaries, to see what lies beyond the horizon.

INTO THE UNKNOWN.

THE **KERMADECS**

Map labels

165°E 168°E 171°E 174°E 177°E 180° 177°W 174°W

26°
29°
32°
35°
38°
41°
44°
47°
50°
53°
56°

SOUTH PACIFIC OCEAN

Tasman Sea

KERMADEC RIDGE

LOUISVILLE SEAMOUNT CHAIN

KERMADEC TRENCH

Hinepuia
Rakahore
Gamble
Putoto
Hinetapeka
Raoul Island
Meyer Island
Herald Islets
Giggenbach
Kermadec Islands N. Z.
Macauley Island
Macauley
Cheeseman Island
Curtis
Curtis Island
Havre
Havre Rock
L'Esperance Rock
Wright
Oliver / Speight
Haungaroa
Kuiwai
Cole
Ngatoroirangi
Sonne
Silent
Brothers
Healy
Kibblewhite
Yokosuka
Giljanes
Rapuhia
Thompson
Rumble II West
Rumble III
Rumble II East
Rumble IV
Lillie
Clark
Rumble V
Tangaroa
Whakatane
White Is.

COLVILLE RIDGE
HAVRE TROUGH
KERMADEC RIDGE

North Cape
Whangarei
Auckland
Tauranga
Whakatane
North Island
New Plymouth
Napier
Gisborne
East Cape

NEW ZEALAND

Nelson
★ **Wellington**

South Island
Christchurch
Timaru
Dunedin
Invercargill
Stewart Island

Chatham Islands
New Zealand
Chatham Island
Pitt Island

Bounty Islands
N.Z.

Antipodes Islands
N.Z.

Auckland Islands
N.Z.

Campbell Island
N.Z.

Square kilometre and mile figures are approximate.

◯ Kermadec Islands Marine Reserve

▲ Submarine volcano, also known as seamount

0 kilometres   400
0 nautical miles   200

DAVID E. CHANDLER

NORTH PACIFIC OCEAN
Hawaii
EQUATOR
SOUTH PACIFIC OCEAN
AUSTRALIA
AREA ENLARGED ABOVE
NEW ZEALAND

FRONTIER WILDERNESS DEEP

– these are words that excite our imagination and inspire scientific endeavour.

Straddling the known and unknown of our knowledge and understanding, frontiers have always inspired enthusiasm for scientific exploration and discovery. Frontiers are where the unknown draws attention and propels curious explorers off on new and inspiring journeys.

New Zealand's Kermadec region is such a frontier – a place that has drawn explorers from all corners of the globe for generations. From the earliest Polynesian voyagers to whalers and pioneers, sailors and conservationists, the Kermadec region has attracted those who are keen to push the boundaries, to see what lies beyond the horizon. Today that horizon runs not only across the 630,000 square kilometres of the Kermadec seas, but also down to its furthest depths – 10,000 metres deep.

For two days in August 2010, the Pew Environment Group, in partnership with Te Papa Tongarewa, co-hosted the symposium *DEEP – Talks and Thoughts Celebrating Diversity in New Zealand's Untouched Kermadecs.* In celebration of the United Nations International Year of Biodiversity, the symposium brought together over 140 scientists, researchers, policymakers and interested parties to connect existing knowledge, understanding, inquiry and imaginings about the Kermadec region.
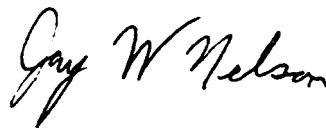
The Kermadec region is a place of remarkable character and diversity: dark, cold depths of the Kermadec Tonga Trench; super-heated vents of the Kermadec arc; a vast expanse through which iconic ocean travellers move; an ocean teaming with both tropical and temperate flora and fauna.

The papers presented at DEEP, and now published here, represent the work and knowledge of today's Kermadec explorers. They range across the disciplines of geology, biology, history and anthropology. Each paper is a detailed profiling of specific places, species and patterns of life across the Kermadec region. Read as a collection, they provide us with our first opportunity to understand how the features of this region come together and interact in one of the world's great ocean wilderness areas.
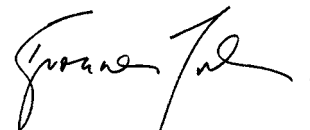
Discovery, connection, collaboration – more words to excite and inspire.

DEEP provided a unique opportunity to explore a remarkable place. In doing so, it facilitated today's explorers to uncover unexpected connections and identify opportunities for future collaboration.

The Pew Environment Group is honoured to sponsor publication of this unique compilation of science and discovery. We look forward to a future full of scientific exploration and collaboration across the Kermadec region.

Jay Nelson
DIRECTOR – GLOBAL OCEAN LEGACY,
PEW ENVIRONMENT GROUP

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DIRECTOR, KERMADEC INITIATIVE,
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CONTENTS

ORIGINS AND INFLUENCES

DEEP

30|31.08.2010 WELLINGTON NZ

The Kermadec volcanic region:
An overview of geological discoveries from the last decade

Ian Wright

The Kermadec region has been the focus of very significant geological discovery over the last decade. This presentation highlights important facets of this geological research and provides a framework for more detailed presentations at this symposium of ongoing research in the Kermadec region. The presentation discusses (1) the Kermadec volcanic arc setting, (2) new multibeam and submersible technology, (3) undersea discovery and exploration, (4) Kermadec Islands as emergent volcanoes, (5) submarine volcanic processes, (6) volcano and seafloor longevity, (7) serendipitous science and (8) seamounts and biodiversity.

The Kermadec region, with its line of volcanoes extending between New Zealand and Tonga (Figure 1), owes its existence to being the boundary where two of the Earth's larger tectonic plates collide. This collision, with the Pacific Plate sliding beneath the Australian Plate, creates the >10,000 m deep Kermadec Trench, the linear, north-east trending zone of earthquakes and active volcanoes (the southern sector of the Pacific Ring of Fire), and a backarc zone, west of the volcanoes, of active crustal rifting and faulting. Where the Kermadec seafloor has been the most comprehensively mapped nearest New Zealand (Figure 2), the Kermadec region is one of the most complex areas of global seafloor with an extremely heterogeneous seascape of both isolated and chain volcanoes (the active Kermadec volcanic arc), pervasively faulted and deformed volcanic basement and elongate 3,000–4,000 m deep rift basins that form a contiguous line near the axis of the backarc region, all of which are bounded by the Colville Ridge to the north-west and Kermadec Ridge to the south-east.

A significant facet of Kermadec research has been the use of seafloor multibeam mapping and manned submersible technology. Traditionally advances in marine science have occurred with new technology. Seafloor multibeam mapping has a fan of hundreds of downwards looking acoustic echo-sounder beams (beneath a ship) that now routinely survey strips of the seafloor up to 5–10 km in width at a vertical resolution of 1–2 m in 3,000 m deep water. Such seafloor mapping technology has been the basis for the vast majority of new geological discoveries, providing accurate measurements of seafloor morphology but also characterising different types of seafloor substrate type (Figure 3). Similarly, collaborative deep-diving expeditions using German, Japanese and US manned submersibles have provided further insight into active seafloor processes. Three such expeditions to the Kermadec region have occurred over the last 8 years, focusing on studies of seafloor hydrothermal venting and associated vent biota. The advantage of submersibles is that they allow detailed sampling, including temperature measurement and fluid sampling of hydrothermal vents, recovery of specific hydrothermal chimney and vent species, sampling of specific sulfide chimneys and video imaging of vent sites and seamounts.

An important part of Kermadec research has been undersea discovery and exploration – equivalent to the early geological mapping of onshore New Zealand in the mid-1880s. For marine scientists, this comes as no surprise, but the discovery of over 20 submarine volcanoes comparable in size to the onshore Ruapehu or Taranaki volcanoes holds great interest for the public. All these volcano discoveries are not in

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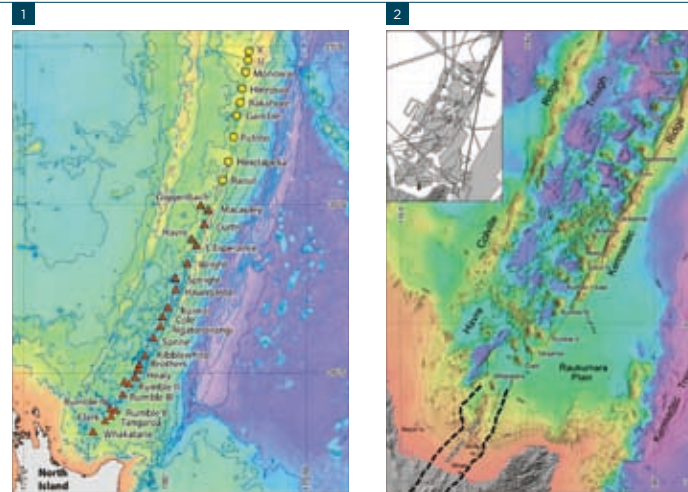i.wright@noc.soton.ac.uk

FIGURE 1. The linear north-east-trending line of individually named stratovolcanoes (red triangles) and caldera volcanoes (yellow circles) of the Kermadec volcanic arc extending between New Zealand and southern Tonga associated with the Pacific–Australian Plate collision (after Wright *et al.*, 2006; Graham *et al.*, 2008).

FIGURE 2. Seafloor bathymetry north-east of New Zealand showing the highly complex structure of the Kermadec Ridge (including the isolated volcanoes of the active arc immediately north-west of the Kermadec Ridge), Havre Trough and Colville Ridge (after Wysoczanski *et al.*, 2010).

remote areas of the ocean. Two smaller caldera volcanoes (some 4–5 km in diameter) have been mapped within <20 km of the Raoul Island shoreline. Though few things are absolute, all the major volcanoes along the active line of volcanism (the Kermadec arc) are interpreted as now mapped. However, in the wider Kermadec region, including the Havre Trough backarc and bounding Kermadec and Colville Ridges, the extent of seafloor multibeam mapping is probably <10%, meaning that there are many more geological structures (including volcanoes) that remain to be discovered and mapped.

The Kermadec Islands (principally Raoul and Macauley Islands, but including Curtis and Cheeseman Islets and Havre Rock) form the most visible components of the Kermadecs, and are the basis of the 200 mile exclusive economic zone, marine reserves, seabird colonies and oceanic subtropical vegetation. However, Raoul and Macauley Islands are also the partially emergent crests of large submarine volcanoes. In the case of Raoul Island (Figure 4), the submerged flanks and proximal seascape of the volcano comprise the two previously unknown caldera volcanoes (described above) and a series of sediment waves that appear to distribute subaerial and littoral eruption products into the deeper flanking basins. For Macauley, the island constitutes only 5% in area of a larger dominantly submerged volcano that includes a 10 km long and 1,000 m deep caldera, an elongate dome adorned with small volcanic cones that shoal to <80 m water depth and a series of concentric and canyon-bounded sediment waves that similarly are currently interpreted to record the transport of eruption products from the proximal eruption vent.

Nearly 20 years ago, the prevailing view (due to very limited data) was that submarine volcanic arcs that formed the western Pacific rim of the Ring of Fire were basaltic – andesite stratovolcanoes (i.e., volcanic massifs built with alternating layers of lava and volcaniclastic sediment with a bulk chemical composition of <63% SiO_2 weight volume). From the mid-1990s, seafloor mapping began to image caldera volcanoes, i.e., volcanoes with fault-bounded cauldron depressions where, following eruption, the evacuated magma chamber has collapsed within itself (Figure 5). Sampling of these calderas produced a second surprise. Many of these calderas are covered with extensive pumice deposits (Figure 5) sourced from the caldera vent and have bulk compositions of >68–70 SiO_2 weight volume – they are dacite and rhyolite in composition. This observation is significant. Dacite and rhyolite lavas tend be more gas-charged with higher contents of dissolved volatiles within the magma, e.g., water, CO, and SO_2. These gases (but principally water) are the prime determinant of how explosive an eruption can be. The inference that underwater explosive volcanic eruptions can occur within water depths of 500–1,000 m has required a significant change in physical volcanology understanding. Much of this change has been driven by observations from the Kermadecs and other active submarine volcanoes over the last decade. The process of actually observing a large submarine eruption is virtually impossible, but the mechanism by which these eruptions occur underwater is interpreted to be one where an eruption column some hundreds of metres in height is sheathed by a cupola of steam that effectively insulates the eruption from the surrounding ambient ocean. This process allows
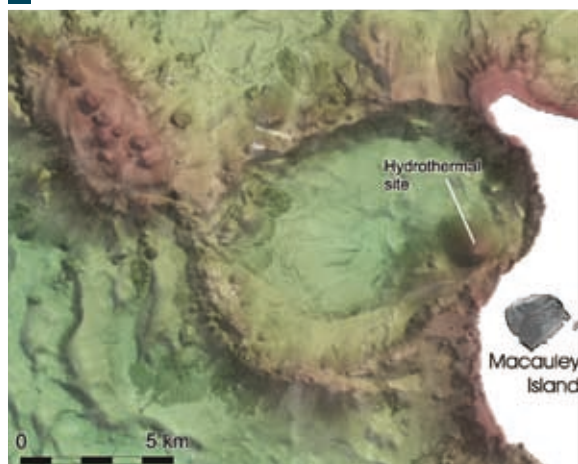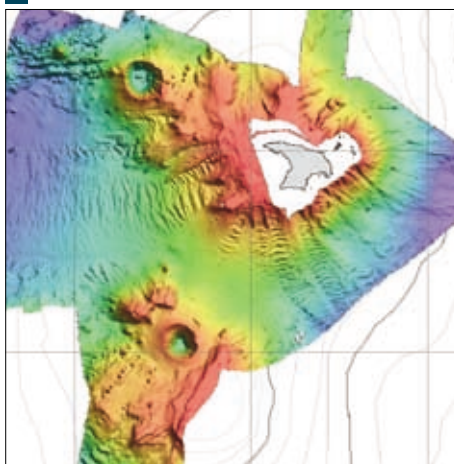
explosive expansion and fragmentation within the eruption column to produce pumice, which, when cooling, settles out of the eruption column (and possibly dispersed by ocean currents) to mantle the seafloor with pumice deposits. This may not be the full answer, though. More detailed studies of pumice density and chemistry show that some pumices are cooled in different ways that are not yet fully understood.

Seafloor video imagery and repeat multibeam surveys of specific volcanoes show the seafloor is dynamic, going through cycles of edifice collapse and reconstruction on time scales of years. Such observations have implications for the longevity, or otherwise, of seafloor biota. Manned submersible and towed video surveys on many volcanoes reveal very young lava flows and volcanic sediment deposits mantle significant areas of active arc volcanoes, limiting the growth of encrusting megafauna. Many volcano flanks are routinely mantled with carapaces of lava and fresh volcanic pumice sourced from the eruption vent at the edifice crest. Similarly, repeat multibeam surveys of Monowai and Rumble III volcanoes reveal that Kermadec volcanoes can sustain cycles of construction and destruction. At Monowai, multibeam surveys in 1998, 2004 and 2007 show two cycles of edifice collapse (Figure 6) interspersed with reconstructing cone growth over a 9-year period. One flank failure between 1998 and 2004 caused an elevation collapse of up to 165 m in elevation, with a down-slope volume displacement of 0.1 km^3 over an area of ~1.51 km^2.

Scientific research is at times serendipitous – a chance discovery leading to a completely new and major line of research. This has happened in the Kermadecs. In 1994, we discovered from seafloor mapping the first Kermadec caldera volcanoes – Brothers, Healy and Rumble II West. In 1996, a research voyage, whilst undertaking seafloor rock dredging trying to establish volcano compositions, recovered the first small fist-sized samples of mineralised sulfides from Brothers and Rumble II West calderas. Fortuitously, the rock dredging also recovered the first battered specimens of the hydrothermal vent shrimp (*Alvinocaris*) from Brothers. Here was the first tentative evidence of active seafloor hydrothermal venting and that such hydrothermalism was creating sulfide mineralization on the seafloor. These discoveries of less than six sulfide hand specimens and two battered *Alvinocaris* hydrothermal shrimp specimens have subsequently lead to a whole range of hydrothermal research along the entire Kermadec–Tonga arc. Such research has included at least five hydrothermal plume-mapping voyages (measuring diagnostic and elevated concentrations of dissolved metals in the water-column) (Figure 7), targeted seafloor video surveys and two separate manned submersible expeditions sampling hydrothermal vent fluids and hydrothermal vent biota. Much of this research has focused on the Brothers caldera volcano. Subsequent surveys of Brothers volcano have included autonomous underwater vehicle (AUV) and seismic reflection surveys to better document the nature and extent of sulfide mineralization.

FIGURE 3. Merged seafloor bathymetry and back-scatter imagery data from multibeam surveying the submarine flanks of Macauley Island.

FIGURE 4. Modern seafloor multibeam mapping data from the submarine flanks of Raoul Island showing the discovery of two small calderas north-west and south-west, respectively, of the island (NIWA unpublished data).
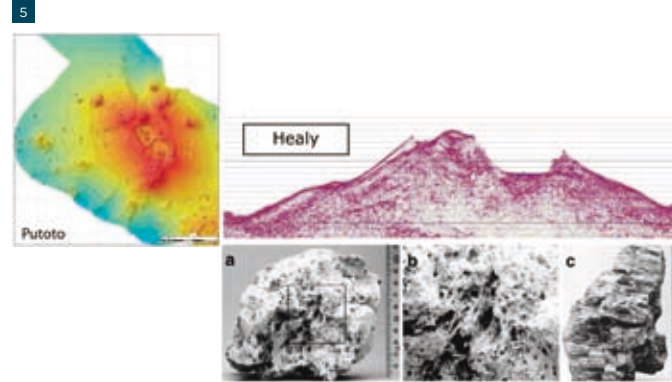
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FIGURE 5. Examples of caldera volcanoes now known in the Kermadec region including Putoto surveyed by multibeam mapping, and Healy by seismic reflection profiling. The lower box shows examples of seafloor pumice recovered from the Healy caldera (from Wright *et al.*, 2003).

Similarly, submarine geological research over the last decade has spurned other marine research. Submarine volcanoes that range up to 25–30 km in diameter and 2,400 m in relief form seamounts with biological and ecological settings different from the surrounding deeper ocean (Figure 8). Seafloor mapping, including multibeam and video surveying, has made significant insight into Kermadec seamount ecology and biology. To date, the two prime thrusts of this latter research are trying to document (1) spatial relationships between seafloor geology and substrate type, habitat heterogeneity and benthic biodiversity, and (2) the biology of vent fauna associated with various hydrothermal systems along the Kermadec arc.

In summary, a decade of marine research in the Kermadec region has provided unprecedented, but still incomplete, insight of submarine caldera volcanoes, temporal scale of edifice construction/destruction, interaction between volcanism and tectonic faulting, dispersal of volcanic eruptives into deeper basins and distribution of hydrothermal venting and provided a basis for seamount biodiversity studies.

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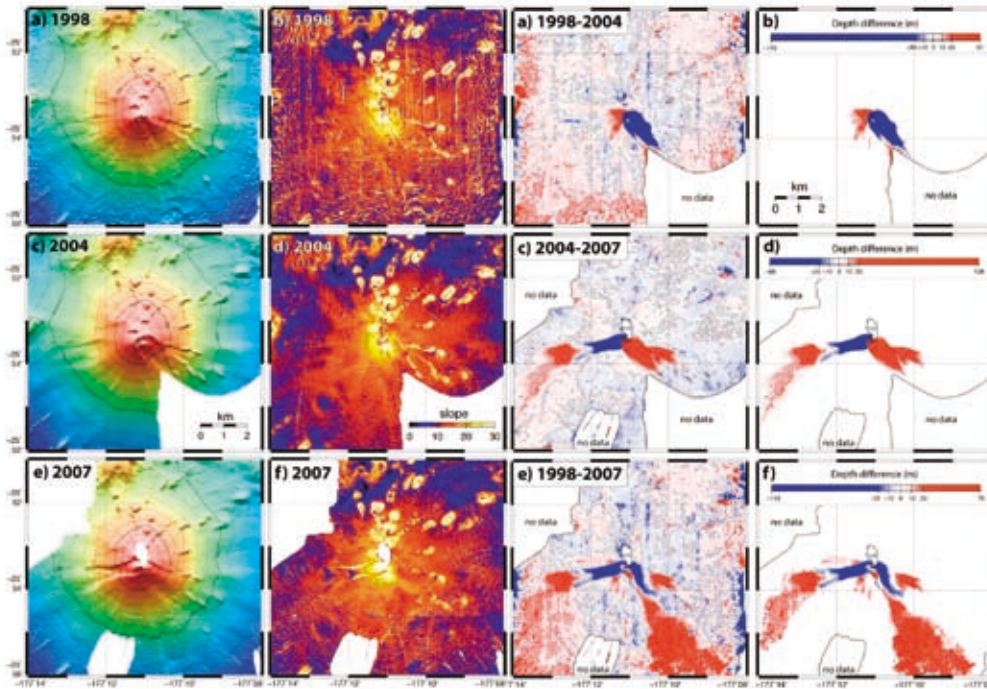
FIGURE 6. Repeat multibeam surveys in 1998, 2004 and 2007 (far left column) that show significant changes in edifice morphology of Monowai cone volcano, with slope angles (left centre column) and raw and corrected elevation changes (negative as blue and positive in red) in the two right columns (from Chadwick et al., 2008).
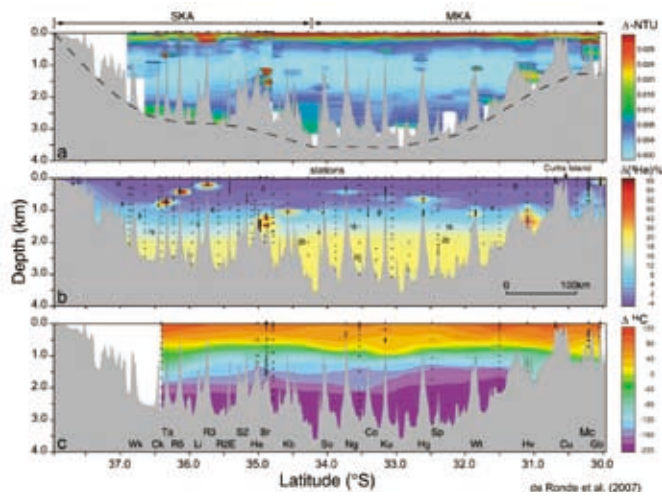
FIGURE 7. Chemical (δ[^{3}He]% and Δ^{14}C) and physical properties (light transmission – ΔNTU) of the southern Kermadec arc showing the presence of hydrothermal plumes along the volcanic arc between New Zealand and Macauley Island (from de Ronde et al., 2007).
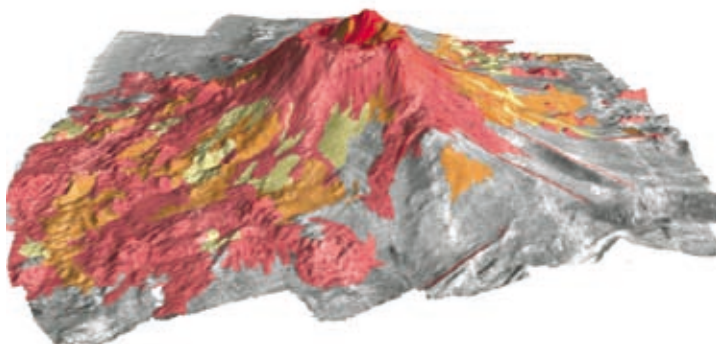
FIGURE 8. Seafloor geology and substrate type interpretation of the submarine Haungaroa volcano that forms the basis of seamount studies to understand the distribution of seafloor biodiversity.

Submarine massive sulfide mineralization and hydrothermal activity along the Kermadec arc, the world's most hydrothermally active

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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 and 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 submarine arcs 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 analogues of ancient VMS ore-forming processes, mid-ocean ridge settings are difficult targets in terms of mineral exploration owing to the depth (typically ≥ 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 on 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). This elevated gold also 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 (Figure 1). The Kermadec arc is the most systematically explored submarine arc in the world for hydrothermal activity. Exploration over the last 10 years has shown that the majority of the volcanoes and calderas along the arc are hydrothermally active, ranging from diffuse low-temperature venting to robust black-smoker style venting with associated VMS mineralization such as at Brothers volcano. Massive sulfide samples have also been recovered from Clark volcano and Rumble II West caldera. The primary exploration tool has been by mapping hydrothermal plumes in the water column above submarine volcanoes, utilising a number of sensors to detect both physical (e.g., light-scattering) and chemical (e.g., ^3He, Fe, Mn, CH_4) anomalies. Subsequent vectoring 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.

THE KERMADEC ARC

The Kermadec arc represents the southern half of the ~2,500 km long Kermadec-Tonga arc, formed by the subduction of the Pacific Plate westwards underneath the Australia Plate (Figure 1). The southern portion of the Kermadec arc front (south of ~32°S) is represented by submarine stratovolcanoes that occur west of
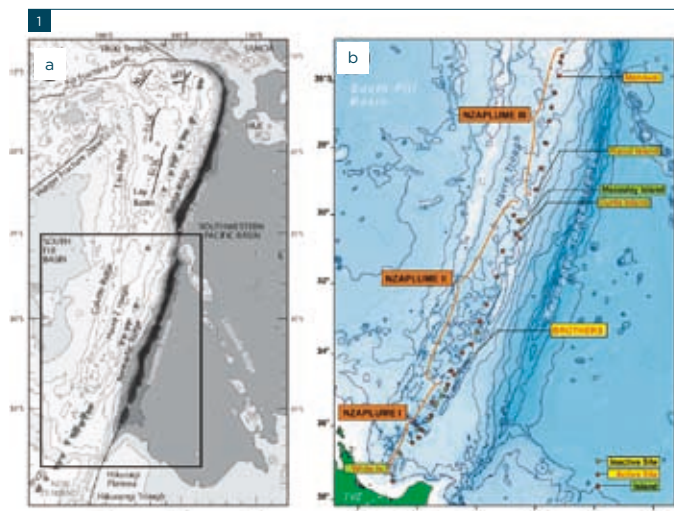
the high-standing Kermadec Ridge (Figure 1) (Wright *et al.*, 1996). The southward transition from oceanic to continental crust, combined with subduction of continentally derived sediments and overthickened oceanic crust of the Hikurangi Plateau, results in a variety of magma source compositions that are reflected in the elemental and isotopic composition of erupted products along the arc and likely reflects in 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 (Figure 1), which is southward propagating and undergoing active extension. This backarc complex evolves from north to south as oceanic spreading in the central and northern Lau Basin, through rifting of arc crust along the southernmost Lau Basin and the Havre Trough and includes 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 undergoes 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 15–20 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).

HYDROTHERMAL PLUMES, VENTS AND MINERALIZATION

Prior to 1996, active hydrothermal activity along the submarine portion of the Kermadec was unknown (Wright *et al.*, 1998). Subsequently, 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 centres shown by the exploration work 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) (Figure 2). A variety of sophisticated technologies is utilised 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 principal 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 (Figures 2A and 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
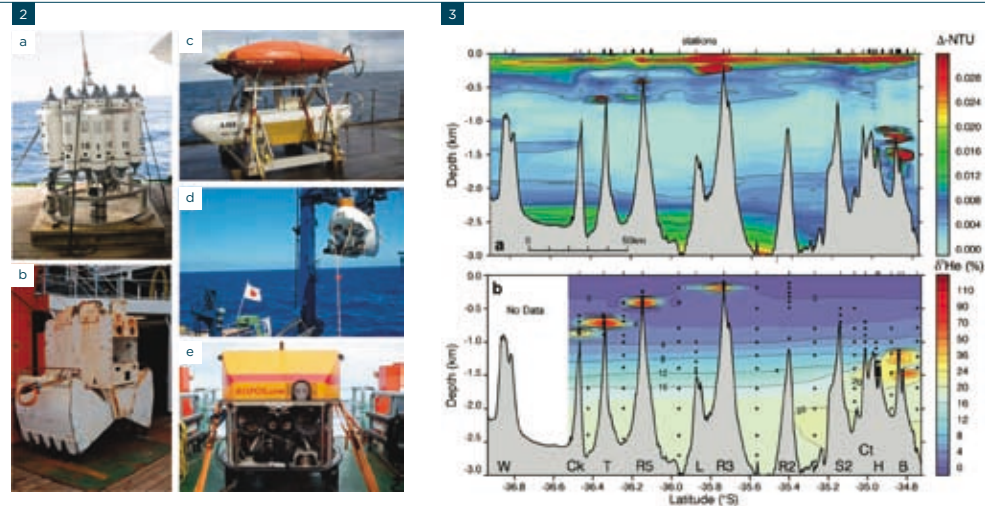
FIGURE 2. Since 2001, GNS has mounted six research expeditions to the Kermadec arc (NZAPLUME I, II and III, ROVARK, and two legs of NZASRoF), as well as participated in some nine cruises led by groups from Japan, Canada and Germany. These cruises have involved the use of plume mapping (CTDO), manned (*Shinkai, Pisces*) and unmanned (*ROPOS*, QUEST) submersibles and autonomous underwater vehicles (AUVs, e.g., ABE). (A) CTDO rosette, RV *Sonne*, July 2007; (B) TV grab, RV *Sonne*, April 2007; (C) ABE after a mapping mission on Brothers Caldera, RV *Sonne*, July 2007; (D) JAMSTEC submersible *Shinkai* 6500, being deployed in the Havre Trough, October 2006; (E) ROV *ROPOS* in operation on the RV *Sonne*, April 2007.

FIGURE 3. Longitudinal profile of the southern-most part of the Kermadec arc, showing contoured results for light scattering (A) and helium isotopes (B). Light scattering is represented as ΔNTU, where NTU is nephelometric turbidity units, a non-dimensional optical standard. Volcano names are: W = Whakatane, Ck = Clark, T = Tangaroa, L = Lillie, R5 = Rumble V, R3 = Rumble III, R2 = Rumble II East, S2 = Silent II, Ct = Cotton, H = Healy, B = Brothers (after de Ronde *et al.*, 2001).

presence of venting-associated particulates (primarily Fe- and Mn-oxyhydroxides), Eh and CH$_4$ (de Ronde *et al.*, 2001).

During plume mapping exercises using the CTDO, discrete water samples are also collected (Figure 2A), permitting more detailed ship- and shore-based geochemical and isotopic characterisation, including total dissolvable Fe and Mn, CH$_4$, H$_2$S and He isotopes. 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). Given that submarine arc volcanoes have depths to their summits ranging between >1,800 m and ~100 m, plumes occur predominantly in shallow and mid-water depths through the water column (Figure 3). The chemical compositions of hydrothermal plumes along the Kermadec arc are different to those at mid-ocean ridges and commonly have elevated concentrations of Fe, H$_2$S and CO$_2$; Fe/Mn values range from 0.2 to 18, at the high end, significantly greater than those typically found at mid-ocean ridges (Massoth and de Ronde, 2006). In addition, because the depths of venting on the arc volcanoes is typically shallower than that which occurs on the ridge crests, maximum venting temperatures are generally lower, constrained by the pressure-dependent boiling point of hydrothermal fluids.

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

deployed at 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. Future cruises will also use a new generation of AUV to map more of the volcanoes of the arc in greater detail.

The most extensive exploration to date has been carried out at the 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°C) emanations from the young cone in the southern part of the caldera, and (2) high-temperature (max. 302°C) metal-rich emanations from the NW caldera site (Figure 4). Here, sulfides crop out over a ~200 x 600 m zone (de Ronde *et al.*, 2005) that includes numerous sulfide chimney spires between 1 and 5 m tall. Numerous active chimneys occur around a depth centred 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. Two dominant types, Cu-Fe-rich and Zn-Ba ± Pb-rich, characterise mineralization at Brothers. 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).

CHALLENGES AND FUTURE DIRECTIONS

There are currently three exploration companies dedicated to exploring for seafloor massive sulfides: (1) Nautilus Minerals, which has greater than 370,000 km^2 of tenements off-shore of Papua New Guinea, Fiji, Tonga and the Solomon Islands; (2) Neptune Minerals, which has

FIGURE 4. (A) Black smoker from NW caldera site, Brothers, venting at 274°C; (B) Inactive chimneys from Brothers; (C) Interior of massive sulfide chimney from Brothers, dominated by pyrite, chalcopyrite, sphalerite and barite; (D) Diffuse venting (68°C) at Cone site, Brothers. The pale yellow/white material is dominantly elemental sulfur forming a crust over sediment.
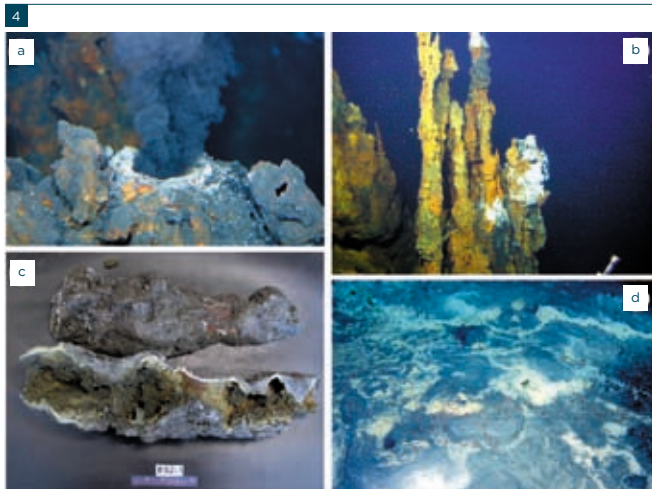
exploration licences of greater than 278,000 km^2 along the Kermadec arc in New Zealand waters as well as in the waters of Papua New Guinea, the Federated States of Micronesia and Vanuatu; and (3) Bluewater Minerals, Inc (now owned by SMM Project LLZ, with a minority stake held by Odyssey Marine Exploration). Nautilus Minerals is in the mine planning stages to recover Cu-Au resources in 1,500 m of water in the Bismarck Sea, near Papua New Guinea. Interest in the Kermadec arc is driven by our desire as scientists to understand hydrothermal systems and the geology of the associated volcanoes and biology and diversity of the vent communities. The hydrothermal systems and massive sulfide mineralization offer unparalleled opportunities to better understand ancient on-land metal resources in terms of how they formed, the time scales at which they formed, and how dynamic and the variability in time and space. Although the Kermadec arc is one of the better-studied arc systems in the world, we still know very little about the individual volcanic and hydrothermal systems that occur there, the extent of the hydrothermal systems and their biodiversity. Thus, the Kermadec arc represents an invaluable resource for New Zealand as a natural scientific laboratory, an archive of vent-associated biology and a potential source of mineral and biological wealth for the country and future generations to come.

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Submarine massive sulfide mineralization and hydrothermal activity
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Some aspects of volcanic and seismic activity in the Kermadecs

Brad Scott

The Kermadecs are a collection of volcanic islands, submarine seamounts (some volcanically active) and a deep oceanic trench. In terms of global plate tectonics, it is the area where the Pacific Plate is forced under the Australian Plate at about 40 mm per year (Figure 1) – a zone that extends north-east from New Zealand, towards Tonga, and is a focus for volcanic and seismic activity.

The seismic activity is generated by the subduction of the Pacific Plate under the Australian Plate, and is very active in this area (Figure 2). The area about Raoul Island would typically experience four or five events per year over magnitude 5. Earthquakes that create ground shaking stronger than MM8 (produces landslides etc.) have occurred four times since 1973. The largest earthquake near Raoul Island since 1973 is a magnitude 8.2 on 14 January 1976. Tsunami is a hazard in the Kermadecs, from both local and distal sources. There are now two tsunami recording sites on Raoul Island.

A significant aspect of the Kermadec region is the volcanism, most of which is submarine in nature. Historic subaerial volcanic activity is known from Raoul Island in 1814, 1870, 1964 and 2006. There was submarine activity nearby in 1886. Raoul Island is the summit of a large volcanic massif, and the eruptive history is summarised by Lloyd and Nathan (1981). Volcanism in the last 4,000 years has focused on the destruction of the Moumoukai cone, formation of the Raoul caldera about 3,300 years ago, formation of the Denham Bay caldera about 2,000 years ago and further modification of the Raoul caldera about 1,350 years BP (Figure 3). Many smaller events have occurred since then (Lloyd and Nathan, 1981). The historic activity has occurred in both the Raoul and Denham Bay calderas.

Since the eruptive activity in 1964, a monitoring regime has been in place at Raoul Island. This has focused on the Blue and Green crater lakes (water levels and temperatures), with ground temperatures started in 1980 and lake levelling in 1993. Chemistry of springs, lakes and fumaroles has also been derived, showing waters that are mixed with seawater. Since the early 1950s, there has also been a seismograph on the island. Since the 1964, eruption there have been several volcano-seismic crises. Some have resulted in lake level changes, but there were no eruptions until 2006. The fatal March 2006 eruption occurred 4 days after a volcano seismic crisis.

Following the 2006 eruption, a new regime of monitoring was installed to replace the destroyed sites and enhance the safety of people on the island. Today, this includes a CTBTO seismic site operated by the USGS, a seismic site operated by GNS near the Met Annex and one funded by DoC in the crater. DoC has also funded automated water level and temperature recording of Green Lake and the temperature of Marker Bay pool. The GeoNet project has added a web cam. Regular temperature and chemical sampling continues of selected springs and lakes. A VSAT data link has also been installed on the island, and this now enables data to be reviewed in New Zealand in near real time. In 2009, LINZ also established two tide gauges to record tsunami data. Some of these data can be seen online at www.geonet.org.nz/volcano/activity/kermadec-islands/index.html .

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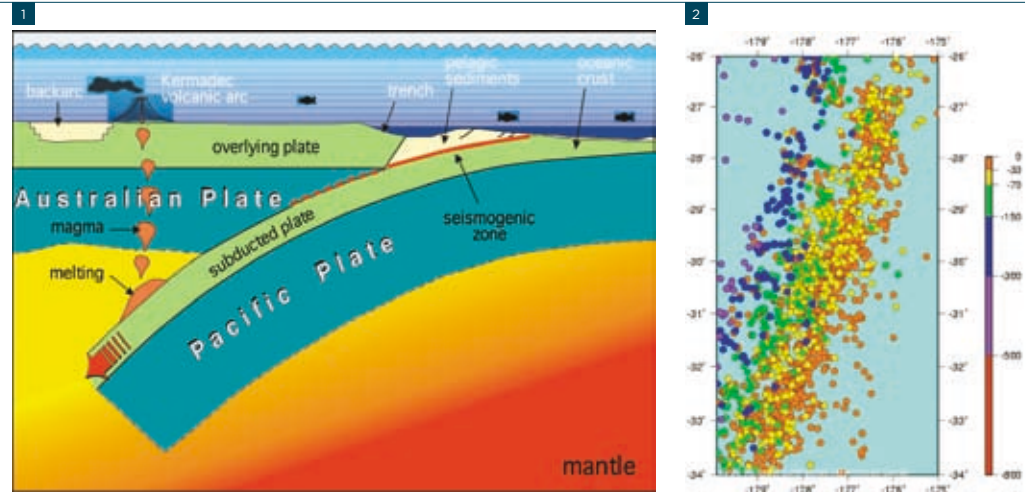
FIGURE 1. Simplified cross-section through the central Kermadec region showing the subducting Pacific Plate, the seismogenic zone where it rubs past the Australian Plate, the deep melting and surface/submarine volcanism.

FIGURE 2. Map showing earthquake locations and depths (zoned by colour) in the central Kermadec region. Plotted events are for the period 1970–2010 and greater than magnitude 5 (1,972 events).

The March 2006 eruption occurred from many vents and generated very directional blasts within the crater area (Figure 4). No activity was noted in Denham Bay. The eruption was of a similar size to the November 1964 eruption.

Currently, Monowai submarine volcano to the north of Raoul Island is intermittently active. Acoustic (sound) and seismic signals are currently being recorded and show an increase in activity during the 2008–2010 period. Oceanographic research has shown changes in the form of Monowai during recent eruptions 1998–2004 (Wright *et al.*, 2008). In October 2009 a Ministry of Fisheries flight observed activity at Monowai. A discoloured plume extended several kilometres down wind (Figure 5). ■

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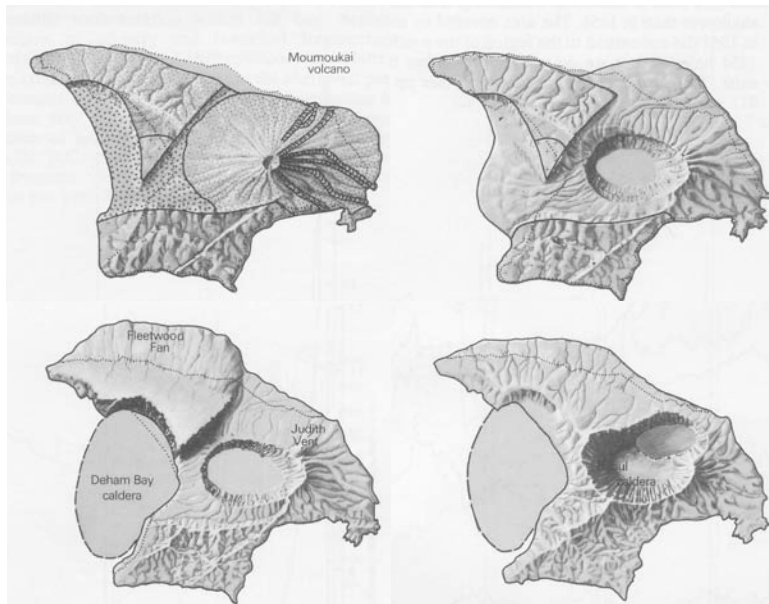
FIGURE 3. Geological history sketches from Lloyd and Nathan (1981) showing the Moumoukai cone development about 4,000 BP (top left); formation of Matatirohia-Oneraki caldera about 3,100 BP (top right); formation of Denham Bay caldera 2,160 BP and Judith vent about 1,800 BP (lower left) and the modern Raoul caldera about 1,350 BP.

FIGURE 4. Annotated aerial photograph of the Green Lake area showing the locations of vents active in March 2006 and the directions of the blasts from those vents.

FIGURE 5. Views of activity at Monowai on 27 October 2009. (A) As viewed by the Modus satellite, (B and C) photography from the RNZAF taken during a Ministry of Fisheries flight.
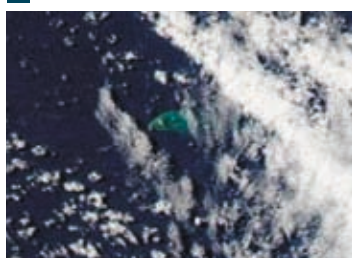
New insights into explosive volcanic eruption processes and products in the Kermadec volcanic arc

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Submarine explosive volcanism involving felsic magmas (that is, with >63 weight % SiO_2) and associated with the large-scale eruption of pumice and formation of collapse calderas is proving to be widespread along intraoceanic arcs globally. Such eruptions in the Kermadec arc would have major impacts on the ecosystems around the volcanoes, and some of these events may have been large enough in the past to pose threats to mainland New Zealand (tsunamis, pumice rafts obstructing shipping, ash clouds disrupting air traffic). Our group is studying the chemical processes that gave rise to these felsic magmas and the physical processes involved in their eruptions. We are using case studies of pyroclastic deposits erupted from four caldera volcanoes in the Kermadec arc: Raoul, a previously unknown volcano ('New volcano') 25 km SW of Raoul Island, Macauley and Healy. The deposits have been sampled from subaerial sections (Raoul, Macauley) and by dredging from the submerged volcano flanks (New, Macauley, Healy). Suites of clasts from the 16-32 mm size fraction of each sample have been analysed for density and shape to quantify the physical state of the magma on eruption. Larger pumice clasts have been analysed by X-ray fluorescence techniques to determine their major-element compositions, inductively-coupled plasma-mass spectrometry to get trace-element data, and the individual minerals growing in the magma when it was erupted have been extracted and analysed by electron microprobe.

For Raoul, New and Healy volcanoes, whole-rock major element compositions fall within a limited compositional range within individual eruptions at Raoul or at the volcano as a whole

(New, Healy). In contrast, pumice dredged from around Macauley volcano covers a wide compositional range indicating that there have been multiple felsic eruptions contributing to the formation of Macauley caldera, not just the Sandy Bay tephra exposed on Macauley Island. Distinctive crystal populations in both pumice samples and xenoliths of deep-sourced plutonic rocks found in the deposits suggest that many of the crystals did not grow in the felsic magmas but were mixed in from other sources including SiO_2-poorer gabbros and SiO_2-richer tonalites. Such open-system mixing is ubiquitous in magmas from the four Kermadec volcanoes studied here. Felsic magmas, co-eruptive mafic enclaves and previously erupted basalts sampled by other workers from Macauley and Raoul show subparallel patterns in concentration of the rare-earth elements. In addition, crystal compositions and zonations in these compositions imply that the mafic and felsic magmas have a strong genetic linkage. Examination of whole-rock, glass and mineral chemistry shows that evolved felsic magmas can be generated at each volcano through 60–75% crystal fractionation of a low-SiO_2 basaltic (mafic) parent. Our findings are not consistent with proposals for felsic magma generation through melting of the ~15 km deep crust, as previously suggested for the Kermadec and other western Pacific arcs. Although crystallization is the dominant process driving melt evolution towards felsic compositions in the Kermadec volcanoes, the magmatic systems are open to contributions from both newly arriving melts and previously crystallized plutonic bodies forming the walls, roof and floor of the magma chamber. Such open-system

*Key findings from physical studies of the eruption
products relate to the contrast in behaviour of the
eruptions between subaerial and submarine settings.*

processes occur in variable amounts between the magmas represented by individual eruptions and are largely reflected by small-scale compositional variations between eruption units. Larger-scale trends in chemical compositions of the felsic magmas between the four volcanoes reflect their positions along the arc that, in turn, may reflect structural changes in the dynamics of the subduction zone and variations in the amount of sediment influx.

Key findings from physical studies of the eruption products relate to the contrast in behaviour of the eruptions between subaerial and submarine settings. Density spectra for clasts from subaerial 'dry' deposits on Raoul Island have narrow unimodal distributions with peaks corresponding to vesicularities of 80–85 volume %, regardless of the size or inferred vigour of the eruption. This characteristic is shared by the products of numerous other 'dry' eruptions worldwide and reflects a universal pattern in the breaking behaviour of foaming magma as it leaves the vent during eruption. The incoming of external water ('wet' eruption) or syn-eruptive degassing generates modes of denser clasts characterised by fewer but coarser vesicles and the presence of minute crystals (microlites), which grew in the glassy material while it was still hot but degassing. The subaerial Sandy Bay tephra on Macauley shows field evidence for a wet eruption style, but the vesicularity also has a prominent mode at 81–83 volume % and only a minor tail of denser clasts, suggesting that the access of water had only a limited effect in this powerful eruption. Submarine dredged material from New, Macauley and Healy volcanoes shows two contrasting vesiculation patterns. At New and

Healy, vesicularities are unimodal at 79–85 volume %, and on density characteristics alone, the pumice clasts dredged from the seafloor cannot be distinguished from subaerial eruption products. Of particular importance is the fact that a minor proportion of clasts show pink oxidation, implying that eruption plumes reached the atmosphere through 0.5 to >1 km of water. At Macauley, in contrast, vesicularities are bimodal at ~71–79 % and 90–92 volume % and represent an intermediate style of subaqueous explosive activity, with two stages of vesicle growth in and fragmentation of the clasts during eruption. Blebs of foaming magma break up during eruption on the ocean floor at ~60 volume % vesicularity. These blebs float to the ocean surface and continue to inflate internally to up to 90+ volume % vesicularity, then break up as water enters the clast along cooling joints, releasing fragments with the bimodal density characteristics to sediment to the ocean floor. Although stratigraphy and geochemistry can distinguish separate subaerial eruptions on Raoul, dredge sampling has no stratigraphic constraints. Geochemical data show that the dredged Macauley material represents at least four different magmas and that many eruptions contributed to the seafloor ejecta blanket and caldera formation. At Healy, the broad uniformity of erupted compositions do not allow such inferences to be made. Submarine explosive volcanism at high eruption rates generates clasts with many similarities to their subaerial counterparts and implies that contrasts between the products of submarine eruptions and their subaerial equivalents where material has been transported into marine settings may be difficult.

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Many questions still remain about explosive magmatism in the Kermadec arc. Some issues that are currently under further investigation follow.

1. There are few constraints on the volcanic history of the Kermadec volcanoes in terms of timing, number of eruptions and the total eruptive volume. An eruptive history is only partially defined for the subaerial volcanoes, and particularly at Macauley, there are pumice types that are unaccounted for in the subaerial stratigraphy seen on the island. Deep sea tephra records may help better define the timing and compositional changes in eruptions from these volcanoes, and studies of such cores are under way. Samples could also be collected from caldera walls and/or submarine cliff sections by remotely operated vehicle. This would place some relative timing constraints on the material collected from the seafloor, which cannot be achieved by dredging.

2. Zircon crystals from a boulder of high-SiO_2 plutonic material on Raoul Island have been dated as being 1.25 ± 0.06 million years old by Mortimer *et al.*, (2010). This demonstrates that the generation of high-SiO_2 magmas (and, presumably, associated explosive volcanism and caldera formation) at volcanoes like Raoul is not a recent development but simply the latest in many such episodes. Further dating studies are being undertaken on the plutonic rocks from Raoul and Macauley. An ongoing challenge is to decipher what controls the change from larger-volume mafic, lower SiO_2 volcanism generating lava flows to moderate-volume felsic, higher SiO_2 volcanism generating explosive eruptions.

3. The lack of zoning or reaction rims on magnesian olivine crystals found out of place in felsic pumices implies that magma mixing in the Kermadec magmatic systems occurs shortly prior to or during eruption. We are investigating the time scales involved in this mixing, but preliminary results suggest that there may be only hours or less implied. Magma mixing may be an important trigger for felsic explosive eruptions at the Kermadec volcanoes and may occur with little warning. ∎

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Geophysical characterisation of the Kermadec arc-backarc system: New data from the May 2010 KARMA voyage

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The intra-oceanic volcanic Kermadec arc-Havre Trough system (Figure 1) is associated with the subduction of the Pacific Plate beneath the Australian Plate along the 10,000 m deep Kermadec Trench. The arc-backarc system extends northwards from the intracontinental Taupo Rift that characterises the North Island central volcanic region of New Zealand, through a transition zone in the off-shore Bay of Plenty. To the north, subduction of the Louisville seamount chain marks the boundary of the Kermadec arc and the Tonga arc.

The Kermadec arc is a well-developed frontal arc comprising more than 30 volcanic complexes generally limited to a thin band west of the Kermadec Ridge. To the west, the arc is bounded by the 4,000+ m deep Havre Trough and Colville Ridge. The Colville and Kermadec Ridges are relict arcs rifted apart ~6 Ma. Over two-thirds of Kermadec arc volcanoes are hydrothermally active (de Ronde *et al.*, 2007) with associated thriving bio-communities, such as at Brothers silicic caldera.

Despite extensive mapping and sampling in the region, there are still vast areas unexplored using geophysical methods. These include high-definition multibeam bathymetry, multi-channel seismic (MCS) reflection data, as well as magnetic and gravity geopotential data. Existing data were largely acquired over a number of oceanographic voyages since the mid-90s (Graham *et al.*, 2008; Wright, 1993; Wright *et al.*, 2006; Wysoczanski *et al.*, 2010). Geological sampling in the region is scarce, which, together with the paucity of seismic reflection data, inhibits the development of a good understanding of the causative relationships between magmatism and faulting.

The aim of geophysical investigation in the Kermadec region is: (1) to improve our understanding of the tectonic and volcanic characteristics of the volcanic system, including arc-backarc evolution, magmatic modes (dyking, explosive and effusive volcanism), tectonic control on volcanism and the generation of new crust, alteration, edifice collapse and sedimentation processes; (2) to determine the mechanisms of hydrothermal fluid circulation at a variety of scales and document the spatial distribution of mineralized ore bodies and associated zones of hydrothermal flow, in order to provide an improved knowledge of the volcano-scale, subsurface structures and processes; and (3) to provide new methods of mapping the distribution of massive sulfide deposits hosted within Kermadec volcanoes.

The latest research voyage in this region was the May 2010 KARMA (Kermadec ARc MinerAls) voyage, onboard RV *Tangaroa*. The voyage enabled the acquisition of ~830 km of MCS data, the mapping of more than ~3,000 km^2 of seafloor using a 30 kHz EM300 multibeam bathymetry system, the collection of rock samples at 22 sites and acquisition of more than 1000 km of magnetic and gravity data. Regional ESE-WNW trending MCS transects run across the entire arc-backarc system from Kermadec Ridge to Colville Ridge (Figure 2). Volcano-scale seismic profiles focused on Brothers, Rumble II West and East volcanoes. Finally, a pseudo-3D MCS experiment targeted the hydrothermal field on the north-west caldera rim of the Brothers volcano.

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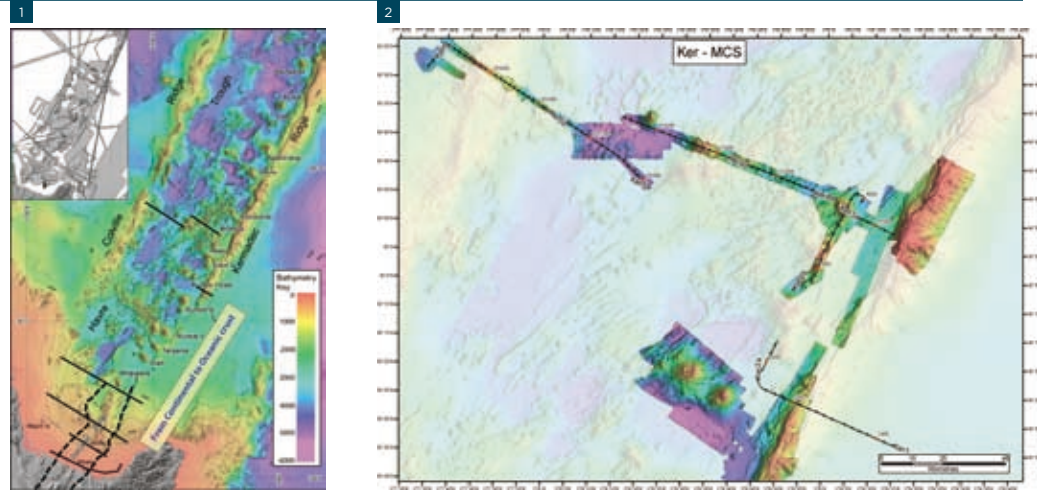g.lamarche@niwa.co.nz

FIGURE 1. The Taupo Volcanic Zone in the central North Island of New Zealand to the Kermadec arc-backarc system. Red lines indicate multi-channel seismic reflection profiles shown in Figure 4.

FIGURE 2. Regional arc-wide multi-Channel seismic reflection profiles acquired during the KARMA voyage with multibeam data collected during the voyage.

MORPHOLOGY AND STRUCTURE OF THE KERMADEC ARC-BACKARC SYSTEM

The quality and accuracy of the geophysical data acquired over the years from the coast of the Bay of Plenty northwards has enabled scientists to identify a large variety of geological structures and landforms associated with volcanic and tectonic activity or sedimentary processes, from submetre to kilometre scale.

In the coastal Bay of Plenty (Figures 3 and 4 bottom), high sediment delivery from local rivers has resulted in a flat and smooth seafloor. Pervasive NE-trending scarps ranging from a few to hundreds of metres in height indicate active faulting associated with the intense seismicity that affects the region (Lamarche *et al.*, 2006). Around Mayor Island, a myriad of small cones, most likely of volcanic origin, is imaged in the bathymetry and suggests recent volcanic activity or slope instability.

In the outer Bay of Plenty, north of White Island, the topography is dominated by NE-trending troughs and canyons, such as the White Island and Tauranga canyons infilled with sediments, and volcanic edifices or ridges, such as Whakatane volcano (Figures 3 and 4). Topographic relief reaches 1,000 m from the deepest trough to the top of the shallowest volcano. The region marks the transition from intracontinental deformation to the south to intraoceanic deformation to the north and corresponds to a ~80 km left-lateral offset of the rift axes from the Whakatane to the Ngatoro grabens. Northwards, the Havre Trough deepens to more than 4,000 m of water depth. Topographic relief in the central Kermadec

arc reaches almost 2,000 m in height in response to active rifting in the Havre Trough.

The morphology of the eastern Kermadec region is dominated by volcanic edifices, including cones and calderas. Seafloor morphology clearly shows signs of volcano flank collapses. Seafloor fault scarps also indicate active faulting and seismic activity, and large arcuate scarps suggest massive slope instability on the flank of the Kermadec Ridge.

Seismic transects between the Kermadec and Colville Ridges cross an extensive field of densely distributed NE-SW trending, almost continuous fissure ridges, some of which have associated volcanic cones. These volcanic cones include the Yokosuka volcano, whose summit lies in 1,000 m water depth and rises 1,500 m above the surrounding seafloor. The Gill, in ~1,200 m of water depth, and Yokosuka volcanoes are both characterised by prominent radial ridges and satellite cones up to 1 km in diameter. Sediment-filled grabens are observed between Yokosuka and Gill volcanoes, as in many other places in the backarc. To the west, the western Havre Trough graben consists of two sediment-filled rifts bounded by ~300 m high fault-controlled rift intrusives. These intervening sediment-filled rifts typically have 200 to 500 m thickness of sediment infill. All significant faults across this region, including those feeding rift intrusives, face west.

The NW border of the Havre Trough is characterised by extensive and prominent extensional faults aligned NE-SW, i.e., parallel, and abut the Colville Ridge to the west.
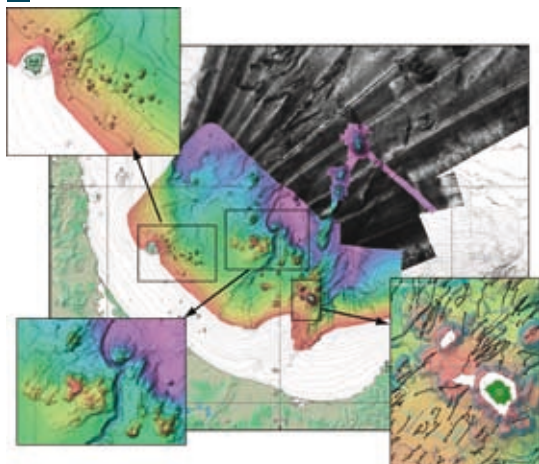
These tectonic features overprint the magmatic features, suggesting that magmatism predates faulting.

The western flank of the Kermadec Ridge and the eastern flank of the Colville Ridge are extremely steep and include arcuous escarpments, suggesting massive submarine slope failures have happened in the geological past. The axial Colville Ridge proper rises to a water depth of 1,270 m and comprises volcanic cone constructs and ridges surrounded by sedimentary deposits.

VOLCANO SCALE MORPHOLOGY AND STRUCTURE

The seismic data collected during the KARMA voyage cover the south-western flank of Silent II volcanoes and traverse Healy caldera and associated cones (Figure 5). The profile images are characterised by high coherency, low frequency and low amplitude reflections that are strikingly different to the rest of the profile where incoherent high amplitude reflections prevail. Units lying at high angular unconformity likely represent pumice layers. The northern slope and south caldera wall of Healy volcano are clearly down-faulted to the north with the units outcropping at the seafloor scarp. From this geometry, the original cone can be reconstructed and development of the existing caldera modelled.

New multibeam data over Rumble II West and East show NE-trending fissure ridges and extensional faults through the centre Rumble II West, indicating that it is being rifted apart. Rumble II West caldera contains an inner, younger caldera in the south-east region of the main caldera that is overprinted by a line of small cones on its NW wall. Both Rumble II West

and East have small cones associated with the central dividing fissure ridges, which are more extensive especially on the north-east and south-west slopes of Rumble II East (Figure 6).

Multibeam data collected over Brothers caldera edifice mostly duplicate previously collected data, with no significant changes in the region. However, the new survey extent also links Brothers to the Kermadec Ridge to the south-east, and to the north-west to the Colville Ridge.

To the SE of Brothers, a couple of new fissure ridges have been surveyed, and closer to the Kermadec Ridge is a newly imaged sediment package that appears to be unaltered by volcanic or tectonic influences. This sediment unit seems to be the base of the slope of the Kermadec Ridge as the water depth gradually increases towards the ridge (Figure 7).

BROTHERS PSEUDO-3D SEISMIC EXPERIMENT

The Brothers pseudo-3D MCS experiment consisted of acquiring a series of 2D seismic lines run at 25 m spacing in a NW-SE orientation over the NW rim of Brothers caldera (Figure 8). The experiment is a first for NIWA and aims at producing a 3D image of the hydrothermal field including active venting and mineralization known over the Brothers NW caldera rim. Sixty three lines were acquired in total. This very challenging operation included strict requirements to keep the vessel on course for the planned 111 lines spaced just 25 m apart.

At present, there is still some debate about how hydrothermal mineralization will be manifested on seismic data. Metallic sulfide particles are dense and a consolidated unit could have high
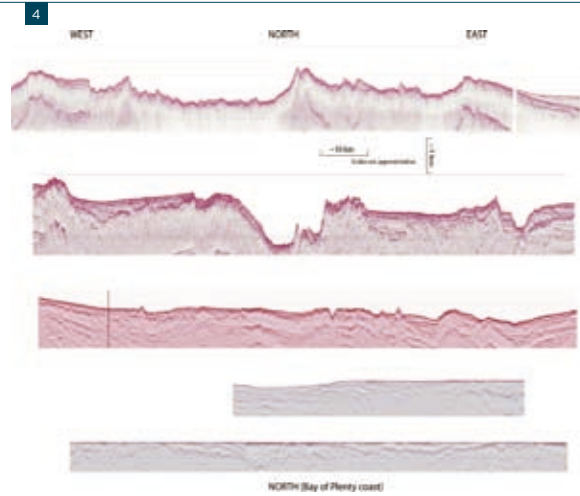
FIGURE 4. Series of multi-channel seismic reflection transect acquired across the entire arc-backarc system from the coast of the Bay of Plenty (bottom profile) to the central Kermadec arc (top profiles). Approximate locations of profiles is indicated on Figure 1 (red lines).

impedance contrast with the surroundings to produce a high amplitude reflection. Conversely sulfide chimneys, small compared to the dominant seismic wavelengths, would only scatter the seismic energy while inactive vent fields, with collapsed chimney structures forming mineralized breccias, may not produce a bright reflection. If the seismic characteristics of the hydrothermal venting are to be determined, due to the difficulties associated with imaging in such steep, volcanic environments, significant work will have to be applied post-cruise to improve the quality of the images and study the seismic attributes. These results will then have to be calibrated against everything else known about the volcanism and hydrothermal venting and mineralization at Brothers seamount to determine whether seismic imaging of hydrothermal mineralization provides a viable exploration tool. ■

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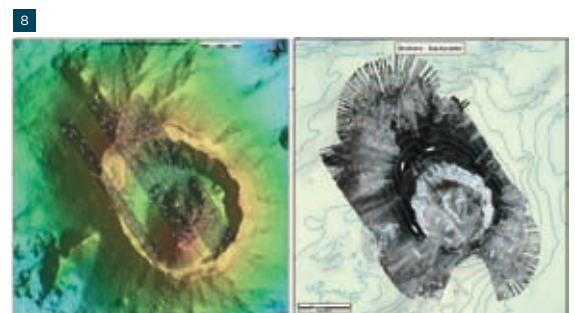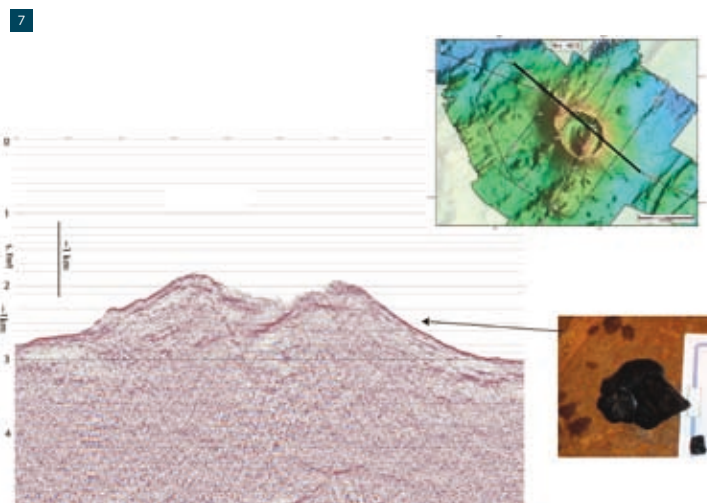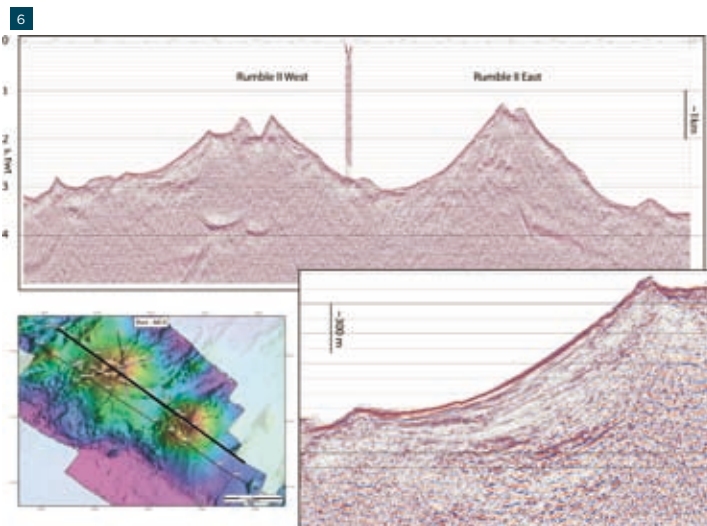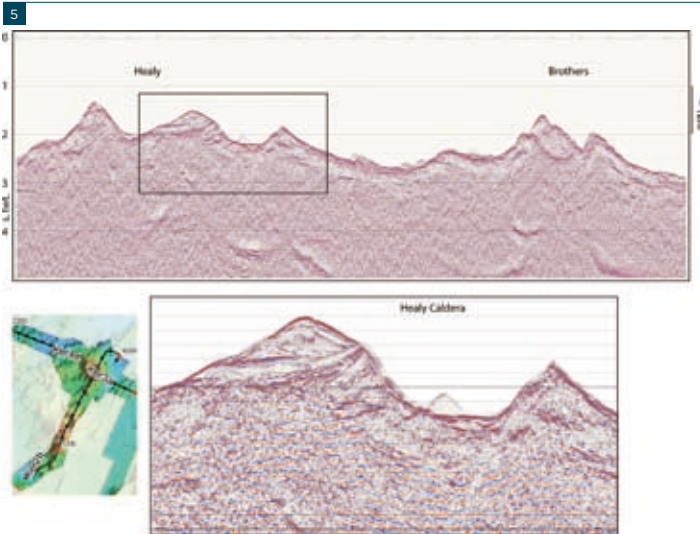
FIGURE 5. Seismic reflection profiles of Healy and Brothers volcanoes.

FIGURE 6. Seismic profile over Rumble II West and East.

FIGURE 7. Seismic section over Brothers caldera. Arrow indicates the approximate location of where the sample was collected.

FIGURE 8. Ship track of the pseudo-3D seismic experiment over Brothers caldera and resulting back-scatter data collected.

IN THE MIDST OF AN OCEAN

DEEP

30|31.08.2010 WELLINGTON NZ

Motion in the ocean: Biological oceanography of the Kermadec region – migration and connectivity of marine flora and fauna

Tom Trnski, Malcolm Francis, Clinton Duffy, Steve Chiswell and Wendy Nelson

The open ocean is popularly viewed as a uniform, featureless environment that lacks orientation cues for animals. However, confirmed migration routes of large vertebrates – such as humpback whales, white sharks and swordfish – in the ocean is not entirely random. That is, there are patterns emerging that indicate that these large vertebrates are using environmental cues to navigate their migration routes, and these patterns are found in three dimensions, for example, swordfish show diel differences in swimming depth.

These large vertebrates are aware of their surroundings and are able to navigate over large distances using hydrographic and continental features. Senses that are known to be used in long-distance migrations include sight, smell and sound; other senses such as lateral lines or orientation to polarised light or variations in magnetic fields are found or confirmed only in some species.

Plotting the dispersal potential of large marine vertebrates and pelagic invertebrates over time demonstrates that their dispersal ability early in their life history is relatively limited, but it is high for the remainder of their life. Contrast this with the dispersal ability of the vast majority of marine species – the macroalgae and animals, including most fishes and invertebrates. Their maximum dispersal ability is highest early in their life history, during the egg and larval stage. Once they settle in their juvenile or adult habitat, they are attached to their settlement site, either rigidly in the case of attached plants and animals or, if they are free-swimming, remain within a limited space. These site-associated species are termed "benthic" or "demersal". Most marine species rely on the egg and larval

stages to undergo dispersal, and the transition to a benthic or demersal lifestyle is termed "settlement".

Taking snapper (Pagrus auratus) as an example of a typical marine species, the adults spawn pelagic eggs that hatch larvae. As larvae develop, their swimming ability improves, as does their sensory ability. After a period of larval development, the larvae become competent to settle. This assumes they are near a settlement site – the ability to locate suitable settlement sites is the subject of this presentation.

Fish eggs average about 1 mm in diameter, larvae hatch from the eggs at about 2 mm length, and the larvae are competent to settle from about 10 mm in length, a few weeks to a few months after hatching. The size of eggs and larvae, and the larval duration, varies widely among fish species, but these averages provide a guide to common sizes and larval duration. Egg and larval size is smaller, and larval duration is shorter, in marine invertebrates.

Considering the scale of the south-west Pacific region, there are large expanses of ocean peppered with islands that provide suitable habitat for shallow-water species. For most marine species, it is the larval stage that disperse across the expanse of ocean between the islands, and it is the larvae that provide the connectivity among isolated populations. It is only relatively recently that the islands of the Kermadec region have emerged above sea level, estimated to be within the last 2.5 million years. Thus, for at least the shallow-water flora and fauna, the species that occur in the Kermadec Islands must have dispersed from nearby islands, a distance of 900 km or more. The islands closest to the Kermadec Islands are

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*We now know that fish larvae need to swim to
increase the likelihood of dispersing greater distances
than explained by passive particle models.
But how fast can fish larvae swim?*

Tonga to the north, Norfolk Island to the west and northern New Zealand to the south.

The Kermadec Islands are broadly connected to other parts of the South Pacific through the counter-clockwise currents of the South Pacific Gyre. In particular, the eastward-flowing Tasman Front delivers large volumes of water from a southward-flowing western boundary current – the East Australian Current, which transfers large volumes of tropical water to temperate latitudes. The Tasman Front averages 20–25 cm/s, but this is not a conveyor belt of eastward-flowing water. It is better described as a meander, with large variations in current direction and velocity. Its average latitudinal position is at 32°S.

Regional hydrodynamic models have been used to estimate the potential dispersal of eggs and larvae of marine species between the southern islands of the Kermadecs and northern New Zealand. These dispersal models assumed that larval dispersal was passive – that the larvae are unable to swim to influence their dispersal. These dispersal models confirm that regional currents are relatively weak or at least not strongly directional. Note that any tidally driven currents are non-directional, as flow alternates between tidal cycles. The dispersal pattern generated by this model suggests that dispersal is diffusive rather than directional and that it would take about 50 days for a passive particle to reach from New Zealand to an island in the southern Kermadecs or vice versa. Fifty days is longer than the larval duration of most marine species, thus passive dispersal does not provide a likely mechanism for dispersal from adjacent islands to the Kermadec Islands. This is further confirmed by the occasional observation

of juveniles of species endemic to the Kermadec Islands in northern New Zealand. The larval duration of all of these species is less than 30 days, which, according to the dispersal model, is too short for passively dispersing larvae to traverse the 900+ km.

If the Tasman Front behaved as a conveyor-belt current, it would take 41 days to cover a minimum of 900 km from the nearest island to the Kermadecs, assuming average velocity. Even under these perfect conditions, larvae behaving as passive particles are unlikely to provide settlers to the Kermadecs from the nearest islands.

We now know that fish larvae need to swim to increase the likelihood of dispersing greater distances than explained by passive particle models. But how fast can fish larvae swim? Research in the 1990s by Rebecca Fisher, Jeff Leis, Ilona Stobutski and others caused a paradigm shift in thinking about the swimming and navigational ability of fish larvae (Leis and Carson-Ewart, 2003; Leis and Fisher, 2006, and references therein). Firstly, they demonstrated that fish larvae are remarkably strong swimmers and that the size and morphology of the larvae had some influence on their swimming speed. Incorporating larval swimming into dispersal models demonstrated that larvae could swim tens of kilometres a day, profoundly influencing their long-distance dispersal ability.

But swimming speed alone will only increase the rate of diffusion from a release point. In order to increase the likelihood of dispersing to suitable settlement habitat, an ability to navigate in the open ocean environment is also required. Recent research by Danielle Dixson, Jeff Leis and Craig Radford and others has demonstrated that

swimming direction is not random and that there are a number of environmental cues and sensory systems that are involved in navigation by fish larvae (Atema *et al*, 2002; Dixson *et al.*, 2008; Leis and Lockett, 2005; Radford *et al.*, 2007). Among these cues are reef sounds that can be detected up to 10 km away and provide a directional cue for larvae competent to settle. Olfactory cues can direct larvae to suitable settlement. Vision is an obvious sense, even though it operates at a scale of only up to tens of metres; fish larvae may have better visual abilities than divers that are following them, by swimming towards the seafloor or avoiding predators before observed by divers swimming with the larvae. The ability to detect variation in magnetic fields has been demonstrated in salmon, and there is evidence of a sun compass in some species as their swimming direction varies depending on the time of day. Also, in the last few years, remarkably consistent results have shown a high rate of return of larvae to the site at which eggs were spawned by their parents. This self-recruitment has been estimated to be between 35% and 65% in a number of studies by Hugo Harrison, Geoff Jones, Simon Thorrold, David Williamson and others (Jones *et al.*, 2005; Almany *et al.*, 2007). This is an extremely high proportion of larvae that return to the site from where they were spawned.

Although most of the research on larval swimming and navigation has been demonstrated with fish larvae, larvae of invertebrates also have strong swimming and navigational abilities, particularly in crustaceans like lobsters, which return to natal islands and continents after many months in the ocean, and crab larvae, which navigate their return to estuarine nurseries.

These results demonstrate that larvae are not passive particles, but rather that they can strongly influence their dispersal and in many cases overcome the ambient currents to enhance settlement in suitable habitat.

This ability to influence dispersal has important implications for models of larval dispersal and connectivity among islands. Just as the physical environment varies over space and time, so does the response of larvae to their environment – the physical environment and behavioural responses to that environment determine the success or failure of the ability of larvae to locate suitable settlement habitat. This variability is difficult to capture in small marine reserves, as their success as a source of larvae or a settlement sink will vary with time.

Integrating what is known so far on the currents of the Kermadec region and the swimming and navigational abilities of larvae, a hypothesis can be developed on the connectivity of the Kermadec Islands to each other and between the Kermadecs and nearby islands. Self-recruitment of larvae to the source of the eggs is likely to be frequent, as is exchange of larvae among the Kermadec Islands given the scale of separation between adjacent islands is tens to only a few hundred kilometres. This is supported by a number of coastal species endemic to the Kermadec Islands. With current direction and strength varying over time, delivery of larvae that were spawned at Norfolk Island is likely to occur occasionally. There is likely infrequent two-way dispersal between the Kermadec Islands and northern New Zealand, supported by a strong overlap in species composition, and the occasional dispersal of Kermadec Island endemics to northern New Zealand.

Comparing the known shorefish diversity of the Kermadec Islands with the regional Pacific region, the fish fauna appears relatively depauperate. Partly it is because shallow-water species diversity diminishes at higher latitudes and along the easterly axis, but it is also a reflection of the small number of surveys that have been undertaken in the Kermadecs. We are still in the discovery phase of knowledge about the marine biodiversity of the Kermadec Islands. Improving our knowledge of the species that occur in the Kermadec Islands will enhance our understanding of the relative isolation of the Kermadec marine populations, and their connectivity to other populations in the south-west Pacific. ■

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Impacts on the vegetation of Raoul Island

Carol West, Bill Sykes and David Havell

ORIGINS OF THE FLORA

The terrestrial flora of the Kermadecs is derived from long-distance dispersal via ocean currents, wind or birds. The relationships of the Kermadec flora are overwhelmingly with the New Zealand mainland and off-shore islands. With the exception of two species, the forest and shrubland are dominated by trees, shrubs and tree ferns that are either endemics closely related to New Zealand species, species derived from New Zealand species, or they are New Zealand species. An exception to this pattern is that the ferns and fern allies, and the coastal dunes and grasslands, are dominated by species with a southern hemisphere or tropical Pacific distribution.

Only a few plants originate from the tropical islands to the north; two to three of these have their closest relations in tropical East Polynesia (Cook Islands and French Polynesia). *Scaevola gracilis* was originally regarded as endemic but subsequently recognised as the same as a species hitherto thought to be endemic to Tonga. Also, there are two or three species or subspecies that have their closest relations in the much older Norfolk Island, which is due west of Raoul Island (Figure 1).

Isolation and land surface age and height determine native flora diversity. Length and degree of human occupation determines exotic flora numbers (Table 1).

The flora is disharmonic. Many genera and species that occur in northern New Zealand mainland, the subtropical SW Pacific islands of Norfolk and Lord Howe, as well as tropical islands in Fiji and Tonga to the north are absent from the Kermadecs, e.g., *Geniostoma, Dodonaea, Dysoxylum, Streblus, Pouteria,*

Korthalsella, Clematis, conifers, cycads, lianes and some fern families, e.g., Gleicheniaceae, Marattiaceae.

The plants that dispersed to Raoul and survived are well adapted to natural disturbances such as cyclones, landslides, floods and volcanic eruptions. Even-aged pohutukawa forest grew after the 1964 eruption. Following the 2006 eruption, some trees have sprouted epicormically and will survive as pohutukawa did after the 1964 eruption. It will be interesting to see what forest cover grows following this eruption, since goats and rats, present after the 1964 eruption are no longer present.

IMPACTS OF HUMAN ACTIVITY

Humans first arrived on Raoul Island in the late 13th century and have lived there intermittently to the present day. They are responsible for the introduction of a range of plants and animals, some of which exerted major impact on the native flora and fauna and have been eradicated (Table 2). Many of these exotics occur in association with historic sites. There is almost twice the number of introduced plants on Raoul Island than native species (Table 1).

Several plant species introduced by Maori from Polynesia still flourish on Raoul Island. Ti pore *(Cordyline fruticosa)* was introduced for fibre and as a famine food. Candlenut *(Aleurites moluccana)* has an oily seed that was used as a light source, and black dye was extracted also.

During the 19th century, Denham Bay flat and the northern terraces were settled. Many plants were introduced at this stage, some of which persist to this day, and a few of which are weeds targeted for eradication. Obvious species are Norfolk pines *(Araucaria heterophylla),* on the

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| 1 |

	LORD HOWE	NORFOLK	RAOUL
Indigenous spp.	241	139	118
Endemic spp.	105	44	25
Exotic spp.	218	341	202

| 2 |

DATE	ACTIVITY	DATE	ACTIVITY
c. 1280 AD	First Polynesians	1914	Bells depart, Raoul abandoned
	Kiore introduced	1921	Wreck of *Columbia River*
1788	European discovery		**Norway rats invade**
1800–10	Whalers active	1934	Flora and Fauna Reserve
	Goats introduced	1937	Meteorological station established
1836	First European settlers	1972	Weed eradication began
	Cats introduced	1984	**Goats eradicated**
1854	First naturalists visit	1989	DOC replaces Met Service
1872	First settlement phase ended	2002	**Rats eradicated**
1878	Bell family arrives	2003	**Cats eradicated**

TABLE 1. Current known approximate floral statistics for the three islands at similar latitude but of varying age, size and remoteness. The number of indigenous species plus endemic species gives the total native flora. Figures are based on Sykes *et al.,* (2000) for Raoul, de Lange *et al.,* (2005) for Norfolk and Green (1994) for Lord Howe Island.

TABLE 2. Timeline of human activity.

northern terraces, and figs *(Ficus carica)* which have occupied quite large areas in some places, like one in Denham Bay that, in 2008, 33 m^2.

Raoul Island oranges *(Citrus sinensis)* are famous. A few remain from the earliest European settlers, but the majority was planted in the mid 1900s when an orchard was established.

IMPACTS OF GOATS

Goats had a major impact on the vegetation, virtually eliminating some species like Raoul *Hebe (Hebe breviracemosa)*. They browsed in the canopy of pohutukawa trees, allowing more light to reach the forest floor, thus promoting light-demanding but unpalatable weed species like the aroid lily *(Alocasia brisbanensis)*. Goats probably eliminated several species from the indigenous flora.

Coprosma acutifolia responded quickly to reducing goat numbers and, by 1980, had "almost regained its status as an important subcanopy tree in many parts of Raoul Island". (Sykes, 1980). After the goat eradication in 1984, many other species responded positively, becoming quite prominent.

Presumed extinct in 1966 as a result of goat browsing, one plant of Raoul *Hebe* was found and protected in 1993. Cuttings from this plant were grown and planted out. Seedlings were grown from cutting-grown plants. After goat eradication, new populations began to be discovered in the course of weed eradication work. After rat eradication, further populations of Raoul *Hebe* were discovered and known populations began to flourish (Figure 2).

The current *Hebe* planting programme indicates that Raoul *Hebe* does best in open to semi-open sites in the upper ridge system and ravines. However, Oliver (1911) found plants on a landslip site on the floor of Denham Bay, and occasional transplants survive in the dry forest above Low Flat. This indicates that, given requirements of moisture and light, the Raoul *Hebe* should be a common component in disturbed habitats, e.g., on landslips, similar to New Zealand *Hebe* species such as *Hebe stricta*. The main threats to current plantings at the moment are shading by ferns and weeds.

IMPACTS OF RATS

Norway rats *(Rattus norvegicus)* and kiore *(R. exulans)* were eradicated from Raoul Island in 2002. The impact of rats, when present, is not as obvious as the impact of goats. Once eradicated, however, the impact, as measured by the response of suppressed species populations, is shown to have been severe for some species.

Vegetation changes have been recorded in nine 30 m^2 quadrats since 1993. There were four measurements within the plots prior to rat eradication and two measurements subsequently. Plots are located in wet (>100 m altitude) and dry forest, the latter divided between forests disturbed by human activity and those subject primarily to natural disturbance.

Nikau seed production is abundant, as recorded within the plots, but the majority of seeds and seedlings were destroyed by rats. However, after rats were eradicated, the majority of seeds germinated (Figure 3). Dense carpets of nikau seedlings occur in some places, and a wide range of indigenous seedlings is now common.

3

SCIENTIFIC NAME	COMMON NAME
Anredera cordifolia	Madeira vine
Caesalpinia decapetala	Mysore thorn
Olea europaea subsp. *africana*	African olive
Passiflora edulis	black passionfruit
Psidium cattleianum	purple guava
Psidium guajava	yellow guava
Selaginella kraussiana	selaginella
Senna septemptrionalis	buttercup bush

4

SCIENTIFIC NAME	COMMON NAME
Cortaderia selloana	pampas grass
Ficus macrophylla	Moreton Bay fig
Foeniculum vulgare	fennel
Furcraea foetida	Mauritius hemp
Gomphocarpus fruticosus	swan plant
Macadamia tetraphylla	macadamia
Nerium oleander	oleander
Phyllostachys aurea	bamboo
Pinus radiata	radiata pine
Populus nigra	Lombardy poplar
Senecio jacobaea	ragwort

An unexpected outcome of the rat eradication was the emergence of the tropical army worm *(Spodoptera litura)*, which is now defoliating the aroid lily.

IMPACTS OF WEEDS

Eight introduced plant species are currently targeted for eradication (Table 3). One consequence of the disharmony of the natural flora is that certain vegetative life forms such as the climbing or lianoid habit are naturally absent from the Kermadecs. This seems to be connected to the fact that three of the major weeds listed in Table 3 are climbing or scrambling plants. All of these species competitively displace the indigenous flora. *Selaginella* was first recorded in 1999, indicating the need for ongoing vigilance and improved quarantine practices.

Weed eradication takes time, as plants can be hard to find, hard to kill or invisible in the seed bank. However, to date, 11 species appear to have been eradicated (Table 4): lack of certainty relates to the first and third factors just mentioned. Most of the species eradicated were deliberate introductions. Ragwort is probably the sole exception.

Before the rat eradication, black passionfruit seedlings were among the more commonly encountered of the weeds targeted for eradication, but this species, much more so than the rest, responded strongly by greatly increasing due to the absence of rats. Although the vines can grow to maturity quickly, it is likely that a lot of the response seen here is from the seed bank (Figure 4). Mature black passionfruit vines can produce large crops of fruits.

Although the fruit can be hard to spot on the forest floor, the fallen foliage is readily seen. Every seed in a fruit can germinate – up to 100 seedlings per fruit.

SUMMARY

The terrestrial habitats of the Kermadec Islands are an important part of the biodiversity of the New Zealand realm because of their isolated position in subtropical latitudes and special floral composition. In recognising this, it is imperative that we are aware of their great vulnerability to the invasion and spread of foreign organisms, thus necessitating ongoing management to reduce current impacts and continual vigilance to prevent establishment of new invasive species. ∎

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TABLE 3. Key weeds to be eradicated from Raoul Island.

TABLE 4. Weed species possibly eradicated from Raoul Island.

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THE KERMADECS

FIGURE 1. *Rhopalostylis baueri* on Raoul Island: originally recognised as a separate species (*R. cheesemanii*) but now regarded as part of the Norfolk Island species.

FIGURE 2. Number of *Hebe breviracemosa* plants recorded on Raoul Island since 1983, when one plant was found alive.
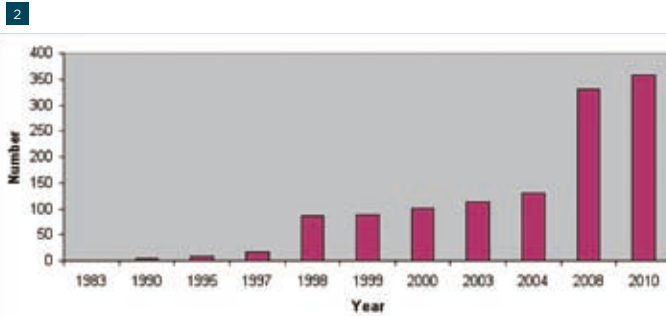
FIGURE 3. Number of Kermadec nikau seedlings recorded in permanent plots on Raoul Island. Rats were eradicated in 2002 after the plots were remeasured.
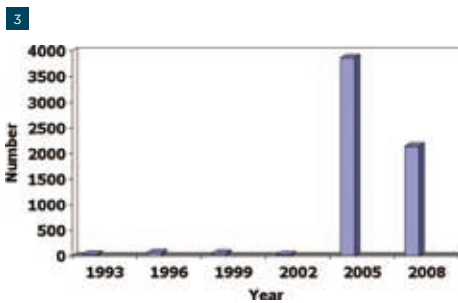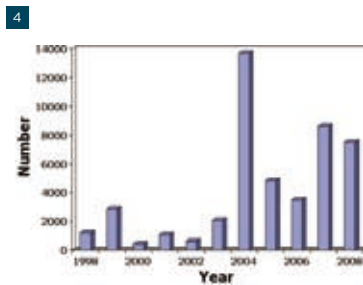
FIGURE 4. Number of black passionfruit seedlings removed from Raoul Island before and after the rat eradication in 2002.

Birds of the forest, lakes and shores

Dick Veitch

We know about 41 species of birds that live, or have lived, in the forest, lakes and shores of the Kermadec Islands. This knowledge is sparse and relatively recent. It comes from the journals of the whalers of the 1800s, then the occasional naturalist like W.R.B. Oliver and Tom Iredale of the early 1900s. Around 1900, the Bell family lived on Raoul, and they contributed to our knowledge. The Coastwatchers of WWII provided records as did the Ornithological Society expedition of 1966/67. Throughout this latter period, staff of the Meteorological Service and now the Department of Conservation have added to our knowledge. That gives some knowledge about birds over a mere 150 years, but it contributes hugely to our ability to connect Raoul firmly to the New Zealand ornithological scene.

Alongside this bird knowledge is the record of change to the birds' habitat. Polynesian voyagers, possibly earlier than 1250, brought *Rattus exulans* to Macauley and Raoul from both the Pacific islands and from New Zealand. We now know that this little rat probably caused change to the forest ecosystem and may have eradicated bird species from these islands. Cats and goats were left on Raoul, and goats on Macauley, prior to 1836. That was the era of leaving food items on islands for shipwrecked mariners. Norway rats reached Raoul in 1921 from a shipwreck.

Through modification to the vegetation and direct predation, these introduced mammals caused huge change to the bird fauna of the Kermadec Islands. Now, all the mammals are gone, and we are seeing a reversal of the changes they wrought.

Most of the shorebird species seen on Raoul migrate back and forth between their non-breeding range of New Zealand and eastern Australia to breed in Siberia and Alaska. A few of these, usually on the southbound migration, drop out at the Kermadecs and probably die there. Intermittent habitat changes like unusually low lake levels or eruption-created mudflats may create suitable habitat for a short time. The mown grass of the airstrip and front lawn of the hostel provide a habitat for a few Pacific golden plover. This species was probably also a regular visitor to Macauley Island when it was heavily goat-grazed.

Only one species of migratory shorebird, the Siberian tattler, which uses the rocky shoreline, can probably claim the Kermadec Islands as "home", but even this species has not been recorded as present in every ornithological report.

Our banded dotterel, some of which migrate to Australia, has been occasional visitors. Spur-winged plovers – since they became abundant in northern New Zealand – have moved onto the few open spaces on Raoul.

The lakes of Raoul provide a permanent habitat for grey duck and pukeko. Three other duck species, including mallard, Canada geese and five heron species have also been recorded occasionally. Canada geese reached Raoul only after they became abundant in northern New Zealand and cattle egrets only after they became regular migrants between Australia and New Zealand.

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Tui are present only on Raoul Island and are usually the most abundant bird in the forest. The Kermadec parakeet is an endemic subspecies of the red-crowned parakeet on mainland New Zealand. It has always been abundant on Macauley Island and on the Herald Islets. Parakeets were plentiful on Raoul in 1836 but were not recorded between then and their return after the eradication of cats and rats by 2004. Kingfishers were considered to be common all over Raoul when the island was grazed by goats, but now that the vegetation has grown, they are found around the rocky shore with only occasional sightings along the roads. Spotless crakes were breeding on Raoul around 1900 but were not present later in that century. A population remained on the Meyer Islands, and since cat and rat eradication, they have repopulated Raoul.

There was once a pigeon in the forests of Raoul Island but it was exterminated by the impacts of cats, rats, goats and hunters before any specimens could be collected. A bone found by archaeologists confirms that this was the New Zealand pigeon.

A recent arrival is the welcome swallow, which was first seen in 1972 – a short time after it became abundant in northern New Zealand. It is a winter visitor, and so far, there is no evidence of breeding.

The two cuckoo species have also been on Raoul – shining cuckoos rarely, but long-tailed cuckoos may be there all year. Silvereyes have been there occasionally. Nine introduced European passerines have been recorded on Raoul. Most have been seen occasionally on other islands in the Kermadec group. Blackbirds,

song thrushes and starlings are now permanent. Yellowhammer, chaffinch, greenfinch, goldfinch and redpoll were first recorded around the early 1900s, and they surely came from New Zealand.

It is notable that the tui is a bird that could have come only from New Zealand. Parakeets are most likely to have come from New Zealand, as did the populations of this genus on Lord Howe and Norfolk Islands. The numerous European passerines probably came from New Zealand after their introduction and increase there. Notable is the yellowhammer, which is not present in Australia. Spur-winged plovers and welcome swallows are Australian native birds, but they reached Raoul only after they became abundant throughout New Zealand. Canada geese are not present in Australia and were seen on Raoul only after they became abundant in northern mainland New Zealand.

CONSERVATION ACTIONS TO CONSIDER

A megapode was reported to be present, but never confirmed. Using Raoul for conservation of one of the megapode species could be considered.

Banded rail were reported but never confirmed. I believe it highly likely that they were on Raoul and could now be considered for reintroduction.

The duck population could be maintained as grey duck only.

The New Zealand pigeon was present. The forest habitat has now regenerated to a condition where pigeons should survive, so they could be considered for reintroduction. ∎

Diversity, biogeography and abundance of Kermadec Islands coastal fishes

Malcolm P. Francis and Russell G. Cole

Situated in the subtropical belt of the south-west Pacific Ocean, and spanning about 250 km and 2.2 degrees of latitude, the Kermadec Islands harbour a fascinating mix of tropical, subtropical and temperate fishes (Francis, 1993). The islands are small specks of land in a large ocean, with the nearest significant land mass (New Zealand) being about 730 km away. The coastal fish fauna of the Kermadecs is strongly influenced by the remoteness of the islands and the low frequency of recruitment of fish larvae from upstream sources. Here, we review published and unpublished information on the diversity, biogeography and abundance of Kermadec Islands coastal fishes. We define coastal fishes as those species likely to occur within 50 m of the surface and 1 km of the shore, excluding oceanic pelagic species. Most species covered by this study are reef fish, but species living on or in sand are also included.

DIVERSITY AND BIOGEOGRAPHY

The first checklist of Kermadec Islands fishes was published 100 years ago by Waite (1910), and updated 2 years later (Waite 1912) (Figure 1, Table 1). Waite's checklist contained 32 species of coastal fishes, many of which were collected by the naturalist W.R.B. Oliver who spent 9 months at the islands. After a gap of 73 years, the fauna was more than doubled to 72 species when Paulin and Stewart (1985) listed the Kermadecs teleost fishes held in the Museum of New Zealand Te Papa Tongarewa. During the mid 1980s and early 1990s, several scientific expeditions (Schiel *et al.*, 1986; Francis *et al.*, 1987; Francis, 1991) observed, photographed and collected many new fishes, mostly by scuba diving, resulting in another doubling of the fauna to 145 species (Francis, 1993). Since then, the known fauna has increased more modestly,

largely as a result of a 2004 scientific expedition (Duffy, 2005), to the present total of 165 species. The richness of Kermadecs coastal fishes is therefore relatively low: Norfolk Island and Lord Howe Island, which are situated west of the Kermadecs in similar latitudes, have much higher species richness – 268 and 476 coastal fishes respectively (Francis, 1993; unpubl. data).

The Kermadec Islands fish fauna is composed mainly of subtropical (45%) and tropical (42%) species, with a small proportion (12%) of temperate species (Francis, 1993; unpubl. data) (Figure 2). Norfolk and Lord Howe Islands have higher proportions of tropical fishes (60% and 70% respectively) and lower proportions of subtropical (33% and 25% respectively) and temperate (6% and 4% respectively) species. There is a clear decline in the proportion of tropical species and an increase in the proportion of subtropical and temperate species from west (Lord Howe Island) to east (Kermadec Islands) (Figure 2).

Kermadec Islands coastal fishes have distributions ranging from very broad (worldwide) to very narrow (endemic to the Kermadecs). Species with Indo-Pacific Ocean (35%) or south-west Pacific Ocean (23%) distributions dominate the fauna (Figure 3). Widespread species, with Pacific Ocean distributions or wider, account for 54% of the fauna. Species with distributions limited to the Kermadecs and one or more of Lord Howe Island, Norfolk Island and New Zealand are relatively uncommon (10%).

Only eight species (5% of the fauna) are endemic to the Kermadec Islands (Table 2). Endemic species are defined here as those fishes that are restricted to the Kermadec

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STUDY	NUMBER OF SPECIES
Waite (1910, 1912)	32
Paulin and Stewart (1985)	72
Schiel *et al.*, (1986)	82
Francis *et al.*, (1987)	112
Francis (1991)	138
Francis (1993)	145
Duffy (2005)	165

TABLE 1. Number of coastal fish species known from the Kermadec Islands as a result of significant studies of the fish fauna (arranged in chronological order).

Islands apart from extremely rare strays that have dispersed elsewhere by larval drift. Several of the Kermadec endemics have been reported from elsewhere. *Chrysiptera rapanui* was described from Easter Island in the eastern Pacific, but specimens from there lack the yellow coloration found in Kermadecs fishes (Allen, 1991). The latter are probably genetically isolated from Easter Island fish and distinct at the subspecies or species level. A single individual of the yellow Kermadecs morph of *C. rapanui* was photographed at the Poor Knights Islands in north-eastern New Zealand in 1984–86 (Francis *et al*., 1999). *Parma kermadecensis* (Figure 4) has also been reported from the Poor Knights Islands: a pair was observed at the same location regularly between April 1997 and September 2007 (Francis *et al*., 1999; unpubl. obs. compiled by M.P. Francis). *Girella fimbriata* (Figure 5) has occasionally been observed off north-eastern North Island: four sightings, three of which were supported by photographs, were made at Great Barrier Island, Rakitu Island, Lady Alice Island and Motiti Island between 2002 and 2010 (unpubl. obs. compiled by M.P. Francis). The remaining five endemic fishes, including three that are undescribed, are not known from outside the Kermadec Islands. Seven of the eight endemic fishes have reproductive modes that result in limited dispersal capabilities (Table 2). Two species produce live young without a larval phase, and five species lay benthic eggs from which well developed larvae hatch; the planktonic larval durations of these species is probably very short. Only *Girella fimbriata* is thought to produce pelagic eggs that are amenable to widespread dispersal, though the larval duration of this species is unknown.

Only two species are restricted to the Kermadecs and New Zealand (and are therefore New Zealand endemics). *Chromis dispilus* is an abundant damselfish at both the Kermadecs (Francis *et al*., 1987) and north-eastern North Island. *Optivus elongatus* is patchily distributed at the Kermadecs, being common only at Curtis and Cheeseman Islands (Francis *et al*., 1987) and is common around north-eastern North Island. Four species (*Scorpaena cookii*, *Chironemus microlepis*, *Genicanthus semicinctus* and *Engyprosopon raoulensis*) are restricted to the Kermadecs and either or both of Lord Howe and Norfolk Islands. However, *Genicanthus semicinctus* should be regarded as a Lord Howe endemic as it is otherwise known only from one Raoul Island specimen.

ABUNDANCE

Estimates of coastal fish abundance have been made by scuba divers in four recent studies (Schiel *et al*., 1986; Francis *et al*., 1987; Cole *et al*., 1992; Cole, 2001). The wide latitudinal spread of the Kermadec Islands is reflected in latitudinal trends in abundance for 35% of coastal fishes. Francis *et al*., (1987) classified 77 species as abundant, common, occasional, rare or absent. They found that five species decreased in abundance northwards, 18 species increased in abundance northwards, four species peaked in abundance in the central Kermadecs and 50 species showed no latitudinal trend (Figure 6).

Studies that counted fish in measured transects or during a timed period of observation focused mainly or completely on Raoul Island at the northern end of the Kermadecs (Schiel *et al*., 1986; Cole *et al*., 1992; Cole, 2001). Cole *et al*., (1992) found strong depth gradients for many

FAMILY	SPECIES	COMMON NAME	REPRODUCTIVE MODE
Triakidae	*Mustelus* sp.	Kermadec rig	L
Bythitidae	*Mircobrotula puniceus* (Anderson, 2007)	Orange brotula	L
Pomacentridae	*Parma kermadecensis* (Allen, 1987)	Kermadec scalyfin	B
Pomacentridae	*Chrysiptera rapanui* (Greenfield and Hensley, 1970)	Kermadec demoiselle	B
Girellidae	*Girella fimbriata* (McCuloch, 1920)	Caramel drummer	P
Tripterygiidae	*Enneapterygius kermadecensis* (Fricke, 1994)	Kermadec triplefin	B
Gobiidae	*Eviota* sp.	Goby	B
Gobiesocidae	Undescribed genus and species	Urchin clingfish	B

fishes. The schooling species *Bathystethus cultratus*, *Labracoglossa nitida* and *Kyphosus bigibbus* were much more abundant in shallow (0–10 m) water than in moderate depth (10–18 m) or deep water (greater than 18 m), whereas *Chromis dispilus* were most abundant in moderate and deep water, and *Girella cyanea* showed no pattern with depth. For demersal fishes, a suite of five species (*Cheilodactylus ephippium*, *Trachypoma macracanthus*, *Stegastes fasciolatus*, *Notocirrhitus splendens* and *Aplodactylus etheridgii*) was most abundant in shallow water, two species (*Aulacocephalus temmincki* and *Chrysiptera rapanui*) were most abundant in deep water, and five species (*Parma kermadecensis*, *Acanthistius cinctus*, *Notolabrus inscriptus*, *Pseudolabrus luculentus* and *Plagiotremus tapeinosoma*) showed no trend. The observed depth patterns result in distinct fish communities occurring in different depth ranges.

Although tropical species form the largest component of the Kermadecs fish fauna, subtropical species are generally the most abundant fishes. The latter include the planktivorous species *Bathystethus cultratus*, *Labracoglossa nitida*, *Kyphosus bigibbus*, *Chromis dispilus*, *Chrysiptera rapanui* and *Scorpis violaceus*; the herbivorous *Stegastes fasciolatus*, *Aplodactylus etheridgii* and *Parma kermadecensis*; and the carnivorous *Pseudolabrus luculentus* (Cole *et al.*, 1992).

Top predators are common at the Kermadecs, notably Galapagos sharks (*Carcharhinus galapagensis*) and spotted black grouper (*Epinephelus daemelii*). Both these species are mainly restricted to depths less than 50 m, and

consequently, they have a small habitat area at the Kermadecs. Both species are also long-lived, slow-growing and have low reproductive rates. These habitat and biological characteristics combine to make them highly vulnerable to fishing. Marine reserve status at the Kermadec Islands has protected these species and maintained them at natural levels of abundance; elsewhere, they have been severely depleted by fishing.

CONCLUSIONS

The coastal fish fauna of the Kermadec Islands is not particularly diverse, comprising 165 known species. It consists mainly of tropical and subtropical species, but with a significant temperate component. Many Kermadecs fishes have wide geographic distributions, but some have very restricted distributions, including eight species that are endemic to the islands. Subtropical species are generally the most abundant fishes in coastal waters. Many species exhibit strong latitudinal and depth gradients in abundance, leading to complex spatial variation in the composition of fish communities. The lack of significant fishing around the Kermadec Islands has resulted in a healthy and very visible population of top predators, especially sharks and groupers. The mix of fish species present, the abundance of subtropical species, and the existence of many top predators, produce a unique and fascinating coastal fish fauna at the Kermadecs. ∎

TABLE 2. Kermadec Islands endemic coastal fishes. Reproductive modes: L, live-bearer; B, benthic eggs; P, pelagic eggs.
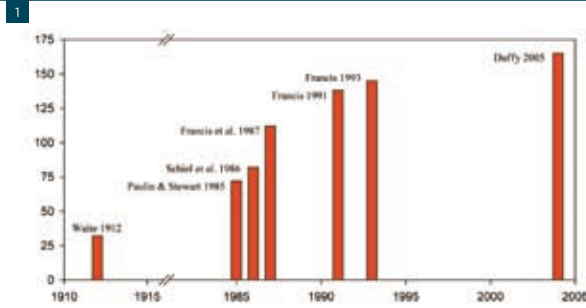
FIGURE 1. Number of coastal fish species known from the Kermadec Islands as a result of significant studies of the fish fauna. See Table 1 for details. Note the break in the time axis.

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Diversity, biogeography and abundance
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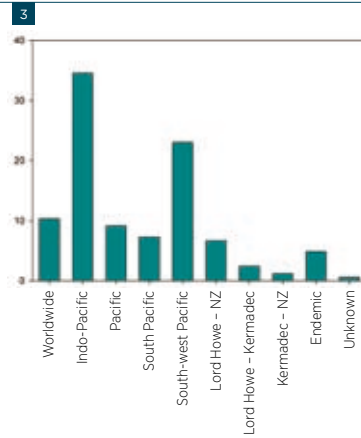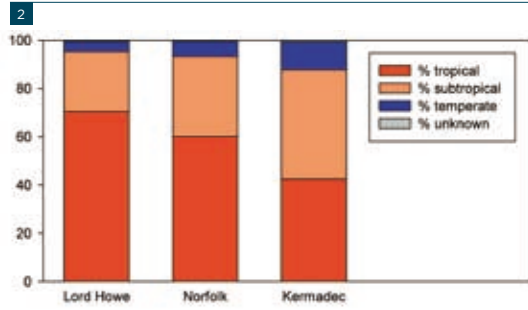
FIGURE 2. Kermadec Islands coastal fishes classified by major water temperature zone.

FIGURE 3. Geographic distribution of Kermadec Islands coastal fishes.

FIGURE 4. Kermadec scalyfin, *Parma kermadecensis*.

FIGURE 5. Caramel drummer, *Girella fimbriata*.
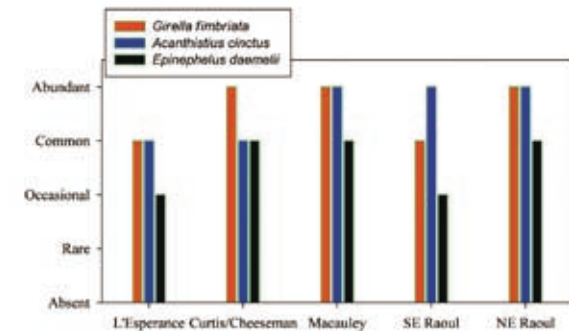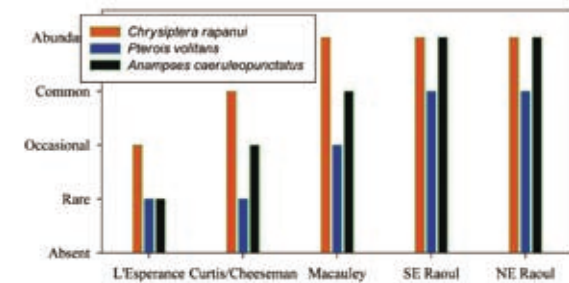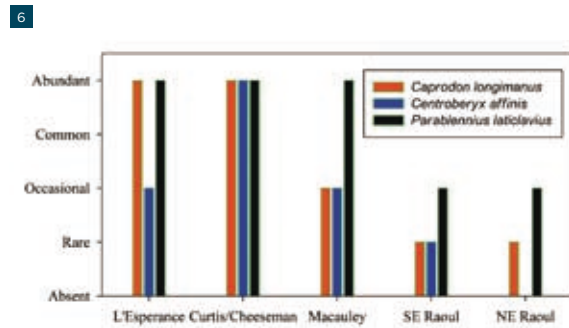
FIGURE 6. Latitudinal trends in abundance of selected Kermadecs coastal fishes. Top: abundance decreasing northwards; middle: abundance increasing northwards; bottom: no abundance trend. Raoul Island at the northern end of the chain is represented by two sites. Data plotted from Francis *et al.*, (1987).

Subtidal biodiversity and community composition of the Kermadec Islands

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The focus of this paper is on shallow-water systems less than 30 m in depth. The paper reviews published work relating to (1) Macroinvertebrate diversity, (2) community composition, (3) water column properties, (4) genetic connectivity, and (5) phylogeography and evolutionary affinities. I conclude by highlighting some interesting and pressing research questions for shallow subtidal macrobenthic communities at the Kermadec Islands.

Only three things are important in real estate – location, location, location – and obviously the Kermadec Island group has all three. Located between 29°S and 31°S, the islands are New Zealand's only subtropical territory. The islands form the south-west corner of the Polynesian marine triangle (the other corners being the Hawaiian Islands in the north and Rapa Nui or Easter Island to the east). The islands are of volcanic origin and are relatively young – 0.6 to 1.4 million years. Perhaps the most interesting aspect though, at least from the perspective of a marine biologist, is that the marine environment at the Kermadecs is as close to "pristine" as it is possible to find anywhere in the world.

Isolation is a key driver explaining the macrobenthic biodiversity of the Kermadecs. The isolation of the islands means that new recruits have to travel a long distance to get to the islands. This geographic isolation often gives rises to genetic isolation, which results in the formation of new species (allopatric speciation), which, in turn, generates the high levels of endemism that we see in some groups. For endemic species, populations are reliant of self-recruitment. The Kermadec Islands therefore provide an opportunity to examine some fundamental components of evolutionary biology and phylogeography – namely, colonisation, speciation and self-recruitment.

MACROINVERTEBRATE DIVERSITY

The focus here is on three groups of animals – the corals and associated *Symbiodinium*, the molluscs and the echinoderms.

Corals – The Kermadec Islands are a high-latitude "marginal" site at the limit of distribution of most coral species. As a consequence, there is no reef formation and species diversity is low. Coral diversity shows affinities with subtropical SW Pacific islands, not with New Zealand. There is only one recorded endemic species – *Coenocyathus brooki*. In the northern Kermadec Islands, there are 17 hermatypic (stony) and seven ahermatypic (soft) species, whereas in the southern islands, there are two hermatypes and two ahermatypes. Most species exist in <30 m of water and are predominantly encrusting growth forms (e.g., *Hydnophora, Goniastrea, Montastrea*) or large flat colonies (e.g., *Turbinaria* – Figure 1). There is only one branching species (*Pocillopora damicornis*). Many species are restricted to caves and overhangs (e.g., *Dendrophyllia*). According to Brook (1999), cover is highest (20–40%) around Raoul Island at 1–6 m depth, although other work reports values of <10% in most places (Wicks *et al*., 2010a). Further south, cover is low (<1%). Historically, there has been high species turnover (extinctions, new recruitments, speciation).

Stony corals exist in a mutualistic relationship with single-celled green microalgae called zooxanthellae, most of which are members of the genus *Symbiodinium*. At the Kermadec

Islands, five *Symbiodinium* clades have been identified from five coral species – *Turbinaria frondens, Hydnophora pilosa, Monastrea curta, Sinularia* sp*.* and *Capnella* sp*.* (Wicks *et al*., 2010b). The novel *Symbiodinium* clades have been placed in Clade C, which is considered to be composed of generalists. Together, the high latitude zooxanthellae at the Kermadec Islands and Lord Howe Island form a separate biogeographic province. In a world of global warming and increasing ocean acidification, these findings have implications for coral health and ecosystem resilience.

Molluscs – Brook (1998) reports 358 species of molluscs, including nine polyplacophorans, 45 bivalves, 302 gastropods and two cephalopods. Of these, 68 species (~19%) are endemic. The fauna is dominated by tropical western and central Pacific Ocean species and is depauperate at the species/genus level. It is, for example, less diverse than the molluscan faunas of Lord Howe, Norfolk and Pitcairn Islands. The fauna reflects the isolation, subtropical location and limited habitat types of the Kermadec Islands, and there is evidence of faunal turnover.

Echinoderms – There are five very abundant urchins at the Kermadec Islands (Figure 2), but no kina as found on the New Zealand mainland. Dive surveys (Figure 3) reveal lots of adults but no juveniles, raising questions about cryptic recruits. Urchins occur at high biomass and high densities, and their grazing activities must influence community composition. The vertical distributions of urchins at the Kermadec Islands are very similar to those in north-east New Zealand.

Perhaps the best known echinoderm at the Kermadec Islands is the crown of thorns starfish,

Acanthaster planci. It is infrequent at the northern-most islands (Raoul group) and absent from the southern island groups. It is a coral-feeding starfish and may play an important role in determining the abundance and distributions of corals.

MACROBENTHIC COMMUNITY STRUCTURE

A limited number of studies have been carried out to quantify the patterns of subtidal zonation within and among the island groups (Schiel *et al*., 1986; Cole *et al*., 1992; Gardner *et al*., 2006; Wicks *et al*., 2010a). These studies report different patterns of community structure, most probably because each survey is only a brief snapshot of a small area, rather than because each site is different from every other site. What does emerge from these studies is that giant limpets are abundant at low tide and into the shallow subtidal, urchins are abundant at 0–10 m depth, hard corals are abundant 0–5 m and also 15–20 m (variable response among studies) and soft corals are abundant at 10–20 m. Typically, macroalgal cover is greater than coral cover but by how much varies dramatically among studies, and bare substrate (coral rubble/sand) increases with depth. A high degree of variability in community structure is reported among (neighbouring) sites both within individual studies and between studies.

WATER COLUMN PROPERTIES

The most striking feature of the water column at the Kermadec Islands is how very clear the water is (Figure 3). This arises because particle concentrations are very low (range 0.10–12.02 FTU; mean 2 FTU) and because the chlorophyll concentration is also very low (range 0–5 µg.l^{-1}; mean 0.25 µg.l^{-1}) (Gardner *et al*., 2006). Nonetheless, there are well developed and

FIGURE 1. Plate-forming coral (*Turbinaria*) at Meyer Island, with the yellow five-armed starfish (unknown species) and the brown urchin (*Heliocidaris tuberculata*).

FIGURE 2. Blue/black urchin (*Centrostephanus rodgersii*) at Raoul Island.
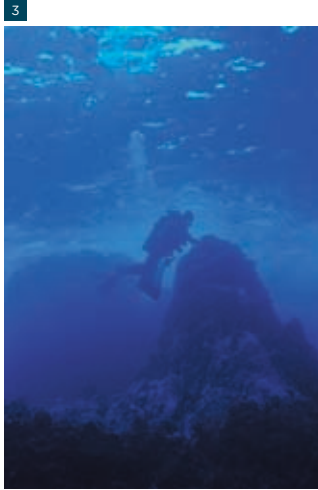
abundant suspension feeding species (e.g.,
molluscs, echinoderms, crustaceans) that
make their living by feeding on the suspended
particulates that do exist. So the big questions
here are (1) what are suspension feeding
organisms feeding on? and (2) where are the
particulates coming from? We don't know.

GENETIC CONNECTIVITY

There are a number of fundamental questions
in biology about patterns and processes of
recruitment to small, isolated islands. How do
the larvae of species reach the islands? For
endemic species, how do the larvae recruit back
to the islands (i.e., self-recruitment)? Fred Brook
(1999) suggested that many "corals are stable,
self-maintaining populations", and it is self-
evident that all Kermadec-endemic species are
self-maintaining and that their populations must
persist via self-recruitment. Does the small spatial
scale of the islands (often less than 1,000 m
between islands within an island group) imply
an absence of genetic structure? Recent work
on two endemic limpet species has answered
this question (Wood and Gardner, 2007). The
giant limpet *Scutellastra kermadecensis* was
sampled at nine northern sites around Raoul
Island and at Macauley and Curtis Islands,
whereas *Siphonaria raoulensis* was sampled
from six northern sites around Raoul Island. For
both species, significant genetic differentiation
was reported, with limited connectivity among
populations separated by <1 km. For *S.
kermadecensis,* there was clear evidence of a
north-south split, with populations on the south
coast of Raoul Island showing greatest affinity
with the southern populations on Macauley and
Curtis Islands. *S. raoulensis* showed no evidence
of a north-south split (this may be because

limited sampling precludes a meaningful test),
but it did show evidence of genetic structure.
The main conclusion is that, for both species,
most larvae do not disperse far, possibly
because of local hydrographic features that
act as barriers to gene flow.

PHYLOGEOGRAPHY AND EVOLUTIONARY AFFINITIES

Research across a number of animal groups
indicates that the macrobenthic communities
at the Kermadec Islands are composed of three
main groups: (1) tropical, with influences from
Tonga, New Caledonia, Fiji and the Minerva
Reefs, and possibly also the Great Barrier Reef
in Australia; (2) subtropical, with influences
from Norfolk Island, Lord Howe Island and
north-eastern Australia; and (3) temperate,
with greatest affinity to mainland north-east
New Zealand, but some affinity to eastern
Australia as well.

RESEARCH PRIORITIES FOR BIODIVERSITY

- A full biodiversity inventory – intertidal and
  subtidal – all habitats.

- Is Meyer Island (just off Raoul Island) a
  biodiversity hotspot?

- Endemism and evolutionary affiliations
  of the biota.

RESEARCH PRIORITIES FOR ECOLOGY

- Extent of macrobenthic community spatial
  variability:
  - among the three island groups
  - within the three island groups.

- Extent of macrobenthic community temporal
  variability – time-series data for multiple sites
  across all island groups.

- Water column research – particulates,
chlorophyll, dissolved organic matter:
time-series data for multiple sites across
all island groups.

RESEARCH PRIORITIES FOR GENETICS

- Genetic variability/stability:
  - among the three island groups
  - within the three island groups.

- Where do new recruits come from?

- Life-history adaptations to maximise
larval retention.

- Hydrodynamic influences on gene flow.

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Seabirds of the Kermadec Islands

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This will provide an overview of the diversity of the Kermadec seabird fauna including information about the distribution and ecology of each of the 14 species that breed in the group. An outline of their annual cycle, breeding seasons and migration behaviour will be covered in the talk. Three taxa are endemic to the group. These include Kermadec storm petrel (*Pelagodroma albiclunis*), Kermadec little shearwater (*Puffinus assimilis kermadecensis*) and white-naped petrel (*Pterodroma cervicalis*), although a few pairs of the latter have been found breeding on Philip Island, off Norfolk Island.

The seabirds spread their breeding activities over four main breeding periods. Six species including Tasman booby (*Sula dactylatra tasmani*), sooty tern (*Onychoprion fuscatus serratus*), grey noddy (*Procelsterna cerulea albivitta*), brown noddy (*Anous stolidus pileatus*), black noddy (*Anous minutus minutus*) and white tern (*Gygis alba candida*) are mainly spring/summer breeders. Four species including wedge-tailed shearwater (*Puffinus pacificus pacificus*), white-naped petrel, black-winged petrel (*Pterodroma nigripennis*) and red-tailed tropicbird (*Phaethon rubricauda*) are mainly summer/autumn breeders. White-bellied storm petrels (*Fregetta grallaria grallaria*) nest in autumn/winter in rock crevices and on cliff ledges. Kermadec storm petrels nest in winter/spring, possibly to avoid burrow competition with the abundant summer-nesting species. Kermadec little shearwaters also nest in winter/spring and can use the same burrows as the summer-breeding black-winged petrels. Kermadec petrels (*Pterodroma neglecta neglecta*) are surface nesting petrels with two breeding peaks, one in summer and the other in autumn/winter.

Four of the Kermadec seabird species migrate to the north Pacific Ocean after the breeding season (wedge-tailed shearwater, black-winged petrel, white-naped petrel and Kermadec petrel). The remaining species are either dispersive in the South Pacific after breeding or are relatively sedentary. The movements of all species are poorly known and need further study.

The seabirds are widely distributed in the group but the major breeding concentrations are on the southern islands, especially on Macauley Island, which has the most abundant seabird population in the New Zealand region. Macauley is dominated by black-winged petrels with around 2–3 million pairs present, the largest *Pterodroma* petrel colony in the world. Large numbers of this species also nest on Curtis Island. Kermadec little shearwaters are the next most abundant species with a huge colony of 100,000 pairs on Curtis Island, probably the largest colony of this species in the world. Tens of thousands of wedge-tailed shearwaters, grey noddies and sooty terns also nest at the Kermadec Islands. The Kermadec petrel population is the largest outside of the Pitcairn group. The remaining species have smaller populations from tens to hundreds of pairs. The world population of Kermadec storm petrels nest on top of Haszard Islet (off Macauley), but the species might also nest on the Meyer Islands. Apparently, white terns were not seen for nearly 10 years, so it is possible that they have recolonised after feral pests were removed from Raoul Island.

The major threats to Kermadec seabirds have been rodents, feral cats and goats. The former pest species were removed by poison drops in the 2000s. Goats were taken off Macauley in 1970 and Raoul by 1985. Vegetation changes have

The seabirds are widely distributed in the group but the major breeding concentrations are on the southern islands, especially on Macauley Island, which has the most abundant seabird population in the New Zealand region.

been significant on Macauley. These changes initially improved the habitats for seabirds after 2 centuries of goat trampling, but in the past decade, the succession of tall dense fern cover may be impacting on both the burrowing seabirds and the terns and boobies. Volcanism is a constant threat, and the 2006 eruption on Raoul Island shows that volcanic ash and possibly fires triggered during eruptions could have major impacts on seabirds in the future. The most devastating impact for seabirds, however, was the introduction of feral cats and Norway rats to Raoul Island in the 1800s and early 1900s. This resulted in the near loss of all breeding species during the 20th century including significant populations of the summer-nesting group of Kermadec petrels and the extirpation of white-naped petrels from Raoul Island.

The removal of rats and cats has resulted in early re-establishment of black-winged petrel and a few pairs of wedge-tailed shearwaters. Over time, more species should begin nesting on Raoul Island. Acoustic attraction systems have been installed on Raoul Island to encourage white-naped petrels to recolonise the island. Translocation of chicks may also be required in the future. Acoustic attraction could also be useful on Macauley Island to entice the smaller petrels back onto the main plateau. The tall fern succession on Macauley is potentially making it difficult for burrowing petrels to access their burrows and to take off in flight. Some native shrub species are spreading on the island but active management for a period to get seabirds over the successional hump should be considered. Planting of native shrub species or control of the fern (cutting or spraying) are options to be considered.

The Kermadec group retains some of the most pristine islands in the Pacific Ocean. The Meyers, Haszard, Curtis, Cheeseman and L'Esperance Rock have never had introduced mammalian pests and are relatively unaffected by introduced plants (compared to Raoul Island). These islands provide some of the best remaining examples of seabird-dominated ecosystems on oceanic islands in the Pacific Ocean.

More work is needed on reassessing population sizes of seabirds, understanding population trends, study of breeding cycles and assessing the taxonomy of some of the seabird species. Assessments of seabird movements, migrations and their diets are needed for most of the Kermadec seabird species, but the single most important management action is to maintain mammalian pest-free status in the group and to carry out regular checking of the islands to look for evidence of pest incursions.

IN CONCLUSION

- The Kermadec Islands are an internationally important breeding area for seabirds, with the largest *Pterodroma* petrel colony in the world.
- The Kermadec Islands have three endemic seabird species/subspecies and key breeding populations of at least three other species.
- The Kermadec Islands have five nationally threatened seabird species.
- The Kermadec Islands have some of the most pristine remaining examples of seabird-dominated volcanic island ecosystems in the world. ∎

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FOOTPRINTS

DEEP
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The Kermadec Islands and ancient Polynesian long-distance ocean voyaging

Peter Adds

Until the discovery of Mayor Island (Bay of Plenty) obsidian in an archaeological excavation at Low Flat on Raoul Island, theories about ancient Maori long-distance two-way voyaging in the Pacific were essentially limited to the Chatham Islands. The Chatham and Kermadec Islands are located a similar distance from Aotearoa, but there are known to be Maori traditions of at least limited contact between Moriori and Maori from the South Island. There is a range of other evidence from the Chathams that supports the possibility of contact as well. This evidence is missing for the Kermadecs.

The discovery of the obsidian on the Kermadec Islands opens up the possibility of return voyaging to tropical east Polynesia from New Zealand. There is also an, as yet, unsubstantiated claim for obsidian sourced to the Kermadecs being found in the South Island. If substantiated, this would strengthen a claim for regular two-way voyaging. The Kermadec Islands are located on a much more direct track to tropical east Polynesia than the Chatham Islands are. They are therefore more suitably located to serve as a potential stopover on such voyaging. However, the evidence for this is far from conclusive. The presence of the Mayor Island obsidian in the Kermadecs could be explained just as easily by one boat from New Zealand arriving in the Kermadecs and returning to Aotearoa-New Zealand in a single event. Less likely, given the amount of obsidian that was found, is the possibility of regular two-way voyaging events between the Kermadecs and Aotearoa-New Zealand.

There is now substantial literature on ancient Pacific voyaging. In respect of Aotearoa, the general consensus has been that it is highly unlikely that regular, or indeed any, two-way voyaging between Aotearoa and the tropical east Polynesian homeland ever occurred. The conventional scientific view is that, once the first settlers from east Polynesia arrived in Aotearoa, they effectively cut any link with their homelands back in the tropical east, despite having the ability to easily return if they needed to. This is thought primarily to have been a consequence of the huge distances between the two places but also because, having arrived here, there was little need to travel elsewhere. Aotearoa was fully self-contained in the sense that everything the new migrants needed to survive, and indeed thrive on, had either been brought with them or was available locally. Without the need or desire to travel, it would only have taken a generation or two to lose the specialist knowledge about how to make return voyages to their Polynesian homeland and how to build the necessary canoes to do it. However, the fact that people were apparently able to make voyages to the Chatham Islands suggests that voyages to the Kermadec Islands were within the capability of Maori too.

In the isolation of Aotearoa, and in a remarkably short timeframe, the east Polynesians that arrived transformed culturally in their new homeland into Maori. There is no evidence for a significant influx of other Polynesians arriving in Aotearoa after the transformation. A significant arrival would have produced a change in culture to the, by then, existing Maori culture that could be observed archaeologically or linguistically – especially if such an arrival had come from the geographically closer west Polynesia. No such evidence has ever been found. If regular two-way voyaging did occur, it must have been for

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Referring to these as "traditional rumours", Maori scholar Te Rangi Hiroa (Sir Peter Buck) discussed how both the Aotea and Kurahaupo canoes reportedly used the Kermadec Islands as a site to make repairs on their voyages to New Zealand.

a short period before the cultural transformation occurred. The arrival of a single canoe after transformation would not have been likely to produce any significant change. Any people that might have stayed would have been absorbed and assimilated into the dominant and more numerous Maori population and would not be traceable archaeologically or linguistically.

While there are no known Maori traditions of contact between the Kermadec Islands and Maori from Aotearoa, there are traditions that speak of the Kermadecs as a stopover on the voyage to New Zealand from the Hawaiki homeland. Referring to these as "traditional rumours", Maori scholar Te Rangi Hiroa (Sir Peter Buck) discussed how both the Aotea and Kurahaupo canoes reportedly used the Kermadec Islands as a site to make repairs on their voyages to New Zealand. In the case of the Kurahaupo, the damage was so bad that the crew were forced to transfer to the Aotea canoe. Hiroa's use of the term "rumour" to describe these traditions is indicative of the reliability that can be placed on them. The purpose of Polynesian origin traditions was not to document real historical fact in the way that a historian might do today. Their purpose was more to do with identity and ties to land, and in this context, precise details of events and locations were not critical to their intended purpose. However, the fact that such traditions exist suggests that at least knowledge of the Kermadecs amongst Maori was known.

If the presence of Mayor Island obsidian in the Kermadec Islands supports the possibility of return voyaging between east Polynesia and Aotearoa, it also adds support for a theory of multiple settlement of Aotearoa rather than a single settlement. It is possible for the Maori population of Aotearoa to be the product of one boat arriving from east Polynesia with sufficient numbers of people to successfully colonise the whole country. More likely, however, is that several boats arrived rather than one. Multiple settlement, however, relies on an initial discovery of Aotearoa and a return voyage to tropical east Polynesia. Computer simulations and experimental voyaging suggest that the possibility of drifting to Aotearoa is highly unlikely. A deliberate course in our direction is therefore necessary. A deliberate course to the south-west over several thousand kilometres from east Polynesia by one canoe to an unknown destination is therefore also highly unlikely. At least one return voyage after initial discovery is more likely. Once home, the discoverer could relay information to others about how to find their way back to Aotearoa. Recent studies of Maori mitochondrial DNA also support a theory for multiple settlement. ∎

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A brief history and prehistory of Raoul Island

Andy Dodd

The first people to discover and settle the Kermadecs were of Polynesian origin, but by the arrival of Europeans at the end of the 18th century, the islands had been deserted. On the balance of currently available evidence, it's likely that the first human arrival on Raoul Island was during the late 13th or early 14th centuries. Settlement appears to have been of relatively short duration but involved multiple visits, including people returning from New Zealand back into the subtropical Pacific.

That the islands had been first inhabited by Polynesians was apparent from at least as early as the 1880s when stone adzes were recovered during the clearing of the Farm Terrace. Consideration of the adzes within an archaeological typology would later conclude a Cook Islands origin from the 14th to 15th centuries, with one possible exception believed to have been of New Zealand origin (Duff, 1968).

The first archaeological investigations on Raoul Island were directed by Atholl Anderson in 1978 (Anderson, 1980). Two distinct cultural layers were noted at Low Flat, separated by pumice and ash deposits. A number of oven features contained the Kermadec giant limpet, sea urchin spines, several species of shearwater and petrel, as well as dog and rat, and a human tooth and an imitation whale tooth pendant were also recovered. An adze preform and a concentration of basalt flakes pointed to the manufacture of stone tools, and a likely source for raw material was noted at Denham Bay where a number of large basalt blades were encountered. Petrographic characterisation of obsidian recovered from the excavation was carried out in 1986, comparing the 11 samples from Raoul to 66 known sources across the Pacific, including

28 from New Zealand. Five were found to be most compatible with a Raoul Island source and six found to be most compatible with a Mayor Island (Bay of Plenty) source (Leach *et al.*, 1986).

In 1990, the Department of Conservation initiated the Kermadec Island Archaeological Project. This involved an extensive review of the literature and included excavations at Low Flat, the Farm Terrace and Coral Bay (Johnson, 1995). Additional radiocarbon dates were submitted, but age ranges from the upper and lower cultural layers were statistically indistinguishable. Johnson concluded that, while it was possible that the two layers represented independent settlements, he considered it more likely that the pumice event resulted in the burial and temporary abandonment of parts of the site which were then reoccupied soon after. Samples from the Farm Terrace and Coral Bay yielded radiocarbon dates similar to those from Low Flat. Four incomplete adzes brought the total number from Raoul to 18, and other finds included hammer stones, a drill point, coral abraders and an assemblage of over 500 basalt and obsidian flakes.

Like New Zealand, of the four commensal Polynesian animal introductions, only the Pacific rat, or kiore, and dog are known to have been present on Raoul. The study of kiore mtDNA across the Pacific, including samples from Raoul Island, has provided another avenue of enquiry into prehistory along with the archaeological evidence. Interestingly, the samples from Raoul Island demonstrated a greater genetic diversity than expected, suggesting multiple introductions and therefore multiple instances of human contact with the islands (Matisoo-Smith *et al.*, 1999). Botanical remnants associated with the

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*The first European sighting of Raoul Island occurred
in 1788 by Captain Sever of the convict transport
Lady Penrhyn while on route from Australia to Tahiti.*

Polynesian settlement most notably include the candlenut (*Aleurites moluccana)*, cabbage tree (*Cordyline fruticosa)* and taro *(Colocasia esculenta),* although neither sea-rafted natural dispersal for candelnut nor early 19th century introduction of taro or cabbage tree can be definitively ruled out (Johnson, 1995).

The first European sighting of Raoul Island occurred in 1788 by Captain Sever of the convict transport *Lady Penrhyn* while en route from Australia to Tahiti (Smyth, 1788, as cited by Johnson, 1991). Five years later, unaware of Sever's discovery, French explorer D'Entrecasteaux, in command of the *Recherche* and *Esperance,* was the next to sight Raoul. D'Entrecasteaux claimed discovery of Raoul. He named the island chain Kermadecs after the captain of the *Recherche*, and Raoul Island was named after the quartermaster. The name Sunday Island was bestowed in 1796 by Captain Raven of the *Britannia*, who, while aware of Sever's discovery of Macaulay and Curtis, was not aware of D'Entrecasteaux's visit (Collins, 1798, as cited by Johnson, 1991).

The first Europeans to land on Raoul were almost certainly whalers, although, to date, no written accounts are available prior to 1814. Whaling in the South Pacific commenced from 1790s, and at its height in the 1830s, up to 30 vessels might be seen in a single day in the vicinity of L'Esperance Rock. Ship-based whalers needed to call in at Raoul to get water and firewood for rendering down whales at sea. These vessels were predominantly of French and American nationality, and the waters around the Kermadec Islands were commonly known as the French Rock whaling grounds. It was during this period that goats and pigs were liberated on

Raoul and Macauley to establish a population that might provide a sustainable source of fresh meat for whalers (Johnson, 1991).

The first record of 19th century settlement on Raoul occurred in 1836 when Captain Rhodes of the whaler *Australian* visited and found James Reed living there with his family and a number of deserters from the whaler *Cheviot*. Reed established cultivations in Denham Bay and, on occasion, was able to supply provision to visiting ships. Other 19th century settlements included those of the Bakers, Halsteads, Cooks and Coverts. They tended to be marginal and of short duration, the majority lasting a few to a dozen years (Johnson, 1991).

The best known of the settler families, the Bells, arrived in Denham Bay in 1878. They lived fairly marginally in Denham Bay until about 1880, before moving to a site just below Fleetwood bluff at Low Flat. The Bells were an industrious family and, with the assistance of Niuean labourers, were eventually able to clear an area of bush and establish plantations of a wide variety of produce including taro, yams, kumara, beans, maize, oranges, lemons, limes, citrons, shaddocks, cherimoya, pawpaw, bananas, guavas, sugar cane and peanuts, as well as "ordinary vegetables" besides. They were also supplied Havana tobacco, tea, coffee, figs and white grapes courtesy of Governor George Grey, then living on Kawau Island (Morton, 1957).

In July 1886, Captain Clayton of HMS *Diamond* erected a flagstaff in Denham Bay with a proclamation of British sovereignty attached. A year later on 17 August 1887, the New Zealand Government annexed the Kermadecs. The island was subdivided to provide several grazing runs, which were offered for lease at public auction,

leaving Bell with only his settlement on the terraces and cultivations at Low Flat. The 1887 annexation was deemed illegal in 1893, but in 1894, the government only awarded Bell 275 acres with the right to rent the remainder. Bell sold his grant in 1899 but remained on the island until 1901. He returned twice to the island, settling in Denham Bay, but never met with the same success and eventually left for good in 1914 (Smith, 1887; Johnson, 1991).

The subsequently deserted island was used as a haven by the German commerce raider *Wolf* in 1917. While there repairing damage to his boilers, Neger used the seaplane *Wolfchen* to capture the cargo steamer *Wairuna* and the four-masted schooner *Winslow* (Hoyt, 1974). Later that same year, the Curtis Island castaway depot was raided by the German naval captain and escaped prisoner of war Count Felix Von Luckner. Von Luckner was intercepted at the Kermadecs by the armed steamer *Iris* and returned to New Zealand.

During the 1930s, remote islands were being developed for long-distance ocean air services. Raoul's topography and exposed coasts made it unsuitable for an air base, so it was decided to reserve the island only for meteorological and aeradio facilities, which were first established in 1937. In August 1939, an expedition left Auckland in the *Miena* to establish a more permanent meteorological facility. Landing facilities were constructed at Fishing Rock in 1939 and Boat Cove in 1940. The first buildings to be erected were the hostel, hospital and store and a series of six single accommodation huts were located to the east of the hostel in the location of the present day annex building. The new complex was largely completed by 1940, and a further

grant of funding allowed for the construction of the meteorological station office. At the same time, 100 acres of oranges were planted behind the hostel, intended to supply the New Zealand market. A 30 acre farm was established to the west of the station to provide the meteorological station staff with fresh produce.

From 1942 to 1945, a coastwatchers station was maintained on Raoul, no doubt to avoid a repeat of the losses sustained there in WWI. But despite this precaution, German commerce raiders *Orion* and *Komet* successfully used the southern end of the Kermadecs for a rendezvous after sinking the *Rangitane* in 1940 (Haigh, 1968).

In addition to the *Wairuna* and *Winslow*, a number of 20th century wrecks have been reported on the Kermadecs. The earliest are the barque *Malmen* (1902), the *Columbia River* (1921) and the schooner *Petrel* (1935) (Ingram, 2007). Wrecks for which specific locations are known include the *Picton* (1978) in Sunshine Cove, the yacht *Shiner* at Boat Cove, *Salano* near Hutchison Bluff and the Japanese trawler *Kinei Maru* (1986), which dominates the beach at Denham Bay. While not notable for their antiquity, they do have interesting stories that add colour to the island's recent history.

The unallocated titles on Raoul Island were gazetted as a flora and fauna reserve in 1934, with the last freehold portion taken under the Public Works Act for the meteorological station. In 1970, a weed control programme was under way, and by 1972, so was the New Zealand Forest Service's goat eradication programme. The huts at Denham Bay, Mahoe Ridge and Hutchison Bluff were built for the purpose of hunting less accessible parts of the island, and eradication was successfully concluded in 1985.

On 1 April 1978, the remainder of the Kermadec
Islands were reclassified as a nature reserve
under the Reserves Act 1977 and vested in the
Department of Lands and Survey. In April 1987,
management was transferred to the Department
of Conservation. In 1988, the Meteorological
Service agreed to the remaining 111 ha block
being managed by the Department of
Conservation, who would also undertake the
meteorological programme. In 1990, the
protection of the Kermadecs in their oceanic
environment was achieved by the establishment
of a marine reserve to the 12 nautical mile limit. ■

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BEYOND LIGHT

DEEP
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Deep-sea benthic sampling in the Kermadec region: Past, present, future

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ABSTRACT

Biological sampling of the Kermadec region began with the arrival of HMS *Challenger* in New Zealand waters in 1874. However, there were few voyages after that until the 1990s, when research started to focus on the line of arc volcanoes in the region. Surveys in the last decade have been dedicated largely to sampling seamount and trench habitats and describing hydrothermal vent communities. Collaborative international science programmes have developed, and several expeditions between 2004 and 2007 have used submersibles and remotely operated vehicles. The distribution and density of sampling overall is patchy, and most biological data cover a relatively small number of benthic taxa. Without a significant increase in future sampling effort, it will not be possible to describe with any confidence the assemblage composition, abundance and patterns of diversity of the deep-sea benthos in the region.

HISTORICAL EXPEDITIONS

Historical expeditions to the Kermadec Ridge and Trench began with HMS *Challenger* in 1874 when six trawls were carried out between 1,000 and 5,600 m. The region was then not sampled until *Galathea II* in 1952 used trawls and sledges to sample abyssal depths in the trench region, ranging from 2,600 to 8,200 m, and *Vityaz* in 1958 used trawls and grabs to sample even deeper into the trench at 8,900–9,900 m.

A second "phase" of more frequent sampling took place between 1960 and 1998 conducted by the New Zealand Oceanographic Institute (NZOI) and Ministry of Fisheries. There were several trips to the Kermadec region, but the biological data collection was often an add-on or small component of the scientific voyages,

and most biological samples were obtained from geological surveys. Opportunistic sampling of bycatch from fish surveys also occurred, mostly near the islands or south in the Bay of Plenty. Sampling gear type as a consequence was very mixed (grabs, corers, Agassiz trawls, rock dredge) and incomplete processing was common, which resulted in a taxonomic bias where only some faunal groups were examined.

CURRENT RESEARCH

From the late 1990s, biological sampling has increased as the geological studies focused on the southern Kermadec arc volcanoes began to highlight the occurrence of hydrothermal vent fauna. Several NIWA biological programmes since 1999 have been Foundation for Research, Science and Technology (FRST) funded, with support from the Ministry of Fisheries (e.g., Seamounts Project, ocean-Earth change) and have consisted of an integrated multidisciplinary approach (combining geology, oceanography, biology) using NIWA research vessels *Kaharoa* and *Tangaroa* (Figure 1). Multibeam mapping of the region has collected bathymetric data (Figure 2), video and still images have been obtained using towed cameras such as the NIWA deep-towed image system (DTIS), and direct sampling has used consistent gear types such as the epibenthic sled to collect biological samples (Figure 3).

Collaborative international programmes with NIWA and GNS Science have developed and have included Germany (1998, 2007), Canada (2007), United States (2005, 2008), United Kingdom (2009) and Japan (2004, 2006, 2009). This cooperation has enabled sophisticated sampling equipment to be brought to New Zealand. The use of
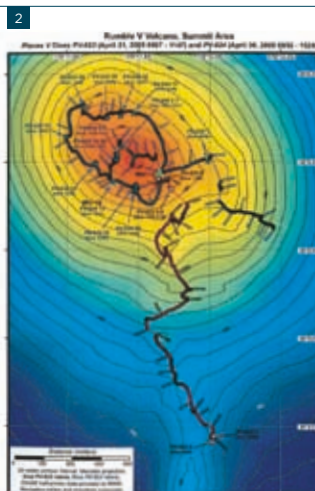
submersibles and remotely operated vehicles (ROVs) has enabled detailed sampling of hydrothermal vent geology and biology on active volcanoes from Clark to Monowai in the EEZ and further north into the Tongan section of the arc. An international Hadal Trench project to the Kermadec Trench on *Kaharoa* in 2010 used baited photographic landers. There has also been scientific collaboration with mining companies. Exploratory surveys with Neptune Minerals were carried out in 2005 and 2007 on Brothers and Rumble II West seamounts.

The most recent work in the region was carried out in May–June 2010 when *Tangaroa* was used to sample Brothers, Rumble II West and Rumble II East seamounts. The deep-sea mining of the Kermadec arc (KARMA) programme has as one of its aims to improve assessment of the likely seafloor impacts of minerals exploitation. The voyage in 2010 mapped the subsurface structure of known active and fossil hydrothermal/mineralization systems and provided baseline biological datasets that can be used to assess and mitigate the potential environmental impacts of future seafloor mining.

FISHERIES SURVEYS

Deep-sea trawl surveys to the region have been carried out since 1994 on several commercial trawlers engaged in orange roughy fishing. Research staff or scientific observers on board these vessels collected fish and some invertebrate data from a number of seamounts in the outer Bay of Plenty and southern section of the Kermadec region from Mercury to Nukuhou Knolls.

BIOLOGICAL DATA SUMMARY

The geographic extent of faunal records available for the Kermadec region includes the area from 25° to 38°S and 176°E to 175°W (Figure 4). To place the Kermadecs in a regional context, station data are shown for both the Kermadec Ridge as well as the non-Kermadec Ridge localities. These 1,300 benthic stations have produced 6,500 records of invertebrate taxa (these are "lots", not species). The invertebrate records are held in the NIWA Invertebrate Collection (NIC). All fish specimens and data are lodged in the National Fish Collection at Te Papa.

FUTURE RESEARCH

Science requirements

Many parts of the Kermadec region remain unsampled or are in an "exploration phase". Research has concentrated on the arc volcanoes/seamounts but needs to improve description of biodiversity of the Kermadec Ridge itself, of the adjacent Colville Ridge, as well as the Havre Trough, Kermadec Trench, Louisville Ridge and the deep abyssal plains. Only then can biodiversity of the Kermadec region be both fully described and evaluated against the wider regional fauna. Few of these other areas have been sampled intensively, and even on the arc seamounts, the megafauna is not completely known, let alone the infauna or microfauna. Even when relatively dense sampling is carried out (e.g., more than 15 sled tows), the number of species caught continues to increase (Figure 5), which makes estimates of "rarity" and endemism very difficult. A wider range of gear types is needed to describe the biodiversity.

More emphasis is needed to examine community structure (not just composition) and processes, connectivity issues (the Kermadec region is well suited for examining "stepping stone" hypotheses), and studies of the factors driving or influencing community composition and

FIGURE 1. NIWA research vessel *Tangaroa.*

FIGURE 2. Multibeam data and sampling track on Rumble V seamount.
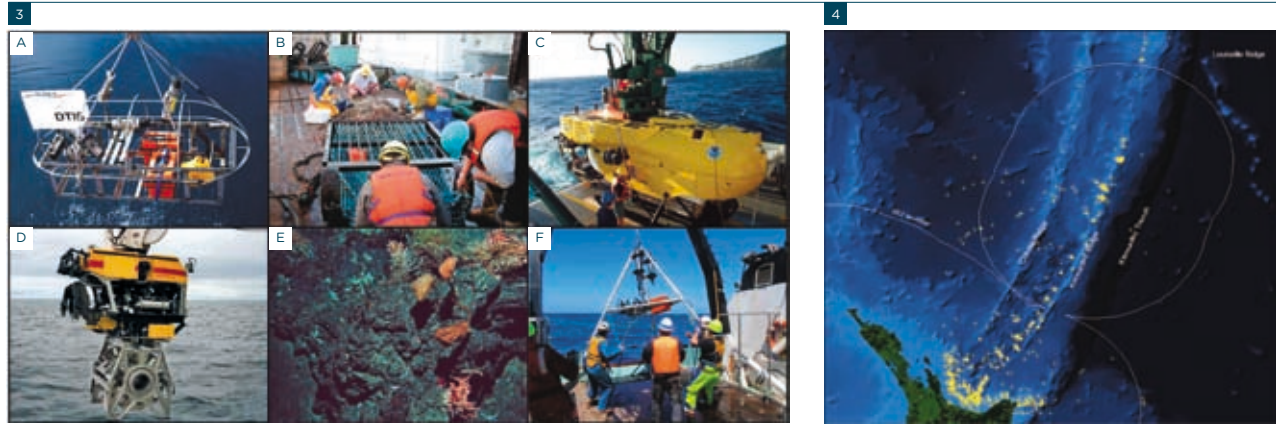
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THE **KERMADECS**

FIGURE 3. Sampling gear: (A) NIWA
towed camera system DTIS;
(B) epibenthic sled; (C) submersible;
D) ROV; (E) in situ image of benthos
on Kermadec Ridge; and (F)
baited lander.

FIGURE 4. Sampling sites in the
Kermadec region and adjacent areas.

FIGURE 5. Species accumulation curve
comparing seamount sample data.

abundance are required. By necessity, this requires multidisciplinary studies. The Kermadec region is a continuum (not a discrete crossroads), and as such, linking multiple habitat types such, as seamounts-ridges-vents-seeps-slope-deep seafloor is an important component of the science.
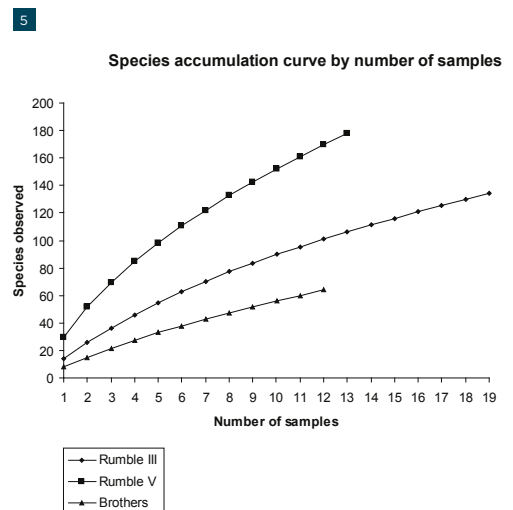
FUTURE RESEARCH SURVEYS

In 2011, some of these science objectives will be addressed. A planned Oceans 2020 survey on *Tangaroa*, supported by LINZ and Ministry of Fisheries, will take place where GNS-NIWA and Woods Hole Oceanographic Institution (USA) will survey three seamounts (Clark, Rumble II West, Healy) and study geophysics and seafloor biology. Equipment to be used includes an autonomous underwater vehicle (AUV) with multiple geophysical and chemical sensors and a towed camera system to image the seafloor benthos.

In 2011 and 2012, the UK-Japan-NIWA Hadal programme will continue research in the Kermadec Trench using *Kaharoa.* Lander deployments will be made in the trench, and sled and beam trawl sampling may be carried out. In 2011, an international RENEWZ hydrothermal vent programme may also take place. In 2012, there will be a NIWA Deep-Sea Communities voyage to the southern end of the Kermadec Ridge, during which biological sampling of seamounts-canyon-slope and hydrothermal vent habitat will take place. It is anticipated minerals exploration surveys may resume in the area and that New Zealand scientists will be part of these to provide biological support to assess and mitigate the potential environmental impacts of seafloor mining.

Species accumulation curve by number of samples

Invertebrate communities associated with seamounts on the Kermadec volcanic arc

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ABSTRACT

The seamounts of the Kermadec region have been the focus of a number of scientific expeditions in recent years. Observations on substrate types and associated biological communities have been made using ROVs, submersibles and towed camera systems, as well as direct samples from epibenthic sleds. Analysis of NIWA-held datasets was carried out to describe seamount biodiversity (excluding hydrothermal vent fauna). Faunal assemblage composition differs among seamounts, and the differences are influenced by environmental characteristics such as substrate type and depth. Results of a recent expedition to the region are also given. These describe the diversity and distribution of deep-sea corals, including stony corals, black corals and gorgonian corals, on three seamounts.

INTRODUCTION

Seamounts are prominent features of New Zealand's underwater topography (Figure 1), with over 1,000 recorded from both within the exclusive economic zone (EEZ) and adjacent high seas region. Several of the 731 seamounts within our EEZ are extremely large features and match the size of Mount Taranaki and Mount Ruapehu. Seamounts are often sites of high productivity and the focus of important commercial fisheries. High levels of biodiversity, endemism and new species records are often reported. However, they can also comprise fragile habitat susceptible to disturbance from fishing and mining.

The Kermadec region contains over 30 seamounts comprising basaltic-andesitic stratovolcanoes and silicic caldera complexes. Biological sampling in recent years has focused on documenting the biodiversity of seamounts and associated hydrothermal vents and how this varies with substrate composition and stability, which are potentially important factors driving species composition on seamounts.

This paper describes the diversity of the non-vent fauna on a number of seamounts in the Kermadec region, with a focus on Cnidaria, primarily corals. We discuss the variability of the deep-sea invertebrate fauna, examining differences between seamounts and regions.

CORALS

The New Zealand deep-sea region has a well studied, diverse cold-water coral fauna. The corals are widespread and abundant but also vulnerable to human impacts (e.g., Clark, 2010). The list of protected corals has now been revised (Department of Conservation Wildlife Act 2010), and along with the previously protected black corals (all species in the order Antipatharia) and the red hydrocoral *Errina* sp., a number of coral groups are now protected: gorgonian corals – all species in the order Gorgonacea; stony corals – all species in the order Scleractinia; hydrozoa (hydra-like animals) hydrocorals – all species in the family Stylasteridae.

In the Kermadec region, there is the unique situation of there being both are both warm-water and cold-water corals present. The warm-water (hermatypic) zooxanthellate stony corals (with symbiotic microalgae) are at or near their southernmost limit at shallow depths around the islands (Brook, 1999). Of the 17 hermatypic species including genera such as *Pocillopora* and *Tubinaria*, all but one are found on the Australian Great Barrier Reef, but none is reef-forming at the Kermadec Islands. Ahermatypic

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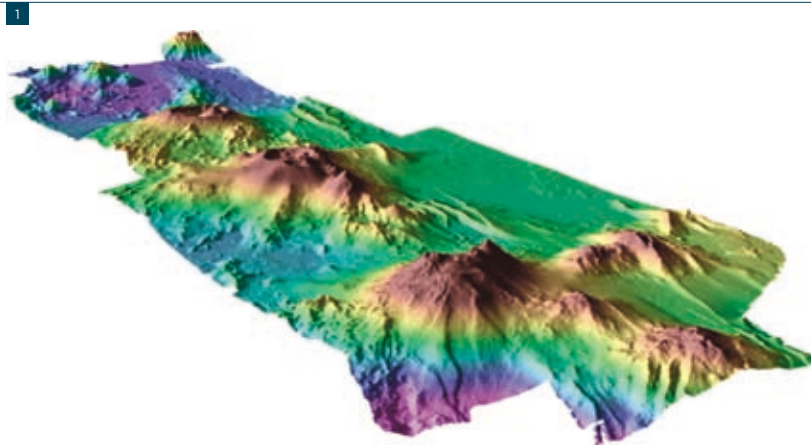d.tracey@niwa.co.nz

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FIGURE 1. Seamount bathymetry.

azooxanthellate corals such as black, gorgonian, scleractinian and stylasterid corals occur in deeper waters along the ridge.

Over 1,400 deep-sea coral specimens have been directly sampled or identified from video and still photographs on Kermadec seamounts. Twenty-one genera of black corals have been identified from the sampling, including genera *Leiopathes* and *Bathypathes* (Figure 2A). The charismatic bubblegum octocoral species (Figure 2B) *Paragorgia arborea, P. kaupeka, P. maunga* and *P. whero* are also present. This is a group that can produce massive branching colonies. Many other gorgonians are present, including bamboo corals, the precious coral *Corallium* and the golden corals *Metallogorgia* (Figure 2C) and *Chrysogorgia*. On some seamounts, scleractinian cup corals and the matrix-forming stony corals (Figure 3) are well represented and include the northern species *Oculina virgosa*, endemic to New Zealand. Some corals have a northern distribution, found both on the Kermadec seamounts and also in adjacent waters; others are found in abundance throughout the New Zealand region on and off seamount features.

OTHER FAUNAL GROUPS

Sponges (hexactinellid glass sponges and Demospongiae) are another important megafauna group in the region. Note the brittle stars associated with the glass sponges in Figure 2D. Common, too, are echinoderms such as the deep-sea urchin *Dermichinus horridus (*Figure 2E*)* and a recently found deep-sea echinoid with a northern distribution, *Aspidodiadema* sp. Ophiuroids (brittle stars), polychaete marine worms and Chirostylidae (squat lobsters)

(Figure 2F) can be abundant and associated with black corals and gorgonian corals.

SEAMOUNT DIFFERENCES

In 2002, benthic invertebrate data were collected from a voyage on the NIWA research vessel *Tangaroa* to several seamounts: Giggenbach, Macauley, Havre, Haungaroa, Ngatoroirangi, Sonne, GI4 and GI9. Data were examined using non-metric multidimensional scaling ordination plots (NMDS) to investigate differences between and within the seamounts. Results from the direct sampling using the epibenthic sled (over 400 samples) showed no real differences in the faunal composition between the seamounts. However, using the camera stills data, there were some between-seamount differences in community composition for the 18 main taxonomic groups (Beaumont *et al.*, 2009).

Seamount biodiversity in the Kermadec region was further studied on a *Tangaroa* voyage in 2004 that sampled several Bay of Plenty seamounts in the southern part of the arc (Figure 4). Whakatane, Otara, Nukuhou, Tuatoru, Rungapapa, Mahina and Tumokemoke were sampled and species richness investigated. Results from epibenthic sled sampling (over 500 samples) showed differences in the estimated number of species for each of the seven seamounts (Rowden and Clark., in press). Mahina and Nukuhou had the highest estimated number of species and Tumokemoke, with the same sampling effort, the least number of species.

To examine faunal variation, seamount data from these trips were compared with data collected from seamount regions throughout New Zealand. Preliminary results from multivariate analyses showed a statistically
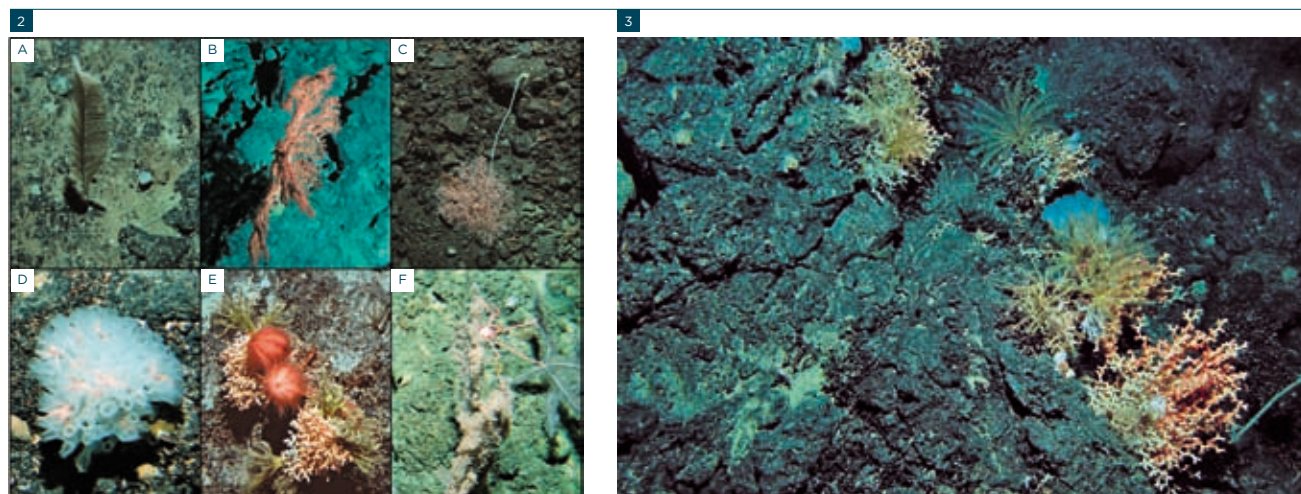
significant difference between assemblages on different seamounts, but patterns differed by phylum. Some clustering by region was seen for sponges, but polychaete worms showed more spread. The seamount benthic assemblages showed considerable variation, and overall, there was no "location effect" distinguishing the Kermadec seamounts from other groups in New Zealand.

CURRENT RESEARCH

In 2010, a *Tangaroa* (KARMA) voyage surveyed Brothers, Rumble II West and Rumble II East seamounts in the southern Kermadec region using an epibenthic sled and DTIS towed camera system. Direct sampling produced 2,978 invertebrate and fish specimens comprising 121 taxa from 12 phyla. A total of 8,097 camera stills were collected (Clark, 2010). The sampling effort during KARMA was at a much higher level than for previous surveys and will enable more robust between-, and within-, seamount comparisons to be made. The benthic fauna data from the KARMA voyage are yet to be analysed, but preliminary observations showed that, at Rumble II West and Rumble II East, live corals (e.g., the scleractinian *Solenosmilia variabilis* and gorgonian corals such as Isididae and Primnoidae) were present along the outer rim of the caldera and cone where they were exposed to potentially higher current flow. This dynamic environment would bring more food and result in less sedimentation. In contrast, on Brothers seamount, there were no stony corals observed, which may be due to the greater depth of this seamount and/or the chemistry of the seamount, which has extensive hydrothermal activity. Exposed hard substrates showed sparse growth of other coral, e.g., golden corals

(*Metallogorgia, Iridogorgia),* sea whip *Radicipes*, black corals (*Bathypathes* and *Paranthipathes*) and stylasterid hydrocorals. Glass sponges were also present.

FUTURE WORK

Further species identification and data analyses from the DTIS transects from the KARMA voyage will enable a greater understanding of the benthic biodiversity of invertebrate communities associated with seamounts. Nevertheless, sampling has not been sufficient to fully describe community composition, and more biological surveys are required to improve description of the biodiversity of deep-water habitats both along the arc and elsewhere in the vicinity of the Kermadec Ridge. These surveys need to employ systematic sampling strategies and consistent gear that enable robust comparisons of sites both within and between seamounts and between habitats (such as slope and ridge peaks).

ACKNOWLEDGEMENTS

FIGURE 2. (A) Black coral, (B) bubblegum coral, (C) golden coral, (D) glass sponge with brittle stars, (E) *Dermichinus* urchin, (F) squat lobsters on black coral.

FIGURE 3. Branching stony corals (Scleractinia) in situ.

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FIGURE 4. Bay of Plenty seamount sites.

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Biological communities associated with areas of hydrothermal venting on the Kermadec volcanic arc

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WHAT ARE VENT COMMUNITIES?

In the deep sea, faunal communities associated with the venting of hydrothermal fluids at plate boundaries were first discovered in 1977 on the East Pacific Rise. How was it possible for such abundant life to exist at such an extreme environment, so remote and seemingly independent from life at the ocean's surface? Over the years, studies have revealed that large and obvious fauna such as clams and tubeworms rely upon a process known as chemosynthesis. Microbes are able to synthesise energy by metabolising elements, such as sulfides, contained within the hydrothermal fluids. In turn, these microbes provide, either directly or indirectly, the energy source for the larger fauna. Some of these microbes live as endo- or epi-symbionts with the larger fauna. Subsequently, other chemosynthetic-based ecosystems have been found to exist in the deep sea at cold seeps, whale and wood falls.

Typically, vent communities have low species diversity but are dominated by a few species that occur in high abundances. These include the aforementioned clams and tubeworms, as well as shrimp and mussels. At vent sites where the stability of the hydrothermal venting is short-lived, the dominant species may change over time as the environmental conditions at the vent change or they become succeeded by superior competitors. As well as species that are directly tied to the chemosynthetic processes (that is, species only found at vents or vent endemics), there are a number of species that may be considered "background" species but nonetheless form a close association with the hydrothermal vent site. These species are also considered to be part of the "vent community".

WHEN WERE VENT COMMUNITIES DISCOVERED IN THE NEW ZEALAND REGION?

Hydrothermal venting activity was first discovered in the shallow waters of the Bay of Plenty in the late 1960s and early 1970s. Acoustic records revealed the existence of bubble plumes emanating from the seafloor surface between White Island and Whale Island. The first direct biological observations of these shallow vent sites were made in 1987. The targeted collection of seafloor images and specimens from the vent communities of seamounts in deeper water further north along the Kermadec volcanic arc did not begin until 1998.

WHERE ARE THE VENT COMMUNITIES THAT WE KNOW OF?

As of 2010, geological and geochemical investigations have provided evidence that >20 volcanoes or seamounts along the Kermadec arc are, or are likely to be, sites of hydrothermal venting. Biological studies have confirmed the presence of vent communities on roughly half of these seamounts over the >1,000 km length of the Kermadec arc, from just off the beaches of the Bay of Plenty to beyond the edge of New Zealand's EEZ. Studies have revealed that many of the seamounts have multiple sites of venting including high-temperature "black smoker" chimneys, point-source venting at lower temperatures from rock fissures and diffuse venting through volcanic sands. The vent-associated communities occur at water depths as shallow as 10 m or less, to approximately 1,700 m.

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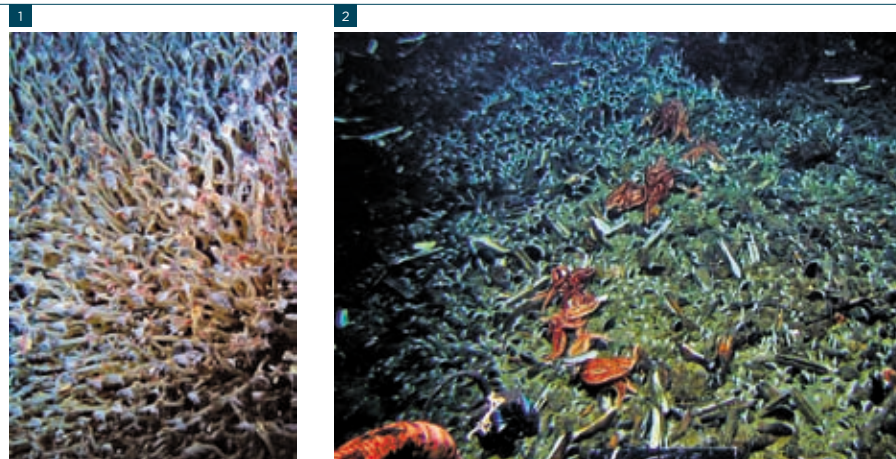a.rowden@niwa.co.nz

FIGURE 1. Dense stand of the stalked barnacle *(Vulcanolepis osheai).*

FIGURE 2. *Gigantidas gladius* mussel bed and seastar *Rumbleaster eructans.*

WHAT ARE THE "KEY" VENT SPECIES IN NZ?

The stalked barnacle *Vucanolepis osheai* (Figure 1) was the first vent-specific species to be described from New Zealand waters. Submersible and towed camera observations have revealed that this barnacle occurs in very high numbers and represents a large biomass at some sites. Japanese researchers have confirmed that this barnacle possesses epi-symbiotic bacteria.

A number of bathymodiolid mussel species have now been identified and described from Kermadec vent sites, including *Giganidas gladius* (Figure 2) the very distinctive blade-like mussel. All of the mussel species can occur in high numbers and form "beds" or "clumps" representing high biomass and a substrate for other species, and food for large numbers of predatory starfish (e.g., *Rumbleaster eructans*) and gastropods.

A number of shrimp species are found at the vents, including the typical vent alvinocarid shrimps – *Alvinocaris longirostris, Alvinocaris niwa* and *Alvinocaris alexander*. These shrimps can occur in small or large "swarms" (Figure 3) and are typical of some vent sites in the Kermadec region.

Sibloglinid or vestimentiferan tubeworms that are found to dominate some vents elsewhere in the world are not found in high abundance at Kermadec sites. They have been found in relatively small clumps – the most obvious species is *Lamellibranchia juni* (Figure 4), which, to date, has only been found at two seamounts on the arc.

There are quite a number of species found at vent sites that do not directly or wholly rely upon chemosynthesis for their nutrition. Foremost among these sorts of taxa at Kermadec vents are a number of species of crab and two fish species. The most conspicuous crab is the lithotid *Paralomis hirtella* and the most obvious fish is the eelpout *Pyrolycus moelleri* (Figure 4).

WHAT ARE THE MAIN FINDINGS TO DATE?

Community composition differs between sites on a seamount. For example, on Rumble V seamount, mussel beds occur at diffuse venting sites whilst communities are dominated by shrimp at point-venting sites. A similar pattern of at least two types of vent communities have been observed at sites on other seamounts in the region. There are also differences between the vent communities seen on the different seamounts along the Kermadec arc, for example, communities may be dominated by one type of mussel in the southern part of the arc and another towards the northern part.

Environmental conditions at different sites on a seamount can be quite different, for example, in terms of vent fluid temperature (which, in turn, will influence the chemical environment and the microbial community on which some of the fauna directly depend). These venting temperature differences are also partly related to depth, and other depth-related factors are also likely to influence the patterns observed (e.g., because of the general physiological tolerances of particular species). Some inter-seamount differences in community

composition will be related to the same sort of environmental changes observed between sites on a seamount, but larger-scale patterns could also relate to the dispersal abilities and wider environmental tolerances of particular species.

IS THE KERMADEC REGION SPECIAL?

A number of species are currently thought to be endemic to the Kermadec vents. These species include two species of bathymodiolid mussel, two species of alvinocarid shrimp, two species of stalked barnacle, one species of vestimentiferan and the eelpout fish. However, their endemic status is not assured, and genetic studies or further sampling may reveal that they occur elsewhere.

Many of these species have close relatives elsewhere, mostly in the western Pacific but also in the eastern Pacific and even the Atlantic. A number of the species at Kermadec vents are also found at other vent sites in the western Pacific, particularly further north in the Lau Basin (near Fiji) and off Japan. Despite the number of shared species, the occurrence of apparent endemics indicates that there is some dissimilarity between Kermadec vent communities and those found elsewhere. However, it should be noted that the level of sampling and sample description so far achieved for the Kermadec region makes any indications of dissimilarity or similarity preliminary.

WHAT FUTURE RESEARCH IS REQUIRED?

Clearly there is much work to do before we have a reasonable description of the composition and structure of vent communities in the Kermadec region, after which we may be able to make a robust estimate of the number of species at the Kermadec vents. Past the basic community descriptions, we like to try and understand what environmental drivers account for the observed differences in composition between sites and seamounts. Extending our genetic studies and understanding connectivity among populations would give us another means to understand the distinctness of any particular community. In the wider context of understanding the relationships between vent communities and those that surround them, it would be useful to determine the species overlap with non-vent communities as well as other chemosynthetic-based communities in the region, e.g., at seeps. In terms of global perspective, we'd like to know how similar or dissimilar Kermadec vent communities are to those elsewhere in the ocean, particular in the western Pacific. ■

FIGURE 3. Alvinocarid shrimp swarm in the vicinity of a point-source vent.

FIGURE 4. Community around a point-source vent, including mussels, shrimp, the vestimentiferan tubeworm *(Lamellibranchia juni)*, the lithotid crab *(Paralomis hirtella)* and the eelpout fish *(Pyrolycus moelleri)*. Images courtesy of JAMSTEC, GNS, NIWA and NOAA.

Bryozoan diversity and endemism along the Kermadec arc – a review

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The colonial marine invertebrates known as Bryozoa – sea mats, moss animals and lace corals – are well represented in New Zealand waters, currently comprising 953 species in 339 genera and 118 families in the exclusive economic zone, of which 331 (~35%) of the species are undescribed (Gordon et al., 2009). What proportion of this diversity is represented in the Kermadec region (trench, arc, backarc area), how many species are endemic and what can be said about the distribution of the phylum there?

A review was made of all literature pertaining to the region, in which the Bryozoa are among the best known phyla. The largest bryozoan class, Gymnolaemata, was monographed more than a quarter century ago (Gordon, 1984), and additional species have been reported since (Gordon, 1985, In press), but collecting began as early as the 1870s, when the historic oceanographic expedition of HMS *Challenger* reported three species of bryozoans from a single station, at 951 m depth, on 14 July 1874 (Busk, 1884; Hamilton, 1896). Subsequently, the HMDS *Galathea* deep-sea expedition sampled in the trench area in February 1952. Twelve bryozoan species were obtained from six stations, ranging in depth from 2,470 m to 8,300 m, the latter being the deepest station anywhere in the world yielding a bryozoan (Hayward, 1981). Later, in 1974, the then New Zealand Oceanographic Institute of the DSIR (Department of Scientific and Industrial Research) undertook a cruise along the Kermadec Ridge, sampling from the intertidal zone to more than 1,150 m. Some recent cruises in the region undertaken by NIWA included a unique sample of a bryozoan from a hot vent on a seamount. The total number of stations yielding bryozoans

from all these cruises is 70, and total bryozoan diversity in the Kermadec regions is currently 270 species in 162 genera and 72 families. These figures also include bryozoans pertaining to the class Stenolaemata (Gordon, pers. data), about which little has been formally published.

Bryozoan colonies come in a range of shapes and sizes (Figures 1-4). At the Kermadecs, the smallest are tiny spot and runner colonies that are just visible to the naked eye; the largest achieve colonies sizes of about 10–15 cm height or width. The commonest colonial morphology (74% of species) is that of two-dimensional sheet-like crusts on hard substrata. Some 13% are flexibly erect tufted or bushy forms, 3% are flexible and frondose, 3% are robust rigidly calcified forms, 3% are more delicate rigid-erect tree-like or lacy, fenestrate colonies, and fewer than 1% of species are free-living on sandy sediments or bore into shells (Gordon, 1987).

In terms of distribution, most species are rare. Of the 270 species, 104 occurred at a single locality, 97 occurred at two to five localities, 46 species occurred at six to ten localities, 21 species occurred at 11–15 localities, three species occurred at 16–20 localities and two species occurred at 21–30 localities. The commonest species were *Puellina scripta* (27 stations), *Crepidacantha crinispina* (24 stations), *Chaperia multispinosa* and *Hippothoa flagellum* (19 stations) and *Crepidacantha bracebridgei* (17 stations).

In terms of species diversity per individual station, 34 stations had 1–10 species (14 had one species only), 11 stations had 11–20 species, 12 stations had 21–30 species, four stations had 31–40 species, two stations had 41–50 species, three stations had 51–60 species, no stations
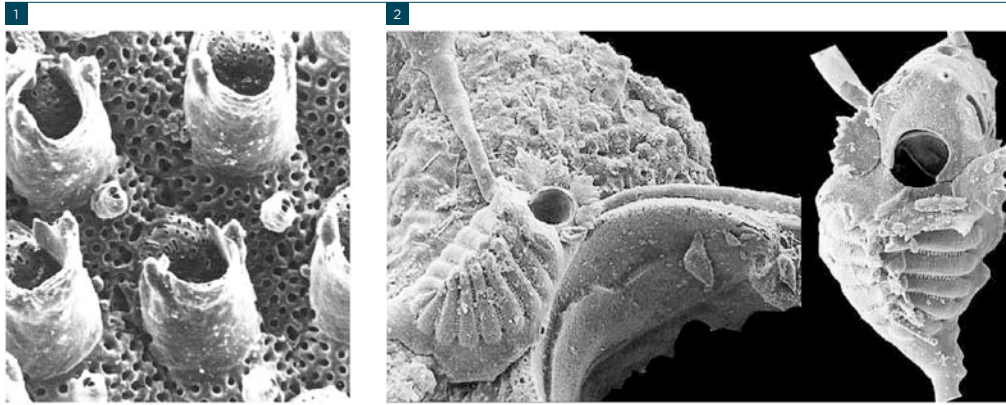
had 61–70 species, and one station had 71–80 species (73 species). The overall average (270 species, 70 stations) was 16 species per station. Geographically, however, where in the Kermadec region, and at what depths, were the most speciose stations located? Were they in shallow water, at shelf depths or in deep water? Where they at Raoul Island in coral biotopes, further south on the ridge or on submerged volcanoes in vent areas?

The highest-diversity bryozoan locality, NIWA station K837, at 110–125 m depth near Macauley Island, had 73 species; others, also at shelf depths, were in the vicinity of Curtis and Cheeseman Islands, e.g., NIWA stations K851, 104–106 m depth, with 58 species; K855, 115–125 m depth, with 55 species; and K856, 125–130 m depth, with 48 species. Further to the north, station K820, north-west of Raoul Island at 29o13' S, 95–122 m depth, had 55 species; south of Esperance Rock (33o02' S), station K795, 270–350 m depth, had 49 species.

The five most speciose bryozoan families in the Kermadec region were Calloporidae (18 species), Celleporidae (17 species), Candidae (16 species), Microporellidae (15 species) and Smittinidae (15 species).

The biogeographic relationships of the Kermadec fauna comprise the following components — widespread Pacific (30%), endemic (29%), New Zealand only (23%), Australasian (including New Zealand) (9%) and cold southern/deep water (9%). There are four monotypic endemic bryozoan genera in the region — *Kermadecazoon* (Bitectiporidae) (*Tilbrook, 2006) (Figure 1), *Reginelloides* (Cribrilinidae) (Soule, Soule and Chaney, 1995)

(Figure 2), *Tenthrulina* (Gordon, 1984) (Figure 3) and *Zygopalme* (Eurystomellidae) (Gordon, Mawatari and Kajihara, 2002) (Figure 4). Among the most recent significant new bryozoan discoveries was the finding of the first-known endemic vent-faunal bryozoan, a new species of *Parachnoidea* (Ctenostomata) encrusting the vent mussel *Gigantidas gladius* on Rumble V seamount (Gordon, In press). ∎

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FIGURE 1. *Kermadecazoon exallos* (Gordon, 1984).

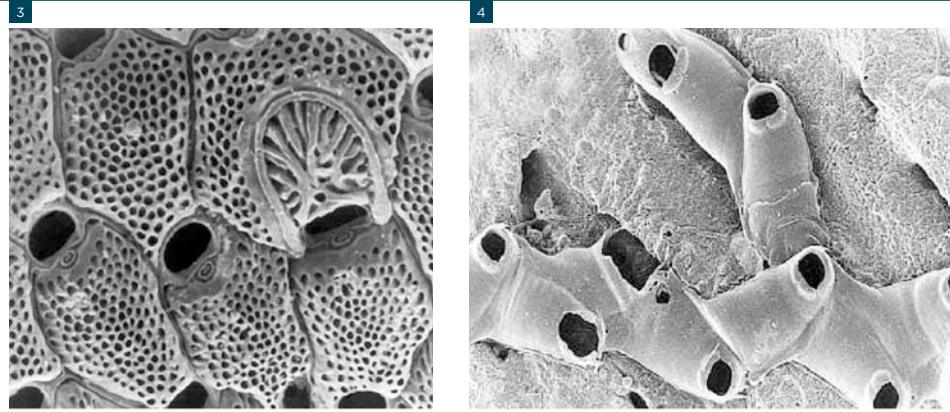**FIGURE 2.** *Reginelloides stolonifera* (Gordon, 1984).

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FIGURE 3. *Tenthrenulina dispar*
Gordon, 1984.

FIGURE 4. *Zygopalme crystalline*
(Gordon, 1984).

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Beyond light –
the great unknown

Andrew Stewart and Malcolm Clark

The Kermadec Ridge and Trench as discussed here are bound by New Zealand's exclusive economic zone (EEZ) drawn around the islands in the Kermadec group, extending south into the outer Bay of Plenty. It covers an area from 26ºS to 36ºS and 177ºE to 174ºW and is over 10,000 m deep at its deepest point. The area includes the Kermadec-Colville Ridge, which is the only subtropical ridge in the EEZ, and the Kermadec Trench, which is one of only five trenches worldwide that are deeper than 10,000 m and is the second deepest trench in the Southern Hemisphere.

Over 50% of the New Zealand EEZ is deeper than 2,000 m, but the scientific sampling effort carried out to date amounts to less than 0.2% of that area, with 80% of the effort being focused in the 0–1,000 m depth range. The Kermadec region is one of the most poorly sampled regions in the EEZ with a correspondingly low sampling rate in deep water.

This paper focuses on deep-water fishes from the Kermadec region, which are defined here as those species occurring below the shelf break at 200 m depth.

SAMPLE DATA SOURCES

Knowledge of the fish fauna from the Kermadec Ridge has been derived mainly from surveys by RNZFA *Tui* (1962) and RV *James Cook* (1976), which comprised almost entirely mid-water sampling. More recently, collections have been made by Ministry of Fisheries Scientific Observers (1992–2010) subsampling by catch on commercial fishing vessels. This has been supplemented by NIWA/GNS sampling along the Kermadec Ridge and volcanic arc, primarily as incidental catches from geological and benthic invertebrate surveys. Voucher specimens taken on these surveys have been identified and registered into the National Fish Collection (NFC) held by the Museum of New Zealand Te Papa Tongarewa (Te Papa).

To date, there have been only two expeditions that have actually sampled the fish fauna of the Kermadec Trench: the Danish *Galathea* Expedition and the Russian *Vitjaz* Expedition. Both of these were done in the 1950s (see paper by Clark *et al.*, in these proceedings), with specimens held in overseas collections. The results of these two global expeditions have contributed much of the scientific knowledge about hadal fish fauna globally.

THE FISH FAUNA

Information on the Kermadec fish fauna for this paper has been derived from the NFC database, supplemented by published information from the previous overseas expeditions.

Based on the NFC and other records, about 1,330 fish species are currently known from the New Zealand EEZ. Of these, 308 species are recorded from the Kermadec region, representing about 23% of the total. There are 200 species known to occur below 200 m depth. The NFC holds 1,572 lots from the Kermadec region, of which 574 lots are from deeper than 200 m. Removing those species known to be exclusively epipelagic (0–200 m mid-water, e.g., tunas, billfishes) or mesopelagic (200–1,000 m mid-water, e.g., stomiiformes, lanternfishes), there are only 65 lots of demersal and benthic fishes. These comprise 12 benthic species and 31 demersal species: five of these species are commercial and 10 appear to be endemic to the Kermadec Ridge.

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FIGURE 1. A newly discovered species, *Sladinia* sp., found on Wright seamount at 1,000–1,178 m and Rumble II Seamount at 1,194 m. Photo NOAA/GNS/NIWA.

FIGURE 2. *Bathyuroconger vincinis* found on Wright seamount at 1,000–1,178 m. Photo NOAA/GNS/NIWA.

In 2005, a joint USA-New Zealand expedition (called the Ring of Fire Expedition) used deep submersibles and captured images of species too small to be taken on a baited hook and on seafloor that was too rough to sample using conventional fisheries gear (Figures 1 and 2). Species observed from the video included new species records (e.g., *Chaunax* spp.), new family records (Lophiidae) and species that could not be identified to any family. Ministry of Fisheries observers on fishing vessels can also have difficulty identifying species accurately or recognising potentially new species. Several records in their bycatch lists represent possible new records or major range extensions but are not supported by voucher specimens. Currently, surface line fisheries only operate, but voucher specimens are still urgently sought. This has highlighted the paucity of knowledge about the fish fauna of the region and the need for a comprehensive biodiversity survey followed by taxonomic analysis.

The abyssal and hadal regions (3,500 m to more than 8,000 m) are even more poorly known than the ridge and seamount habitats of the Kermadec region. Based on overseas surveys, the fishes from these depths tend to be dominated by Liparidae (snailfishes), with at least one endemic species (*Notoliparis kermadecensis*); Aphyonidae (very small, fragile and poorly known); Ophidiidae (cuskeels) including the deepest living fish, *Abyssoalbrotula galathea*; Macrouridae (rattails) which include some of the most globally widespread species (*Coryphaenoides armatus*); Synaphobranchidae (basketwork eels), which are difficult to identify; and Ipnopidae (feelerfishes), which are very fragile and rare in collections globally. A recent

series of trawls on the southern abyssal plain by NIWA collected the first Stephanoberycidae (pricklefish) for the New Zealand EEZ.

CONCLUDING REMARKS

How much do we know? After 100 years of opportunistic collecting in the Kermadec region, 43 benthic and demersal fish species are supported by voucher specimens in the NFC, with only a handful of additional records held in overseas institutions. Combinations of new taxa and poorly known taxa create identification problems for scientists, industry and observers. There has been a steady accumulation of species recorded from the region every time sampling is undertaken. A recent NIWA voyage collected five new species records and a new family record for the New Zealand EEZ, as well as specimens of species rare in collections (and it was not a fish-sampling trip). The fauna is effectively so poorly known we have no basis at this time for knowing how much we do not know.

This issue of incomplete knowledge of fish compositions goes beyond creating species lists. The Kermadec Ridge and Trench region forms a significant part of our EEZ. New Zealand is a signatory to the Rio Convention on Biodiversity and has ratified that treaty, which now forms part of the stated Biodiversity Strategy. In order to understand, manage and conserve the biodiversity of the Kermadec region, as well as set limits of human activities in the region, a comprehensive survey is needed to establish a baseline of current fish faunal composition. Such a baseline is most meaningful and robust when supported by accessible voucher specimens with accurate and testable identifications. ∎

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Sea turtles of the Kermadec Islands: More questions than answers

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Sea turtles are found circumglobally throughout all the world's ocean basins, occurring most commonly in tropical to temperate waters. Mostly, nesting is restricted to between 30°N and 30°S, and of the seven extant species found worldwide, five species are known to range across the South Pacific. These are the green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), loggerhead (*Caretta caretta*), olive ridley (*Lepidochelys olivacea*) and leatherback turtle (*Dermochelys coriacea*). Of these, three species – the green, hawksbill and leatherback turtle – have been recorded within the Kermadec Islands region. Lying equidistant between temperate New Zealand and tropical Tonga, the Kermadec Islands subtropical location, at ~30°S, potentially provides an important foraging habitat for these sea turtle species.

In general, sea turtles are slow-growing, long-lived reptiles (Chaloupka and Limpus, 1996; Limpus and Chaloupka 1997; van Dam, 1999). Their sexual maturity is delayed (Chaloupka and Musick, 1997; Miller, 1997), and breeding adults display strong natal homing behaviour and nest site fidelity (Meylan *et al.,* 1990; Lohmann *et al.*, 1997; Lohmann and Lohmann, 1998). All species exhibit complex life history patterns that are marked by distinct ontogenetic habitat shifts, coupled with long-distance breeding/foraging migrations in some species (Bjorndal, 1997; Bolten, 2003). Consequently, a population's total range can be extensive – encompassing coastal nesting areas, epipelagic habitat, foraging grounds and migratory pathways (Balazs 1976; Hirth, 1997; Lohmann and Lohmann 1998; Bolten, 2003; Luschi *et al.,* 2003; Boyle and Limpus, 2008).

For the Kermadecs, despite records spanning more than 100 years, there is a dearth of information comprising only a handful of documented records for the entire region. This is understandable given the extreme isolation and widespread distribution of this group of islands. In addition, their rugged landform, exposed coastline and frequent volcanic activity have not been conducive to human settlement. Accordingly, the islands have only been sporadically inhabited by people over the last 150 years or so, with only Raoul Island, the largest and most northern island, ever being settled for any length of time.

The first documented record was by W. B. Oliver (Oliver, 1911) where, in his paper 'Notes on Reptiles and Mammals in the Kermadec Islands', he describes a large female green turtle being shot by Mr R.S. Bell at Denham Bay in May 1908. He also makes several other interesting points that still appear relevant today. Firstly, Oliver notes that green and possibly hawksbill turtles were frequently observed (feeding) and that turtles were noticed mainly in the summer months between January and March with as "…many as five or six being seen at one time". He also notes that "…they do not breed in the Kermadecs, but go north to warmer regions". So, historically, we see the presence of green and hawksbill turtles, possible seasonality and no evidence of breeding.

Since Oliver's first record, a vast gap of information exists, with no other confirmed sightings documented until 1985 (Figure 1). From this period forward, only 34 documented sightings have been recorded. These are, in order of abundance, green (17), unidentified (12),

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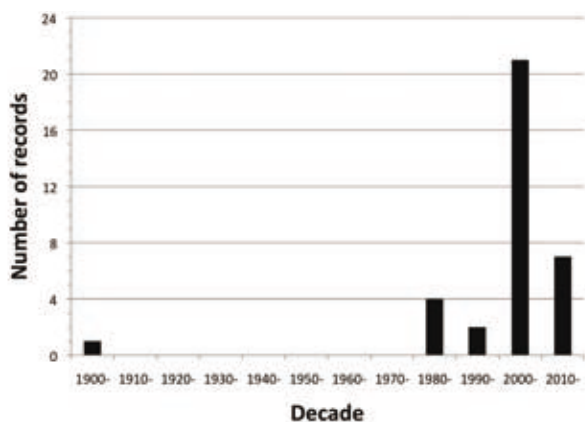
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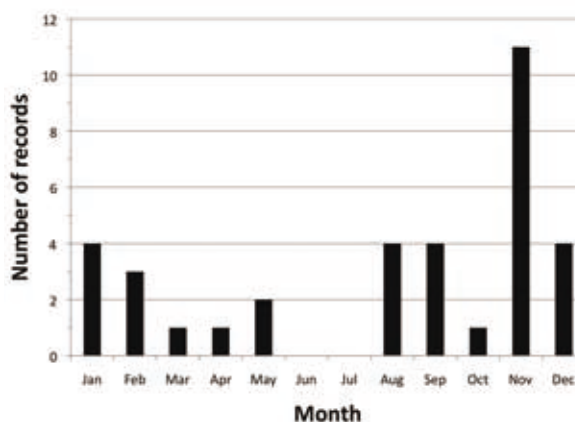
leatherback (4) and hawksbill (2). Apart from the total low number of documented records, the numbers of records also fluctuate considerably on an annual basis. This can be related to the presence or absence of people (e.g. Department of Conservation field staff) and whether sightings were documented. For example, for the decade from 2000–2009, approximately 48% (*n* = 10) were recorded in 2004 alone, while none was recorded in the years 2000, 2002, 2003, 2005 and 2007. Further still, the numbers of records also vary considerably between months within any one year, for example, for the same year (2004), nine records from a total of 10 were recorded during a single month (November).

The distribution of sightings (Figure 3 however, shows a clearer pattern, which appears to reflect the biology of the species observed rather than observer bias. All green and hawksbill turtle sightings have been recorded in nearshore habitats, which is consistent with our current understanding of these species. Following a period of oceanic dispersal by post-hatchlings, also known as the "lost years" (Bolten and Balazs, 1982; Carr, 1987), these species undergo ontogenetic habitat shifts, where juveniles are observed to settle out of the post-hatchling pelagic dispersal phase into neritic habitats (Hirth, 1997; Musick and Limpus, 1997; Bass, 1999; Meylan, 1999; Arthur *et al.,* 2008). This could account, at least in part, for the presence of greens and hawksbills observed in near-shore habitats at the islands. In contrast to the records of green and hawksbill turtles, all leatherback observations were recorded in the pelagic zone far off-shore (Figure 3). All four leatherback records were derived from accounts of animals

caught incidentally as bycatch in the New Zealand long-line fisheries operating in the region (Department of Conservation, unpub. data; Rowe, 2009). These species are predominantly a pelagic species, occupying and foraging in this zone throughout their lives (Saba *et al.,* 2008).

For the two other species that are known to range throughout the South Pacific, i.e., the olive ridley and loggerhead, it is yet unclear as to why there is an absence of records for the Kermadec region. This question is particularly relevant for loggerheads, where, despite moderate nesting populations along the east coast of Australia, no records exist for the Kermadec Islands. The present understanding that loggerheads undertake substantially longer transoceanic developmental migrations (Bowen *et al.,* 1995; Bolten *et al.,* 1998) than either the green or hawksbills, before settling into neritic habitats as (sub)adults may be a potential explanation.

Finally, expanding on Oliver's note on the apparent seasonality of sea turtles at the Kermadecs, Figure 2 shows most sightings do occur during the warmer summer months. However, it should be noted that this, once again, most likely relates to the absence of observers (or observation conducive activities) during the winter months. Overall, inferring trends about the occurrence and habitat use of sea turtles at the Kermadecs, from such a small number of records, is problematic. Only further study will overcome this and provide more answers into our understanding of the sea turtles at the Kermadec Islands.

Nevertheless, in view of the biological characteristics described above, sea turtles are

FIGURE 1. Records of sea turtles from the Kermadec Islands (all species; *n* = 35) grouped by decade from 1908–2010. Note: sightings for the decade category 2010– only includes records from January–August, 2010 (i.e., 8 months).

FIGURE 2. Records of sea turtles from the Kermadec Islands (all species; *n* = 35) grouped by month from 1908–2010 (August).

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vulnerable to anthropogenic-related decline. Although historically abundant, human over-exploitation, habitat loss and degradation have caused significant declines in abundance of all species worldwide. Consequently, all species are listed in the International Union for the Conservation of Nature's Red List of Threatened Species (IUCN, 2007). Within this context, the Kermadec Islands region may constitute a regionally significant area for the conservation of sea turtle populations in the South Pacific.

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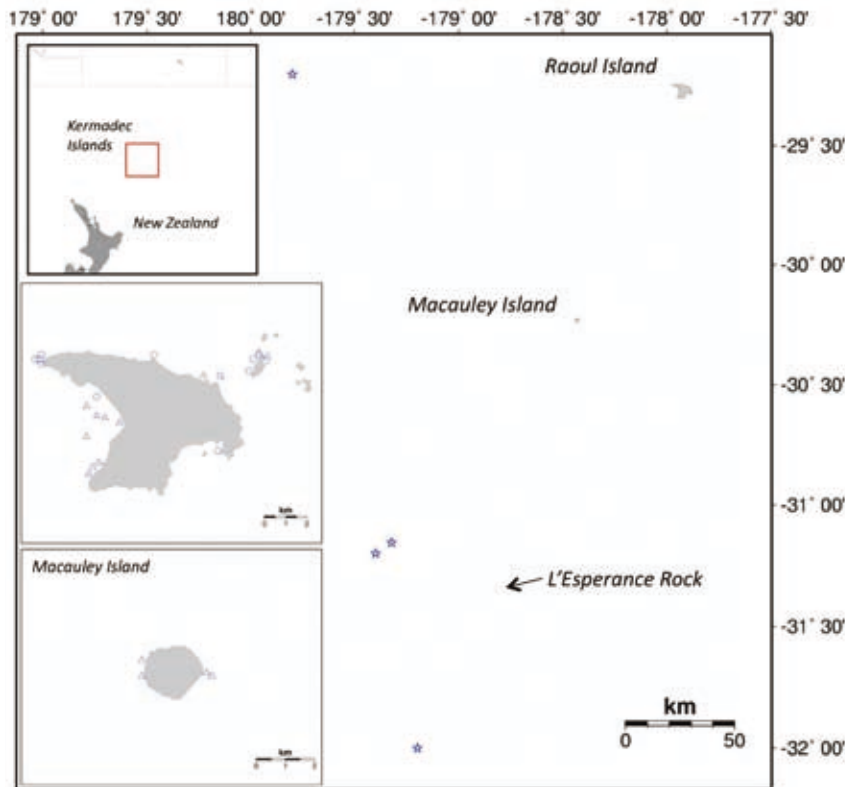
FIGURE 3. Distribution of sea turtle records from the Kermadec Islands (all species; *n* = 35) from 1908–2010 (August). Key Δ – *Chelonia mydas* (*n* = 17), ☆ – *Dermochelys coriacea* (*n* = 4), ▢ – *Eretmochelys imbricata* (*n* =2), o – unidentified (*n* = 12).

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Sharks and rays of the Kermadec Islands and north Kermadec Ridge: Species of interest, conservation and scientific significance

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The demersal fish fauna of the Kermadec Ridge, including the chondrichthyan (sharks, rays and chimaeras) fishes, has received little scientific attention. There have been no systematic fishery surveys of the ridge. Consequently, research has largely been limited to taxonomy of serendipitously obtained material or specimens collected by scientific observers aboard commercial fishing vessels. Here we review existing information on the chondrichthyan fauna of the north Kermadec Ridge between 28° 48'S and 32° 46'S, a distance of ~452 km, which encompasses the Kermadec Islands, and briefly comment on the scientific and conservation significance of the populations occurring there. Our sources of information included species records obtained from the scientific literature (Murray, 1895; Günther, 1889; Waite, 1910; Garrick, 1982; Francis, 1985, 1991, 1993; Francis *et al.*, 1987; Bagley *et al.*, 2000; Duffy, 2007; Duffy and Last, 2007a, b; Beaumont *et al.*, 2009), personal observations and unpublished data, underwater photographs provided to us by E. Gosse, M. Fraser, P. Mesley and K. Westerskov, museum specimens (Museum of New Zealand Te Papa Tongarewa) and the Ministry of Fisheries Catch Effort Database.

We recorded a total of 37 species from 20 families from the north Kermadec Ridge (Table 1). This represents about one-third (31%) of the total New Zealand chondrichthyan fauna. Over half (54%) of the species are globally distributed, and the next largest grouping are species restricted to the Kermadec Ridge, northern New Zealand, the Norfolk Ridge and eastern Australia (13.5%). Three species (8%), *Squalus raoulensis*, *Cephaloscyllium* sp. and *Mustelus* sp., appear to be endemic to the north Kermadec Ridge and possibly the Tonga Ridge.

About 35% of the species inhabit the upper slope (bathyal species) (Table 1), compared to more than 60% for the total New Zealand fauna. Families that appear to be under-represented, probably due to insufficient sampling, are the Dalatiidae (kitefin sharks), Etmopteridae (lantern sharks), Somniosidae (sleeper sharks), Scyliorhinidae (cat sharks), Rajidae (skates) and Chimaeridae (ghost sharks). In addition, the widespread deep-water and pelagic species *Chlamydoselachus anguineus*, *Somniosus antarcticus*, *Rhincodon typus*, *Pseudocarcharias kamoharai*, *Manta birostris* and *Mobula japanica* almost certainly occur in the region. The actual chondrichthyan species richness is therefore likely to be at least 43 species. This level of diversity would be comparable to that observed for other subtropical and tropical islands in the south-west Pacific (C. Duffy, unpublished data). Environment-based predictions of demersal fish distributions (Leathwick *et al.*, 2006a, b; 2008) indicate an additional 12 species, including five ghost sharks, may occur on the north Kermadec Ridge.

Protected shark species occurring on the north Kermadec Ridge include the smalltooth sandtiger (*Odontaspis ferox*) and white shark (*Carcharodon carcharias*). Mature male smalltooth sandtigers appear to aggregate, possibly seasonally, in shallow water at L'Esperance Rock, whereas tagging studies indicate white sharks from New Zealand aggregation sites generally migrate through the region en route to other parts of the south-west Pacific.

The insular shelf and slope ecosystems of the Kermadec Islands Marine Reserve and its environs are almost globally unique due to their essentially untouched nature. The shallow (less

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than 50 m depth) reef fish assemblages are characterised by high abundances and biomasses of large predatory (*Epinephelus daemelii*, *Carcharhinus galapagensis*) and herbivorous fishes, providing a rare opportunity to investigate marine community structure and function unmodified by fishing. In slightly deeper habitats (50–300 m depth), large groupers (*E. octofasciatus*) and spiny dogfishes (*Squalus* spp.) appear to be the dominant demersal predators and, in places, bass (*Polyprion americanus*) and bluenose (*Hyperoglyphe antarctica*) may be abundant.

Our knowledge of the fishes of the Kermadec Ridge, including large species such as sharks and rays, is still very incomplete. We estimate that between six and 20 chondrichthyans remain to be recorded from the north Kermadec Ridge. The discovery of three endemic species of demersal sharks on the north Kermadec Ridge is consistent with the ongoing discovery of previously undescribed shark species in similar habitats in Australian and New Caledonian waters and suggests that more endemic chondrichthyans are likely to occur along the Kermadec and Tonga arcs. Regional connectivity of shark and ray populations occurring on the Kermadec Ridge is unknown, as are patterns of distribution, abundance and habitat use. The efficacy of protection afforded to shark populations by the Kermadec Islands Marine Reserve is unknown, but it seems likely that the discontinuous boundaries do not encompass all of the habitat of highly mobile species such as the Galapagos shark. Deep-water demersal species are also likely to move beyond the marine reserve where continuous habitat extends beyond its boundaries.

Sharks have been specifically excluded from the limited number of ecological studies conducted at the Kermadec Islands. A more complete understanding of the marine ecology of the Kermadec Islands Marine Reserve will require an understanding of the ecological significance of large predatory fishes and their direct and indirect effects upon assemblage structure and function. It would be instructive to investigate the feeding ecology and document the distribution and abundance of Galapagos sharks in relation to their main prey species within the reserve, as well as carry out experimental studies of the role of herbivory in structuring shallow subtidal benthic communities at the Kermadec Islands.

ACKNOWLEDGEMENTS

TABLE 1. Chondrichthyan fishes recorded from the north Kermadec Ridge and Kermadec Islands Marine Reserve. An asterisk indicates species records requiring confirmation. Unpublished records based upon Museum of New Zealand specimens are prefixed by NMNZ, followed by the fish collection (P.) registration number.

FAMILY	SPECIES	COMMON NAME	DISTRIBUTION	HABITAT/DEPTH RANGE	SOURCE
Hexanchidae	*Heptranchias perlo*	sharpnose sevengill shark	cosmopolitan	bathyal, surface – 1,000 m depth, usually below 200 m	Ministry of Fisheries Catch Effort Database
Hexanchidae	*Hexanchus griseus*	sixgill shark	cosmopolitan	bathyal, surface – 2,500 m depth, usually below 200 m	Ministry of Fisheries Catch Effort Database
Centrophoridae	*Centrophorus harrissoni*	Harrisson's dogfish	Kermadec Ridge, Three Kings Ridge, Norfolk Ridge, New Caledonia, eastern Australia	bathyal, 450–1048 m	Duffy (2007)
Centrophoridae	*Deania calcea**	shovelnose spiny dogfish	cosmopolitan	bathyal, 60–1,490 m, usually below 200 m	Beaumont *et al.*, (2009)
Dalatiidae	*Dalatias licha*	seal shark, kitefin shark	cosmopolitan	bathyal, 40–1,800 m depth, usually below 200 m	Ministry of Fisheries Catch Effort Database
Dalatiidae	*Isistius brasiliensis*	cookiecutter shark	circumglobal in subtropical and tropical zone	pelagic, surface – 3,700 m depth	NMNZ P.007238
Etmopteridae	*Etmopterus* cf. *lucifer**	Lucifer dogfish, blackbelly lantern shark	cosmopolitan	bathypelagic, 150–1,250 m depth	NMNZ P.034816
Somniosidae	*Centroscymnus owstoni*	smooth skin dogfish	South-west Atlantic and Pacific	bathyal, upper slope, 100–1,500 m depth	Ministry of Fisheries Catch Effort Database
Somniosidae	*Scymnodon ringens*	knifetooth dogfish	North Atlantic and New Zealand	bathypelagic, 200–1,600 m depth	Ministry of Fisheries Catch Effort Database
Squalidae	*Cirrhigaleus australis*	mandarin dogfish	western Pacific, eastern Australia, New Zealand to Japan	bathyal	Beaumont *et al.*, (2009)
Squalidae	*Squalus acanthias**	spiny dogfish	cosmopolitan	demersal, surface – 1,460 m depth	Beaumont *et al.*, (2009)
Squalidae	*Squalus griffini*	northern spiny dogfish	Norfolk Ridge, Kermadec Ridge, Louisville Ridge, North and northern South Islands, Chatham Islands	demersal, upper slope, 80–320 m depth	Duffy and Last (2007b)
Squalidae	*Squalus raoulensis*	Kermadec spurdog	North Kermadec Ridge and ?Tonga Ridge	bathyal, 300–320 m depth	Duffy and Last (2007a); Duffy (unpub. data)
Alopiidae	*Alopias superciliosus*	bigeye thresher shark	cosmopolitan in tropical and temperate waters	pelagic	Bagley *et al.*, (2000)
Odontaspididae	*Odontaspis ferox*	small tooth sandtiger shark	cosmopolitan in tropical and temperate waters	benthopelagic, outer shelf to upper slope	Francis (1991); Francis (1993)
Cetorhinidae	*Cetorhinus maximus*	basking shark	cosmopolitan in temperate waters	pelagic, surface – 1,000 m depth	Morton (1957)
Lamnidae	*Carcharodon carcharias*	great white shark	cosmopolitan in tropical and temperate waters	pelagic, surface – 1,200 m depth	Duffy *et al.*, (in review)
Lamnidae	*Isurus oxyrinchus*	shortfin mako	cosmopolitan in tropical and temperate waters	pelagic, surface to 300 m depth	Ross and Bailey (1986b); Bagley *et al.*, (2000)

FAMILY	SPECIES	COMMON NAME	DISTRIBUTION	HABITAT/DEPTH RANGE	SOURCE
Lamnidae	*Lamna nasus*	porbeagle shark	widespread, amphi-temperate	pelagic, surface – 715 m depth	Bagley *et al*., (2000)
Scyliorhinidae	*Apristurus* sp.	deepwater catshark	unknown	bathyal	Beaumont *et al*., (2009)
Scyliorhinidae	*Cephaloscyllium* sp.	carpet shark	endemic	demersal	NMNZ P.029764
Pseudotriakidae	*Gollum attenuatus*	slender smoothhound	Norfolk Ridge, Kermadec Ridge, North Island	bathyal, 125–970 m depth	Beaumont *et al*., (2009)
Triakidae	*Galeorhinus galeus*	school shark	widespread, amphitemperate	benthopelagic, surface – 1,100 m depth	Ministry of Fisheries Catch Effort Database
Triakidae	*Mustelus* sp.	Kermadec rig	endemic	demersal, 8–125 m	Francis *et al*., (1987); Francis (1993)
Carcharhinidae	*Carcharhinus amblyrhynchos**	grey reef shark	Indo-Pacific	benthopelagic, coral reefs, surface to 300 m depth	Francis (1993)
Carcharhinidae	*Carcharhinus brachyurus**	bronze whaler	cosmopolitan in tropical and temperate waters	benthopelagic	Beaumont *et al*., (2009)
Carcharhinidae	*Carcharhinus galapagensis*	Galapagos shark	cosmopolitan in tropical and temperate waters	benthopelagic, oceanic islands and seamounts	Garrick (1982); Francis (1993)
Carcharhinidae	*Carcharhinus longimanus*	oceanic whitetip shark	cosmopolitan in tropical and temperate waters	pelagic, surface – 230 m depth	Ministry of Fisheries Catch Effort Database
Carcharhinidae	*Galeocerdo cuvier*	tiger shark	cosmopolitan in tropical and temperate waters	benthopelagic, inshore to 371 m	Francis (1993)
Carcharhinidae	*Prionace glauca*	blue shark	cosmopolitan in tropical and temperate waters	pelagic, surface to 350 m depth	Bagley *et al*., (2000)
Sphyrnidae	*Sphyrna zygaena*	smooth hammerhead shark	cosmopolitan in tropical and temperate waters	pelagic, surface to 300 m depth	Francis (1993)
Torpedinidae	*Torpedo fairchildi**	electric ray, torpedo	New Zealand	demersal, 5–1,153 m depth	Ministry of Fisheries Catch Effort Database
Rajidae	unidentified sp.	skate	unknown	bathyal	Ministry of Fisheries Catch Effort Database
Dasyatidae	*Dasyatis brevicaudata*	shorttailed stingray	cosmopolitan in tropical and temperate waters	demersal, intertidal – 476 m depth	Francis *et al*., (1987); Francis (1993)
Dasyatidae	*Pteroplatytrygon violacea*	pelagic stingray	cosmopolitan in tropical and temperate waters	pelagic, surface – 381 m depth	Bagley *et al*., (2000)
Myliobatidae	*Myliobatis tenuicaudatus*	eagle ray	Kermadecs, New Zealand, Norfolk Island	demersal, intertidal – 160 m depth	Francis *et al*., (1987); Francis (1993)
Chimaeridae	unidentified sp.	ghost shark	unknown	bathyal	Ministry of Fisheries Catch Effort Database

Sharks and rays of the Kermadec Islands and north Kermadec Ridge:
Species of interest, conservation and scientific significance

THE
KERMADECS

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Migrations and patterns of seabird occurrence in the Kermadec region

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Seabirds are a highly visible component of the Kermadec region's marine environment; they are also an important top-order predator. This paper discusses the occurrence and foraging behaviour of seabirds that breed on the Kermadec Islands and those that visit the region. Six of the 14 resident seabirds are pelagic feeders that forage over a large area (<1,000 km) during the breeding season, while other residents capture a large proportion of their food in waters immediately surrounding the islands. Seabirds of southern, subtropical and tropical origin generally occur within the Kermadec region during non-breeding migration, but some species that nest far from the region also visit during their breeding season. At-sea observations since 1970, together with recent tracking studies of species from northern New Zealand off-shore islands and western North America, provide spatio-temporal information about distributions. Detailed information about the foraging biology of the region's seabird taxa and marine habitat affinities is either fragmentary or non-existent. Extralimital subtropical Pacific Ocean studies are included herein to discuss likely foraging behaviour and diet.

DISCUSSION

Observations of seabirds collected from ships approaching the Kermadec Islands reveal patterns of occurrence and distribution at sea. Upon departing New Zealand, seabirds with limited ranges at sea including the gulls, terns, gannets, penguins and some petrels and shearwaters, are left behind at the shelf edge. Once in oceanic waters, pelagic species are encountered and include a mix of birds breeding on New Zealand northern off-shore islands together with birds from New Zealand sub-Antarctic islands and possibly farther afield. Mid-way between New Zealand and the

Kermadec Islands, sightings of birds include those that breed on the Kermadec Islands. All Kermadec Islands, and presently with the exception of Raoul Island, are crowded with seabirds. Once within the islands' vicinity, the number of seabirds increases dramatically: not only those with smaller foraging ranges such as the Kermadec shearwater (*Puffinus assimilis kermadecensis*), white-bellied storm petrel (*Fregetta grallaria grallaria*), Kermadec storm petrel (*Pelagodroma albiclunis*) (Figure 1), grey ternlet (*Procelsterna cerulea albivitta*) and black noddies (*Anous minutus*) (C Gaskin pers obs.), but also those that undertake vast pelagic movements to and from their colonies, for example, the Kermadec petrel (*Pterodroma neglecta neglecta*), white-naped petrel (*P. cervicalis*) (Figure 2) and sooty tern (*Onychoprion fuscata serrata*) (C. Gaskin, pers, obs.). Observations include birds resting or preening on the water around the islands, as well as some visitors from farther afield.

Bird-borne tracking data gained from geolocators and satellite tags provide us with insights into oceanic range utilisation in more detail. Grey-faced petrels (*Pterodroma macroptera gouldi*) breed in New Zealand during winter. Consistent with at-sea observations, tracking data from 2006 and 2007 showed some grey-faced petrels used the Kermadec region (MacLeod *et al.,* 2008). Indications are that grey-faced petrels are most frequently located in waters with moderate sea surface temperatures (~15°C), moderately high productivity and variable bathymetry (2,000–5,000 m). These data, together with similar tracking data from black petrels (*Procellaria parkinsoni*), highlight the large distances these two species forage over during the breeding season (E. Bell, unpubl.d). Black petrel tracking data from Great Barrier Island during

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FIGURE 1. Kermadec storm petrel
(*Pelagodroma albiclunis*).
Photo Gareth Rapley.

2005/2006 also indicate range utilisation within the Kermadec region. Migrating species, outside their breeding season, show a different pattern. Birds moving south from the north Pacific back to New Zealand include flesh-footed shearwater (*Puffinus carneipes*, Bethell's Beach, 1 from 3, September 2006) (Rayner *et al.,* in press), black-winged petrel (*Pterodroma nigripennis*, Chatham Islands, 2 from 5, September 2008) (G. Taylor & M. Rayner, unpubl.) and Cook's petrels (*P. cookii*) (Little Barrier Island, 5 from 11, November 2009) (Rayner *et al.,* in review). All showed a fairly rapid passage through the Kermadec region. Satellite tracking of sooty shearwaters captured off the western US seaboard (Tracking Sooty Shearwaters in the California Current: 2004–2009[1]) provides greater resolution data showing a broad migration pathway centred to the east of the Kermadec Trench. One bird in 2008, travelled around Raoul and spent some time just to the south of Curtis, before heading off to the Colville Ridge en route south to mainland New Zealand waters and the Southern Ocean (see: www.seaturtle.org/tracking/?project_id=282).

Currently, there are no tracking data for Kermadec breeding seabirds. However, we know from at-sea observations that Kermadec birds such as white-naped petrel, black-winged petrel, wedge-tailed shearwater (*Puffinus pacificus*) (Figure 3) and sooty tern range widely during the breeding season (Gaskin, in press). The migration of southern-breeding storm petrels towards the equator during the seasonal cooling of subtropical and tropical waters is well known for both the western and eastern Pacific Ocean. We now

[1] A project of Pacific Procellariid Research Consortium in conjunction with Moss Landing Marine Labs, USGS, California Sea Grant, and NOAA National Marine Sanctuaries and Northwest Fisheries Science Center.

have good evidence indicating likely "wintering grounds" for the central South Pacific shows the accumulated occurrence of storm petrels north of New Zealand for the months between May and October from at -sea observations (Gaskin, in press).

Seabirds use a variety of techniques to capture prey including those in the Kermadec species, which have their own strategies for finding and catching food. Two foraging techniques used in the Kermadec region include associating in mixed-species flock-feeding over subsurface predators, like tuna and kingfish. This mode is a feature of subtropical and especially tropical waters where birds often are dubbed "tuna birds". That sort of activity can include birds picking off flying fish (or flying squid), which themselves are escaping tuna or other fast-moving predatory fish and cetaceans. Secondly, nocturnal feeding is adopted by some species and has been documented in white-naped, black-winged and Kermadec petrels and among storm petrels. Nocturnal petrels usually feed alone but sometimes in the company of other seabirds including the grey-faced petrel.

For seabirds breeding in the Kermadec region, we must draw inferences from studies for the same or closely related species that breed elsewhere to speculate what Kermadec seabirds might be feeding on. Inference here is drawn from studies on Hawaiian seabirds and those of the eastern Pacific Ocean. Birds have been grouped according to foraging range – the circles at 12 nm and 200 nm and beyond. Proportions and species in each diet likely will be different for Kermadec seabirds, but it is clear seabirds utilise the whole of the Kermadec region and areas beyond. Food may be ephemeral in occurrence
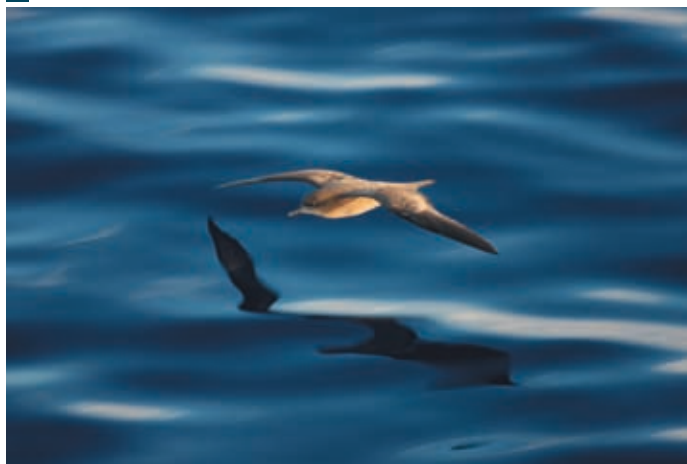
and require extensive and energy-costly foraging trips for some birds. Some of the pelagic birds also will find food closer to islands, taking advantage of the complexity of the region's submarine topography with its trenches, basins, ridges, seamounts and islands and their influence over water masses, currents and, consequently, over the associated marine life.

MARINE FAUNA POTENTIALLY IMPORTANT TO KERMADEC SEABIRDS

- Tuna and swordfish long-line fisheries dominate those operating in Kermadec waters. A number of Kermadec seabirds feed in association with these subsurface predators, in particular, tuna – the so-called "tuna birds".

- Ommastrephid squids are surface-dwelling cephlapods and are common and widespread in all warm waters. Harrison (1990) noted that the frequency with which seabirds (and tuna and dolphins) feed on juvenile squid implies that squid are a very important component of the subtropical marine ecosystem.

- Flyingfish (Exocoetidae) and flying squid taken in flight or just after they (the fish) land in the water. Commonly observed for masked boobies, pterodroma petrels and some shearwaters.

- Diurnal feeding on non-cephalopod invertebrates, and fish eggs and fish larvae. These are likely to be important for storm petrels, grey ternlets and black noddies.

- Vertical migration of smaller mesopelagic fishes, cephalopods and planktonic creatures.

- It is quite possible that a significant component of the diet of grey ternlets and white-bellied storm petrel and Kermadec storm petrel consists of sea striders (Halobates spp.) (Harrison and Seki, 1987; Spear et al., 2007).

CONCLUSION

We are a long way from fully understanding the relationships between seabirds occurring in the Kermadec region and the local physical and biological oceanographic processes. There currently is the need for a great deal of future research with seabird biologists working in close collaboration with other marine biologists and oceanographers. In terms of future research into seabirds' foraging behaviour, a start has been made. New Zealand Department of Conservation staff have fitted geolocators to black-winged petrels breeding on Raoul Island, part of MR's research fellowship investigating seabirds, specifically Cookilaria petrels, as indicators of ocean hotspots for resource management.

The Kermadec Islands are challenging places to work – they are remote islands and require major and costly expeditions, and seabirds themselves don't make it easy. Their burrowing and the sheer density within colonies make these islands extremely sensitive places for research teams to move about on. Seabirds breeding at the Kermadecs, plus those that visit, utilise a vast area – far greater than the precious surrounding 12 nm marine area currently reserved. Seabirds allow us to take at least two perspectives on this:

1. Seabird populations are dependent on a healthy marine ecosystem and, with growing populations in the wake of eradication programmes, there is an imperative to better understand the dynamics at play across the whole region, including fisheries interactions and influences.

2. Seabirds target productive marine habitats where they integrate ecological signals, presenting useful biological indicators for understanding variation in marine

FIGURE 2. White-naped petrel (*Pterodroma cervicalis*). Photo Peter Harrison.

FIGURE 3. Wedge-tailed shearwater (*Puffinus pacificus*). Photo Gareth Rapley.
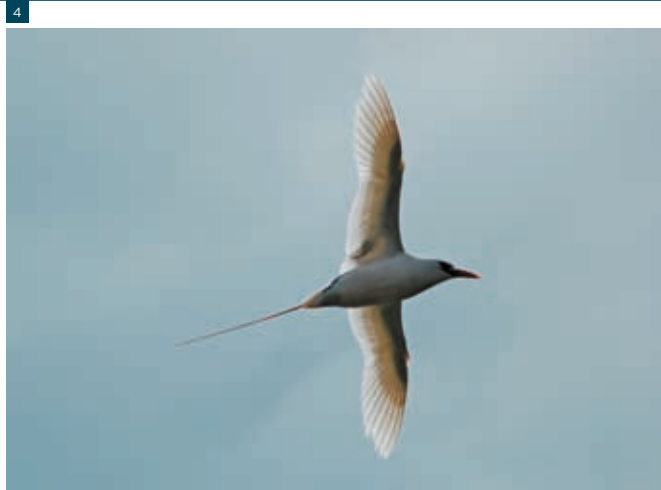
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FIGURE 4. Red-tailed tropicbird
(*Phaethon rubricauda*).
Photo Karen Baird.

productivity in space and time. Seabirds can potentially teach us a great deal about the state of that marine environment and future ecosystem responses to climate change or changes brought on by certain fisheries.

Further information and maps can be found at: www.thekermadecs.org/sites/default/files/content/Migration patterns of seabird occurrence in the Kermadec region.pdf.

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Towards an estimate of whale stocks in Kermadec waters before sail whaling began

Rhys Richards

In 1935, Charles Townsend published in New York in the prestigious journal *Zoologica* four huge charts covering a global survey of the 53,877 whales killed by American sail whalers in 744 ships on 1,665 voyages. His source was the data he had extracted from hundreds of American whaling logbooks and journals (Townsend, 1935). Since then, the total number of American voyages has been recalculated as over 16,000, for which about 4,000 logbooks survive (Lund, 2001). Townsend's sample covered about 10% of the American whaling voyages globally and, one assumes, about 10% of their global catch. On a pro rata basis, the estimated number of whales killed by American sail whalemen before 1900 should rise to about half a million, that is, in total, only a quarter as many as the two million killed by modern whaling since 1900.

Townsend's sample is a huge resource – vast record of where whales were found during the American whaling period and, equally important, where whales were not found across the oceans. Townsend was a zoologist. His charts show the various commercial species, the regions and actual locations of whale kills, the month and, to a less precise degree, the number of whales killed.

No comparable source exists for the non-American whaleships, but at a broad estimate of the voyages made by the British and Australian whalefleets, plus a few made by the small French fleet, plus a few voyages from German, Canadian and other minor ports, probably totalled almost 5,000 voyages, for which only about 250 logbooks survive. Pro rata, these non-Americans altogether probably killed about another 165,000 whales. Unfortunately, only about 250 logbooks remain for all the non-American voyages, so the main sources for these voyages are contemporary newspapers and, more recently, various published trans-Pacific shipping arrivals and departures lists (Richards, 2002a).

In recent years, zoologists and others have begun to realise that Townsend's pioneer work provides a vast database from which good indications can be drawn, not of the exact numbers involved, but certainly of the scale of the slaughter place by place. His charts are a "fossilised record" from which to estimate how many whales were removed and, from that and the generational cycles, how many whales there were originally, region by region, before sail whaling began, what were the original stocks, and what was the baseline from which to assess the recovery up to the present day.

What then, do Townsend's global charts tell us about the whales at the Kermadecs? The great whale species hunted commercially in the South Pacific were only three – southern right whales (*Eubalaena australis*), humpback whales (*Megalaptera novaaeangliae lalandi*) and sperm whales (*Physeter catadon*).

RIGHT WHALES

Townsend's global chart shows that no right whales were killed close to the Kermadecs (Figure 1). One right whale was seen from Raoul in October 1967 and two together in 1973, but they are the only sightings ever recorded from ashore (DOC staff members). However, several hundred kilometres to the south-east, Townsend's charts show that American whalers killed more than a hundred right whales in November and December. I have argued elsewhere that this location was at the northern

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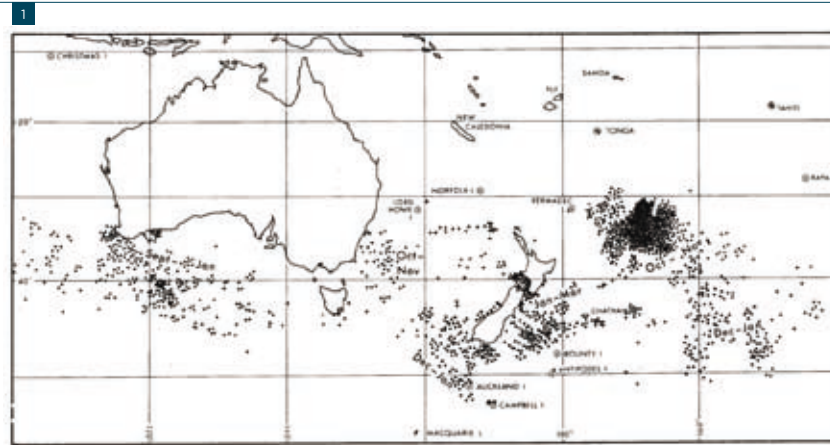73 SEAVIEW ROAD, PAREMATA, PORIRUA 5024
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FIGURE 1. Right whale catches by American whaleships in Australasian waters up to 1913 (after Townsend, 1935).

most stage of their annual migration, with the males waiting there for the arrival of the females after calving in the sheltered bays about southern New Zealand each winter from June and July onwards. In just eight winters from 1835 to 1842, a combination of off-shore, bay and shore whaling killed at least 14,000 adults. Up to a further 4,000 adults were killed by 1850, including the remnant Townsend showed in the area well south-east of the Kermadecs (Richards, 2002b). The southern right whales were hunted so close to extinction that not one was seen on the coasts of New Zealand for 36 years from 1927 to 1963, and the recovery since has been very slow (Richards, 2009).

HUMPBACK WHALES

Townsend's chart again shows none of that species was killed at or close to the Kermadecs (Figure 2), yet his global chart is still invaluable as a clear record of the routes followed by humpbacks on their migrations. His chart shows a large concentration of humpback were killed by US whaleships west of New Caledonia and in the Chesterfield Islands in August and September only. More than twice as many were killed around Tonga in the same months. A few more were killed just north-east of the tip of New Zealand again in the same months of August and September only, plus a few in Cook Strait between our North and South Islands.

The task, then, is to explain how these humpback kills appear in three locations in the same months but nowhere else in any other months. This needs recourse to whaling lore, namely that the humpbacks swam too fast for old-style rowing boats to keep up with them, so humpbacks were scarcely ever targeted except

on their breeding grounds when they slowed down, that is, to say that the humpbacks made their annual migrations unmolested from cold Antarctic waters to the warmer waters on the tropic of Capricorn at 23°S, but were vulnerable to sail whaling only when breeding. Even on their return journeys south, the humpbacks swam too fast (Richards, 2000), and for much of the sail whaling period, there were easier-to-catch whale alternatives elsewhere so why bother chasing humpbacks, except perhaps when bored or for training purposes.

Sightings of humpbacks were often recorded in US logbooks and journals, but not consistently, and I doubt whether a big search for evidence of them migrating through Kermadec waters would be realistic or profitable. Townsend's chart confirms, however, that there must be dozens of US logs that record periods spent at their breeding grounds.

SPERM WHALES

Sperm whaling began off northern New Zealand and the Kermadecs in about 1792. The islands were used as a useful navigation point on the route used by early trading vessels from Port Jackson to Tahiti from 1802 onwards, and the captains told the Sydney merchants of the sperm whales seen off the Kermadecs (Turnbull, 1813). Sydney-based whaleships were cruising on the Kermadec grounds frequently by 1810 or earlier. After 1820, the Kermadecs were a major sperm whaling ground (Figure 3), with a peak in the decade 1830 to 1840 and some whaling continuing well into the 1880s.

Sperm whales, *Physeter catadon*, are conspicuous for their low bushy spouts, which

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project well forward at an angle of about 45 degrees. They have long, blunt and almost rectangular heads and large conspicuous teeth in their narrow lower jaws. Their main habitat is equatorial, where they congregate in large family groups under a big bull harem master, but wanderers may be found at all seasons in all waters between latitudes 50°N and S. At the Equator, sperm whales are gregarious and often in large schools of mixed ages and both sexes, and many are small (Richards, 2000).

Male sperm whales grow very much larger than females. In southern summers, males that lack a harem may wander far south, with some large and solitary, or near-solitary males venturing well into cold sub-Antarctic waters. Especially where strong ocean currents push up against deep rocky shores, sperm whales dive deep to attack and dismember giant squid.

The three main locations for sperm whaling in New Zealand waters, all shown on Townsend's maps, were the Kermadec Islands, south of Pitt Island at the Chathams, and at Solanders Rocks in Foveaux Strait. At all three locations, ocean currents meet steep deep-water cliffs. Massive upwellings ensue, apparently bringing deep-sea squid closer to the surface and more vulnerable to sperm whales, especially the larger and deeper diving male bull whales. Some old sail whalers believed that the males brought up lots of squid in order to feed the females.

American whaleships were active in the right whale fishery at New Zealand, but always their main quarry were the sperm whales whose oil was worth three times as much as right whale oil. According to Townsend's sample, sperm whales made up three-quarters of the total American catch globally. At the Kermadecs, practically all the whales killed by the Americans and non-Americans alike would have been sperm whales.

A comprehensive survey was made in 1959 by Paul Canham of all the references he could find in newspapers and whaling records to American whaling in the greater New Zealand area (Canham, 1959). From this, I was able in 1980 to calculate that, on a month by month basis, 30% of all mentions were in north and north-east New Zealand, and a further 24% were at and in the close vicinity of the Kermadec Islands. In all of those northern areas, the fishery was targeted entirely on sperm whales (Richards, 1982).

American logbooks and journals are readily available on many kilometres of microfilm already in New Zealand and already indexed day by day. These include 744 cruises in Kermadec waters, with about half near Raoul Island and a quarter further south near French Rock. A preliminary search of Australian newspapers revealed at least 19 visits by British and Australian-based whaleships before 1840 (Mark Howard, pers. comm.), and a further search would certainly reveal many more visits. Meanwhile, Townsend's charts show well the seasons, namely that a few sperm whales were present in Kermadec waters each January, February, March and April, but that by far the greatest number were present in May. There were practically none killed there from May to December when the main grounds were from Tonga and Fiji to the Equator, where sperm whales were present throughout the year.
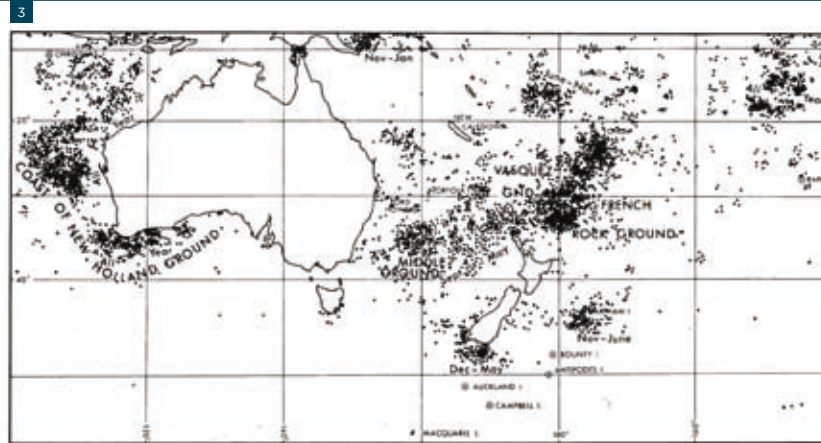
FIGURE 3. Sperm whale catches by American whaleships in Australasian waters up to 1920 (after Townsend, 1935).

The task of using these records to make a broad estimate of the sperm whale stocks exploited in Kermadec waters, and thereby a minimum number present before commercial exploitation began, is certainly do-able, but it's not been done yet. What is needed first are clear guidelines on the objectives of the survey: What area is to be covered? What data to collect, what to calculate, and what to estimate? If there are specific guidelines set, it could be done. ■

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The Kermadec Islands and the endangered humpback whales of Oceania

Rochelle Constantine, Claire Garrigue and Karen Baird

Over two million whales were killed in the Southern Hemisphere mainly during the 20th century (Clapham and Baker, 2009). Of these, 208,359 were humpback whales, probably the best known of all the great whales due to their annual migration that often brings them close to land between their summer Antarctic feeding grounds and the tropical breeding grounds. The whales of most interest to us are those from the International Whaling Commission (IWC) – designated feeding Areas V and VI, south of east Australia (EA), New Zealand (NZ) and the Oceania region of the South Pacific, roughly spanning from New Caledonia to French Polynesia. Most commercial whaling occurred on the Antarctic feeding grounds, but over 13,000 whales were also killed as they migrated north past New Zealand, east Australia and, to a lesser extent, Norfolk Island. In the early 1960s, the humpback whale stocks from Areas V and VI crashed, and the IWC placed a moratorium on hunting humpback whales to protect the stocks. Unfortunately, the situation was worse than expected, as the Soviet whalers continued to hunt humpbacks in Area V until 1973 and had provided false catch data to the IWC; the true numbers were not revealed until many years later (Yablokov et al., 1998; Mikhalev, 2000; Clapham and Ivashchenko, 2009). The total 20th century catch of humpback whales for Areas V and VI was 56,522 whales, with 25,474 (20,630 from Area V, south of EA and NZ) taken illegally by the Soviet fleet in the 1959–60 and 1960–61 summer seasons in Antarctica (Clapham et al., 2009). The revelation of the true catch statistics were immensely helpful as we could then begin to understand why the humpbacks of Oceania are not recovering as well as other populations despite 45 years of protection.

Recent modelling of the stock recovery for the EA and Oceania populations showed that the humpbacks of EA were recovering at a rate of 10.6% per annum, but the Oceania subpopulation recovery is considerably slower, no doubt due to the large-scale over-exploitation of this stock (Jackson et al., 2009; Constantine et al., 2010). The humpbacks of Oceania have fidelity to breeding grounds and low levels of interchange between regions (Garrigue et al., In press a), and this is shown by the genetic differences between regions (Garrigue et al., 2004; Olavarria et al., 2007). They are distinct from the EA subpopulation with very low levels of interchange (Garrigue et al., In press b; Anderson et al., 2010). As a result of the massive decline in numbers, genetic distinctiveness and slow recovery, the humpback whales of Oceania have been listed as endangered by the IUCN. A population estimate for the humpback whales of Oceania using photo-identification images of flukes and molecular markers found that, between 1999 and 2004, there were 3,520 whales (Constantine et al., 2010).

Sightings of humpback whales in NZ waters are still low compared to historic data, but we know that whales that migrate past NZ today are most similar to New Caledonian whales, with a few links to Tonga (Olavarria et al., 2006; Constantine et al., 2007). However, the data are very limited so satellite tagging work in New Caledonia in 2007 revealed some interesting findings, especially about the unknown importance of seamounts to the whales (Garrigue et al., 2010). Several whales migrating from New Caledonia travelled in a south-south-east direction, taking them past Norfolk Island, the east coast of NZ and past the Kermadec Islands. A male humpback spent 6 days around the Kermadecs

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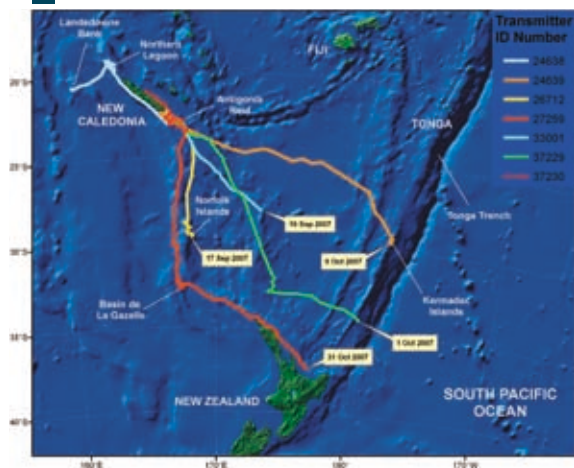FIGURE 1. Mother and calf humpback whales at Raoul Island. Photo Karen Baird.

before continuing south. However, not all whales migrated past the Kermadecs, which made the reports of humpback whales seen by DOC staff on Raoul Island very interesting. On 7 November 2008, a team of observers sat at multiple points around Raoul Island for approximately 3 hours and reported every sighting and, where possible, whether it was an adult or calf. After accounting for double-up sightings, they reported a total of 61 individuals, including several mother-calf pairs (Potier, 2008) (Figure 1). It was felt that the survey was conducted later than the peak of whales passing the Kermadecs, so on 9 October 2009, another land-based survey was conducted, and this time, 112 individuals were sighted, with fewer mother-calf pairs sighted (Brown, 2009). This is likely due to mothers leaving the breeding grounds later and being slowed by their newborns as they travel south. The number of whales reported at the Kermadecs is remarkable when you consider the survey was for only a few hours on a single day. It is clear that the Kermadec Islands are an important part of the migratory corridor for humpback whales. The source of these whales is currently unknown, but it is likely that whales will be migrating from New Caledonia (as shown by Garrigue *et al.*, 2010, Figure 2) and Tonga, with some likely coming from the remnant populations around Fiji and Vanuatu. Very little data exist on the individual identification of whales at the Kermadec Islands, only a few fluke photographs have been taken, and no tissue samples have been collected for molecular analyses.

Oceania has one of only two endangered humpback whale subpopulations in the world and the Kermadec Island waters are apparently an important, and poorly understood, part of

the migration path to their Antarctic feeding grounds. The recovery of the Oceania subpopulation is so slow that no trend in recovery can be calculated, which means they are still extremely vulnerable to any threat (Constantine *et al.*, 2010). The Japanese have 50 humpback whales listed as part of their JARPA II lethal science programme (Nishiwaki *et al.*, 2007). New Zealand is committed to conserving the populations of great whales that have been decimated by years of hunting. With the Kermadec Islands and other off-shore NZ waters being important to the Oceania population, it is important that NZ commits to research on the Kermadec humpback whales to help us track their slow recovery.

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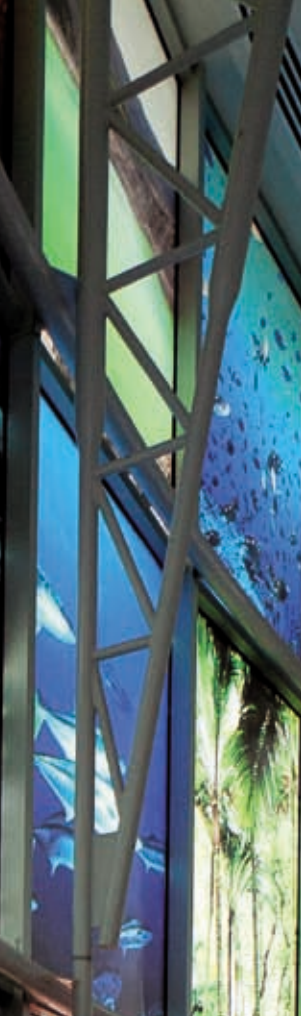
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FIGURE 2. Tracks of satellite-monitored humpback whales on their southern migration from New Caledonia 2007 (from Garrigue *et al.,* 2010).

THE **KERMADECS**

CONTRIBUTING PHOTOGRAPHERS

THANK
YOU

The symposium DEEP – Talks and Thoughts Celebrating Diversity in New Zealand's Untouched Kermadecs would never have been possible without the contributions, participation and support of New Zealand science, government, academic and NGO institutions and communities.

Te Papa Tongarewa truly became 'Our Place' for the 2 days of the symposium – a place where we came together, looked, listened, talked, shared and imagined the full scope of diversity across the Kermadec region. Our thanks to Te Papa for being such a welcoming and engaged symposium host.

The participation of scientists, academics, historians and commentators from across the disciplines enriched our understanding of the Kermadec region beyond anything we had imagined. Their voices, their knowledge and their call to continue exploring, sharing and connecting are an inspiration.

The stunning Kermadec windows of Te Papa, the pages of Kermadec publications and the slides and presentations seen at the symposium owe their vibrancy and impact to the imagination and talent of the group of photographers who have captured the Kermadecs in their lenses. We are extremely grateful for the generosity of all those who have shared their Kermadec impressions with us.

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A special thanks to Bob Zuur of WWF New Zealand for the striking image of the Kermadec window at Te Papa (opposite). This image, and the many others that Bob took – recording the speakers and interactions of the symposium (see www.thekermadecs.org) – provide a wonderful record of the Kermadec gathering and its spirit of connection and collaboration.

To all those who attended the DEEP symposium, thank you for joining in the celebration of New Zealand's untouched Kermadecs.

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