2.4. New Zealand – Primary Site

(Replaced December 23, 2013)

2.4.1. Background and Motivation: Relationships to SCD questions

New Zealand offers a wealth of opportunities as a primary site for GeoPRISMS subduction zone research. Aspects of all of the SCD key questions can be effectively addressed at specific locations within the New Zealand primary site. The New Zealand primary site can be broken down into six geographic regions (Figure 2.19), which offer unique combinations of GeoPRISMS research targets. From south to north, these locations include: the Puysegur Trench (subduction initiation), Fiordland (exhumed Mesozoic arc crust), Hikurangi Margin (seismogenic zone processes; feedbacks between sedimentation, climate and forearc deformation), the Taupo Volcanic Zone (TVZ; arc volcanism and intra-arc and back-arc rifting), the southern Kermadec Arc (arc volcanism), and the Havre Trough (back-arc rifting) (Figure 2.19).

The New Zealand primary site also offers plentiful opportunities for international collaborations and associated leveraging of resources, including major ongoing and planned efforts within the New Zealand-based geoscience community and by Japanese and European groups. Although the science priorities identified for the New Zealand Primary Site are many and varied, we expect many can be realistically accomplished over the next ten years due to the additional resources of the broader, international community that can be brought to bear on these topics.

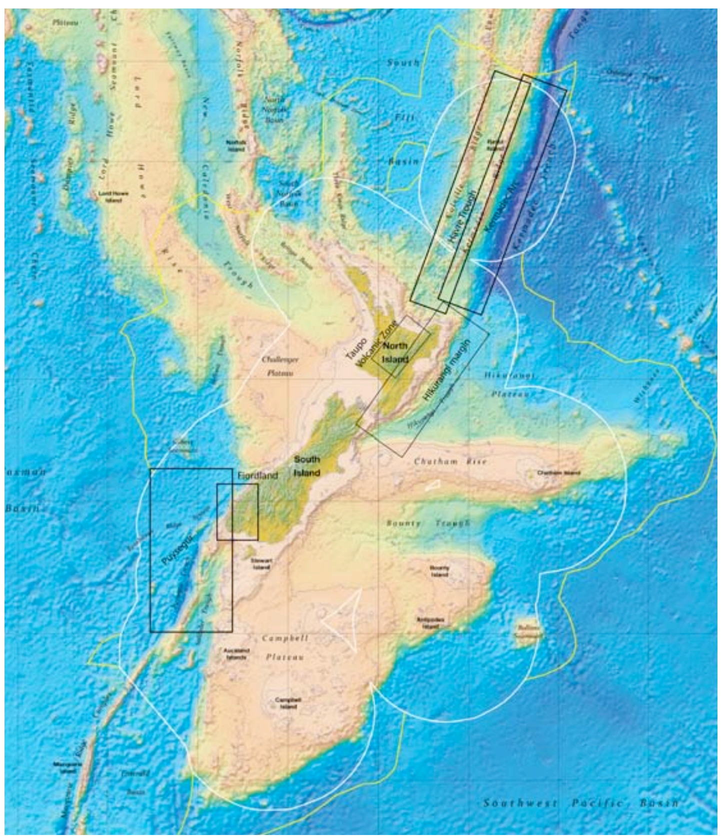

Figure 2.19. Bathymetry and Topography of the New Zealand region, with major tectonic and geographic features labeled, as well as boxes labeled for the main regions of SCD GeoPRISMS interest discussed here. Data from GNS Science.

2.4.1.1. Key science questions to address at the New Zealand primary site

New Zealand's rock record reflects various phases of subduction since Cambrian times through to the present day, and is currently the site of two oppositely dipping subduction zones: the Hikurangi/Kermadec system in the north, and the Puysegur Trench in the south. From the Puysegur trench offshore the South Island, to the Hikurangi and Kermadec subduction systems in the North, there is a rich record of active and ancient subduction margin processes, from subduction initiation through to fully developed, mature subduction systems.

For simplicity, the seven SCD key questions (Section 2.1) can be organized into four over-arching questions to be addressed at the New Zealand primary site. The four questions, discussed in more detail below, are:

- *What are the geological, geochemical and geophysical responses to subduction initiation and early arc evolution, and how do they affect subduction zone development?*
- *What are the pathways and sources of magmas and volatiles emerging in the arc and forearc, and how do these processes interact with upper plate extension?*
- *What controls subduction thrust fault slip behavior and its spatial variability?*
- *What are the feedbacks between climate, sedimentation, and forearc deformation?*

New Zealand is the site of two of only a few well-preserved examples of subduction initiation worldwide, including the newly initiating Puysegur Trench to the south of New Zealand, and an outstanding record of Eocene subduction initiation at the Tonga-Kermadec-Hikurangi Trench in the north. Unique opportunities exist to decipher the structural, stratigraphic and volcanic record of subduction initiation within the context of an active system and a well-established plate motion history. Exhumation of Fiordand's Paleozoic to Mesozoic crystalline basement began in the Late Miocene in response to subduction initiation at the Puysegur Trench. Likewise, at the Hikurangi and Kermadec margins, arc rocks, sedimentary basins, and allochthons preserve a potentially rich record of Cenozoic subduction initiation that appears analogous to that recently described from the earlier MARGINS focus site in the Izu-Bonin-Mariana (IBM) system. Questions to be addressed at the New Zealand focus site include: How does the new slab first enter the mantle? What is the fluid expression and thermal structure of subduction initiation? What is the relationship between initiation and the onset of magmatism? Focused geophysical surveys can tackle fundamental questions about the onset of convergence and associated vertical motions, offshore thermal and crustal structure, newly developing arc volcanism, and the geometry of subduction initiation.

The Kermadec Arc and Taupo volcanic zone (TVZ) offer prime settings to understand magmatic and volatile fluxes at a well-developed volcanic arc from the forearc through to the backarc. The full spectrum of Early Miocene to Recent arc-related volcanism is uniquely accessible along strike in New Zealand, from discrete arc-front volcanoes and a developed back-arc spreading center to nascent back-arc rifting of an existing, mature upper plate, to the complete shutdown of subduction volcanism south of Mount Ruapehu in the central North Island. These dynamic surface expressions of underlying processes provide an important test of the relationship between slab and mantle wedge conditions and processes (dehydration, melting, and the vectors of solid and fluid flow) and the emergence of their products at the surface. Moreover, there is outstanding accessibility to fluids emerging in the onshore forearc in seeps and springs, that enable a look at volatile pathways and sources above the shallow portion of the subduction thrust (e.g., <50 km depth). Finally, in Fiordland, South Island, the only pristine Cretaceous arc section in the Circum-Pacific offers a prime locale to investigate the root zones of an ancient arc, at outcrop scale.

Some of the major questions to be addressed include: How does the mafic flux from the mantle translate to voluminous rhyolitic magma production? What is the nature of interaction between volcanism and upper plate extension? Comparison of the Kermadec Arc corridors with the TVZ affords an opportunity to assess the influence of the continental/oceanic crust transition in the overlying plate and the nature of the subducting plate on arc development. The New Zealand-Kermadec margin also provides an ideal location to distinguish tracers of contributions of magmatic assimilation to the upper plate and the addition of subducted sediment to the magma source region, as the upper plate composition changes from continental to oceanic along strike.

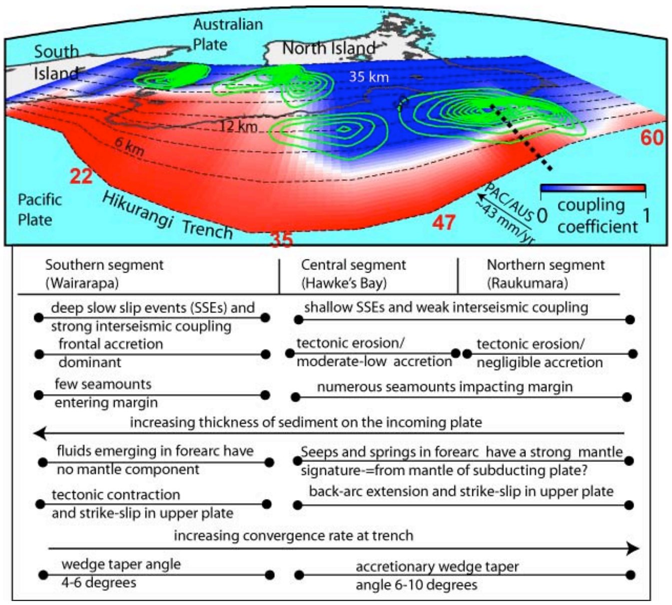

Figure 2.20. Perspective view of the Hikurangi margin illustrating the portions of the subduction interface that undergo stick-slip (red) vs. aseismic slip (blue), in the context of other along-strike variations in subduction margin characteristics. Green contours show areas of slip in slow slip events since 2002. Convergence rates at the trench are labeled as red numbers (mm/yr). Pacific/Australia convergence shown by black arrow. Black dashed line shows location of proposed IODP drilling transect. Courtesy of Laura Wallace.

Systematic along-strike variations in interface locking behaviour and slow slip events (SSEs) provide an unparalleled setting to test hypothesized physical controls on megathrust locking and SSE behavior (Figure 2.20). These major changes in megathrust behavior also correlate with changes in sediment thickness and accretion, convergence rate, seafloor roughness on the incoming plate, and upper plate stress state. Together, these changes likely play an important role in the subduction thrust behavior. Integrated geophysical, geological, and geochemical studies of the onshore and offshore forearc and incoming plate are expected to reveal the major controls on variations in subduction interface behavior. Key questions related to this topic are: How do topography and material of the incoming plate control fault zone structure and slip behavior? What is the slip behavior and rheology of the near-trench portion of subduction fault and what controls it? What is the role of fluids in controlling megathrust behavior and slow slip events? Has the subduction thrust produced great earthquakes in the past, and how does the distribution of these relate to its modern behavior?

The east coast of the North Island preserves thick sedimentary successions in subsiding shelf and slope basins. The storage of riverine sediment in shelf basins and bypassing to the slope are complex functions of margin deformation rates relative to sediment supply, and rapidly varying eustasy in the Quaternary. The accommodation space developed on the shelf allows for the development of thick sequences and an extremely high-resolution record (relative to passive margins) of climate change (e.g., ENSO) and mass fluxes for areas sensitive to both terrestrial and marine influences. Major questions relating to this topic can be raised: What are the pathways and timescales of sediment input? What is the role of large subduction megathrust earthquakes in landscape evolution? What are the feedbacks between the sedimentary inputs (both from the land, and the incoming plate) and accretionary wedge development? How does elemental cycling vary across the forearc? How does seamount and Hikurangi Plateau subduction influence uplift, erosion, and deformation of the onshore margin, and the evolution of the accretionary wedge?

2.4.1.2. Geographic focus areas

The scientific topics outlined above correlate well with distinct geographic focus areas in and around New Zealand (Figure 2.19). The characteristics and opportunities for GeoPRISMS and collaborative research for each of these areas, as framed by community discussions, are detailed in the sections below. In addition, the community determined that certain topics are best addressed through the study of exhumed terranes, which preserve archives of deeper processes that cannot be studied in-situ. Potential research efforts of this type might effectively make use of existing data and observations, which can be viewed through a GeoPRISMS lens to address certain thematic questions that cannot be resolved in any one location. The next sections of this plan are organized geographically, from south to north, and highlight the scientific rationale and possible studies in each region in turn, followed by the studies of exhumed terranes. Timing, staging and partnership opportunities are described in later sections. In the following sections, bulleted lists indicate the primary SCD key topics that can be addressed in each region, with those in ***bold*** being the main priorities.

2.4.2. Puysegur Trench

SCD Key Topics

- ***Subduction zone initiation and arc system formation***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Geochemical products of subduction and creation of continental crust***
- *Effects of volatile release and transfer on the plate-boundary interface*
- *Feedbacks between surface processes and subduction dynamics*

The Puysegur Trench region provides unique opportunities to identify and investigate the key physical parameters involved in the geodynamics of subduction initiation, as it is a juvenile subduction zone "caught in the act" of initiation. In addition, vertical motions associated with this process have led to deep exhumation of the only pristine Cretaceous arc section in the Circum-Pacific, found in Fiordland in the South Island, which offers a prime locale to investigate the root zones of an ancient arc at outcrop scale.

The Puysegur Trench region (Figure 2.21) bears the hallmarks of nascent subduction and arc magmatism, and provides extraordinary opportunities to address the SCD science questions (some uniquely so). The Puysegur subduction zone initiated about 12 million years ago and was associated with profound vertical motions across the shoreline (for example driving the uplift that ultimately led to the spectacular Fiordland landscape). The youth of the geological structure, the lack of subsequent over-printing, the clearly identifiable nature of the earlier tectonic state, and the well-constrained plate tectonic motions make this incipient boundary globally unique and a natural laboratory to study the initiation of subduction.

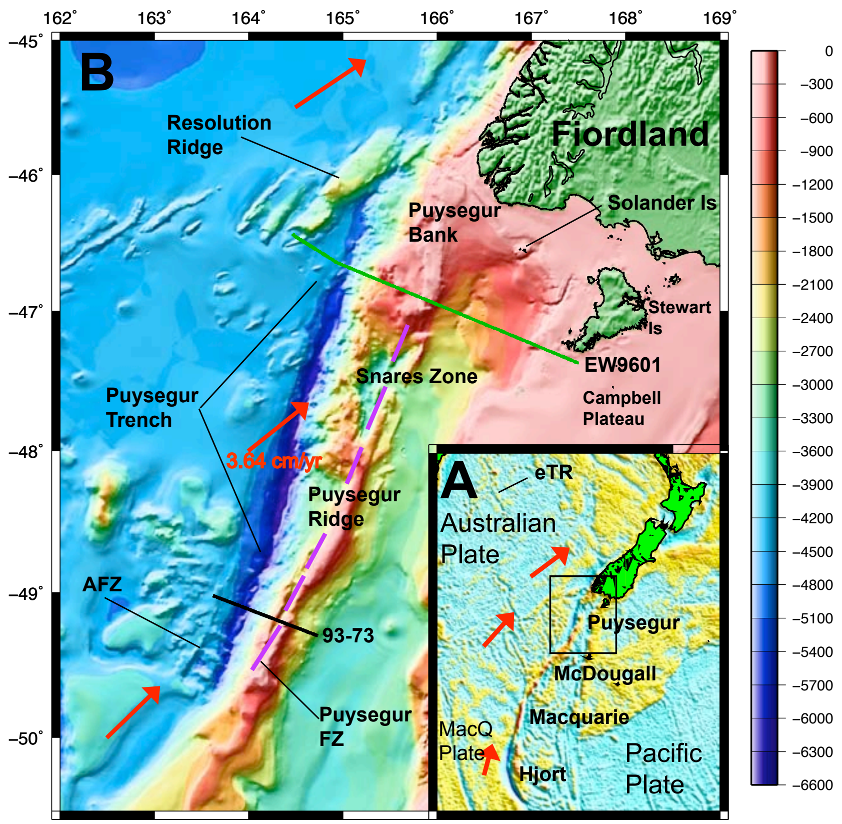

Figure 2.21. A. Location of the Puysegur focus area (black rectangle). Puysegur is one of four sectors of the Macquarie Ridge Complex (MRC). Base map is free-air gravity inferred from satellite altimetry. B. Bathymetry (depth in meters) of the Puysegur Ridge and Trench region just to the south of the South Island of New Zealand. The sector denoted Puysegur Trench has experienced active subduction. AFZ is l'Atalante Fracture Zone. The Puysegur Fault Zone is shown as dashed purple line. Bathymetry assembled by NIWA. Red arrows denote relative motion of AUS or MACQ with respect to fixed PAC from MORVEL present day plate model (DeMets et al., 2010).

Key questions relating to subduction initiation, which could be addressed in the Puysegur subduction zone, are how does the balance of forces acting on the plates change at the onset of subduction, and what are the spatial and temporal effects of these changes. During the early phase in the initiation of many subduction zones, the external forces lead to compression, formation of a new seismogenic thrust interface localizing the occurrence of great earthquakes, and the descent of a slab tip into the mantle. Eventually, the balance reaches a tipping point when the negative buoyancy of the slab (local slab pull) starts to drive the system. At this time, we do not understand this process or associated sequence of events very well, and studies of Puysegur will allow us to address this question empirically. Important questions to be addressed include: What is the dip of the new plate interface in juvenile and evolved settings? What is the difference in the force balance associated with these different settings? How does the crust compress and thicken as subduction initiation unfolds? How is the topography controlled by the thickness of the crust and slab pull? What is the three-dimensional shape of the slab and how does it correlate with the space-time evolution of vertical motions and volcanism?

The converging plate in a subduction zone also causes enormous cumulative deformations in the over-riding plate, such that after millions of years of convergence the earliest stages of that evolution are erased away. This influences how deformation across the subduction zone evolves in space and time, and in particular, how deformation is distributed between the upper plate and slip along the plate boundary. The Puysegur boundary allows us to study this earliest phase of deformation and how the partitioning of deformation has changed over time.

Another question that can be addressed in this setting is at what stage of subduction development do volatiles start to be released from the downgoing plate. Furthermore, what role do these volatiles play in defining mantle rheology? The volatile content and release budget of mature arc settings has been extensively modeled for many systems worldwide. However, recent geophysical studies of the Marlborough region show that fluids are exsolving continuously along the plate interface and rising into the crust well before the circulating mantle wedge is established. The along-strike sequential growth of the Puysegur subduction zone serves as a proxy for time snapshots at different stages of development. Volatiles are only now being injected into upper mantle, thus defining a unique opportunity to better understand how volatiles affect mantle rheology. Volatiles profoundly influence the viscosity of the mantle wedge, which in turn governs the dip of the slab in the upper mantle. Here we have an opportunity to study a slab that has now just started to perturb the upper mantle and to examine how conditions vary along strike at increasingly younger states of initiation.

The volcanic products of the incipient arc are quite limited, however, the study of those that occur provides us with a unique opportunity to study volcanic sequences unperturbed by subsequent over-printing or tectonic loss. Through the time-transgressive nature of the Puysegur system, we have a chance to image melt accumulation in the deep crust prior to magma ascent and arc volcanism. In this way, we can examine the geochemical products during the earliest stages of subduction, to understand how these influence the formation and modification of new continental crust.

The Puysegur area has enormous advantages as a natural laboratory for the study of subduction initiation and associated processes: the initial tectonic state of the system has been reconstructed; the convergence between the Australian and Pacific plates is well constrained during the entire phase of subduction initiation; and study of existing topography and gravity suggests that Puysegur is currently in the midst of a critical transition from forced to self-sustaining subduction. No other incipient subduction zones shares these advantages.

2.4.2.1. Existing Datasets and Studies in the Area and Data Gaps

The remote location of Puysegur, extending from the southern extreme of New Zealand into the Southern Ocean (Figure 2.21), has limited its prior characterization, leaving several open avenues for GeoPRISMS research. What is known comes from several geophysical, geodynamic and petrologic studies. The regional plate kinematic history since 45 Ma as deduced from magnetic lineation and fracture zones constrains the timing of convergence initiation to 12-15

Ma. Previous work in the Fiordland segment has documented the seismicity and tomography below Fiordland, as well as the Miocene rock uplift history (see Figure 2.22). Only the emergent "tip" of the nascent magmatic arc, Solander Island volcano, has been mapped and geochemically analyzed. There are gravity and bathymetry data with some swath coverage, as well as reflection seismic that provide a stratigraphic framework on and across the Puysegur Bank into the Solander Basin. A particularly notable survey was the GEODYNZ project with the French R/V L'Atalante which shot 11 active source seismic lines over the Puysegur ridge during the early 1990's; unfortunately this survey imaged no structures below about 3 s two-way travel time (TWTT). Most of the MCS lines have been shot close to the shore on the continental shelf. Seismic interpretation of these lines has benefited from lithostratigraphic information from two deep petroleum wells and some offshore surface cores.

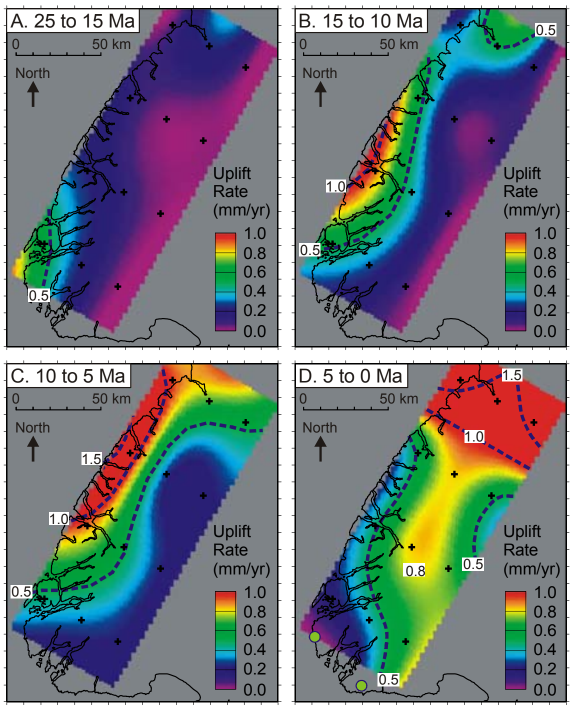

Figure 2.22. Evolution of rock uplift in Fiordland from a 3D (2 in space and one in time) inversion using 410 apatite and zircon fission track and (U-Th)/He ages, The data set is amongst the most comprehensive anywhere for such a compact region. The inversion showed the onset of rapid exhumation at 25–15 Ma in southwest Fiordland, immediately following a time of significant change in regional plate motions. During the period 15–5 Ma, the locus of rapid exhumation broadened and migrated toward the northeast at ~30% of the plate motion rate. This signal has been interpreted as being driven by the earliest phase of subduction initiation. From Sutherland et al. (2009).

A number of knowledge and data gaps remain in the Puysegur region pertaining to dynamics, rheology, magmatism and element transfer. These include uncertainties in the overall offshore crustal structure, the geometries of the new slab and associated subduction interface, as well as lack of knowledge about the seismic and electrical structure of the mantle wedge and deep crust, and the thermal structure of and heat flow across the nascent plate boundary. The limited offshore field studies have incompletely defined the nature of the incoming plate, and composition and structure of the new trench. New field studies could help to constrain the age of vertical motions along the Puysegur Ridge.

2.4.2.2. Potential GeoPRISMS Studies and Contributions

A range of GeoPRISMS studies are feasible in the Puysegur area, and can contribute to several fundamental questions relating to subduction initiation. Two key questions guide these efforts: (1) What is the geodynamic evolution during subduction initiation? (2) How do volatiles first emerge from a new subduction zone?

Active source geophysical surveys: Active source seismic surveys, combining multi-channel seismic (MCS) and OBS wide-angle surveys, are needed to resolve the structure of the crust and lithosphere. Ideally, at least two transects would cross the Puysegur Trench and Ridge: in a more juvenile setting to the south where the Ridge is presently uplifting, and in a more evolved setting that has started to subside. Seismic studies can help constrain gravity models to test dynamic models for force coupling between the nascent slab and Puysegur Ridge. In addition, geophysical constraints are necessary to determine the dip and character of the new thrust interface. MCS lines will also be necessary for siting future IODP drill sites on the margins of the Puysegur Bank, where offshore seismic reflection data indicate compression, uplift and erosion of the nearshore stratigraphic section. Controlled-source electromagnetic and magnetotelluric (CSEM/MT) transects are needed to constrain variations in the hydration state of the incoming crust and uppermost mantle prior to subduction, and to detect fluids released along the thrust interface and escaping into the overlying forearc mantle and crust.

Onshore-offshore MT, heat flow, and passive seismic surveys: Geophysical properties would help to constrain the presence and distribution of volatiles in the lower crust and upper mantle. Heat flow data would better constrain the thermal models of the downgoing slab and thus the nature of volatiles or melts imaged geophysically. The integration of the present day structure of the slab with the convergence history will provide the boundary conditions needed to track the motion of the slab and volatiles into the mantle, and their role in early melting and lithospheric deformation. An offshore/onshore passive source seismic experiment would constrain the distribution of inferred seismicity that might define the incipient Benioff Zone along strike. Onshore seismometers within Fiordland could reveal tremor activity, often attributed to movement of volatiles away from the seismogenic interface. Both MT and passive seismic data can assess if subducted oceanic crustal eclogitization is underway even at this early stage, as has been imaged for more mature systems elsewhere.

Offshore dredging, swath mapping, and coring: Marine mapping and samples are needed to document the nature of the incoming plate from south to north, including the sediment cover, composition and properties of the trench fill, and degree of alteration of the subducting crust. These studies will better define aspects of the upper plate, including the nature of the sediment cover on Puysegur Ridge, and the extent and nature of the submarine volcanic record associated with subduction.

Ocean drilling: IODP drilling will be essential to test existing structural and stratigraphic interpretations, and to more fully constrain the space-time evolution of evolving topography associated with subduction initiation, in particular, associated vertical motions (e.g., Figure 2.22), and the timing and geochemical nature of the development of the nascent magmatic arc.

2.4.3. Hikurangi Margin

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns at subduction zones***
- ***Effects of volatile release and transfer on the plate-boundary interface***
- ***Feedbacks between surface processes and subduction dynamics***
- *Volatile storage, transfer, and release in subduction systems*

The Hikurangi margin is well suited to studying the causes and consequences of the spectrum of slip behavior along subduction megathrusts, given geophysical and geological evidence for pronounced along-strike changes in margin tectonics and subduction interface behavior. Also a complete late Neogene record of strain, and tectonic and eustatic controls on sedimentation in the Hikurangi subduction wedge are preserved along the east coast of the North Island and in adjacent submarine basins. The well-preserved sedimentary record makes it an ideal location to address the feedbacks between climate, sedimentation and forearc deformation.

Dramatic and systematic along-strike changes in megathrust slip behavior along the Hikurangi Margin, including variations in both interseismic locking and the character of slow slip events, coincide with variations in other fundamental margin characteristics, such as subduction erosion vs. accretion, and roughness of the incoming plate. This makes the Hikurangi Margin (Figures 2.20 and 2.23) an ideal natural laboratory to investigate hypotheses for the processes that govern the occurrence of megathrust earthquakes, as well as spatial and temporal variations of slip

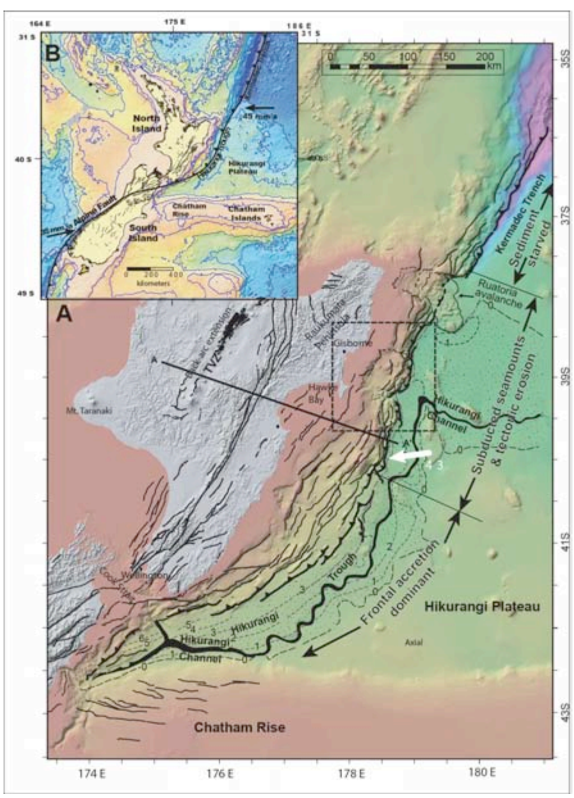

Figure 2.23. Detailed bathymetry and fault distributions of the onshore and offshore Hikurangi margin (after Barnes et al., 2010). Black dashed contours east of the Trench show sediment thicknesses on the incoming plate (in km). Black dashed box shows shallow slow slip area that is the focus of IODP proposals.

behavior. The correlation of along-strike variations in fault slip behavior with changes in the character and roughness of the subducting crust, the extent of frontal accretion, upper plate stress state (and potentially permeability), taper angle, and fluid seep geochemistry all suggest potential links between fluid release, pore pressure, and fault strength and slip behavior.

The Hikurangi subduction margin is especially well suited as a focus area to study dewatering and fluid fluxes in the forearc. Previous studies documented deeply sourced and chemically distinct fluids emanating from an extensive network of seeps and mud volcanoes onshore, and although less well studied, fluid seepage likely extends offshore as at other subduction zones. Notably, variations in the deeply sourced component of seep fluids may also correspond to along-strike changes in the extent of sediment accretion, taper angle, and interseismic locking.

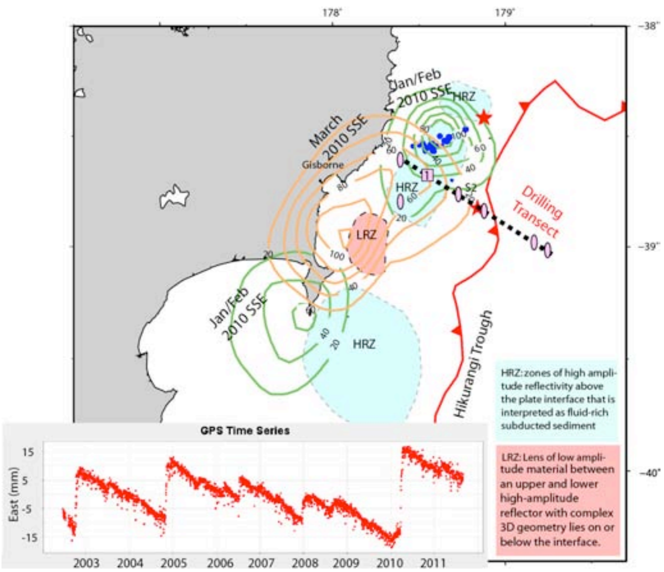

Figure 2.24. Location of slip on the northern Hikurangi interface in the January/February (green contours) and the March/April (orange contours) 2010 SSEs (Wallace and Beavan, 2010) and the reflective properties of the subduction interface (Bell et al., 2010; see key for explanation). Black dashed line shows the location of the proposed IODP drilling transect line, pink square shows the proposed riser drill hole to intersect the SSE source, and pink ellipses are the riserless sites. Blue dots are locations of triggered seismicity during the January/February 2010 SSE. Red stars are the location of two tsunamigenic subduction interface earthquakes (Mw 6.9-7.1) in March and May of 1947. Inset figure in lower left shows the east component of the position timeseries for a cGPS site near Gisborne to demonstrate the repeatability of SSEs since they were first observed in 2002.

Large slow slip events (SSE) occur here with periodicities ranging from 1-5 years (e.g., Figure 2.24). The short interval between the SSE's provides the opportunity for observations through multiple complete slow slip event cycles, with the possibility of identifying important pre-slip and post-slip processes. There are also important opportunities to conduct research to refine the record of prehistoric subduction megathrust ruptures, and to assess the spatial and temporal relationships between earthquakes that occur on the megathrust and within the upper plate.

Owing to its relatively compact scale, the Hikurangi margin may be the most tractable location in the world to demonstrate how along-strike variations in subduction inputs affect long-term rates of accretionary-prism growth, subduction erosion, and fault-slip behavior. The influence of basement structure and topography on stratigraphy on the subducting plate is particularly important in this context. At the same time, sediment provenance and transport paths from continental sources to abyssal sinks (including submarine canyons, trench-floor channels, and large-scale mass-transport deposits) are known to evolve in response to both climate-eustasy and subduction dynamics. In the case of Hikurangi, the opportunity now exists to build beyond the foundation of MARGINS Source-to-Sink, which focused mostly on the Holocene Waipaoa River watershed and adjacent continental shelf.

Key questions that can be addressed along the Hikurangi margin include: What controls the spectrum of fault slip behavior on the shallow subduction thrust? What determines along-strike variations in seismogenic zone geometry of the megathrust? What is the relationship between megathrust earthquakes and upper plate deformation? What role do the subducting plate and incoming sedimentary section play in subduction margin dynamics, fault behavior, accretionary wedge development, and uplift and exhumation of the margin, and what are the feedbacks among these processes? How do volatile and fluid release, cycling, and the hydrological setting of the Hikurangi margin impact megathrust processes and subduction margin development?

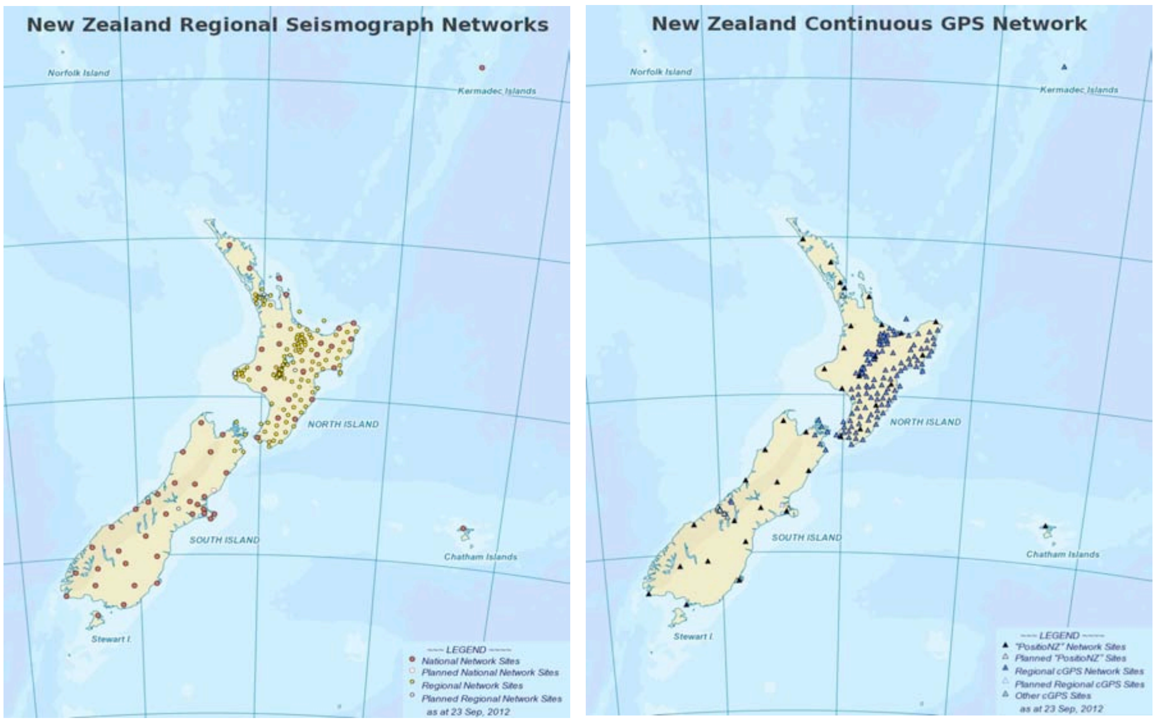

Figure 2.25. Left: GeoNet seismograph network. Right: GeoNet Continuous GPS (cGPS) network. Note the high density of cGPS and seismographs along the Hikurangi margin relative to other parts of the country. The data from these networks are available at www.geonet.org.nz.

2.4.3.1. Existing Datasets in the Area and Data Gaps

New Zealand has made a large investment over the last decade in land-based seismic and geodetic monitoring (Figure 2.25; from www.geonet.org.nz), as well as a range of other geophysical studies. The establishment of permanent geophysical monitoring networks, along with numerous studies using temporary instrument deployments, have permitted the development of regional-scale models of 3D seismic velocity and attenuation structure and crustal deformation along the margin. Continuous GPS (cGPS) and seismological data from the GeoNet network are publicly available; a comprehensive catalog of earthquakes is also maintained by GeoNet; cGPS data have been used to identify slow slip events on the Hikurangi subduction thrust from 2002 to the present, and an extensive campaign GPS network provides a regional picture of crustal deformation over a longer period of time (e.g., last 15-20 years).

The New Zealand government and New Zealand and international researchers have been expanding the database of onshore and offshore 2D active-source seismic data. Surveys conducted by the Ministry of Economic Development between 2005-2009 resulted in ~8000 line kilometers of industry-quality 2D seismic data over the offshore Hikurangi margin. In 2007, wide-angle seismic data were acquired across the Hikurangi Plateau and the eastern part of the Raukumara forearc basin as part of the MANGO project. GNS Science, Tokyo University, and the University of Southern California recently conducted an onshore/offshore seismic transect (the SAHKE transect) to image the strongly locked portion of the southern Hikurangi margin. The 2001 North Island GeopHysical Transect (NIGHT) project collected onshore-offshore reflection and refraction data across the central North Island, including 300 km of multichannel seismic data (MCS) data. In addition, the petroleum industry has gathered vast datasets offshore New Zealand (note, all industry seismic data collected in New Zealand become open file within five years after acquisition). Onshore, there is also substantial MT data in volcanic areas, and the collection of MT data in the onshore Hikurangi forearc is currently ramping up. More detailed imaging (e.g., 3D seismic) at the northern Hikurangi margin could, for the first time, reveal the detailed properties of a plate interface undergoing slow slip and aseismic creep. Similarly, an onshore and offshore active and passive seismic experiment at north Hikurangi could reveal broader scale processes within the upper plate and interface. An onshore passive seismic and continuous MT experiment is already underway by GNS Science to investigate temporal variations in seismicity and conductivity related to slow slip events at north Hikurangi.

From 1993-2010, the New Zealand government funded the production of new, high-quality geologic maps of New Zealand at 1:250000 scale, including the onshore Hikurangi margin. The maps are underpinned by all available existing geological data, and additional fieldwork was undertaken in areas where data were lacking. New Zealand researchers have developed a long-term stratigraphic history of the Hikurangi margin. Regional rock-exhumation and million year timescale vertical motion data for the margin are available from geological markers and sparse thermochronometric ages. The Waipaoa catchment at the northern Hikurangi margin also was a MARGINS Source to Sink (S2S) focus area, so substantial onshore and offshore datasets exist for that area. Additional geological samples and cores are still needed, together with thermochronology to further constrain feedbacks between climate, sedimentation and tectonics.

Substantial paleoseismological and active fault research has been conducted on many of the onshore Hikurangi margin faults. There is a publicly available, comprehensive dataset of all known onshore active faults and their slip rates, and a good understanding of the past earthquake history of many of the most active faults. Hikurangi has some of the most extensive marine terraces of any subduction margin, providing a record of coastal uplift in relation to subduction margin processes. These aspects make it well suited to addressing questions about the relationship between upper plate deformation and processes on the subduction thrust. However, the record of prehistoric subduction interface earthquakes is relatively poor, and additional paleoseismic work, both onshore and offshore (e.g., turbidites) is needed to address this.

High volumes of fluids emerge at springs and seeps in the forearc at Hikurangi, making it an ideal place to examine volatile release from the shallow forearc portion of the subduction zone (e.g., <30 km depth). Fluid geochemistry has been documented by New Zealand researchers in many locations, and additional data collection is underway. To date, however, little work has been done on the geochemistry of fluids emerging at the offshore forearc, which is needed to assess volatile release along the shallowest portion of the plate interface (e.g., <12 km depth).

2.4.3.2. Potential GeoPRISMS Studies

Although many high-quality datasets exist for the Hikurangi margin, additional data are necessary to address GeoPRISMS SCD questions. Examples of such studies are detailed below.

Geophysical Studies: Heat flow data will constrain the thermal structure of the SSE source region, and help to determine the role that temperature might play (if any) in along-strike variation of seismogenic zone geometry at Hikurangi. Ocean Bottom Seismometer (OBS) deployments will serve to characterize seismicity, tremor and crustal structure in the shallow slow slip regions, of particular importance during a slow slip event cycle. Seafloor and sub-seafloor geodetic studies are needed to investigate the slip behavior of the shallow Hikurangi subduction thrust. Additional onshore geodetic instrumentation, such as strain meters and tilt meters, and densification of the existing cGPS network (current spacing is ~30 km) would reveal more subtle SSE characteristics and smaller deformation events. A targeted 3D seismic survey at north Hikurangi would help to constrain the physical properties of the slow slip portion of the shallow subduction thrust. Offshore MT and controlled-source electromagnetic (CSEM) profiles could map along strike variations in the fluid content of the crust and mantle to constrain volatile transfer and release along the megathrust, complementing existing onshore MT efforts. Integrated interpretation (e.g., by numerical modeling) of geophysical observables between north and south Hikurangi can help to discern which parameters are responsible for the bimodal SSE behavior and variations in coupling that are observed along the margin.

Paleoseismology Studies: An improved paleoseismic record of the Hikurangi Margin will help in establishing a paleoseismic record and evidence for large subduction zone events. This would involve investigations of new sites onshore along the Hikurangi Margin together with acquiring correlative offshore archives from marine turbidites. Defining the extent of paleoearthquakes and quantifying the vertical land-level motion throughout multiple earthquake cycles will to clarify the relationship between upper plate fault movement and movement on the subduction thrust, yield more precise measurements of coseismic and interseismic deformation over timescales of decades to centuries, provide more extensive measurements of post-earthquake vertical deformation for prehistoric earthquakes.

Fluid and Rock Sampling and Observatories: Direct sampling of the materials and fluids that compose the margin is also critical. A comprehensive characterization of subduction inputs (e.g., through IODP drilling and coring) will provide key knowledge about the incoming sediments, rocks, and pore fluids that ultimately control the lithologic and hydrological properties of the subduction interface, and the geochemical contributions to the volcanic arc. Coordinated onshore sampling of outcrops will allow along-strike assessment of sediment composition going back into the Pliocene, which can be integrated with offshore observations and interpretations to obtain a more comprehensive understanding of margin evolution. Hydrological and fluid geochemical processes and pathways can be constrained through combined onshore measurements and offshore observatories at proposed IODP holes at north Hikurangi. Measurements spanning multiple slow slip event cycles will reveal the role that the margin hydrogeology and fluid release play in SSE occurrence. Integration of these observations with passive and active seismic surveys of the Hikurangi Margin will help to assess how these materials and properties change down dip, and how they influence megathrust behavior. Numerical modeling studies can help to test interpretations of these datasets, and to further refine sampling and data acquisition strategies.

Sediment Feedbacks and Structural Evolution: Finally, a holistic characterization of the trench wedge will be necessary if we hope to tease apart the episodic and/or cyclic influences of canyon incision, climate change, eustatic sea level fluctuations, submarine mass wasting, and uplift/unroofing of sediment sources, and their role in controlling margin behavior. The interplay between subduction accretion and erosion, as well as the structural architecture of the frontal prism, are acutely sensitive to incoming sediment thickness, mineralogy, and texture, so it is likewise important to document how those linkages have varied and responded along strike over time scales that extend back into the Pliocene. High-resolution active source seismic imaging, geological sampling both onshore and offshore, as well as proposed IODP drilling at Hikurangi are needed to address these issues.

2.4.4. Taupo Volcanic Zone

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Volatile storage, transfer, and release in subduction systems***
- *Effects of volatile release and transfer on the plate-boundary interface*
- *Spatial-temporal deformation patterns at subduction zones*

The Taupo Volcanic Zone is well known to be the most productive rhyolitic system on Earth. The region also coincides with substantial extensional faulting. Some of the major topics to be addressed in this region include: How does the mafic flux from the mantle translate to voluminous rhyolitic magma production? What is the nature of interaction between volcanism and upper plate extension? How does arc front volcanism relate to voluminous rhyolite production? How do the magmatic and hydrothermal systems in the volcanic arc respond to events in the adjacent seismogenic zone?

The Taupo Volcanic Zone (TVZ) is recognized as one of the prime regions of the world for studying subduction-related rifting and associated silicic volcanism and hydrothermal circulation (Figure 2.26). Thus the TVZ offers important opportunities for GeoPRISMS-related science and for collaboration between GeoPRISMS scientists and international partners. Ongoing research into the volcanic, tectonic and other features of the region for many decades has resulted in a number of large data sets and mature studies that can be incorporated into GeoPRISMS studies. In addition, the presence of geothermal resources within the region means that there has been considerable public and private investment in defining and understanding the geology and geologic resources of the region, providing a number of large relevant geophysical data sets. There are also key questions that can be addressed relating to the links between the TVZ and the structure and composition of the overriding and subducting plates, and also to the transition from continental rifting to oceanic subduction and rifting in the Kermadec system.

The TVZ offers opportunities to investigate questions related to the widespread crustal extensional faulting, active throughout the TVZ. The significant Pleistocene-Holocene cover from ongoing volcanism also provides opportunities for dating fault movement and rates of slip. The rapid ongoing extension within the region is also a major influence on volcanism and thus the TVZ offers excellent opportunities for understanding the relationship and interplay between magmatism and deformation. As the only GeoPRISMS SCD site with a considerable component

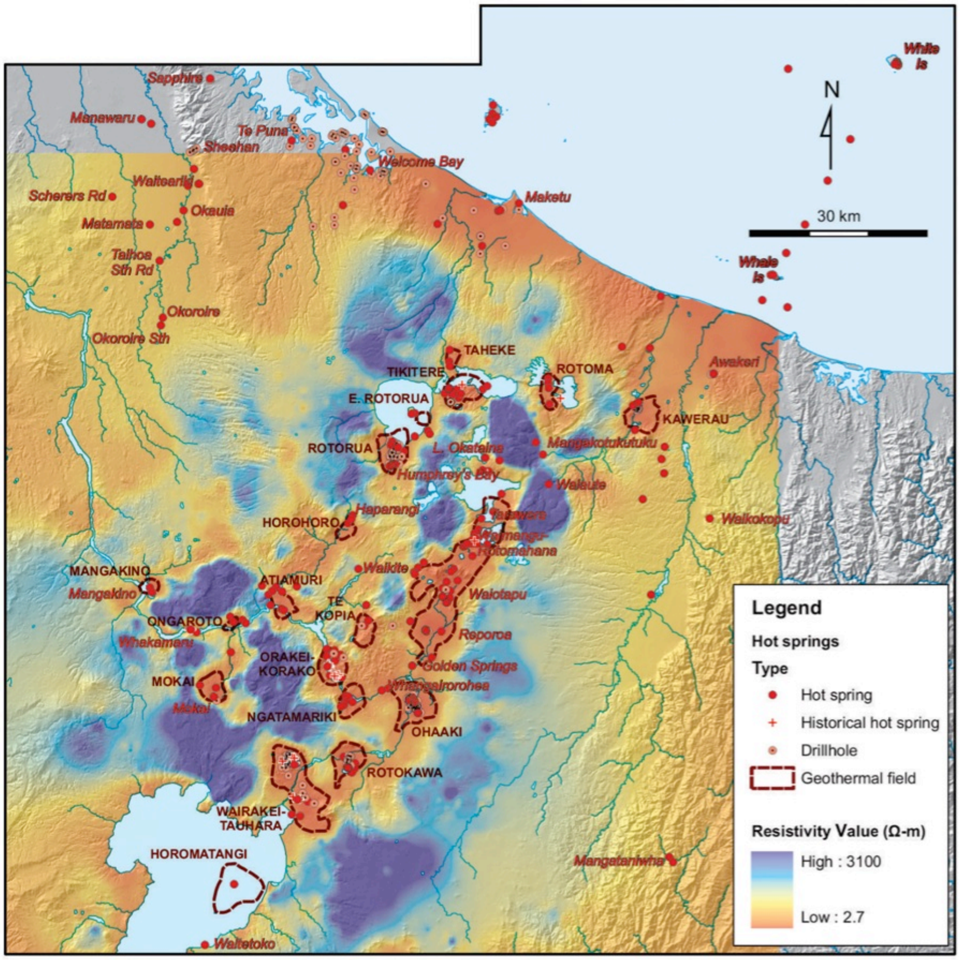

Figure 2.26. Resistivity map of the central TVZ and locations of hot springs and drill holes. Some active fault scarps are also visible in the topographic relief model. From Leonard et al., 2010.

of back arc rifting and with a recent history of voluminous rhyolitic eruptions, the TVZ provides insight into the relationships and interplay between faulting and magmatism, the role of the crust as a "filter" for mantle derived magmas, and the relationship between extensive crustal melts in rifts and more conventional intermediate magmatism along the arc front.

Also of interest in the TVZ is the study of crustal volatile fluxes and their effects on intermediate and rhyolitic crustal magmatism in crust of variable thickness that is currently experiencing differing degrees of extension. In addition, although basaltic rocks are relatively uncommon in this area, the tremendous spatial and temporal coverage of silicic volcanism provides opportunities for looking at equivalent spatial and temporal variability in volatile fluxes associated with volcanism. There also may be definable relationships between volatile fluxes and the voluminous crustal melting zones that feed rhyolitic centers, and the mantle and magmatic contributions to volatile fluxes expressed as geothermal systems. Because of the paucity of primitive or near primitive volcanic rocks in the TVZ and adjacent volcanic arc, the opportunities to address issues of mantle wedge composition and magma generation are relatively limited. However, the TVZ offers unsurpassed opportunities to investigate the role of the crust in filtering and modifying mantle-derived magma and associated volatile fluxes.

Changes in the composition and structure of the subducting Hikurangi Plateau also should be reflected in variations in volatile fluxes, and potentially, in magmatism and crustal structure.

In addition to the research themes outlined for the SCD initiative, it is worth noting that studies within the TVZ also have the potential to address important themes within the GeoPRISMS Rift Evolution and Initiation (RIE) initiative. These include: How do fundamental rifting processes (such as tectonics, magmatism, and erosion, transport, and sedimentation), and the feedbacks between them, evolve in time and space? What are the mechanisms and consequences of fluid and volatile exchange between the Earth, oceans, and atmosphere at rifted continental margins?

2.4.4.1. Existing Datasets and Studies in the Area and Data Gaps

A large number of existing studies have addressed magmatism, physical volcanology, structure, geothermal, heat flow and other aspects of the TVZ. The TVZ is predominantly terrestrial, and geological and volcano maps are available at a range of scales. Swath bathymetry and high-resolution seismic profiles have been collected in some of the lakes and in the northern, submarine TVZ. Active faults are well expressed and their kinematics and seismic histories have been characterized using tephra stratigraphy and chronology, all of which are publicly available (http://data.gns.cri.nz/af/). There are also extensive tephra, rock and geochemistry datasets (http://pet.gns.cri.nz/) and logs available for numerous boreholes (Figure 2.26), primarily drilled for geothermal resource exploration and evaluation. Various geophysical datasets exist at a regional scale, including gravity, MT, and resistivity (Figure 2.26), and localized geophysical datasets exist at selected volcanic centers and active faults, for example, gravity, GPR seismic reflection and 3D MT. Extensive seismograph, strong motion, and cGPS networks span the onshore TVZ, as well as visual, gas, and chemistry volcano monitoring. All datasets are publicly available (www.geonet.org.nz).

In addition, several large geophysical experiments have been completed. These include the 2001 North Island GeopHysical Transect (NIGHT) active source experiment, which collected seismic reflection and refraction data across the central TVZ and the Hikurangi margin. The simultaneous Central North Island Passive Seismic Experiment (CNIPSE) collected seismic data from a dense network across the central North Island. Identified data gaps include high resolution bathymetry and MT data for Lake Taupo, better controls on structure in the upper 20 km, and the location and nature of magma reservoirs, and other data on the physical properties of rocks and partial melts that can be related to existing and future geophysical measurements.

2.4.4.2. Potential GeoPRISMS Studies

Although no single major geophysical experiment was identified by the community to address topics of interest in the TVZ, it was widely recognized that there are abundant opportunities for focused studies that can identify and address key data gaps or refine data sets or models of subduction and extensional processes within the Taupo zone. Examples include:

Geophysical imaging and associated studies: Seismic imaging of magmatic bodies and vents, sampling of fluids and rocks, and focused MT studies are all necessary to improve identification and resolution of magmatic features and crustal structure in the TVZ. High-resolution datasets from such efforts could be used to constrain new or existing numerical models.

Magma genesis and evolution: Further studies of magma genesis, particularly those providing data on magma production and volatile transfer rates, and the thermal history of magma storage zones, would contribute to better understanding of crustal generation and geochemical cycling.

Structural evolution and magmatism: The relationship between magmatism and the structural evolution of the TVZ was also recognized as an important area for future research opportunities. This might include integration of high-resolution geophysical, structural and geochronological studies to further constrain the timing and nature of extensional faulting and the relationship between extension and ongoing magmatism.

The relationship between TVZ and Hikurangi Margin: Coupled investigations of the TVZ and adjacent Hikurangi Margin could also form the basis for future studies. These might include definition of corridors or transects that image the top of the subducting Hikurangi Plateau from the trench to beneath the back arc in the TVZ, with associated fluid and rock sampling, and geophysical studies. Along-strike changes could be addressed in corridors or transects along the TVZ, or from the TVZ to the Kermadec Arc.

Data compilation and synthesis: One unique feature of the TVZ is the large amount of previous work that has been done through academic studies, governmental research organization and private sources. For this reason, a useful investment via GeoPRISMS may be a more detailed evaluation and compilation of existing resources and more detailed gap analysis (perhaps within separate disciplines) for guidance regarding placement of GeoPRISMS resources.

2.4.5. Kermadec Arc

SCD Key Topics

- ***Volatile storage, transfer, and release in oceanic subduction systems***
- ***Geochemical products of subduction and creation of continental crust***
- ***Subduction zone initiation and arc system formation***

The Kermadec-Havre Trough region includes a well-preserved example of Eocene subduction initiation, providing unique opportunities to examine the structural, stratigraphic and volcanic record associated with subduction initiation and subsequent arc evolution. This area is also ideally suited to the study of volatile fluxes from the fore-arc to the back-arc, and to determine the effects of along-strike changes in composition and sediment inputs of the incoming plate. The presence of rhyolitic magma also provides opportunities for study of silicic magma formation in oceanic arc systems.

The Kermadec Arc – Havre Trough (KAHT) and Tonga arc systems extend over 3000 km from latitude 15° to 40°S, forming the southwestern quadrant of the circum-Pacific subduction system. In the KAHT, older Pacific plate lithosphere (> 80 Ma) subducts westwards beneath the Australian plate at the Kermadec Trench. Convergence rates at 31°S are 80–85 mm/year, representing a Pacific plate vector of about 65 mm/year, together with trenchward migration of the Kermadec Ridge of 15–20 mm/year. The KAHT consists of an arc–backarc basin–remnant arc triplet, with the three sectors of the Kermadec portion of the KAHT, i.e., the Kermadec Ridge, the Havre Trough and the Colville Ridge (Figure 2.27). The KAHT, together with the

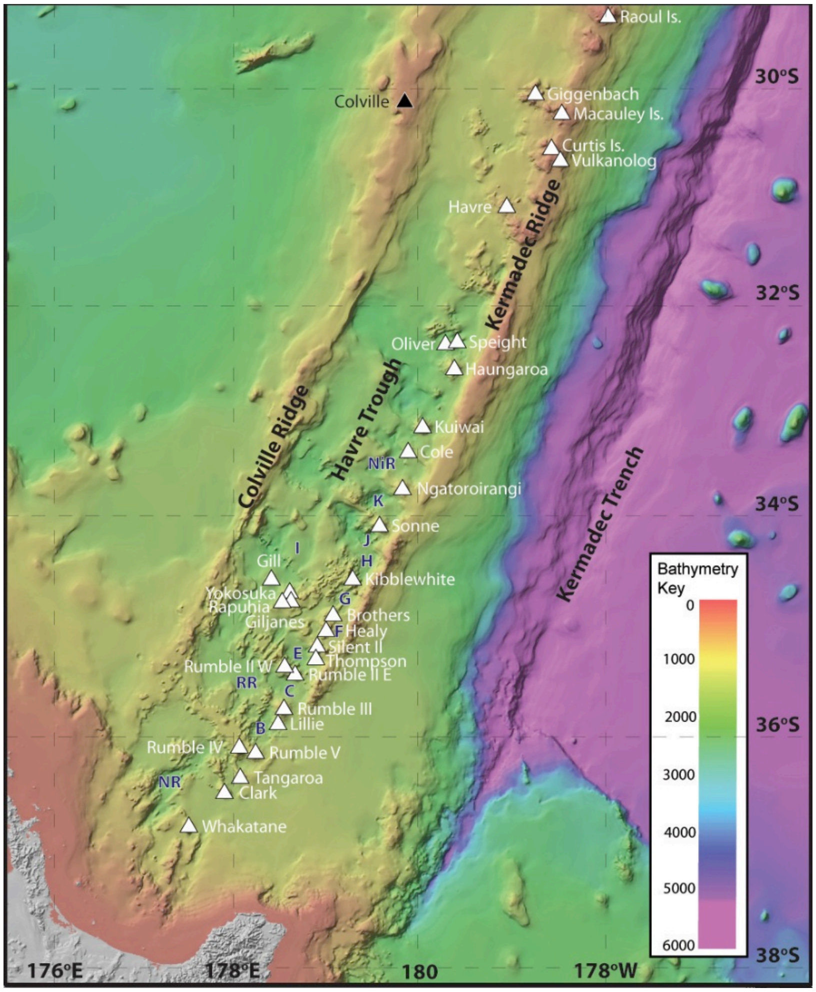

Figure 2.27. Bathymetry of the KAHT system. Triangles represent the locations of individual volcanoes.

Tonga-Lau system to the north collectively define a classic intraoceanic arc – back-arc pair. The KAHT extends north from the Taupo Volcanic Zone of New Zealand, to the Tonga-Lau subduction system. The subduction of the Louisville Seamount chain at ~25°S represents the boundary between the KAHT and Tonga-Lau systems, although the two can be considered coeval. With a well-defined arc front, an ancient proto-arc (the Colville and Kermadec Ridges) and a back-arc > 100 km wide, the KAHT - Tonga-Lau system is a prime setting for investigating a range of arc processes, including arc initiation, tectonic and mass transfer processes, magma genesis and volatile fluxes.

Some of the specific questions that can be addressed though detailed studies of the KAHT and adjacent arc systems include:

- *Is there an observable signature of Hikurangi Plateau subduction along or across-strike?*
- *What are the volatile fluxes in the TVZ/Kermadec/Tonga system and how do they relate to along and across strike variations?*
- *What is the relationship between tectonism, magmatism, and fluid fluxes during the rifting stage of backarc development?*

- *What systematic variation is there in subducted components and what is the partitioning of magmatism and fluxes in the forearc, volcanic front, and back-arc?*
- *How do arcs initiate – what are the timing, mechanisms, rock types etc.? How does the record of arc initiation in the KAHT relate to the well-documented record in the Izu-Bonin-Mariana forearc?*

The broad KAHT system, extending north to Tonga-Lau and west to the Lord Howe Rise, is unique in many respects. The presence of a number of arcs of different age but related to the same system provides an opportunity for understanding the temporal evolution of arcs from their initiation. The presence of the Hikurangi Plateau allows a unique opportunity to investigate the effects of plateau subduction or collision. Hydrothermal venting enables detailed study of active hydrothermal systems and their resource potential. Large silicic calderas provide time scales of rhyolitic volcanism and impacts on society. Finally, the change from continental to oceanic crust, decreasing trench sediment northwards, and the presence of the Hikurangi Plateau to the south, allow examination of changes in volatile fluxes with changing subduction input.

The KAHT system is specifically well suited to the investigation of two SCD Themes: (1) fore-arc to back-arc volatile fluxes and (2) subduction initiation. The Colville and Kermadec ridges preserve material related to Oligocene-Eocene initiation of the KAHT, and studies here will complement advances in understanding subduction initiation in circum-Pacific subduction systems from recent work in the Izu-Bonin Mariana (IBM) system. Moreover, a recently proposed transect of IODP boreholes along and across strike between New Zealand and New Caledonia will quantify the timing and magnitude of vertical motions, compression, and volcanism related to the subduction inception process at the Tonga/Kermadec/Hikurangi trench.. In concert with the TVZ, the KAHT provides the opportunity to examine volatile fluxes, magma genesis and other processes in the transition from oceanic to continental convergence regimes, and from volcanic front to extensional back arc environments. Numerous volcanoes (Figure 2.27) also provide opportunities for studying magma and volatile fluxes along and across the arc. The presence of abundant silicic magma also provides opportunities for study of silicic magma formation in oceanic arc systems.

Previous work in the Izu-Bonin-Mariana (IBM) forearc provides insights into subduction initiation that can be tested in the KAHT. Recent IBM studies illustrated that most or all of its length consists of an ophiolitic geology with depleted peridotite overlain successively by gabbro, diabase, MORB-like basalts, and boninites. Several studies have postulated that this sequence was associated with subduction initiation at 52 Ma and the first 7-8 million years of early arc development. Similar rocks with similar ages have been dredged from the southern Tonga forearc, suggesting that the Early Eocene Pacific subduction initiation could have extended this far south, although complexities in the forearc crust compositions and ages stretching from the Cretaceous to Pliocene allow for alternative geological interpretations. The age of subduction initiation in the IBM system corresponds with a significant reorganization of global plate motions, as well as a hot-house climate (the Early Eocene Climate Optimum), illustrating this could have been a globally significant tectonic event and a contributor to climate change. Proposed IODP drilling to investigate subduction inception at the Tonga-Kermadecs will enable tests of predictions from alternate classes of geodynamic models for subduction initiation developed in the context of global plate kinematics.

The KAHT is less well studied than its northern extension in Tonga-Lau but enough work has been done in the last decade, and has been proposed recently by collaborating countries, that GeoPRISMS projects are well-timed. As the only GeoPRISMS focus site to include backarc spreading processes, the KAHT also blurs the boundary between SCD and RIE scientific objectives by extending study of the Taupo Volcanic Zone rift into the oceanic realm. From a magmatic point of view, this also creates opportunities to explore how mantle deformation and melting processes evolve from the fluid-rich corner-flow flux melting of island arcs into the drier mid-ocean ridge-like decompression melting of mature backarc spreading centers such as the Central Lau Spreading Center to the north. Transects extending from the subducting Pacific Plate, across the KAHT, and into the older South Fiji backarc basin to the west can capture this range of scientific objectives.

2.4.5.1. Existing Datasets and Studies in the Area and Data Gaps

Since initial studies of the KAHT in the 1960's, many of which were seminal in developing models for arc and back-arc subduction processes, our understanding of this subduction system has increased substantially. As the KAHT system is nearly completely submarine, with the exception of a few small islands that are the emergent tips of submarine volcanoes, studies have depended on a number of research cruises, predominantly by New Zealand but also US, German, Japanese and in the early years of exploration, Russian research voyages. Initial bathymetry and tectonic models were based on satellite data and airborne geophysical surveys. The recent advent of higher resolution (12 kHz and now 30 kHz) swath mapping systems bathymetry has led to a significant increase of data, leading to the discovery of most of the volcanoes and compilation of detailed maps. Even so, only the southern KAHT (south of 35.2°S) has been mapped in any detail. North of this, only the volcanoes of the arc front have been mapped, with the back-arc and fore-arc almost completely unknown.

Despite the fact that arc front volcanoes make up < 5% of the areal extent of the KAHT, they have received almost all of the scientific attention. This is in part historic, as the southern seamounts were known to the fishing industry and as some were seismically active (e.g., the "Rumble" volcanoes), they became the first scientific targets. The discovery of hydrothermal venting on the volcanoes, and associated economic deposits, intensified interest in the edifices. Most of the arc-front volcanoes have now been swath mapped and sampled by dredge, and explored for hydrothermal activity, with only a few edifices explored in any detail by ROV, most notably Brothers Caldera.

Due to the costs of ship time and need for expensive equipment to explore the KAHT, a number of significant gaps persist in our knowledge of the system. Only the region south of 32°S has been surveyed in any detail through swath mapping, and even here much of the data is low quality due to old instrumentation or poor weather conditions. North of this, the arc front volcanoes have been mapped, but the Havre Trough and Colville and Kermadec Ridges remain poorly explored. The forearc in particular has received little attention anywhere in the KAHT.

Even in areas that have been swath mapped, there is a paucity of geophysical data, in particular, geopotential data, including magnetic, gravity data, electromagnetic and heat flow data. High quality backscatter data are also lacking, and seismic data are limited. Several single channel seismic lines and two recent multi-channel seismic lines that cross the KAHT perpendicular to the trench have been acquired. Multi-channel seismic lines have also been acquired over several arc front volcanoes, but the coverage is still quite sparse.

In addition, there are only limited areas with detailed sampling and surveying. The majority of sampling has been through rock dredging with very little coring. Most of this work has been carried out on the arc front volcanoes with very little investigation in the back-arc region or on the ridges. ROV, AUV and manned submersible surveys have been few and concentrated on only a few volcanic edifices, notably ones that are hydrothermally active, as well as one basin (Ngatoroirangi Rift) in the Havre Trough. Even camera observations for the rest of the system are sparse.

2.4.5.2. Potential GeoPRISMS Studies

The consensus opinion of the community at the New Zealand focus site workshop was that the most efficient approach to address the key scientific questions in the KAHT, given the large surface area of the system, was to concentrate efforts on geographical ‘corridors’ rather than individual disparate regions for each study. This would involve focused multidisciplinary research on one or more corridors ~100 km wide extending from the Pacific Plate, across the trench and to the western side of the Colville Ridge. Individual research voyages would ideally follow a nested approach, building on and adding to previously acquired datasets, along one or more of the corridors. Only with detailed knowledge of focused areas, obtained through interdisciplinary, multinational studies, can the key scientific questions be adequately addressed. The number of or locations of potential corridors remain to be decided, and workshops to address these key decisions are essential. A need to compile a database and to compare it with Izu-Bonin, Central America, Chile, Aleutians, Cascadia is also encouraged.

The KAHT system also offers potential locations to investigate the length scale and timing of subduction initiation at the southern end of the western Pacific arc and back-arc systems. The bathymetry of the Kermadec forearc is like that of the southern Tonga forearc, but the area is presently unsampled. The escarpments on either side of the Havre trough also offer potential outcrops of early arc crust, but likewise have been poorly studied. Dredging and detailed bathymetric investigations of these areas are clearly needed, perhaps followed by diving and drilling if warranted. The Lord Howe Rise region offers important opportunities to quantify the timing and magnitude of vertical motions, compression, and volcanism related to subduction initation, including dramatic deepening of the New Caledonia Trough during subduction inception.

A number of overlapping studies are seen as important to adequately survey and sample the corridors. In order to achieve the key objectives, detailed coordination of field campaigns (ship schedules, proposal writing/deadlines) will be helpful; this could be facilitated by the GeoPRISMS Office and website. Plans for focused data acquisition and prioritization of data sets will be determined at future community planning workshops. Example studies include:

Swath mapping, gravity and magnetics: Swath mapping, which has been carried out locally over certain features, could be completed for the selected corridor(s) at a suitable resolution (30 kHz), along with complementary geopotential studies, including gravity and magnetics.

Hydrothermal studies: Fluid sampling and mapping of the water column could be carried out over suitable areas. These measurements would provide background data, helping to identify key submarine features, and would provide key information for tectonic models.

Physical sampling by rock dredge, ROV, and IODP drilling: Key targets include the incoming Pacific Plate and Hikurangi Plateau material, primitive arc and back-arc samples, well-exposed early-arc igneous sequences, old arc (Colville) material, rhyolitic sequences, and hydrothermal fluids and deposits. There are two existing IODP proposals to (a) investigate the stratigraphic record of Tonga-Kermadec-Hikurangi subduction inception, and (b) to investigate the hydrothermal system at Brothers Volcano in the Kermadec Arc.

Deep tow and AUV studies: These surveys would be focused on selected targets, particularly hydrothermal systems, which have been identified through other means.

Regional geophysical surveys: Active and passive OBS surveys, electromagnetic studies, and heat flow measurements would help to assess crustal porosity and permeability, and the distribution and role of fluid pathways in the crust and mantle wedge.

2.4.6. Exhumed & Remnant Terranes – The Fiordland Example

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Subduction zone initiation and arc system formation***
- *Feedbacks between surface processes and subduction dynamics*

Exhumed terranes across New Zealand offer excellent opportunities to address several SCD thematic studies, and also provide unique views into deep arc roots that bear on understanding active subduction zones around the world. For the example highlighted here, exposures of lower arc crust in Fiordland allow examination of fluid and magma transfer processes, geochemical modification and diversification of arc magmas, and thermal and material transfer processes from the mantle wedge to the lower crust during arc construction and collapse.

The New Zealand primary site includes the exhumed Early Cretaceous deep crust of Fiordland (Figure 2.28), which is of particular significance as a well-preserved example of a deep arc root. The eclogite-granulite transition is observed here, representing dioritic crust that equilibrated as deep as ~65 km prior to extensional exhumation in the mid-Late Cretaceous, and transpressional uplift from the Miocene to present. For comparison, mid to shallow levels of the same arc are also present adjacent to Fiordland along the strike of the arc in Westland (Figure 2.28). Coeval volcanics are rare, but equivalents may exist in a possible continuation of the same arc in Queensland, eastern Australia. Together with adjacent forearc, accretionary wedge, fossil "trench" and jammed Hikurangi Plateau, the exhumed Triassic-Early Cretaceous subduction zone is apparently the only well-preserved exhumed Cretaceous subduction margin in the western Pacific region. Thus it provides unique opportunities to look deep inside a continental arc to tackle SCD questions that cannot be addressed in active settings.

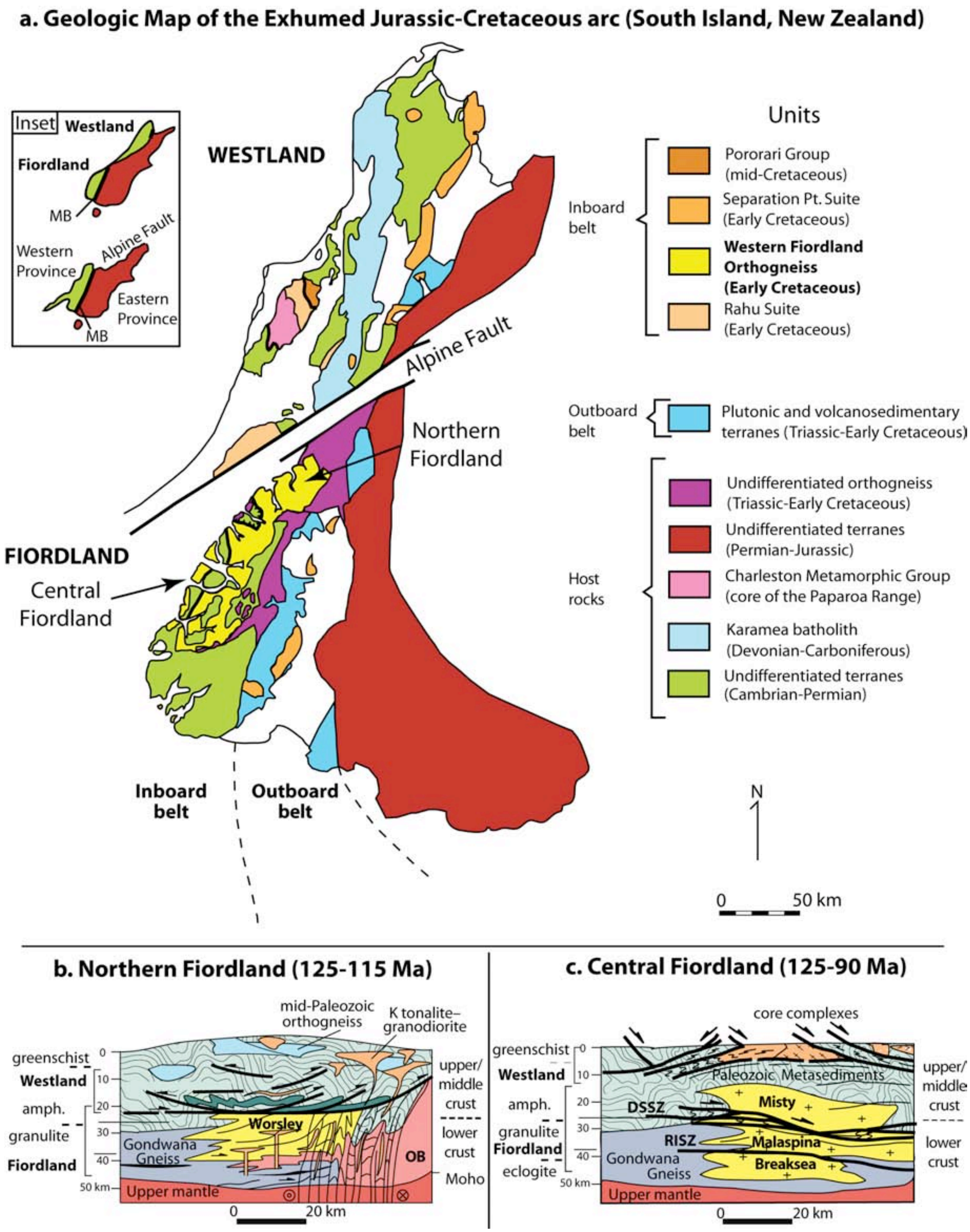

Figure 2.28. (a) Simplified geologic map of the western part of the South Island, New Zealand (after Klepeis et al. 2004; Miller and Snoke, 2009). Inset shows present configuration (top) and Cretaceous arc after removing slip along the Alpine fault. Schematic lithospheric profiles of (b) Northern Fiordland, showing syn-magmatic contraction, and (c) Southern Fiordland, illustrating post-magmatic extension (both after Klepeis et al., 2003). OB = outboard belt; RISZ = Resolution Island Shear Zone; DSSZ = Doubtful Sound Shear Zone; amph = amphibolite.

The Jurassic to Cretaceous New Zealand arc may also be the best global example of Phanerozoic tonalite-trondhjemite-granodiorite suite (TTG)-like magmatism, which is common in Archean rocks worldwide. TTG rocks in Fiordland are characterized by high Sr/Y values indicating magma equilibration with a garnet-rich, plagioclase poor residue. The broad geochemical diversity of TTG rocks in Fiordland, and their relatively large proportion (c. 50%) among the local plutonic rocks, may be unique and provides the opportunity to understand the genesis and evolution of these magmas in the roots of a continental arc. Strong similarities of these plutons with the Peninsular Ranges Batholith of North America suggest that the distinctive characteristics of the Median Batholith magmas are not unique, and therefore have global significance to understanding arc processes.

Studies of exhumed terranes, such as those exposed in Fiordland, are complementary to studies of active subduction in the SCD primary sites, defining a thematic component of GeoPRISMS research. The following key SCD questions can be well addressed in the exhumed deep crustal exposures in Fiordland (and shallower equivalents):

What are the geochemical products of subduction zones and how do these influence the formation of new continental crust? The Triassic-Early Cretaceous continental margin arc (i.e., Median Batholith) is composed of two margin parallel plutonic belts (Figure 2.28). The outboard belt has typical subduction-related chemistry, whereas the inboard belt is dominated by plutons of TTG-like/adakitic/high Sr/Y (HiSY) compositions. The especially strong HiSY signature of these rocks, related to the stability of garnet in the source region, makes them prime candidates for studies into the origin of such rocks and the production of dense garnet-rich cumulates at the base of the arc.

What are the rates and processes of arc crust growth and differentiation, and how is arc crust transformed to continental crust? The TTG-like magmas appear to have been formed in high-flux events at overall rates 4-10 times faster than the earlier "normal" arc magmas. The rapid change to TTG-like magmatism during the last 25 Ma of arc magmatism likely holds important clues to the formation and differentiation of arc crust, and to the growth of continental crust in general. Preliminary data suggest a two stage development of crust is likely, involving (a) 235-130 Ma typical mantle wedge-derived magmatism causing basaltic underplating, during which derivatives from the zone of Melting Assimilation Storage and Hybridization (MASH) were emplaced into the upper crust, followed by (b) 130-105 Ma TTG-like magmas produced by partial melting of the earlier underplated material. The unique exposures in Fiordland and Westland thus enable the study of the transformation from arc to continental crust, including the metamorphism and partial melting of earlier igneous and metasedimentary rocks. For example, rocks from the exposed lower crust preserve thermal and barometric evidence that suggest arc contraction and deep burial and loading, followed by delamination of dense lower crustal residues and uplift and exhumation. However, there is still uncertainty in the magnitude and extent of this loading, which must be resolved to evaluate mass transfer and its relationship with magma emplacement.

What processes drive thermal and vertical changes to arc crust during magmatic construction? Three large plutons (1000-2000 km^2) of the Cretaceous Western Fiordland Orthogneiss dominate Fiordland. They were emplaced within a brief 10 Ma period into the crust and then buried to lower crustal conditions. Strong garnet signatures in the compositions of these plutons suggest that Fiordland magmas equilibrated with significant volumes of high density eclogitic residues. Current work supports the notion that magmatism operated in concert with granulite- and eclogite-facies metamorphism. Subsequent retrograde metamorphism preserves near isobaric and spatially heterogeneous cooling and reheating. Metastability is common, suggesting that loading and rebound was transient and that average geothermal gradients may have been lower than expected.

What are the physical and chemical conditions that control the evolution of subduction zones and subduction zone magmas, including the evolution of mature arc systems? Fiordland offers insight into the evolution of mature arc systems. Long-lived 'normal' basalt-andesite-dacite-rhyolite (BADR) arc magmatism in New Zealand operated for nearly 100 Ma, and was followed by a relatively brief period of high-flux TTG magmatism for 25 Ma. The physical conditions of the arc during this transition remain to be resolved, including why magmatism suddenly ceased at 105 Ma. Furthermore, it would useful to understand the possible links between subduction cessation and geochemical changes in arc magmas from BADR to TTG-like compositions. In addition, what role does the Hikurangi Plateau play in the cessation of subduction?

What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics? The possible delamination of high density residues may have enabled significant surface uplift by isostatic rebound, and development of a prominent mountain range above the arc. Removal of a high-density lithospheric root may also have been associated with a shift from contraction to extension across the arc, and also basin formation. Focused isotopic, thermobarometric, and thermochonological studies are needed to test these hypotheses and better understand their relationships to arc evolution.

2.4.6.1. Existing Datasets and Studies in the Area and Data Gaps

Although difficult terrain and weather limits easy access to much of Fiordland, GNS Science recently completed a new 1:250,000 geological map of New Zealand (Q-Map Series), which includes a new map of Fiordland completed in 2010 (Figure 2.28). This map and associated text summarizes the current state of knowledge in the region. GNS Science also operates a comprehensive sample collection and analytical database (http://pet.gns.cri.nz/). Data for Fiordland include 12,358 records, 1,539 geochemical analyses, 5,262 magnetic susceptibility analyses, and 325 geo-thermochronological analyses. For example, the GNS Science mapping program has distinguished several major intrusive bodies that comprise the Western Fiordland Orthogniess, and established the presence of eclogites of likely cumulate origin defining the deepest parts of the arc exposed in the Breaksea Sound region. In addition, zircon geochronology has confirmed the rapid emplacement of plutons, apparently overlapping with arc contraction and thickening. Substantial whole rock XRF chemistry exists for the region, however, rare earth element and isotopic data are underrepresented in existing data sets.

Thus, there are a number of gaps in the datasets in Fiordland related to arc magmatism, metamorphism and deformation. In particular, geochemical characterization of deep-crustal arc plutons is lacking, and thus, geochemical and isotopic changes associated with arc magmatism are poorly understood. Timescales of arc construction are lacking for parts of Fiordland, and no systematic geochronology studies have been undertaken. High-temperature thermochronology studies are also limited, resulting in apparently contradictory data from the same region. New

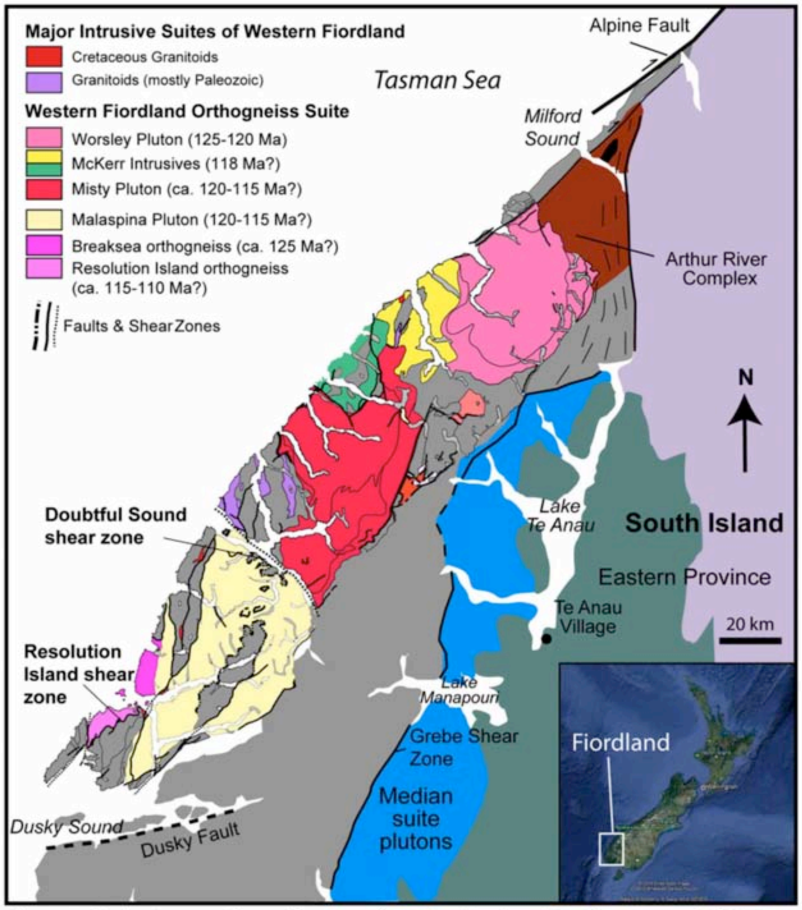

Figure 2.28. Geologic map of central and northern Fiordland resulting from 6-year GNS mapping program (after Allibone et al., 2009; Stowell, personal communication).

field-based studies, coupled with geochemical and isotopic analyses and integration of existing data, would help to establish the relationships between arc magmatism, vertical motions, and thermal changes, and associated lower crustal flow processes.

Some geophysical constraints on arc structure exist from previous and ongoing efforts, but new opportunities exist to augment these datasets. Passive seismic studies completed in Fiordland, resulted in 3D velocity and attenuation models and surface wave models. Earthquake data (continuous broadband since 2005; short-period triggered events prior to that) are available from GeoNet (http://www.geonet.org.nz/), and could be used to update models or to apply additional techniques, although permanent stations are sparse. Gravity data that could be used to improve crustal models are available across New Zealand (http://www.nzpam.govt.nz/cms/pdf-library/petroleum-conferences-1/2013/presentations/Advantage_2013_Davy.pdf).

2.4.6.2. Potential GeoPRISMS Studies

GeoPRISMS provides the impetus for coordinated, interdisciplinary approaches integrating structural geology, metamorphic petrology, geochemistry, geochronology, and geophysical studies with field, analytical, modeling and experimental approach with a primary goal of understanding transport and redistribution processes occurring at high pressure and temperature within the dynamic subduction zone environment. Planned work should include cooperative transport and sampling for multidisciplinary studies on single sample sets that could be lodged in PETLAB. Specific questions that can be addressed include:

Geochemical Sampling and Analyses: Sparse samples exist and limited analyses have been conducted to address some of the basic questions relating to the evolution of this ancient arc. More complete sampling, particularly of plutonic rocks that may record processes associated with lithospheric delamination, basaltic underplating, and intra-arc extension, will provide direct opportunities to analyze the geodynamic interpretations posed above. A focus on rocks that record the sudden and complete switch to HiSY TTG-like plutonism at c. 135 Ma would be key to understanding this episode. In addition, rare earth element and isotopic studies remain to be carried out in the area.

Thermochronology: Characterization of the processes that drove deep burial to 10-20 km, and subsequent exhumation of the arc roots now exposed in Fiordland, require systematic high-temperature thermochronology studies that could resolve timescales and rates of loading and exhumation, and the spatial distribution of regional flow paths in the crust. These data can be integrated with thermobarometry estimates and constraints on lithospheric velocity structure to assess arc composition and associated vertical motions responsible for the present structure. The timing of the cessation of subduction may also be resolved by study of the relict accretionary wedge. Similarly, the timing of the onset of rifting and the nature of the rifting processes can be examined.

Geologic Mapping: The recently completed more detailed geological mapping of Fiordland conducted by GNS Science provides a strong base to build on for additional geological mapping, in particular, to identify and date key deformation zones and structures, both brittle and ductile, and to document patterns and signatures of crustal melting, magma mixing, and flow, indicative of deep crustal flow that accommodates lateral and vertical motions.

2.4.7. Numerical and Experimental Studies

The New Zealand plate boundary is an excellent natural laboratory for understanding physical processes that control subduction, rifting, and volcanic arcs. Many high-quality geophysical and geological datasets already exist to constrain models, and to link with experimental datasets. Several IODP drilling campaigns are proposed and/or awaiting possible scheduling, and will provide opportunities to obtain samples for experimental studies, as well as key datasets to better constrain models. Critical gaps that could be addressed by modeling and experimental studies include: (1) the effect of along-strike flow and transport along the New Zealand plate boundary on dynamics of subduction, magmatism and rifting; (2) links between fluid-flow, heat-flow and mechanics at a range of timescales from millions of years to seconds; and (3) the laboratory study of rock properties from the New Zealand plate boundary. Below, we describe the potential role such studies could play for key SCD topics.

2.4.7.1. Numerical and Analog Modeling

Current generation numerical models of New Zealand tectonics have focused on diverse topics, such as the dynamics of accretion and subduction; the interaction of magma and rift tectonics; coupled tectonic-climate feedbacks; and the effect of subduction initiation on mantle flow and deformation of the overriding plate. Improved 3D numerical and analogue modeling techniques make this an ideal time to advance such modeling efforts via GeoPRISMS-related science and partnerships.

For example, numerical models of subduction initiation suggest a change from forced to self-sustaining subduction as the incipient lower plate is pushed downwards. The Puysegur-Fiordland region may currently be transitioning to a self-sustaining system. This is the only subduction zone presently in this critical state, and enhanced 2D and 3D numerical models of this transition, combined with new geophysical datasets, offer an unprecedented opportunity to understand subduction initiation processes and the forces operating on young subduction systems. Dynamic models that track the evolution of transform and normal faults making up the initial Australian-Pacific plate boundary into the present convergent setting will be essential. How the evolution of and geometry of the shear zone is reflected in the growth of topography on and offshore will be essential to exploit the current (such as the rock uplift in Fiordland) and expected (seismic structure) constraints. Further north, the Tonga-Kermadec system has well-preserved sedimentation and geochemical signatures of subduction initiation that place strong constraints on the timing of the onset of convergence and associated vertical motions relative to regional tectonic events, offshore thermal and crustal structure, newly developing arc volcanism, and the geometry of subduction initiation. These constraints can be used to test numerical models of subduction zone initiation.

Numerical models can also test the hypothesis that changes in subduction angle and subducted material along-strike in the Tonga-Kermadec arc have strongly influenced the geochemical signature of volatiles and magma. Similarly, detailed “subduction factory” calculations for the combined subduction/rift system onshore North Island can explore questions about the nature of magmatic products, particularly the change from andesite to rhyolite dominated magmatic systems in the TVZ, and help to understand the extremely high heat-flow and volatile flux component emerging through this rift. Preliminary tectonic modeling of this rift suggests a feedback between rifting and volcanism, but further coupled numerical models including fluid and volatile fluxes are needed to understand this process. Improved modeling of melt generation would help address magma-tectonic interactions.

The Hikurangi subduction margin offshore of the North Island, New Zealand is prime territory for numerical models to explain the contrasting slip behavior along its length. The cause of the abrupt change in subduction zone locking depth and distribution and the frequency of slow-slip events along-strike is not well-understood. The Hikurangi margin is an ideal test-case for modeling studies to explore whether fluid pressure variations, changes in incoming subducting sediment and/or lower plate, changes in stress in the over-riding plate, or other effects are responsible for subduction thrust fault slip behavior and its spatial variability. Numerical models coupling a variety of timescales, from millions of years to decadal timescales (plate geometry; effect of subducting an ocean plateau on mantle dynamics, upper plate stress, fluid production and pressure, and their influence on stress accumulation and release during the seismic cycle) are needed. Improved thermal models are also required, incorporating fluid flow, upper mantle viscosity changes associated with partial melt, and informed by new and existing heat-flow measurements and more detailed information on subduction inputs. Rate-and-state and earthquake simulator models specifically adapted to include upper plate structure and the geometry of the subduction interface could be constructed, in order to explore interactions between the subduction thrust and the overlying plate and forearc. Dynamic models of slow-slip events propagating along-strike can be used to inform the effect of these events on hazards.

Sediments are generated in response to tectonic and magmatic forcing, and commonly contain a record of these events – for example seismic shaking, uplift, erosion and volcanism. Sediments play a significant role in defining forearc structure, and the mechanical properties of the subducting slab – e.g., roughness, sediment composition, and sediment thickness on and below the subduction thrust. Sophisticated 3D models are available for both lithospheric and surface processes; however, a complete description of an active landscape requires characterization of the interaction between these processes, as well as inclusion of atmospheric driving. At present, available coupling is rudimentary at best. To better understand the linkages between sedimentation and deformation, next generation models coupling both sets of processes must be used. These developments are being facilitated by the Community Surface Dynamics Modeling System (CSDMS) and their Geodynamics Focus Research Group (co-sponsored by GeoPRISMS). Some projects are already underway applying these numerical modeling tools to the New Zealand plate boundary, including projects partly sponsored by the precursor to GeoPRISMS (the MARGINS Source-to-Sink project).

With increasingly high resolution data to constrain models, and identification of short-duration events in the sediment record (e.g., tsunami deposits and turbidite records of past earthquakes), we can expand on current modeling to address targets such as the rheological characteristics of the plate interface, links between upper and lower plate deformation and uplift along the Hikurangi subduction zone, the interplay between rifting and magmatism in the TVZ, and overall influence of sediment budget and its relationship to fluids and magmatism in the subduction/rift system. Such advances require embedded models with higher resolution geological, geophysical and topographic inputs to explore components of the system.

Finally, earthquakes, surface uplift, storms, fires and volcanic eruptions all potentially drive pulses of terrestrial sediment fluxes to the continental shelf and eventually to the subducting plate. The relative contribution of earthquake-driven fluxes is largely unknown at present and is an obvious area that GeoPRISMS-related researchers could explore. Numerical models may help elucidate the role of subduction zone earthquakes in initiating landslides, creating readily mobilized sediment sources, predictions that can be tested against the sediment record.

2.4.7.2. Experimental Studies

Like numerical studies, laboratory experiments conducted under controlled conditions are an essential component of the GeoPRISMS SCD initiative. Experimental programs allow testing of hypotheses related to deformation and rheology in the seismogenic zone and in the upper mantle, fault slip behaviors, metamorphic reaction rates, melting behavior, solubility, and transport of fluids and magmas. Experiments also allow linkage of field observations (e.g., geodetic locking along subduction thrusts; water content in magmas) with underlying physical and chemical processes, and provide key constraints to inform numerical modeling studies. In this context, experimental studies are tightly allied both with thematic studies relevant to *all* primary sites, and with testing of hypotheses specific to individual primary sites.

In conjunction with numerical modeling studies described above, experimental data defining rock properties are a key ingredient in testing hypotheses about both fault and upper plate rheology, hydrogeology, and deformation. For example, laboratory measurements of rock and fault gouge frictional behavior, permeability, and elastic properties are central to understanding the role of frictional properties and stress boundary conditions on the mode of subduction fault slip. The Hikurangi margin of the New Zealand focus site offers an outstanding opportunity to investigate the controls on along-strike variability in locking and the nature of slip on the subduction megathrust. Experimental studies are a key component of testing hypotheses to explain the occurrence of slow slip events at Northern Hikurangi: are the SSE related to a specific fault zone composition with frictional properties that facilitate slow slip? Are they related to elevated pore fluid pressure? Similarly, the role of seamounts as asperities and/or as barriers to slip, and in driving heterogeneous pore fluid pressure and stress distribution along the plate interface, require tight linkage of numerical models (described above) and laboratory data that parameterize models (e.g., permeability, elastic moduli). Detailed measurements of acoustic and electrical properties for relevant subduction zone rocks provides key data to link between *in situ* conditions and properties, and geophysical datasets that remotely sense rock attributes over large regions (e.g., seismic reflectivity, low P-wave speed). Ultimately, these experimental data will provide a basis for quantitative extrapolation of rock properties and *in situ* stress and pore fluid pressure conditions away from boreholes in the shallow subduction zone, and allow rigorous testing of hypothesized causes for anomalous low-velocity and high reflectivity over depths ranging from the trench to the downdip reaches of the seismogenic zone. The plan to drill into a slow-slip zone in the northern Hikurangi margin, if successful, will provide a unique opportunity to access relevant materials for these studies.

The well-studied fluid seeps along the Hikurangi margin provide an exquisitely detailed geochemical record of devolatilization beneath the forearc. Experimental studies that provide detailed constraints on the P-T conditions associated with liberation of specific chemical species during prograde diagenesis and metamorphism (e.g., hydrocarbon generation, thermally driven desorption and release of structurally bound fluid-mobile elements including B and Li, clay dehydration) will yield insights into the source regions for these volatiles observed at the land surface, thereby providing powerful new constraints on the budgets and transport of these volatiles through forearc and subarc.

The rheology of rocks containing partial melt, fluids, and effects of fluid-alteration (e.g., serpentinization) is also critical to understand pathways, fluxes, and sources of volatiles, their relationship to deformation, and to constrain models of these processes – for example, beneath the North Island and offshore in the Tonga-Kermadec arc system. Detailed experimental rock studies that address how tomographic and electrical conductivity signatures relate to these properties (e.g., hydration state, serpentinization) are also needed. Questions include: how do signatures change below the brittle-ductile transition, and as a function of strain? Such studies could also help inform codes that compute changes in density, rheology, melt and fluid content as a function of pressure and temperature changes, particularly if they were based on protolith material representative for New Zealand (e.g., greywacke; anomalous oceanic plateau material; and mantle). For a better understanding of how fluid circulation in the TVZ crust interacts with tectonics and magmatism, we also need improved understanding of how permeability changes with deformation, pressure and temperature.

2.4.8. Research Strategies and Partnerships

The New Zealand primary site is already the focus of significant research efforts within the international community. This affords a wide range of opportunities for linking GeoPRISMS studies with a vast body of previous work on subduction systems in NZ, leveraging existing infrastructure, and collaboration in numerous ongoing and planned investigations. These ongoing endeavors include significant investments from the NZ government and efforts within the NZ geosciences community, as well as active research programs led by Japanese and European-based investigator groups. Any GeoPRISMS studies at the NZ primary site should build on these substantial existing and ongoing studies; there are significant opportunities to leverage GeoPRISMS research investments through collaborations with international partners.

2.4.8.1. New Zealand Resources, Infrastructure & Databases

A large New Zealand-based community of geoscientists has been undertaking a wide range of marine and shore-based investigations at New Zealand's subduction zones for many decades. These investigations include government-funded research focusing on subduction processes conducted by Crown Research Institutes (GNS Science, NIWA), and at several universities. There is relatively strong NZ government support for subduction–related research, due to their relevance for understanding both geohazards and resources. New Zealand maintains a marine geophysical data acquisition and research capability in part via its research vessels, which are owned and operated by NIWA, and in part through oceanographic surveys organized through international collaborations. The largest and most capable New Zealand vessel is the 70 m long RV *Tangaroa*. *Tangaroa* is equipped with a Dynamic Positioning DP2 and a 30 kHz multibeam echo-sounder with full water column capability. NIWA's multichannel seismic reflection acquisition system can easily be deployed from *Tangaroa*. It is also equipped to conduct seafloor sampling (dredging, shallow coring, multicorers, CTD, etc.), and is suitable for the deployment of a range of geological and geophysical equipment such as ROV and AUV.

The GeoNet network discussed previously (Figure 2.25) constitutes a major scientific infrastructure investment dedicated to earthquake, tsunami, volcano and landslide monitoring. GeoNet includes a comprehensive seismograph network that includes 52 broadband national network stations, 126 regional stations, and more than 240 strong ground motion stations. There are 180 continuous GPS sites in New Zealand, with the vast majority of these deployed along the Hikurangi forearc and within the volcanic region of the central North Island. In addition to seismic and cGPS, the volcanic regions also undergo routine water and gas chemistry monitoring. All of the raw data gathered by GeoNet is publicly available on their website: www.geonet.org.nz. Processed time series of the cGPS sites are also openly available. GeoNet routinely locates all detectable earthquakes in New Zealand, and maintains a comprehensive earthquake catalog.

Many of the results and samples from extensive previous geological studies in New Zealand have been integrated into national databases. From 1993-2010, the New Zealand government funded the QMAP project to produce new, high-quality geologic maps of all of New Zealand at 1:250000 scale (see data.gns.cri.nz/geology). The maps are underpinned by all available existing geological data, but extensive fieldwork was also undertaken in areas where such data were lacking. A database of over 177,000 rock and mineral samples gathered from throughout onshore and offshore New Zealand and Antarctica are catalogued in PETLAB (pet.gns.cri.nz). The Fossil

Record Electronic Database (FRED; fred.org.nz) contains information on nearly 100,000 fossil localities in New Zealand and Antarctica. A comprehensive database of New Zealand's active faults is maintained by GNS Science, and is publicly accessible at www.data.gns.cri.nz/af. This database contains detailed information, including fault geometry, kinematics, paleoearthquakes, photographs, and references to published studies on each fault.

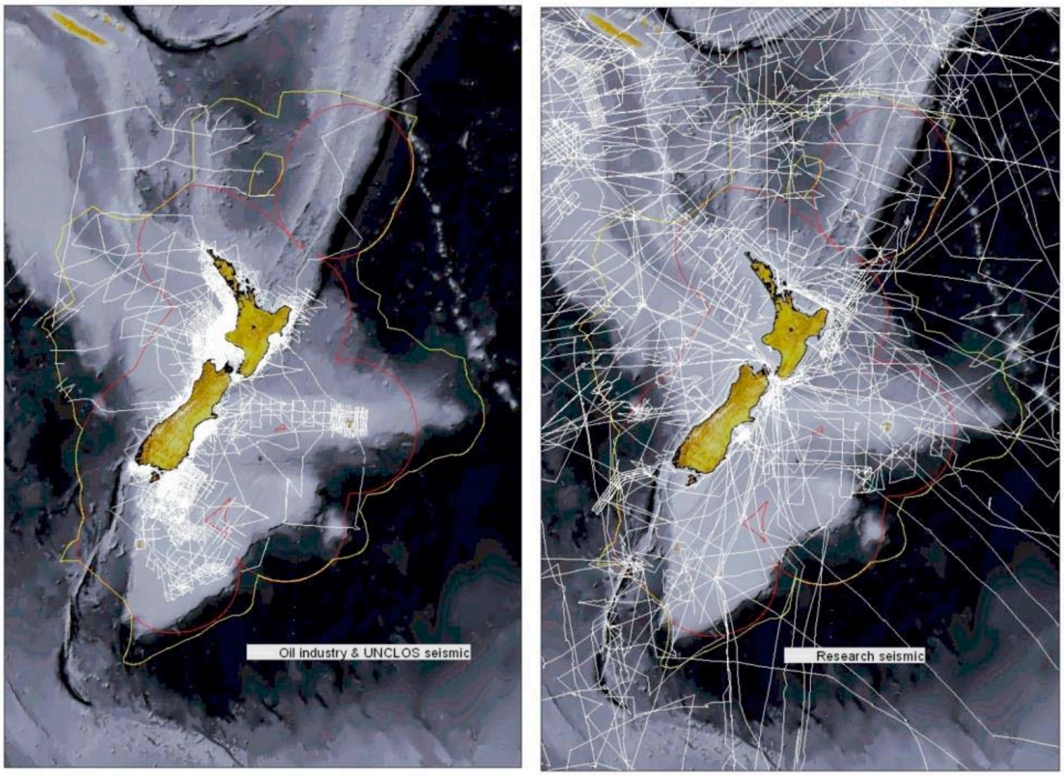

Figure 2.29. Locations where active source seismic data have been acquired. Map on left shows data acquired by industry, or for the purposes of the United Nations Law of the Sea (UNCLOS) project. The figure on the right shows seismic data acquired for research purposes. Source: GNS Science.

A large body of data has also been gathered in New Zealand's offshore environment through both New Zealand-based and international scientists (Figure 2.29). The petroleum industry has also gathered vast datasets in New Zealand waters, and these datasets are required by law to become open file (publicly available) within five years after the data acquisition. Active source seismic data are available through New Zealand Petroleum and Minerals (www.nzpam.govt.nz), a department of the Ministry of Business, Innovation and Employment, or via GNS Science's data portal (http://data.gns.cri.nz/dataportal/). A comprehensive database of bathymetry data offshore New Zealand compiled by the National Institute for Water and Atmospheric Research (NIWA) can be found at: www.bathymetry.co.nz. Rock samples gathered offshore via dredging, seafloor grabs, and shallow coring methods are catalogued in the PETLAB database (pet.gns.cri.nz).

2.4.8.2. International Collaborations

In addition to the research activities being undertaken by the New Zealand-based geoscientific community, there is substantial interest from the global scientific community in subduction-related research in the New Zealand region. Researchers from Germany, Japan, France, the United Kingdom, Australia, and several other countries already have ongoing projects related to subduction in New Zealand. Collaborative international efforts and future international community experiments at the New Zealand primary site offer outstanding opportunities that will greatly amplify the outcomes of any NSF/GeoPRISMS investments there.

Strong tectonic similarities between NZ and Japan, and common interests in seismic and tsunami hazard, has led to mounting interest from Japanese researchers in conducting projects on New Zealand's subduction setting. The University of Tokyo's Earthquake Research Institute (ERI) is heavily involved in the SAHKE project to image the locked part of the Hikurangi subduction interface. ERI and Tohoku University (in collaboration with GNS Science) are conducting pilot deployments of OBS and absolute pressure gauges to investigate slow slip offshore North Hikurangi. Later in 2013, the Japanese submersible Shinkai 6500 is slated to dive at a series of locations along the Kermadec Arc and Kermadec Trench. Japanese researchers are developing plans and proposals to conduct additional future studies in New Zealand, including: OBS and seafloor geodetic studies of slow slip, active source surveys of the subducting Hikurangi Plateau, and offshore magnetotelluric studies of the Hikurangi margin. Moreover, research activities related to the series of IODP proposals for drilling the Hikurangi margin have major Japanese involvement. In the coming years, there is excellent potential for Japanese research vessels to conduct studies in New Zealand waters (such as seismic surveys, OBS deployments, and ROV deployments) that will complement any GeoPRISMS funded studies.

Researchers from Germany have a long-standing interest in New Zealand subduction science, and have conducted a number of studies in the New Zealand region, including the MANGO project (wide-angle seismic data across the Hikurangi and Kermadec margins), and several research cruises to investigate gas hydrates and fluid flow at the offshore Hikurangi margin, explore seafloor hydrothermal systems related to submarine arc volcanoes, and to map and sample the Hikurangi Plateau. Some projects are scheduled to be undertaken using the German research vessel Sonne in 2014/2015, while others are being proposed. One scheduled project is to use MeBo (a seafloor based drilling rig) to core submarine landslides in the region of the proposed IODP drilling transect at North Hikurangi, while another will have a specific focus on hydrothermal systems and their capacity to form mineral deposits and host extreme microorganisms. There is interest among German researchers in conducting geochemical sampling and hydrological monitoring at offshore seeps to investigate the role of hydrogeology in the seismic behavior of the Hikurangi subduction thrust. A proposal is also in development to investigate the evolution of the Vitiaz-Kermadec Arc from arc initiation to arc splitting through formation of the Havre Trough through extensive sampling and detailed mapping (multibeam, gravity, magnetics) along the southern part of the Kermadec and Colville Ridges and Havre Trough. All of these studies will contribute greatly to the major SCD questions outlined for the New Zealand primary site, and will underpin future GeoPRISMS funded studies.

The UK has a long history of research collaboration with New Zealand, particularly in the area of tectonics. Currently, UK researchers are actively collaborating on arc volcanism, mineralization and fault processes within the Kermadec-Tonga Arc, and extensional fault networks within the Taupo backarc. Specifically related to subduction, UK researchers from Universities of Oxford and Durham have conducted active seismic experiments across the Tonga-Kermadec arc, studying the impact of seamount subduction and arc volcano eruptive and collapse processes. Tectono-magmatic interactions and the economic resources of arc volcanic systems within the Kermadec arc have involved both UK-led projects and UK-NZ collaborations primarily between University of Southampton, GNS Science and NIWA, including the newly submitted Brothers volcano IODP proposal. The University of Leeds has collaborated with New Zealand researchers in an active seismic experiment to analyze the large-scale structure of the Hikurangi subduction zone. A number of potential future collaborative experiments, prompted by the IODP proposal for the northern Hikurangi margin, are in the planning or proposal stages. These include support for a 3D seismic proposal within the targeted drilling area (to be submitted to NSF), and an Imperial College, London proposal to conduct a 3D full waveform inversion complementing other seismic studies in the area. In addition, UK partners (primarily Southampton and Imperial) are investigating potential OBS seismic experiments and/or EM-MT to further illuminate structure, physical properties and fluid processes within the subduction forearc, plate boundary and downgoing plate.

A number of researchers from the France, Australia, and Canada also have ongoing interests and involvement in New Zealand subduction research across the entire range of SCD topics, offering additional important partnership opportunities at the New Zealand primary site. In addition to substantial scientific expertise in subduction-related topics, these countries have marine geophysical and laboratory/analytical capabilities that could be brought to bear on a variety of SCD topics. Two proposed French cruises to use the RV L'Atalante to investigate Tonga-Kermadec-Hikurangi subduction initiation have been ranked very highly, and await scheduling.

8.3. International Ocean Discovery Program Opportunities

Historically, the MARGINS and IODP communities have had strong linkages because of IODP subduction drilling efforts at MARGINS focus sites at Nankai, Costa Rica, and the Izu-Bonin-Mariana system. The New Zealand primary site offers an excellent opportunity to continue this relationship between GeoPRISMS and IODP; proposals for three subduction-related projects in New Zealand waters have been submitted to IODP over the last 3 years. The proposals are: (1) Hikurangi margin slow slip event drilling (IODP Proposals 781-MDP; 781A-Full; and 781B-Full); (2) Drilling at the Lord Howe Rise to investigate the Eocene record of Tonga/Kermadec/Hikurangi subduction initiation (IODP Proposal 832-Full); and (3) Drilling at Brother's volcano (Kermadec arc) to investigate the subseafloor hydrology of an arc hydrothermal system, the transfer of metals from magma to seafloor, a range of arc volcanic processes, and the deep biosphere (IODP Proposal 818-Pre). The aims of all three of these proposed projects are strongly allied with GeoPRISMS SCD science questions, and if they are scheduled for drilling, we expect that they will yield significant opportunities for leveraged studies and integration with GeoPRISMS investigations. It is also anticipated that the IODP projects will help motivate and focus future GeoPRISMS studies in New Zealand.

2.4.9. Broader Impacts

2.4.9.1. Geohazards

Given its position astride the boundary zone between the Pacific and Australian Plates, New Zealand is exposed to significant geohazards. The sequence of devastating earthquakes in Christchurch in 2010 and 2011 highlights this, with insured economic losses on the order of 20-30 billion dollars, making it the third costliest earthquake in history. A large proportion of the geohazards that New Zealand faces are related to the Hikurangi/Kermadec and Puysegur subduction plate boundaries. The outcomes of GeoPRISMS SCD efforts in New Zealand will provide important new insights into the seismic, tsunami, and volcanic hazards posed by the subduction zones there.

Subduction margins produce the largest and most destructive earthquakes and tsunamis on Earth. In particular, there is very little knowledge about the past seismic behavior of the Hikurangi subduction, which poses what is arguably the largest "unknown" seismic and tsunami hazard to New Zealand. Can the Hikurangi subduction margin produce giant (Mw ~9.0) earthquakes similar to that observed in Tohoku in 2011? Further paleoseismic studies are needed to address this. New insights gained from GeoPRISMS SCD studies into the cause of the transition from interseismic coupling (southern Hikurangi) to aseismic creep (northern Hikurangi) will have global significance for our knowledge of why some subduction thrusts lock up and produce large earthquakes, while others tend to accommodate plate motion largely aseismically. Knowledge of the mechanics of fault slip behavior on subduction thrust interfaces are necessary to understand and mitigate the hazards posed by these major plate boundary features. Another important outstanding question involves the relationship of slow slip events to major megathrust earthquakes. Can slow slip events trigger major, damaging earthquakes? Due to the strong association between SSEs and microseismicity, New Zealand is an ideal location to evaluate this important, societally relevant question.

New Zealand has been the site of major explosive volcanic eruptions, including supervolcano eruptions at Taupo Caldera, such as the Oruanui eruption 26,500 years ago that produced ~1200 km^3 of eruptive material. Since European settlement, a few smaller-scale eruptions and unrest events have occurred, with the largest being the eruption of Mount Tarawera (~2 km^3 of eruptive material) in 1886. Secondary effects of eruptions have also proven hazardous, such as a lahar in 1953 that took out a railway bridge, killing 151 people, and ash from a 1966 eruption of Ruapehu volcano that disrupted services at several airports. Imaging magma supply at depth via MT or seismic surveys will enable better understanding of the location of potential future eruptions. GeoPRISMS research on volatile cycling and the magmatic plumbing system will enable better understanding of the feedbacks between volatile content, magma chemistry and eruptive style.

2.4.9.2. Economic Resources

The offshore New Zealand region contains petroleum and minerals resources, although the extent of these resources is not fully understood. Studies of the offshore Kermadec arc may yield new insights into the formation of metals at submarine volcanoes. For example, some of the most acidic, high-temperature and metal-rich fluids ever seen occur at the vent sites of Brothers Volcano. Moreover, the hydrothermal system at Brothers contains the ex-solution of gases from the active magmatic system below, thus the transportation of metals to the seafloor and eruption processes can also be studied. Extensive petroleum resources are currently being exploited in the Taranaki Basin, a retroarc foreland basin, which also holds a signature of vertical motions during subduction inception at the Hikurangi margin. Similar basins further north also contain a record of subduction initiation, and any seismic surveys from these areas (and other areas in New Zealand) will contribute to regional characterization of resource potential in these areas. Abundant gas hydrates exist at the offshore Hikurangi margin; seismic, heat flow, and fluid geochemical studies offshore Hikurangi may yield new insights into gas hydrate formation.

2.4.9.3. Engaging Local Communities

The significant geohazard potential of the New Zealand region elicits great public concern and interest in learning about the seismic, tsunami, and volcanic hazards that they are exposed to. It will be important to coordinate public outreach on GeoPRISMS projects at the New Zealand primary site in collaboration with colleagues at New Zealand universities, at GNS Science, and at NIWA. These activities would include media coverage (radio and television interviews, newspaper articles), and directly interfacing with the public through lectures and ship tours. We anticipate that such exchanges will help inspire the next generation of New Zealand geoscientists (including underrepresented groups such as Maori), as well as inform the local population and foster good will. There was substantial local media coverage of the recent GeoPRISMS Implementation Plan workshop for the New Zealand primary site held in Wellington, New Zealand in April 2013. This included several radio interviews on New Zealand National Radio, and high-profile articles in the major newspapers, such as the Dominion Post and New Zealand Herald. In part due to recent disasters such as the Christchurch earthquakes in 2010-2011, the New Zealand public and media have a large appetite for learning about geohazards in New Zealand. This will certainly broaden the impact of any GeoPRISMS funded studies in New Zealand.