

Proceedings of

Kermadec Discoveries and Connections

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PROCEEDINGS OF KERMADEC – DISCOVERIES AND CONNECTIONS

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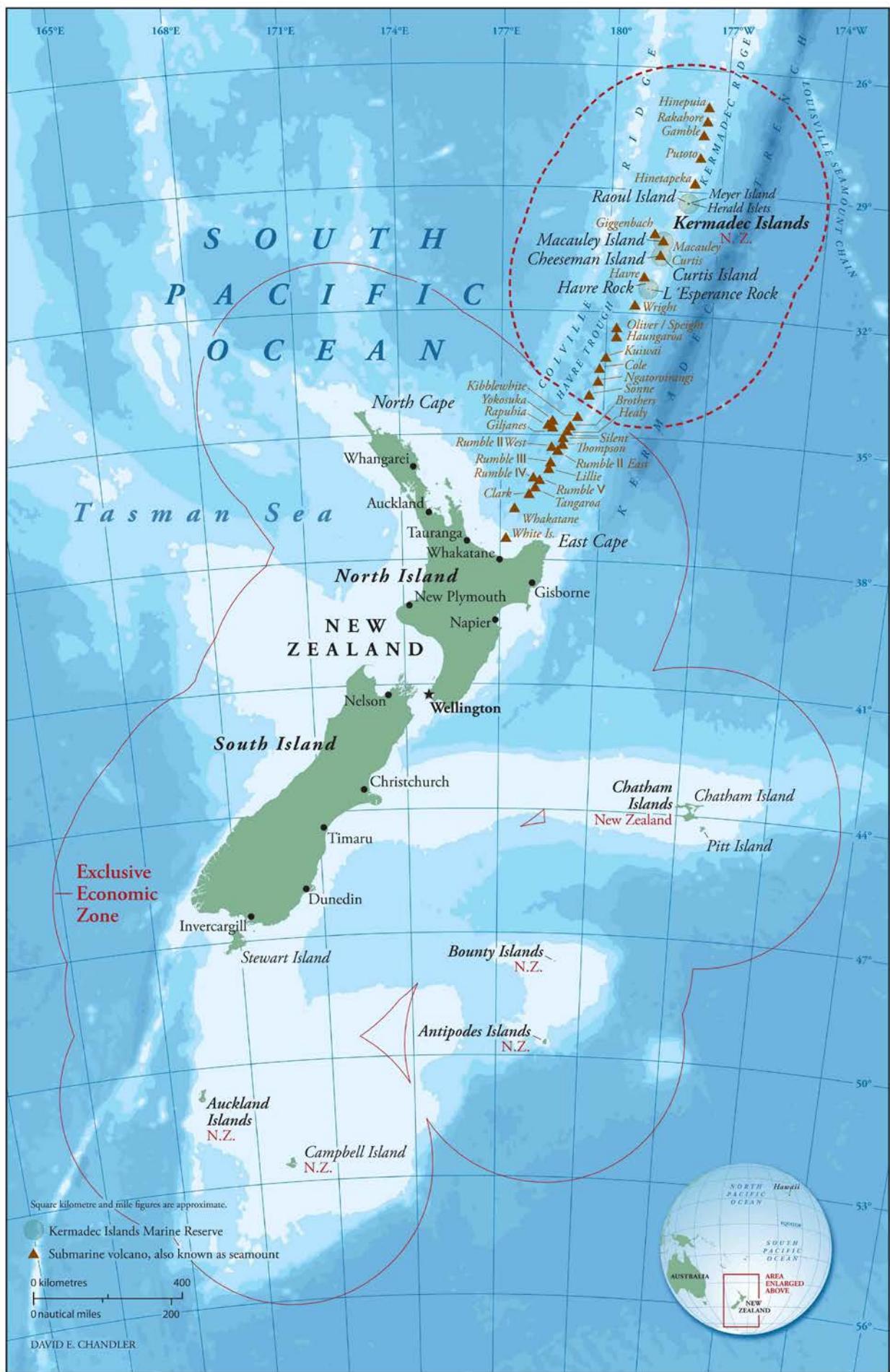
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DISCOVERIES AND CONNECTIONS

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

The Kermadec region of New Zealand represents the last frontier in marine and island exploration. The near pristine waters and island ecology of the Kermadecs offer scientists and conservation agencies a unique research and management opportunity.

In 2010 The Pew Charitable Trusts hosted the first ever Kermadec Science Symposium - *DEEP – Talks and Thoughts Celebrating Diversity in New Zealand’s Untouched Kermadecs*.

Between 2010 and 2015 a number of expeditions have made their way to the Kermadec region – exploring the islands, the near shore waters, the arc, and the deep sea. While scientists estimate that only 5% of the Kermadec region has been explored to date, these recent expeditions (some long planned, others opportunistic) have added significantly to scientists understanding of the Kermadec region, and its relationship to the wider health of ocean systems and species.

The April 2016 Kermadec Science Symposium - *Kermadec – Discoveries and Connections* – hosted by The Pew Charitable Trusts, WWF-NZ and Forest & Bird, brought together mana whenua, scientists, and conservation managers involved with the Kermadec region. Over two days, sitting amidst the works of the latest Kermadec exhibition, scientists reported on their most recent Kermadec expeditions.

The Symposium audience heard about the 15 species new to science identified by the 2011 Kermadec Biodiscovery Expedition; the largest submarine eruption ever recorded (Harve Volcano in July 2012); the discovery of pine pollen from northeastern New Zealand in the depths of the 10,000 m deep Kermadec Tonga Trench; and, the first ever tracking of Oceania Humpback whales from Raoul Island to the waters of Antarctica.

Readers of this Proceedings Document will find the descriptors ‘unique’, ‘never before seen’, ‘first record’, ‘new species’, and ‘distinct’ used frequently in the papers presented – yet further scientific confirmation that the habitats, species and oceanic processes and connections of the Kermadec region are a globally significant.

Scientists presenting to the Symposium also explored the opportunities for scientific research that the recently proposed Kermadec Ocean Sanctuary has the potential to provide. Set out below is a summary of their recommendations for consideration by the future Kermadec Ocean Sanctuary Conservation Board and conservation managers.

On behalf of The Pew Charitable Trusts, WWF-NZ, and Forest and Bird, we thank mana whenua, scientists, conservation managers and ‘Kermadecians’ who contributed their research and their expertise to the 2016 Kermadec Science Symposium.

A special thanks to Kina Scollay and Judith Curren (Our Big Blue Backyard, NHNZ), photographer Richie Robinson, videographer Steve Hathaway, artist/author Gregory O’Brien and Rebecca Priestley, Senior Lecturer and author for the breathtaking images, passionate words and inspiration that they shared at the symposium.

We look forward to their continued expeditions of exploration and discovery, and the growing understanding their research brings to the protection and management of the Kermadec region of New Zealand.

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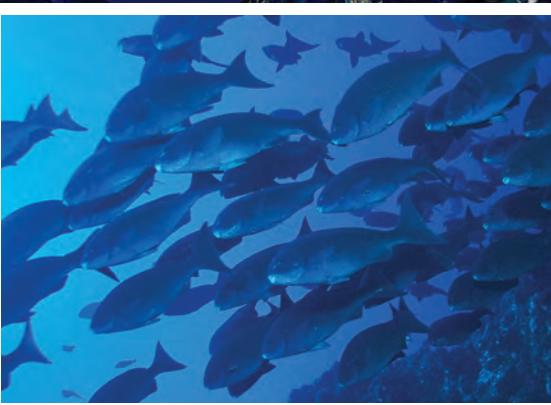
RESEARCH THAT SCIENTISTS WOULD RECOMMEND BE INCORPORATED INTO A SCIENCE PLAN FOR A KERMADEC OCEAN SANCTUARY

- *Scientific exploration and intensive sampling / collection* across the Kermadec region (micro to macro, surface to hadal, vertical and horizontal) to improve biodiversity descriptions and understanding of community composition, abundance, genetic connectivity, and recovery potential (current research focus on about 5% of the region)
- *Geospatial mapping of ocean pelagic species* to determine the importance of the Kermadec region as a habitat and migratory route for oceanic pelagic fish and cetaceans
- *Multidisciplinary and multi-year research programmes* to understand processes, linkages and structural continuum
- *Initiation of fixed, long-term monitoring stations* across the Kermadec region
- *Advanced offshore databases* (submarine structures, volcanic centres, habitat distribution and biodiversity) using new data analysis techniques and statistics and making it easily transferable to end users
- *Identification and analysis* of unidentified samples / material from previous voyages
- *Revisit previous surveys (1990's)* to assess sensitivity to, and impacts of, climate changes on species and systems

WHAT IS NEEDED TO PURSUE THIS RESEARCH ACROSS THE KERMADEC OCEAN SANCTUARY

- *Leadership, infrastructure and capacity* to implement the science plan and support researchers in a timely and effective manner (including streamlining of permitting processes and agreement and co-ordination amongst researchers)
- *Continue and expand collaboration across agencies* (national and international) to facilitate and coordinate multi-disciplinary research, at scale, and including participation of international research vessels and national marine science investment in extraordinary assets for marine science – e.g. AUVs, ROVs
- *A collective of skilled and experienced personnel* (particularly specialist taxonomists and geneticists)
- *Prioritise collections of national significance* to inform and increase the value of expeditions

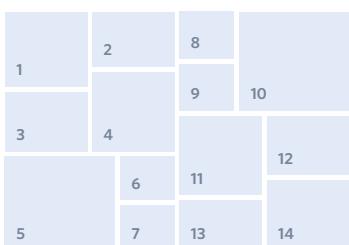




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Ocean Processes in the Kermadec Region

Craig Stevens, Stephen Chiswell, Philip Sutton and Graham Rickard

The Kermadec region plays host to a diverse range of ocean processes at a range of scales. While bathymetrically the region is defined by the combined ridge and trench running to the north-east, from the ocean's perspective it is also defined by the Pacific Ocean basin scale circulation, water column stratification and wind-forcing. Submarine ridges like the Kermadec Ridge create dividing lines in all but the near-surface waters and strongly influence a range of processes (Bostock et al. 2013). This has implications both near-surface and in the abyss. Such ocean processes in the western Pacific have a wide range of implications for New Zealand, as well as globally, in term of weather, climate, and ocean productivity.

GLOBAL SCALES

Compared to other regions of the world, the currents in the Kermadec region are modest. This is largely because the ridge is close to the centre of the South Pacific Ocean subtropical gyre. Consequently there is no strong mean flow when compared to the western boundary currents (like the East Auckland Current) or the flows to the north in the equatorial region, or at high latitudes. Thus circulation in the region is dominated by mesoscale variability rather than mean flows.

The oceans are a critical buffer for heat and CO₂ in the planet's changing climate. The rate of penetration of these properties deep into the water column is an important factor in defining the climate and its evolution. The ridge and trench act as a channel for deep flow within the global thermohaline circulation whereby water cooled at near Antarctica sinks and moves equator-ward. The pathway of this water is a function of bathymetry, the earth's rotation and the density of the water. The Kermadec Trench is one of the few pathways in the Pacific Ocean deeper than 4,000 m. Chiswell et al. (2015) reviews the oceanography of the New Zealand region and describes the Deep Western Boundary Current that carries a mix of Antarctic Bottom Water and Lower Circumpolar Deep Water northwards east of New Zealand along the flank of the

Kermadec Ridge. As this water flows north, its properties become modified and eventually some upwells and returns south as Pacific Deep Water (PDW).

Further north of the Kermadec region the flux of heat and material associated with this boundary current is constrained by the Samoan Passage where recent observations (Voet et al. 2016) identified a volume flux of around 6 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) of water, much of which was 0.8°C or colder. The persistence of this heat transport depends heavily on the degree of turbulent mixing. This mixing is very difficult to determine explicitly. However with sufficient fine scale water property measurements it can be possible to infer mixing rates. The Kermadec Trench region is being utilised by initial experiments looking at ARGO floats with extended depth ranges (Deep ARGO) that have developed sensor technology to cope with pressure and precision requirements, in order to close the oceanic temperature budget (Johnson and Lyman, 2014).

INTERNAL WAVES

The topography in the region is a strong driver of internal tides. This is where the barotropic (surface) tide causes the stratified ocean to interact with bathymetry and results in the generation of internal waves that can then transport energy efficiently over vast distances across the earth. These internal waves eventually break and this allows energy to be removed from the tides and dissipated elsewhere. This creates a transfer in energy that influences mixing throughout the oceans. The region to the north of New Zealand, incorporating both the Kermadec and Norfolk ridges is a regional hot-spot for such energy transformation. The resulting mixing influences climate through heat transport and in doing so connects processes at the 12 hour timescale with climate scales of decades to centuries.

SEAMOUNTS

These topographic features individually and collectively add (contribute (?)) to the

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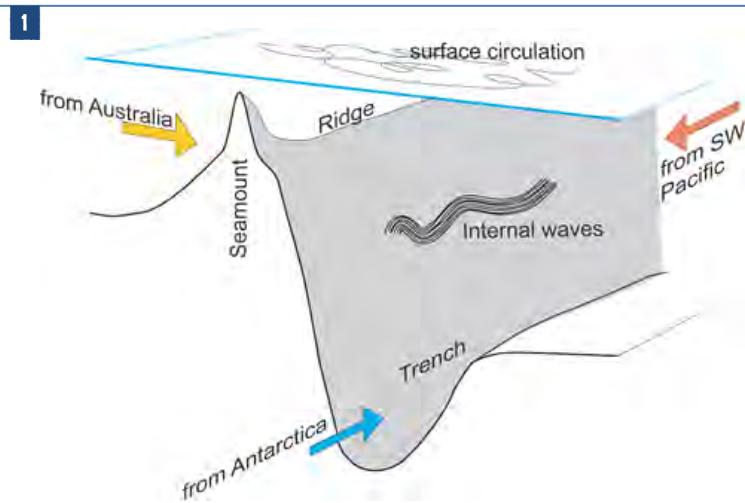


FIGURE 1. Schematic showing a range of water mass provenances and broad structure of the trench/ridge combination

complexity of the ocean-seabed interaction. Certainly the ocean provides a way of connecting isolated seamounts through both advection but also through internal wave interaction. While many of the seamounts are deep (i.e. their crest is well below the photic zone) a number come quite close to the surface (Stevens et al. 2014). Furthermore, the dynamic geology means that geological and oceanographic timescales, normally separable, are occasionally intertwined. For example Rumble III erupted in 2009, resulting in a loss of around 100 m from the crest of the seamount. This increased the summit depth to below that of light penetration and also to below the depth of the maximum seamount interacts with the stratification and the subsequent internal wave formation.

SURFACE PROCESSES

As well as influencing the vertical transport of heat, internal tides described above affect ocean productivity by mixing nutrients, oxygen and/or phytoplankton. Work to the east of the Kermadec ridge considering upper ocean biological productivity found the water column was inundated with 50-80 m peak-to-trough internal waves (Stevens et al. 2012). Potentially this type of high frequency variability dominates as the ridge itself is not particularly apparent in large scale biological mapping (Chiswell et al 2013). Horizontal transport in the near surface is very complex, involving integration of the effect of the changing wind-field. This connects to issues around larval transport, but also fate of material ejected from the active volcanos on the ridge. For example, recent submarine eruptions generated pumice rafting (Bryan et al. 2012) that is then advected over relatively short timescales.

FUTURE INITIATIVES

Water column physics-focused exploration is very expensive and typically is conducted in conjunction with other foci such as seabed disturbance or ocean surface productivity. New technology, e.g. ARGO, Deep ARGO and ocean gliders, is changing

how observational campaigns are conducted. There is great scope to explore physical oceanography from scales varying from climate, through interannual variability (e.g. El Niño) to tidal timescales. Focus could be not only on physical aspects like heat fluxes but also the biophysics of how ocean production is influenced.

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Latest geophysical investigation in the Kermadec Arc Backarc system

Geoffroy Lamarche, Richard Wysoczanski, Sophie Barton

INTRODUCTION

Geophysical techniques have been employed for many years to understand the nature of the Earth's subsurface and to enhance our understanding of volcanic and plate tectonic processes. Many of these techniques, which include seismic, acoustic, magnetic and gravity surveys, are well established whereas others have seen a development in novel new instrumentation and applications in recent years.

Here we give two examples of recent geophysical surveys in the Kermadec Arc back-arc system that highlight the techniques used, both traditional and novel, and how they have contributed to increase our understanding of the natural processes that control the development of this volcanic system. These are multi-channel seismic (MCS) surveys to examine the structure of the Havre Trough and multibeam echosounder (MBES) seafloor and water column data to map the distribution of hydrothermal vents.

SEISMIC PROFILES REVEAL THE STRUCTURE OF THE HAVRE TROUGH

Seismic reflection profiling provides images of the relationship between the sedimentary cover and an actively faulted volcanic basement, which provides a means to constrain the geometry of the arc-backarc system at depth. It is a technique that has been established and little changed for decades, yet it remains an essential tool for providing images of the sub-seafloor.

Seismic data is acquired using sonic waves that propagate through the water column and the geological layers. These waves are reflected back to the source where they are recorded and processed to generate seismic profiles that show the architecture of the geological strata beneath the seafloor from depths of 10 m to > 20 km depending on the power of the system used and frequency content of the outgoing source signal. This gives us a unique view of the structure of the earth and allows us to reconstruct how the crust was built and deformed over time.

Over the past decade several voyages on NIWA's (National Institute of Water and Atmospheric Research) research vessel *Tangaroa* have acquired seismic reflection profiles between the Colville and Kermadec Ridges, including the breadth of the Havre Trough, to study the age and mechanism of volcanism and rifting in this region. These include profiles, south to north, from the Bay of Plenty (voyage TAN0810 "BoPEC"; Lamarche et al., 2008), the southern Havre Trough at 36°S (TAN1513, "SAMSARA"; Wysoczanski et al., 2015) and at 34.5°S (TAN1007 "KARMA"; Lamarche et al., 2010) and from the northern Kermadec Arc at 31°S (TAN1213, "NIRVANA"; Wysoczanski et al., 2013). The results of these profiles show that the proto-Kermadec Arc, the Colville Arc active at least 17 Ma ago, was split on its forearc side when opening of the Havre Trough commenced (Eccles et al., 2012). The present day Colville Ridge is interpreted as the remnant of the volcanoes of the Colville Arc. By contrast, the Kermadec Ridge to the east is comprised of volcanic sediments that would have formed the ring plain around the ancient volcanoes. These sediments have since been back-tilted and uplifted to form the Kermadec Ridge. An important implication of this is that it is the Colville Ridge that is more likely to host mineral resources such as volcanogenic massive sulphide deposits than the Kermadec Ridge.

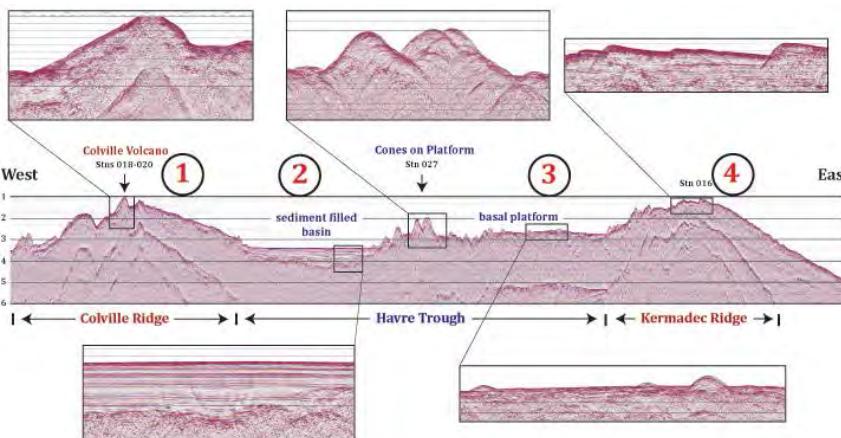
An example of one of these MCS profiles, acquired during the NIRVANA voyage, is shown in Figure 1. It shows from east to west:

1. An eroded volcano of the Colville Arc (Colville Volcano; Wysoczanski et al., 2014) sitting atop the Colville Ridge, which shows no seismic structure indicating it is comprised of hard volcanic rock
2. Deep sediment filled basins. Notably the base of these basins is the same depth

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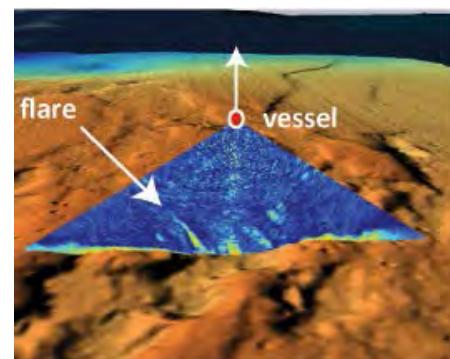


FIGURE 1. MCS profile conducted during the NIRVANA voyage, from the Colville Ridge in the west, across the Havre Trough, and over the Kermadec Ridge in the east (from Wysoczanski et al., 2013). Numbered circles refer to bullet points described in the text. The vertical scale has been exaggerated.

FIGURE 2. An example of an echogram, showing a hydrothermal vent plume, generated by a single MBES ping as described in the text. The echogram forms a triangle from the point source (the vessel) and extends laterally to the sea floor. As the vessel continues to move (here towards the top of the figure) further echograms are generated that can be stacked into long profiles. The echograms are coloured by amplitude of the sonar reflection, which indicates the density contrast between the object imaged and the surrounding water.

as the deep sediment-poor basins of the southern Havre Trough indicating that the only difference between basins in the north and south is that the northern basins are filled with sediment derived from the Colville Ridge; the southern basins are sediment starved as the Colville Ridge is too thin at that location to provide sediment. Also notable is that the sediment package is nearly 1 km thick and shows no evidence of faulting except at its base, suggesting that the basins in the west ceased rifting shortly after opening of the Havre Trough began.

3. A basal platform in the central Havre Trough topped with volcanic cones. The lack of seismic structure indicates that the platform is comprised of hard volcanic rock, although whether it is old Colville crust that has been rifted or new crust formed during opening of the Havre Trough is equivocal. The cones however are young and the shallow sediment filled basins are faulted suggesting more recent tectonic activity in the east than the west.
4. Back-tilted sediments of the Kermadec Ridge, indicating a volcanogenic sediment origin for this ridge with little or no magmatic activity.

These results provide a new interpretation of the development of the ridges and trough: that the Colville Arc rifted on its forearc side, that the Colville Ridge is the dissected Colville Arc chain, and that there is no difference, other than sediment infill, between the basins of the northern and southern Havre Trough. This new model of the system has only been made possible by the acquisition of MCS data, which was not previously available when older models were constructed.

DETECTING AND IMAGING HYDROTHERMAL VENTS THROUGH ACOUSTIC WATER COLUMN DATA.

As with seismic acquisition, MBES technology has become an essential tool for imaging beneath the sea surface; in this case

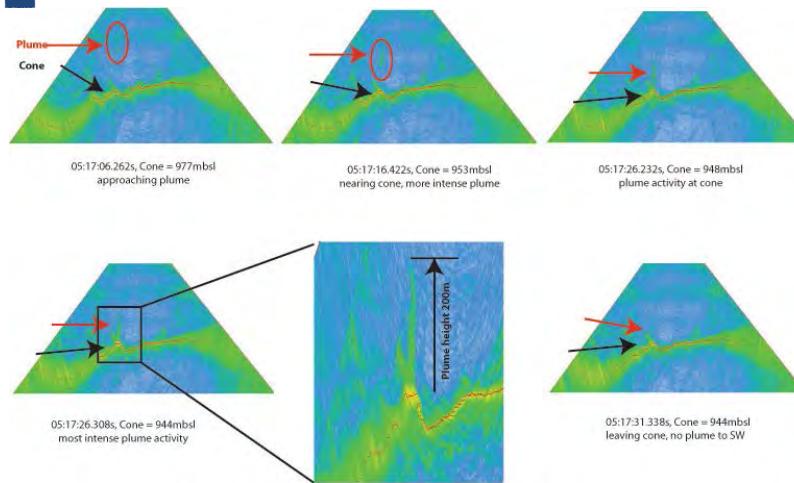
for generating maps of the seafloor rather than the sub-seafloor. MBES technology has developed rapidly, with echosounders specifically designed for different water depths, including high resolution (1 m) systems mounted on autonomous underwater vehicles that provide stunning images of features on the ocean floor. One important advance in recent years is the ability of MBES systems to image not just the seafloor, but the water column, allowing us to detect features in the water that provide a backscatter signal, such as hydrothermal plumes.

Gas bubble and fluid discharge are easily identified as water-column "flares" on sonar echograms (Figure 2). Backscatter echoes generated within the water column are recorded using shipboard MBES, such as NIWA's Kongsberg EM302 system. Each echosounder ping provides a 2-dimensional triangular echogram from the ship, extending laterally to the ocean floor (Figure 2). Individual echograms are generated as the ship moves providing continuous coverage of the water column. The width at the base of the echogram is 4 to 7 times larger than the water depth, i.e. in 1000 m of water a 5 km swath of seafloor for each ping is not uncommon.

An example of hydrothermal venting detected in deep water (> 900 m) occurred during the 2012 NIRVANA voyage to Havre volcano, which had erupted two months earlier (Wysoczanski et al., this volume). Multibeam mapping of the eruption site showed the growth of several small cones (< 250 m) during the eruption (Carey et al., 2014). Water column data detected a 200 m high hydrothermal plume emanating from one of these cones confirming that the volcano was hydrothermally active (Figure 3).

The ability of MBES water column data to locate hydrothermal plumes was also evident during the SAMSARA voyage in 2015, where water column data was collected over four volcanoes (Clark, Tangaroa, Rumble III and Rumble V) with

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known hydrothermal vent sites (de Ronde et al., 2007). These included sites of diffuse (low temperature) and focused (high temperature) vents. For each volcano, venting was imaged in the water column above the sites of known hydrothermal activity. Large plumes 200 m and 210 m high were imaged from Clark (Figure 4) and Rumble III, respectively. In some cases, re-surveying of the vent sites showed activity to be ephemeral.

Water column data collected by MBES is a new way to detect the presence of hydrothermal vents and to monitor their activity. This includes low temperature diffuse venting, which can otherwise be difficult to detect. However there are complications. First of all, swim bladders of fish produce reflective intensities similar to seep bubbles and care must be taken not to misidentify colonies of fish as hydrothermal plumes, such as showing a point source on substrate for the plume. Second, not all vents may be visible as gas bubbles capable of disturbing the beam may not emanate from some vents, e.g. due to low temperatures or deep water inhibiting gas separation. The more expensive and time consuming technique of He isotope analysis of the water column (e.g. de Ronde et al., 2007) is still the most definitive method of locating hydrothermal vents. However, as shown here, water column data is also a viable means of detecting hydrothermal vent activity – and of monitoring temporal changes on a short (hourly) to long (yearly) scale.

FUTURE INITIATIVES.

Geophysical surveying remains an integral tool for understanding the processes that have occurred, and are occurring, in the Kermadec Arc. In the case of the techniques described here, further seismic and water column surveys will be conducted in future. In addition to MCS surveys, significant seismic survey initiatives would include the deployment of ocean bottom seismometers to monitor seismic and acoustic events in the Kermadecs, and of seismic refraction profiles to provide images of the deep crust

and mantle. As water column data imaging is a new technique, very little data has been collected in the Kermadec region to date. However, as it can now be collected routinely during any bathymetric survey the areal extent of the water column imaged should rapidly increase with each future marine survey. The data collected will give us important insights into the location and activity of hydrothermal activity and perhaps can even be adapted for other applications, such as in fisheries.

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FIGURE 3. Echograms acquired over Havre volcano on the 16th October 2012, during the NIRVANA voyage. The series of echograms are time stamped and show the echograms acquired as the vessel travels towards a hydrothermal plume emanating from one of the new volcanic cones formed during the eruption. At first the plume is seen only in the water column, but as the vessel travelled over the cone the plume can be seen to originate from the cone's summit. After the final echogram, acquired five seconds after the previous one, no sign of the plume indicating could be seen, indicating that it was dispersed in the opposite direction (to the northwest) to the vessel's course (to the southeast).

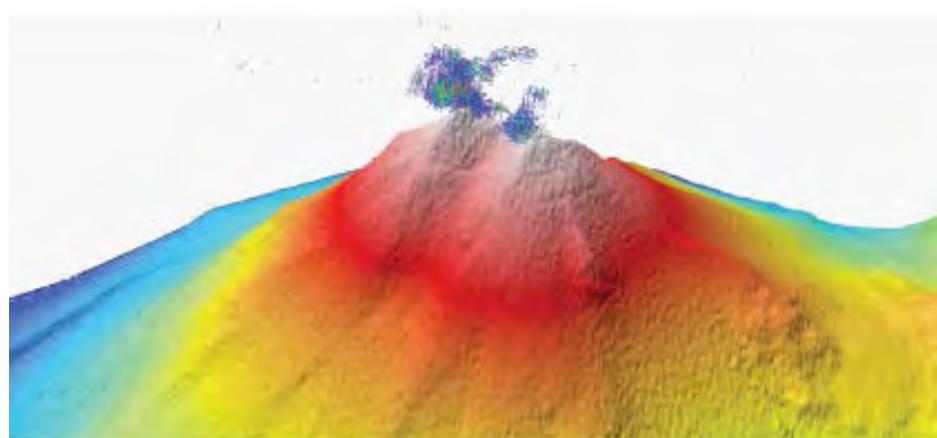


FIGURE 4. MBES data from multiple swaths acquired over Clark volcano were combined to produce a 3D image of the NW cone of Clark volcano. Hydrothermal vents, at the sites described by de Ronde et al. (2014), can be seen emanating from the cone

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The Colville Arc: Insights into the magmatism that shaped the Colville and Kermadec Ridges

Monica Handler, Richard Wysoczanski, Christian Timm

INTRODUCTION

The modern Kermadec region is shaped by magmatism generated by the collision of the Pacific and Australian tectonic plates (Figure 1). The Pacific plate dives (subducts) beneath the Australian Plate giving rise to the arcuate chain of largely submarine volcanoes that form the active Kermadec volcanic arc, stretching some 1600 km northward of New Zealand's Bay of Plenty and including the emergent Kermadec Islands. Subduction zones such as the Kermadec Arc are sites of potentially explosive volcanism and of crustal growth, and are also a major interface for recycling of material among the deep Earth, the crust, the oceans and atmosphere via subduction, magmatism and hydrothermal venting.

Some of the major volcanic and bathymetric features defining the Kermadec region are the result of an older manifestation of subduction volcanism. The Colville volcanic arc was active from at least ca. 17 Ma until opening of the Havre Trough split the Colville Arc asunder, producing two sub-parallel ridges: the Colville Ridge to the west and Kermadec Ridge to the east (e.g. Mortimer et al., 2010). These two ridges bracket the modern Kermadec arc – Havre Trough back-arc system.

Most research into magmatism in the region has focused on the active Kermadec arc volcanoes and, to a much lesser extent, the ridges and basins of the actively rifting Havre Trough. The Colville and Kermadec Ridges however, represent approximately 30% of the magmatic material produced by subduction processes in this region, yet little is known of the composition or history of these edifices. Investigations into the magmatic history of the Colville Arc provide insights into the tectono-magmatic history of the region and how subduction systems evolve from individual stratovolcanoes, as typified by the modern Kermadec Arc, to more mature ridge-like edifices produced by the Colville Arc.

COLVILLE ARC LAVAS

Fresh lava samples from the Colville and Kermadec Ridges were collected in three dredges undertaken by the R/V *Tangaroa* KARMA cruise (Kermadec ARc Minerals) in May 2010 (Figure 1). Major and trace element data and mineral chemistries of the Colville Arc lavas can be compared to modern day Kermadec Arc and Havre Trough lavas, with both similarities and striking differences observed.

The Colville lavas range in composition from basalt to basaltic andesite (46 – 53 wt% SiO₂), with variable vesicularity (0 – 25%), and contain an abundance of crystals (phenocrysts), up to 60% (e.g. Figure 2). The most striking differences from lavas of the modern arc are the accumulation of a large crystal cargo dominated by plagioclase, with rare orthopyroxene and olivine, and distinctly higher potassium contents in both the lavas and the minerals (Figure 2). The bulk lava compositions represent a combination of liquid melt and crystal cargo. Quenched magmatic melts, however, are also present as groundmass glasses and olivine-hosted melt inclusions in a Kermadec Ridge sample. These follow classic tholeiitic melt evolution trends that are very similar to the modern volcanic front magmas and melts, but are offset to higher K₂O contents (Figure 2). By contrast, the bulk lavas differ markedly from the modern Kermadec Arc lavas, with generally lower SiO₂ and MgO, and higher Al₂O₃ and K₂O concentrations (figure 2). All but K₂O can be explained by accumulation of plagioclase crystals, whereas the higher K₂O concentrations in the Colville Arc lavas and accompanying higher K₂O contents of the plagioclase crystals require the magmatic system to have been distinctly more K-rich in the past. The higher crystal loads also suggest significant differences in the magmatic plumbing system in the ridges compared with the present day volcanoes.

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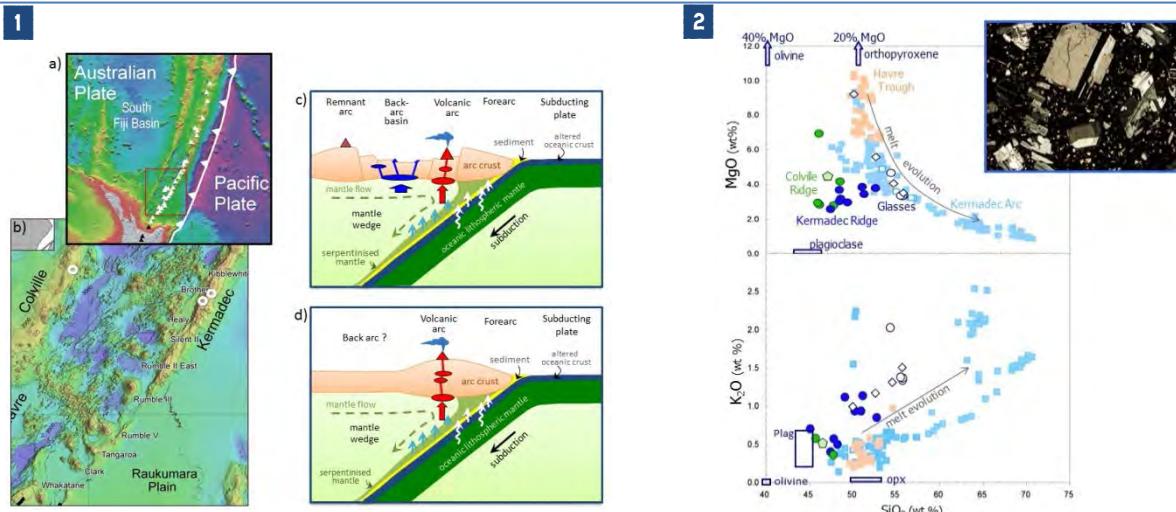
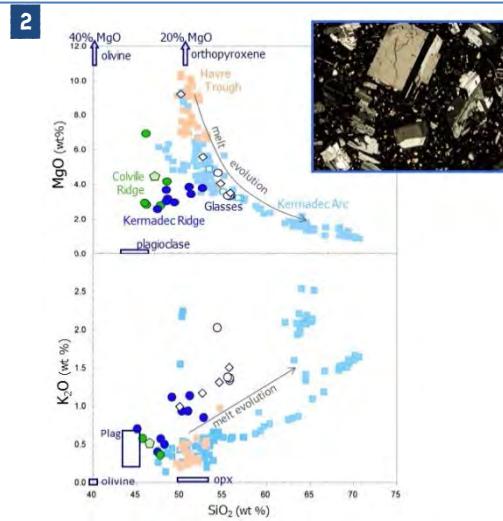


FIGURE 1. - a) - b)
Bathymetric maps showing the Kermadec arc volcanoes (white triangles) and boundary between the Pacific and Australian Plates (a), inset showing location of the sample dredges (white circles) (b).
c)- d) Schematic cross sections running NW-SE across the plate boundary showing the modern Kermadec arc - Havre Trough back arc system and remnants of the Colville arc (c) and likely configuration of the older Colville arc (d). White and pale blue arrows represent transfer of elements via fluids or melts into the overlying mantle wedge. Red arrow represents melting of mantle wedge to produce volcanic front magmas, blue arrow indicates melting beneath the back arc basin.

FIGURE 2. Major element compositions (MgO and K_2O vs SiO_2) of bulk samples from the Colville arc (Colville Ridge = green circles, Kermadec Ridge = red circles), modern Kermadec arc (pale blue squares) and Havre Trough back arc (pink squares). Quenched melts (glass) shown by open diamonds (melt inclusions), open circles (groundmass glass) and open squares (Kermadec arc glasses). The composition of mineral phases are shown by labelled boxes (plag = plagioclase, opx = orthopyroxene). The bulk samples are a mixture of melt (glasses) and minerals (mainly plagioclase, with lesser amounts of orthopyroxene \pm olivine). Inset - photomicrograph of a thin section of a Colville lava from the Kermadec Ridge, in cross-polarised light, showing large grey phenocrysts of plagioclase in a dark glassy groundmass. Field of view approx. 2 cm.



Trace elements provide insights into mass movement of elements through the subduction zone. Elements that are typically mobilised by fluids or sediment melts trace the dehydration of the subducting Pacific oceanic plate and melting of subducting sediment, respectively, as the oceanic plate descends into the mantle, and the transfer of these elements from the Pacific plate to the magma source (mantle wedge) and ultimately into the overlying crust (e.g. Figure 1). Classic indicators of fluids (e.g. Ba/Nb ratios) and sediment melts (e.g. La/Sm) show no significant difference between the recycled subducted components of the older Colville and modern Kermadec arcs, suggesting the dynamics of the subducting plate have not changed substantially over time. By contrast, trace elements that are not affected by these recycling processes suggest the nature of the mantle source has changed. Specifically, tracers of prior melt depletion of the source (e.g. Nb/Zr) are more similar to the modern back arc basin lavas of the Havre Trough than to the modern volcanic front lavas. This can most simply be explained if there was no back arc basin associated with Colville Arc (Figure 1), and hence that extension and rifting commenced with the opening of the Havre Trough some 2 - 5 million years ago with volcanic arc magmatism being refocused along the new Kermadec Arc.

over time. How, and over what time frame, were the ridges of the Colville Arc constructed and then pulled apart to essentially start over with a new locus of volcanic activity?

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FUTURE INITIATIVES

The samples of the Colville Arc presented in this study quite literally just scrap the surface of the major magmatic edifices of the Colville and Kermadec Ridges. Since the 2010 R/V *Tangaroa* voyage, further expeditions have been undertaken or are scheduled to map and sample the Colville Ridge and immediate surrounds, including a multinational, German-led expedition of the R/V *Sonne* in early 2017. Such programmes of seafloor mapping and targeted sampling, ideally through the use of remotely operated vehicles and other submersibles, are critical to build up an understanding of how this tectonic boundary has evolved

Havre 2012: The largest historic submarine eruption the world has never seen

Richard Wysoczanski, Monica Handler, Rebecca Carey

INTRODUCTION

The eruption of Havre volcano in July 2012 is the largest submarine eruption ever documented. Despite its size (it was larger than the destructive eruption of Mt Tarawera in 1886) the eruption was not actually seen and evidence of an underwater eruption was only discovered several weeks later when its most conspicuous product, a pumice raft covering an area the size of Canterbury, was sighted. The search for the source of the pumice raft ensued, with satellite imagery and seismic data suggesting that it originated from Havre volcano in the northern Kermadec Arc.

VOLCANOES OF THE KERMADEC ARC

The Kermadec Arc is a chain of ~ 40 volcanoes extending some 1600 km northwest from New Zealand (Wysoczanski and Clark, 2010). To the south lie the volcanoes of the offshore Bay of Plenty and Taupo Volcanic Zone of central North Island, built atop continental crust. The volcanoes of the Kermadec arc, however, occur on oceanic crust with a base as much as 4000 m below the sea surface. Despite the depth of their base many are larger than Mt Ruapehu, with Rumble III being twice the size. In a few cases the tips of volcanoes are emergent above the sea surface: these peaks compose the Kermadec Islands.

Volcanos generally occur as two types: large conical stratovolcanoes such as Mts Taranaki and Ruapehu, and caldera volcanoes with large elliptical vents, such as Lake Taupo. Stratovolcanoes produce magma that forms lava flows, whereas caldera volcanoes tend to produce large highly explosive eruptions that can generate substantial amounts of pumice. Havre volcano is a submerged caldera volcano at the southern end of the Kermadec Island chain that in 2012 explosively erupted to produce a large amount of pumice that breached the ocean surface to form a

pumice raft that spanned much of the Pacific.

THE PUMICE RAFT AND THE HUNT FOR ITS ORIGIN

The first sighting of the pumice raft was by a passenger, Maggie de Grauw, on a commercial flight from Apia to Auckland, on July 31st, 2012. Within days scientists worldwide, including in New Zealand, Australia, Belgium, Tahiti, the US and the UK, were searching for the source of the raft. Through a combination of earthquake and hydroacoustic data and NASA's MODIS satellite images the origin of the raft was linked to an eruption of Havre volcano on July 17th. On August 10th, a NZRAF Orion patrol plane flying from Samoa to New Zealand photographed the raft, which then spanned an area the size of Canterbury. The location of the raft was relayed to the *HMNZS Canterbury* then on route to Raoul Island. The vessel diverted from its course to intercept the raft, which they found to be 0.6 – 1.0 m thick and composed of pumice ranging from cm-sized clasts to clasts larger than a soccer ball. A few days later, when the crew reached Raoul Island, they found clasts of the pumice scattered on the beach. Over the next several years the raft dispersed pumice across the Pacific, with for example, pumice washing up on beaches in northern New Zealand, Australia and Tonga.

A more complete description of the search for the origin of the pumice raft can be found in the September 2012 issue (volume 37. No. 9) of the Smithsonian's Bulletin of the Global Volcanism Network. An account of the first encounter of the raft on board *HMNZS Canterbury* can be found in Priestley (2012). A detailed description of the dispersion of the raft is presented in Jutzeler et al. (2014).

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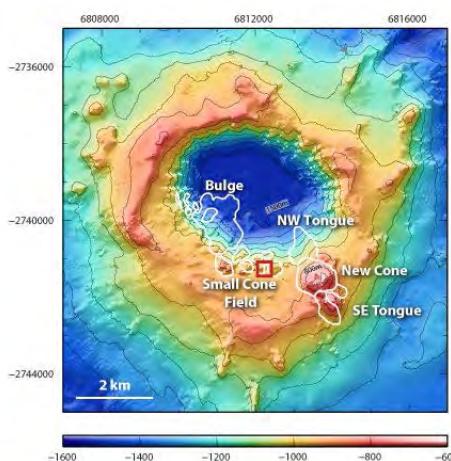


FIGURE 1. Havre volcano in the Kermadec Arc, ~900 km NNE from the Bay of Plenty. Changes to the seafloor found during the *R/V Tangaroa* voyage in October 2012 are shown, with new cones and a bulge in the SW caldera rim prominent features of the eruption (from Carey et al., 2014). The red box in the Small Cone Field is enlarged as Figure 2.

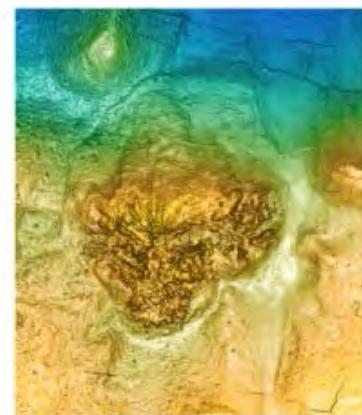
FIGURE 2. Enlarged view of a cone of the Small Cone Field (red box of Figure 1) as mapped by EM122 shipboard bathymetry (left) and AUV *Sentry* bathymetry (right). Both images were acquired during the *R/V Roger Revelle* voyage in 2015 and clearly show the vastly superior resolution of the bathymetry acquired by AUV operations. Field of view is ~350 m across.

2



Havre_EM122

Havre_Sentry



VOLCANIC PRODUCTS OF THE ERUPTION AND THE NEED FOR SUBMERSIBLE VEHICLES.

In October 2012 a NIWA voyage of the research vessel *Tangaroa* examined Havre volcano two months after the eruption. Comparison of bathymetric data collected during this survey with data collected prior to the eruption (Wright et al., 2006) found evidence for the growth of several new volcanic features up to 250 m high, and up to 50 m of new material on the western rim of the caldera wall (Carey et al., 2014). Material recovered from the volcano was found to be of the same composition as pumice sampled from the raft and deposited on beaches in northern New Zealand, confirming the volcano as the source of the raft. The volume of material erupted was estimated at 1.5 km² and the magnitude of the eruption at 5 on the volcanic explosivity index (Newhall and Self, 1982). Put into perspective, subaerial eruptions of this size occur five times per century, with the Havre eruption being larger than both the fatal Mt St Helens eruption of 1980, and the Tarawera eruption of 1886 that destroyed the pink and white terraces.

In March 2015 a second voyage to Havre, funded by the US National Science Foundation, was conducted using the Scripps Institute of Oceanography research vessel *Roger Revelle*. This voyage included the dual deployment of the AUV (autonomous underwater vehicle) *Sentry*, used to construct a high resolution map of the volcano, and the ROV (remotely operated vehicle) *Jason*, to collect samples of the eruption products and images of the seafloor. This survey, based on significantly more intense surveying and sampling than the previous shipboard survey, resulted in the most detailed examination of a submarine eruption from a caldera ever undertaken.

The unique combination of detailed mapping by *Sentry*, and the sampling and video images taken by *Jason*, revealed a desolate submarine landscape devoid of life presumably decimated by the eruption and not yet recovered. Whereas shipboard bathymetry (at a resolution of ~ 25 m) could only reveal changes to the seafloor, mapping by *Sentry* (at 1 m resolution) and imagery by *Jason* showed a number of individual lava flows, giant car-sized pumice blocks, mass wasting deposits, volcanic domes, ash deposits and hydrothermal venting. The data from this survey will be analysed for several years to come, yet already our knowledge of the products and transport styles of large pumice-producing submarine eruptions, never before seen *in situ*, has changed our understanding of these dramatic eruptions. Importantly, it is only with the use of state of the art technology such as AUV's and ROV's that we are able to more comprehensively understand submarine processes. Shipboard surveying, whilst fast and adequate for many purposes, only reveals the shadows of the sea floor: submersibles the full colour picture (Figure 2).

HAVRE 2010: INCREASING OUR UNDERSTANDING OF SUBMARINE VOLCANIC ERUPTIONS

The results of the two surveys to Havre show a complex picture of the eruption dynamics of a large submarine caldera eruption. Notably, they show that volcanic pumice-producing eruption plumes can originate from vents 900 m deep, and that the overlying water mass does not prevent plumes from entering the Earth's atmosphere. They also highlight the fact that the submarine volcanoes of the Kermadec Arc are chemically distinct: pumice from the raft, pumice washed up on beaches across the Pacific, and pumice from the seafloor at Havre volcano were all found to be chemically similar and distinct from pumice produced from other Kermadec

arc volcanoes. Indeed pumice from other volcanoes were also found to be chemically unique to each individual volcano, potentially allowing the origin of pumice rafts both past and future to be identified. Furthermore, it was several weeks before the eruption was even known to have occurred, and then only through serendipity due to the keen eyes of an airline passenger. How many eruptions occur on the ocean bottom and go unnoticed? Just how volcanically active are volcanoes of the world's oceans? Perhaps most surprising of all is that the surface manifestation of this eruption – a pumice raft – does not at all represent the diversity and often synchronous eruptive activity of multiple vents on the seafloor. The ~5 km wide caldera structure itself was virtually unmodified during this event, raising the question just how large (and destructive) was the eruption(s) that formed Havre's caldera and those of the similar caldera volcanoes of the Kermadec Arc?

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Deep-sea benthic sampling in the Kermadec region: recent research efforts and the need for a coordinated and integrated approach to future sampling

Malcolm R. Clark, Ashley A. Rowden, Geoffroy Lamarche

A QUICK RECAP

Clark et al. (2010) described three general phases of deep-sea survey work and biological sampling in the Kermadec region:

- 1) Historical expeditions—these comprised the large global exploration surveys of the *Challenger* (1874), *Galethea II* (1952), and *Vityaz* (1958).
- 2) Mixed New Zealand institute sampling—the period from 1960 through to the late 1990s saw wider geological, oceanographic, and biological surveys by the New Zealand Oceanographic Institute, Ministry of Fisheries, and the newly formed NIWA. Most surveys occurred close to the Kermadec Islands, or inshore Bay of Plenty. However, in the 1990s there was an increase in geological studies of the Kermadec Arc seamounts, and interest in commercial fisheries and their bycatch.
- 3) Targeted biological surveys—during the decade from 1999 to the first symposium in 2010, there were a number of survey programmes developed through the government’s “public good science fund” that had specific biological objectives to improve knowledge of biodiversity. There was also a shift towards more integrated and multidisciplinary studies, and the start of surveys focused on assessing mineral resources of the region. This phase also saw the development of strong international linkages with Germany, Japan, USA, Canada, and the UK.

The status of deep-sea benthic invertebrate sampling in 2010 was that there were about 400 sampling stations recorded in the NIWA Invertebrate Collection database, with 2400 records (“lots”) of invertebrate taxa, comprising approximately 240 “species” (operational taxonomic units). Fish

records held at Te Papa comprised 570 lots of deep-sea taxa, with 43 species known.

CURRENT RESEARCH

Since 2010, research surveys have continued their focus on the seamounts of the Kermadec Arc, with a particular emphasis on understanding the geological nature and environmental characteristics of mineral deposits. However, considerable research has also been undertaken at almost the other extreme, the Kermadec Trench, which at about 10 km depth is one of the deepest areas of seafloor on the planet. In total, there have been 11 major voyages that have included sampling in the proposed Ocean Sanctuary, or the area immediately to the south along the back-arc (Table 1).

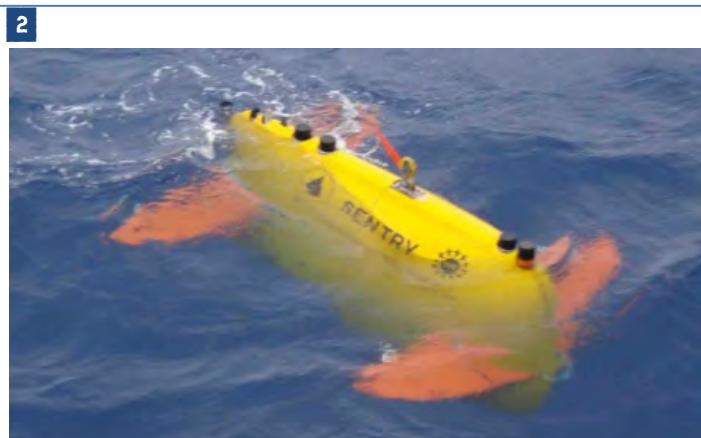
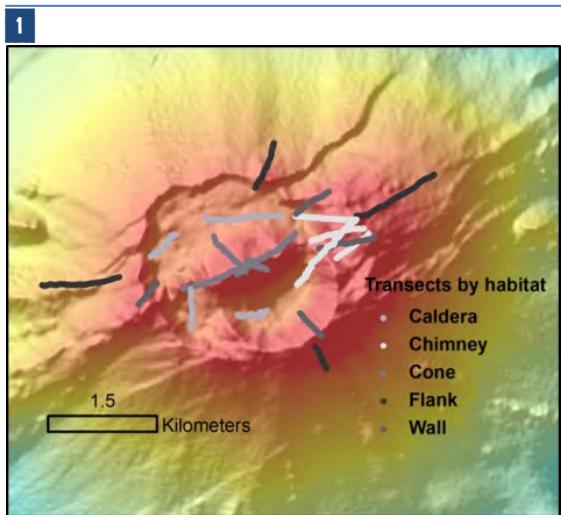
KERMADEC ARC

The suite of surveys that covered a variety of back-arc seamounts have progressed three key aspects of investigations into the biodiversity of the region:

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TABLE 1: Summary of research voyages carried out in the general Kermadec region between 2010 and 2015. Parentheses indicate limited, or selected, sampling

Year	Voyage	Location	Camera	Samples
2010	TAN1007	Rumble II West, Brothers seamounts	Yes	Yes
2011	TAN1104	Clark, Brothers, Healy, Lillie, Rumble III seamounts	Yes	Yes
	Neptune	Rumble II West, Rumble IV, Brothers, Clark seamounts	Yes (ROV)	(Yes)
	KAH1109	Kermadec Trench	Yes (lander)	(Yes)
2012	TAN1206	Whakatane, Tangaroa, Clark seamounts	Yes	Yes
	TAN1213	Clark, Tangaroa, Rumble III, Havre, Rumble IV, Rumble V, Sonne, SO1 seamounts	No	Yes
	KAH1202	Kermadec Trench	Yes (lander)	(Yes)
2013	YK13-11	Hinepuia Seamount	Yes	(Yes)
	KAH1301	Kermadec Trench	Yes (lander)	(Yes)
2014	HADES	Kermadec Trench	Yes	(Yes)
2015	MESH	Havre Seamount	Yes	(Yes)



- understanding of broad patterns of hydrothermal vent communities, and describing the composition of associated, but inactive, communities
- additional sampling to fill gaps in the middle and northern region of the Kermadec Arc where seamounts had not been sampled
- surveying areas of the Colville Ridge (to the west of the Kermadec Ridge) that has been very poorly sampled

The “KARMA” survey (TAN1007) studied three southern Kermadec Arc seamounts in detail, with both geological and biological objectives focused on understanding the characteristics of active and inactive sites of interest for their seafloor minerals (SMS; seafloor massive sulphides). Brothers has SMS and is active, Rumble II West has SMS but is largely inactive, and Rumble II East does not have SMS, and is inactive. In addition to among-seamount comparisons, the survey was stratified within seamounts, with sampling of the cone, outer flank, caldera wall, chimney field and caldera floor features (Figure 1). This sampling provided extensive biological data that was presented at the symposium, and described by Boschen et al (this volume).

SMS mineral deposits were also the target of a commercial survey by Neptune Resources in 2011, which focused on Rumble II West with photographic transects carried out by an ROV. This survey covered both areas of commercial prospectivity, and a potential reference (protected) site.

Detailed bathymetric mapping and studies of the geochemistry of seamounts to understand SMS distribution was also a central objective of “NZASMS” (TAN1104), which was a collaborative survey between GNS, Woods Hole Oceanographic Institution (WHOI), and NIWA. This survey used the WHOI autonomous underwater vehicle “Sentry” (Figure 2). A biological

highlight was the first benthic sampling of Cotton and Lillie seamounts.

The “NIRVANA” survey (TAN1213) covered a large area from 30°S to 37°S, including active vent sites (Havre, Rumble III, Rumble V), inactive ridges (Colville and Kermadec) and deep basins in between the ridges. Although geological sampling was the main priority, extensive biological collection also occurred, with a number of new species records from a seamount on the Colville Ridge.

Assessing the biodiversity of multiple habitats was the key driver of NIWA’s Vulnerable Deep-Sea Communities project. Its second survey (TAN1206) sampled a number of seamounts, as well as hydrothermal sites, canyon, and slope areas in the southern Kermadec region. This survey, coupled with an earlier one on the Hikurangi margin near Cook Strait, has found differences in species composition and abundance among habitats, as well as differences in biodiversity patterns between areas.

Active seamounts in the northern region of the Kermadec Arc were a target of the joint JAMSTEC-NIWA-GNS voyage (YK13-11), which was part of a global Japanese survey of deep and extreme habitats. Two dives of the Shinkai 6500 submersible were carried out on Hinepuia volcano, which was believed to be active, but had never been sampled. A hydrothermal vent source was located, with extensive beds of a bathymodiolid mussel (Figure 3).

The last survey of the back-arc complex was conducted by US researchers in 2015, and involved principally geological investigations of the effects of the volcanic eruption in 2012 (see paper in this volume by Handler et al.) with seafloor mapping, photography and sampling with an ROV.

KERMADEC TRENCH

The Kermadec Trench has been the

FIGURE 1. Photographic transects carried out during TAN1007 on Rumble II West Seamount, showing the sampling stratification by topography.

FIGURE 2. The AUV “Sentry” about to commence a dive during the TAN1104 research voyage

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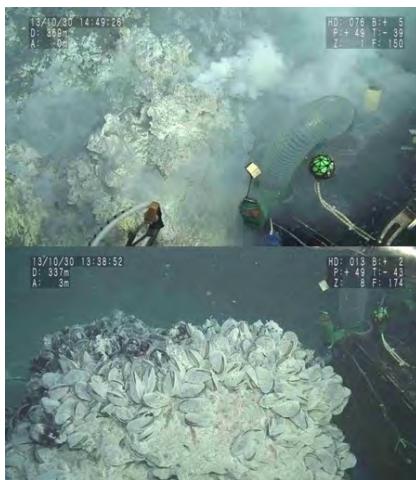


FIGURE 3. Hinepuia Seamount, showing the hydrothermal vent (top) and a bed of bathymodiolid mussels (bottom) imaged from the submersible during the YK13-11 research voyage.

FIGURE 4. Deploying a hadal lander off R.V. Kaharoa, targeting the seafloor of the Kermadec Trench 10 km below.

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subject of the international research programmes "HADEEP" and "HADES".

HADEEP was a global project lead by the University of Aberdeen and partnered in the New Zealand region by NIWA. Surveys included all the large trenches in the Pacific Ocean. There were 4 surveys of the Kermadec Trench, using baited photographic landers (Figure 4), and crustacean and fish traps. In addition to investigating latitudinal (trench axis) and longitudinal (depth) gradients within the Kermadec Trench, sampling enabled detailed comparisons with biodiversity in other Pacific trenches (e.g., Tonga, New Hebrides, Marianas, Peru-Chile).

HADES, with a large international contingent of scientists lead by the US, surveyed the trench in 2014. This survey, using the WHOI hybrid ROV *Nereus*, landers, and traps, is described by Mills et al. this volume).

THE CURRENT STATUS

The surveys described above have considerably improved our coverage and sampling intensity in the area of the proposed Kermadec Ocean Sanctuary. A further 200 invertebrate records have been added to the NIWA Invertebrate Collection database, and a large number of seafloor photographs have been collected. Additional sampling of the Colville Ridge, as well as new sites along the back-arc, have expanded the coverage from 2010 (Figure 5). Importantly, the sampling conducted along the Arc to the south of the sanctuary area (e.g., TAN1007, Neptune, TAN1104) and in multiple habitats (e.g., TAN1206, TAN1213) is improving our understanding of patterns of biodiversity, and the environmental drivers affecting benthic community composition and abundance in the general Kermadec region.

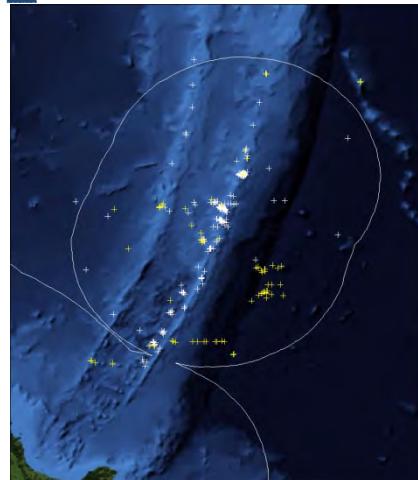
FUTURE RESEARCH

The key issues remain largely the same as those described in 2010. In particular

there are three main aspects of sampling that need to be improved:

- 1) Many parts of the Kermadec region remain unsampled. The spatial coverage has improved since 2010, but there are still large gaps in the geographical coverage. In addition, there has been a strong sampling bias towards depths down to 1500 m, and little sampling below this depth to provide an understanding of the biodiversity of deeper ecosystems. Temporal coverage is also poor, with few sites being monitored over time to understand longer term changes in their biodiversity.
- 2) Research has concentrated on seamounts, but needs to focus more on the Kermadec Ridge, the adjacent Colville Ridge, as well as the Havre Trough, Kermadec Trench, Louisville Ridge, and the deep abyssal plains and basins. Only with improved knowledge of the multitude of habitat types in the area, and taking a community-level approach, can biodiversity of the Kermadec Ocean Sanctuary area as a whole be fully described and evaluated against the wider regional fauna.
- 3) Few sites have been sampled intensively, and even on the seamounts the mega epifauna is not completely known, let alone infauna or macro- and microfauna. The TAN1007 survey showed the gains that can be made with more intensive sampling on a smaller number of sites, but this detailed approach needs to be partnered with wider-scale studies to provide the regional context. A range of gear types, and disciplines, is needed to describe biodiversity and its associated environmental determinants.

The challenges facing the achievement of this increased level of sampling include the need for a structured strategic plan to ensure the best science



is done in the right places at the right times. High technology equipment may be needed (stressing the need for international partnerships with AUV, ROV gear), and it is critical to retain, or increase, the skilled and experienced personnel required to carry out a coordinated and integrated research plan.

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The Foundation for Research, Science & Technology, Ministry of Science and Innovation, Ministry of Business, Innovation and Employment, Ministry of Fisheries, Department of Conservation, Census of Marine Life Seamounts Programme (CenSeam), and Neptune Minerals for funding and contributing to research in the area. We acknowledge the collaborative input of NOAA, JAMSTEC, WHOI, University of Aberdeen and GNS in recent international surveys. Thanks to Sadie Mills for database extracts. We acknowledge the efforts of The Pew Charitable Trusts in running the Symposium.

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FIGURE 5. The location of stations with records of benthic invertebrates in the general region of the proposed Kermadec Ocean Sanctuary (data from NIWA Invertebrate Collection). White symbols = samples taken before May 2010, yellow symbols = samples taken between May 2010 and April 2016.

Current status of the biogeography of hydrothermal vent communities of western Pacific Ocean back-arc basins and volcanoes

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INTRODUCTION

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. Since then studies have revealed that many species, such as certain clams and tubeworms, rely upon a process known as chemosynthesis. This alternative source of energy production is at the base of an entire ecosystem. Microbes are able to synthesize energy by metabolizing compounds, such as sulphides, contained within the hydrothermal fluids. In turn these microbes provide, either directly or indirectly, the energy source for the larger fauna. Some of the microbes live as endo or epi-symbionts with these fauna (Van Dover, 2000).

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 certain species of shrimp, snails, barnacles, mussels and other fauna. At vent sites where the occurrence of hydrothermal venting is relatively 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 chemosynthetic processes, there are a number of others that form a close yet indirect association with the hydrothermal vent site. These species are also considered to be part of what we call the vent community (Van Dover, 2000).

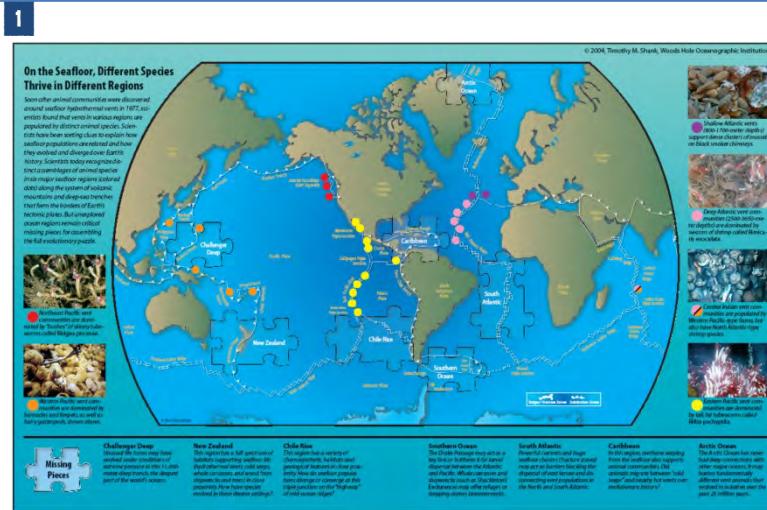
DEVELOPMENT OF A BIOGEOGRAPHY FOR HYDROTHERMAL VENT FAUNA

In 2002 the first account of global composition and distribution of vent communities was published with a biogeographic map. This biogeographic scheme identified six provinces, including a single western Pacific province, which did not include an analysis of any data from the New Zealand region (Van Dover et al., 2002). Two years later, Shank (2004) reproduced Van Dover et al.'s

biogeographic scheme on a map to identify the location of the 'missing pieces of the puzzle', that if filled should reveal much about the evolution of life at hydrothermal vents. The New Zealand region was one of the missing pieces identified by Shank (Figure 1).

The first biogeographic analysis of the western Pacific region was published in 2006. This scheme identified two provinces for vent fauna, but the authors chose not to include the sparse data available at the time for the New Zealand region in their analysis (Desbruyères et al., 2006). Therefore the relationship between the vent fauna of the New Zealand region and rest of the western Pacific continued to be unresolved.

The Census of Marine Life project on chemosynthetic ecosystems (ChEss) compiled data for vent fauna into a publicly available database (ChEssBase), which Bachraty et al. (2009) used as the basis for a new global biogeographic scheme. Their analysis, which included data from just two sites in the New Zealand region, identified six provinces. This scheme divided the western Pacific into two provinces, but the southwest Pacific province included the New Zealand region and also the Indian Ocean. Using some additional data, but a very different and innovative analysis method, Moalic et al. (2012) identified five global provinces for hydrothermal fauna. Their scheme placed the New Zealand fauna in a single western Pacific province. After sampling hydrothermal vents in the Southern Ocean, Rogers et al. (2012) added their data to those compiled by Bachraty et al. (2009) and re-analysed it using a different methodology. Their analysis identified 11 provinces globally, identifying four provinces in the western Pacific, including a distinct New Zealand province (Figure 2).



DEVELOPING A NEW VENT BIOGEOGRAPHY FOR THE WESTERN PACIFIC OCEAN

The most recent biogeographic schemes have included only very limited data from the early phase of sampling of deep-sea vents in 1998 (Wright et al., 1998) and 2001 (Clark & O'Shea 2001) in the New Zealand region. Since then targeted sampling and imagery, including that provided by manned submersibles and remotely operated vehicles (ROVs), has provided more data on vent fauna from over 20 sites along the Kermadec Arc. The use of specialised sampling technology has only been possible through collaboration between New Zealand scientific institutions and international partners from Japan in 2004 and 2013, USA in 2005, 2009 and 2014, and Germany and Canada in 2007. While some of these samples have been analysed and have provided descriptions of vent endemic species (e.g., Muira & Kojima, 2006; McLay, 2007; Ahyong (2009); Cosey & Marshall, 2010), and contributed to our basic understanding of the regional composition and distribution of vent communities associated with the Kermadec volcanic arc (described at the previous Kermadec Science Symposium, Rowden et al., 2010), data have not yet been compiled or analysed to help better define the biogeographic status of the New Zealand region.

NIWA does not have a vent-specific science project, but we have been collecting biological data from vents as a side product of a number of deep-sea projects that may, for example, focus on geological structure of the Kermadec Arc, seamount biodiversity, the potential effect of seabed mining, or through international collaborations. Some funding has recently been provided to facilitate a biogeographic analysis of New Zealand's fauna, and the findings of a preliminary analysis are briefly reported here.

For this analysis, data from eight vent sites on Kermadec volcanoes were added to the data compiled by Bachraty et al. (2009) for

the western Pacific only, and reanalysed using multivariate cluster analysis and a routine that identifies non-random structure in the similarity between faunal data from the sampled sites. This analysis identified four faunal groups (and one at an outlier site), or biogeographic provinces, which includes a distinct New Zealand province (Figure 3). While this analysis is only preliminary, the addition of more data (available since the initial compilation) to the analysis is expected to reveal the same result. There are a number of types of vent communities within the New Zealand region (Rowden et al., 2010), but they are all sufficiently distinct from those found elsewhere to consider the hydrothermal vent communities of the Kermadec area unique.

THE ENVIRONMENTAL MANAGEMENT IMPLICATIONS OF A DISTINCT NEW ZEALAND OR KERMADEC BIOGEOGRAPHIC PROVINCE

If the proposed Kermadec Ocean Sanctuary is implemented (<http://www.mfe.govt.nz/node/21209/>), the vent fauna that occur within the sanctuary area will not be disturbed by fishing, mining or oil extraction. But does this mean that the integrity of the New Zealand region's vent communities will be adequately protected?

In order to propose the Ocean Sanctuary, the government had to negotiate with parties that have established interests in the area identified for protection (<http://www.mfe.govt.nz/marine/kermadec-ocean-sanctuary>). For example they are currently in negotiation with Nautilus Minerals, which had applied for a Prospecting licence to potentially mine for sulphide deposits, which are found at current or relic hydrothermal vent sites. More than half of Nautilus's application area falls within the proposed sanctuary. To address this established interest, it is possible that the area just outside of the sanctuary, where Nautilus currently holds a prospecting permit, may be expanded.

FIGURE 1: The missing pieces in the global biogeography of hydrothermal vent fauna (source: Shank, 2004).

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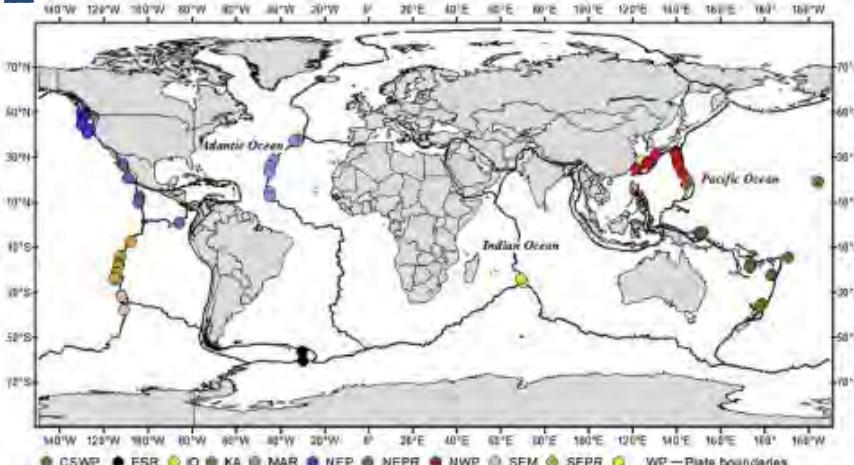


FIGURE 2: Global biography of hydrothermal vent fauna (Source: Boschen et al. 2013, after Rogers et al. 2012)

FIGURE 3: Preliminary biogeography of the hydrothermal vent fauna of the western Pacific Ocean (sites included in the analysis are numbered; site symbols with the same colours have similar vent communities; sites 19-26, coloured yellow, represent a distinct New Zealand province).

This area just outside of the sanctuary also contains vent communities, some of which the ones within the sanctuary. Some sites are within a fisheries Benthic Protection Area but these may be unprotected from any future deep-sea mining. Some of the communities contain vent-endemic species that are found within the sanctuary, but the continuation of populations there may depend on receiving larvae from outside of the sanctuary (Boschen et al., 2015, see also Gardner et al., this report). Thus, in order to ensure the protection of the unique vent communities of the New Zealand region, the Kermadec Ocean Sanctuary alone is insufficient. Rather a network of protected areas is required (Boschen et al., 2015, 2016), selected according to the international guidelines for protecting chemosynthetic ecosystems (Van Dover et al., 2012).

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All the scientists, in New Zealand and overseas, who have contributed to our knowledge of vent communities in the Kermadec region (there are many). All institutes in New Zealand and overseas who have actively supported and encouraged research in this field (there are not so many). All funders (there are even fewer).

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Ecological diversity of hydrothermal vents, and issues for management of seabed mining

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MINERAL RESOURCES OF THE KERMADEC REGION

The seabed within the New Zealand Exclusive Economic Zone (EEZ) offers multiple opportunities for mineral extraction, including seafloor massive sulfide (SMS) deposits. These form through hydrothermal activity and can occur at a tonnage and mineral grade comparable to land-based deposits, making them attractive to mining companies (Boschen et al., 2013; Hannington et al., 2011). Such deposits form along the Kermadec Volcanic Arc, stretching northeast from the North Island towards Tonga. Of the 78 seamounts along the Arc, at least 16 are known to be hydrothermally active (Fig. 1), with many of these occurring in areas that have been previously licenced for the prospecting phase of SMS mining (<https://permits.nzpam.govt.nz/aca/>). New Zealand deposits are particularly rich in copper, zinc, iron and gold, and occur within exploitable depths (Wright et al., 1998; de Ronde et al., 2011).

ECOLOGICAL DIVERSITY OF SMS DEPOSITS

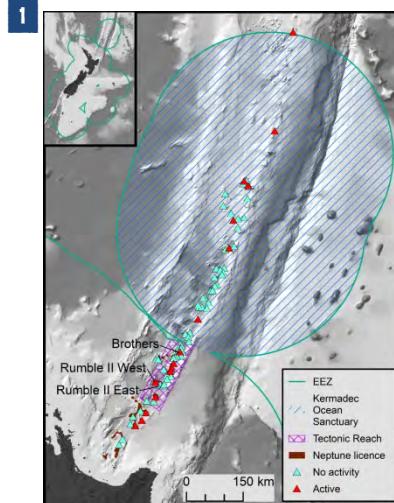
Sites of SMS deposition also have considerable biological value. Hydrothermally active areas support unique chemosynthetic communities that are reliant on the hydrothermal activity at these environments (reviewed by Van Dover, 2000). Where hydrothermal activity has ceased, relict (inactive) deposits support diverse communities of slow growing sessile suspension-feeders (Galkin, 1997; Collins et al., 2012), with the potential for development of a further community adapted to the weathered sulfide environment of inactive deposits (Van Dover, 2011). All these communities are vulnerable to mining disturbance, with mining activities expected to remove all large organisms and their habitat in the immediate area to be mined, along with downstream effects from turbidity plumes (Van Dover, 2011; 2014). Before suitable mitigation strategies for seabed mining can be designed, there needs to be a thorough understanding of the seabed communities that could be affected.

SEAMOUNT COMMUNITY STRUCTURE

Two surveys were undertaken on seamounts on the southern Kermadec Volcanic Arc to assess the structure of benthic communities potentially at risk from SMS mining. Towed video footage and environmental data were obtained to investigate the patterns of benthic megafauna distribution, community structure and association with environmental variables, both within and amongst three seamounts (Boschen et al., 2015). Each seamount had different levels of hydrothermal activity: Rumble II East has no history of hydrothermal activity, Brothers is hydrothermally active and Rumble II West is predominantly inactive (Fig. 1). They also occur within close proximity to one another (0.5° latitude) and have overlapping depth ranges: Rumble II East, 907 to 3017 m; Brothers, 1350 to 2250 m; Rumble II West, 1194 to 2994 m (Wright, 1994; Wright and Gamble, 1999).

Video transects were distributed randomly amongst broad-scale habitat strata (caldera floor, caldera wall, seamount cone, seamount flank and chimney fields) defined a priori based on general topography from a previous multibeam survey. Both fauna and substratum type were identified from the video, which was split into 200 m sections for analysis. Additional environmental parameters (depth, backscatter, rugosity, aspect, slope and three measures of curvature) were extracted from multibeam data. The relationship between the faunal distribution data and environmental variables was assessed using multivariate statistical routines.

In total, 186 putative taxa were identified from 249 video segments and assigned to 20 assemblage types (communities). Community structure was significantly different amongst the three seamounts, with some communities found at multiple seamounts and others appearing to be restricted to just one (Fig. 2). A priori defined habitat (nested within seamount) also contributed to explaining variation in community structure.



Magnetivity, as a proxy for hydrothermal activity, explained most of the variation in community structure amongst seamounts, with depth, topography, substratum (and magnetivity for Brothers) explaining most within seamounts. Overall, environmental proxies were able to explain 26 – 47% of the variation in community structure within and amongst seamounts.

A key result was the identification of ‘unique’ communities that were restricted to specific locations on individual seamounts. In the case of Brothers and Rumble II West, these communities appeared to coincide with hydrothermally-formed chimney structures, indicative of SMS deposits (Fig. 2). This provided some support for the existence of unique communities colonising inactive sulfides.

MINE AND REFERENCE SITE COMMUNITY COMPARISON

Patterns of benthic megafauna distribution and community structure were further examined in a second study, using video data from an industry survey with a Remotely Operated Vehicle (ROV). Two sites were surveyed, a proposed mine site (Proteus 1) and a proposed Reference Site close together on the northeast flank of Rumble II West (Boschen et al., 2016b).

Fauna and substratum type were identified from the video, which was split into 15 m segments for analysis. Additional environmental data (depth, backscatter, aspect, slope and three measures of curvature) were extracted from multibeam data. The relationship between the faunal distribution data and the environmental variables was again assessed using multivariate statistical routines.

In total, 42 putative taxa were identified from 153 video segments and assigned to 11 communities. Despite being only 200 m distant, the two sites had significantly different community structure, with only a subset of the total communities present located at the proposed Reference Site (Fig. 3). Whilst five communities were found at both sites, six communities were unique to

the proposed mine site. This suggests that on its own, the proposed Reference Site would not be representative and therefore insufficient as a protected area in the case of mining at Proteus 1.

The most important environmental descriptors in the models were largely those related to hydrothermal activity (active and inactive chimneys; dead vent mussel shells; altered sediment and oxide deposits). Communities unique to Proteus 1 occurred in locations associated with hydrothermal activity, including inactive chimney structures, providing further evidence for the existence of communities in association with inactive sulfides. The occurrence of hydrothermally active and inactive structures within close proximity suggests that protection should include a larger area that encompasses both habitat types.

KEY MANAGEMENT CONCLUSIONS

The surveys reported here show strong differences in community composition at a range of spatial scales. Such patterns require detailed surveys, as environmental proxies alone may be inadequate to reveal fine-scale complexity. Hence evaluation of management options needs to be based on robust baseline survey work, and operate over differing spatial scales. Large-scale patterns of biodiversity need to be known to establish the regional context of smaller areas/seamounts of interest to mining companies. However, even within a seamount, differing geophysical and geochemical conditions mean faunal communities will vary over 10s' of meters. This has important implications for the scale at which management needs to occur, and it will differ between sites.

One of the mitigation strategies to preserve benthic communities within a prospective mining region is by providing protected or ‘set-aside’ areas with similar physical and biological characteristics to the mine site that are designated as no-impact zones (Coffey Natural Systems, 2008; International Seabed Authority, 2010; Collins et al., 2012). Such protected areas need to support communities with taxonomic composition,

FIGURE 1. The location of marine boundaries, protected areas, SMS prospecting licenses and seamounts along the Kermadec Volcanic Arc, relative to New Zealand. Main figure: the New Zealand Exclusive Economic Zone (EEZ: green line), the Kermadec Benthic Protection Area (BPA) and the proposed Kermadec Ocean Sanctuary (blue diagonal lines), Tectonic Reach BPA (purple hash), Neptune Minerals Inc. prospecting licence areas (dark brown), and seamounts coded by hydrothermal activity: no hydrothermal activity detected (no activity: pale green triangles) and active (red triangles). The three labelled seamounts (Brothers, Rumble II West, Rumble II East) are the locations for the three studies. Inset: New Zealand mainland and EEZ.

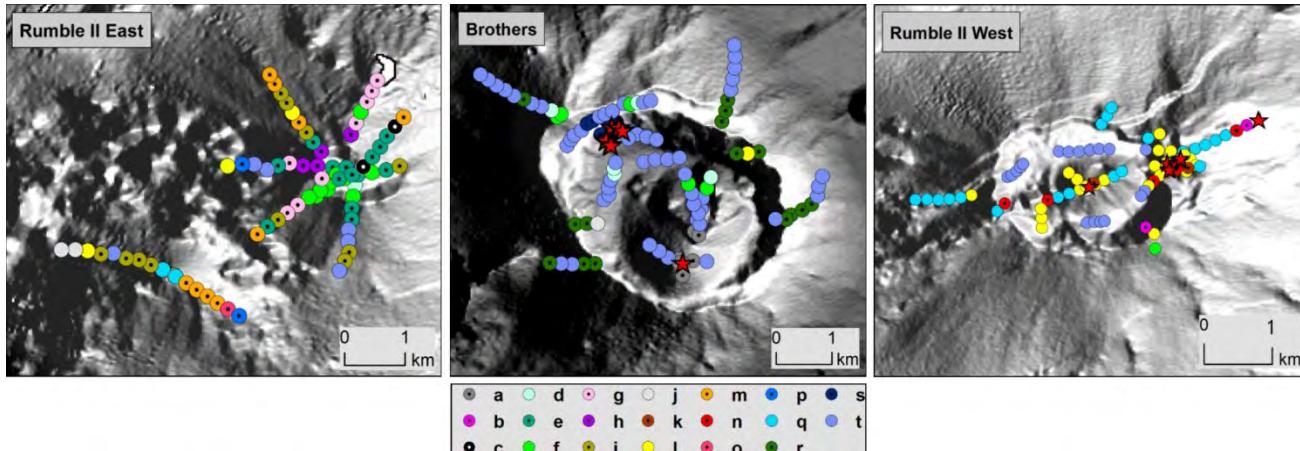


FIGURE 2. Digital terrain model maps of community (a – t) distribution over the three study seamounts. Symbols with a black centre indicate assemblages unique to one seamount. Red stars indicate the locations of hydrothermal vent chimney structures from video observations. Reproduced from Boschen et al. (2015) with permission from Inter-Research. Copyright for the figure remains with Inter-Research.

abundance and diversity similar to the mine site.

The newly announced Kermadec Ocean Sanctuary (<http://www.mfe.govt.nz/node/21209/>) will provide protection from SMS mining for all of the communities at SMS deposits in the far north of the EEZ (Fig. 1). However, many of the benthic communities at seamounts south of the Sanctuary are not afforded the same protection. Brothers, Rumble II East and Rumble II West are within a current Benthic Protection Area and are protected from bottom trawling, but there are no current restrictions relating to mining within this area. To fully protect these communities, protected areas need to form a coherent network, with high connectivity within and amongst seamounts to facilitate genetic exchange and the maintenance of healthy populations (International Seabed Authority, 2011; Van Dover et al., 2012; Boschen et al., 2016a). Such a network would provide protection for the diversity of habitats and associated benthic communities on Kermadec Volcanic Arc seamounts.

ACKNOWLEDGEMENTS

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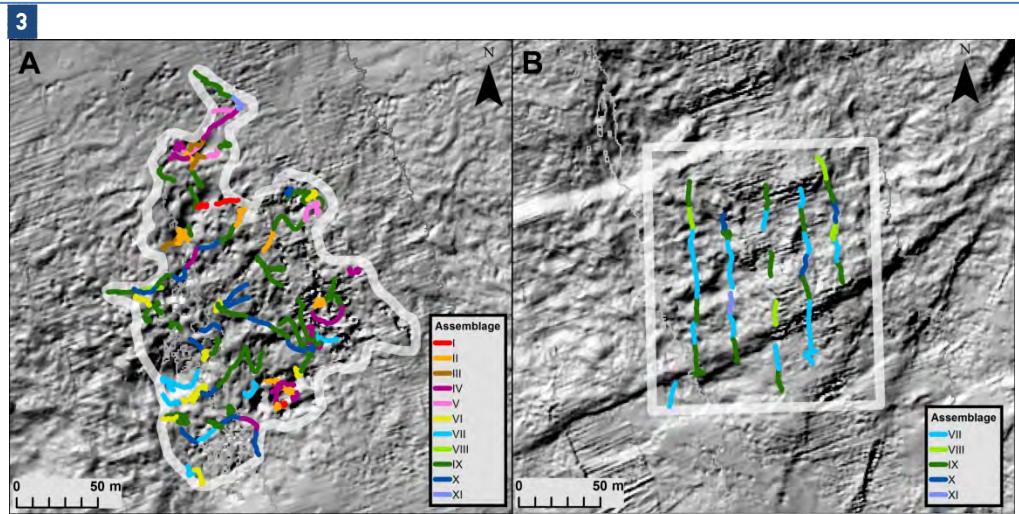
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FIGURE 3. Digital terrain model maps of community (I to XI) distribution over Proteus 1 (A) and the Reference Site (B). The thick pale grey lines indicate the spatial extent of each site. Reproduced from Boschen et al. (2016b) under Creative Commons Attribution-Non Commercial-No Derivatives License (CC BY NC ND).

Connectivity of Vulnerable Marine Ecosystem indicator taxa: genetic data to inform environmental management of the Kermadec region

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INTRODUCTION

Connectivity involves the movement of individuals between populations and helps to define how similar (high level of connectedness) or how dissimilar (low level of connectedness) the populations are. Connectivity may involve the movement of any or all stages of the life history of a taxon, from larva through juvenile to adult. Information about genetic connectedness helps to inform managers about the potential vulnerability of populations to activities such as mining and fishing, and to design spatial management measures to protect marine ecosystems from human disturbance (Cowen & Sponaugle 2009, Boschen et al. 2013, Van Dover 2014).

Vulnerable marine ecosystems (VMEs) are susceptible to damage or disturbance from human activities such as fishing, mining and dumping (FAO 2009). VME indicator taxa (FAO 2009) are defined as those that are unique or rare, functionally significant, fragile, structurally complex, slow to recover or may never recover, exhibit slow growth, late age of maturity, low or unpredictable recruitment, and are long lived (FAO 2009).

The proposed Kermadec Ocean Sanctuary covers 15% of New Zealand's Exclusive Economic Zone (EEZ) and is topographically rich, including the world's longest undersea volcanic arc and one of the deepest trenches, whilst containing a high proportion of endemic species. The Kermadec region hosts deep-sea fauna that are considered to be indicators of VMEs, including corals, sponges and mussels found at hydrothermal vents. However, genetic structure and connectivity of these populations within and beyond the Kermadec Ocean Sanctuary are poorly understood.

In the present paper we describe levels of genetic diversity and patterns of connectivity for one mussel species, two sponge species and five coral species from the New Zealand EEZ (and in some cases beyond), with special reference to the region of the Kermadec Ocean Sanctuary.

Our aim is to better understand temporal and spatial genetic connectivity and genetic diversity and how these are influenced by life-history characteristics and by processes such as physical oceanography (currents and flow – e.g., White et al. 2010). We anticipate that this new information can be used to inform decisions about the design of a network of marine protected areas in the EEZ that will include the Kermadec Ocean Sanctuary.

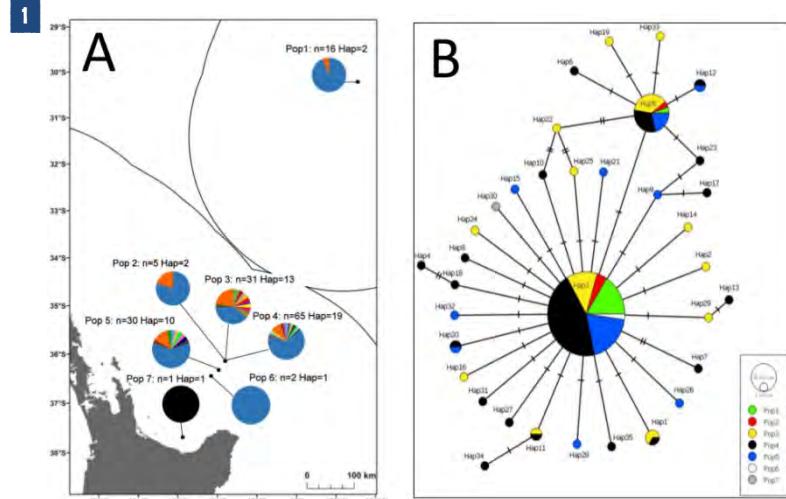
THE HYDROTHERMAL VENT MUSSEL, *GIGANTIDAS GLADIUS*

G. gladius is endemic to an 830 km section of the Kermadec Volcanic Arc at depths of 191 – 884 m. We used archived material from the NIWA Invertebrate Collection (NIC) and were able to obtain good quality DNA from 150 of the 942 mussels that were tested from seven sites, ranging from the far north to the far south of the mussel's distribution (Fig. 1A). We assessed genetic variation by sequencing the cytochrome c oxidase subunit I (*COI*) gene from the mitochondrial genome (Boschen et al. 2015).

We observed 35 different *COI* haplotypes (genetic variants), of which 28 (83%) were observed only once. Haplotype 1 (blue) was observed in all populations except Calypso Vent (Fig. 1A). The star-like haplotype network (Fig. 1B) suggests a recent expansion event (probably < 10,000 years ago). Overall, there was limited population differentiation, consistent with high levels of gene flow. Greater *COI* haplotypic diversity existed within central populations, and lower diversity was observed at both ends of the mussel's range (Fig. 1A). Rumble V seamount had the highest diversity and may be acting as a source population.

SPONGES - *POECILLAESTRA LAMINARIS* AND *PENARES PALMATOCLADA*

Samples of *P. laminaris* and *P. palmatoaclada* were obtained from the NIC. For *P. laminaris* we sequenced the *COI* and cytochrome b (Cytb) mitochondrial genes, whilst for *P. palmatoaclada* we sequenced the *COI* and the 12S mitochondrial genes (Zeng et al. in prep).



For *P. laminaris* we observed clear evidence of a pronounced north-south split in genetic structure (Fig. 2A). For both gene regions, cooler colours (e.g., dark blues) representing northern haplotypes were strongly differentiated from warmer colours (e.g., pinks, oranges and yellows) representing southern haplotypes. The Kermadec population sits within the northern group and the Chatham Rise appears to be an area of genetic mixing. There is a barrier to gene flow between the Kermadec region and all other regions (based on results from both COI and Cytb), indicating that the Kermadec population of *P. laminaris* is isolated from all other populations within the New Zealand EEZ. Generally, the pattern of gene flow (connectivity) observed for *P. laminaris* is in agreement with the known patterns of current flow, suggesting that oceanographic dynamics are important in both connecting areas and also isolating areas.

For *P. palmatoclada* small sample sizes makes interpreting the results more difficult than for *P. laminaris*. We observed high levels of genetic diversity and no obvious evidence of regional differentiation (Fig. 2B). There were no apparent barriers to gene flow for *P. palmatoclada*. The uncertainty associated with small sample sizes limits our ability to provide robust advice to managers for this species about the spatial distribution of marine protected areas in the EEZ.

CORALS - DESMOPHYLLUM DIANTHUS, ENALLOPSAMMIA ROSTRATA, GONIOCORELLA DUMOSA, MADREpora OCULATA AND SOLENOSMILIA VARIABILIS

Samples of all five coral species were obtained from the NIC and new material was collected from recent research cruises (Fig 3A). We employed existing and developed new microsatellite genetic markers to help quantify population genetic structure and connectivity (a microsatellite locus is a short, simple nuclear DNA

sequence) (Holland et al. in prep, Zeng et al. in prep).

For *D. dianthus* we assayed genetic variation in 348 individuals. A range of analyses revealed that there was pronounced regional differentiation amongst populations of *D. dianthus*. The principal components plot (Fig. 3B) revealed the differentiation of the northern populations (Kermadec and Louisville seamounts – Valerie, 39South, Forde) from all other populations. In addition, there was strong evidence of genetic differentiation based on depth, with shallow (< 800 m) and deep (> 1000 m) populations being significantly different. The Kermadec population had almost exclusively deep-water affinity, with the exception of one individual collected from White Island (at 180 m depth). These findings confirm both the differentiation of the Kermadec (and Louisville) population from all other populations and also the differentiation of deep versus shallow water populations (previously reported by Miller et al. 2011 for a different genetic marker), with depth acting as a barrier to gene flow at about 800-1000 m.

For *E. rostrata* we obtained samples of 39 individuals from seven regions (Table 1) and sequenced the ITS region (nuclear DNA). Populations from the Chatham Rise region were significantly different from those of the north and the south, but populations from the northern and southern regions were not significantly different. The explanation for this finding is that the Chatham Rise region is an area of mixing from both the north and south, with the result that the central region's populations (Graveyard knolls and the east Chatham Rise) exhibit higher levels of genetic diversity. Therefore, the northerly Kermadec population falls within a largely undifferentiated group that covers most of the New Zealand EEZ.

FIGURE 1. Location of 7 sampled populations within the distribution of the hydrothermal vent mussel, *Gigantidias gladius*. (A) Haplotype diversity along the Kermadec Volcanic Arc. Each haplotype is represented by a different coloured slice of the pie chart. "n" is the number of individuals sequenced per population, "Hap" is the number of haplotypes, and (B) Minimum-spanning haplotype network for all *Gigantidias gladius* individuals from the seven populations. Circle size is proportional to the number of individuals with that haplotype, lines indicate relatedness of haplotypes. Line breaks indicate mutational steps in the connectivity between haplotypes (taken from Boschen et al. 2015). Pop 1 = Macauley Volcano, Pop2 = Rumble V Seamount sample1, Pop3 = Rumble V Seamount sample2, Pop4 = Rumble V Seamount sample3, Pop5 = Tangaroa Seamount, Pop6 = Clark Seamount, Pop7 = Calypso Vent.

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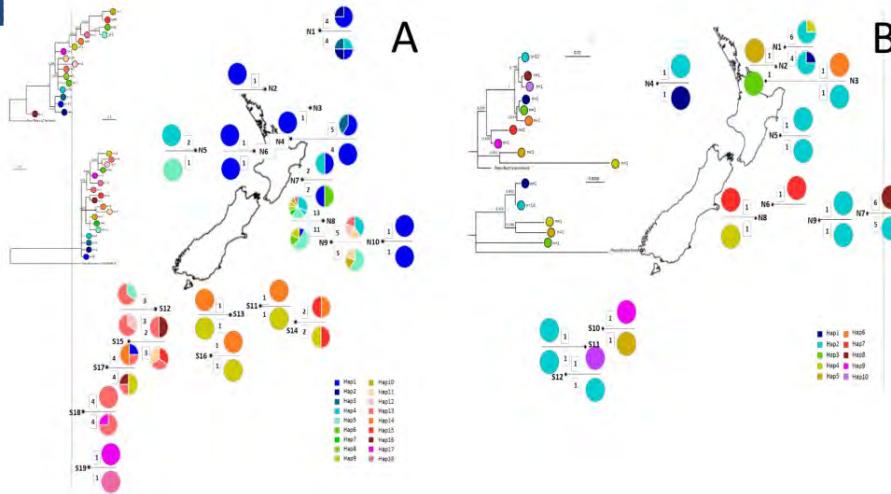


TABLE 1. List of regions from which samples were collected for four coral species, *Enallopsammia rostrata*, *Goniocorella dumosa*, *Madrepora oculata* and *Solenosmilia variabilis*. Sampled locations reflect availability of archived material in the NIC as well as new samples collected for this project.

<i>Enallopsammia rostrata</i>	<i>Goniocorella dumosa</i>	<i>Madrepora oculata</i>	<i>Solenosmilia variabilis</i>
Campbell/Bounty plateau	Auckland Plateau	Campbell Plateau	Bollons Plateau
Chatham Rise - east	Campbell Plateau	Challenger Plateau	Bounty Plateau
Chatham Rise - southwest	Challenger Plateau	Chatham Rise	Bounty Trough
Graveyard Seamount on the Chatham Rise	Chatham Rise	Kermadec Arc	Campbell Plateau
Kermadecs, northwest of New Zealand	Hikurangi Margin		Chatham Rise
Macquarie Ridge region	Kermadec Arc		Hikurangi Margin
	Macquarie Ridge		Kermadec Arc
			Louisville Seamount Chain
			Macquarie Ridge
			Tasman Sea

FIGURE 2. Haplotypic diversity distributions and regional differentiation for two species of sponge. (A) *Poecillastra laminaris* - COI (above the line) and Cytb (below the line) and (B) *Penares palmatoclada* - COI (above the line) and I2S (below the line). In both panels the number of haplotypes is given above and below the line for the two respective gene regions. A simple North versus South (BY6 versus BY10) testing framework is employed – populations are labelled N (North) or S (South) accordingly. To the left in both panels – phylogenetic trees for both gene regions showing evolutionary relatedness amongst the respective haplotypes.

For *G. dumosa* we assayed microsatellite variation at 27 loci for samples from seven regions (Table 1). A discriminant analysis of principle components (DAPC) and assignment analysis were applied to reveal the extent of genetic similarity (populations which are close together in the DAPC plot are similar) and differentiation that exists. This plot helps with the accurate assignment of each individual to its population of origin. The most obvious feature in the DAPC plot (Fig. 4A top) is the group of purple coded Kermadec samples that appears to the right. This feature is matched by the large block of purple to the right of the assignment panel (Fig. 4A bottom), indicating that the Kermadec samples can be assigned correctly to their population of origin. Thus, for *G. dumosa* the most divergent population is from the Kermadec region. Analysis of the presence and location of a barrier to gene flow confirms that the Kermadec population is genetically isolated from all other populations.

For *M. oculata* we assayed microsatellite variation for samples at 11 loci from four regions (Table 1). The DAPC plot and the assignment panel both reveal that the Kermadec region populations are differentiated from all other regions (dark brown Kermadec samples to the right hand side of the DAPC plot; dark brown panel to the right of the assignment test (Fig. 4B)). Populations from all four regions assayed

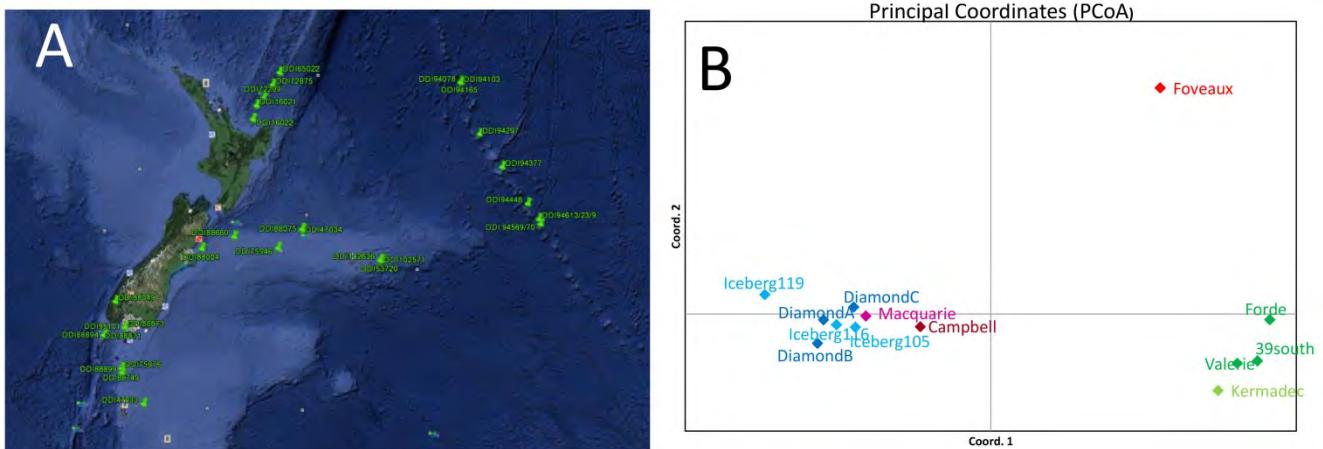
here are reasonably different from one another, suggesting low gene flow amongst the four regions. Analysis of barriers to gene flow confirms that the Kermadec population is genetically isolated from all other populations, as for *G. dumosa*.

For *S. variabilis* we assayed microsatellite variation at 27 loci for samples from ten regions (Table 1). The most pronounced result is the high degree of difference of the Louisville Seamount Chain population (purple) from all other populations (Fig. 4C). This is followed by the separation of the Kermadec population (medium brown) from all other populations. The remaining eight regional populations show medium to high degrees of overlap within the DAPC plot. These results, reinforced by the high level of accuracy of the assignment tests (bottom panel, Fig. 4C), highlight the differentiation of the Louisville and Kermadec populations from each other and from all other populations. Analysis of barriers to gene flow confirms that the Kermadec population is genetically isolated from all other populations.

CONCLUSIONS AND RECOMMENDATIONS

For the Kermadec-endemic vent mussel, *G. gladius*, we have found evidence of high levels of genetic connectivity within the region, and evidence that there may be source and sink populations. Populations at the edges of the species' distribution are

3



differentiated from those in the centre of the range. Because Rumble V seamount had the highest genetic diversity and may be acting as a source population, this suggests that this population may require special protection.

Examination of genetic population structure for sponge and coral species illustrates that the placement of the Kermadecs in a regional connectivity setting is species-specific. Populations in the Kermadec region may be connected to other northern populations (e.g., the sponge, *P. laminaris*) or may be connected to all other New Zealand EEZ populations (e.g., the sponge, *P. palmatoclada*) or may only be connected to the Louisville Seamount chain (e.g., the coral, *D. dianthus*). Alternatively, populations of the Kermadec region may be differentiated from all/most other regions of New Zealand (e.g., the corals *G. dumosa*, *M. oculina* and *S. variabilis*).

Although connectivity patterns vary, our research provides strong evidence across multiple species that the Kermadec region is genetically differentiated from other parts of the New Zealand EEZ and beyond the EEZ. Our results indicate that the Kermadec region requires separate management, even for cosmopolitan species. In addition, not all sites within the Kermadec region are the same in terms of genetic diversity and/or genetic connectivity. The establishment of the Kermadec Ocean Sanctuary will contribute towards ensuring the protection of VME indicator taxa. However, to ensure more widespread protection for populations of such taxa, the sanctuary should form part of a wider network of marine protected areas in the New Zealand EEZ.

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FIGURE 3. *Desmophyllum dianthus*. (A) The locations of samples of *D. dianthus* used in the present study, and (B) Principal Components Analysis (PCA) of samples showing population and regional separation.

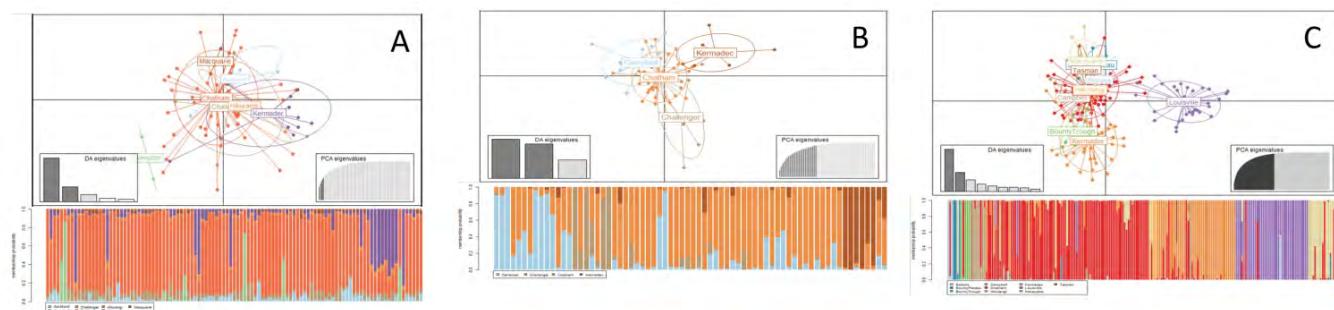


FIGURE 4. Discriminant analysis of principal components plots and assignment plots for 3 corals - (A) *Goniocorella dumosa*, (B) *Madrepora oculata* and (C) *Solenosmilia variabilis*. Note that colours used in the upper panel of each plot (DAPC plot) to designate populations are used in the lower panel (assignment plot) to designate the same populations.

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Protected coral communities on the Kermadec Volcanic Arc: recorded and predicted distributions, and risks from ocean acidification

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INTRODUCTION

The New Zealand region has a rich diversity of Anthozoan corals (Phylum Cnidaria). The Kermadec area is unique in the New Zealand region in having a coral fauna that includes both temperate warm-water (hermatypic) zooxanthellate (those with symbiotic microalgae for photosynthesis) scleractinian stony corals, and ahermatypic azooxanthellate stony corals, found well beyond the photic zone in colder deep waters. Of the 17 shallow hermatypic species, all but one is found on the Great Barrier Reef and these species are at or near their southernmost limit at shallow depths around Kermadec Islands (Brook 1999). The shallow corals occurring close to shore include large habitat-forming species belonging to the scleractinian genus *Tubinaria* (Figure 1).

In deeper waters on the slope and seamounts, corals include those protected under the New Zealand Wildlife Act: Black corals, order Antipatharia; Gorgonian corals, order Alcyonacea (previously known as Gorgonacea); Stony corals (cup and branching forms), order Scleractinia; hydrocorals in the family Stylasteridae. These corals are indicator taxa for vulnerable marine ecosystems (VMEs) because they provide refuge and shelter for some fish and numerous invertebrates, but can easily be damaged and disturbed by fishing and other human activities (Figure 1).

NIWA research activities on deep-sea corals has encompassed species identification, distribution, anthropogenic impacts, and efforts to understand age, growth, and recovery after disturbance. More recently we have investigated how the changing state of the ocean (temperature, ocean salinity, ocean oxygen and acidification) will affect marine organisms. Here we report on recent research to evaluate the impact of ocean acidification on deep-sea corals. The diversity and distribution of corals in the Kermadec region was described at the 2010 Kermadec science symposium (in Tracey et al. 2010). Since then, seamounts in the southern part of the region have continued

to be the target of scientific expeditions (see Clark et al. 2016 in this issue for data sources). These recent expeditions have provided new data for corals, and here we provide a list of the coral records in the Kermadec region, including some revised identifications.

CORAL DIVERSITY IN THE KERMADEC REGION

Data were obtained from the NIWA Invertebrate Collection database Specify for the Kermadec Ocean Sanctuary area. There are 775 records for deepsea corals in the sanctuary area, of which 621 are from depths over 200 m. A total of 580 deep-sea corals have been identified to Order level, but identifications down to genus and/or species level are incomplete (Appendix 1).

The most diverse group in the sanctuary area are the gorgonian octocorals, with 39 genera represented; including the Primnoidae and Pleaxauridae sea fans, along with bubblegum octocoral, bamboo corals, the precious coral *Corallium*, and the golden corals *Metallogorgia* and *Chrysogorgia*. Nine genera of black corals have been identified from sampling in the area, including Antipathes and Bathypathes. Cup corals are most diverse form of stony corals with 26 genera, while the matrix-forming form of stony corals is represented by only 18 records (4 genera). Hydrocorals in the Stylasteridae are diverse, with 12 species from this family present in the sanctuary area. Table 1 summarises records for the protected corals recorded in depths greater than 200 m. Several of the records have not yet been identified to genus or species.

OCEAN ACIDIFICATION IMPACTS ON CORAL DISTRIBUTION

Corals are potentially under threat from climate change, with CO₂ levels increasing at depths in the ocean at which corals are likely to thrive. The water's suitability for carbonate formation is determined by the carbonate saturation state (represented by the Greek letter omega, Ω). As Ω reduces, growth for certain organisms becomes increasingly difficult, ultimately threatening

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FIGURE 1. Left; The warm-water (hermatypic) stony coral *Tubinaria* spp. located close to the Kermadec islands (image Malcolm Francis). Right; The deep-water (ahermatypic) stony coral *Solenosmilia variabilis* located on a seamount along the Kermadec Ridge (image NIWA).

an organism's survival. The depth at which the aragonite (the form of carbonate that stony corals use for building their skeletons) saturation state $\Omega = 1$ is termed the aragonite saturation horizon (ASH). Below this depth the ocean is under-saturated with aragonite. The ASH is predicted to shoal to depths as shallow as 300–400 m in the New Zealand region by 2100 (Taylor et al., 2012) and it is likely to affect the distribution of stony corals in the region. It is also likely that gorgonian corals, that use high magnesium calcite, will also be significantly affected by this reduction in carbonate saturation states (Bostock et al. 2015).

Habitat suitability models have been used to predict suitable environment for the corals in the New Zealand region (Tracey et al., 2011; Baird et al., 2013) and these, together with model simulations used to represent the current and future state of the carbonate variables (Taylor et al. 2012), were used to predict changes in the regions coral distributions due to changing marine environmental conditions (Anderson et al. 2015). From the work by Anderson et al. (2015) we were able to show the predicted suitable environment for the Kermadec region for four species of stony coral (combined) (Figure 2). In the future prediction scenario, (Figure 2, right panel) there is a considerable reduction in habitat suitability for stony corals, 50–100 % probability remains in a central portion of the ridge and at the northern limits. The remaining areas in the Kermadec region indicate low probability of these deep-sea corals occurring by 2100.

The predicted changes in suitable habitat for coral species can help inform environmental managers which areas might act as possible 'sanctuaries' or 'refuges' for these corals in the future.

OCEAN ACIDIFICATION IMPACTS ON CORAL PHYSIOLOGY AND GROWTH

To complement the modelling work we undertook experiments to determine the effect of ocean acidification on the dissolution of coral skeletons. (Tracey et al. 2014; Gammon 2016).

Over 12-months, colonies of the stony coral *Solenosmilia variabilis* were maintained in temperature controlled (~3.5°C) continuous flow-through tanks. A control group of coral colonies was held in seawater with pH 7.88 and a treatment group in pH 7.65. Changes in growth and morphology, measurements of respiration and intracellular pH (pHi) were taken (Figure 3). Respiration and growth rates were variable and not influenced by the reduced seawater pH. A loss in the colouration of coral skeletons was observed in the treatment group and was attributed to a loss of coral tissue (referred to as coenochyme or coenosarc) (Figure 3). This finding could indicate a reallocation of energy, allowing for the maintenance of those other physiological parameters measured (e.g. growth and respiration rates). Several studies show that deep-sea corals can maintain constant skeletal growth as seawater pH declines. There are however implications for the functioning and vitality of the coral if its skeleton is weakened, and health jeopardised, through this loss in skeletal tissue (Hennige et al. 2015).

The experimental research is an important first step towards understanding the sensitivity of deep-sea corals to ocean acidification and the potential for acclimation, and suggests that in many respects, *S. variabilis* might not be susceptible to end-of-century projections of ocean acidification. Nevertheless, the observed tissue loss warrants further investigation to assess its long-term implications. Furthermore, the impacts on corals at varying pH levels and temperature, and the interactive effects of other ecological parameters such as food availability, need to be tested.

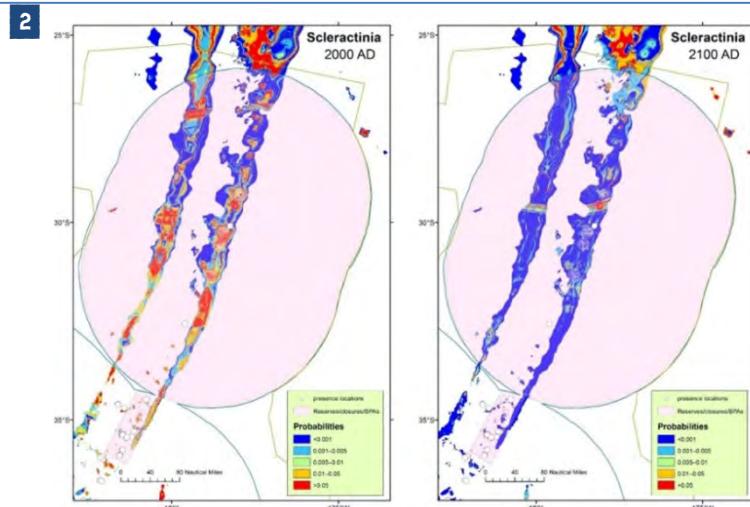


TABLE 1. Summary of the occurrence of protected corals (>200 m) in the Kermadec Ocean Sanctuary.
Note: some groups have not been identified to genera or species, hence the total numbers do not necessarily equal the number of sample records

Order	Common Name	Number of samples	No of Families represented	Number of samples (number of Genera (G) represented)	Number of samples (number of (spp) represented)
Scleractinia	Stony branching / cup corals	154	11	21 (7 G.)	136 (55 spp)
Alcyonacea	Gorgonian octocorals	240	8	161 (39 G.)	47 (19 spp)
Antipatharia	Black corals	43	5	21 (9 G.)	21 (11 spp)
Anthoathecata	Calcified hydrocorals	66	1	18 (7 G.)	42 (12 spp)

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FIGURE 2. Estimated probability of occurrence of suitable habitat for branching scleractinian coral species (*Solenosmilia variabilis*, *Goniocorella dumosa*, *Enallopsammia rostrata*, and *Madrepora oculata*) from Boosted Regression Tree habitat suitability models. Left panel: present day; Right panel: 2100 AD. Habitat suitability is predicted between 200-2000m only. (Maps reproduced from Anderson et al. 2015 with permission from DOC).

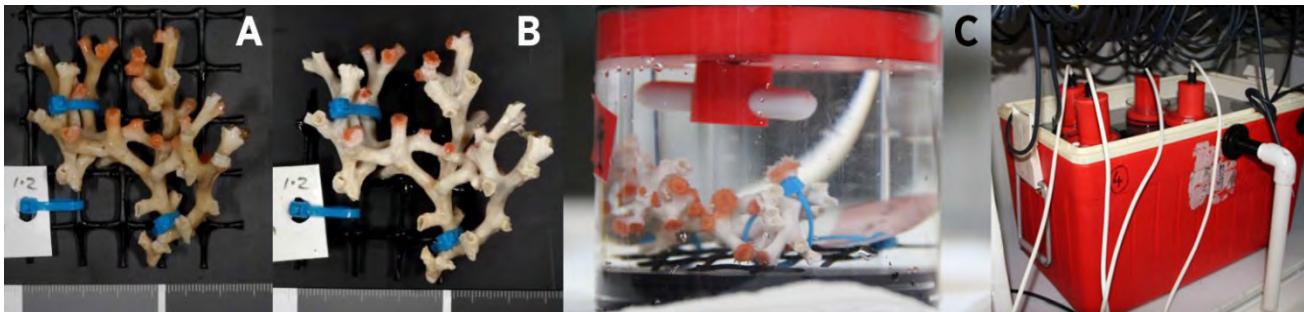


FIGURE 3. *Solenosmilia variabilis* colony prior to experiment (A) and after six months of exposure (B) to a reduced pH treatment. Note a visible loss in the pink colouration at the branch tips. (C) shows colony in respiration chamber during OA experiment to ascertain impacts of changing pH. (Images NIWA and Malindi Gammon)

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Appendix 1: Coral fauna in the Kermadec Ocean Sanctuary (as of Feb 2016). For completeness protected and un-protected forms (soft corals, zoanthids, and sea pens) are also listed.

Order	Common names	Family	Genus	Species	Count
Alcyonacea					6
	Gorgonian Acanthogorgiid	Acanthogorgiidae			14
			Acanthogorgia	1	
Soft corals		Alcyoniidae	Anthomastus	21	
			Bathyalcyon	9	
			Anthothelidae	1	
	Gorgonian Golden corals	Chrysogorgiidae	Victorgorgia	1	
			Chrysogorgia	13	
			Iridogorgia	2	
			Isidoides	1	
			Isidoides armata	2	

Order	Common names	Family	Genus	Species	Count
	Precious corals	Coralliidae	Metallogorgia		1
			Corallium		2
			Hemicorallium		20
			Hemicorallium	abyssale	7
			Hemicorallium	imperiale	1
			Hemicorallium	laauense	3
			Paracorallium		2
	Gorgonian	Gorgoniidae			2
	Bamboo corals	Isididae	Acanella		3
			Isidella		1
			Keratoisis		10
			Keratoisis	hikurangiensis	2
			Keratoisis	peara	1
			Lepidisis		9
			Orstomisis	crosnieri	2
		Nephtheidae			2
			Drifa		1
		Nidaliidae	Chironephthya		2
	Bubblegum corals	Paragorgiidae	Sibogagorgia	tautahi	1
	Plexaurid sea fans	Plexauridae			21
			Anthomuricea		5
			Bebryce		2
			Euplexaura		1
			Muriceides		1
			Paracis		12
			Paramuricea		1
			Placogorgia		2
			Scleracis		1
			Swiftia		1
			Villogorgia		2
	Primnoids sea fans, sea whips	Primnoidae			3
			Callogorgia		6
			Calyptrophora		18
			Calyptrophora	clinata	2
			Calyptrophora	cucullata	5
			Calyptrophora	diaphana	2
			Calyptrophora	wyvillei	2
			Candidella	helminthophora	2
			Fanellia		3
			Narella		10
			Narella	clavata	3
			Narella	hypocalyx	2
			Narella	parva	3
			Narella	studeri	3
			Narella	vulgaris	5
			Primnoella	distans	4
			Thouarella		3
		Taiaroiidiae	Taiaroa	tauhou	1
					19
Anthoathecata	Calcified hydrocorals	Stylasteridae			6
			Calyptopora		1
			Calyptopora	reticulata	1
			Conopora		4
			Conopora	laevis	11
			Conopora	verrucosa	3
			Cryptelia		4
			Cryptelia	polypoma	1
			Cryptelia	studeri	3
			Errina		1
			Errina	sinuosa	10
			Inferiolabiata		1
			Lepidopora		1
			Lepidopora	microstylus	1
			Lepidopora	sarmentosa	1

Order	Common names	Family	Genus	Species	Count
			Lepidotheca	altispina	2
			Styaster		6
			Styaster	eguchii	1
			Styaster	imbricatus	1
			Styaster	sinuosa	7
Antipatharia	Black corals				1
		Antipathidae	Antipathes		1
			Antipathes	gracilis	3
			Antipathes	leptocrada	2
			Antipathes	plana	1
			Antipathes	valdiviae	1
			Stichopathes		5
			Stichopathes	variabilis	5
		Aphanipathidae	Acanthopathes	undulata	3
			Asteriopathes		1
			Phanopathes	zealandica	1
		Leiopathidae	Leiopathes		3
			Leiopathes	bullosa	1
		Schizopathidae	Bathypathes		1
			Bathypathes	patula	1
			Stauropathes		1
		Stylopathidae	Stylopathes		8
			Stylopathes	columnaris	1
			Stylopathes	tenuispina	2
Coronatae	Thecate hydroids		Nausithoe		1
Leptothecata		Aglaopheniidae	Lytocarpia	alata	1
		Campanulinidae			2
		Halopterididae	Corhiza	scotiae	1
		Lafoeidae	Acryptolaria		2
			Acryptolaria	conferta	2
			Acryptolaria	crassicaulis	1
			Acryptolaria	patagonica	3
			Cryptolaria	pectinata	3
			Cryptolaria	pectinata	
			Lafoea	dumosa	1
			Zygophylax		1
			Zygophylax	sibogae	3
			Zygophylax	tizardensis	3
		Plumulariidae	Plumularia		1
Pennatulacea	Sea pen	Umbellulidae	Umbellula		1
Scleractinia	Stony corals, branching and cup form				2
		Agariciidae	Leptoseris	papyracea	1
		Anthemiphylliidae	Anthemiphyllia	dentata	2
		Caryophylliidae	Anomocora	fecunda	1
			Aulocyathus	recidivus	1
			Bourneotrochus	stellulatus	1
			Caryophyllia		5
			Caryophyllia	ambrosia	1
			Caryophyllia	diomedae	4
			Caryophyllia	elongata	2
			Caryophyllia	hawaiensis	1
			Caryophyllia	lamellifera	1
			Caryophyllia	rugosa	5
			Caryophyllia	scobinosa	3
			Conotrochus	brunneus	3
			Crispatotrochus	rugosus	1
			Deltocyathus		1
			Deltocyathus	formosus	4
			Desmophyllum	cristagalli	1
			Desmophyllum	dianthus	6
			Goniocorella	dumosa	2
			Labyrinthocyathus	limatulus	1

Order	Common names	Family	Genus	Species	Count
			<i>Polycyathus</i>		1
			<i>Solenosmilia</i>	<i>variabilis</i>	6
			<i>Stephanocyathus</i>	<i>coronatus</i>	1
			<i>Stephanocyathus</i>	<i>regius</i>	1
			<i>Stephanocyathus</i>	<i>spiniger</i>	2
			<i>Tethocyathus</i>	<i>virgatus</i>	2
			<i>Trochocyathus</i>	<i>cepulla</i>	1
			<i>Trochocyathus</i>	<i>gordonii</i>	4
			<i>Trochocyathus</i>	<i>hastatus</i>	2
			<i>Vaughanella</i>	<i>multipalifera</i>	2
			<i>Vaughanella</i>	<i>oreophila</i>	1
		Dendrophylliidae	<i>Balanophyllia</i>		3
			<i>Balanophyllia</i>	<i>crassitheca</i>	2
			<i>Dendrophyllia</i>	<i>alcocki</i>	7
			<i>Dendrophyllia</i>	<i>arbuscula</i>	1
			<i>Eguchipsammia</i>	<i>fistula</i>	4
			<i>Eguchipsammia</i>	<i>gaditana</i>	2
			<i>Eguchipsammia</i>	<i>japonica</i>	3
			<i>Enallopssammia</i>	<i>rostrata</i>	8
		Flabellidae	<i>Flabellum</i>		2
			<i>Flabellum</i>	<i>aotearoa</i>	1
			<i>Flabellum</i>	<i>hoffmeisteri</i>	4
			<i>Flabellum</i>	<i>knoxi</i>	1
			<i>Flabellum</i>	<i>lowekeyesi</i>	1
			<i>Flabellum</i>	<i>messum</i>	3
			<i>Javania</i>	<i>lamprotichum</i>	2
			<i>Javania</i>	<i>pachytheca</i>	3
			<i>Polymyces</i>	<i>wellsi</i>	6
			<i>Rhizotrochus</i>	<i>flabelliformis</i>	1
			<i>Truncatoflabellum</i>	<i>arcuatum</i>	4
		Fungiidae	<i>Fungiacyathus</i>	<i>margaretae</i>	1
			<i>Fungiacyathus</i>	<i>pusillus pacificus</i>	2
			<i>Fungiacyathus</i>	<i>stephanus</i>	1
		Gardineriidae	<i>Gardineria</i>		2
		Guyniidae	<i>Stenocyathus</i>	<i>vermiformis</i>	5
		Micrabaciidae	<i>Letepsammia</i>	<i>formosissima</i>	3
		Micrabaciidae	<i>Letepsammia</i>	<i>superstes</i>	2
		Oculinidae	<i>Madrepora</i>		2
			<i>Madrepora</i>	<i>oculata</i>	6
					85
Zoantharia	Zoanthids				2
		Epizoanthidae	<i>Epizoanthus</i>		1
		Epizoanthidae	<i>Epizoanthus</i>	<i>paguriphilus</i>	1
		Parazoanthidae		<i>Savalia</i>	1
		Zoanthidae			1

10,000 m under the sea: an overview of the HADES expedition to Kermadec Trench

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The hadal zone of the world oceans (6000–11,000 m) occupies <1% of the marine realm and is found almost exclusively in trenches but represents ~40% of the total ocean depth range. Jamieson et al. (2010 & 2015) have reviewed the current state of knowledge about the hydrology, physical characteristics, food supply, ecology and biodiversity of life in hadal trenches. This review concluded that, there appears to be a high level of endemism based on the few specimens collected from historical sampling efforts in the 1950s (Danish *Galathea* and Soviet *Vityaz* expeditions), but because trenches are still largely unexplored there is a lot we do not know about the ecological structure and functioning of hadal environments. However, relatively recent advances in technology using remotely operated vehicles (ROV) and landers can help us explore hadal trenches in greater detail.

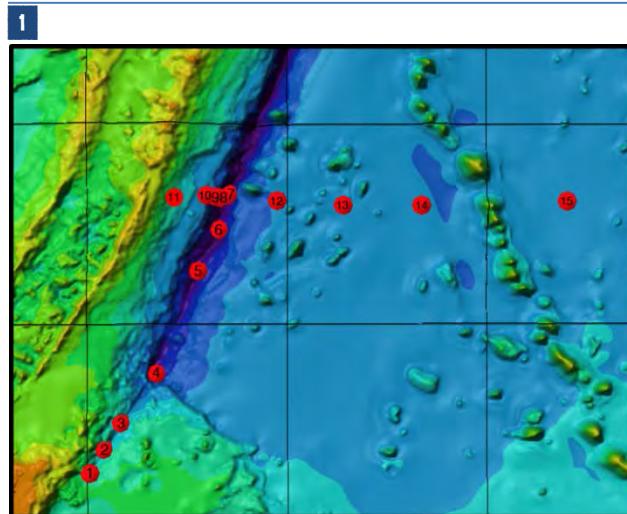
Through funding by the US National Science Foundation, the Hadal Ecosystems Studies (HADES) research programme has principal investigators from seven institutions from around the world, and aims to examine: (1) the composition and distribution of hadal species, (2) physiological adaptations of hadal organisms to extreme pressures, (3) relationships between food supply and the abundance and biomass of trench organisms, (4) metabolic rates/energetic demands of trench biota, and (5) the role of depth and topography on genetic divergence and spatial connectivity of trench populations. The programme was designed to be highly collaborative and multidisciplinary and initiate a 'global tour' of the world's little known hadal trenches, using the world's first full-ocean depth hybrid ROV in conjunction with full-ocean depth elevators and imaging landers.

In April 2014 the research vessel *Thomas G. Thompson* set sail from Auckland, New Zealand on a 40-day expedition to explore one of the world's deepest hadal trenches, the Kermadec Trench. An international

scientific team of 33 scientists from 11 different institutions were onboard. There were six specific expedition goals:

1. Determine the composition, abundance, and diversity (i.e., community structure) of mega-, macro-, and meiofauna at 1000m intervals from 4000m to 10,000m along the Kermadec Trench axis and the adjacent abyssal plain;
2. Quantify the distribution of particulate organic carbon and bacterial biomass in the Kermadec Trench and adjacent abyssal environment;
3. Relate carbon/biomass distribution to faunal community structure, depth and topography in these environments;
4. Determine whether the topographic features of the Kermadec Trench and adjacent abyssal plain and/or depth variation (and their predicted environmental heterogeneities) promote speciation, endemism and/or genetic divergence through genetic isolation of multiple species' populations;
5. Determine if the metabolic/respiration rates of Kermadec Trench fauna relate to depth or resource availability;
6. Determine species-specific depth-related responses to pressure- via counteracting osmolytes ("piezolytes").

Thirteen sampling sites at 4000 to 10,000 m depths along the trench axis and adjacent abyssal plain were planned to provide contrasts between abyssal and hadal environments (Fig. 1). Sampling was to be conducted mainly using the hybrid remotely operated vehicle *Nereus*, as well as landers with baited video cameras, fish/amphipod traps and water samplers, and a megafaunal respirometer deployed via an 'elevator', which also had water sampling bottles onboard (Fig 2.).



The dive plan for *Nereus* included suction sampling of benthic invertebrates for experiments in the respirometer chambers and for specimen vouchers, coring to obtain sediments, and video imaging transects.

Several of the planned *Nereus* dives did not take place following a series of technical problems with the ROV, winch, fibre optic cable, and crane, which along with some bad weather, meant that the sampling plan was delayed. There were four fully-completed *Nereus* dives at 6000, 7000, 8000, and 9000 m and two partial dives at 4000 and 10,000 m. The final dive culminated in the loss of the ROV at a depth of 9977 m, near the deepest point of the Kermadec Trench. It is thought that the vehicle imploded under the extreme pressure at that depth, and all that was recovered of it were some pieces of floating plastic debris at the sea surface 24 hours later. Despite the setbacks with the *Nereus*, the research teams successfully deployed fish traps and landers at all planned depths, measured hadal animal respiration in situ, and were able to collect a number of specimens, sediment cores and many hours of camera footage.

A total of 378 fish, invertebrate, sediment and water sample lots were registered into the HADES Specify database during the expedition, which were split nearly 2000 ways for various analyses. The following results are preliminary findings from unpublished voyage reports:

Sixty-seven specimens of fish were kept as morphological vouchers comprising eight 'species' or operational taxonomic units (OTUs). Some of these fish are likely to be undescribed species. A total of 160 lots (6402 specimens) of invertebrates representing 57 OTUs were kept as morphological vouchers. Most of the invertebrates were bait-attending amphipods from the fish trap and Hadal-lander deployments, but several new and

rarely collected hadal species were amongst the samples. The snail fish, *Notoliparis kermadecensis* was the most abundant fish collected in the trench, and all of them were obtained from below 7000 m depth. There also may be a new species of snail fish, and the specimens were amongst the deepest fish ever caught in the Kermadec Trench (7560 m). A single specimen of the supergiant amphipod *Alicella gigantea* was also the deepest ever collected in the Trench at 7200 m. A rare specimen of prawn, possibly *Benthesicymus crenatus*, was the first specimen of its species to be collected from the Trench. An undescribed anemone-like species of octocoral was discovered at 8065 m, and a tube-forming anemone described from the Kermadec Trench in 1956, *Galatheanthemum hadale*, was collected at 7133 m (Fig. 3).

The landers deployed at abyssal and hadal depths returned over 14,000 images and 56 hours of video enabling the characterisation of bait-attending fauna and their features, including deep-sea fish zonation, feeding, and swimming behaviours (Linley et al., 2016).

Sediment cores were obtained from four *Nereus* deployments between 6000–9000 m and are being used for a range of analyses including foraminiferal, macro- and meiofaunal community structure, biochemical composition and biomarkers, metagenomic profiles of bacteria, cultures of extremophilic trench microbes and physical sediment characteristics.

The cellular salt-water balancing piezolyte/osmolyte trimethylamine N-oxide (TMAO) was successfully extracted from fish from a range of depths and tissue concentrations were found to increase linearly with depth as predicted (Linley et al., 2016). Body wall tissues and fluids were extracted from a number of invertebrate taxa and frozen for further analyses of osmolyte content.

FIGURE 1. Planned HADES Kermadec sampling sites (red dots) along the trench axis and out along the abyssal plain. Credit: HADES Kermadec Expedition.

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FIGURE 2. Gear types used on the HADES Kermadec Trench Expedition. Clockwise from left: The Elevator (carries water sampling bottles and the respirometer chambers), large and small fishtraps, Abyssal-lander, Hadal-lander (with amphipod trap), HROV Nereus. Credit: HADES Kermadec Trench Expedition, WHOI (Nereus image).

FIGURE 3. Examples of invertebrate fauna collected on the HADES Kermadec Trench Expedition. Clockwise from top left: Prawn, *Benthesicymus ?crenatus* Spence Bate, 1881, total length (TL): 19.1 cm, from 6061 m; Super giant amphipod, *Alicella gigantea* Chevreux, 1899, TL: 18.25 cm, from 7200 m; Tube-forming anemone, *Galatheanthemum ?hadale* Carlgren, 1956, collected at 7133 m; Undescribed octocoral species, TL: 39 mm, from 8065 m. Photo credits: Kerry McCulloch, WHOI, HADES Kermadec expedition

Samples of invertebrate gonads were dissected and fixed in either glutaraldehyde and then post-fixed in osmium tetroxide for transmission electron microscopy, or in formalin for paraffin histology, to examine gonad ultrastructure. These preparations will help researchers to understand the reproductive mechanisms employed by hadal invertebrates and will provide insights into population connectivity and the potential for speciation in trenches.

Respiration rates of eleven animals from seven taxa were successfully recorded in-situ at 4000, 7000, and 8000 m. These rates represent the first in-situ measurements below 4000 m, and combined with biomass suggest higher megafaunal community respiration than anticipated (Nunnally et al. submitted).

A total of 24,748 subsamples or whole individuals of megafauna specimens, 98 % of which were bait attracted amphipods, and seven sediment cores were preserved for genetics analyses.

Nine hour-long video transects of the seafloor were recorded by Nereus between 4000–10,000 m. Initial observations indicate relatively high heterogeneity in substrate types and megafaunal communities between sites.

Further analyses and at least 35 collaborative scientific papers are planned, and initial results from this expedition suggest that trench ecosystems are more complex and varied than previously thought. There are plans under consideration for the development of new hadal assets, including a full-ocean depth vehicle capable of remote-operation, to be constructed by the WHOI in future. Samples from this expedition will complement those from sampling efforts in other trenches, for example the HADES Mariana Trench expedition, which was completed in November 2014. The HADES expeditions will provide a more comprehensive picture of the biodiversity found in trenches, and in particular the results from the Kermadec Trench will add to our knowledge of the

biodiversity, structure and functioning of a range of deep-sea habitats around New Zealand made through other NIWA deep-sea research programmes.

ACKNOWLEDGMENTS

HADES project is an international collaborative effort funded by the Biological Oceanography Program of the US National Science Foundation (OCE-1131620 to TMS). NIWA staff time onboard was provided by the project ‘Impact of resource use on vulnerable deep-sea communities’ project (CO1X0906), funded by the New Zealand Foundation for Research, Science and Technology. Heartfelt thanks to all crew, science, engineering and technical staff and students onboard the R/V Thomas G. Thompson.

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The unseen multitude: life in the sediments of Kermadec and Tonga trenches

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INTRODUCTION

Animal life in marine sediments is dominated by small organisms (meiofauna) barely visible to the naked eye. These animals are surprisingly diverse, and none more so than nematode worms, which can be represented by over 100 species in a single handful of mud. Nematodes and other meiofauna are common throughout the world's oceans from shallow coastal habitats to the abyss (Giere 2009). However our knowledge of this group in New Zealand waters remains limited, particularly in remote habitats such as the Kermadec Trench.

Deep trench environments between 6000 and 11 000 metres depths represent the last frontier in marine exploration. Early sampling expeditions in the trenches focused on the relatively large fauna, but it wasn't until the 1960s that meshes fine enough for retaining the small meiofaunal organisms were used. Until recently, no sediment cores had ever been obtained from the Kermadec Trench, or from the neighbouring Tonga Trench to the north, meaning that the most abundant component of the fauna in these trenches had not yet been investigated at all. A research cruise to Tonga Trench in 2013 (led by the Japan Agency for Marine-Earth Science & Technology, JAMSTEC) and another to the Kermadec Trench in 2014 (led by the Woods Hole Oceanographic Institution, WHOI), provided the first opportunities to obtain quantitative samples from the deepest parts of these ecosystems and describe their meiofaunal communities. Sampling was conducted using a hadal lander, JAMSTEC's manned submersible *Shinkai 6500* (capable of diving to a depth of 6500 m), and WHOI's remotely operated vehicle *Nereus* (capable to dive to the deepest parts of the oceans at about 11 000 m). Sampling in the Tonga Trench was conducted in Horizon Deep at 10 800 m, the world's second deepest point in the ocean, and on the edge of the trench at about 6250 m. In Kermadec Trench, cores were collected at 6000, 7000, 8000, and 9000 m depths. These sampling expeditions yielded

the deepest sediment cores ever analysed anywhere, which therefore contributed precious new data on life in extreme environments.

MEIOFAUNA OF THE KERMADEC AND TONGA TRENCHES

The meiofauna of Kermadec and Tonga trenches was dominated by nematode worms (Figure 1), which comprised over 95% of the meiofauna, but other organisms such as copepod crustaceans were also present. Larger sediment fauna (or macrofauna), which are typically common in shallower environments, were rare in the trench, and were represented by a few bivalve molluscs and juvenile annelid worms. This finding is consistent with observations in other deep-sea environments across the globe which show that the average size of fauna tends to decrease with increasing water depth, presumably due to decreasing availability of food resources (Rex et al. 2006). The abundance of meiofauna, however, was surprisingly high, and ranged from tens of thousands of individuals per square metre of sediment to almost half a million per square metre in the Horizon Deep (Figure 2). The presence of such high densities in Horizon Deep was unexpected, and indicates the presence of relatively high concentrations of food resources in the sediment (Leduc et al. in press). Although the reasons for this high food availability are yet to be confirmed, they are likely to be related to the funnelling effect of the steep topography of the trench, which may act to concentrate fine food particles at the deepest point (Ichino et al. 2015). Similar processes occur at a smaller scale in submarine canyons along the margins of continents (De Leo et al. 2010).

There was no consistent depth-related trends in meiofauna abundance in the trenches but a positive correlation was found between the concentration of pollen in the sediments and the abundance of meiofauna (Figure 3). This finding indicates that pollen may be a good indicator of food availability and/or that wind-dispersed terrestrial organic matter itself makes an

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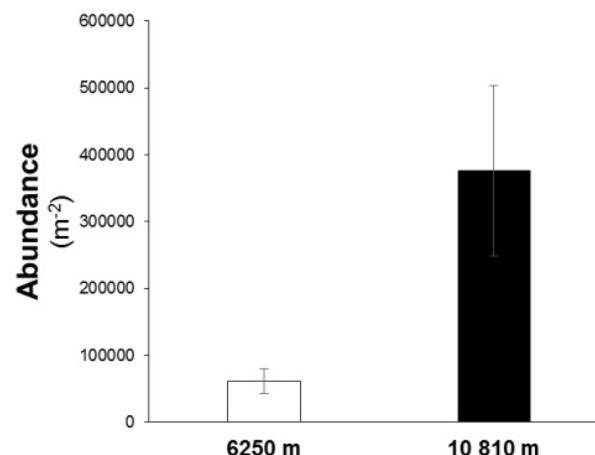
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FIGURE 1. Newly discovered nematode species from Kermadec Trench, *Manganonema rowdeni*. This genus is exclusively found in deep-sea habitats and feeds on bacteria.

FIGURE 2. Mean abundance of meiofauna at the two Tonga Trench study sites (6250 and 10 800 m), expressed as number of individuals per square metre of sediment. Error bars are standard deviations from the mean

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important contribution to the diet of animals living in trenches. Detailed comparisons using scanning electron microscopy showed that much of the pollen in both Kermadec and Tonga trenches originated from pine (*Pinus radiata*), most likely from forests in northeastern New Zealand (Figure 4). Although pollen is relatively common in deep-sea sediments near continents (Crouch et al. 2010), the presence of *Pinus radiata* pollen over 3000 km away from the nearest source, and at such great depths, provides tantalising hints of anthropogenic influence in environments we may have thought were too remote to ever be impacted by human activities. If pollen can accumulate in deep trench environments, what else might possibly make its way there? Sadly, unpublished data collected by researchers of the University of Aberdeen suggests that some pollutants are present in trenches (A. Jamieson, pers. com.), which illustrates just how tightly interconnected all of the world's ecosystems are.

The diversity of trench meiofauna was high, with a total of 55 nematode species present in Tonga Trench samples and 109 nematode species in Kermadec Trench samples. These records represent a substantial addition to the known species diversity in trench habitats; for example, only a dozen or so animal species had been reported from Horizon Deep previously, and the analysis of four core samples yielded an additional 36 nematode species. Most nematode species appear to be new to science but belong to families often recorded from other deep-sea environments. So far, eleven new nematode species and two new genera have been described and several more await description (Leduc 2015a, b). A parasitic nematode species was also discovered inside amphipod crustaceans in Kermadec Trench (7000–10 000 m); this new find represents the first record of a parasite beyond 6000 m depth anywhere in the world (Figure 5). It is likely that similar parasites will be found in other trenches

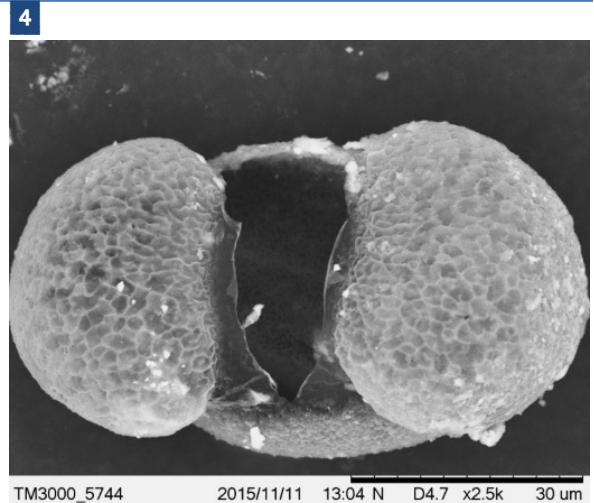
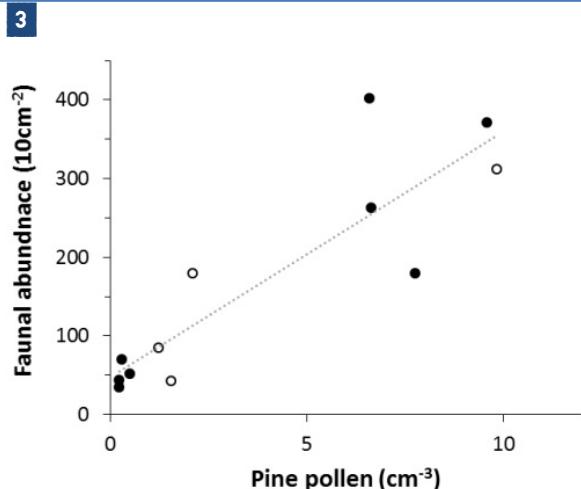
where potential amphipod crustacean hosts are also common (Leduc & Wilson 2016).

FUTURE RESEARCH

The results presented here demonstrate that the fauna of trench habitats is largely dominated by the small sediment fauna, which remains poorly known relative to the larger fauna. Many basic ecological questions remain unanswered: for example how do meiofauna communities differ between trench and abyssal plain environments, and among trenches? What environmental/evolutionary factors may be driving variation in meiofaunal communities within trenches? It is hoped that future sampling expeditions to the Kermadec and Tonga trenches, preferably with the involvement of New Zealand researchers, continue to expand their focus to include the smallest, but most abundant and diverse, components of seabed communities.

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FIGURE 3. Relationship between abundance of pine pollen in the sediments and the abundance of fauna in the Kermadec (empty circles) and Tonga trenches (filled circles).

FIGURE 4. Scanning electron micrograph of a pine (*Pinus radiata*) pollen from Horizon Deep sediments in Tonga Trench (10 800 m), which likely originated from more than 3000 km away in northeastern New Zealand. The maximum width of the pollen is about 70 microns.

FIGURE 5. Freshly caught amphipod crustacean from 7250 m in the Kermadec Trench. This specimen is parasitized by several spaghetti-like nematodes which can be seen through the amphipod's cuticle. The amphipod measures about 15 mm in length.

2005 Ring of Fire – Kermadec - Tonga Arc expedition – A pilot’s tale

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In April of 2005, the New Zealand American Submarine Ring of Fire 2005 voyage departed from Pago Pago, American Samoa. The aim of the expedition was to explore the geology, biology and chemistry of submarine volcanoes along the largely unexplored Kermadec Arc. Using the University of Hawai'i's research ship RV Kaimikai-O-Kanaloa and the Pisces IV and Pisces V submersibles the expedition completed multiple dives on 13 active submarine volcanoes. The expedition was the culmination of seafloor mapping and oceanographic surveys conducted jointly by New Zealand and U.S. scientists over 5 years prior to the voyage. Two New Zealand Crown Research Institutes (Geological and Nuclear Sciences, or GNS, and National Institute of Water and Atmospheric Research, or NIWA), and the NOAA Ocean Exploration Program joined together to provide the funding and scientific expertise to make the expedition possible. 58 scientists from 21 participating institutes representing the disciplines of geology, chemistry and biology took part in the voyage.

The voyage used two human occupied submersibles, Pisces IV and V, to explore the undersea volcanoes. The Pisces submersibles are rugged working class submersibles that are well suited for volcano exploration. The submersibles take a crew of three, one pilot and two passengers. The vehicles are rated for dives down to 2000m and have a working dive duration of eight hours.

Prior to the 2005 Ring of Fire expedition the HURL submersible pilots and technicians had 15 years of experience diving on Hawaii's active submarine volcano Loihi.

VAILULU'U SEAMOUNT

The expedition began with dives on Vailulu'u Seamount, in American Samoa. Maps made of this seamount in 2000 showed a large caldera in the centre of the volcano. Seabeam mapping from the KOK the night before first Pisces dive to the volcano in 2005 revealed a 300m high cone

had developed in the center of the caldera. Pisces V explored the caldera and new cone and discovered unique areas such as "Eel City" and the "Moat of Death". Instruments were placed on Vailulu'u on these initial dives, which were then collected at the end of the expedition after three months of recording.

MONOWAI SEAMOUNT

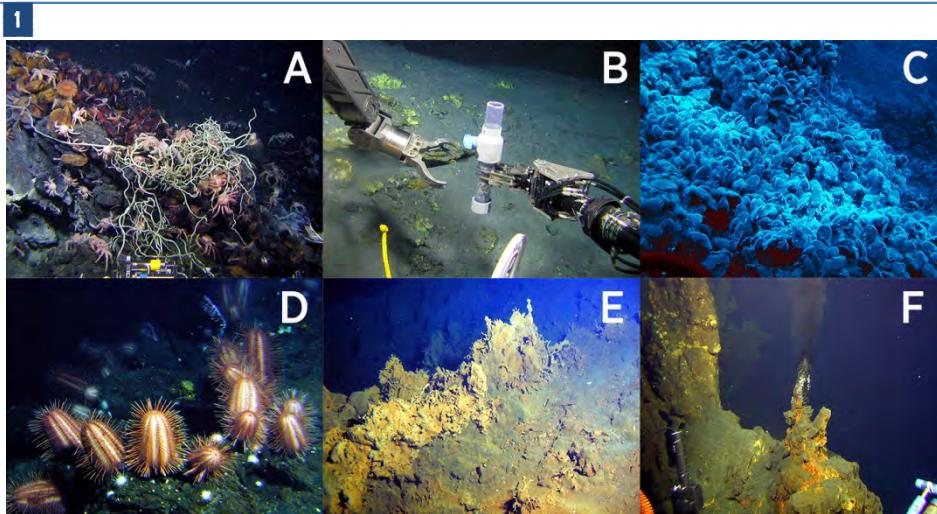
Diving on Monowai seamount was HURL's first real exposure to dense hydrothermal biota fields that would be observed throughout the Kermadec volcanoes. Areas of diffused venting and sulfur deposits were surrounded by extraordinary bio-mass and bio-diversity such as mussels, tubeworms, shrimp, vent fish, and the main predator, red crabs, which were found in high densities, not seen at other seamounts that were explored (Figure 1A). Only one part of Monowai volcano was explored on the edge of the massive caldera. The summit of the volcano was deemed too active to dive on.

MACAULEY SEAMOUNT

Macauley Seamount has a gigantic caldera with a small volcanic cone on one side. The dives on Macauley explored this cone, which had an 80m wide and 100m deep explosion crater on the top. The submersible was piloted down into this explosion crater, where a sandy bottom, 30m wide, was discovered. Flatfish were found to be living on this sandy bottom. The temperature in the sand was 158°C, and when the temperature probe was removed sulfur deposits squeezed out from the sand (Figure 1B).

GIGGENBACH SEAMOUNT

Giggenbach seamount was a relatively shallow dive, at only 164m. Ambient light reached the summit, and schools of fish were present. Several large, and very curious, spotted black groupers followed the submersible, interested in what they were up to. Evidence of past venting was found, with old chimneys, and sulfur deposits present. Towards the end of the dive, diffuse venting was found with large fields of thousands of mussels, which were covered



with a thick, white, stringy bacterial mat (Figure 1C).

RUMBLE 'V' SEAMOUNT

Rumble V is a classic-looking volcano. A cone that rises from the seabed at over 2 kilometres water depth to a summit only metres across, that occurs at just less than 400 metres beneath the surface of sea. A mix of vent sites and typical (non-hydrothermally active) seamount features were found, with large oval, orange sea urchins (reminiscent of cacti) living on young basalt flows (Figure 3). Diffuse venting areas were found and large beds of mussels (different from those found on Monowai) were also seen. Evidence of fishing activity on the top of Rumble 'V' was also found – lost lines festooned the top and were a real entanglement danger to the Pisces V submersible.

CLARK SEAMOUNT

Clark Seamount had two peaks, relatively close to each other. Hydrothermal venting was found at one peak, but not at the other. At the peak with venting activity, two massive 6m tall sulfide chimneys were found, with water temperatures up to 221°C measured at the base of the largest chimney. Large fields of barnacles dominated the vent fauna here. At the second peak, where there was no vent activity, many brightly coloured corals and sea pens were discovered.

HEALY SEAMOUNT

Healy Volcano's main caldera and surrounding seafloor were littered with pumice fragments from its last major eruption, estimated to be less than 5000 years ago. The venting sites at Healy were covered with blankets of orange-red microbial mats and delicate and intricate chimneys composed of material rich in iron and silica (Figure 1E). The temperatures were relatively low, at only 34°C, and no large fauna was found to be associated with these vents.

BROTHERS SEAMOUNT

Brothers is a caldera volcano, with the bottom of the caldera located at 1850m

deep, with caldera walls between 400-500m high. Inside this 3km wide caldera there is also a cone formation. Brothers was characterized by some extraordinary black smoker chimneys, on the northern side of the caldera (Figure 1F). The water venting at this site was the hottest encountered at 290°C. These temperatures are such that they can affect the rocks on the sea floor, altering them such that their original minerals are completely replaced by other, different minerals which often results in the rocks being a lighter colour than they were originally.

Overall, the success of the New Zealand American Submarine Ring of Fire 2005 Expedition underscores the value of international collaborations in ocean exploration, particularly those where both partners bring expertise, resources and a commitment to a multi-year effort to define sites for more focused exploration. The Pisces submersibles completed 61 of 56 scheduled dives planned for the expedition. The discoveries made during the Kermadec Arc expedition showed how unique these volcanoes and their chemosynthetic vent communities are, and how much potential there is for more discoveries on those extraordinary volcanoes yet to be explored.

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FIGURE 1. A) Spaghetti-like tubeworms happily living amongst mussels, anemones, a vent fish, and hungry crabs. Most of these animals are only found at seafloor hot spring sites.

B) Pisces V samples deposits of elemental sulfur (yellow) that were extruded on the seafloor.

C) The shallow depth to the top of Giggenbach volcano (~100 m) meant that sunlight penetrated the ocean, enabling Pisces V to navigate without its lights at times.

D) Deep-sea urchins (reminiscent of cacti) grow on the lavas at Rumble V volcano. This is the first time that this species has been observed alive on the seafloor

E) Iron precipitates grow in bizarre tubular twists at Healy submarine volcano.

F) Metal rich high-temperature venting on the northwest caldera wall of Brothers Volcano produces these black smoker chimneys. Images courtesy of New Zealand-American Submarine Ring of Fire 2005 Exploration, NOAA Vents Program.

Rate of species discovery in coastal waters of the Kermadec Islands and opportunities for future research

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Scientific exploration of the biodiversity of the Kermadec Islands commenced in 1854 with a visit by John MacGillivray and John Milne, followed by deepwater exploration by HMS *Challenger* (1874), and terrestrial and coastal exploration in 1887 by Thomas Cheeseman during the annexation of the islands by the New Zealand government on behalf of the English empire. It was almost 100 years later, in 1984, before the first dedicated coastal marine survey was undertaken by Howard Choat, Mike Kingsford and David Schiel from Auckland University's Leigh Marine Laboratory; this survey was cut short due to the sinking shortly after their arrival of their research vessel in Boat Cove, Raoul Island. Subsequent visits to the islands have been highly episodic and opportunistic due to the remoteness of the islands and expense of supporting research at the islands (Trnski & de Lange, 2015).

In May, 2011, the largest biodiversity survey of the islands was led by the Auckland Museum: the Kermadec Biodiscovery Expedition 2011 (Trnski & de Lange, 2015). This expedition brought together 13 scientists, a photographer and science journalist to build on existing knowledge of the biodiversity of the islands and report on their discoveries (Trnski & Schlumpf, 2015). Authors in this bulletin described 15 species new to science and recorded more than 350 species from the Kermadec Islands, and the New Zealand Exclusive Economic Zone, for the first time. These samples continue to be studied by taxonomists and additional species have since been described, as have additional species records been documented. The goal of these studies has been to develop more accurate models of the relatedness, and the connectivity, among the marine populations at the Kermadec Islands to other islands in the region, as well as to northern New Zealand.

The documentation of marine species recorded at the Kermadec Islands has been

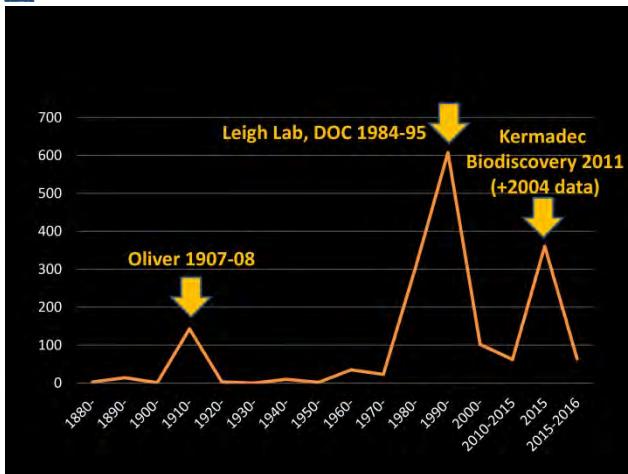
as episodic as the opportunities for scientists to visit the islands with three main periods of increase in known species (Figure 1): the 10-month long Oliver Expedition of 1907-1908, multiple visits by staff from Leigh Marine Laboratory and the Department of Conservation (DOC) between 1985 and 1995, and the Kermadec Biodiscovery Expedition 2011 (which included results of a preceding visit by DOC, NIWA and National Museum of New Zealand scientists in 2004). This data was derived from an annotated checklist of marine species first published by Duffy and Ahyong (2015), and updated as additional species are recorded from the Kermadec Islands.

The rate of species discovery has been highly variable depending on the taxon. Examining some of these in detail provides a long-term perspective on the factors that influence knowledge of biodiversity from an area.

Considering the single-celled organisms, almost all of the Foraminifera known were recorded in a single monograph (Hayward *et al.*, 1999). Dinoflagellates have only recently been recorded (Wicks *et al.*, 2010) but they do include several species that produce ciguatera toxins (Rhodes *et al.*, 2014).

The number of species of macroalgae recorded from the Kermadec Islands has rapidly increased since the 1980s (Figure 3). Macroalgae differ from mainland New Zealand in that large brown kelps do not dominate, and about 50% of species at the Kermadec Islands do not occur in mainland New Zealand. There are strong affinities with tropical taxa and a low level of endemism. Algal abundance and diversity is highly variable among seasons and years, with many species recorded from only a single specimen, thus estimates of diversity and relative abundance of species has been dependent upon infrequent opportunities for collections.

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Coastal sponge diversity appears to be low. The first dedicated sponge survey of the Kermadec Islands by a sponge taxonomist occurred in late 2015. This resulted in a 50% increase in the species recorded from the islands (Figure 4), and work to confirm their identity is ongoing.

Crustacean diversity recorded has increased rapidly in the last three decades as different taxa are studied in detail (Figure 5). A major increase in known diversity resulted from the Kermadec Biodiscovery Expedition 2011 which had a dedicated team of invertebrate collectors.

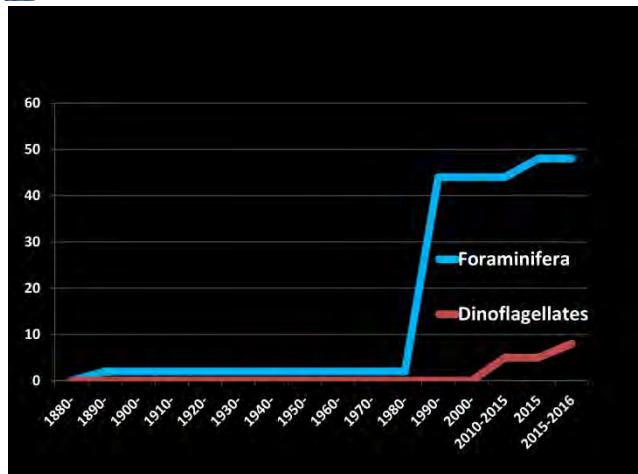
Almost all known species of bryozoans known from the Kermadec Islands were recorded in publications by Dennis Gordon in the 1980s (listed in Duffy & Ahyong, 2015) (Figure 6). Similarly, a single publication by Fred Brook greatly increased the known species of coastal molluscs, and gastropods in particular (Brook, 1998) (Figure 7).

And finally fish records continue to increase with subsequent visits (Figure 8). A visit by the senior author in late 2015 added another nine species to those recorded to date, an addition of about 6% to the known coastal fish fauna.

There are now over 1,750 coastal species recorded from the Kermadec Islands, and the rate of discovery is still increasing (Figure 9). As more surveys take place using alternative methods, many additional taxa will be recorded. Focus on poorly sampled groups will uncover more diversity, for example of nematodes, polychaetes and crustacea. Similarly, sampling midwater and pelagic habitats, and depths beyond 30 m diving depth has been rarely undertaken.

The common thread through this pattern of species discovery is that it has relied on a small number of individuals with limited resources and a high level of motivation to work in this remote area. But the opportunities for discovery are high, providing reward for biodiversity researchers. Progress, however, is slow due

2



to the small number of targeted collections, but also the capacity for taxonomic expertise to study the samples.

Besides basic documentation of species known from the Kermadec Islands, these studies provide a baseline to monitor changes in species distributions over time, especially as we move from a qualitative to more quantitative approach to documenting species distributions and abundance. Recent genetic approaches provide novel insights into the biogeographic relationships of the Kermadec Islands, and their connection to other islands in the southwest Pacific region.

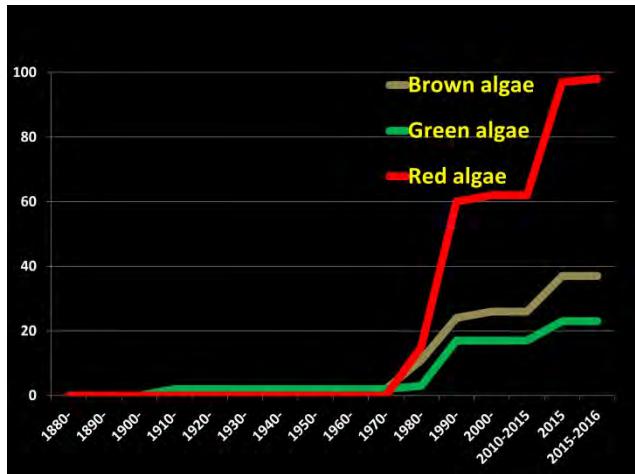
NOTE

Coastal waters are to a depth of 50 m. For this paper, it includes species with an offshore distribution that may venture into shallow coastal waters (e.g. tunas), but excludes mesopelagic species that are usually distributed in deep oceanic waters (e.g. lanternfishes), even though they may occasionally be recorded in coastal waters

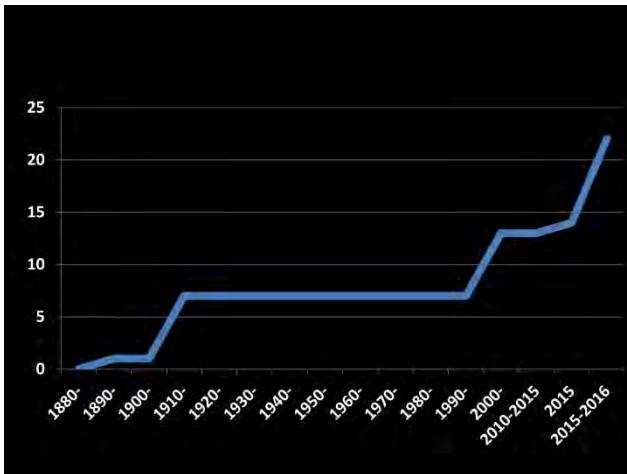
FIGURE 1. Coastal marine species recorded from the Kermadec Islands since the 1880s, within each decade until 2010, and from 2010 to 2014, 2015 (the results of the Kermadec Biodiscovery Expedition 2011), and since 2015. Three significant phases of discovery coincide with major research effort in 1907-1908, from 1984-1995, and in 2004 and 2011.

FIGURE 2. Cumulative number of species of Foraminifera and dinoflagellates recorded from coastal waters of the Kermadec Islands since the 1880s.

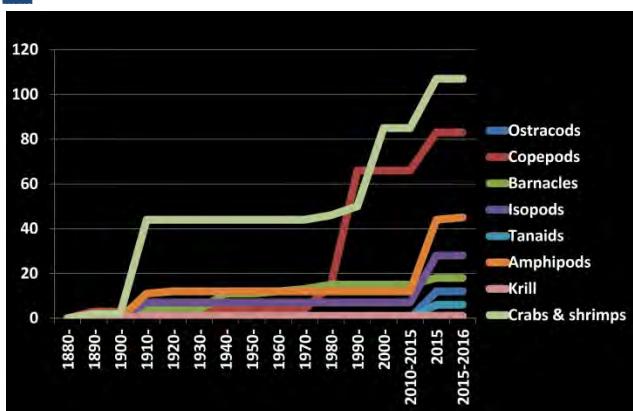
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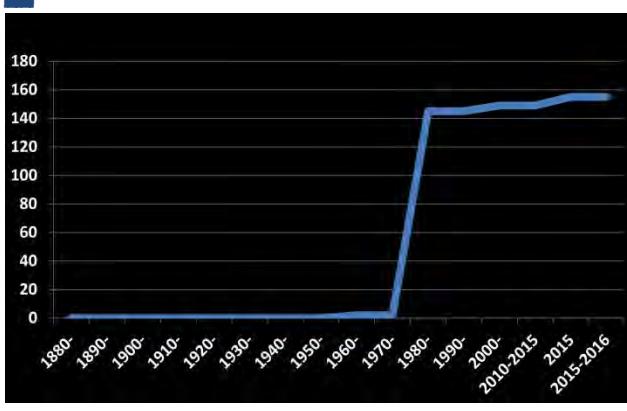
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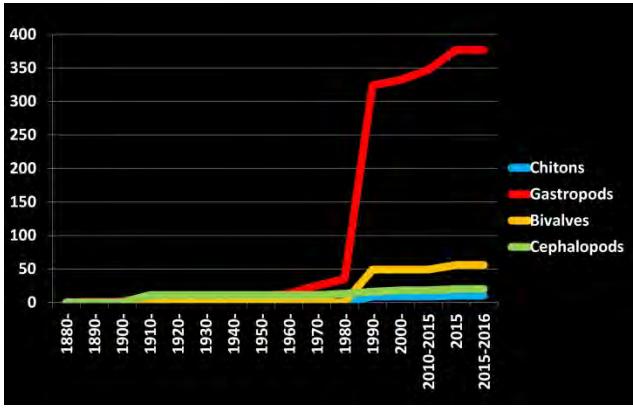
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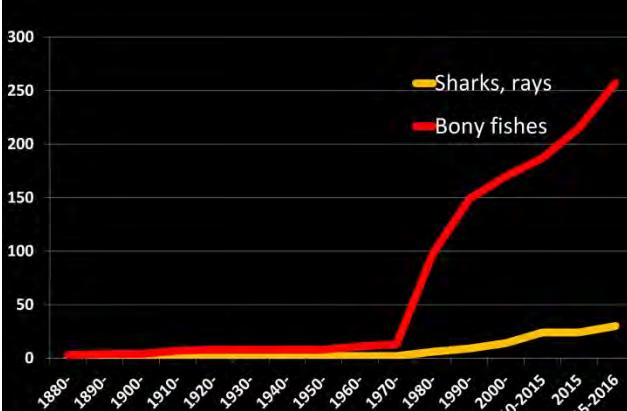


FIGURE 3. Cumulative number of species of macroalgae recorded from coastal waters of the Kermadec Islands since the 1880s.

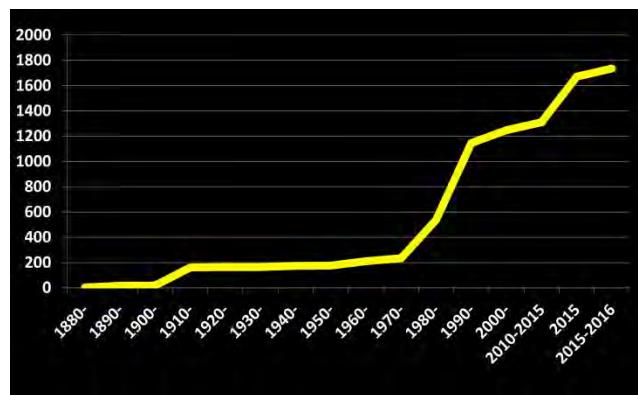
FIGURE 4. Cumulative number of species of sponges recorded from coastal waters of the Kermadec Islands since the 1880s.

FIGURE 5. Cumulative number of species of crustaceans recorded from coastal waters of the Kermadec Islands since the 1880s.

FIGURE 6. Cumulative number of species of bryozoans recorded from coastal waters of the Kermadec Islands since the 1880s.

FIGURE 7. Cumulative number of species of molluscs recorded from coastal waters of the Kermadec Islands since the 1880s.

FIGURE 8. Cumulative number of species of fishes recorded from coastal waters of the Kermadec Islands since the 1880s.



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FIGURE 9. Cumulative number of species recorded from coastal waters of the Kermadec Islands since the 1880s.

The Kermadec corridor – an important habitat for migrating oceanic fishes?

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The New Zealand Government intends to establish a Kermadec Ocean Sanctuary (KOS) over the waters lying 12–200 nautical miles (22–370 km) from the Kermadec Islands. The KOS will encompass a large area of open ocean, and parts of two major submarine features, the Kermadec and Colville ridges. All fishing is currently banned within the Kermadec Islands Marine Reserve (the area within 12 n.m. of the Kermadec Islands), and fishing on or within 100 m of the seabed is banned throughout the Kermadec Benthic Protection Area (KBPA) (which extends to 200 n.m. from the Kermadec Islands)¹. In the proposed KOS, there will be a complete ban on fishing, which will extend the current BPA ban on benthic fishing to other fisheries, including surface fisheries that exploit oceanic pelagic fishes.

Historical catches of pelagic fishes in Fisheries Management Area (FMA) 10 (New Zealand fishery waters surrounding the Kermadec Islands out to 200 n.m.) have been small. In the period 2008–2003, only 185 t of pelagic fishes were reported caught in the region (Ministry for Primary Industries, unpublished data). The catch comprised mostly swordfish (*Xiphias gladius*, 77 t), albacore tuna (*Thunnus alalunga*, 46 t), blue shark (*Prionace glauca*, 25 t), bigeye tuna (*Thunnus obesus*, 17 t) and moonfish (*Lampris guttatus*, 16 t). FMA 10 catches made up only 0.3–2.9% of the total New Zealand catches of those species, and came mainly from the south-west quadrant of FMA 10. Fishers holding quota for these pelagic species are entitled to take their catch elsewhere in the New Zealand Exclusive Economic Zone, and are not restricted to FMA 10.

In order to inform the debate on the impact of the KOS on pelagic fisheries, answers to the following questions are important:

1. What oceanic pelagic species occur in FMA 10?
2. How long do they reside there?
3. Where do they migrate from and to?
4. How important is the KOS to them?

These questions cannot yet be answered confidently. Here we review the available information on the presence of pelagic fishes in the Kermadec region, and their movement through it. Relevant information comes from three main sources: (a) commercial fishery data, (b) conventional tagging studies (using plastic tags), and (c) electronic tagging studies (using satellite-communicating tags).

There is a large commercial longline fishery for albacore tuna in tropical waters north of New Zealand (mainly 10–30 °S), with catches declining rapidly south of 30 °S (OFP-SPC and the WCPFC Secretariat 2015). Seasonal variation in catch rates indicates that albacore make north-south migrations (Langley & Hampton 2005). Catches in New Zealand waters are restricted to summer (Griggs et al. 2014), whereas catches in the latitude of the Kermadec region (25–35 °S) peak in autumn-winter (Langley & Hampton 2005). Albacore tagged with conventional tags in the South Pacific, including New Zealand, migrate north to the tropical Pacific (Labelle & Hampton 2003; Secretariat for the Pacific Community unpubl. data). Similarly, conventional tagging of shortfin mako sharks (*Isurus oxyrinchus*) in New Zealand waters shows a strong movement northwards to tropical regions, particularly to Fiji and New Caledonia, with a significant number also moving westward to eastern Australia (Holdsworth & Saul 2014). The New Zealand skipjack tuna (*Katsuwonus pelamis*) purse seine fishery exploits schools of fish that migrate south from tropical waters in summer (Langley 2011).

Many other large, tropical, oceanic fishes occur in northern New Zealand waters only in summer and early autumn, suggesting

¹ Fisheries (Benthic Protection Areas) Regulations 2007:
<http://www.legislation.govt.nz/regulation/public/2007/0308/latest/DLM973968.html>

The Kermadec corridor plays an important role in the lives of many migrating oceanic fishes

that they too migrate seasonally between the tropical South Pacific and New Zealand; they include whale shark (*Rhincodon typus*), oceanic whitetip shark (*Carcharhinus longimanus*), tiger shark (*Galeocerdo cuvier*), giant manta ray (*Manta birostris*), spinetail devilray (*Mobula japonica*), wahoo (*Acanthocybium solandri*), moonfish, sunfish (*Mola mola*, *M. ramsayi*, and *Masturus lanceolatus*), striped marlin (*Kajikia audax*), blue marlin (*Makaira nigricans*) and yellowfin tuna (*T. albacares*).

Recently, electronic tags have been used to track the movements of some pelagic species tagged in New Zealand. These tags provide multiple positions along the migratory paths, enabling collection of information on the routes, timing and speed of migrations. Some species associate strongly with the Kermadec Ridge, whereas others migrate through the Kermadec region in oceanic waters, apparently oblivious to the presence of the Ridge. Juvenile shortfin mako sharks tagged off Northland departed from coastal waters in winter–spring and migrated to the Kermadec Ridge where they stayed for up to 2.4 months (apart from periodic loops away from the ridge into oceanic waters) or travelled closely along the ridge in both directions (M. Francis and M. Shivji, unpubl. data). White sharks (*Carcharodon carcharias*) migrated from southern New Zealand to the tropical South Pacific and north-eastern Australia in winter–spring, and several have been tracked through the Kermadec region en route to Tonga and New Caledonia (Duffy et al. 2012). Recently a white shark that had been photo-identified at Stewart Island, and recorded by an acoustic tracking receiver at the Chesterfield Reefs in the Coral Sea (Francis et al. 2015a), was seen feeding on a whale carcass at Raoul Island. Swordfish and striped marlin also migrate northwards to the tropics from New Zealand, some of them through the Kermadec region (Holdsworth et al. 2010, Sippel et al. 2011).

Although there is currently little direct evidence for tropical species migrating southwards to New Zealand waters, there is

ample conventional and electronic tagging evidence for a northwards migration of tropical pelagic species at the end of summer. When combined with the large number of tropical species occurring in northern North Island waters during summer, but rarely in other seasons, this suggests there is a large-scale two-way migration of tropical species between northern New Zealand and the tropics every summer. These migrations involve many species of large-bodied animals, and some of them at least are sufficiently abundant to support commercial fisheries that take thousands of tonnes annually. This indicates that there is a major seasonal transfer of fish biomass between New Zealand and the tropical Pacific every year.

Conversely, cool temperate species including porbeagle shark (*Lamna nasus*), southern bluefin tuna (*Thunnus maccoyii*) and Pacific bluefin tuna (*T. orientalis*) have been tracked northwards from southern New Zealand in autumn–winter to subtropical waters north of New Zealand, reaching their northern limit in the Kermadec region (Francis et al. 2015b; Ministry for Primary Industries, unpubl. data).

The Kermadec region serves different roles for different species: it may function as a destination and seasonal home for some species (e.g. mako shark); it may be a waypoint on the migration routes of others or a temporary foraging area (e.g. white shark, striped marlin); or it may simply be a water body that must be traversed to get from New Zealand to the tropics and back. Regardless of the specific function, the Kermadec corridor plays an important role in the lives of many migrating oceanic fishes.

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Kermadec Islands constitute a migratory corridor for the humpback whales breeding in New Caledonia

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The humpback whale is the most intensively studied species of baleen whale. These long-range migrants which occur in all oceans around the world, summer in high-latitude feeding grounds, and winter in tropical, typically coastal, calving and breeding grounds. Yet, many aspects of these migrations remain a mystery, and the routes they follow in-between their summer and winter destinations is not very well known at least in the South Pacific Ocean.

The first information on movements of individual humpback whales in the South Pacific came from the Discovery tagging programme in the 1950's and 1960's. Since their development in the 1920's the discovery tags have been one of the major tools used by biologists in the study of whales. These small stainless-steel bolts, stamped with information about the tagging agency, were fired into the whale by means of a shotgun in order to penetrate skin and blubber. When recovered during the flensing process they were returned to provide important information on the individual or species. Between 1932 and 1984 over 23,000 whales of at least 11 species were marked with discovery tags. Among this number more than 5,000 discovery tags were deployed on humpback whales in the Southern Hemisphere with roughly 2,000 in the Antarctic Area V located south of New Caledonia and New Zealand. These marks gave invaluable information on movement patterns of whales throughout the Southern Hemisphere. The few tags deployed in the south Pacific Island waters of Vanuatu and New Caledonia, Fiji, Tonga indicated the first connection between two islands of Oceania and the Antarctic: Fiji Area V and VI, Tonga are V and I. They also provided the first information on the link between Fiji and the migratory corridors or East Australia and New Zealand. Finally, they showed links between migratory corridors between East Australia and New Zealand, and between New Zealand and Norfolk Island. But no exchanges between the islands of Oceania were revealed by this method and more specifically it didn't provide any information

on movements of humpback whales tagged in the vicinity of New Caledonia (Paton 2014).

The lagoons and reefs of New Caledonia have recently been included in the UNESCO World Wide Heritage List. They display intact ecosystems and provide habitat to a number of emblematic of threatened marine species such as dugongs, sea turtles, sea birds and cetaceans. A small and endangered population of humpback whales wintering there has been under study every year over a two to three month period for the last 20 years.

The ability to identify individual humpback whales by distinctive natural marking and/or genetic markers has been used to create a photo-identification catalogue (N=1,200), and a genetic database (N=1,031; 70% of which are also photo-identified) for New Caledonia. They were used to characterize the humpback whale population of New Caledonia (Garrigue et al. 2001), to track the movement patterns of an individual through both space and time – including migration and dispersal (Garrigue et al. 2011a, Garrigue et al. 2011b), to conduct detailed behavior studies, and to determine the age, the growth rate (Orgeret et al. 2014), the breeding success and the population size (Constantine et al. 2012, Garrigue et al. 2004).

New Caledonia is a breeding ground for a small population of humpback whales that recently presented an anomalous increase, in population leading us to hypothesize immigration from other areas. These whales show high fidelity to the area with roughly 25% of known individual whales observed each year. A limited number of movements of humpbacks were discovered within the vast South Pacific Ocean. Most of the connections between New Caledonia and the other wintering grounds of Oceania have been found with Tonga. Few movements were highlighted between New Caledonia and neighbouring Vanuatu and Fiji, and only two ocean-wide movements were documented over the years with the

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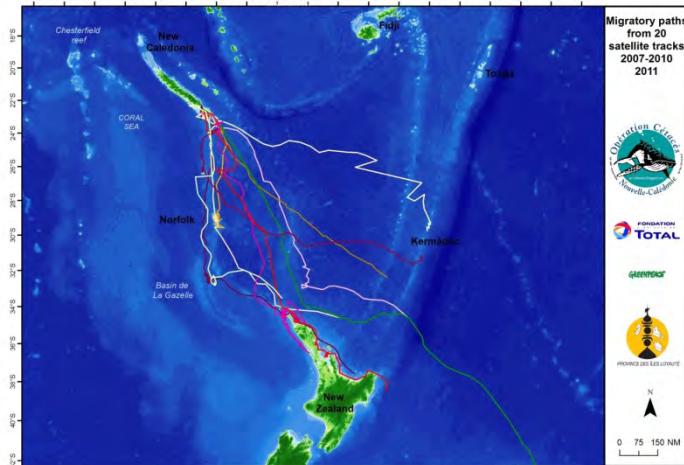


FIGURE 1. Tracks of 20 humpback whales tagged in New Caledonia between 2007 and 2011.

Cook Islands and French Polynesia. Most of the whales resighted between regions have been identified only once in each region, highlighting the fidelity of the whales to their breeding ground, the low level of interchange within Oceania and the apparent transient nature of the movement between breeding grounds. Males sing a song previously sung on the east coast of Australia. It's part of the Oceania subpopulation which has been classified as endangered by IUCN in 2009 (Childerhouse et al. 2009).

More recently the use of telemetry has provided interesting information on migratory movement of whale tagged in New Caledonia. Between 2007 and 2012, 37 humpback whales were equipped with Argos satellite tags in New Caledonia in order to study their movements during their breeding season, and their southern migration towards Antarctic feeding grounds. Twenty-one of these individuals were monitored after they initiated their southern migration from their winter breeding ground in New Caledonia. Three-quarters of the tagged whales headed in a south-south-easterly direction. They travelled along widely dispersed migratory paths spread longitudinally over 1,600km between the Kermadec Ridge and the Norfolk Ridge (Garrigue et al. 2015) (Figure 1).

There opportunistic comparison of the photo-ID and genetic data originated from New Caledonia with those of New Zealand, then combined with the information provided by the use of satellite telemetry revealed a total of 24 whales observed in both areas, including 10 females and 14 males (Steel et al. 2011, Steel et al. 2008, Constantine et al. 2007). When sighted in New Caledonia most of the whales were adults (83%) but three individuals were first observed as calves, and one as a juvenile, before being resighted as adults in New Zealand. Five females were observed with calves in New Caledonia, some of them several times across different years. These 24 individuals were encountered a total of 52 times in New Caledonian over a period of

21 years, from 1994 until 2015. And at least one third of these whales were encountered on more than one year in New Caledonia. These results confirm the connection between the breeding ground of New Caledonia and the migratory corridor of New Zealand and suggest that at least part of the breeding population of New Caledonia passes through New Zealand waters on their southbound migration.

In addition, telemetry data revealed a direct connection between the breeding ground of New Caledonia and the Kermadec Ridge, with one adult male and one adult female observed in both areas. The male, regularly observed in New Caledonia since 2003 and tagged in 2007, travelled in the direction of the Kermadec Ridge until Raoul Island where it stayed for seven days before the tag stopped transmitting. The female was observed only once in New Caledonia in 2011, the year it was tagged as a mother accompanied by a calf. It travelled until the Kermadec Ridge where it stopped just before the end of the tag transmission (Garrigue et al. 2010). Roughly the same percentage of females are found in both corridors and some calves born in the vicinity of the New Caledonian breeding ground have been resighted in both migratory corridors of New Zealand and the Kermadec Islands, suggesting that females with and without calves use both pathways.

The “Great Humpback Whale Trail” was conducted in September-October 2015. During this expedition photo-ID and skin samples were collected from humpback whales during a 13 day period, leading to 157 whales being individually identified (128 using photo-ID and 78 genotypes) (Constantine et al. 2016, this conference). Including the data previously collected, the total number of unique individuals identified in the Kermadec region reaches 162 individuals. The comparison of the data with the available information from New Caledonia revealed that 10 (6%) of these have previously been encountered in New Caledonia – nine were recognised using photo-ID only, and one by genotype only. One individual was first identified in New

These results confirm the connection between the breeding ground of New Caledonia and the migratory corridor of New Zealand.

Telemetry data revealed a direct connection between the breeding ground of New Caledonia and the Kermadec Ridge.

Caledonia as a calf 16 years before it was resighted as a mother during the Great Humpback Whale Trail expedition. With the information coming from telemetry a total of 12 individual whales observed in New Caledonia have passed through the Kermadec Islands, with 41% of those observed more than one year in New Caledonia. This high percentage of resighting whales could suggest a regular use of this migratory corridor and a permanent connection between the breeding ground of New Caledonia and the Kermadec Islands. This sheds a new light on linkage between feeding and breeding grounds and will help to understand the slow recovery of Oceania's humpback whales.

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The Kermadec Islands and ‘The Great Humpback Whale Trail’

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Extensive commercial whaling during the 20th century drove humpback whales (*Megaptera novaeangliae*) close to extinction (Clapham & Ivashchenko 2009). Since the cessation of whaling, humpback populations have been rebuilding but the Oceania population has been slow to recover and remains endangered (Childerhouse et al. 2008, Constantine et al. 2012). Throughout Oceania there is sub-population structuring as humpbacks typically return to their breeding ground origins. Recent work has shown that different age- and sex-class groups prefer different habitat when on their breeding grounds, but this is not a limiting factor to the recovery of Oceania's whales (Lindsay et al. 2016). In order to examine possible reasons for their slow recovery, our attention turned to the migration paths and unknown Southern Ocean feeding grounds of our humpbacks as part of the Southern Ocean Research Partnership, International Whaling Commission project on Humpback Whale Connectivity.

Since 2008, land-based observations by DOC based on Raoul Island have revealed that the Kermadec waters are frequented by humpback whales from mid-September to mid-November as they migrate to their Antarctic feeding grounds. Single four-hour surveys have reported up to 153 whales passing Raoul Island (e.g., Brown 2010) with the peak in sightings mid-September - mid-November (Gibson 2014). In late September to mid-October 2015, we undertook a multidisciplinary study deploying satellite tags into humpbacks as they migrated south past Raoul Island and identifying individuals using genetic and natural markers to determine the feeding grounds, population structure and movements of humpbacks throughout the Antarctic.

Over 13 days of small-boat based surveys at Raoul, we surveyed 1,480 km around Raoul Island and encountered 127 pods of humpback whales with a cumulative total of 235 adults and 37 calves. We successfully deployed 24 satellite tags with 18 tags transmitting for longer than 21 days and the

longest transmission exceeding 7 months duration. The tag data showed whales travelling through the Kermadec Island chain then diverging paths as they migrated south. Whales were spread ~3,500 km from west of the Ross Sea through to the Bellingshausen Sea, near the west Antarctic Peninsula (Figure 1). The longest migration from Raoul Island until the whales stopped to feed in Antarctica was approximately 7,000km and took nine weeks to complete. This does not reflect the entire migration as the whale had travelled ~1,600km from its Oceania breeding ground and then continued to move shorter distances whilst on the feeding grounds; so a conservative estimate is ~8,600km from the breeding to feeding grounds which is close to the longest reported migration (Robbins et al. 2011, Stevick et al. 2010). Four whales migrated to the Bellingshausen Sea region, so this long migration is undertaken by many Oceania whales. Four whales passed the NZ mainland and Chatham Islands, but the majority travelled through the South Pacific in a southeasterly direction.

We collected 85 small tissue samples either from biopsy systems (n = 73) or sloughed skin (n = 12); of these, 54 had a blubber sample attached that will be used for progesterone analysis. Genotyping identified 78 individuals with a female bias (29 males: 44 females: 4 unknown). When the genotypes were matched to previously identified whales from Oceania, east Australia Antarctica, we identified four whales previously sampled on their breeding grounds, including two of the tagged whales known from Tonga. There was one match to New Caledonia (females - 1999), two matches to Tonga (female - 2003 and male - 2005) and one match to American Samoa (male - 2009).

We photo-identified 128 individual whales via the unique pattern of marks on the underside of their flukes and included, an additional five whales photographed in previous years, for a total catalogue of 133 individuals (although this may grow with recent acquisition of new photos). The

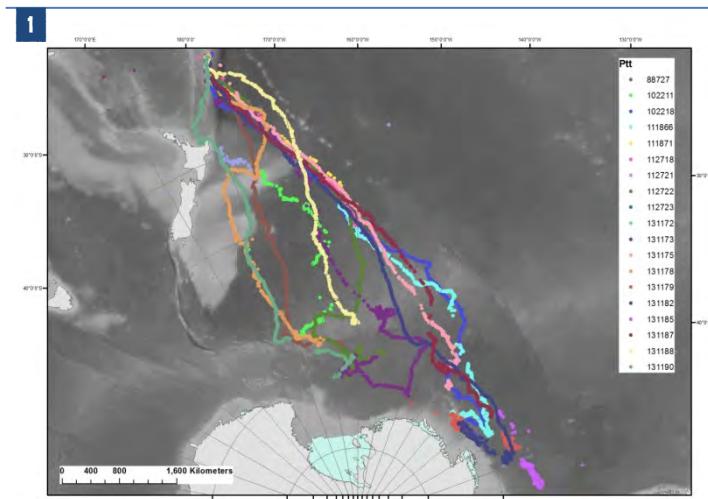


photo-identification matching is currently underway but breeding ground catalogues from New Caledonia to the Cook Islands, migratory corridors of New Zealand and Norfolk Island, and SORP catalogues from Antarctic waters south of New Zealand, have been matched. We found 13 whales identified from their breeding grounds; nine from New Caledonia, and one each from Tonga, Niue, American Samoa and the Cook Islands. There were no matches to mainland New Zealand and matching has yet to be undertaken with east Australia and other larger Antarctic catalogues.

In addition, we recorded four hours of song over 10 recording sessions spread throughout the field season. We recorded a range of song types, perhaps reflective of the diversity of breeding ground origins of these whales. Ongoing analysis of these data will examine whether Raoul Island is a place where songs are shared between different sub-populations of whales, part of their well-documented cultural transmission of song (Garland et al. 2011).

Our research has revealed that humpback whales migrating past Raoul originate from several Oceania breeding grounds spread over ~3,600 km including New Caledonia, Tonga, Niue, American Samoa and the Cook Islands. The close linkages with New Caledonia and New Zealand have been reported previously, including tagged whales migrating past the Kermadecs (Garrigue et al. 2011, Garrigue et al. 2016). Whale residency time at Raoul ranged from periods of <1 day to 21 days with all age- and sex-class groups passing by the island. Exactly why so many humpbacks from many breeding grounds pass through Kermadec waters is unknown - although may be related to the importance of social aggregations (Clapham & Zerbini 2015) - but this provided an excellent opportunity to go to northernmost NZ to understand the importance of southernmost NZ to humpbacks; Antarctica. The majority of whales swam directly to Antarctic waters without stopping along their migration path, but there were some that took a longer route via mainland New Zealand (a mother-

calf pair), doubled back on their southeasterly path, or stopped before Antarctica possibly to feed. Further analysis of the fine-scale tag data will reveal more details about the whales' paths and important habitat along the way. Now we have determined individual feeding grounds, newly developed isoscape models based on isotope markers will allow us to assign feeding grounds and provide baseline data on how future changes may influence their spatial distribution, stock recovery and role in Southern Ocean ecosystem function.

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FIGURE 1. Migration path of humpback whales from Raoul Island to Antarctica from October 2015 until April 2016.

Is Raoul Island a place where songs are shared between different sub-populations of whales, part of their well-documented cultural transmission of song? Humpback whales migrating past Raoul originate from several Oceania breeding grounds spread over ~3,600 km including New Caledonia, Tonga, Niue, American Samoa and the Cook Islands.

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New Zealand's Southern Right Whales: Reason for Hope

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The southern right whales of New Zealand were decimated by 19th century shore- and ship-based whaling. During this time, the whaling industry killed a total of 34,000–38,800 right whales around New Zealand, reducing the population to only ~15–20 adult females by the early 1900s. Despite international protection, illegal whaling by the Soviet Union in the 1960s resulted in further losses to the remnant New Zealand population. Assessment of historical whaling records showed that whales were distributed extensively around mainland New Zealand, the sub-Antarctic Islands and the Louisville Ridge. Reconstructing catch records, historical sightings data and levels of genetic diversity and gene flow can help understand population recovery and distribution. Today right whales are largely concentrated in Ross Harbour, Auckland Islands with increasing numbers reported at Campbell Island and around southern mainland NZ during the winter breeding season. These whales are part of the same genetic stock with several whales moving between the mainland and the sub-Antarctic Islands. Contemporary sightings records are largely confined to coastal regions and known wintering grounds with offshore habitat use and feeding grounds still poorly understood. Recent satellite tagging revealed that at least some right whales travel west from the Auckland Islands to forage near the subtropical front. Stable isotope data suggest they are preying on copepods and krill; this is consistent with historical records of stomach samples from Soviet whalers. The New Zealand population is currently estimated to number about 2,100, or <12% of their pre-exploitation abundance and the stock is increasing slowly but steadily in numbers. The Auckland Islands is the only significant calving ground in NZ but whales are reported more frequently in coastal waters of the mainland, especially in Te Wae Wae Bay. Evidence suggests mother-calf pairs seek sheltered habitats for nursing which provides insights into areas of the mainland likely to be recolonised and managed to minimize anthropogenic impacts. The increase in numbers of whales

and expanding range provides us with hope that they may return throughout all their former NZ range. Spatial modelling predicting offshore foraging habitat for right whales under different climate scenarios highlights the once abundant Louisville ridge region adjacent to the Kermadecs as an area of importance, just as it once was.

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A building biodiversity story for the shallow marine biodiversity of the Kermadec Archipelago

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The biodiversity of an island, and the processes contributing to it, will change over time. Initially biodiversity will increase as species colonise the island from elsewhere. Depending on population connectivity with other regions, some species may then speciate or go locally extinct. Later, as niches fill, interactions among species can lead to the competitive exclusion of some resident and colonising species. The Kermadec Archipelago can offer a globally unique insight into the how these three processes – *colonisation, connectivity, and competition* – shape biodiversity. The islands of the archipelago are small, they make up one of the most remote archipelagos in the world, and they have an unusual combination of temperate and tropical species. In light of our globally changing climate, directional changes in the mix of tropical and temperate species at the Kermadec Islands may serve as an early warning for more widespread biodiversity change. Our research takes a multi-disciplinary approach to investigate the role of colonisation, connectivity, and competition in shaping the shallow marine biodiversity of the Kermadec Archipelago, and to predict what levels of biodiversity and community compositions we may expect in future.

COLONISATION:

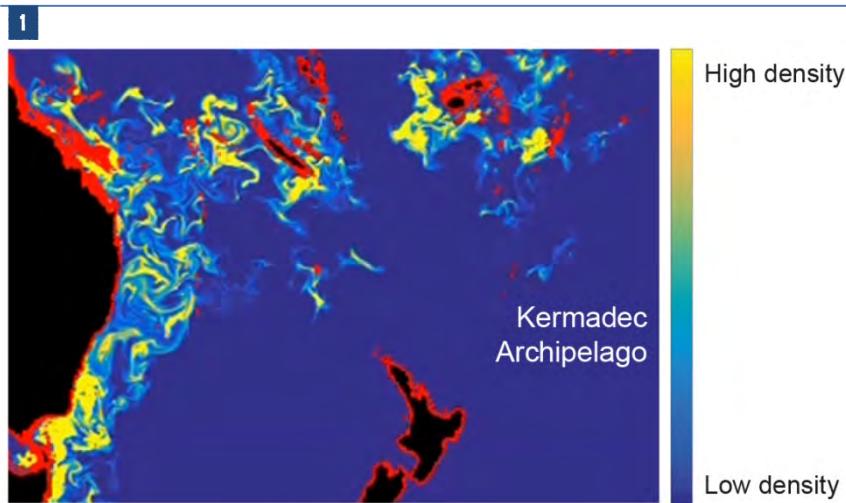
Several expeditions have now expanded our knowledge of the reef fishes and marine invertebrates surrounding the Kermadec Islands (complete checklist in Duffy and Ahyong 2015). Findings suggest that the reef biodiversity of the Kermadec Islands is relatively depauperate (e.g. fishes, Francis and Duffy 2015), but the number of species recorded at the islands continues to increase with each expedition. For example, during the most recent biodiscovery expedition (November 2015), the tropical yellow-spotted wrasse, *Macropharyngodon negrosensis*, was observed in Boat Cove for the first time, despite this location being among the most surveyed in the Kermadec Archipelago (e.g. Schiel et al. 1986, Francis et al. 1987, Cole et al. 2010). These trends indicate that colonisation of the Kermadec

Archipelago is on-going, and these colonising species are increasingly from the tropics (Francis and Duffy 2015).

Colonisation of the Kermadec Islands by any given species will be influenced by both the ocean currents and a species' dispersal characteristics. Most reef fishes and marine invertebrates disperse in the open ocean as eggs and larvae before becoming reef dwelling adults. However, each species varies in how long they can spend in the open ocean and consequently how far they can disperse. Using a biological-oceanographic model we are able to infer what dispersal characteristics (e.g. egg type and pelagic larval duration) have enabled species to colonise the Kermadec Islands, where they have likely dispersed from, and therefore what species are likely to colonise the Kermadec Islands in future (for a similar approach see Treml et al. 2015). Our preliminary results indicate that colonisation of the Kermadec Islands may be very rare, even for species that can disperse in the ocean for up to 30 days (Fig. 1). Our future research will simulate the colonisation potential and pathways for many more reef species from surrounding regions of the Southwest Pacific, and will investigate in what seasons and years (e.g. El Niño, La Niña) the Kermadec Islands are likely to have higher rates of colonisation.

CONNECTIVITY:

Recent research has highlighted the diversity and abundance of tropical marine species at the Kermadec Islands (Richards and Liggins 2015), yet there has been little investigation into their population connectivity with tropical regions and how these populations persist in this sub-tropical zone. Our connectivity research used a population genetic survey to investigate connectivity for populations of the Crown-of-Thorns seastar (*Acanthaster planci*) and the Collector urchin (*Tripneustes gratilla*; for full details see Liggins et al. 2014). These species occur throughout the tropical Indo-Pacific Ocean, including the Kermadec Islands. Since the first published records of the Crown-of-Thorns seastar and the



Collector urchin at the Kermadec Islands, both species have been repeatedly recorded at the island group (reviewed in Liggins et al. 2014). However, it was not clear whether the populations of the Kermadec Islands were sustained by local reproduction or reliant on immigration from other regions.

Our research findings suggest that the Crown-of-Thorns seastar and Collector urchin populations of Raoul Island have a similar history of connectivity with the wider Indo-Pacific. In both species, the population contained only one genetic type (i.e. haplotype) that was also found in other locations (Fig. 2). The genetic affinities (i.e. the shared haplotype) of the seastar with American Samoa, Vanuatu, and the northern Great Barrier Reef, suggest colonisation of Raoul Island may have been from these locations, or from a source common to all of these regions. In the urchin, the source of the Raoul Island population was difficult to infer, as the haplotype found at Raoul is also shared across much of the surveyed species range.

The low genetic diversity of the populations at Raoul Island is unusual and contrasts with the high levels of genetic diversity found in most other Indo-Pacific populations of the Crown-of-Thorns seastar and Collector urchin. This pattern of low genetic diversity is consistent with a population founded by only a few colonists, after which the population has likely been sustained by local reproduction. Our simulations of immigration events confirmed that it is highly unlikely that the patterns of genetic variation that we observed could result from immigration events (see Liggins et al. 2014). Most other populations sampled for both species also contained haplotypes that were unique (endemic) to their population (Fig. 2). The lack of unique haplotypes at Raoul Island likely indicates that these populations are relatively young. The short geological history (1.8 – 3 million years old, Watt 1975) of the Kermadec Islands supports this notion of recent colonisation.

Therefore, despite both the Crown-of-Thorns seastar and Collector urchin being relatively high dispersal species (~28 and 18 day pelagic larval duration, respectively), our research indicates they may have only recently colonised Raoul Island, and these Kermadec populations are not well connected to elsewhere in the Indo-Pacific. Moreover, despite Raoul Island providing marginal habitat for tropical organisms, these populations persist through local reproduction. Unfortunately, this lack of genetic diversity and connectivity of the Raoul Island populations of Crown-of-Thorns seastar and Collector urchin means these populations are not resilient, but will be vulnerable to local extinction.

COMPETITION:

There are finite resources and niches available on the reefs around the Kermadec Islands for which species will compete, and some will go extinct. At present we know very little about these interactions among species at the Kermadec Islands, and how interactions among species could impact local population dynamics and persistence. One guild of species that have been the subject of several past research efforts are macroinvertebrates, and in particular the urchin species (Schiel et al. 1986, Cole et al. 1992, Gardner et al. 2006). Urchins are renowned for driving community and ecosystem changes (Ling et al. 2015). At the Kermadec Islands, several urchin species exist in very high numbers, and in places these species are completely interspersed on the reef. During our November 2015 expedition we surveyed the occurrence of these urchin species to quantify niche segregation, alternative use of available resources, and to detect any change in the community composition since previous surveys. We hope that analysis of such structured surveys and behavioural observations will provide a glimpse into the species interactions that will likely structure the reef biodiversity of the Kermadec Archipelago into the future.

FIGURE 1. The simulated distribution and density of biological particles (i.e. eggs and larvae) after 30 days travelling on ocean currents. Red regions represent suitable reef habitat for shallow marine species from which biological particles are released. In this simulation eggs/larvae were released from all locations, except mainland New Zealand. After 30 days travelling on ocean currents very few biological particles are in the vicinity of the Kermadec Archipelago. A plume of biological particles originating from the Raoul Island group can be seen east of the islands.

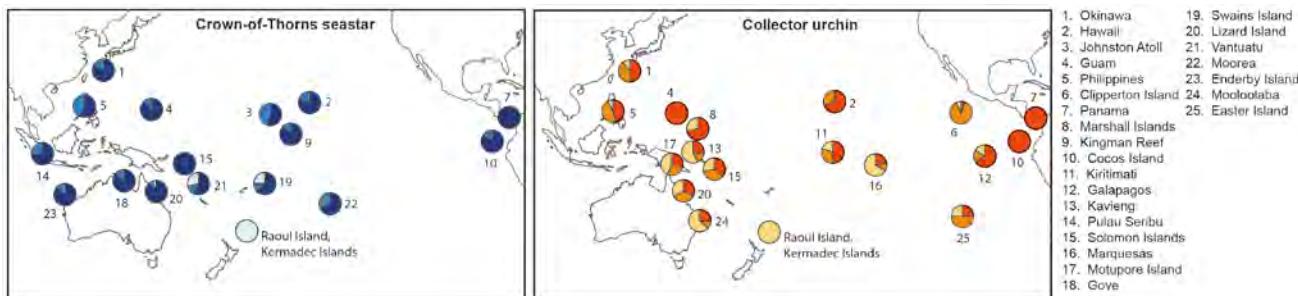


FIGURE 2. Map of surveyed locations and their genetic (i.e. haplotypic) composition for the Crown-of-Thorns seastar (*Acanthaster planci*, top) and Collector urchin (*Tripneustes gratilla*, bottom). Pies indicate the proportion of individuals that share the haplotype found in Raoul Island (lightest tone), the proportion of individuals that have a haplotype unique to their population (medium tone), and the proportion of individuals that have a haplotype that is shared among locations, but not found in Raoul Island (darkest tone). In both species, the Raoul Island population has low genetic diversity and no endemic haplotypes. (Figure modified from Liggins et al 2014.)

SUMMARY:

- Colonisation of the Kermadec Islands by shallow marine species is likely rare and relatively recent, but it is ongoing. Our colonisation research uses biological-oceanographic modelling to infer what dispersal characteristics have enabled species to colonise the Kermadec Islands, where they have likely dispersed from, and therefore what species are likely to colonise the Kermadec Islands. In future, we will extend our modelling to predict species range extensions and colonisations of New Zealand via the Kermadec Archipelago.
- There is little population connectivity between Indo-Pacific reefs and Raoul Island for two common, high dispersal echinoderm species based on our genetic survey. Our research continues to address population connectivity among the wider Indo-Pacific and the Kermadec Islands, and into New Zealand, using a greater suite of species and genetic markers.
- Our future colonisation and connectivity research will require access to the southern islands of the Kermadec Archipelago – Macauley, Curtis, and Cheeseman Islands, and L’Esperance and Havre Rocks – to undertake biodiversity surveys to inform models and to undertake genetic sampling.
- Establishment of standardised long-term and regular monitoring of the reef communities across all the islands of the Kermadec Archipelago will be crucial for quantifying potential competitive interactions (and extinctions) among species in the current community of the Kermadec Islands, and to recognise and predict future community transitions.

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Doing whatever it takes to survive: examining morphological divergence in high-latitude, reef-building corals

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Despite covering less than 1% of the earth's surface, coral reefs support 25% of the world's marine biodiversity, as well as provide food, livelihoods and ecosystem services for hundreds of millions of people. Interestingly, the reef-building corals which are the foundation for these astonishing ecosystems are themselves the product of a symbiotic association between two different types of organisms: a cnidarian closely related to sea anemones; and a group of single-celled microalgae called zooxanthellae. Zooxanthellae live within the tissues of the cnidarian and contribute nutrients to the symbiosis as a by-product of photosynthesis. Without their zooxanthellae corals would struggle to survive in nutrient-poor tropical waters. In turn, the cnidarian captures food from the water column, like an anemone, and excretes a limestone skeleton that provides structural support and protection – it is the growth of this skeleton that builds coral reefs.

Corals, and all the biodiversity coral reefs support, are under the immediate threat of global climate change. Increases in ocean temperature trigger a cascade of physiological responses that can cause the cnidarian to evict the zooxanthellae, giving corals a characteristic “bleached” appearance (Hoegh-Guldberg 1999). For example, the 2015-2016 mass coral bleaching event currently affecting the southern hemisphere has had a dramatic effect coral reefs on Northern Great barrier Reef: an 81% of reefs have suffered severe coral bleaching (ARC Centre of Excellence in Coral Reef Studies 2016). Moreover, coral reefs in areas such as the Fijian Islands have recently experienced both, mass coral bleaching and severe storm conditions. The synergistic effect of these two climatic events can severely limit the potential for reefs to recover. Alarmingly, if current climate trends persist, the frequency and magnitude of extreme climatic events such as ocean warming and severe storms are predicted to increase in the future (Hoegh-Guldberg and Bruno 2010).

Although human-mediated climate change is proceeding at a rate our planet has never experienced, coral reefs have endured large-scale climatic changes in the past. During the warm interglacial periods, when regions at higher latitudes became more favourable for coral growth, coral reefs existed at higher latitudes than their current latitudinal limits (Greenstein and Pandolfi 2008; Kiessling 2001). This pattern of range expansion and contraction in response to changes in global ocean conditions gives us some hope that coral reefs may be able to endure some level of human-mediated climate change. Sea temperature however, is not the only factor limiting where corals can live. At higher latitudes temperature, the concentration of aragonite (a chemical essential to the formation coral skeletons), and the amount of light available to the zooxanthellae become too extreme for most corals to endure (Kleypas et al. 1999; Muir et al. 2015).

Recent studies focusing on the most diverse group of reef building corals – the staghorn corals – have shown that the amount of light corals receive during winter is the most likely factor limiting the depths and latitudes where corals can survive (Muir et al. 2015). Climate change is predicted to alter sea temperature and the concentration of aragonite such that regions nearer the poles will become more favourable for coral growth; however, climate change is not predicted to dramatically affect the amount of light hitting the ocean surface. Thus, while corals may find some refuge at higher latitudes, corals will not be able to outrun human-mediated climate change indefinitely. Eventually, corals may find it difficult to colonise high-latitude regions because there is insufficient light to sustain their metabolic demands.

Nevertheless, corals are currently extending their ranges towards both the north and south poles (Baird et al. 2012; Yamano et al. 2011), implying that corals have not reached their absolute environmental limit yet. Importantly, the corals at the leading edge of this contemporary range expansion are

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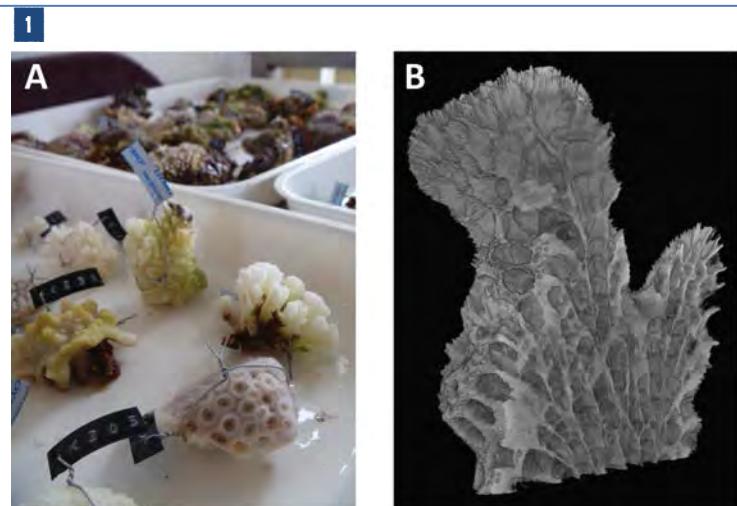


FIGURE 1 A) Individually labelled and photographed coral fragments collected from Raoul Island, Kermadec archipelago. B) MicroCT image of *Pocillopora damicornis* showing internal skeletal structures. These images will enable us to visualise and measure morphological features that allow corals to survive at high latitude locations such as the Kermadec archipelago.

not a random sample of all possible species of coral. The coral species living at high latitudes have morphological and physiological characteristics that allow them to survive, and even thrive in conditions too extreme for other coral species (Sommer et al. 2014). Moreover, some coral species occur in both low and high latitudes. Understanding, why some species can tolerate conditions at high latitudes whereas others struggle to survive, and how individuals of the same species living in high and low latitudes differ from each other will allow us to calibrate if corals could escape the increasingly hostile climatic conditions they are likely to face at low latitudes.

The Kermadec archipelago, and the Raoul Island group in particular, is New Zealand's reef-building coral capital. In certain parts of the archipelago, live corals can cover most of the available substrate (Brook 1999; Schiel et al. 1986; Wicks et al. 2010), and the skeletons of dead corals become the foundation for live corals to establish and grow. Nevertheless, even for the corals capable of colonising this remote archipelago, the marginal conditions for coral growth afforded by the island's unique land and seascapes impose significant challenges. Accordingly, the coral fauna of the Kermadec archipelago are a collection of hardy species commonly found at high-latitude, southern-hemisphere locations (Wicks et al. 2010). During our recent expedition to the Kermadec archipelago in November 2015 we collected over 300 coral specimens from the shallow reefs (< 30 meters) that surround Raoul Island (Figure 1A). Preliminary analyses of these data suggest that the coral community composition and depth distributions of these corals have remained relatively constant over past 30 years (Brook 1999; Richards and Liggins 2015; Wicks et al. 2010).

In the second phase of our analysis we will collect fine-scale measurements of the morphology of the corals we collected (Figure 1B). Just as the environment has filtered the species pool, individuals of the same species should exhibit signatures of

natural selection for morphological characters that allow them to tolerate the environmental conditions at high latitudes. Using these collections we aim to investigate how the morphology of corals living in this remote, high-latitude location differ from populations of these same species occurring at lower latitudes as well as in other high-latitude locations where these corals occur (e.g. Lord Howe Island). These data will allow us better understand how reef-building corals have adapted or acclimated to the challenges associated with living in high-latitude locations.

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The Kermadec archipelago, and the Raoul Island group in particular, is New Zealand's reef-building coral capital.

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Cephalopod fauna of the Kermadec Islands: Much left to learn

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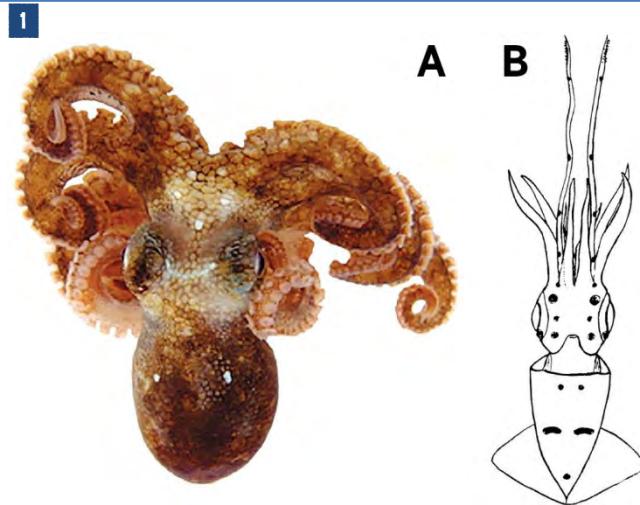
New Zealand waters are home to one of the highest known diversities of cephalopods occurring around any country. Our squid, octopus, and vampire squid taxa are already reported at over 100 species (Spencer et al., 2014), with many more awaiting formal recognition. In several regions in particular, including the northern waters of our Exclusive Economic Zone (EEZ), examinations of new material regularly reveal new cephalopod taxa and new local records, keeping members of the AUT Lab for Cephalopod Ecology and Systematics (ALCES) busy and intrigued.

While academic knowledge of our cephalopod diversity has advanced considerably since the first region-specific scientific publication over 100 years ago, these animals have also been a legendary presence in New Zealand history and folklore for far longer. The Polynesian navigator Kupe is said to have reached Aotearoa while in pursuit of a giant wheke (*Octopus*) that had been consuming the fish on which his people relied on for food in Hawaiki. Kupe's final battle with this Leviathan (known as Te Wheke O Muturangi) is said to have taken place in Cook Strait, where he slew it, leaving only the Brothers Islands to represent its remains (the eyeballs; Whatahoro, 1913). The giant cephalopods—squid in particular—that reside in our waters continue to fascinate New Zealand's public and the world on a wider stage, with over 130 specimens of giant squid having been encountered and examined by scientists within the past 25 years, providing material for numerous publications, public talks, and documentaries. However, the vast majority of New Zealand's cephalopod fauna is comprised of smaller (although equally fascinating) species, many of which dwell in the deep sea. Even the best-sampled regions of our EEZ, such as the Chatham Rise, continue to reveal novel (undescribed) taxa; specimens encountered the less-sampled regions, such as our northern waters, almost routinely prove to be either new records for New Zealand or species that have not yet been formally described.

Of the three shallow-water octopus species encountered by the 2011 Kermadec Biodescovery Expedition, one was new to science (*Octopus jollyorum*, Fig. 1A) and another had previously been known from just a handful of female or immature specimens (Reid & Wilson, 2015).

Scientific efforts to catalogue in the cephalopod fauna of the Kermadecs began just over 100 years ago, with Berry (1914; 1916) and Oliver (1915) together reporting a total of 40 specimens from the region, attributed to a remarkable 17 species (six octopuses, nine squids and two nautiluses) of which several were new to science (e.g., *Lampradioteuthis megaleia*, Fig. 1B). It should be noted, however, that the two nautilus species reputed to reside in the area, *N. pompilius* and *N. macromphalus*, were both—and remain—reported based only on broken shell fragments, which are well known to drift and should not on their own be considered conclusive proof of species presence in any region (House, 2010). Duffy & Ahyong (2015) conducted a literature review of the Kermadecs' marine flora and fauna, including cephalopods, updating the number of reported octopus species to 12 and squid to 15, plus the two alleged nautiluses. This checklist updated the names of some locally occurring taxa to reflect systematic revisions that had occurred in the intervening century (e.g., *Onychoteuthis aequimanus* replacing the recently resolved *O. "banksii"* species complex; Bolstad, 2010) and appears to be the most accurate published synopsis of Kermadec cephalopods to date.

However, much work remains to be done before a full understanding of the region's true cephalopod species composition is achieved. An uncritical review of the species names presently attributed to Kermadec-sourced cephalopod specimens housed in the Museum of New Zealand Te Papa Tongarewa (over 200 specimen lots, about 6% of the Museum's cephalopod holdings) reveals 10 octopus and more than 30 squid species (double the number reported by Duffy & Ahyong in 2015)—more



than 30% of New Zealand's presently reported total cephalopod diversity. The majority of the squid specimens among this material were collected by midwater trawls by the RV *James Cook* in the 1970s—some 40 years ago—with little new material in the interim. This is not surprising, as few recent fishing or survey activities have been conducted in the area using similar gear, and these animals are notoriously difficult to sample, being active swimmers with good vision, and thus well able to avoid most other collection methods.

A careful and detailed review of this existing material, together with a smaller number of additional specimens contained within the invertebrate collections housed at the National Institute for Water and Atmospheric Research, Ltd (NIWA), is needed in order to establish the true cephalopod diversity represented by these holdings, and to provide a good basis for comparison with new material, should any become available. As the northern waters of New Zealand's EEZ remain among the least-sampled areas, it is fully expected that new local records and undescribed species will be encountered in the Kermadec region in the future. At present, several higher-level taxa (genera and even families) are known to occur in the area (pers. obs.) that have not yet been formally added to the growing tally of New Zealand's cephalopod taxa.

In particular, it would be useful to obtain tissue samples of any new material that may be encountered from northern waters, for genetic comparison both with taxa from elsewhere in New Zealand and from further afield. An increasing body of evidence indicates that cephalopod species historically considered to be cosmopolitan or wide ranging often prove, upon closer inspection, to represent several (or many) distinct, geographically restricted species (e.g., Bolstad, 2010; Braid & Bolstad, 2015). This appears to be particularly true around certain island groups in the Pacific, including New Zealand. Given the unique oceanographic conditions of the Kermadec region compared with other sectors of the

EEZ, the future discovery of new geographic records and entirely undescribed species is highly likely.

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FIGURE 1: Two cephalopod species first described from the Kermadec Islands. (A) *Octopus jollyorum* (reproduced from original description in Reid & Wilson, 2015, fig. 38), (B) *Lampadoteuthis megaleia* (reproduced from original description in Berry, 1916, fig. 4).

Terrestrial invertebrates of the Kermadec Islands

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The Kermadec archipelago is part of a linear series of volcano summits produced by subduction of the Pacific continental plate beneath the Australian plate. The islands, which are no older than one million years above present sea level, support a terrestrial biota that has arrived comparatively recently via wind, wings and water from neighbouring landmasses including New Zealand, New Caledonia, Lord Howe and Norfolk islands.

Although endemic bird species occur on all the Kermadec islands, endemism is low for the remainder of the biota with only Raoul Island, the largest of the group at 2938 ha, maintaining several endemic tree species. Similarly, the terrestrial invertebrate fauna also displays low endemism and is depauperate in many species of large flightless forms.

A BRIEF HISTORY OF ENTOMOLOGICAL COLLECTING ON THE KERMADEC ISLANDS

The first concerted scientific expedition to the Kermadecs was the 1907 'Oliver' expedition, during which terrestrial invertebrates were collected along with many plant species. After a relatively quiet period during the two world wars, invertebrate collecting was resumed in the 1960s with two New Zealand Ornithological Society expeditions in 1964 (curtailed by a volcanic eruption) and in 1966/67. These expeditions produced the largest yield of invertebrate species and subsequent papers to date. Charles Watt, the expedition entomologist, summarised the Kermadec insect fauna as fragmentary and with low endemism. However, at least 17 descriptive papers were produced as a result of these two expeditions, by far the highest

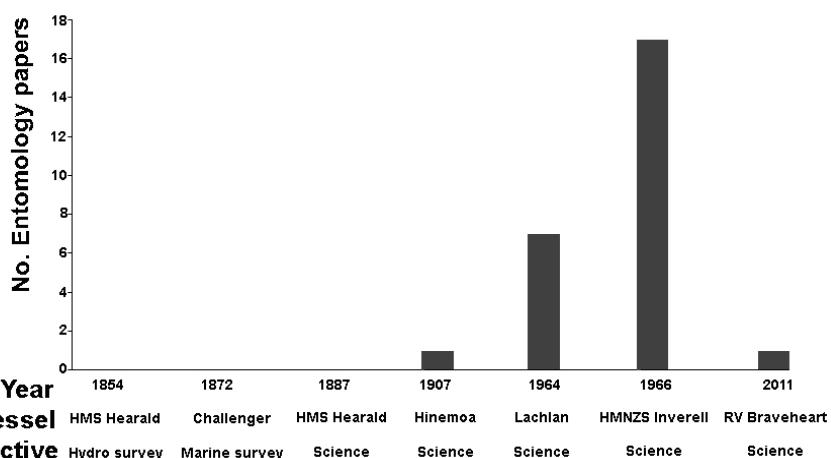
concentration of knowledge about Kermadec terrestrial invertebrates (Figure 1).

Since Watt's visit, invertebrate collecting on the Kermadecs has been intermittent. In 2002, Terry Greene (Department of Conservation DOC) made mention of several beetle and fly species following a visit to Macauley Island in lieu of a poison drop to eradicate rats. The recent May 2011 Bio-discovery expedition provided another opportunity to make collections from several islands in the Kermadec group, forming the basis of this work. The expedition, led by Dr Tom Trnski (Auckland Museum), resulted in landings on seven of the 15 Kermadec Islands, including; Raoul, the Meyer pair, North Chanter, Macauley, Cheeseman and L'Esperance Rock. The latter four islands were new collection locations.

A total of 118 invertebrate taxa were collected during the expedition, of which 12 were recognised to genus only and are potentially new species for the region. New location records for 47 species were also established. Of the un-recognised taxa, seven were diptera (flies) and, surprisingly, from an equal number of families and genera. However, the genus to species ratio for collected fauna was 1:1.07, suggesting limited speciation. Table 1 summarises the invertebrate fauna for the islands visited during the 2011 expedition.

Species area plots of the invertebrate yield demonstrated a characteristic asymptotic curve. Insect species dominated the samples from Raoul, Macauley and Cheeseman islands while L'Esperance Rock produced higher numbers of arachnid taxa (Figures 2 and 3).

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**TABLE 1.** Summary data table of the Kermadec Island terrestrial invertebrate records from the 2011 bio-discovery expedition.

	Raoul	Meyers	North Chanter	Macauley	Cheeseman	L'Esperance Rock
Hectares (km²)	2938 (29.38)	8 (0.08)	5 (0.05)	308 (3.08)	7.6 (0.076)	5 (0.05)
Date of visit	May 15-16 & 18-19, 2011	May 12-13, 2011	May 16, 2011	May 21-23, 2011	May 24, 2011	May 26, 2011
Number of days and/or hours collecting	3 days/16 hrs	4 hrs	2hrs	2 days/8hrs	3hrs	2hrs
No. of RTU's collected per island	87	13	7	26	11	9
Number of potentially new species	7 Araneae <i>Hulua</i> sp. (Desidae) Diptera <i>Paradasyshelea</i> sp. (Ceratopogonidae) <i>Achalcus</i> sp. (Dolichopodidae) <i>Hydrellia</i> sp. (Ephydriidae) <i>Atherigona</i> sp. (Muscidae) <i>Megaselia</i> sp. (Phoridae) Gastropoda <i>Flammulina</i> sp. (Charopidae)	2 Diptera <i>Sphaeroceridae</i> sp. <i>Fergusonina</i> sp. (Fergusoninidae)	0	1 <i>Psychodidae</i> sp.	1 <i>Fannia</i> sp. (Fannidae)	1 <i>Protochelifer</i> sp. (Cheliferidae)
No. of endemic taxa	5	0	0	1	0	?
No. of species with new location records	33	4	7	17	11	8
No. of species with flightless forms	42	6	1	8	3	3

BIOGEOGRAPHY OBSERVATIONS

The Kermadecs present a model case-study of island biogeography. The combination of oceanic isolation, a youthful geology and high disturbance is reflected by the assemblage of vagrant invertebrates capable of travelling by wind, water and wings and, more recently, via human activity. The islands are also very significant as a 'natural laboratory' for the study of evolutionary principles (i.e. rates of colonisation, taxonomic composition of colonisers and incipient endemism). Moreover, the near pristine condition of the Kermadec Islands means we have an

'ecological clean room', making them valuable for global monitoring of human activities elsewhere.

The number of invertebrate species on the Kermadec islands increased as an arithmetic function in proportion to island area (Figure 4). This is typical of island biogeographic theory and showed that Raoul Island had the highest yield of invertebrates (including diversity and biomass) while L'Esperance Rock the least. Similarly, the relationship between the linear distances between islands and the proportion of shared taxa, demonstrated a weak negative correlation (Figure 5).

FIGURE 1. Relative numbers of Entomological papers published per expedition to the Kermadec Islands

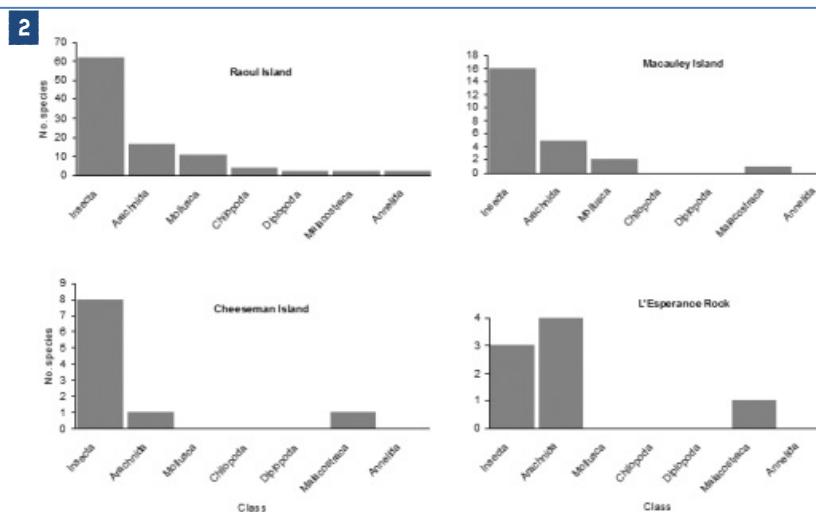


FIGURE 2. Simple species / area bar plots for the four principle islands visited during the 2011 bio-discovery expedition.

While this study found an inverse relationship between taxa shared between islands and linear distance, it is probable that distance is less significant to the faunal composition than habitat suitability. For many groups the diversity of habitats between islands may be a greater impediment to colonisation than crossing the ocean, the resultant effect being an ecological filter. The outcome of this effect could be differential survival of many taxonomic groups on a few islands but with complete colonisation of a select few taxa on all islands.

ECOLOGICAL SIGNIFICANCE OF THE ISLANDS

The subtropical location of the Kermadec Islands means the group are subject to trade winds and westerly moving ocean gyres. Raoul Island is located well within these global systems and is sufficiently large in space, persistent in time and with enough ecosystem heterogeneity for some endemism to have arisen (particularly amongst ground-dwelling forest taxa). Raoul Island's coastline and land area are also extensive enough for continuous random immigration to effectively balance chance extinction.

However, the absence of large, flightless invertebrates on the Kermadec Islands (for example, tree weta, carabid beetles, tunnel web spiders and heavy carnivorous snails) is, in the first instance, due to isolation and size. Human-introduced pests (rats, cats, birds and hedgehogs?), no doubt had an impact on the invertebrate fauna and may have driven any large-bodied taxa to extinction (although evidence for 'hopeful monsters' is sorely lacking). Blackbirds *Turdus merula* remain on Raoul Island and are probably still having an impact on the small suite of indigenous fauna.

Observations from this work suggest that an 'ecological filtering' effect exists between the islands and may be a function of habitat heterogeneity, island size and human-induced ecological change. Community

resilience is one method of measuring this ecological filter where the smaller islands may be ecologically unstable in the absence of continuous immigration while grading toward increased stability on the larger islands.

This finding has implications for conservation, and an understanding of this type of community structure on the islands is probably necessary for management. It is also crucial that some form of ecological monitoring, using a selection of indicator taxa (plant and invertebrate), be considered for the terrestrial environments of the Kermadec Islands. Furthermore, the Kermadec Islands not only present a model of island biogeographic theory; they also offer some tantalising resource partitioning patterns and a datum against which we can compare the effects of human activities globally. As it is, the near pristine terrestrial ecology of the Kermadec Islands demands that our scientific and conservation agencies work together, mindfully, to see these islands protected at a global level.

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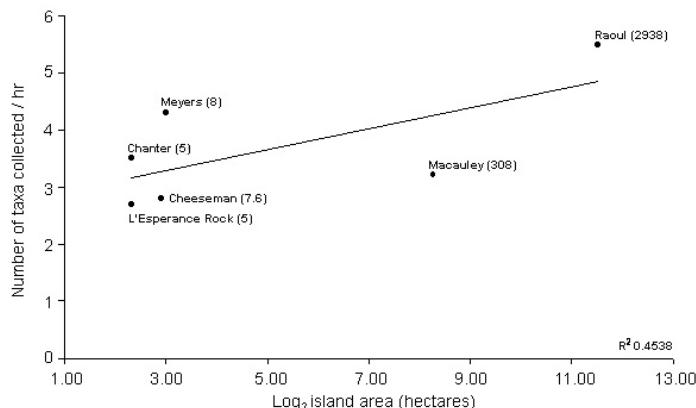


FIGURE 3. Characteristic species area curve for the principle Kermadec islands sampled during the May 2011 expedition.

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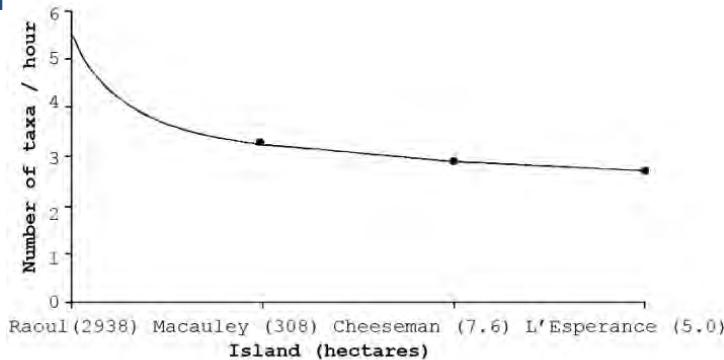


FIGURE 4. The number of invertebrate species collected on the Kermadec islands increases linearly in proportion to island area

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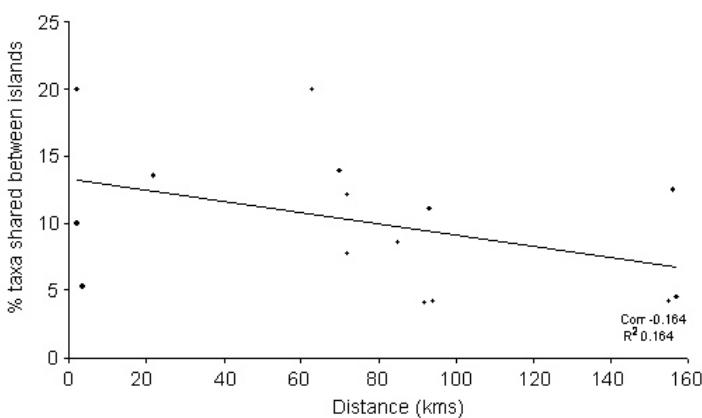


FIGURE 5. The proportion of taxa shared between islands decreases as a weak function of linear distance between islands.

Seabirds return to an oceanic island: Raoul Island, northern Kermadec Islands

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The 620,000 square kilometres that make up the most northerly part of Aotearoa New Zealand's 200 nautical mile Exclusive Economic Zone exists because of the Kermadec Islands. Remote, truly oceanic, these islands crown a long submarine ridge that stretches from the North Island to Tonga. All volcanic, two of them active, the islands are home to millions of seabirds: petrels, shearwaters, storm petrels, tropicbirds, boobies, terns and noddies, a sub-tropical-temperate mix of species. Many South Pacific Islands, including New Zealand, have experienced population declines of birds caused by the introduction of alien predators. A significant example is Raoul Island; the largest of the Kermadec Islands (2943 ha, next largest is Macauley Island 324 ha). These declines resulted from predator introductions following human visitation and settlement from the 1400s, including human predation of seabirds.. One of the world's great seabird colonies had been all but annihilated. We present on the return of seabirds to Raoul Island, from 2004 to the present day.

Truly oceanic islands are predominantly seabird islands – or should be! Seabirds provide a seamless link between land and sea. While they breed on land, they are also truly marine creatures, perfectly adapted for life at sea. The newly announced proposed Kermadec Ocean Sanctuary is their realm – Raoul Island is around 1000kms from the nearest land mass, New Zealand's North Island. We have no idea of how many seabirds there would have been on Raoul Island prior to introduction of predators and pests – first Pacific rats with Polynesian voyaging and occasional settlement, then – cats, Norway rats, goats, pigs and dogs – with European visits and settlement. However, we get a sense of how many birds there might have been by first comparing Raoul to Macauley Island (150kms to the south). In 1988 it was estimated that Macauley had something like 5.8 million birds breeding there. Raoul is almost 10 times the size of Macauley (2938 ha compared to 315 ha). The accounts from visitors in the 19th century and early 20th also

give a sense as to the numbers of birds that must have been on Raoul. However, by then populations were on the decline to the ravages of predators as well as the harvesting by settlers and sailors.

Only a handful of species remained by the end of the twentieth century; their numbers considerably lower than early reports indicated. However, there were still birds enough in the 1800s for Raoul to offer two petrel species new to science: 1) The first Kermadec petrel was collected by MacGillivray, the naturalist on board the HMS Herald, when it visited the Kermadec Islands in 1854. The specimens were forgotten until 1863 when it was finally described by Schlegel – *Pterodroma neglecta*. In fact, the specimens were not actually collected from Raoul itself, but the Meyer Islands a few kilometres away; something that may have significance for some recent work. 2) Specimens of White-naped Petrel (or the Sunday Island Petrel after an early name for Raoul 'Sunday Island') were given to Cheeseman, director of the Auckland Museum – who sent them on to Salvin in the United Kingdom where it was formerly described. The species was known only from Raoul until discovery of its breeding on Macauley Island in the 1974.

The 1908 Kermadec Scientific Expedition saw a team of five led by W.R.B. Oliver spend a year on Raoul, joining the Bell family who had settled on the island in the 1800s. During their ten months on the island they made collections of the fauna and flora, studied the geology of the island, and made full meteorological observations. Iredale wrote extensively about both birds and molluscs and it is from his notes we get a very clear picture on the status of seabirds at the time. He describes arriving on the island, "the first attraction was the multitude of birds encircling the tops of trees in every direction. As night fell, the noise increased ..."

Roy Bell kept a diary after the scientific team left until the Bell family left the island for the last time in 1910. His entries relating

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to seabirds, while mainly about their harvesting activities also highlighted the declining populations through predation. To quote Bell's diary: "Short-billed Titis [Black-winged Petrels] flying about Titi Knob. Saw three just killed by cats." "June 6 – King (Roy's brother) came home through the crater reports could not find any black or white burrowers. Saw some black burrowers on beach but were freshly dead. White burrowers have all been robbed of the eggs this year so it is hard to tell."

Norway rats made their way onto the island via shipwreck in 1921, dramatically increasing the rate of seabird decline, while cats continued their slaughter. By the time of the 1969 Ornithological Society of New Zealand expedition to the Kermadec Islands seabird numbers had crashed. Expedition leader Don Merton wrote that "The extinction of the Kermadec Petrel as a breeding species "on Raoul is now virtually complete and was predicted by Davison (1938) when in 1937 he noted heavy predation by both Norway Rats (eggs) and cats (adult birds)."

Of black-winged petrels he added: "The abundance of cat-eaten remains proved that these small petrels were attempting to use their ancestral breeding grounds in spite of heavy predation. The largest cat- "midden" found was on the farm and on 23/1/67 it contained the remains of 44 Black-winged Petrels within a 10 yard radius."

GROUND ZERO FOR SEABIRDS

By the end of the 20th Century Raoul was practically devoid of seabirds – all the petrels and shearwaters were gone. The only species remaining were a few Red-tailed tropicbirds that nested on cliff ledges, a handful of white terns that nested in trees and a few sooty terns persisting on the beaches. Birds continued to try and breed, like the black-winged petrels, but they were easy game for the cats and rats. The annihilation of what must have been one of the World's great seabird islands was almost complete.

A NEW ERA DAWNS

In 2002 cats and rats were eradicated from Raoul. Goats that had had a devastating impact on plant growth and also disturbed ground nesting birds and damaged burrows had already been eradicated in the 1970s. Luckily, the Meyer and Herald Islands, just a few kilometres from Raoul were pest and predator free and consequently jam-packed with seabirds – and not only seabirds also parakeet and spotless crake. It was only a matter of time before birds would make their way back to Raoul and survive without the depredation of rats and cats.

The DOC programme manager for the Kermadecs from 2006-2010 was keen to see science and monitoring integrated into the DOC work plan. Staff reports were showing a steady increase in birds returning to breed on Raoul. Seabird teams were organised for month-long stays in 2007 and 2008. By 2006 a few pairs of Kermadec petrels were found nesting at two locations (Figure 1). But not all returns were going smoothly. The white-naped or Sunday Island petrels were recorded in February in two consecutive years (2005, 2006), caught by what staff on the island dub 'Velcro grass' growing on the western-most of the northern terraces. Burrs caught in their feathers in such numbers the birds were unable to fly. These two birds were found on the beach below the terrace where the grass grows. Staff members managed to rid one of the birds of the burrs and it was released safely from the cliff edge near the hostel.

Acoustic attraction is now being used as an effective means to provide seabirds with a helping hand. Playback of recordings is used to mimic colonies attracting passing birds which in time will nest and start to breed. The technique is proving very successful, provided the target species are within range and can hear the calls. In 2007 DOC's Technical Support Unit installed three acoustic attraction systems on Raoul and these have been successful in attracting birds to the sites. CG and DOC staff have recently made some refinements – using new recordings, improving the equipment and also relocating two of the systems based on findings on the ground.

FIGURE 1. A Kermadec petrel chick in its nest, at a coastal site on Raoul Island.



FIGURE 2. Measuring Kermadec petrel chicks at Wilson's Point, Raoul Island.

FIGURE 3. A Kermadec storm petrel being monitored.



By 2011 staff and visitors to the island were starting to see a rebound, although in terms of numbers, hardly noticeable compared to the numbers lost. But the lift in species diversity was much more marked and signalled that populations would recover significantly, in time.

The results from the first tracking of any Kermadec species were staggering. MR trained DOC staff going to Raoul to attach geolocator loggers onto breeding black-winged petrels. 14 of these were retrieved by team members the following year and tracking showed birds travelling large distances while provisioning chicks – some going well to the south of the Chatham Islands, some deep into the Tasman Sea and others up amongst the Pacific Islands. They also spend a lot of time out over the Kermadec Trench and further east.

In October 2015 CG and MM took the opportunity to spend two weeks on Raoul Island, with the University of Auckland whale expedition lead by R. Constantine (Figures 2 and 3). With support from DOC staff on the island they followed up on recent reports from the Raoul team of birds nesting; they checked sites that Gaskin and Baird had visited in 2008. They also took the opportunity to collect blood and feather samples from winter and summer-breeding Kermadec petrels to investigate the possibility of two distinct populations. Their timing, by chance, was spot on finding winter-breeding chicks close to fledging stage, and summer-breeding adults just returning to the islands which were nest building. Subsequent DNA analysis of these samples by TS suggests that there is no or limited haplotype sharing between the populations. However, further more in-depth research is required to follow up on this very promising result.

There is no historical record of two of the smallest Kermadec seabirds, the Kermadec Little Shearwater and Kermadec Storm-petrel, breeding on Raoul prior to the final eradication of predators in 2002. Finding these birds on Raoul was evidence of the outstanding success of programmes such as

this one that eradicate mammalian predators on islands.

FUTURE DIRECTION OF SEABIRD RESEARCH

1. Long term monitoring of and support for the recolonisation of seabird populations to Raoul and the restoration process is essential. Every restoration island has its own dynamic, in particular the speed and ways in which species recolonize naturally in the wake of the eradication of pests and predators.
2. Basic biology of many of Raoul's species are needed including population dynamics, tracking and stable isotope studies to understand their relationship with their marine environment and the impacts of changes in the marine environment including from climate disruption.
3. Phylogenetic studies of red-tailed tropicbirds, masked booby and the small *Puffinus* shearwater complex; international collaborations are already underway; Status of the Kermadec storm petrel – full species or sub-species? With Kermadec Petrel, determine what is the status of the summer and winter breeding populations and relationship with other Pacific populations – there is a Pacific-wide collaboration underway with a link to Indian Ocean birds.

MEETING CHALLENGES

1. One of the biggest challenges to seabird research in the northern Kermadec Islands, that of finding easily accessible seabirds in numbers sufficient to warrant study, has been overcome with the return of seabirds to Raoul.
2. The seabird research team already enjoys a good working relationship with DOC – both at management level and with staff on the island. A two way process, one that we believe can only strengthen over coming years. Ideally we would want to see seabird researchers on Raoul for three months, six months and year-long postings - subject to funding.

Seabirds, as marine creatures, have a vital role in helping develop our understanding of the complex marine world of the future Kermadec Ocean Sanctuary.

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- 3. And seabirds which as their name implies, are marine creatures, but must come to land to breed. We are able to study foraging ecology and movement of seabirds within the marine environment – from land.

Finally, seabirds, as marine creatures, have a vital role in helping develop our understanding of the complex marine world of the future Kermadec Ocean Sanctuary

Kermadec – Discoveries and Connections

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For those of you who haven't just spent a day at the Kermadec Science Symposium, I'll give you a bit of geographic context for this exhibition.

The Kermadec Islands are a northeast trending line of volcanic islands about halfway between Auckland and Tonga. The Islands stretch over 2 degrees of latitude, or 250 km. But in recent years, exploration of the ocean between New Zealand and Tonga has revealed that these islands are part of a 2500 km chain of mostly underwater volcanoes. This line of mountains is the longest underwater volcanic arc on the planet and the most hydrothermally active. The volcanoes mark the collision between the Pacific and Australian Plates. On the east side of the collision zone is the Kermadec-Tonga Trench, a slash in the ocean floor that extends 10,800 metres deep.

There's a long history of people visiting these islands – from Polynesian voyagers, to whalers, to European orange farmers, to today's meteorological technicians and conservation workers, but there have never been any permanent inhabitants.

Perhaps it's because the islands are not very hospitable. This line of volcanic islands is prone to eruptions and earthquakes and damaging storms. The seas, though, are warm and welcoming. The waters around the islands provide a sanctuary for a unique mix of tropical, sub-tropical and temperate species of fish. This is a rare ecosystem, where large predators rule, untroubled by fishing lines or nets. These waters are home to sharks, giant groupers, turtles and 35 species of dolphins and migrating whales.

On Raoul Island, the largest of the Kermadec Islands, some species are familiar: the island is home to local species of pukeko, kakariki, pohukutawa and nikau.

Other species in the region are strange and exotic, like fish that fly through the air, or seabirds that dive deep into the ocean to catch their prey.

Beneath the waves is a zone of imagination, of barnacles, tubeworms, kelps, and starfish. Every time scientists visit they discover new species.

While I first heard about the Kermadecs during my research into New Zealand's nuclear history – in the 1950s there was a proposal to use the remote and isolated Kermadecs as a site to test the British hydrogen bombs – I learned about the geography, geology, biology and history of the Kermadecs from artists.

In 2011, artist Gregory O'Brien, and Bronwen Golder, New Zealand's Pew director, asked me to write a chapter for the book *Kermadec*, which documented the visit of this group of artists to the Kermadecs on board the HMNZS Otago.

I learned about the geography and the volcanology of the islands from **Gregory O'Brien's** paintings, prints and poetry (Figure 1).

I got a different perspective on the Raoul Island geology from **Phil Dadson's** rock records.

I learned about the islands' vegetation from **Elizabeth Thomson's** metal sculptures (Figure 2).

I learned about the colonial and whaling histories from **Fiona Hall and Robin White's** tapa cloths and etchings (Figure 3).

I learned about the wild energy of the ocean from **Jason O'Hara's** videos.

I learned about the Kermadec's Pasifika connections from **John Pule's** etchings and paintings and poems.

I learned about invasive species, and flotsam and jetsam encroaching on the islands, from **Bruce Foster's** photographs and videos.



And I was awakened to the campaign to protect the Kermadecs by **John Reynolds'** playful and provocative installations.

In 2012, Bruce and I visited the Kermadecs with a group of scientists, including marine biologists Rochelle Constantine, Clinton Duffy and Libby Liggins and geologist Helen Bostock.

Bronwen chose to sponsor artists to go to the Kermadecs because these were the people she saw as most likely to be able to connect and communicate with the public about this special part of the world. Now, scientists were sponsored to collect evidence for why this was such a special and unique environment.

We spent six days at anchor off Raoul Island (Figure 4).

Rochelle photographed whale flukes and chased whales and dolphins with a biopsy gun, hoping for skin and blubber samples.

Clinton caught and wrestled Galapagos sharks, weighing, tagging and taking fin samples.

Bruce got fixated on the jandals – always the left (?) foot – washed up on the pumice-laden beaches of Raoul Island.

For me, the most exciting thing, was the pumice: the enormous pumice raft – satellite images identified it as the size of a small country – we sailed through on our way north, that Richard Wysoczanski and others have since identified as coming from the Harve underwater volcano, and the biggest underwater volcanic eruption ever recorded.

All of us – scientists, artists, writers and photographers, became – through our communication, our research, our art – part of the campaign to protect the Kermadecs and establish the ocean sanctuary that was announced late last year.

Science and art might seem, at first glance, to be two different worlds, but in these islands the disciplines intersect, with both



artists and scientists diving into this new environment, each group forearmed with copious research, driven by a desire to discover, to interpret, to see things no one has seen before. In the Kermadecs, art and science merged when a flying fish that Fiona Hall found and photographed (Figure 5) – it jumped onto the ship – was later delivered to the Auckland Museum and discovered to be new to science.

Sometimes, art and science really merged, like when John Reynolds turned release of a Raoul Island weather balloon into a photographed piece of performance art.

As we can see from today's science symposium and exhibition opening, five years after the first Pew-sponsored voyage, artists and scientists continue to work together, informing and celebrating each others' work and each talking about the Kermadecs from their different disciplinary perspectives.

For me, the unlikely partner in this collaboration was not artists or scientists, but the military.

Commander Simon Rooke, who captained the Otago voyage in 2011, said to me "I could barely spell art before I took the artists to the Kermadecs".

He said just as he and his crew had some preconceived notions about what artists were like, he also said he was pretty sure the artists had some preconceived ideas about the military. In Commander Rooke's words, "both of us kind of met in the middle and learned from each other."

The same would be true for the voyage I was on. The Canterbury's captain, Commander Sean Stewart, and all his crew fully supported the scientific projects, flying us to and from Raoul Island by helicopter, driving us around the island in their rigid hull inflatable boats, lowering the back of the ship so we could go shark fishing at night, and competing to see who could find the biggest sample of pumice.

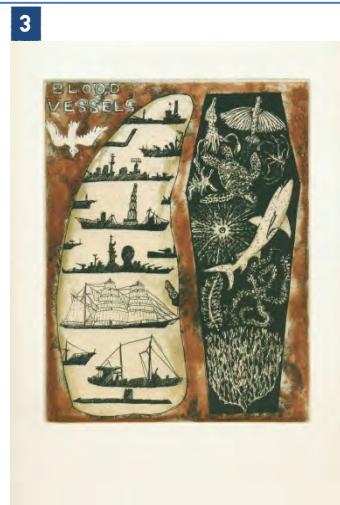


FIGURE 1. Untitled, Gregory O'Brien, 2012.

FIGURE 2. Sunday Island, Elizabeth Thomson, 2011.

FIGURE 3. Scrimshaw, Fiona Hall, 2011.

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FIGURE 4. HMNZS Canterbury, anchored at Raoul Island in 2012.

FIGURE 5. Artist Fiona Hall photographs a flying fish which landed on the deck of HMNZS Otago on their voyage to Raoul Island in 2011.

The surprising thing we learned was the extent to which the New Zealand Navy see themselves as guardians of our marine environment – we were all aligned in our desire to protect the Kermadec region. As Bronwen described them, the Navy were “the most passionate advocates for the ocean I’ve ever encountered”.

By the end of both voyages, our captains were, like us, advocates for the Kermadecs, and supporters of the campaign to create the Kermadec Ocean Sanctuary.

Poetry, a church pulpit and an ocean sanctuary 11 May 2016

Gregory O'Brien

ONE OF A GROUP OF NINE ARTISTS WHO TRAVELED TO RAOUL ISLAND IN 2011, GREGORY O'BRIEN PAINTED THE PULPIT WHICH WAS INSTALLED ON STAGE DURING THE KERMADEC SYMPOSIUM.

I
Whether situated in a church or not, a pulpit is indelibly stamped with a set of beliefs, aspirations and a vision of how the world might be. It also speaks of lessons both imparted and learnt. Originally painted a dull off-white, the church pulpit was procured from a Christchurch emporium in the mid-90s. An austere specimen, probably of Salvation Army or Baptist origin, it sat in my studio for nearly two decades, biding its time.

Early in 2013, I took to it with a paintbrush, working up a stylised version of the annual Raoul Island whale survey on its interior surfaces; the outer panels soon bore a vista of Raoul and the motif of the Luck Bird/Holy Spirit/Bird of Peace, which I had discovered on Easter Island. When it was first exhibited, at the Sarjeant Gallery Whanganui, late 2014, the pulpit was accompanied by a label which invited gallery-goers to stand inside it and hold forth about any topic whatsoever--as long as it was *something they deeply believed in*.

At the end of that showing, the work returned to my studio, where it gathered dust for two further years until, upon the government's announcement of a Kermadec sanctuary, it was brought back into commission and I added a few new details. In the beak of the Luck Bird, on the pulpit's front, I painted a celebratory ribbon bearing the letters K E R M A D E C. On the inside panels, I added two texts from my poem-sequence 'Whale Years'. The first spoke to and of the endangered or compromised ocean:

Arms and legs of the plundered sea
for whom is it
you dance?

The second pulpit-text asked a question of the sea—just as the sea is always questioning us:

Ocean-sound, what is it
you listen for?

II
What do artists bring back from an experience like the 2011 voyage on the HMNZS Otago through the Kermadec waters and onwards to Tonga? Whereas scientists might return from such an expedition with samples, evidence, empirical knowledge and theories, artists bring back a store of imagery, nuances and flavours, juxtapositions, the rhythm and texture of a place and of the state of being displaced. The challenge facing the Kermadec artists was to make viewers feel the same empathy with the region which they—myself included--now felt, and to allow the public to enter that imaginative relationship. The objective was to bring the remote, unvisited waters of the Kermadec region into a compelling sense of nearness or intimacy.

In his 2015 encyclical on the environment, *Laudato Si*, Pope Francis spoke appositely of the importance of art in such a context: 'It cannot be maintained that empirical science provides a complete explanation of life, the interplay of all creatures and the whole of reality.' The purely scientific approach, he pointed out, left insufficient room 'for aesthetic sensibility, poetry, or even reason's ability to grasp the ultimate meaning and purpose of things...'

III
A few weeks before its appearance at the Kermadec Seminar, the pulpit spent a day at the Beehive in Wellington. In an inspired piece of staging, choreographed by Bronwen Golder, the Prime Minister John Key announced the introduction into parliament of the Kermadec Bill from within the confines of the pulpit, with a fizzing, oceanic work by John Reynolds on the wall behind (Figure 1). Fittingly, Key and the other ministers stood, as if at the bridge or prow of a seagoing vessel, while an electric,

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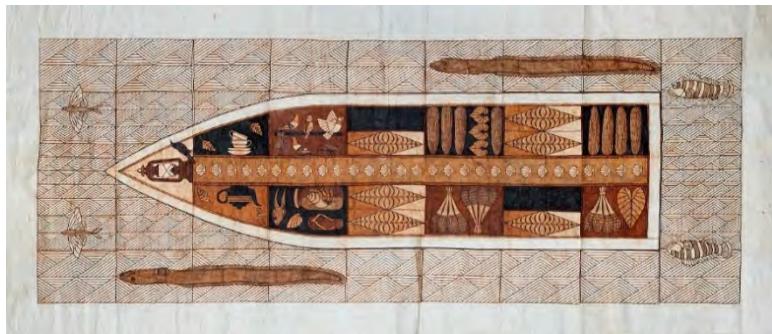


FIGURE 1.Rt Hon John Key, introduces the Kermadec Ocean Sanctuary Bill into Parliament., standing behind the pulpit.

FIGURE 2. Small axe, Nous sommes la petite hâche, Robin White 2014

oxygenic, life-encompassing blueness stretched out behind them. It felt like being in the middle of a purposeful and timely voyage—one that artists like Robin White and others had been exploring in their art for the past five years or more (Figure 2).

IV

In entering memory, places like the Kermadecs also enter our imaginations. The state of the world outside becomes one with innermost being. Whether we are scientists or artists (or both), we are simultaneously blessed and haunted by our experiences of these powerful, unique places. At an exhibition opening at the Tauranga Art Gallery, late in 2011, I recall a serious-looking visitor introducing himself to me then proceeding to take one shoe off, and then his sock. Immediately, I set to wondering about his state of mind. A moment later, however, I realised the purpose of this manoeuvre: On the instep of his right foot there was a detailed map of Raoul Island, overlaid with the outline of a turtle. He had been stationed on the island for six formative months of his life. With the tattoo in place, he explained, he would now spend the rest of his life walking on Raoul Island.

None of us ever quite leave these places behind. The following year, at an exhibition of Kermadec-related works at the Bowen Galleries in Wellington, a woman visitor told me a story about an ancient groper off Fishing Rock, from her time on Raoul Island 20 years earlier. She was clearly haunted by this fish and the effect it had upon those who encountered it. After she told me the story, I too was entranced. And her recollection of that groper became one of the central threads in my long poem ‘Memory of a Fish’ (which was included in *Whale Years*, AUP 2015).

V

The South Pacific is an ocean of narratives—real and imagined. It is also an immense reservoir of songs and statements, of lyrical flights and impassioned argument—a medley of voices captured in John Reynolds’s installation, which was also on display during the seminar (Figure 3). In this

work John Reynolds is lending the blue Kermadec waters the most human and variable of voices.

Completed on the day of the sanctuary announcement in September 2015, my long poem, ‘Ode to the Kermadec Trench’ deposited me back on the aft deck of the HMNZS Otago, just outside the Rope Room, where naval ratings are taught the language of tying knots, of bringing together different strands—a task not unlike that which we, as artists, set ourselves. In my oceanic ode, I spoke directly to the Trench, as if it was a person I knew, or am now coming to know:

... Under your tutelage
we are humbled, shaken
at times pummelled

into submission. Yet
there is nothing
you resolve, at least

not on our terms:
Your business is
unfinishing. Or so runs

the wisdom of the Rope Room:
the sea has
no end, only

loose ends. With your nocturnal traffic
of dog-fish, lamp-post-fish
taxi-fish, all manner of

neon fish, lost
diamond fish. And Raoul
is nothing more than

a traffic island in this
teeming metropolis....

VI

Like others who are involved in the Kermadec project, I’ve spent much of the past five years sailing around one particular word--‘sanctuary’--a word which stems from the Latin root, ‘sanctus’, meaning holy or hallowed. It’s a word we hope will soon apply to the waters around the Kermadec Islands. But it’s also a word for which we would wish a broader meaning in terms of all the oceans of the world. In that regard,

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and on behalf of the Kermadec artists, I invoke the spirits of Herman Melville and Walt Whitman, and of William Blake who wrote: 'Everything that lives is holy'. That all humanity's endeavours, on sea as on land, might be prefaced by such a statement.

FIGURE 3.BlueTopia, John Reynolds 2015



For artists and scientists, the Kermadec Islands, where birds fly underwater and fish jump into the air, where black smokers spew into the sea and earthquakes shake the land, are a place of imagination and inspiration. For the seabirds, sea creatures and marine mammals that live on and around the islands, they are a safe passage from breeding grounds to feeding grounds and, to many species, home.”

Rebecca Priestley, science historian and writer